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# Development of an ion transport system for singly charged ion injection into an electron string ion source (ESIS) charge-breeder



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### Abstract

A  $1+$  ion delivery system was designed and constructed for the purpose of ion injection into the Electron String Ion Source (ESIS) charge-breeder at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia. The transport system was initially developed at iThemba LABS in Cape Town. This system includes a Liquid Metal Ion Source (LMIS) and an ion extraction and focusing system. The ion delivery system is used to produce  $\text{Ga}^+$  and  $\text{Au}^+$  ions which are transported through a beam-line system consisting of charged particle optics such as focusing einzel-lenses, an electrical quadrupole switchyard for  $90^\circ$  beam bending, and subsequent correction and focusing lenses before the entry port into the ESIS. A replica of the full system was created and used to study injection and ion transport efficiency before implementation with the ESIS. A multi-wire harp beam profilometer was used to study ion beam profiles and to obtain geometric parameters of  $\text{Ga}^+$  beams.

$\text{Ga}^+$  injection into the KRION 6T ESIS was performed successfully using the ion injection system. The extraction of multiply charged gallium was successful after  $1+$  injection into the KRION 6T ESIS, with a maximum charge-state of  $23+$ . Although  $1+$  to  $n+$  injection has been performed with similar Electron Beam Ion Source (EBIS) devices, this work is the first case of  $1+$  to  $n+$  injection using the ESIS.

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# Contents

|                                                                     |             |
|---------------------------------------------------------------------|-------------|
| <b>Contents</b>                                                     | <b>i</b>    |
| <b>List of Figures</b>                                              | <b>vi</b>   |
| <b>List of Tables</b>                                               | <b>xi</b>   |
| <b>Acknowledgments</b>                                              | <b>xiii</b> |
| <b>1 Introduction</b>                                               | <b>1</b>    |
| 1.1 The Quest for Highly Charged Ions . . . . .                     | 1           |
| 1.1.1 High Charge States for Acceleration . . . . .                 | 2           |
| 1.1.2 Rare isotopes at iThemba LABS . . . . .                       | 3           |
| 1.1.3 Production of highly charged radio-active ion beams . . . . . | 4           |
| 1.1.4 Short breeding time . . . . .                                 | 5           |
| 1.1.5 Beam Purity . . . . .                                         | 5           |
| 1.1.6 Single charge-state . . . . .                                 | 6           |
| 1.2 Charge Breeding: Overview . . . . .                             | 6           |
| 1.2.1 The First Method: In-Flight Charge Stripping . . . . .        | 7           |
| 1.2.2 Electron Cyclotron Resonance Ion Source (ECRIS) . . . . .     | 7           |
| 1.2.3 Electron Beam Ion Source (EBIS) . . . . .                     | 13          |
| 1.2.4 Electron String Ion Source (ESIS) . . . . .                   | 17          |

|          |                                                                         |           |
|----------|-------------------------------------------------------------------------|-----------|
| 1.3      | Research Goal: External Injection of Singly Charged Ions into the ESIS  | 21        |
| 1.3.1    | External Singly Charged Ion Injection . . . . .                         | 21        |
| 1.3.2    | Design of an Ion Transport System for Accelerator Experiments           | 23        |
| <b>2</b> | <b>Charge Breeding and External Injection of Ions</b>                   | <b>25</b> |
| 2.1      | Beam Physics and Ion Transport . . . . .                                | 25        |
| 2.1.1    | Modelling a Charged Particle Beam . . . . .                             | 26        |
| 2.1.2    | Emittance . . . . .                                                     | 26        |
| 2.1.3    | Charge Breeder Acceptance . . . . .                                     | 32        |
| 2.1.4    | Efficiency . . . . .                                                    | 33        |
| 2.2      | Modelling Ionization Processes in EBIS and ESIS . . . . .               | 34        |
| 2.2.1    | Ion Trap Physics . . . . .                                              | 35        |
| 2.2.2    | The Electron String . . . . .                                           | 36        |
| 2.2.3    | Ionization Process: Electron-Impact Ionization . . . . .                | 36        |
| 2.2.4    | Competing Processes . . . . .                                           | 42        |
| 2.2.5    | Cooling Techniques . . . . .                                            | 45        |
| 2.2.6    | Modelling Charge State Evolution . . . . .                              | 46        |
| <b>3</b> | <b>Beam Transport Simulations</b>                                       | <b>50</b> |
| 3.1      | Opera 3D: TOSCA . . . . .                                               | 50        |
| 3.2      | SIMION . . . . .                                                        | 51        |
| 3.3      | Simulation Boxes . . . . .                                              | 52        |
| <b>4</b> | <b>Development of Injection System</b>                                  | <b>53</b> |
| 4.1      | Overview of required system . . . . .                                   | 54        |
| 4.1.1    | Summary of System Requirements . . . . .                                | 56        |
| 4.2      | Simulations of ion source extraction, focusing and quadrupole bending . | 56        |
| 4.2.1    | TOSCA Simulations . . . . .                                             | 57        |

|          |                                                                    |           |
|----------|--------------------------------------------------------------------|-----------|
| 4.2.2    | SIMION Simulations . . . . .                                       | 61        |
| 4.3      | The Liquid Metal Ion Source . . . . .                              | 61        |
| 4.4      | Building the ion delivery system . . . . .                         | 64        |
| 4.4.1    | The $\text{Ga}^+$ LMIS delivery system . . . . .                   | 64        |
| 4.4.2    | Electrical considerations . . . . .                                | 68        |
| 4.4.3    | Adjustable parameters . . . . .                                    | 69        |
| 4.5      | Testing the system . . . . .                                       | 69        |
| 4.5.1    | Validation of $\text{Ga}^+$ ions . . . . .                         | 71        |
| 4.5.2    | Stability . . . . .                                                | 72        |
| 4.5.3    | Electrode biasing for ideal ion current . . . . .                  | 73        |
| 4.5.4    | Ion current loss between FC1 and FC2 . . . . .                     | 74        |
| 4.5.5    | Optimum tip-to-plate distance, $d$ . . . . .                       | 77        |
| 4.5.6    | Design improvements . . . . .                                      | 78        |
| 4.5.7    | Conclusions for ion assembly prototype tests . . . . .             | 79        |
| 4.6      | The DRE-EBIT Quadrupole Switch-yard . . . . .                      | 79        |
| 4.7      | Optimizing the ion injection transport system . . . . .            | 81        |
| 4.7.1    | Ion current measurements: straight vs bending directions . . . . . | 81        |
| 4.7.2    | Pulse-mode . . . . .                                               | 82        |
| 4.8      | Completion of Injection System . . . . .                           | 87        |
| 4.8.1    | The Next Phase . . . . .                                           | 87        |
| <b>5</b> | <b>Singly Charged Ion Beam Measurements</b>                        | <b>89</b> |
| 5.1      | Initial Ion Beam Analysis . . . . .                                | 90        |
| 5.2      | Beam Profile Measurements . . . . .                                | 90        |
| 5.2.1    | The Harp Beam Profilometer . . . . .                               | 91        |
| 5.2.2    | KRION 6-T ion injection and extraction components . . . . .        | 92        |
| 5.2.3    | Data acquisition . . . . .                                         | 94        |

|          |                                                                        |            |
|----------|------------------------------------------------------------------------|------------|
| 5.2.4    | Calculation of transverse emittance and beam-width . . . . .           | 95         |
| 5.3      | Harp Beam Profiling: Initial Experimental Results . . . . .            | 102        |
| 5.3.1    | Analysis and discussion: Harp beam profiling . . . . .                 | 107        |
| 5.3.2    | ESIS injection considerations . . . . .                                | 108        |
| 5.4      | Experiments for Optimizing Pulsed Beam Bending . . . . .               | 110        |
| 5.4.1    | Optimizing ion optics for lower energy beams, with pulse-mode .        | 111        |
| 5.4.2    | Pulse-timing settings and harp delay . . . . .                         | 118        |
| <b>6</b> | <b>Ion Transport System Tests with Replica ESIS Entry-Port</b>         | <b>123</b> |
| 6.1      | Design of Complete Ion Transport System . . . . .                      | 123        |
| 6.2      | First ESIS Injection Measurements with Replica Entrance Port . . . . . | 126        |
| 6.2.1    | Experimental parameter settings . . . . .                              | 127        |
| 6.2.2    | Measurements of beam half-width . . . . .                              | 129        |
| 6.2.3    | Measurements of beam axial offset . . . . .                            | 131        |
| 6.2.4    | Best results . . . . .                                                 | 131        |
| 6.3      | Refined ESIS Injection Measurements with Replica Entrance Port . . .   | 133        |
| 6.3.1    | Refining beam alignment and focusing onto the harp . . . . .           | 133        |
| 6.3.2    | Refined Beam Measurements . . . . .                                    | 134        |
| 6.3.3    | Replica ESIS Injection Results . . . . .                               | 134        |
| 6.3.4    | Beam Visualization . . . . .                                           | 144        |
| 6.3.5    | Discussion: Best ESIS Injection Results . . . . .                      | 145        |
| 6.4      | Conclusions of Replica ESIS Experiments . . . . .                      | 145        |
| <b>7</b> | <b>ESIS Charge Multiplication from Singly Charged Ion Injection</b>    | <b>150</b> |
| 7.1      | Experiment Setup . . . . .                                             | 151        |
| 7.1.1    | Ion Transport into KRION 6T ESIS . . . . .                             | 151        |
| 7.1.2    | Vacuum Conditions . . . . .                                            | 155        |
| 7.1.3    | System Configuration for 1.7 keV Ga <sup>+</sup> ions . . . . .        | 155        |

|          |                                                                    |            |
|----------|--------------------------------------------------------------------|------------|
| 7.2      | Ion Extraction from KRION . . . . .                                | 159        |
| 7.2.1    | Fast Extraction . . . . .                                          | 159        |
| 7.2.2    | Slow Extraction . . . . .                                          | 160        |
| 7.2.3    | Measuring highly charged ions . . . . .                            | 160        |
| 7.3      | Charge Multiplication . . . . .                                    | 162        |
| 7.3.1    | Initial tests with xenon . . . . .                                 | 162        |
| 7.3.2    | Ga <sup>1+</sup> injection . . . . .                               | 162        |
| 7.3.3    | Ga <sup>n+</sup> results . . . . .                                 | 162        |
| 7.3.4    | ESIS A/q spectra using CBSIM-Analysis . . . . .                    | 164        |
| 7.3.5    | Conclusion of Ion Injection Experiments . . . . .                  | 172        |
| <b>8</b> | <b>Discussion and Conclusion</b>                                   | <b>173</b> |
| 8.1      | Charge Breeding Efficiency . . . . .                               | 173        |
| 8.1.1    | Efficiency result and limitations in efficiency measurements . . . | 175        |
| 8.2      | Discussion of results . . . . .                                    | 176        |
| 8.2.1    | ESIS neutralization during charge breeding . . . . .               | 176        |
| 8.3      | Feasibility of singly charged ion injection into ESIS . . . . .    | 178        |
| 8.3.1    | Prospects of ESIS Charge Breeding at iThemba LABS . . . . .        | 179        |
| 8.4      | Future work with 1+ ESIS injection . . . . .                       | 179        |
| 8.5      | Future prospects of 1+ to n+ charge-breeding with ESIS . . . . .   | 180        |
| 8.6      | Word of thanks . . . . .                                           | 180        |
|          | <b>Bibliography</b>                                                | <b>182</b> |

# List of Figures

|      |                                                                                                                                                                    |    |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 1.1  | ECRIS Operation Scheme . . . . .                                                                                                                                   | 9  |
| 1.2  | ECRIS Pb A/q Spectra . . . . .                                                                                                                                     | 11 |
| 1.3  | ECRISworldwide . . . . .                                                                                                                                           | 12 |
| 1.4  | EBIS Operation Scheme . . . . .                                                                                                                                    | 15 |
| 1.5  | EBISworldwide . . . . .                                                                                                                                            | 16 |
| 1.6  | Long confinement argon A/q spectrum from Dresden EBIS-A [30]. The<br>y-scale is in arbitrary units showing the relative abundance of the charge-<br>state. . . . . | 17 |
| 1.7  | Extracted argon A/q from SUPERNANOGUN ECRIS [31]. The y-scale<br>is in arbitrary units showing the relative abundance of the charge-state. . . . .                 | 17 |
| 1.8  | ESIS Operation Scheme . . . . .                                                                                                                                    | 18 |
| 1.9  | 300 ms confinement of argon in KRION-2T ESIS . . . . .                                                                                                             | 20 |
| 1.10 | 500 ms confinement of argon in KRION-2T ESIS. . . . .                                                                                                              | 20 |
| 1.11 | Dresden LMAIS Beam Fascility . . . . .                                                                                                                             | 23 |
| 2.1  | Emittance and Phase Space . . . . .                                                                                                                                | 28 |
| 2.2  | Formation of Electron String . . . . .                                                                                                                             | 37 |
| 2.3  | SingleIonization . . . . .                                                                                                                                         | 39 |
| 2.4  | DoubleIonization . . . . .                                                                                                                                         | 39 |

|      |                                                             |    |
|------|-------------------------------------------------------------|----|
| 2.5  | DoubleIonization . . . . .                                  | 41 |
| 2.6  | Evolution of Ge charge-states . . . . .                     | 48 |
| 4.1  | Injection with Biased Switch-Yard . . . . .                 | 55 |
| 4.2  | Extraction with Un-biased Switch-Yard . . . . .             | 55 |
| 4.3  | Simplified overview in TOSCA . . . . .                      | 57 |
| 4.4  | TOSCA: Switch-yard . . . . .                                | 58 |
| 4.5  | TOSCA Bending X phase-space . . . . .                       | 59 |
| 4.6  | TOSCA Bending Z phase-space . . . . .                       | 59 |
| 4.7  | TOSCA: Correctors . . . . .                                 | 60 |
| 4.8  | SIMION Bending Example . . . . .                            | 61 |
| 4.9  | gallium LMIS . . . . .                                      | 62 |
| 4.10 | Taylor Cone Formation . . . . .                             | 63 |
| 4.11 | Mechanical Schematic of Prototype . . . . .                 | 64 |
| 4.12 | AP-Tech LMIS Dimensions . . . . .                           | 65 |
| 4.13 | Prototype Ion Gun . . . . .                                 | 66 |
| 4.14 | LMIS Assembly Circuit Diagram . . . . .                     | 68 |
| 4.15 | Magnet Lab Test Bench . . . . .                             | 70 |
| 4.16 | Test Bench Diagram . . . . .                                | 71 |
| 4.17 | First Stability Measurement . . . . .                       | 72 |
| 4.18 | Electrode biasing effect on $\text{Ga}^+$ current . . . . . | 74 |
| 4.19 | Ion Transmission between two Faraday Cups . . . . .         | 76 |
| 4.20 | Dre-EBIT Electric Quadrupole Switch-yard . . . . .          | 80 |
| 4.21 | Initial Ion Bending Setup . . . . .                         | 80 |
| 4.22 | First Bending Tests . . . . .                               | 81 |
| 4.23 | First Technical Drawing . . . . .                           | 88 |
| 5.1  | Harp profilometer . . . . .                                 | 91 |

|      |                                                               |     |
|------|---------------------------------------------------------------|-----|
| 5.2  | Injection and extraction cycle . . . . .                      | 93  |
| 5.3  | Harp data acquisition . . . . .                               | 94  |
| 5.4  | Data analysis flowchart for HIBA.m . . . . .                  | 96  |
| 5.5  | HIBA.m output . . . . .                                       | 97  |
| 5.6  | Fitting Gaussians to beam profiles . . . . .                  | 98  |
| 5.7  | Emittance determination . . . . .                             | 101 |
| 5.8  | Exp A: Emittance . . . . .                                    | 105 |
| 5.9  | Exp A: Min. beam width . . . . .                              | 105 |
| 5.10 | Exp A: Beam width in x . . . . .                              | 106 |
| 5.11 | Harp after extended use . . . . .                             | 109 |
| 5.12 | Profilometer location post bending . . . . .                  | 111 |
| 5.13 | Optimizing extractor plate bias for 2.4 keV beam . . . . .    | 114 |
| 5.14 | Optimizing einzel lens bias for 2.4 keV beam . . . . .        | 114 |
| 5.15 | Optimizing extractor plate bias for 2.5 keV beam . . . . .    | 115 |
| 5.16 | Optimizing einzel lens bias for 2.5 keV beam . . . . .        | 115 |
| 5.17 | Optimizing quadrupole switch-yard for 2.4 keV beam . . . . .  | 116 |
| 5.18 | Effect of harp delay on beam width . . . . .                  | 120 |
| 5.19 | Effect of harp delay on current measured by the harp. . . . . | 120 |
| 5.20 | Effect of harp delay on y-width along beam-axis . . . . .     | 121 |
| 6.1  | Complete Transport System with ESIS replica . . . . .         | 124 |
| 6.2  | Photograph of Complete Transport System . . . . .             | 127 |
| 6.3  | Trial 3: Beam Width . . . . .                                 | 129 |
| 6.4  | Trial 3: Beam Offset . . . . .                                | 131 |
| 6.5  | Beam Refining . . . . .                                       | 134 |
| 6.6  | Summed beam profiles for Trial 1. . . . .                     | 137 |
|      | (a) X-Profiles . . . . .                                      | 137 |

|      |                                                                                                                                                  |     |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| (b)  | Y-Profiles . . . . .                                                                                                                             | 137 |
| 6.7  | Summed beam profiles for Trial 2. . . . .                                                                                                        | 137 |
| (a)  | X-Profiles . . . . .                                                                                                                             | 137 |
| (b)  | Y-Profiles . . . . .                                                                                                                             | 137 |
| 6.8  | Summed beam profiles for Trial 3. . . . .                                                                                                        | 138 |
| (a)  | X-Profiles . . . . .                                                                                                                             | 138 |
| (b)  | Y-Profiles . . . . .                                                                                                                             | 138 |
| 6.9  | Summed beam profiles for Trial 4. . . . .                                                                                                        | 138 |
| (a)  | X-Profiles . . . . .                                                                                                                             | 138 |
| (b)  | Y-Profiles . . . . .                                                                                                                             | 138 |
| 6.10 | Summed beam profiles for Trial 5. . . . .                                                                                                        | 138 |
| (a)  | X-Profiles . . . . .                                                                                                                             | 138 |
| (b)  | Y-Profiles . . . . .                                                                                                                             | 138 |
| 6.11 | Minimum Half-widths: Saturated . . . . .                                                                                                         | 140 |
| 6.12 | Minimum Half-widths: Best . . . . .                                                                                                              | 141 |
| 6.13 | Axial Offset Example . . . . .                                                                                                                   | 142 |
| 6.14 | Axial Offset Best Beam . . . . .                                                                                                                 | 143 |
| 6.15 | Side-view obtained from colour-mapping the beam profiles as current<br>density measured by the harp at six locations. Trials 1, 2 and 3. . . . . | 146 |
| (a)  | Trial 1: X side view . . . . .                                                                                                                   | 146 |
| (b)  | Trial 1:Y side view . . . . .                                                                                                                    | 146 |
| (c)  | Trial 2: X side view . . . . .                                                                                                                   | 146 |
| (d)  | Trial 2: Y side view . . . . .                                                                                                                   | 146 |
| (e)  | Trial 3: X side view . . . . .                                                                                                                   | 146 |
| (f)  | Trial 3: Y side view . . . . .                                                                                                                   | 146 |
| 6.16 | Side-view obtained from colour-mapping the beam profiles as current<br>density measured by the harp at six locations. Trials 4 and 5. . . . .    | 147 |

|      |                                                           |     |
|------|-----------------------------------------------------------|-----|
| (a)  | Trial 4: X side view . . . . .                            | 147 |
| (b)  | Trial 4: Y side view . . . . .                            | 147 |
| (c)  | Trial 5: X side view . . . . .                            | 147 |
| (d)  | Trial 5: Y side view . . . . .                            | 147 |
| 6.17 | Beam-density maps at six harp locations. Trial 5. . . . . | 148 |
| (a)  | D = 4 mm . . . . .                                        | 148 |
| (b)  | D = 8 mm . . . . .                                        | 148 |
| (c)  | D = 12 mm . . . . .                                       | 148 |
| (d)  | D = 16 mm . . . . .                                       | 148 |
| (e)  | D = 20 mm . . . . .                                       | 148 |
| (f)  | D = 24 mm . . . . .                                       | 148 |
| 7.1  | Final Scheme . . . . .                                    | 152 |
| 7.2  | Timing Scheme . . . . .                                   | 158 |
| 7.3  | Voltage-Chopper . . . . .                                 | 161 |
| 7.4  | HC xenon . . . . .                                        | 163 |
| 7.5  | Charge Species Contaminants . . . . .                     | 165 |
| 7.6  | Gallium 17+ Peak . . . . .                                | 166 |
| 7.7  | Gallium 15+ Peak . . . . .                                | 167 |
| 7.8  | Gallium Mixed Peaks . . . . .                             | 168 |
| 7.9  | CBSIMcalculation . . . . .                                | 169 |
| 7.10 | Gallium Peaks . . . . .                                   | 171 |
| 8.1  | 0.4nC all charge-states . . . . .                         | 174 |
| 8.2  | SAIF Map . . . . .                                        | 181 |

# List of Tables

|     |                                                                                                                                                          |     |
|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 1.1 | Electron Gun Power Consumption of an EBIS compared to the ESIS . .                                                                                       | 19  |
| 4.1 | Electrode Settings for First Successful Ion Beam Bending . . . . .                                                                                       | 82  |
| 5.1 | Experiment A: Un-normalized and normalized transverse emittance re-<br>sults with increasing beam energy . . . . .                                       | 104 |
| 5.2 | Experiment B: Transverse emittance results for higher total ion current,<br>at higher beam-widths. . . . .                                               | 106 |
| 5.3 | Experiment C: Transverse emittance results after 90° quadrupole bend-<br>ing, at lower ion current. . . . .                                              | 107 |
| 5.4 | Ion-optics settings for optimal beam bending with varying beam energy<br>given by $U_{ex}$ . . . . .                                                     | 112 |
| 5.5 | Results for optimal beam bending with varying beam energy . . . . .                                                                                      | 112 |
| 5.6 | Optimal bias settings on extractor plate and einzel lenses prior switch-<br>yard for maximum current delivered in the straight pass direction $I_{SC}$ . | 113 |
| 5.7 | Constant ion-optics biasing for pulse-timing investigations of 2.0 keV beam                                                                              | 118 |
| 5.8 | Investigating emittance for varying harp-delay times . . . . .                                                                                           | 122 |

|     |                                                                                                                                                                                                                                                            |     |
|-----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 6.1 | Ion optics biasing and pulse settings for first replica injection tests. Voltages not mentioned here were varied between the trials, and harp delay times for each trial were 1.5 ms, 1.3 ms and 1.5 ms again, respectively for Trials 1, 2 and 3. . . . . | 128 |
| 6.2 | Comparison of results between initial ion-injection test Trials 2 and 3. .                                                                                                                                                                                 | 132 |
| 6.3 | Ion-optics biasing for Trials 2 and 3. . . . .                                                                                                                                                                                                             | 132 |
| 6.4 | Ion-optics biasing for best replica ESIS injection results. All values listed are in kV. . . . .                                                                                                                                                           | 135 |
| 6.5 | Pulse-mode settings for ion injection into replica ESIS. All values are in milli-seconds. Harp integration time was 500 $\mu$ s for Trials 1-4, and 800 $\mu$ s for Trial 5. . . . .                                                                       | 136 |
| 6.6 | Beam transmission between quadrupole switch-yard and harp profilometer. Harp current at closest position ( $D = 0.4$ cm) is compared to straight collector current while switch-yard is un-powered. . . . .                                                | 139 |
| 6.7 | Analysis of beam offsets in X-transverse direction for five trials . . . . .                                                                                                                                                                               | 142 |
| 6.8 | Analysis of beam offsets in Y-transverse direction for five trials . . . . .                                                                                                                                                                               | 142 |
| 6.9 | 90 % Transverse emittance results for replica ESIS injection Trials 1 to 5.                                                                                                                                                                                | 144 |
| 7.1 | Ion-optics biasing for real ESIS injection experiments. . . . .                                                                                                                                                                                            | 156 |
| 7.2 | KRION 6T ESIS settings for $\text{Ga}^+$ injection . . . . .                                                                                                                                                                                               | 164 |
| 7.3 | Charge states of gallium obtained with increasing $\tau_{confine}$ . . . . .                                                                                                                                                                               | 170 |
| 7.4 | Estimating ESIS current-density with CBSIM-Analysis . . . . .                                                                                                                                                                                              | 170 |
| 7.5 | Electron energies in electron string[75] . . . . .                                                                                                                                                                                                         | 172 |
| 8.1 | Comparison of Performance Characteristics of Various Charge-Breeders. Normalized emittance values are noted with a *. . . . .                                                                                                                              | 177 |

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# Chapter 1

## Introduction

### 1.1 The Quest for Highly Charged Ions

The production and delivery of multiply charged or highly charged ions (HCIs) and isotopes is of fundamental importance for particle accelerators and the nuclear and particle physics experiments these accelerators are designed to perform. Ion sources known as charge-breeders, capable of delivering HCIs, have become prolific in high energy physics laboratories around the world.

A particle accelerator uses electric fields to increase the energy of a charged particle beam. At non-relativistic velocities, the amount of kinetic energy,  $T$ , received by an ion from an electric field is proportional to its electric charge,  $Q$ , multiplied by the potential difference, or voltage,  $V$ , across the accelerating gap where the electric field exists:

$$T = QV$$

The electric charge of an ion is equal to the number of missing or added electrons, or charge-state,  $n$ , multiplied by the charge of an electron,  $q$ ,

$$Q = nq$$

It is clear that if  $n$  is large, the beam will obtain higher energies for a given accelerator gap voltage. It is therefore advantageous to begin the acceleration process with highly charged ions which can be provided by a charge-breeder.

A charge-breeder essentially ionizes atoms and multiplies electric charge on ions by removing electrons through the bombardment of these atoms or ions with high energy electrons. This ionization process is ideal for creating HCIs in short amounts of time.

This duration is shortened significantly by increasing the electron current density within the confining/trapping volume of the charge-breeder.

Electric or magnetic fields are used to trap the ions, confining them as they undergo this charge-breeding process. The energy barriers caused by the electric or magnetic trap can be operated like sluice-gates, which upon lowering releases the HCIs into the particle accelerator or other experiments<sup>1</sup>.

Various types of experiments make use of HCIs. At the Large Hadron Collider (LHC) in CERN, Geneva, Switzerland, two counter rotating beams of highly charged lead ions are smashed into each other in order to study the quark-gluon plasma and myriad sub-atomic particles produced by the collision energy, and to perhaps glimpse the Higgs-Boson. Similar experiments are performed at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), New York, USA. Many laboratories also make use of HCI beams in fixed target experiments such as iThemba LABS, South Africa, to study nuclear fusion and fission reactions. The reaction complex, and decaying daughter nuclei allow the exploration of nuclear structure and the radioactive decay channels of interesting isotopes and even the nuclear "Terra-Incognita", where new atoms and isotopes not yet present on the table of nuclides may still be discovered.

Certain charge-breeders may also be engineered to favour a particular specification depending on the purpose of the beam and experiments.

### 1.1.1 High Charge States for Acceleration

The charge-to-mass ratio,  $Q/A$ , is important for reaching higher energy beams with both linear and cyclotron accelerators. However the pulsed EM fields of the accelerating RF-cavities used in both types of accelerators require a range of acceptable  $Q/A$  values for efficient beam transport. Lighter ions can easily reach maximum  $Q/A$  values such as 1.0 for hydrogen, or 0.5 for helium. Unfortunately, heavier ions possessing the same  $Q/A$  ratio as contaminant species are difficult to separate using analysing magnets, therefore a certain charge-state that will give a unique  $Q/A$  value may be chosen in order to ensure a certain element under scrutiny is not contaminated. A  $Q/A$  ratio can be chosen for this that will be unique to the selected species, and impossible to find in any contaminants, thereby eliminating the possibility of their being contaminating species with the same  $Q/A$  in the charge-breeder output. This can be easily achieved with heavier ions as more choices for  $Q$  are available. Furthermore, masking can also be caused by isobars of the same charge-state. Isobars are other atoms/isotopes with the same mass as the atom/isotope of interest.

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<sup>1</sup>Although HCIs are extracted from charge-breeders for post-acceleration, it is rare for them to be completely free of electrons - due to strongly bound K-shell electrons. Therefore stripper foils of copper, aluminium or other materials are often placed in the beam path during post-acceleration, which serve to strip off these excess electrons, leaving naked nuclei to undergo experiments - at the price of beam current and efficiency. This was also the first method of obtaining HCI beams before charge-breeders had been invented.

The  $Q/A$  ratio is important for acceleration using a cyclotron: The orbital radius, the radio-frequency accelerating electric fields, the velocity and hence period within the cyclotron, are all dependent on  $Q/A$  of the ion beam. Furthermore, the energy per nucleon attainable with a cyclotron is proportional to  $(Q/A)^2$ . Thus it is essential to reach high ratios with the heavier elements, which is often the main pre-requisite to be mass-selected and post-accelerated after charge-breeding. Stripping the ion to higher charge-states, if required, can be achieved by stripper-foils in the beams flight path. The charge-to-mass ratio is also applicable in time-of-flight charge-state spectra measurement techniques, as the ion velocity depends on the  $Q/A$  value, and the highest  $Q/A$  ratio ions arrive at the detector first. This is also important for linear acceleration which is more commonly used for investigating short-lived radioactive isotopes and their half-lives.

The acceleration of highly charged heavy-ions is now performed in many laboratories world-wide, for example, locally at iThemba LABS, at Argonne National Laboratories (ANL) in USA, at Legnaro National Laboratories in Italy, GANIL, in Caen, France, and the list goes on [1]. The work done in this thesis is in collaboration with the Joint Institute for Nuclear Research (JINR), in Dubna, Russia, which is also where the Nuclotron accelerator is based.

The KRION 6-Tesla Electron String Ion Source (ESIS) is one of the charge-breeders used to provide the Nuclotron with HCIs. This charge breeder can produce a large output of very highly charged ions, and is unique in being the only charge-breeder of its type in the world. A massive nuclear and particle physics project is also being planned at JINR in order to study phases of the quark-gluon plasma in the early universe. This project is called NICA - Nuclotron-based Ion Collider facility, a particle accelerator that will require the use of HCIs from the Krion 6-T ESIS or similar, to reach energies near the TeV range [2].

### 1.1.2 Rare isotopes at iThemba LABS

A new facility to produce Radioactive-Ion Beams (RIBs) by fissioning uranium, is being developed at iThemba LABS, in Cape Town, South Africa. The work presented in this thesis has been undertaken to inform the development of the South African Isotope Facility (SAIF) [3] about the option of using an ESIS as a charge-breeder for RIBs. This facility will use fission fragments as RIBs, which are generally heavier elements, necessitating the requirement for charge-breeding in order to attain high energies efficiently. The work in this thesis serves as an early stage of research and development in building a charge-breeder at iThemba LABS for the post-acceleration of RIBs.

An Electron Beam Ion Source (EBIS) or Electron String Ion Source (ESIS) type charge-breeder offers many advantages for such rare-isotope production experiments. The ESIS in particular - the design and processes of which will be explained in great detail

in Chapters 1 and 2 - has many merits that highlight its usefulness. Clean-beams with limited contamination and high single charge-states, high through-put, and short breeding times and duty cycle characterize the ESIS. Each of these merits will be detailed in Section 1.2.4. The advantages of EBIS make it the chosen charge-breeding method for the EURISOL project[4], and for rare ion beam creation at CARIBU[5], TRIUMF[6], and CERN[7].

### 1.1.3 Production of highly charged radio-active ion beams

Isotope Separation Online (ISOL) was largely pioneered at ISOLDE, CERN[7], and is proposed for the SAIF project of iThemba LABS.

In ISOL, the RIB production target is "thick", meaning that the reaction products stay trapped in the target once they are produced. The Radioactive Experiment at ISOLDE, or REX-ISOLDE, was developed to study RIBS after their charge-multiplication in the REX-EBIS[8]. In this facility, rare isotopes are produced by bombarding a target of uranium carbide with protons of up to 1.4 GeV. Rare isotopes are created via fission, fragmentation and spallation reactions [7]. The radioactive products are released by heating the target, after which they migrate to a 1+ ion-source (typically either a surface ionizer, a laser ion-source, or a plasma ionizer [9]). Low energy ( < 60 keV) RIBs in the 1+ charge-state are directed to a mass analyser to purify the beam, ionized to a low charge-state, and directed into a Penning-trap. The ions are then cooled and bunched within the trap before being injected into the REX-EBIS. After spending some time confined in the EBIS, the charge-bred ions are then extracted for post-acceleration in a linear accelerator for further experimentation and studies.

At iThemba LABS, the SAIF project proposes the use of 66 MeV proton beams to fission uranium in a  $UC_x$  target. Similarly to ISOLDE, isotope separation on-line will be used to transport radioactive nuclei for further charge-breeding with an Electron String Ion Source. The charge-bred ions from ESIS can then be post-accelerated using a linac for experiments.

Low-energy RIBs should be injected into a charge-breeder prior post-acceleration. Charge-breeding time is important as the diffusion/effusion of the radioactive products from the target can be measured in milliseconds. Charge-breeding should not add significantly to this time in order to avoid losses due to radioactive decay. Since RIB intensities are typically many orders of magnitude lower than those of stable beams, high efficiency is also a desired trait.

There are just a few facilities that produce highly charged RIBS. Up to date, ISOLDE[7], CARIBU[5] and TRIUMF[6] are known to employ the use of Electron Beam Ion Sources as charge-breeders during the creation of RIBS.

#### 1.1.4 Short breeding time

A charge-breeder should be able to yield a batch of highly charged ions for a useful beam in a very short amount of time. Not only is this useful for capturing elusive radioactive isotopes that decay very quickly as explained before, but it is also important as a design feature for generating high enough ion current for the worlds biggest particle accelerators that utilize HCIs.

Naturally, the electron-impact ionization, which is the main ionization process in conventional charge-breeders, is counter acted by several competing processes such as radiative recombination and charge capture, so a longer time would be required to reach higher charge-states.

The charge-breeding time,  $\tau$ , to reach a desired charge-state, is therefore an important characteristic of a charge-breeder, and should also be sufficiently short in order to measure short-lived isotopes.

#### 1.1.5 Beam Purity

One purpose of pre-acceleration and charge-breeding processes is to deliver ion beams of a single atomic species, with a required  $Q/A$  ratio for the post-accelerator. Usually a mixture of various species will be caught in the charge-breeder during the ionization process, and therefore several contaminating species may also be extracted in addition to the required particles.

Mass spectrometers or analysing magnets need to be used in most cases in order to separate a clean beam from contaminating species. It is beneficial for a charge breeder to minimize effects which cost the over-all efficiency of the beam transport, such as the contamination of a spectra by species with the same  $Q/A$ . Maximising efficiency is very important when the initial particle count is already low, such as in the case of radioactive isotopes produced in fission experiments or similar. Thus charge breeders that minimize the risk of contaminating beams are favoured.

It is also beneficial to reach  $Q/A$  ratios with a desired species of ions that are not masked by contaminants with the same  $Q/A$  ratio. Only high resolution magnetic spectrometers can resolve isobars that have near identical  $Q/A$  values. In the absence of such a detector, a  $Q/A$  choice can be made to minimize unwanted isobars.

The various means in which contaminants may arise within a charge breeder will be discussed in the next section, where the merits and flaws of the main types of charge breeders are compared.

### 1.1.6 Single charge-state

The ideal beam should also have a narrow charge spread around a desired charge-state, or only a particular charge-state. Every ion in the charge-breeder should reach the same state before extraction with minimal spread over other charge-states. The Q/A selection before post-acceleration will therefore be the most efficient possible.

Radioactive isotopes losses will also be minimized if only one single charge-state of an ion species is produced and accepted by the spectrometer magnets prior to post-acceleration.

## 1.2 Charge Breeding: Overview

The requirement for heavy-ion beams in accelerator experiments first arose in the 1970s. The first accelerators only worked with protons, electrons and lighter, low charge-state ions. The necessity to explore deeper nuclear physics questions encouraged the use of heavy-ion beams and their production therefore became a task that has been improved upon over the decades.

The earliest methods involved a beam of low charge-state ions passing a jet of gas or electrons, which then caused a few steps of ionization with each passing. This method eventually evolved into using various foils placed within the beam path that strip electrons off the ions in the passing beam. Foils are still presently used in accelerators to achieve bare-nuclei after charge breeding, because in many cases the HCIs produced in charge breeding are not completely stripped.

Two main types of devices have since been developed to perform the task of charge-stripping before post-acceleration. They are collectively known as charge-breeders. Firstly, the Electron Cyclotron Resonance Ion Source, or ECRIS [10], has seen use in accelerator laboratories as a source of continuous ions. This device uses a radio-frequency excited plasma of electrons and ions confined in a magnetic bottle to interact with and ionize an injected gas or ion species, which is extracted once a desired charge-state is reached in a continuous mode of operation. ECRIS charge-breeders typically produce a spread-out Q/A spectrum and do not reach very high charge-states for heavier elements. Secondly, the Electron Beam Ion Source, or EBIS, uses a tightly confined electron beam within a strong magnetic solenoid to strip incoming gas or ions to produce HCIs [11]. In this case, the ions are trapped by both the radial potential well caused by the confined electrons, and positive axial barrier potentials on either end of the trapping region. As trapped ions encounter confined electrons, more ionization steps occur. After a certain confinement time one side of the electric trap is opened for the extraction of HCIs. Both ECRIS and EBIS have their advantage and specific uses, and will be discussed herewith.

Finally, a modified version of the EBIS has been developed by Donets, et al, [12],

which uses a strong magnetic field created by superconducting solenoid magnets which confines the electron beam into small radii. This device differs from EBIS in that it also reflects the electron beam back on axis, so that each electron may be reflected several times to make many round-trips in the trapping region before going to the anodes. This combination of strong confining fields and reflected electrons gives rise to a string-like phenomena in the electron beam, which allows this charge-breeder to have a very high charge-state selectivity. This is called an Electron String Ion Source, or ESIS [12].

### 1.2.1 The First Method: In-Flight Charge Stripping

Before sophisticated machines for charge-breeding had been invented, charged particles making orbits in cyclotron type particle accelerators would be brought to higher charge-states by means of in-flight stripping foils.

This was done by inserting sheets of gold, lead or carbon in the beam's path. As the charged particles propagated through the thin material, some electrons would be removed via high energy collisions with stationary atoms within the foil, and these ions would continue to accelerate afterwards subject to the increased electrostatic force afforded by having a higher charge-state [13].

This method had several drawbacks and replacing it became a task for accelerator physicists and engineers in years to come. One failing was that each time the beam encountered the metal foils, some of the ions would be lost, scattered out of the beam. Thus overall efficiency of the cyclotron would be reduced during each orbit of the beam when the foil is encountered.

Secondly, the amount of energy deposited within the stripper foils would limit the foil life-time. Fresh stripper-foils would need to replace older and burned out foils often.

Today, stripper foils are still used in particle accelerators in order to reach even higher charge-states or to create bare-nuclei [13]. In some cases instead of stripping foil, a gas jet is positioned in the beam path and this achieves the same effect without the wear that a foil accumulates [14]. The process is now much more efficient because a charge-breeding machine would have already been tasked to provide highly charged ions prior to post-acceleration, and these ions would have the mass-to-charge ratio required for that particular accelerator's acceptance. Now fewer orbits and hence fewer encounters with charge stripping foils or gasses are required to reach maximum charge-states, or bare nuclei, needed for modern accelerator experiments.

### 1.2.2 Electron Cyclotron Resonance Ion Source (ECRIS)

The Electron Cyclotron Resonance Ion Source, or ECRIS, has been the prevailing charge-breeding technology in use for particle accelerators around the world since their inception in the 1960s [10][15][16].

The ECRIS uses a plasma which is contained in a magnetic bottle and is excited by electromagnetic waves at radio frequencies. The RF excited plasma consists of both ions and electrons oscillating with plasma frequencies given by an RF antennae which is in contact with the material. Before RF is applied, there must exist some gas within the interaction area to form the plasma. Once RF is applied the plasma forms, creating hot electrons and ions that can now interact with an injected atomic species of interest to produce higher charge-states. These ions can then be extracted on the magnetic bottle axis for post-acceleration.

ECRIS also contain a set of hexapole magnets to further confine the plasma and species being charge multiplied. This hexapole field is applied perpendicular to the axial magnetic field. A design for an ECRIS, and the associated axial magnetic bottle field strength is shown in Figure 1.1.

The magnetic bottle fundamental in all modern ECRIS designs may be created by superconducting magnets, and the field strength may reach up to 4.0 T in 4th generation ECRIS like the VENUS [17].

The ECRIS is also the type of charge-breeder presently in use at iThemba LABS. Much work has been performed at iThemba LABS for testing ECRIS for other facilities, such as the Grenoble test ECRIS [18].

## High Output

One major advantage of an ECRIS is its high output. This is achieved due to the constant injection of atomic species into the ECRIS followed by continuous extraction of HCIs of that species after several ionization steps have occurred. There is no need for on or off time - the charge breeding and extraction can be continuous in this design. The mode of constant ion output is called continuous-wave (or cw) extraction. A pulsed mode, called after-glow extraction, is also used commonly with LINACs which necessitate a fixed duty-cycle [19]. In order to match a cyclotron orbit period, control over the pulses or bunches of extracted ions would need to be done externally. Extracted ion current is a function of the number of injected atoms for charge-breeding.

Unlike EBIS design, where one side of the electric trap can be lowered to extract ions, the ECRIS magnetic bottle does not possess such an ease of use. The superconducting magnet can not be quickly powered off. Instead, ions leave the trap region due to their large angles off axis at the extraction side.

## Contamination

One drawback of the ECRIS is the high chance for contamination of the extracted ion beam, by both residual gasses and previously used elements that may still be present, such as those adsorbed on the inner surfaces of the machine, as well as gasses which

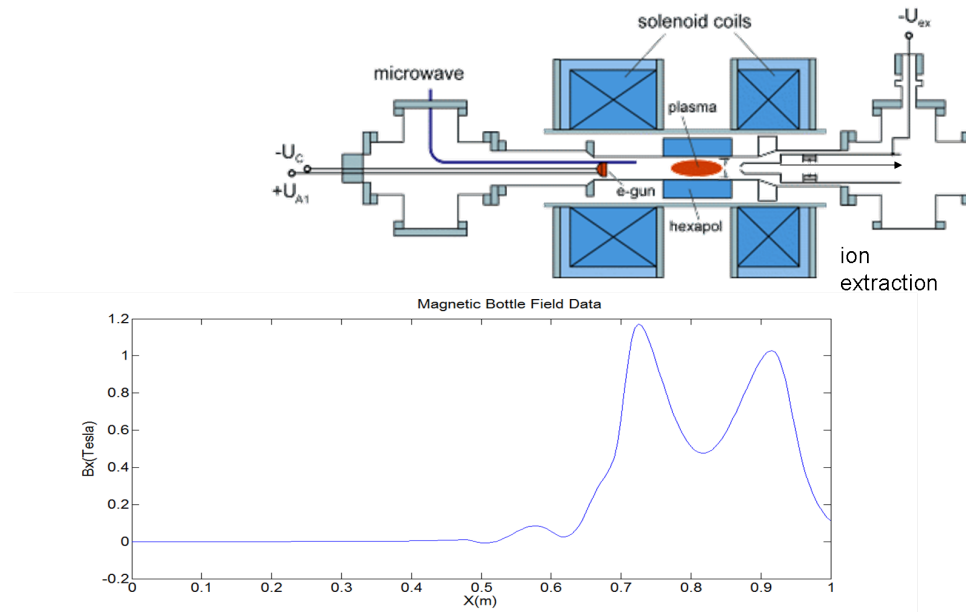


**Figure 1.1:** The Lorentz force causes a spiralling motion of charged particles called cyclotron motion. In an ECRIS, magnetic fields are used to both confine charged particles and to cause electron cyclotron motion of plasma electrons. These cyclotron orbits are driven with a fluctuating electromagnetic field introduced to the plasma using an rf-wave guide. Ionization occurs when atoms or ions encounter these high kinetic energy electrons. The plasma formed is confined in a magnetic bottle field between the two solenoids during which charge multiplication occurs. Extraction of ions through the opposite solenoid is done on axis, and this is suited to continuous-wave mode in ECRIS.

enter through leaks. Primarily, contamination comes from ions or electrons from the plasma hitting the plasma-chamber walls, releasing previously adsorbed material.

Therefore a mass spectrometer is essential should a single atomic species be required for post-acceleration. Typically, a mass separating magnet would be placed immediately after the ECRIS in order to select the required ion species.

This chance of contamination can be reduced, as with all sources of residual gas, by baking at high temperatures. Baking allows adsorbed gasses to out-gas off of surfaces quickly.

Metals that have been adsorbed on internal surfaces will not bake out easily, but also do not pose a big threat of contaminating the beam, as they have dry fused to the conducting surfaces. Non-metals that have been adsorbed in this way are the primary causes for contamination.

Vondrasek *et. al*, have done extensive research into the contamination of both ECRIS and EBIS devices [22]. The most common contaminants found in extracted spectra are the residual gas elements, oxygen, nitrogen and often carbon too.

### Uniform Charge-State Distribution

An image for a typical ECRIS charge-state spectrum is shown in Figure 1.2. The most noticeable aspect about this spectrum is its diversity of charge-states. The charge-state distribution for lead ions is spread over several  $A/Q$  values with no peak dominating the spectrum. This is partially due to lead, Pb, having several similar ionization energies, and partially to processes competing against electron-impact ionization, such as charge exchange.

Charge exchange is difficult to constrain in ECRIS, and is one cause of the wide distribution of charge-states. The wide energy distribution of the ECRIS plasma electrons is another cause for the spread-out charge-state distribution. During confinement within the ECRIS, ions collide with one another, and the ions with higher charge-states have a chance to remove electrons from neutrals or ions of lower charge-states. This is expressed in Equation 2.16:

$$A^{n+} + B = A^{(n-1)+} + B^+ \quad (1.1)$$

The effect of charge-exchange in the EBIS and ESIS will be discussed in Chapter 2.

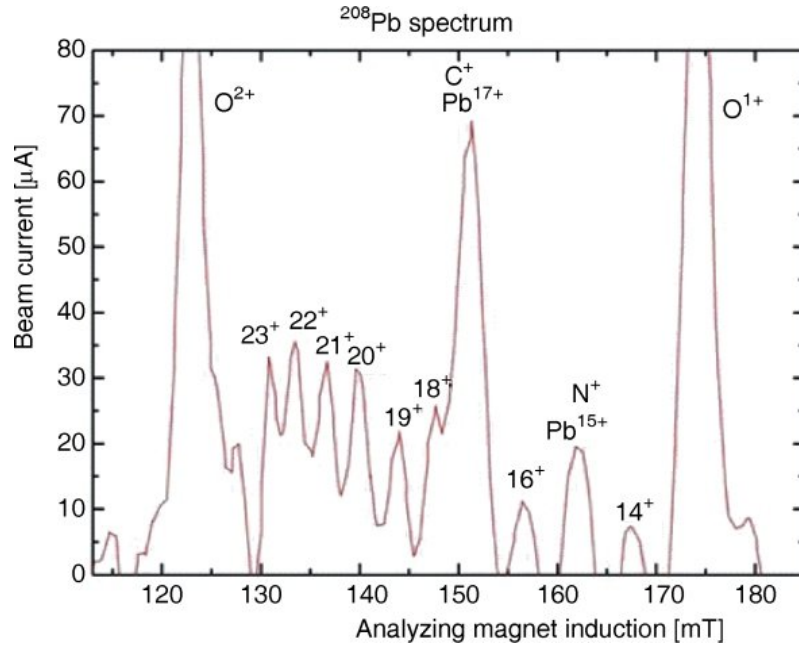


**Figure 1.2:** Pb spectrum taken with a CAPRICE type ECRIS [24], for the optimization of producing  $\text{Pb}^{23+}$ . A wide variety of charge-states of Pb can be seen. Additionally, contaminating species of oxygen and nitrogen are also present. The sharp  $\text{Pb}^{17+}$  peak due to contamination by  $\text{C}^+$ . Improvements in ECRIS technology have allowed for the production of higher charge-states. The data shown above is from 2018 [24].

### Charge States

All charge breeders share three universal traits:

- Increased ion confinement time in the charge breeding volume leads to higher charge-states.
- The energy of electrons and their density increases the charge-state.
- The electron current density (more applicable for EBIS and ESIS) is also an important factor which reduces the time to increase the charge-state.

The ECRIS has been improved over the last few decades in order to reach higher charge-states, but this was not always the case. Due to the charge exchange interactions and the continuous throughput, the extracted spectra were usually of lower charge-states. Now higher plasma electron temperatures can be reached due to advances in RF transmission.

Vondrasek *et al.* have shown that ECRIS technology has consistently been improved and the ECRIS has approached and exceeded the EBIS in some regards [22]. Figure 1.3, compiled by Vondrasek *et al.* shows various efficiencies for charge-breeding with the PHOENIX ECRIS in use at several laboratories world-wide.

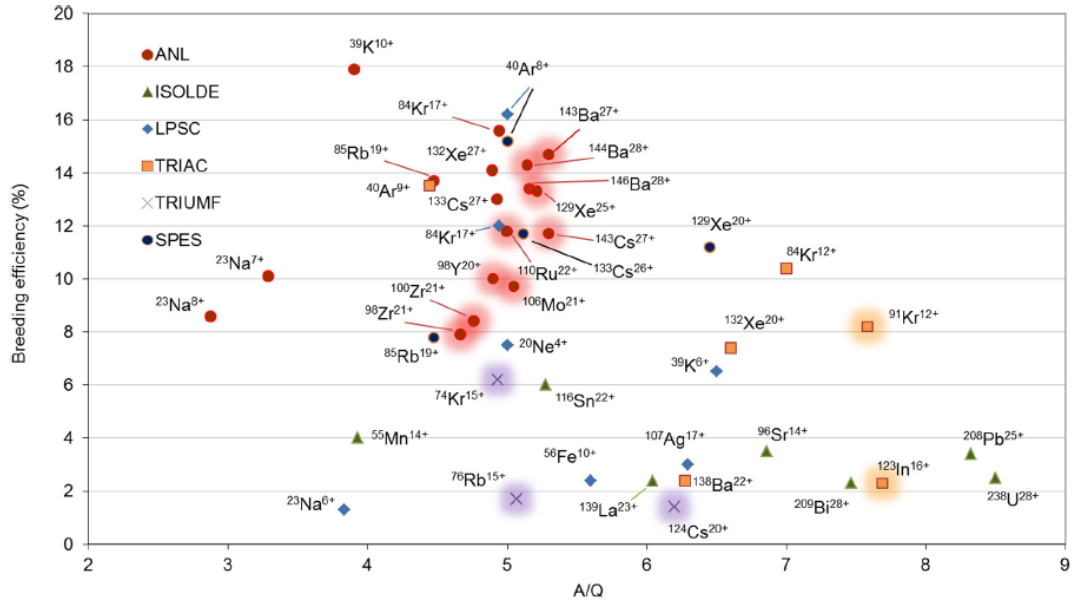


**Figure 1.3:** Efficiency,  $\eta$ , for ECRIS charge-breeding at the various laboratories shown. Radioactive isotopes are shown with a halo around the data-point. Image courtesy of Dr R. Vondrasek, [22].

### 1.2.3 Electron Beam Ion Source (EBIS)

The Electron Beam Ion Source is an electric barrier potential ion trap, with a central axial electron beam [25]. Ions are confined axially by electrostatic barrier potentials at either end of the trap, and they are confined radially by the negative potential of the electron beam. The beam electrons are in-turn confined by a strong radial magnetic field. The first EBIS was proposed and patented by E. D. Donets in the 1967 [11]. The EBIS has since been competing with ECRIS as a charge multiplier, or charge breeding ion source for highly charged ions and is used in many accelerator facilities [26]. The EBIS is also used for the charge-breeding of RIBS [28].

The design consists of a few essential components that allow for both the trapping of ions in addition to the confinement of electrons into a very narrow and dense beam using a strong axial magnetic field. The design of an EBIS is shown in Figure 1.4.

Injected neutral gasses, or in more recent cases [19][29], injected singly charge ions, will interact with the electron beam and become ionized through electron-impact ionization. This is the dominating ionization process for EBIS, among other aiding and competing processes which will be discussed in Chapter 2. Electron-electron bombardment causes ionization of injected atoms or ions when interactions between the electron beam and injected species occur. Ionization through this bombardment occurs when the electron beam energy is greater than the ionization energy of the injected atoms or ions. The rate of this ionization will increase proportionally to the electron current density. Higher charge-states are achieved via longer confinement times within the EBIS together with larger electron beam current densities and energy.

Charge-breeding occurs during the confinement of selected species within the drift tube structure of the EBIS. Ions are confined due to an electrostatic barrier trap - high positive potentials existing on either end of the trap region at greater potential energy than the ion energy, thus preventing escape. Secondly, the negative space-charge of the electron beam causes the positive ions to be further confined radially. Finally a strong axial magnetic field (from 2 to 5 Tesla) serves to both pinch the electron beam into a small radius, and also cause the ion trajectories to be confined on axis, close to or within the electron beam, along the axial magnetic field lines.

The total space-charge capacity given by the summed charge of all electrons within the electron beam is the theoretical limit to the amount of ion charge the EBIS is capable of producing. This is known as full space charge compensation.

EBIS charge-breeding efficiency results are presented in Figure 1.5 for the REX-EBIS at ISOLDE, CERN, the Michigan State University (MSU) EBIS, which is situated at the National Superconducting Cyclotron Laboratory (NSCL) in Michigan, and at Argonne National Laboratory (ANL) in Illinois, USA. These are some of the most active laboratories in the EBIS community and the image provided is courtesy of both R. Vondrasek (ANL) and F. Wenander (REX ISOLDE). [22][14]. EBIS is also in use at Brookhaven National Laboratory (BNL) [79], at DRE-EBIT, in Dresden, Germany

[49], and in Japan, where a miniature EBIS called the micro-EBIS has been developed [23]. In addition to the CRYEBIS in France, where external ion injection was first performed in 1984 [46], several other EBIS facilities have been developed in accelerator laboratories world-wide.

### The Ionization Factor

Two important factors mentioned earlier for charge-breeding, are the confinement time,  $\tau_{confine}$ , and the electron current density  $j_{ebeam}$ . The product of these two values is called the ionization factor  $j_e\tau_{confine}$ . This quantity is very useful for estimating the expected charge-state distribution in EBIS and ESIS experiments. It is easily determined for an EBIS as the electron beam current density is easy to measure or calculate. This is more difficult to ascertain for an ESIS in which case the electrons are reflected, forming the string. A process for estimating  $j_{ebeam}$  will be covered in Chapter 7 along with the evaluation of measured charge-states in  $\text{Ga}^+$  injection measurements.

### Purer Beams

The EBIS does not require a plasma formed from a pre-existing gas as with an ECRIS. Therefore, there will be no contamination of the extracted beam from such added material. The super-conducting solenoids responsible for the high magnetic field of an EBIS, and their associated cryogenic system, can be switched off and taken off-line. Therefore it is possible to bake out the entire system, removing the impurities from the vacuum chamber and drift-tube surfaces, thereby further limiting contaminants.

The EBIS is also more capable of producing a narrow distribution of charge-states for a given species. For an EBIS, and in the same way for an ESIS as discussed in the next section, the ionization factor,  $j_e\tau_{confine}$ , can be characteristic for a given charge-state distribution. In other words, in order to obtain a certain charge-state during breeding, one need only match the product,  $j_e\tau_{confine}$ , with the state required [25]. If the value of this product is increased, the ions produced in an EBIS will have higher charge-states. The method behind this will be detailed in Chapter 2 and exercised in Chapter 7 with real experimental data.

Mass-to-charge spectra of argon ions for EBIS and ECRIS are shown in figures 1.6 and 1.7. Figure 1.6 is from a commercial small sized EBIS from the manufacturer DRESDEN-EBIT [30]. One can see that in a short confinement of around 100ms, a narrow band of highly charged ions centered around  $\text{Ar}^{15+}$  and  $\text{Ar}^{16+}$  was obtained. The ECRIS results in Figure 1.7 on the other hand show low to medium charge-states, which cover a wider distribution. The relative abundances of  $\text{Ar}^{5+}$  through to  $\text{Ar}^{8+}$  is roughly flat. This ECRIS is designed for high-current output of these lower states, and the research team of Zschornack et, al. also use an EBIS instead of an ECRIS should

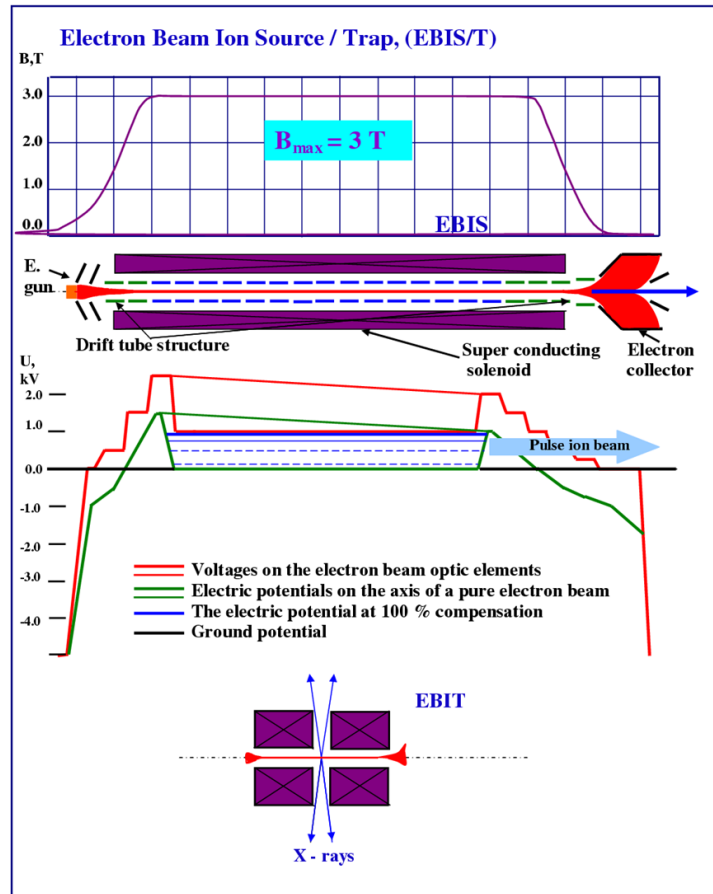


**Figure 1.4:** The operation scheme of an EBIS is shown. The above graph shows the axial magnetic field distribution provided by the super-conducting solenoid, which is maximum at 3T. Below, the drift tube structure housing the electron beam is where the charge breeding occurs. Finally the electric fields creating the electron and ion trapping confines are shown, the reduction of one-side allows the extraction of charge-bred HCIs. Also shown is a mode of operation as an ion trap, which can act as an X-Ray source.

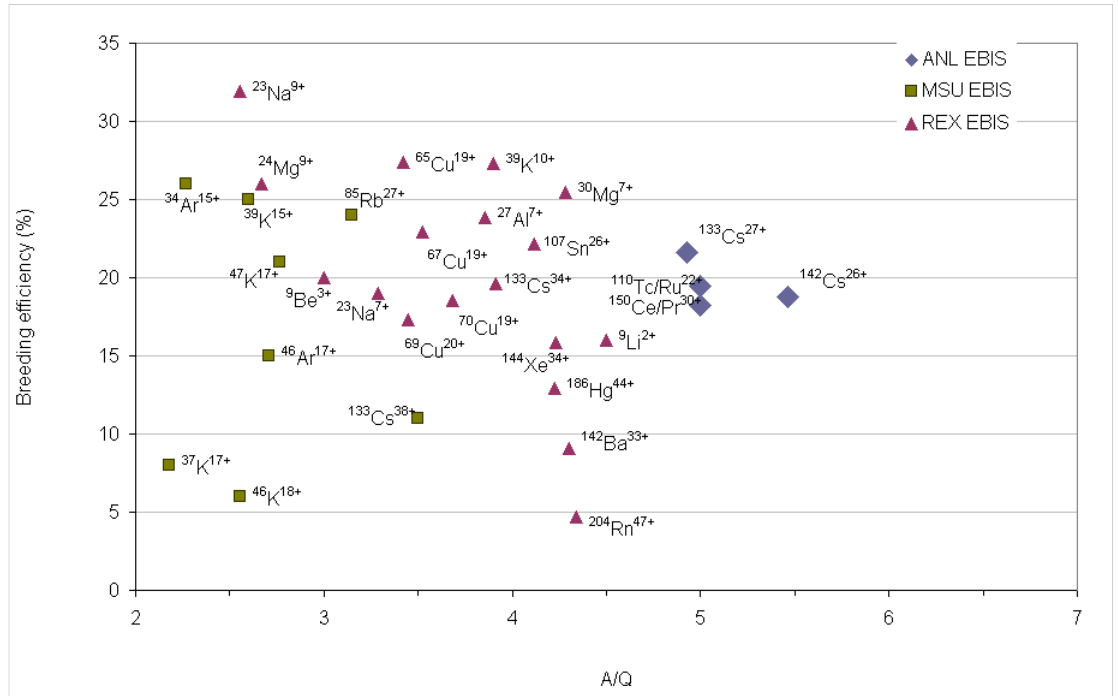


**Figure 1.5:** Efficiency,  $\eta$ , for EBIS charge-breeding at the laboratories shown. Image courtesy of Dr R. Vondrasek, [22].

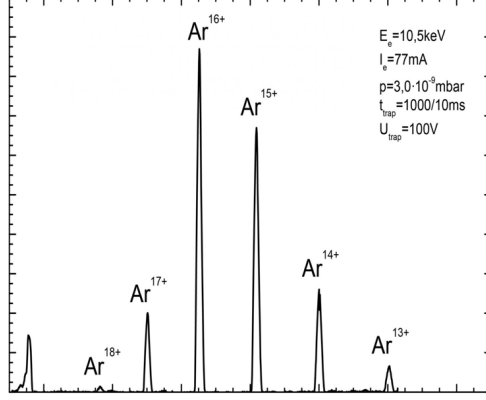


**Figure 1.6:** Long confinement argon A/q spectrum from Dresden EBIS-A [30]. The y-scale is in arbitrary units showing the relative abundance of the charge-state.

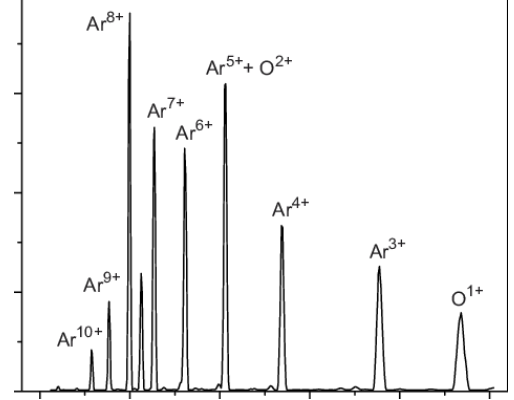


**Figure 1.7:** Extracted argon A/q from SUPERNANOGUN ECRIS [31]. The y-scale is in arbitrary units showing the relative abundance of the charge-state.

they require very high charge-states [31]. The disadvantage is that EBIS extracted HCI current is much lower than that obtainable from an ECRIS.

#### 1.2.4 Electron String Ion Source (ESIS)

The ESIS is basically a modified EBIS which uses the reflection of electrons by an electrostatic reflector. In the case of EBIS, the electrons are dumped on the electron collector at the end of their once-off transit through the device's drift-tubes. With the ESIS, the electrons are reflected several times, taking 50 to 200 passes before they are dumped on the anodes. The formation of the electron string is discussed in E. D Donets *et. al*, [12].

By controlling the "tension" of this reflecting electron beam by confining electrons using extremely high magnetic fields of up to 6 Tesla, and by controlling the negative biasing on either end of the trap, an electron string forms of extremely energetic electrons<sup>1</sup>, that are more confined radially - up to radii of 0.02 mm when compared to the electron beam in an EBIS which have larger radii around 0.1 mm. Where an electron beam can yield a narrow spectra of a few highly charged ions by controlling the electron current density,  $j_e$ , an electron string is more selective, and a desired charge-state can be attained by using the corresponding "frequencies" of the electron string which are again marked by particular ionization factors,  $j_e \tau_{confine}$ . This then provides the narrowest possible charge-state distribution or A/q spectrum with the least contamination out of all previous charge-breeder designs. This fact also allows for higher efficiency HCI beams without the requirement for stringent mass selection before post-acceleration.

<sup>1</sup>The electron string state is very complex. Its structure is quasi-stable and not easily simulated, and therefore it has been under the scrutiny of many studies by Donets *et. al*, [33].

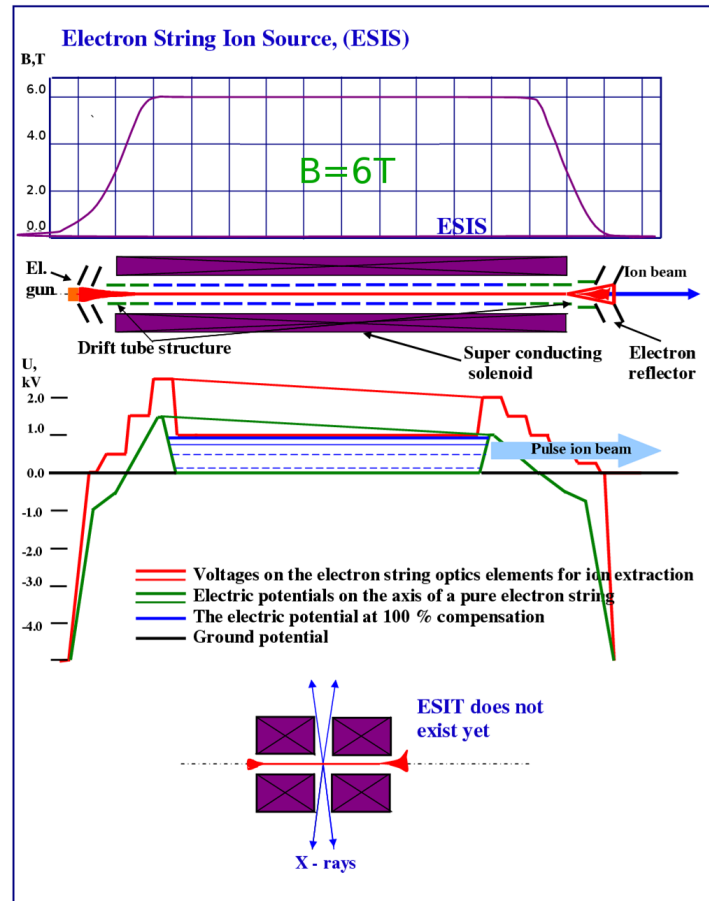


**Figure 1.8:** A large magnetic field (6 Tesla) is used to confine the electrons. Compared to EBIS, the electrons make several transits within the drift tubes forming a string, instead of a single journey from gun to anode. This 'string' provides very selective charge-breeding. Then like an EBIS, charge-bred ions are extracted by lowering the potential of the extraction anode. It is also noted that although Electron Beam Ion Traps (EBIT) are in use today, ESIT has not yet been developed.

The ESIS has been developed by Donets et. al, [12] at JINR in Dubna, in the same laboratory where the first EBIS was developed, and where advances in cryogenic cooling have given rise to super-conducting magnets able to attain some of the largest, constant and stable magnetic fields ever produced (5 to 6 Tesla). The ESIS superconductor operates at liquid helium temperature, around 4.2 Kelvin. The Dubna ESIS is therefore called the cryogenic ionizer, which in Russian gives the prefix "KRION" to the several ESIS devices developed and still under development in Dubna.

### Uncontaminated Beams

Residual gasses are the only contaminants present in ion beams extracted from both EBIS and ESIS charge-breeders. These are typically oxygen, carbon, hydrogen and nitrogen.

The KRION 6-T ESIS operates without "baking-out" to reduce contaminants, for the benefit of the cryogenic solenoid and very precise drift-tube alignment with the magnetic field axis. However, extended periods of running have shown that residual gas contributions decrease over time. Baking can be done off-line, when the cryogenic system is not in use, in order to remove possible adsorbed contaminants from prior experiments using different atoms.

### High Charge States

**Table 1.1:** Electron Gun Power Consumption of an EBIS compared to the ESIS

| $N_e/m$   | EBIS [kW] | ESIS [kW] |
|-----------|-----------|-----------|
| $10^{11}$ | 10        | 0.05      |
| $10^{12}$ | 200       | 0.2       |
| $10^{13}$ | 5000      | 2         |
| $10^{14}$ |           | 20        |
| $10^{15}$ |           | 200       |

In the same way as an EBIS, the ESIS can reach higher charge-states by tailoring the ionization factor  $j_e \tau_{confine}$  to the required state. Compared to EBIS, the ESIS can reach these states without as much power on the electron gun. This is because the current density of the electron string is much greater than that of most electron beams, and due to the electron reflection, many more electrons are present. The charge density of electrons in a beam or string and their associated power costs are compared between both devices in Table 1.1 [12]. The number of electrons per unit length,  $N_e/m$ , is about three orders of magnitude more for the ESIS as seen in Table 1.1. The data presented for ESIS in Table 1.1 is estimated for electron current density,  $j_e = 200 \text{ A/cm}^2$ . For EBIS beams of equivalent radii, a smaller  $j_e = 40 \text{ A/cm}^2$  is expected [8].

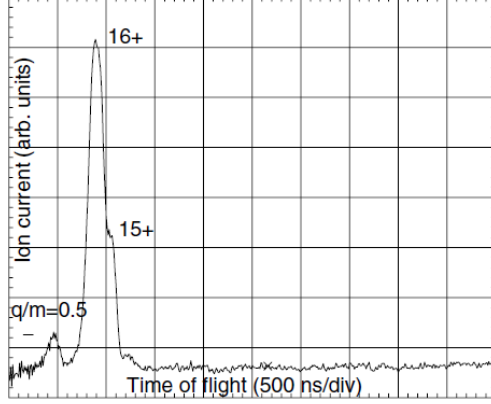


**Figure 1.9:** 300 ms confinement of argon in KRION-2T ESIS

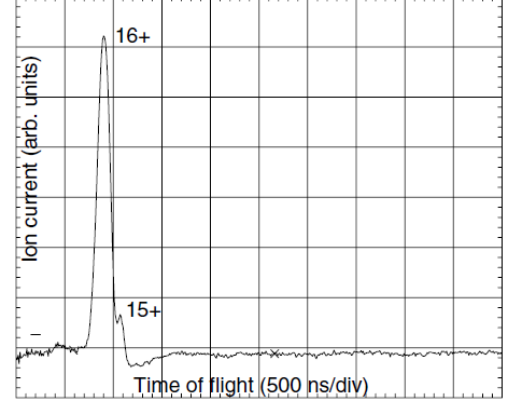


**Figure 1.10:** 500 ms confinement of argon in KRION-2T ESIS.

### Concentrated A/Q Spectra

The ESIS can produce an even narrower band of ion charge-states compared to an EBIS. The target charge-state of EBIS HCIs will be accompanied by several neighbouring charge-states, and some of these may have greater relative abundance than others. One might expect that maximal fully charged ions can be reached given enough confinement time in either device, however due to competing processes such as radiative recombination and charge exchange, longer confinement times lead to a wider spread of charge-states. The mechanism causing this narrowing is due to the electron string containing a narrow distribution of energies compared to a single pass electron beam which is mono-energetic. This causes an extra step in the analysis of extracted HCI time-of-flight spectra for ESIS which gives rise to an enhanced desired A/q. This will be explained in Chapter 7 in the data analysis of ESIS ion extraction results.

The argon spectrum in Figure 1.6 was recorded after a relatively short confinement time of 0.1 s, yet small relative abundances of the highly charged  $\text{Ar}^{17+}$  and  $\text{Ar}^{18+}$  states are seen. These two charge-states are associated with the closed Helium-like electron shell, which have large ionization energies. This makes it easier to concentrate charge-states before the closed-shell ionization energies such as  $\text{Ar}^{15+}$  and  $\text{Ar}^{16+}$ .

ESIS A/q spectra for the production of  $\text{Ar}^{16+}$ , taken from Donets *et. al.*, [33] using the older KRION 2-Tesla ESIS are shown in Figures 1.9 and 1.10. Although the resolution in this spectrum is poor, the presence of only two charge-states is observed. With a spectrometer of higher resolution, the peaks could be separated. It can also be seen that for the increased confinement time of 500 ms, the presence of  $\text{Ar}^{15+}$  is suppressed significantly, producing an almost clean beam of  $\text{Ar}^{16+}$ . The KRION 6T ESIS can create  $\text{Ar}^{16+}$  more easily due to the higher current density,  $j_e$ , being proportional to the third power of the magnetic field,  $N_e \approx B^3$  [12].

The short amount of confinement time in which a narrow band of charge-states can

be reached is an advantage of ESIS type charge-breeders. Quick repetition cycles in tune with post-acceleration is essential for having a high efficiency radioactive ion beam source.

The ESIS can also easily produce concentrated beams of lighter nuclei. This has already seen application in producing  $C^{6+}$  beams for cancer therapy [33].

### 1.3 Research Goal: External Injection of Singly Charged Ions into the ESIS

The KRION 6T ESIS is mainly used to produce HCIs from injected gasses. This is done by radially injecting the selected gas so that it enters the first few system drift-tubes, which are cooled to liquid nitrogen temperatures. The ionized gas then propagates into the colder helium temperature central drift tubes. During this time, the injected gas will encounter and interact with the electron-string, and charge-breeding occurs.

Metal ions are difficult to introduce into the ESIS in this manner as they are not typically available as a gas which can be easily injected. A gaseous metal ligand would be required, a metal based molecule also consisting of other elements, and this of course will introduce these other elements as contaminants into the charge-breeder. The KRION has been used to charge breed iron ions in this manner through the gas injection of ferrocene [34]. Unfortunately, short half-lives preclude the possibility of chemically producing ligands of radioactive metals, although this method can be used with longer-lived radioactive isotopes.

Therefore a different method of injecting metallic elements into the ESIS should be explored. The goal of this research is to achieve this via the axial injection of metallic ions which are already in the  $1+$  charge-state.

#### 1.3.1 External Singly Charged Ion Injection

Internal injection of gold into the ESIS has been successful in the past, using a heated gold coated filament housed inside the system, nearby the drift-tubes. This was used previously by the modified KRION-3T to provide gold ions  $Au^{52+}$  to  $Au^{54+}$  for the Nuclotron in Dubna [35]. The shortcoming of such a source was its life-time, and when the wire filament would vibrate and become damaged, it would be a lengthy procedure to stop the experiment, return everything to room temperature, open the KRION, and replace the gold coated wire.

Externally injecting metal ions should prove to be an easier way to obtain metal HCIs. The stability should be better in order to have longer operation periods before replacing the source, and the replacement process should not interfere with the KRION or other parts of the ongoing experiment.

The external injection of metallic ions into the ESIS has not been attempted before. However, external ion injection into EBIS has been successfully performed at several laboratories around the world. The first such external injection experiments with an EBIS-like charge-breeder were performed using with the CRYEBIS in France using a duoplasmatron primary ion source in 1983 [46].

The REX-EBIS at ISOLDE, CERN, utilizes a large 3T Penning Ion Trap prior to EBIS injection. The REX-EBIS ions originate from various primary ion sources such as MEVVA, hot cathode, and even fission target fragments for radio-nuclide studies [14]. All of these ions are accumulated in the Penning Trap before they are released in bunches and injected axially into the REX-EBIS for charge-breeding.

With the EBIS at Brookhaven National Laboratory (BNL), work has been done by Alessi et. al, to inject ions into their EBIS using a primary Low Energy Vacuum Arc (LEVA) type ion source. Ion currents of  $100\mu\text{A}$  are produced and the EBIS reaches 25% compensation after 2ms of confinement [36]. The already charged ions reach higher charge-states considerably faster than neutrals. BNL have also used hollow-cathode ion sources before upgrading to the more effective LEVA primary ion source.

A liquid metal ion source (LMIS), or more specifically, a liquid metal-alloy ion source (LMAIS) has been used by Thorn et. al, to inject singly charged Gold on axis into the Dresden EBIS-A at Technische Universitat Dresden [29]. The Dresden EBIS-A, was capable of confining  $\text{Au}^{60+}$  - a very high charge-state for gold. As mentioned already, previous internal injection experiments with the modified KRION 3T at Dubna managed to yield up to  $\text{Au}^{54+}$ .

The work at Dresden has been the main influence of the direction of the research presented in this thesis. The beam-line at Dresden incorporated an LMIS that would deliver a beam of ions that were necessarily deflected by 90-degrees and thereafter injected on-axis to the EBIS via means of an electrostatic quadrupole switch-yard [30]. The extracted HCI beam would then pass through the unpowered switch-yard, and subsequently used for experiments. The EBIS-A, LMAIS and Quadrupole deflector responsible for this process is shown in Figure 1.11 . This method will be used in the present research, and elaborated on in Chapter 4, where the design of the ion transport system is covered.

### Access to all elements

Up to date, the injection of metallic elements, especially the refractory metals, into the EBIS and ESIS has proven to be a challenge.

Neutral gasses, or elements naturally available in molecules in the gas state, can easily be used as source materials for experiment. In order to access the metallic elements, and therefore the majority of the periodic table, the injection of these species as positive low charged ions proves to be a useful method.

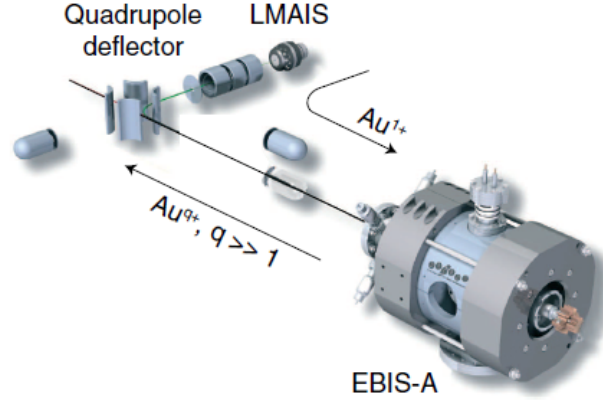


**Figure 1.11:** Singly charged ion injection setup at Technical University in Dresden [36]. The electrostatic quadrupole deflector, or switch-yard, allows for the injection of singly charged ions without interrupting the extracted HCI beam. This will be discussed in detail in Chapter 4.

Essentially, all materials can be accessed this way. Not all may be available as liquid metals or metal alloys, but using these as primary test sources is a useful exercise to ascertain whether a transport system will work for charge injection.

### 1.3.2 Design of an Ion Transport System for Accelerator Experiments

In this research an LMIS will be used as a source for singly charged ions required for external injection into the ESIS. The LMIS is an inexpensive source for singly charged ions and serves as an excellent testing source for the purpose of external injection. In addition to being inexpensive; it is compact, has a long shelf-life, it is stable, and has a high brightness and current output, with a well known angular distribution of ion emission and energy response [66]. More will be covered on the LMIS, and why it is an ideal test source in Chapter 4.

Once the principle of charge injection has been shown to be successful, different ion sources could replace LMIS instead. Eventually, the goal of iThemba LABS is to introduce charged fission fragments into a charge-breeder in order to create exotic beams of rare-isotopes. The work in this thesis will contribute to the first phase of this development via proof of concept [3].

The goal of this research is to develop this ion transport system, similar to the one developed by Thorn et. al shown in Figure 1.11 [29], for the injection of singly charged ions from an LMIS, into the KRION 6T ESIS in Dubna.

This work is a collaborative project between South Africa and The Joint Institute for Nuclear Research (JINR), in Dubna, Russia. The aims of iThemba LABS and JINR

coincide and the success of this experiment will be beneficial to both laboratories. In addition to the ACE project at iThemba LABS, this transport system, once developed, will find use as a primary ion source for KRION ESIS charge-breeding for the big NICA project at JINR, which is under development and scheduled to start experiments in the 2020s.

## Chapter 2

# Charge Breeding and External Injection of Ions

The external injection of singly charged ions into the ESIS, followed by the extraction of a multiply charged ions after charge breeding, encompasses a wide variety of physical processes: The physics of ionization involves atomic physics and statistical mechanics; primary singly charged ions can be produced via processes such as surface ionization, lasers, as well as field evaporation sources like the liquid metal ion source (LMIS) - these methods based more on material physics are preferred for external injection purposes, yet singly charged ions, especially beams containing rare isotopes, are in practice extracted using isotope separation online (ISOL) [37]. Once primary ions are produced and extracted from their source, electromagnetism governs the journey of the beam through the beam-line architecture which contains ion-optical components for focusing, steering and correcting trajectories. Isotope lifetime and corresponding injection schemes of post accelerators (LINAC, Cyclotron etc.) sets the criteria on how efficient and rapidly the transport system will need to operate in order to accelerate RIBs.

In this work, the singly charged ions are produced using a liquid metal ion source. The LMIS produces ions through field ionization: a competition between an applied electrostatic force and the surface tension of the liquid metal - the operation and physics of an LMIS is discussed in Chapter 4.

### 2.1 Beam Physics and Ion Transport

The ion transport system developed in this work is designed to deliver singly charged ions from the primary LMIS into the ESIS, followed by the extraction of HCIs down the same architecture. Ions produced and extracted from the LMIS form a beam which is governed by the electrodynamics of charged particles interacting with electromagnetic

fields of transport system components. These are called "ion-optics" as they act on ion beams similarly to optical lenses acting on light rays.

The physics of a charged beams is well understood. The first electron beams, developed in the 1850s, were cathode-rays produced in evacuated glass bottles called Crooke's Tubes. Since then, ion beams have been created by the earliest particle accelerators in the 1920s, with alpha emitters having been understood by Rutherford two decades before. Today several approaches to modelling the formation and flight of charged particle beams through a system of ion or electron optical elements have been discovered and developed.

### 2.1.1 Modelling a Charged Particle Beam

The physics of charged beams is a many-body problem. Each particle interacts with every near neighbour, causing the beam to expand and diverge due to its own charge.

When such a system of particles encounters external electromagnetic forces, the beam will change shape as the relative position of each particle from the principle axis varies. Each will also undergo a change in momentum causing a varied intensity distribution at the beam focal-point or target. For a beam propagating in the  $z$ -direction, at a given  $z$  position, each particle trajectory can be described by the transverse position values,  $(x, y)$ , and the corresponding transverse momentum values,  $(\dot{x}, \dot{y})$ .

Beam propagation can therefore be calculated with the Hamiltonian for particles within a beam. Trajectories evolve as ions experience external forces, and if these forces are conservative (Hamiltonian) the area of the 4D phase-space traced by  $(x, y)$  and  $(\dot{x}, \dot{y})$  is conserved. This method is especially simple for estimating the propagation of a beam in drift-space, where there are no other forces acting besides the beam's own space-charge repulsion.

It is also possible to use the 6D phase space volume described by the Liouville Theorem. This states that the phase space density for a Hamiltonian system is an invariant of the motion which also means the phase space volume occupied by the system is conserved. Here the longitudinal components,  $z$  and  $\dot{z}$ , are not used, instead the canonical pair of energy and time  $(E, t)$  are favoured for describing the phase-space volume conservation.

### 2.1.2 Emittance

The emittance,  $\varepsilon$ , is a benchmarking value which contains information about a beam - such as its narrowness and how the beam diverges or converges [38]. Emittance can be understood geometrically as the value of the area outlined by an ellipse which contains all the particle trajectory information in phase-space. There are two transverse emittance values for every beam, as well a longitudinal emittance which is important

for energy and timing considerations. Transverse emittance is investigated statistically in Chapter 4 from simulation results, and in Chapter 5, it is measured experimentally.

### Transverse emittance

Transverse emittance is also an ambiguous term as there have been various definitions and uses of emittance. The most commonly measured and used value is the normalized emittance,  $\varepsilon_{N,x}$ , which is a conserved quantity and is calculated by multiplying the measured emittance by the relativistic velocity,  $\beta$ , and gamma factor,  $\gamma$  [39].

$$\varepsilon_{n,x} = \varepsilon_x \beta \gamma \quad (2.1)$$

Transverse emittance,  $\varepsilon_x$ , can be used to compare beams with similar energy where the  $\beta$  values are almost equal, and where the  $\gamma$  value is approximately 1 due to low ion velocity when compared to the speed of light. The normalized emittance is applicable in comparing beams with vastly differing energies and velocities. The normalized emittance does not depend on beam energy while unnormalized transverse emittance does. The multiplication by  $\beta$  accounts for the beam energy. It has been shown, for example in [19], that transverse emittance is inversely proportional to the square-root of beam energy, implying more energetic beams have lower unnormalized emittance. Once normalized by multiplying with  $\beta$ , two beams from the same source, though operating at different energies, will have the same normalized emittance.

For a beam to get from one part of a transport system into another, its emittance must be less than the "acceptance",  $\alpha$ , of the target component. The transverse acceptance of an ESIS, for example, is the geometrical solid angle given by the entrance port into the drift-tube structure and string itself. Naturally, the transverse emittance of an injected beam must be lower than this. The geometrical, or transverse acceptance of the KRION ESIS and other EBIS is discussed later.

A beam propagating on a principle axis, for instance, the  $z$ -direction, will have two transverse directions in which it may spread due to space-charge effects, or in which it may narrow due to ion-optics in the beam line. In addition to these two directions, are the angles in which the transverse trajectory makes with the principle axis. These angles are usually small enough to make a small angle approximation and can be given by the ratio of infinitesimals in the respective transverse direction:

$$x' = dx/dz \quad (2.2)$$

Note that  $x'$  also represents the particle transverse momenta away from the principal axis of propagation. This transverse motion of beam particles can also be thought of as

a beams temperature, where a cool beam will have low emittance, is narrow and mostly parallel with the principal axis.

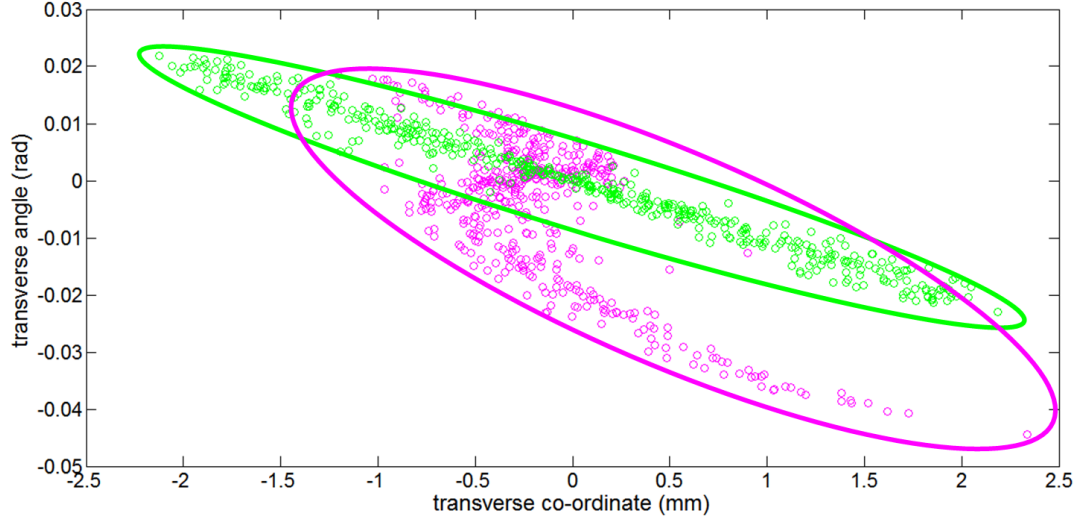


**Figure 2.1:** Example of simulated phase-space plots from SIMION for early ESIS injection simulations. As will be explained in Chapter 4, the data shown above is measured just after the beam has exited the quadrupole switch-yard bender. Here the pink is the  $x$  transverse co-ordinate, and green the  $y$  transverse co-ordinate. The results for the RMS emittance were  $\varepsilon_{RMS,x} = 18.8 \text{ mm.mrad}$  and  $\varepsilon_{RMS,y} = 6.05 \text{ mm.mad}$ . Both values can still be divided by  $\pi$  and the results would both be considered excellent in a real experiment but were obtained from ideal simulations. The pink ellipse covers a larger area in order to cover the outlying points. If 10% of the outliers were removed from the data, this value would decrease significantly. Additionally, these plots reveal the width and centering of the beam. The shape of the spread of data points also determines if the beam is converging or diverging, and any asymmetry is indicative of higher order effects on the beam - such as the dipole aberration from the quadrupole bender optics (explained in Chapter 4) which causes the S-like pattern in the  $x$ -direction.

The transverse emittance can be determined by plotting the phase space for one co-ordinate, eg;  $x'$  against  $x$ . An ellipse can be added to such a graph such that it contains all data, i.e, the trajectory information. The area of this ellipse yields the transverse emittance for that direction. An example is shown in Figure 2.1.

Using this idea one can see that the area of a phase-space ellipse will also give the transverse emittance;

$$\varepsilon_x = \pi * a * b \quad (2.3)$$

Here  $a$  and  $b$  are the semi-minor and major axis of the ellipse. Using the maximum displacement  $x$  and the maximum angle  $x'$  as the semi-major and minor axes, one has

the following expression for transverse emittance;

$$\varepsilon_x = x_{max} * x'_{max} \quad (2.4)$$

From this the units for emittance are given geometrically by  $\pi$ .mm.mrad.

Equation 2.4 is an ideal case which is used to demonstrate the derivation of the unit  $\pi$ .mm.mrad and comes from the area of an un-rotated ellipse in phase-space. In practice, the phase-space of a beam will have rotated, and the "twiss-parameters" can be obtained and used to estimate the emittance in a similar way [71].

### Factors influencing transverse emittance

The normalized transverse emittance for a given source is a constant quantity in a free drift space. The initial value of this emittance is dependent on the way beam particles, in this case ions, leave the source.

Small but bright sources, such as the LMIS, will have small emittance due to the few 10 nm to 10  $\mu$ m area at which field evaporation and ionization occurs. Other sources like MEVVA or FEBIAD that work under arc-discharge, would have higher emittance not only due to larger emitting surfaces or areas, but also due to hotter ion temperatures. Beam "temperature" describes the transverse velocities of the particles, implying colder beams are more focused, while warmer beams are more dispersed.

In secondary ion sources, like the charge-breeders ECRIS, EBIS or ESIS, ions exiting the source are acted on by the fringe magnetic fields which further causes emittance growth. Similar changes to emittance can also occur when being focused or defocused through magnetic lenses.

Ion optical lenses, like einzel lenses, may cause spherical aberrations creating a halo of particles around the centre of the beam. This effect causes a large spread of transverse velocities - or increase in ion temperature and therefore transverse emittance growth. Similarly other ion optical elements may influence the beam emittance through higher order aberrations.

Furthermore, emittance of a beam can grow due to non-linear effects of the charged particle space-charge and heated due to beam instabilities.

### Transverse Emittance from Experiment

A beam profilometer can be used to obtain beam profiles from which the half-width (or radius) of the beam can be measured. In this report,  $\sigma$ , without indices, will often be used to represent this radius, or beam-width,  $x$ , when referring to beam-width measurements. This is different to  $\sigma_{11}$  which represents the square of the half-width. A

Gaussian approximation is taken for every beam profile, and  $\sigma$  is the standard-deviation of the beam which is also the average radius containing 68% of the beam statistically. Using several beam profile measurements taken at many locations on the principle axis, the transverse angles  $x'$  can be estimated too. The result for emittance in a drift-space is shown in Equation 2.5, and the detailed derivation of this equation is covered in Chapter 5.

$$\varepsilon = \sqrt{\sigma_{11}\sigma_{22} - (\sigma_{12})^2} \quad (2.5)$$

In this equation the various  $\sigma_{ij}$  are the matrix elements obtained for the evolution of the emittance in drift-space, with  $\sigma_{11}$  being the average beam radius squared - in  $\text{mm}^2$ , and  $\sigma_{22}$  the average half-angle squared in  $\text{mrad}^2$ . I.e. these sigmas are  $x$  and  $x'$  taken in statistical context of many particle trajectories of a beam. The cross term,  $\sigma_{12}$ , which is the statistical equivalent to  $\sqrt{x * x'}$ , can only be ascertained with larger data sets - i.e. many profile measurements at several distances,  $D$ , along the principle axis. The derivation is shown in Chapter 5.

### Transverse Emittance from Simulations

Simulated ion beams require another method for obtaining emittance. A real beam contains much hidden information and no single trajectory can be picked out - a macroscopic averaging approach is required to gain any knowledge about emittance, and the only way to improve such data is with many profile measurements. In simulations, each and every trajectory is plotted and from this, the experimentalist can understand more details about the beam unavailable in experimental data. The amalgamation of several simulated trajectories can yield similar results to experiment, but a simulation will always have short-comings that prevent a 100% real description of the physics. Therefore a statistical approach is required to calculate the emittance, as shown in Equation 2.6.

$$\varepsilon_{RMS} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x.x' \rangle^2} \quad (2.6)$$

The root-mean-square emittance,  $\varepsilon_{RMS}$ , is obtained by averaging the individual transverse directions,  $x$ , and angles,  $x'$ , taken from simulations. This emittance represents 68 % of the beam particles. It is also easier to calculate the average cross-term,  $\langle x.x' \rangle$ , from simulated data. This has been performed using SIMION simulations and is covered in Chapter 4. The general emittance,  $\varepsilon$ , in Equation 2.5 and the RMS emittance,  $\varepsilon_{RMS}$ , in Equation 2.6 share similar forms. Multiplying either equation by 4 yields the 2-RMS emittance which accounts for 90% of the beam and is used throughout simulations. This 2-RMS emittance value is therefore comparable to transverse emittance values calculated from experimental data using Equation 2.5 multiplied by 4.

### Longitudinal Emittance

The longitudinal emittance of a beam is associated with the longitudinal acceptance of an EBIS or ESIS, cyclotron or other time dependent post acceleration. Longitudinal emittance,  $\varepsilon_l$ , is defined as the product of energy spread in a bunch of ions, and the bunch pulse-length;

$$\varepsilon_l = \Delta E * T_{bunch} [eV.s] \quad (2.7)$$

Since ions are usually extracted in a pulse scheme from a charge-breeder, this must be matched with that of the post accelerator and cyclotron single-turn period and RF acceptance.

### Emittance values in this report

There are several ways in which emittance can be defined. Normalized emittance is commonly used in the field and can be calculated by multiplying the emittance from Equation 2.5 by the relativistic velocity factor,  $\beta$ , and  $\gamma$ . Some authors may quote 2rms-emittance such as  $\varepsilon_{90}\%$ , using only the central 90% of the beam intensity and excluding outer most trajectories. It is important to only compare the emittance of two different beams if the same type of emittance value has been estimated. It is possible to convert from one type of emittance to another for comparison, but it is particularly difficult to compare estimations of statistical rms-emittance obtained in simulations, to the transverse emittance values from beam measurements, as the simulated beams had estimated opening angle between 2 and 5 degrees, and the distribution of ions was not Gaussian but spherical. Therefore in this report no comparisons are made with  $\varepsilon_{RMS}$  from Chapter 4 and with the regular  $\varepsilon$  in Chapter 5. However these emittance values can be compared self consistently with one-another from a specific investigation, which was still useful information for tuning the ion-optics.

Since the emittance is represented by the area of an ellipse traced over the beam trajectories in a phase-space plot, ideal emittance is when that area tends to zero. A distribution of data as a single straight line in such a plot - one where the ellipse area would be zero - represents a perfectly parallel and laminar beam. In experiments such a condition cannot be reached, but may be approached. Hence small values of emittance in  $\pi.mm.mrad$  are always preferable, and beams with  $\varepsilon$  below  $10 \pi.mm.mrad$  are ideal for full transport into a charge-breeder. In the case of the ESIS or EBIS, the transported beam must have small emittance in order for the ions to be incident on the electron string or beam within. This concept is called charge-breeder acceptance.

### Brightness

The beam brightness is defined as the current per unit solid angle. The area of an ellipse with semi-major and semi-minor axes equal to each transverse emittance value gives the solid angle of the ion beam in  $\text{mm}^2\text{mrad}^2$ . The brightness can therefore be calculated via [76]:

$$B = \frac{I}{\pi^2 \varepsilon_x \varepsilon_y} \quad (2.8)$$

The brightness of a beam is a figure of merit used to evaluate beams. High brightness indicates high intensity over a small area. A low emittance beam with high intensity will have a very high brightness.

Techniques for obtaining the brightness of electron beams use measurements of emittance and Equation 2.8. For an example of a brightness determination see the work of Wang *et.al*, [41].

#### 2.1.3 Charge Breeder Acceptance

No interactions between ions and electrons (and therefore no charge multiplication) can be expected if they never encounter each other in a charge-breeder. Therefore, there must be at least some overlap between the areas of an injected ion beam and the electron beam to ensure the probability of interactions. Together with geometrical and other machine factors, this 4D area, similarly to emittance, is calculated in phase-space for an EBIS to be:

$$\alpha_{max} = \pi \frac{r_{ebeam}}{\sqrt{2T_{ext}}} \left( Br_{ebeam} \sqrt{\frac{q}{m}} + \sqrt{\frac{qB^2 r_{ebeam}^2}{4m} + \frac{\rho_l}{2\pi\varepsilon_0}} \right) \quad (2.9)$$

Where  $\alpha$  is the maximum acceptance of the EBIS electron beam,  $B$  the solenoid magnetic field,  $r_{ebeam}$  is the electron beam radius,  $q/m$  the injected ion charge-to-mass ratio and  $T_{ext} = qU_{ext}$  the ion beam energy, and  $\rho_l$  the electron charge per unit length of the beam. In order to have successful external ion injection into the EBIS (or ESIS), the emittance of the externally injected singly charged beam in both transverse directions should be lower than the acceptance,  $\alpha$ , of that charge-breeder.

Equation 2.9 was derived by F. Wenander [19] for EBIS injection by solving the Hamiltonian for the 4D phase-space area of the electron beam and multiplying the solutions

for the transverse canonical co-ordinates,  $x$  and  $x'$ . For EBIS this value is around  $10 \pi \cdot \text{mm} \cdot \text{mrad}$ .

It is only an approximation to use this equation for ESIS predictions as the electron string consists of electrons undergoing many reflections at different energies. The linear current density can only be estimated, and the electron string is considered to have a much smaller acceptance than a beam of electrons. Using this equation for injected gallium ions from  $T_{ext} = 1.7$  to  $6.0$  keV and  $B = 5.0$  T used in this work, and approximate string radius ( $r_e \approx 0.3$  mm) and current density ( $j_e \approx 620$  A/cm<sup>2</sup>), a range of the acceptance is estimated between  $10$  to  $70 \pi \cdot \text{mm} \cdot \text{mrad}$  for ESIS acceptance, with  $10 \pi \cdot \text{mm} \cdot \text{mrad}$  corresponding to a  $60$  keV beam, and  $70 \pi \cdot \text{mm} \cdot \text{mrad}$  to a  $1.7$  keV beam. This implies that externally injected beams of ions should have transverse emittance values lower or at least within this range. Simulations could also be made to obtain electron string/beam acceptance, such as those by Kponou *et. al*, for the BNL EBIS [21].

#### 2.1.4 Efficiency

The efficiency,  $\eta_{breed}$ , of a charge-breeder producing ions of a charge-state  $Q$  is calculated by the ratio of numbers of extracted ions over the number if injected ions. This can be calculated by measuring the ion current going in and coming out of the charge-breeder and taking the ratio:

$$\eta_{breed} = \frac{I_{extracted}(Q)}{Q I_{injected}(1^+)} \quad (2.10)$$

Where  $Q$  is the extracted charge-state. It is clear that charge multiplication of singly charged ions to a higher state  $Q$  has occurred when extracted ion current is higher than injected current. In a perfect example with  $\eta_{breed} = 1$ , where there are no losses, and all ions reach a single charge-state with very little spread in the neighbouring charge-states, the extracted current will be integer multiples,  $Q$ , of the injected current. If there was an  $A/Q$  spread in such an example, this multiple would yield the average charge-state extracted, and the efficiency for each individual charge-state produced should sum to 1.

Due to losses from heating or poor injection, the charge-breeding efficiency will be less than 1. In order to measure this as accurately as possible, a Faraday cup to measure the incoming and outgoing current should be as near as possible to the entrance of the charge-breeder, and movable. A Faraday cup on a pneumatic arm can be positioned before the ESIS during tests to measure the incoming average ion current, and it can then be retracted during extraction. Beam diagnostics for extraction will usually be positioned further down the beam line, such as time-of-flight or beam profiling

equipment. More losses of extracted beam are likely to occur if the distance between extraction and the detector location is long.

In the absence of having detectors nearby the entrance of the charge-breeder, efficiency can only be estimated using detectors placed at other locations. The efficiency calculations in Chapter 7 are tackled using such a configuration.

For the production of rare isotopes, a high breeding efficiency is required to ensure that the highest possible number of isotopes can be extracted and measured from the primary ion source. Such isotopes do not have high abundances within impure samples of a species, and pure injected isotope ions, from a fission ion source for instance, will have low initial yields that should be conserved as much as possible during charge-breeding [8].

### **Transport and Injection Efficiency**

The injection efficiency of singly charged ions from the primary ion source to the charge-breeder can be similarly calculated from ion current beam diagnostics, such as Faraday Cups, along the transport system.

Here the efficiency will be the ratio of the singly charged ion current measured between the source and the detector as close as possible to the charge-breeder entrance. This injection efficiency covers all of the ion losses through the system between those two points and is monitored and optimized during the set up of ion optical elements along the beam line.

This efficiency can also be easily simulated, such was done via SIMION, in this report and is covered in Chapter 5, where only beam transport configurations with 100% were studied further.

## **2.2 Modelling Ionization Processes in EBIS and ESIS**

Ion traps, like EBIS or ESIS, have been in use at many laboratories around the globe for 3 or 4 decades already. The main physical principle of charge-stripping that occurs in the above charge-breeders and ECRIS, is the process of electron-electron bombardment. For ionization of a selected  $A/q$  species to occur, the average energy of the beam (EBIS), string (ESIS) or plasma electrons (ECRIS) must be higher than the particular required ionization level of the element.

This would mean that only electron energy plays a role in the ionization. However, the physical processes within each trap are also dominated by several other factors and competing neutralization processes that would bring the ion back to a lower charge-state.

The degree of space-charge compensation can limit the number of useful HCIs produced, and there will also always be efficiency loss between injection and extraction. All of these factors are described briefly here. The simulation software developed by R. Becker *et. al*, called CBSIM-Analysis [42], was made to tackle these processes and simulate the evolution of ionization within an EBIS charge-breeder. The governing equations of this software stem from the ionization and competing processes discussed herewith. CBSIM-Analysis was utilized, although with methodology adapted for the ESIS, in the analysis of gallium A/q spectra in the final experiments of this research covered in Chapter 7.

### 2.2.1 Ion Trap Physics

In order to trap ions, EBIS and ESIS consist of axial magnetic fields from superconducting solenoids, and a pair of positively charged electrostatic barriers on either end of the ion confinement drift-tube structure. Electrons are then introduced and confined into a narrow beam by the magnetic field. Ions entering the drift-tubes are confined by the negative space-charge of the electrons as well as the electrostatic barriers. In the case of ESIS, another electrostatic trap, with negative potential barriers, is created to confine the electrons between the electron gun and the extraction electrode. Electrons can therefore accumulate within the drift-tubes, making several round trips in the charge-breeding volume, and in this way current density is increased.

### Space-charge Neutralization

The total charge of extracted positive ions from an EBIS or ESIS depends on the amount of electrons confined in the beam or string before external injection. Assuming that electrons leave the system and do not readily add to the beam electrons, there will eventually be a point when all the positive ion charge in the trap equals and neutralizes the electron beam charge. This is called full compensation of the electron beam [12].

Typically, ESIS and EBIS allow for a compensation level of around 50% to 60% to be reached before HCI extraction [12]. Immediately after injection with gas, the compensation is around 90% with ESIS. After this, ion heating effects occur and ions escape the trap which causes the compensation to lower. Such heating effects include electron beam heating due to long range coulomb interactions, and ion-ion energy exchange - which is also due to long range coulomb interaction - and causes higher charge-state ions to lose their energy to lower charge-state ions. To a lesser extent, heating can also be caused by the release of energy in ionization events. The system also cools as the escaping ions carry excess energy away from the system through evaporative cooling [44].

The confinement time of ions should be well below the compensation time - the average time it would take to reach maximum compensation of the electron beam - in order

to have minimal losses and achieve small emittance of an extracted beam. This neutralization of the negative central potential well causes the ion population to heat up which is accompanied by emittance growth, so the effect should be minimized as much as possible [42].

### 2.2.2 The Electron String

The ESIS differs from the EBIS mainly due to the multiply reflected electrons in the case of ESIS. However, these multiple reflections are not what causes the string-like phenomenon of the electron beam, and the system will continue to operate as an EBIS unless a certain condition is met by the injected electrons.

For an electron string to form, electrons are first accumulated in the trap. The injection of electrons must first be slow to reduce heating effects and widening of the beam. The electron current density,  $j_e$ , grows in this time.

Eventually an unstable state arises where there is a virtual cathode, that moves slowly back and forth near the real cathode, caused by this accumulation of electrons. At this point the electron string is ready to form, as the injection of some more electrons after this point brings the confined electrons into a new stable state. This state is the electron string and was discovered by E. D. Donets in 1994 almost accidentally while playing around with the KRION 2-T EBIS [35]. The formation of the electron string is shown in Figure 2.2.

Therefore there is a huge amount of electron current in the string compared to a beam, as accumulation must first occur and the phase of the electrons must transition through the instability. The electron gun energy and the negative trap potentials effect the string, like tension on a physical string. Adjusting such tensions can cause the string to resonate with certain frequencies - bringing this analogy to the ESIS, these frequencies directly relate to a given ionization energy, and this is why the ESIS is particularly good at singling out a specific charge-state with out much or any contamination from neighbouring states.

The actual physics of how the electron string behaves is not completely solved and has several higher order effects in play that must all be solved self consistently. Attempts have been made to study this using many body simulations [33]. However, experimental results have consistently proved that the electron string is the only capable charge-breeding mechanism that can isolate and breed to a specific charge-state  $Q$  [35][43].

### 2.2.3 Ionization Process: Electron-Impact Ionization

ECRIS, EBIS and ESIS charge breeders use the process of electron-impact ionization in order to rapidly ionize a given species. To remove an electron from an atom or ion, a projectile particle must have an energy in excess of the ionization potential.

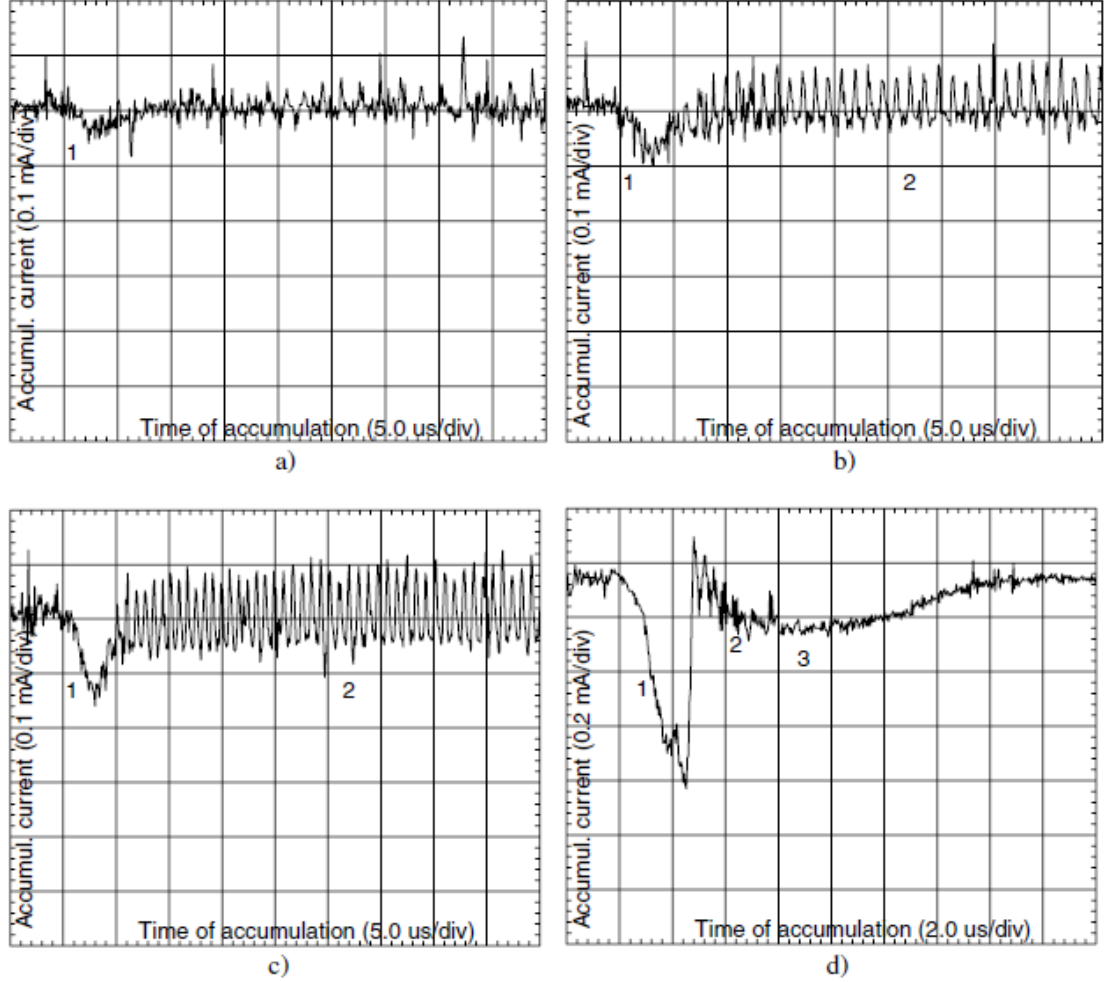
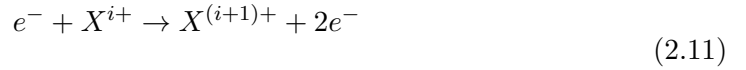


**Figure 2.2:** Oscilloscope images taken during the formation of the electron string by E. E. Donets *et. al* [12]. In each frame, there is more injected electron current. The point marked 1 shows the accumulated electron current in each frame. The unstable state - an increase in the electron current oscillation after accumulation is indicated by 2. This smooths out in frame d where the electron string is formed and a massive amount of electron accumulation is achieved at 3 - the prior instability being self suppressed and vanishing.

Electrons are favoured and more efficient bombardment projectiles when compared with photons or protons. The conservation of energy and momentum in such collisions implies that most or all electron energy will be delivered to a bound electron during near elastic collisions.

When the electron beam energy is sufficient by being higher than the ionization potential, charge stripping via electron bombardment occurs. This can occur in two ways: 1) multiple ionization in a single collision - where many electrons are removed due to the impact of a single beam electron, or 2) multi-step ionization - where a single electron is removed in a collision pushing an ion to the next charge-state, and the charge-state increases this way over multiple subsequent collisions in time [14]. This is represented in equation 2.11, for an atomic species,  $X$ :



The cross-section for double ionization to occur in a single collision is two orders of magnitude lower than for a single ionization. This cross-section dependence on electron energy for Xenon ions is shown in figures 2.3 and 2.4.

The time required to reach a charge-state  $Q$ , after undergoing  $Q-1$  steps, is calculated by summing the times for each single step and is given by;

$$\tau_Q = \sum_{i=1}^{Q-1} \tau_{i \rightarrow Q-1} = \frac{e}{j_e} \sum_{i=1}^{Q-1} \frac{1}{\sigma_{i \rightarrow Q-1}} \quad (2.12)$$

The ionization factor,  $j\tau$ , is derived from Equation 2.12, due to single step ionization being the primary means of reaching high charge-states in EBIS and ESIS. The applied confinement time during ion trapping relates directly to this average time calculated over several steps approximating it closely. Competing processes against this ionization would need to be compensated for by increasing the confinement time. Step-wise ionization cross-sections could also be accurately measured if competing effects are minimized or nullified by using this relationship.

EBIS electron beams are typically 500 eV to 200 keV [44]. This electron energy, tuned by the electron gun, is usually enough to reach very high charge-states in an EBIS. The beam electrons pass through the drift-tubes once before being grounded via the anode on the opposite end. The electron energy is practically mono-energetic.

ESIS electron strings on the other hand, formed by the reflection of electrons back and forth in the drift tubes, pass through this volume multiple times before returning to the electrical circuit. The electron-gun energy is higher than that of the average string electron, as the electrons accumulate in the string and lose energy through several

more collisions between themselves. In this time though, the electron energy is close to being mono-energetic, with only small deviations of the order of 0.1 eV. The advantage is that higher current densities can be reached and the ionization factor,  $j\tau$ , increases considerably for given electron gun power use when compared to EBIS. This was shown in Table 1.1.

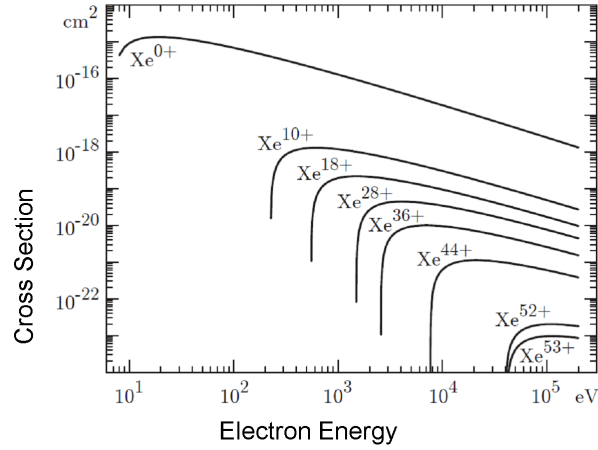


**Figure 2.3:** Calculated cross-sections for single ionization steps of Xenon via electron collision [45].

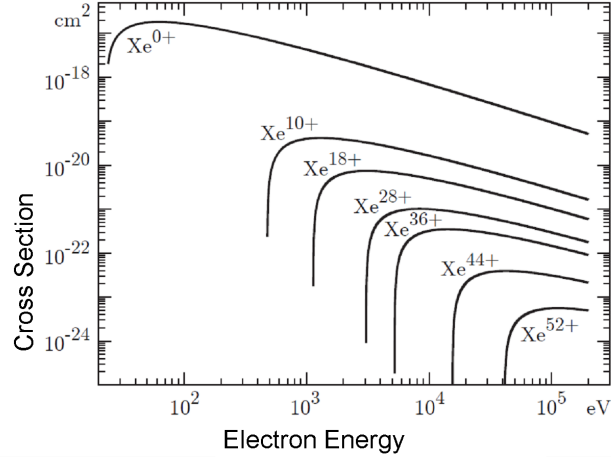


**Figure 2.4:** Calculated cross-sections for double ionization of Xenon via electron collision. The magnitude for the first ionization is two orders of magnitude lower than for single ionization in this case [45].

### Lotz Formula and Ionization Cross-Sections

The cross section, or probability, for electron-electron collisional ionization is estimated using the well known Lotz formula, derived by Lotz in 1967 [47]. This is given in

Equation 2.13.

$$\sigma_{Q \rightarrow Q+1} = (4.5 * 10^{-14}) \sum_{nl} \frac{\ln(E_e/E_{i,nl})}{E_e * E_{i,nl}} [cm^2] \quad (2.13)$$

Here  $\sigma_{Q \rightarrow Q+1}$  denotes the cross-section of ionization from state  $Q$  to the next state  $Q+1$ . The beam electron energy is given by  $E_e$  and the ionization potential is  $E_{i,nl}$  for an ion,  $i$ , within a sub-shell with primary quantum number  $n$  and angular momentum  $l$ .

The graph of Xenon ionization cross-sections in Figure 2.3 were calculated with the Lotz equation. From these graphs it can be seen that the ionization cross-section is at a maximum when the electron energy is around three times the ionization potential. This is very useful information in setting up the electron beam with the aim to reach a specific charge-state for a given ion species. The graphs in Figure 2.4 show the cross-section calculated for a double ionization. Compared to those in Figure 2.3 for a single ionization, the cross-sections are typically two orders of magnitude smaller. Presumably, the cross-section for triple or more ionizations in a single step would be smaller than those for double ionization. From this one can assume that the contribution to ionization comes primarily from single-step ionization, with higher charge-states being reached through multiple single steps.

The Lotz formula does require access to the electron binding energies (ionization potentials) from calculations or tables of measurements. The software for simulating charge-state evolution called CBSim-Analysis, by R. Becker *et. al.*, [49], uses the Lotz formula to calculate cross-sections in addition to known tables for particularly higher charge-states and beam energies. In this vicinity the Lotz formula does not hold as strongly. This software is used extensively in charge-breeding laboratories and will be discussed in more detail in Chapter 7 where it was used to estimate the values of measured charge-states.

The ionization potential of hydrogen-like ions - usually the last step before making naked nuclei - can be easily expressed using Mosley's law:

$$E_{i,k}(Z) = 13.6 * Z^2 [eV] \quad (2.14)$$

This is the familiar hydrogen ground state ionization energy 13.6 eV multiplied by the square of the atomic number  $Z^2$ . However, it is very seldom that heavy nuclei reach such states in a charge-breeder, and usually the experimentalist relies on stripping-foil during post-acceleration to strip HCIs down to their naked nuclei. Substituting equation 2.14 into Lotz's equation gives the approximation of the cross-section between charge-state

$Q$  and  $Q + 1$ :

$$\sigma_{Q \rightarrow Q+1} \approx \frac{10^{-16}}{(Q)^4} \quad (2.15)$$

Ionization energies that are not easily calculated, may be found in tables like those of C. Moore [48]. A plot of these calculated energies against atomic species up to  $Z = 100$  is shown in Figure 2.5. It is clear from this data that to achieve the highest charge-states for heavier atoms, the electron energy of a beam or string should reach above 100 keV.

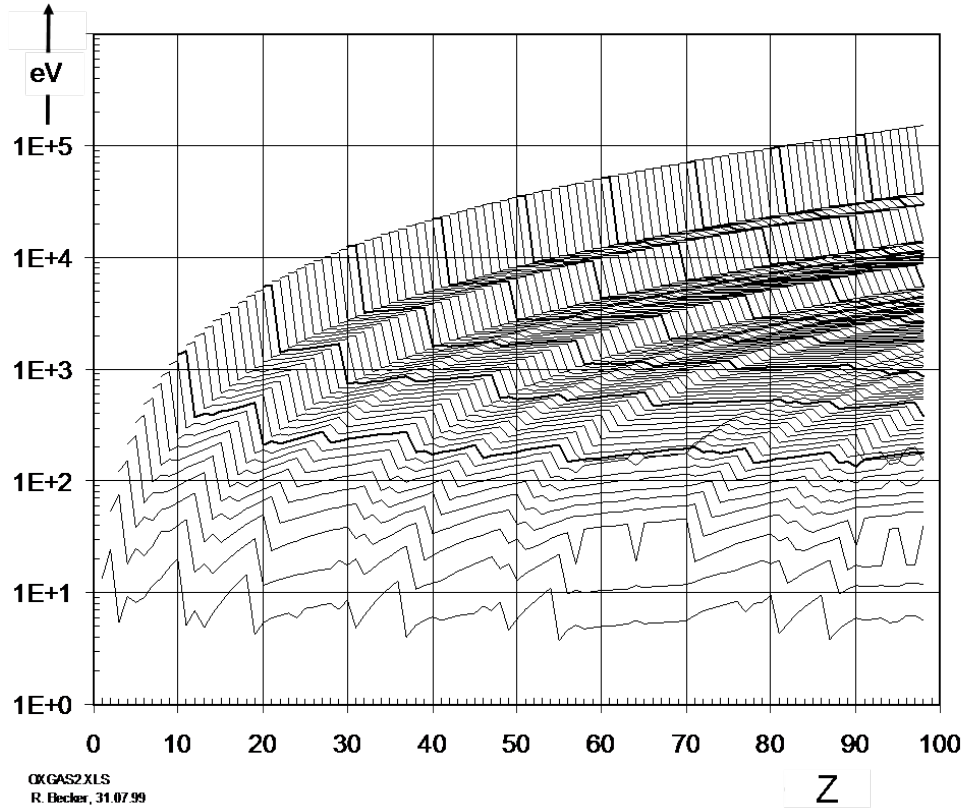


**Figure 2.5:** Ionization energies calculated by C. Moore. The distinct edges indicate a sudden increase in electron binding energy by closed electron shells [48].

### 2.2.4 Competing Processes

The confinement of ions and electrons in the same interaction volume allows for step-wise ionization into higher charge-states via electron-electron collisions. In Chapter 1, in the description of Electron Cyclotron Resonance Ion Sources (ECRIS), charge exchange was blamed for broadening out A/q spectra and inhibiting the full evolution of the highest charge-states for any confinement time. This is a competing process that will always counter-act ionization.

There are a few other processes such as radiative recombination - the time reversed process of photo-ionization, and other heating effects that also compete against ionization. Methods of cooling the ions in order to avoid such heating effects, such as the addition of a buffer gas in the charge-breeding volume, have also been developed. These methods have been essential for the production of highest charge-states achievable in EBIS and ESIS [8][49][50].

#### Charge Exchange

Charge exchange occurs when an ion,  $A^{n+}$  collides with an ion or atom with a lower charge-state,  $B$ , as mentioned briefly in Chapter 1:



Here the neutral (or lower charged ion) is ionized by the strong local electric field of the more highly charged ion, yielding that ion one or more of its electrons, which in turn reduces the charge-state of that ion. This effect is prominent in a very mixed charge-breeding volume containing ions of many states and neutrals, such as in ECRIS. Charge-exchange limits the highest charge-states from being reached in abundance by skewing the achievable spectra toward lower charge-states. The charge-state peaks in such a distribution will also all be similar in their relative abundance - a flattening effect due to the fact that charge-exchange is occurring between all charge-states in the mixture.

The probability for this to occur is given by the cross-section,  $\sigma_{i \rightarrow i-1}$  in Equation 2.17. This approximation was based on many measurements by Salzborn and Muller [51], using only low charge-states and can only approximate these charge-exchange interactions for higher states:

$$\sigma_{i \rightarrow i-1} = (1.43 * 10^{-12}) i^{1.17} P_0^{-2.76} [cm^2] \quad (2.17)$$

This equation is a scaling law that was based on the results of many collision experiments of ion species with charged beams from around 10 to 100 keV, for only a single charge exchange of one electron. The charge-state,  $i$ , is raised to the power of 1.17 from these empirical results and this index decreases for two or more charge exchanges in a single collision.  $P_0$  is the vacuum system pressure in mBar. From this it is evident that the operational pressure in ESIS and EBIS, usually in the  $10^{-8}$  mBar range, is conducive to charge exchange. High charge-states are also self limiting as they are more likely to undergo charge exchange. Charge exchange processes occur more often due to heating effects and therefore cooling methods should be in place to limit this. High charge-states are un-reachable without the aid of a cooling technique [49].

### Radiative Recombination

Radiative recombination occurs when an ion captures a free electron. This is accompanied by the emission of a photon - this process is time reversed of photo-ionization. Photo-ionization occurs when an ion or atom is bombarded by a photon with energy exceeding the electron binding energy, and causes the removal of that electron:



Hence radiative recombination occurs as;



This process occurs frequently in EBIS or ESIS charge-breeders. One emitted photon from radiative recombination may cause photo-ionization in a nearby species if the photon energy is matched with an atoms electron energy levels. However, it is more likely that these emitted photons will be of lower energy and only excite nearby species. When this occurs in the charge-breeding vicinity of an electron beam or string and several highly charged ions, a resonance between excitation and de-excitation can arise due to these absorbed or emitted electrons.

The cross-section for radiative recombination,  $\sigma_{nl}^{RR}$ , can be calculate knowing the cross-section of photo-ionization,  $\sigma_{nl}^{ph}$  using;

$$\sigma_{nl}^{RR}(k) = \frac{(hv)^2}{k^2} \frac{1}{2m_e c^2} \sigma_{nl}^{ph}(k) [cm^2] \quad (2.20)$$

Where  $nl$  is the electron orbital state ionized by a photon of wave number  $k = 2\pi/\lambda$ .

Radiative de-excitation can occur in a similar way to radiative recombination. Atoms or ions absorb photons if and only if the photon energy is equal to the difference between an occupied orbital and a vacant higher orbital. As such, these atoms or ions emit photons when excited electrons return to their ground states. The typical observed photon energies for de-exciting middle Z and heavier atoms are x-rays. These x-ray spectra are very useful in obtaining experimental values for electron impact excitation and ionization, as well as charge exchange cross-sections. This has led to the beneficial use of EBIT type devices as x-ray spectrometers [50].

### Electron-ion Heating

Similarly to charge exchange, the ions in a trapping volume can become excited by the electron beam or string. Here energy is transferred from an electron to an ion without ionizing it. The bound electrons of an excited ion inhabit higher energy levels before decaying to lower levels. Excited ions collide with other ions, transferring their increased internal-energy, and thus exciting un-excited ions while the collision also imparts some kinetic energy. This process causes the excitation of many ions along with an increase in kinetic energy, and spreads out the energy among ions of different species, which in turn causes their trajectories to become more eccentric in the trap. Usually ions are confined within the vicinity of the electron beam or string and follow trajectories along the axial magnetic field lines. Heating causes the average radius of confinement to increase, implying that any extracted ion beam will be of larger radius and emittance. Furthermore, as with charge exchange, electron-ion heating inhibits the evolution of higher charge-states [52].

Heating effects such as this also cause a decrease in the machine efficiency as energetic ions are lost radially after being excited out of their usually oscillatory trajectories. Such effects cause ions to increase their radii so that they are no longer within the electron beam or string and can therefore no longer undergo ionization and are eventually lost to the drift tube walls. Highly charged ions do experience a deeper effective radial potential well caused by the negative beam or string, and therefore become well confined and more difficult to heat by increasing their oscillation radii.

### 2.2.5 Cooling Techniques

Cooling is required to counter-act any heating process that would cause an ion species under study to leave the vicinity of the electron string or beam. Without any collisions, a single ion would follow a helical trajectory - the radial motion is oscillatory due to the magnetic field and the negative potential of the electron string or beam, while the axial motion is linear as an ion is reflected back and forth by the positively biased end drift-tubes, along the main axis of the trap. With several ions, Coulomb scattering as well as charge exchange becomes more probable. This causes an increase in the average orbital radius of an ion, and loss if this is comparable to the drift tube radius.

Cooling is therefore needed to maintain small radii of ions within and around an electron beam or string. The introduction of buffer gas into the system, which itself becomes ionized, or through the strategic use of neutrals or residual gas ions, causes collisions which favour the ions under study.

#### Buffer Gas

Neutral gas injection has been used as a cooling mechanism in charge-breeders including ECRIS [44]. For example, the Penning-trap that bunches singly charged ions before injection into the REX-EBIS at REX-ISOLDE uses helium gas injection to cool these ions, lowering the ion beam emittance before external injection [19]. In a Penning-trap, the helium atoms used for cooling do not get ionized by the other ions as their ionization potential is large, they instead carry away excess energy as they are lighter than the other elements present. Note however that in EBIS or ESIS, this cooling occurs due to the neutral gas becoming ionized so that there will be Coulomb repulsion between the lighter cooling ions and the heavier species of ions under study.

Neutral gas injected in the breeding volume is ionized and cools the charged ions by removing excess energy away after scattering. Scattering causes a decrease in kinetic energy, and hence decreases the radial departure of these ions from the electron beam.

There must be ionization of the neutral gas for cooling. However, once ionized, the lighter mass ions of lower charge-states can continue to cool the highly charged ions within the electron beam through momentum transfer via ion-ion collisions. Helium is particularly useful as a buffer gas because the ionization potential of helium is greater than most secondary ionization potentials of singly charged ions, therefore once ionized, helium ions do not recombine with neutral helium atoms. The buffer gas essentially provides more lighter ions and cooling is achieved through ion-ion collisions.

#### Ion-ion Cooling

Repulsion occurs between positive ions in an EBIS or ESIS. This Coulomb scattering can be used to keep highly charged ions confined within the electron beam. Lightly

charged ions feel strong repulsion from ions of higher charges, yet are not as tightly bound by the magnetic field. More highly charged ions also feel a stronger negative well potential caused by the electron beam,  $U_W$ , due to their higher charge.

Coulomb scattering between a pair of ions is favourable when the momentum exchange carries away excess kinetic energy from the studied highly charged ions, which in turn minimizes the average gyration radii. Two contradictory factors must be reached in order to achieve this; 1) If cooling ions are used, they should have the maximum possible charge in order to carry away excess energy, 2) cooling ions should have the smallest charge-state so that they can escape the system quickly without being similarly confined by the trapping fields. This charge-state should never be larger than that of the ion species undergoing charge-breeding.

These contradictory requirements are helpful in imposing a narrow choice of buffer ions for use. Additionally, with the introduction of different species for this purpose, the space-charge compensation cannot be maximal for the species being charge multiplied, as some neutralization from the buffer species will occur. The effect of space-charge neutralization, or compensation was discussed in section 2.2.1.

Ions in ESIS or EBIS are strongly confined by the radial potential of the electron string or beam. Cooling also occurs when low charge-state ions leave the trap axially as well - this is another way excess momentum is removed from the charge-breeding volume but this contributes to loss of ions.

Due to the constant loss of the more energetic lightly charged ions, ion-ion cooling is also known as evaporative cooling because there is continual loss of coolant ions. Therefore continuous injection of primary ions or some buffer gas is required to continually remove the excess energy from the heated ions keeping them well confined in the trap[50].

### 2.2.6 Modelling Charge State Evolution

The evolution of charge-states from low  $Q$  to high  $Q$  is dominated by electron-impact bombardment as discussed above. All of the aforementioned competing process limit this evolution. In order to model such charge-state evolution together with competing effects, a differential equation should be set up and solved for each ion charge-state. Equation 2.21 shows how these processes can be addressed. Such a formula has been used in the charge-evolution software CBSIM-Analysis to simulate EBIS charge-breeding by R. Becker *et, al* [42].

$$\begin{aligned}
\frac{dn_i}{dt} = & n_e v_e [\sigma_{i-1 \rightarrow i}^{ion} n_{i-1} - (\sigma_{i \rightarrow i+1}^{ion} + \sigma_{i \rightarrow i-1}^{RR}) n_i + \sigma_{i+1 \rightarrow i}^{RR} n_{i+1}] \\
& - n_0 v_{ion} [\sigma_{i \rightarrow i-1}^{ceex} n_{i+1} - \sigma_{i+1 \rightarrow i}^{ceex} n_{i+1}] \\
& - v_i^{coll} e^{\left[ -\frac{iqU_W}{kT_{ion}} \right]} \frac{iqU_W}{kT_{ion}} n_i
\end{aligned}
\tag{2.21}$$

This gives rise to a set of multiply coupled differential equations which must be computed numerically for each ion of charge-state,  $i$ . The processes represented in Equation 2.21 are single step electron impact ionization,  $\sigma_{i-1 \rightarrow i}^{ion}$ , which takes an ion from state  $i-1$  to  $i$ . For single step ionizations of a given ion state, there is also a loss of these ions as they evolve to the next higher state,  $\sigma_{i \rightarrow i+1}^{ion}$ . Radiative re-combination, given by  $\sigma^{RR}$  also contributes to charge-state loss - and an increase in the population of the current charge-state by loss from the next higher state. These processes are given in the first term of Equation 2.21 which is proportional to the population of electrons in the beam,  $n_e$ , and their velocity which is energy dependent,  $v_e$ .

Next, charge-exchange is addressed in the second term of 2.21. This is a loss process with rate proportional to the entire ion population,  $n_0$  and the average ion velocity  $v_{ion}$ . This term includes the loss of ions from this state entering a lower state, and the gain of ions from the next higher state devolving into the current state, the probabilities of which are given by cross-sections  $\sigma_{i \rightarrow i-1}^{ceex}$  and  $\sigma_{i+1 \rightarrow i}^{ceex}$  respectively.

The final term in the modelling of charge-states expressed above takes into account the thermal loss from heating effects given by the Boltzmann distribution, which is proportional to the collision velocities of the ions,  $v_i^{coll}$ . Here  $U_W$  is the negative potential well caused by the electron beam or string.

The solutions of Equation 2.21 predict the charge-state evolution over time, and can be very useful in predicting charge-state from EBIS or ESIS experiments. The relative abundance of an ion species can be plotted against the confinement time,  $\tau$ , or the ionization factor,  $j\tau$ . CBSIM-Analysis charge-state evolution results use the ionization factor on the x-axis. This is very useful in estimating the electron current density if one has obtained a spectra and only knows the confinement time - a useful fact used with ESIS where the electron current density is impossible to measure and otherwise difficult to estimate. In either case the logarithm of this time or ionization factor is often

plotted instead, being natural to the step-wise ionization in the evolution equation. An example of such a plot is given in Figure 2.6.

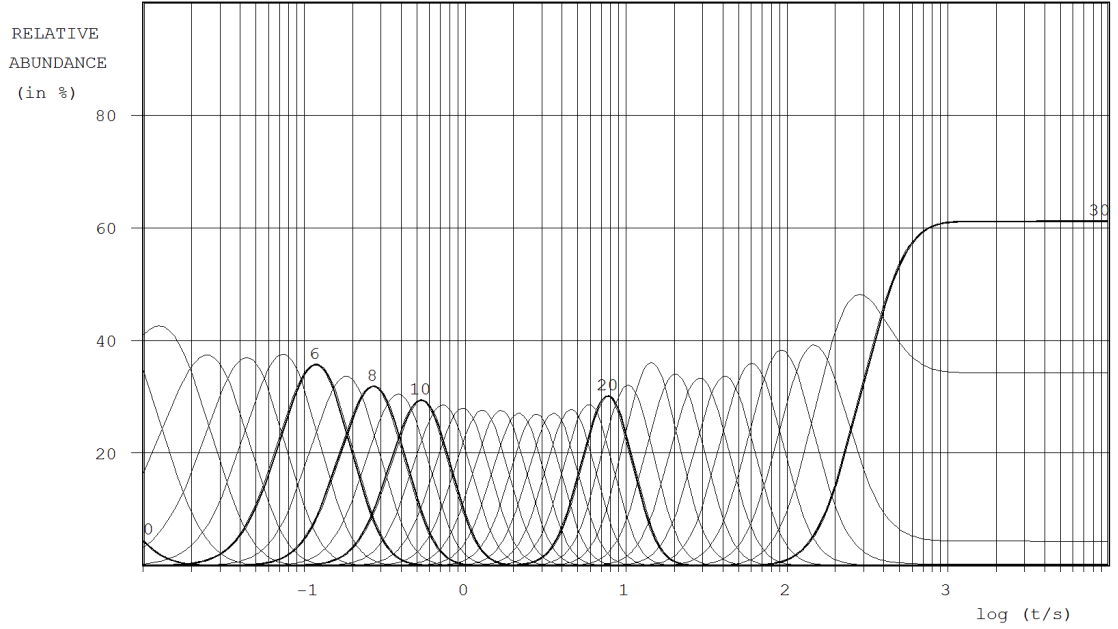


**Figure 2.6:** This figure shows several graphs generated by CBSIM-Analysis calculations for the charge-state evolution of Germanium, using the system of differential equations for each charge-state (Equation 2.21) [49]. These graphs were calculated for a 4 keV electron beam, and includes the competing processes and neutralization of space-charge over time. The highest state reached in this example was  $i = 30+$  shown by the bold line on the right. The experimentalist can insert a vertical line corresponding to the known ionization factor,  $j\tau$ , and the intersections of this with the simulated abundances reveal what charge-states should appear at that particular confinement time or ionization factor. The naked Germanium nucleus has a  $32+$  charge-state. This indicates that the final two electrons are very difficult to remove due to them occupying the closed shell with the highest binding energy of Germanium. Note that the x-axis unit is in  $\log(s)$ , this is because this plot is taken for a small electron current density of  $j_e = 1 \text{ A/cm}^2$ . At working current densities of a few  $100 \text{ A/cm}^2$ , the unit would be in  $\log(ms)$ .

Modelling additional charge-evolution processes, such as buffer gas cooling, can be done using software like CBSIM-Analysis and the effect of cooling which allows for larger proportions of higher charge-states can be observed.

As a side-note, a certain charge-state in experiment or simulations can be pronounced by setting the electron beam energy just below the energy of a closed shell. The shell-closure effect serves to amplify those charge-states before the next closed shell is breached by higher beam energy [53]. This effect can be seen in the charge-state evolution graphs of Figure 2.6 - the maximum charge-state reached in this case was  $30+$ , meaning that the  $1s^2$  closed-shell remains occupied by two electrons.

Note that CBSIM-Analysis is a simulation software designed for EBIS, which has a mono-energetic electron beam, which was 4 keV in the example shown in Figure 2.6. In order to make use of CBSIM-Analysis for ESIS, one must make several simulations corresponding to the distribution of electron energies expected in the electron string, and an average must be taken to estimate the charge-state distribution. It is in this way that ESIS tends to produce purer A/q spectra than EBIS. This method of averaging CBSIM graphs will be explained in detail in Chapter 7.

## Chapter 3

# Beam Transport Simulations

The development of the ion transport system which will both deliver singly charged ions into the ESIS, and extract the highly charged ions after charge breeding, is an experimental process which is covered throughout this thesis. It is therefore necessary to both predict the behaviour of these ion beams before performing experiments, as well as to test the existing experimental parameters via simulations.

Simulations are essential in experimental physics work. They allow benchmarks to be obtained, and they can be used to quickly ascertain various parameters during the performance of actual experiments.

In this work, two simulation programs were utilized in order to both prepare and optimize the experiments. Firstly, the Opera 3D package called TOSCA [56] was employed a-priori to any experiments. This was used to get an initial picture of all the elements required to achieve such an ion transport system. Secondly, SIMION - a program capable of ad-hoc simulations on the fly during real experiments, as well as more detailed ion transport simulations while the experiment is off-line was used extensively throughout the entire research. Both of these will be described in this chapter.

### 3.1 Opera 3D: TOSCA

During the initial phase of this research, the TOSCA package of COBHAM's Opera 3D [56] was used to simulate an EBIS type device and a simple injection system. The results of such simulations were brief and they are included in the first sections of Chapter 4.

There exist several physics packages for Opera 3D, with TOSCA being the most basic. TOSCA can calculate the electric and magnetic fields for a given geometry and current

distribution, and the simulate the electric and magnetic forces on a charged particle. It does not handle, heating or stress or strain and other mechanical movement. Furthermore, it cannot simulate space-charge effects, which would be more applicable to this work. A more expensive Opera 3D package, such as SCALA, is required for space-charge and other charge transport simulations.

TOSCA uses a finite element method of solving the Laplace Equation for electric potentials of a user defined geometry and material. The laboratory configuration including all beam-line elements and their locations with respect to each other, the material from which they are constructed, and the size of simulation space are all specified by the user prior to the execution of the software. This is all set up in the Opera 3D Modeller.

Once the Opera 3D model is ready, the TOSCA software processes the configuration using the post-processor, solving the Poisson equation for each of many small tetrahedral volumes. This triangular mesh size can be specified for each component simulated. The smaller each tetrahedral cell, the more accurate the potentials simulated would be - at the expense of computation time. Therefore, some components in the configuration could be defined to have smaller or larger meshes depending on the accuracy required by the user.

TOSCA was used for only a brief period in the initial stages of this work. The TOSCA license, which is renewable every six months, was only used during the first six months of this research, well before any real experiments had started.

During this period, ideas for what was required for the transport system were tested, and a few key beam-line optic components were investigated, such as the DRE-EBIT Quadrupole Switch-yard, which is discussed in Chapter 4.

## 3.2 SIMION

SIMION [57], similarly to TOSCA, uses a finite difference approach to solving the boundary value problems setup in a user-defined geometry. This user defined geometry is called a "potential array". A user generates the potential array by drawing the design or importing the design into SIMION. Once again, the size of each grid point is user defined, with smaller grid sizes implying greater accuracy at the expense of computation time.

The SIMION potential array is configured to be cylindrically or planar symmetric depending on the geometry. Beam line components are often cylindrically symmetric, however something like the Quadrupole Switch-Yard requires planar symmetry.

Individual parts of a beam-line can be set up separately, with grid sizes suited to the accuracy required. The full transport system could then be simulated by incorporating several potential arrays on a single work bench. Care is needed when it comes to how two potential arrays overlap. Fringe field effects are prominent, therefore the designer

should try to match the fields at the connection of two closely placed potential arrays. This can be done by ensuring that connected electrodes share the same potential.

The biggest advantage of SIMION over TOSCA, is its ease of use especially during real experiments. There is an option to "fast-adjust" voltages on electrodes, which enables the scientist to quickly change and check which potentials are suited for a particular ion-optical element. A working SIMION model of a real experiment can therefore provide immediate insight into the beam behaviour and the power-supply consideration of beam-line optics can be checked and implemented readily.

SIMION was used extensively in this way throughout all experiments conducted in this research. Results, where salient to the work herein, will be presented in side-boxes as discussed in the next section.

SIMION does have several draw-backs that are easily overlooked for its useful purposes discussed above. Space-charge can be 'turned-on' using SIMION however that requires more computational power, and was used only for in depth investigations of statistical root-mean-square emittance,  $\varepsilon_{RMS}$ . Such estimates can only be compared to other emittance calculations from SIMION, and not with real experiments. This is because the ion source emulated is close to, but not in fact the same as a real LMIS. However, one can use the emittance comparisons to decide if one configuration is better than another - evidenced by the one with lowest computed statistical emittance.

In this research SIMION Version 8.1 was used.

### 3.3 Simulation Boxes

The simulations that were performed concurrently or prior to real experiments will be highlighted during the salient sections of this thesis. Simulations performed pertaining to a specific investigation are presented in this work within *boxes*. The reader should be able to follow these simulation boxes fluidly as part of the chapters where they are presented, or the reader may skip over them entirely to just follow the experimental process.

SIMION simulations were performed concurrently with the experimental research, and the results will be presented where applicable in the development of the ion transport-system, namely;

- Simulating LMIS ions from needle-tip (chapter 4)
- Simulating the effect of the ion-gun with differing ion energies,  $U_{ex}$  (chapter 4)
- Emittance study of beam with and without bending (chapter 4)
- Simulating external injection of 1.7 keV  $\text{Ga}^+$  beam (chapter 7)

## Chapter 4

# Development of Injection System

A system for the transport and injection of singly charged ions into the ESIS, and for the subsequent extraction of HCIs after charge-breeding has been developed. Similar systems have been constructed by groups at other laboratories to deliver singly or doubly charged ions into EBIS, such as at REX-EBIS at ISOLDE, CERN, with the use of a Penning Trap to bunch-up ions before EBIS injection [8], and at Brookhaven National Laboratory (BNL), with the use of hollow cathode ion source and an electrostatic deflector [36]. The most salient EBIS injection sharing similar components to this work has been done by Thorn *et. al*, in Dresden, Germany [29]. A comparison of these experimental results with this research can be found in the analysis of results and conclusions in Chapters 6 and 7.

This is the first attempt at injecting already charged ions into an electron string-type charge breeder, and the methodology of this approach is similar to what has been accomplished with the Dre-EBIS at Dresden Technical University by A. Thorn *et. al*, [29], in which singly charged ions are produced by a liquid metal ion source (LMIS) and an electrostatic quadrupole switch-yard is used to control ion beam traffic during the injection, charge-breeding, and extraction phases. The system at BNL utilized a hollow cathode for the initial ion source, and although an electro-static deflector is used instead of a switch-yard, this work remains salient and comparable to the research conducted in this investigation. The injection line being developed for the ESIS in this research will be achieved with singly charged ions from an LMIS, a voltage pulsed quadrupole switch-yard for controlling beam traffic into and out of the ESIS, and finally several focusing systems to ensure that the injected and extracted beams are of low emittance and narrow beam-widths.

This chapter covers the development of this ion injection and extraction system from its conception, through the development of each ion-optical component, to the initial tests and calibration on the test bench for use with the Krion 6T ESIS. Chapter 5 will cover in depth experiments with the working ion-beam and the ESIS.

## 4.1 Overview of required system

The ion injection and extraction transport system that has been developed was designed similarly to the EBIS-A system in Dresden studied by Thorn *et al.* [29]. Injection into the ESIS needs to occur on axis, through the ESIS extraction port, which will deliver singly charged ions directly into the electron-string. Injecting ions into the ESIS radially (as is done with neutral gas charge-breeding) will not be sufficient to confine the ions within the electron string, as the axial magnetic field immediately gives rise to very eccentric ion trajectories. Therefore the ESIS extraction port must be modified so that it can serve as an injection port.

Charge-breeding with ESIS and EBIS devices is most efficient at producing very highly charged ions when operating in a pulse-mode, and when given sufficiently long breeding times. Continuous wave methods of charge-breeding that involve a constant re-supplying of ions or atoms into the charge-breeder and then continuously extracting them from the other side, as is done with ECRIS, may give beams of higher brightness, but these ions do not reach the higher  $Q/A$  ratios that can be expected from EBIS or ESIS.

A pulse-mode injection scheme of *over barrier injection* will be used to deliver pulses of primary singly charged ions to the ESIS. In this case, the injected ions must have a higher energy than the positive ion barrier potential at the injection/extraction port <sup>1</sup>, and sufficient ion current to quickly compensate the space-charge capacity of the ESIS or EBIS. Once ions have been injected in this way, after their first ionization step, they will not be able to escape back past the barrier because their higher charge value means they will be more tightly confined within the electron string and the ion trap region.

Liquid Metal Ion Sources (LMIS) are used to generate singly charged ion beams as the primary ion source. They are high in brightness and current and relatively cheap to use as a first test source. In practice, there is a multitude of options for primary ion sources. A discussion covering ion source options for EBIS charge breeding can be found in Visentin's paper [54]. However, the system will be eventually used for the injection of charged fission fragments [55].

For the Krion 6T ESIS, an ion current of at least  $1.2 \mu\text{A}$  is required during over-barrier injection in order to reach suitable compensation of the electron string's capacitance within the ESIS, which is about 50% [12]. As further charge-breeding occurs, the ion charge state is compensated by missing electrons and a high density of HCIs can be extracted.

An electrical quadrupole switch-yard is used in order to bend the singly charged ions into the injection/extraction line during injection. During the extraction phase, the

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<sup>1</sup>The ion injection energy should be a few 100 eV higher than the barrier potential, which is normally a few kV, and not more than twice the barrier potential. If it is more than twice the barrier potential, the 2+ or higher charge-state ions may still be able to escape over the barrier.

switch-yard is un-powered to allow charge-bred ions to fly straight through the switch-yard for detection or further experiments.

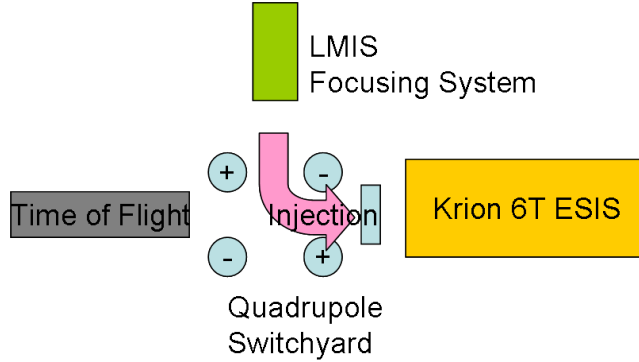


**Figure 4.1:** Simple system schematic showing the biased electrical switch-yard during the ion injection phase into the ESIS.

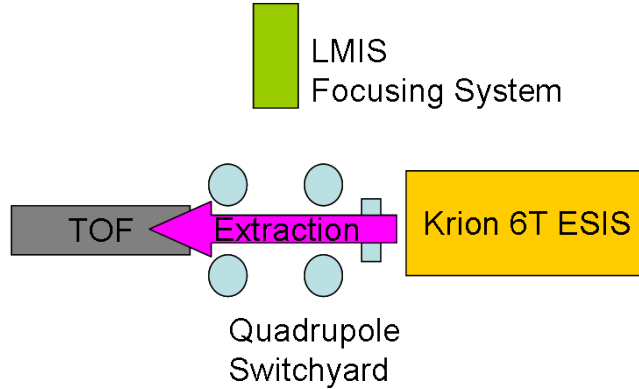


**Figure 4.2:** After ESIS charge-breeding, the extracted HCIs fly through the un-powered switch-yard for detection or to be used in experiments.

The pulsing process of the required system is presented in Figures 4.1 and 4.2. The over-all duty time of this process will therefore include the following phases: injection, charge-breeding, extraction, reset. These phases are also necessarily matched with the reset and string-restoration time within the ESIS.

In terms of ion energy, investigations in this work have ranged from 900 eV to 3 keV, with 1.4 keV to 2.4 keV being the main test energy range in later experiments. The normalized emittance of an ion beam should be less than the acceptance of the EBIS electron beam or ESIS electron string for ion overlap with the electrons to occur. Un-normalized emittance is inversely proportional to the square root of the ion energy making higher energy beams easier to transport into the ESIS due to less emittance growth[14]. However, because ion velocity is also proportional to the square-root of the ion energy, more energetic ions will take shorter times to traverse the length of the

trap and make a round-trip between the reflecting potential barriers, while the duration will be longer for slower ions which therefore have a higher probability of interacting with the electron string<sup>1</sup>. Simulation studies were performed by Kittimanapun *et. al*, [20]. Thus a middle-ground injection energy is required for optimizing beam emittance against breeding-times.

Finally, repeated sets of einzel lenses need be included within the transport system in order to maintain the beam focus. These will usually be positively biased, and may have to be switched from lower to higher biasing during the extraction of HCIs.

#### 4.1.1 Summary of System Requirements

- Same-side ESIS injection and extraction
- Pulsed electric quadrupole switch-yard
- Singly charged ions via LMIS
- Multiple sets of einzel lenses
- $> 1.2 \mu\text{A}$  of ion current for compensation
- High enough energy ions for small divergence
- Low enough energy for high interaction cross-sections and sufficient charge-breeding

## 4.2 Simulations of ion source extraction, focusing and quadrupole bending

The first two components in the transport system were simulated before any real experiments were performed. These are the ion source and initial focusing einzel lenses, and the Dre-EBIT electrical quadrupole switch-yard.

More simulations of the added components became necessary as the transport system was developed beyond the switch-yard. However, the first task of the ion transport system was to produce a focused beam of singly charged ions from an LMIS, and have them injected into the quadrupole switch-yard for  $90^\circ$  bending.

These simulations provide a very useful starting point for the system design, and allow for an estimation of the physical sizes of the beam-line, and also a notion of how the voltage biasing should be applied on the ion-optics for a given ion energy.

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<sup>1</sup>In the external injection experiments presented in Chapter 7, the ion beam energy was 1.7 keV and the barrier potential was 1.5 V. The ion energy within the trap region was therefore equivalent to the difference,  $T = 200 \text{ eV}$ .

The simulations were performed in Opera 3D: TOSCA, and in SIMION.

#### 4.2.1 TOSCA Simulations

A license for Opera 3D: TOSCA was acquired before the experimental phase began. An initial design of the system was created in TOSCA which included the switch-yard primarily, but also extra elements that would be added during the optimization phase (in Chapter 5).

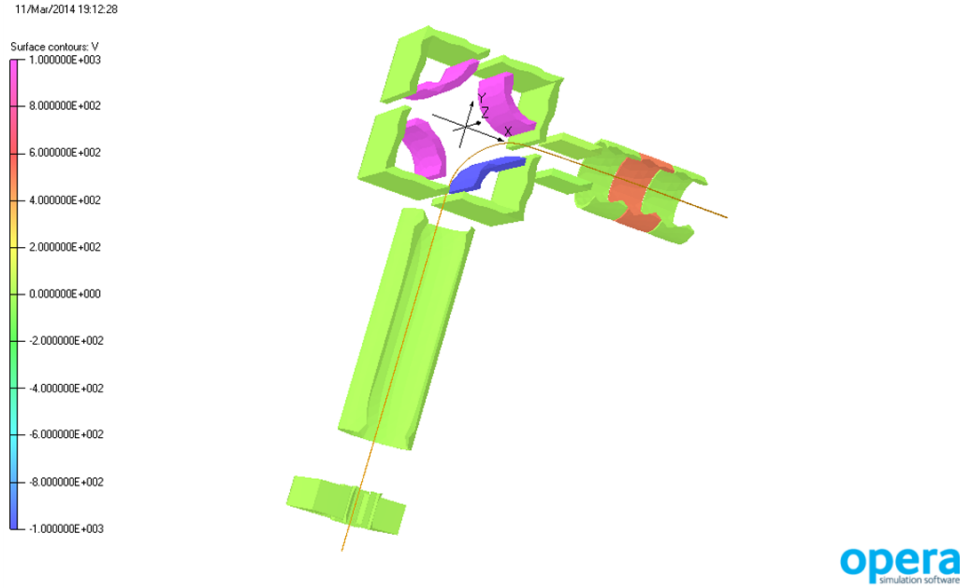


**Figure 4.3:** TOSCA output: (from left to right) Wien filter, drift-tubes (with possible focusing lenses), quadrupole switch-yard, electrostatic bender, focusing einzel lenses, horizontal/vertical steerers (missing from above picture). The trajectory of  $\text{Au}^+$  is shown in orange and starts at the top right and ends at the bottom left. [56]

In addition to being tackled as a whole, each individual component was first created and tested in TOSCA. In each test,  $\text{Au}^+$  was accelerated with 20 kV in the positive x-direction which is the primary axis from the  $\text{Au}^+$  source.

TOSCA, in dealing with only electric and magnetic fields, does not incorporate space-charge considerations in its calculations<sup>1</sup>. This limitation unrealistically keeps the ion beams highly collimated - which can still serve as an extreme condition for the parameters gleaned from the simulations.

Another limitation of TOSCA is the inability to program an emitter surface for the  $\text{Au}^+$  source, which would give a much more accurate initial beam profile and density

<sup>1</sup>Space-charge effects can be simulated in SCALA, another package for Opera 3D

description (for example, Gaussian or plane-wave). Instead it initializes a given number of tracks at even intervals around a declared source point, giving rise to a fairly symmetric array of trajectories to traverse the beam-line.

Due to the simplicity of the ion beam parameters used, the LMIS was not sufficiently modelled in TOSCA. However, a square array as described above was used. The deformation of this square beam as it passes through the ion-optics is still useful in studying the quadrupole switch-yard's effect on emittance.

### The Switch-Yard in TOSCA

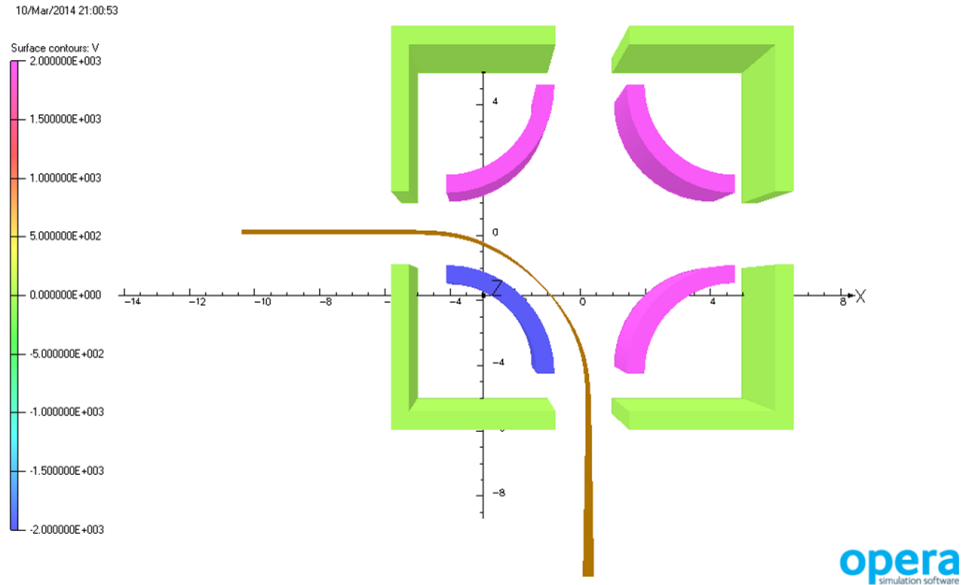


**Figure 4.4:** Modelling singly charged ions of energy 2.8 keV (travelling from the left), successfully deflected with electrodes biased to +2 kV (pink) and -2 kV (blue). In practice, the opposite electrodes are similarly biased to higher voltages, closer to ion beam energies.[56]

The Quadrupole Switch-yard was drawn in Opera 3D (Figure 4.4) to the exact specifications of the Dre-EBIT Quadrupole Switch-yard that would be soon acquired. The ion flights were post-processed by TOSCA.

In Figures 4.5 and 4.6 the phase-spaces of the simulated ion trajectories are shown. These have been recorded at a y-position just after the ion beam has been bent by  $90^\circ$  from the X axis into the Y axis. The spread of the beam in the Z direction is unaffected by any electric fields and is therefore unmodified. However, the beam diverges more strongly in the X direction which can be seen in the positively sloping pattern of trajectories in Figure 4.5.

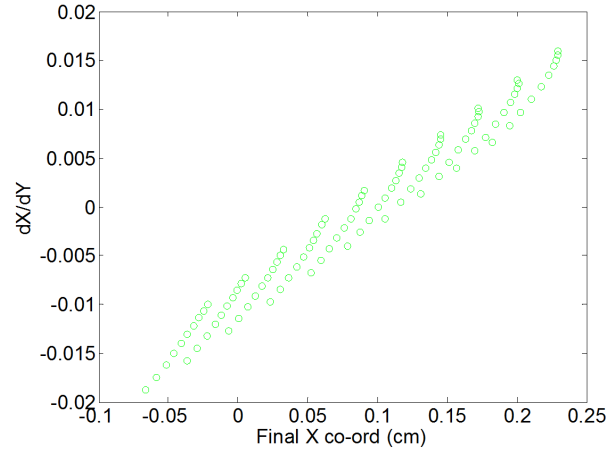


**Figure 4.5:** Phase-space of square beam in x-transverse dimension after 90° bending.

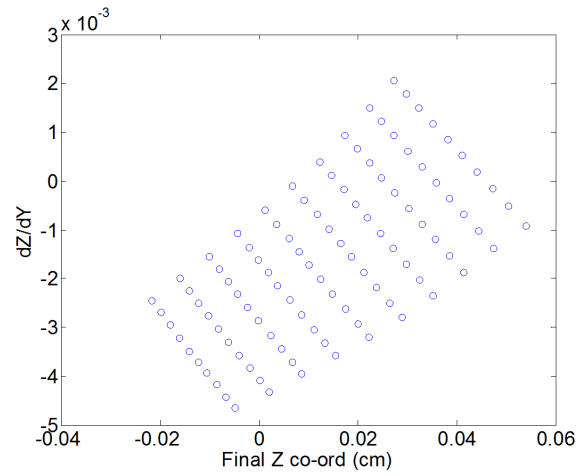


**Figure 4.6:** Phase-space of square beam in z-transverse dimension after 90° bending

Therefore, it would be necessary in practice to include einzel lenses after the bending in order to mitigate this beam divergence.

Additionally, transverse directional electrical deflectors can also be used to readjust factors such as beam offset from the principle axis, which changes from X to Y due to bending.

### Electrical Beam Correctors in TOSCA

Electrical deflector/corrector type ion optics were investigated briefly in Opera 3D: TOSCA. This was done to mitigate divergence in one direction after bending, as well as to make sure the beam is well centred after bending.

These deflectors would not be incorporated into the over-all transport system until the final stages of the construction, however, they are briefly shown here.

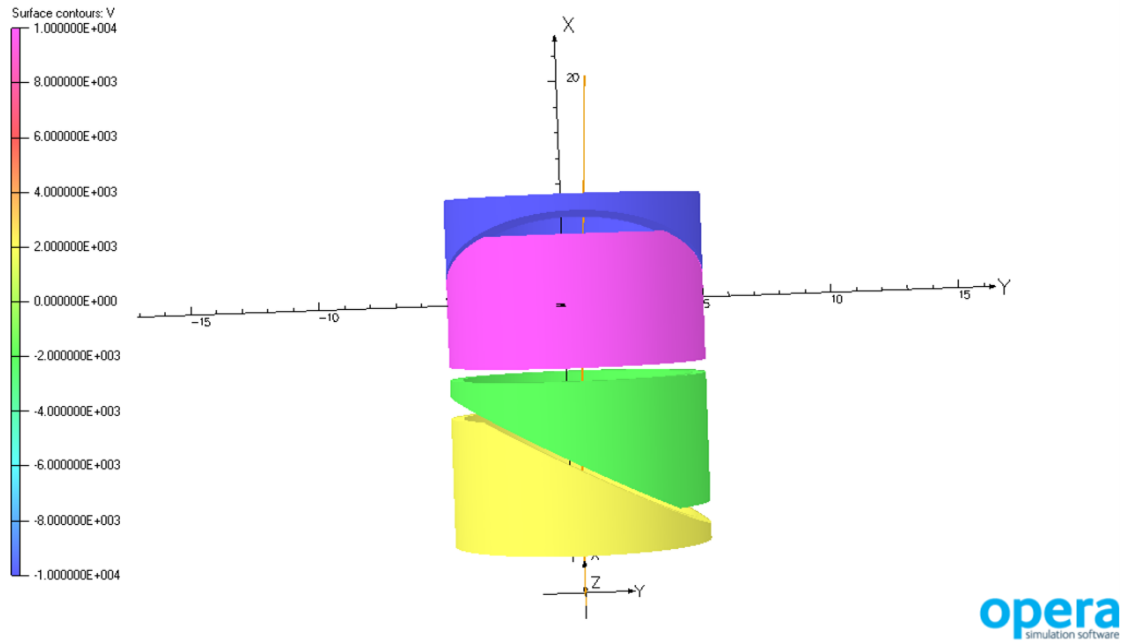


**Figure 4.7:** Transverse direction electrical beam-correctors. These pairs of cylinders can each be biased sufficiently (shown by the different colours) to centre the beam after switch-yard bending. [56]

The beam corrector design as shown in Figure 4.7 is robust for multiple reasons. In addition to having focusing effects, the deflector can also help re-centre an off-centred beam. Finally, because of their cylindrical design, they can be similarly biased to act as an extra set of focusing lenses for the beam exiting the quadrupole switch-yard.

### 4.2.2 SIMION Simulations

SIMION was used to simulate the ion transport system in parallel to the actual development of the LMIS ion delivery system. This software has the feature of fast-adjustable voltage toggles which can be quickly modified to test various ion optics biasing, and readily match those used in experiments [57].

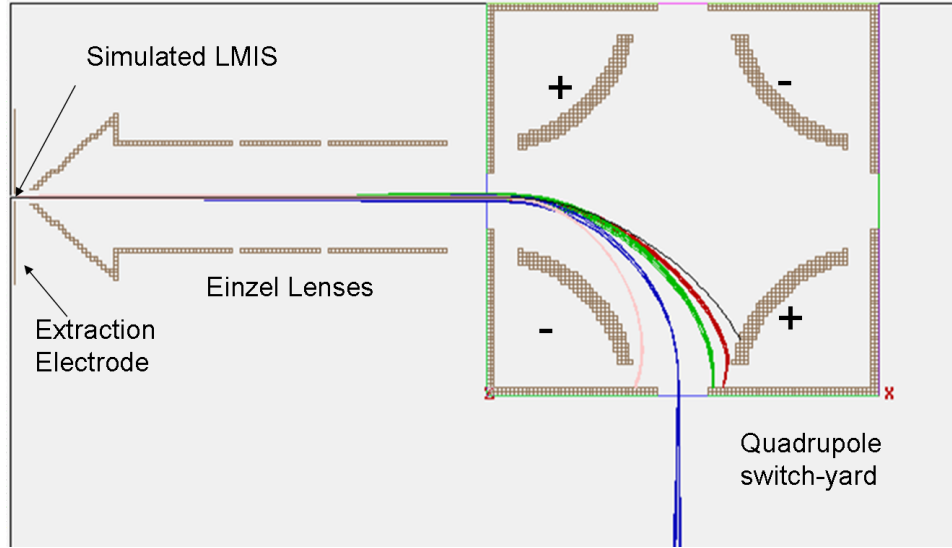


**Figure 4.8:** SIMION example: LMIS assembly and switch-yard with multiple ion trajectories, each of varying energy. Only those ions with energies matched with the switch-yard electrode voltages are deflected perfectly by  $90^\circ$ . However, incoming ions will have an angular distribution associated with the beam energy spread, and even those particles with more eccentric trajectories can be deflected by the quadrupole, and re-focused at the exit. Therefore the switch-yard has energy and angular acceptance that helps to minimize ion losses due to mismatched energy.

Figure 4.8 shows the test design of both the LMIS assembly and switch-yard with multiple trajectories of varying ion energies. The situation in this picture is ideal because there is a very small distance between the last einzel lens and the switch-yard. In practice, the distance is much larger (about 20 cm), and more einzel lenses were included to improve the focusing at the switch-yard entrance in subsequent designs. In the final LMIS assembly, the distance between the last einzel lens and the switch-yard entrance is 5 cm.

## 4.3 The Liquid Metal Ion Source

Liquid metal ion sources (LMIS) and liquid metal alloy ion sources (LMIAS) have several applications. One typical use is the focused-ion-beam (FIB), which is employed

in nano/micro milling and drilling, and ion implantation in micro-chips [58][59][60]. LMIS are also sometimes used as precise altitude and orbit correction thrusters in satellites, and may be used as long distance space propulsion mechanisms in the future [61].

LMIS ion beams are also known to be of high brightness, and have low normalized emittance around  $10 \pi \cdot \text{mm} \cdot \text{mrad} \cdot \sqrt{\text{MeV}}$  on ion extraction from the needle tip [73].

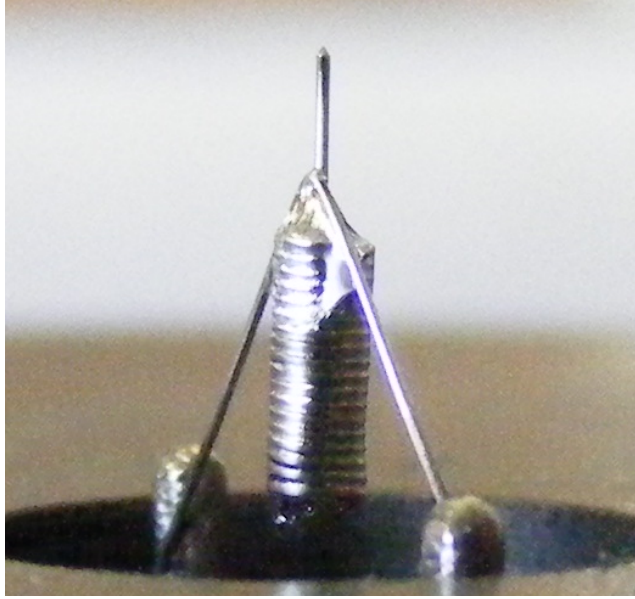


**Figure 4.9:** Photograph of a  $\text{Ga}^+$  LMIS. The reservoir at the bottom contains gallium which becomes liquid when heated, which then rises and wets the needle above.

An LMIS typically consists of a thin, sharp tungsten needle or capillary tube which is connected to a liquid metal reservoir (See Figure 4.9). First a high current of 3 A is applied for 45 s to heat and melt the gallium in the reservoir, which then coats the surface of the LMIS needle via capillary action. The LMIS needle is placed on a high positive voltage bias and a nearby extraction electrode with negative bias creates an electric field which causes the positive ion formation in a process known as field evaporation (See Figure 4.10) [58]. Electric field strengths of around  $10^9 \text{ V/m}$  are required for ionization from the electrodynamically formed Taylor cone on the tip of the LMIS needle or capillary, see Figure 4.10. The Taylor cone is a hydrodynamic geometrical state caused by the equilibrium between the applied electric field and the surface tension of the liquid metal or liquid metal alloy, and usually has a half-angle of  $49.3^\circ$ . The Taylor cone then develops a charged liquid jet at the apex due to the space-charge repulsion in the liquid. Atoms in the jet are then ionized by field ionization caused by the applied electric field, and accelerated through an extraction electrode aperture. Hence an ion beam is created, and the liquid metal ejected as ions is replenished from

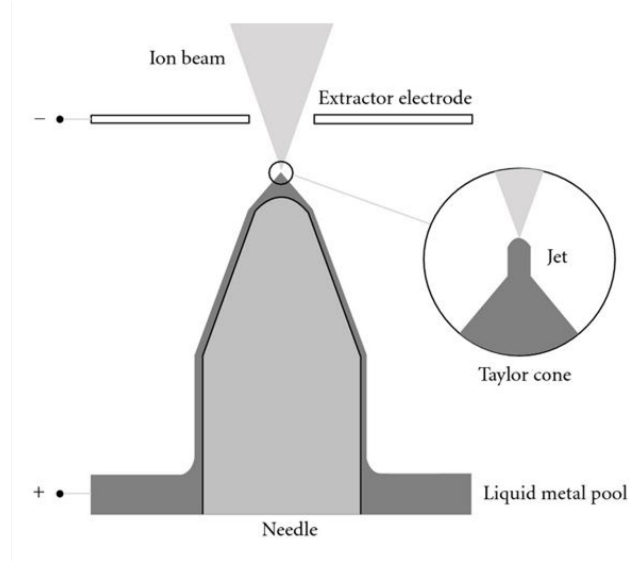


**Figure 4.10:** The needle emitter is on a high positive potential, as is the liquid metal coating it. The liquid metal protrudes further due to the strong positive field forming a Taylor cone. Once the electrostatic repulsion overcomes the surface tension of the liquid, field evaporation of ions occurs.

the reservoir due to hydrodynamic flow and capillary action. Tungsten is typically used for the LMIS needle due to its inertness, low solubility into liquid metals and its very high melting point [64].

Many LMIS applications use gallium for its low melting point (30°C) and excellent wetting properties, but many other ion-sources are available, such as indium which is being used for satellite thrusters [61]. Ion beams of more difficult to use metals are made possible by using their alloys instead, such as gold-silicon alloy which has a melting point at 363 °C, much lower than gold which is 1063 °C. Nevertheless, every LMIS must undergo a short heating cycle before its first use. This ensures the metal liquefies in the reservoir and allows for capillary wetting of the needle.

LMIS can produce a few micro-amps of stable ion current once the hydrostatic equilibrium of the Taylor cone has been formed. Typically no more than 10  $\mu\text{A}$  is recommended for a commercial LMIS. For stable ion beams, a vacuum chamber with low pressure  $< 5 \times 10^{-7}$  Torr is also required. A safe working range for an AP-Tech LMIS is between 1 and 3  $\mu\text{A}$ , giving a life-time of over 3000  $\mu\text{A}$  hours. Higher current output can cause instability and shorter life-times. If the electric field is too large, the Taylor Cone formation can be disrupted, and charged droplets may be expelled instead of ions, and the hydrodynamic restoration of the wetted LMIS surface may also be compromised giving rise to unstable and fluctuating ion currents [62]. This occurs due to un-even coating/wetting of the LMIS needle, forming drier areas on the needle surface which cannot produce a constant ion current. Similar fluctuations are expected when the liq-

uid metal reservoir is close to depletion and the re-wetting process of the LMIS needle is no longer uniform. Thankfully, it is possible to re-fill depleted LMIS, although it is a difficult process which is also likely to break the LMIS unit.

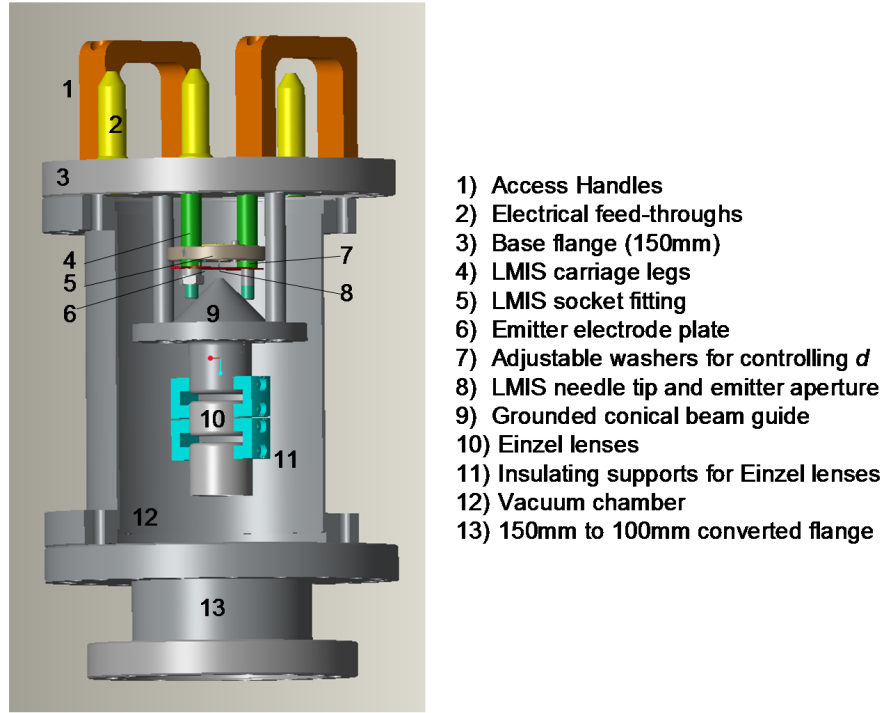


**Figure 4.11:** Mechanical lay-out of the prototype ion delivery system. (*Image courtesy of Z. Dyers, iThemba LABS.* )

## 4.4 Building the ion delivery system

A prototype LMIS assembly was manufactured in the workshop at iThemba LABS where it underwent an initial testing period. The LMIS assembly was designed to easily fit a gallium 69 long-life LMIS purchased from Applied Physics Technologies<sup>1</sup> [63]. The dimensional schematic for the LMIS used is shown in Figure 4.12. A photograph of the resulting prototype is seen in Figure 4.13.

### 4.4.1 The $\text{Ga}^+$ LMIS delivery system

Refer to Figure 4.11. The LMIS carriage and socket (5) was designed so that a delicate LMIS may be easily tipped into the socket from its packaging without the use of hands

<sup>1</sup>[www.a-p-tech.com](http://www.a-p-tech.com)

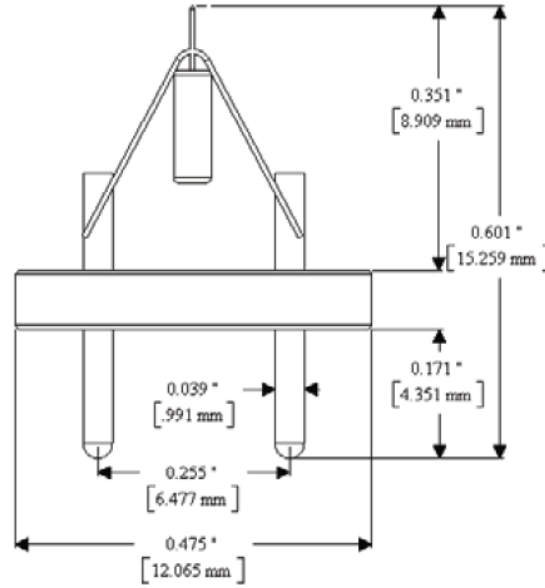


**Figure 4.12:** Schematic of dimensions of an AP-Tech LMIS unit. The LMIS holder within the system was built according to these specifications. *Image courtesy of Applied Physics Technologies, [www.a-p-tech.com](http://www.a-p-tech.com).*

or tweezers. It is fastened in place via a back plate, and the entire carriage is then mounted upon the carriage legs (4). The emitter electrode plate (6) is then set in place so that the aperture is a certain distance,  $d$ , from the needle tip (8), this is determined by finely cut washers (7) which are set in place on either leg before the electrode is placed and fastened tightly with bolts.

After this the electrical optical system (9, 10 & 11) is set in place. Once all components are fastened, high voltage wires from the electrical feed-throughs (2) are connected to the Emitter electrode plate and the central einzel lens. A pair of high current carrying wires is connected to each pin of the LMIS, which will provide 3A heating current for the heating cycle, as well as positive potential,  $U_{ex}$ , which will contribute towards the electrical field giving rise to the  $\text{Ga}^+$  ions [66].

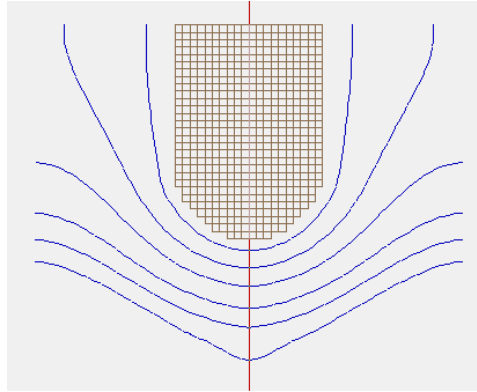
The vacuum chamber casing of the LMIS assembly was designed to connect to the 100 mm test flange on the test bench at the Magnetic Laboratory at iThemba LABS. This converted flange was exchanged to fit a 150 mm flange when connected to the transmission beam line to the ESIS.



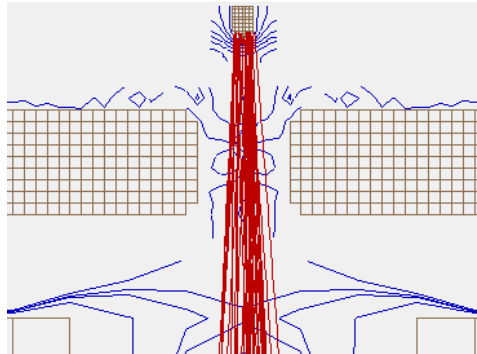
**Figure 4.13:** Photograph of the first LMIS ion extraction and focusing assembly. The LMIS unit is held in place securely and focused on axis. A high positive potential on the LMIS and a high negative potential on the nearby extraction plate provide a strong electric field around  $100 \text{ V/nm}$  which causes field evaporation and metallic ion formation. The ion beam is then shaped and focused by a grounded conical electrode followed by einzel lenses.

**Box 4.1: Simulating ions from the LMIS** Singly charged gallium or gold ions can easily be initialized in SIMION via the "Define Particles" tool. The respective masses and the charge state can be input. The beam is then given an angular spread in a cone distribution (of up to  $5^\circ$  opening angle) for slight variations of each ion's initial velocity, and an energy spread which is close to the real expected energy spread from an LMIS of 5 eV [66].

The ion creation points are then generated over a hemisphere which exactly matches the LMIS tip electrode geometry already drawn in SIMION. The grid size for this electrode is very small at 1 unit = 0.01 mm. This small resolution is required to more accurately simulate the ion beam, and the rest of the system is based on larger grid sizes of 0.5 mm per unit. The needle radius alone is 0.5 mm which is slightly larger than a real LMIS needle at about 0.2 mm. The emitting surface is even smaller in reality, at a diameter of around 0.02 mm from which the Taylor cone extrudes.



**Box Figure 4.1a:** A magnified image of the 0.01 mm grid rendering of the LMIS tip, as well as the potential contours around the source. The LMIS tip shown is biased to 2.5 kV.



**Box Figure 4.1b:** Ion production on the source tip is shown, with trajectories in red. The equipotentials are shown in blue and are more smooth near the smaller grid size of the LMIS, and they become rough for bigger grid sizes. The ions travel almost perpendicularly to the equipotentials, although their initial energy allows for higher forward momentum, as is expected for the electrified sharp point of the LMIS.

## 4.4.2 Electrical considerations

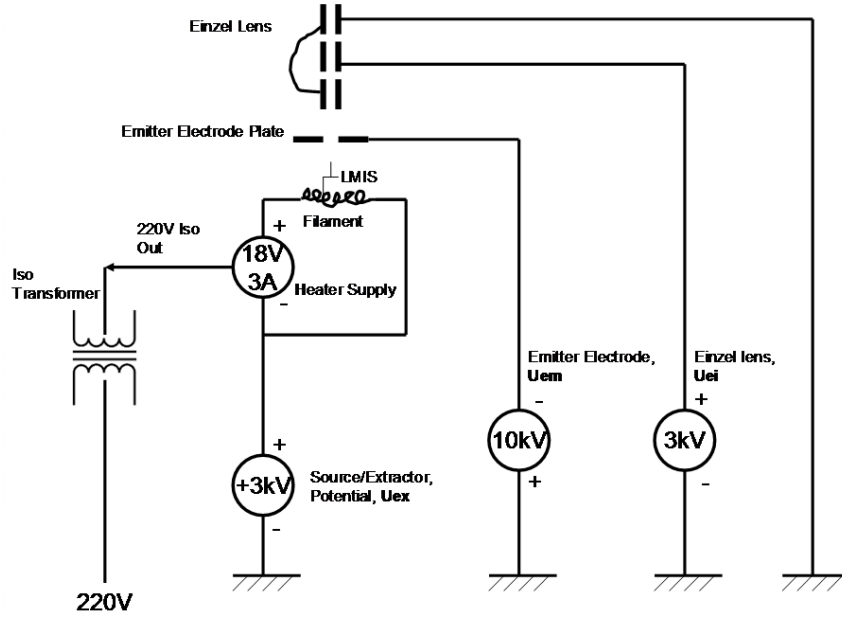


**Figure 4.14:** Electrical circuit for LMIS assembly operation.

Refer to Figure 4.14. The electrical system for the LMIS unit requires two feeds to the LMIS. The LMIS should under-go a heating process before it is used for the first time in order to melt the liquid metal and wet the LMIS needle through capillary action. The AP-Tech specification on these LMIS units suggest a heating current of 3 A for 45 seconds. Therefore, feeds for high current wires are connected to the LMIS fitting's legs in addition to a high-voltage wire for keeping the LMIS on a high tension in order to create an ion current.

The setup shown in Figure 4.14 was designed for the magnetic test laboratory at iThemba LABS, and was based around the existing dipole bending/analysing magnet and the power supplies available there. The voltage supplied to the LMIS, and hence the ion extraction energy, is given by  $U_{ex}$  and this ranges from 200 to 1200 V approximately. Higher  $qU_{ex}$  ions cannot pass through the magnetic bender as the current provided to the magnet coils is limited to 10 A. The bending force of the dipole magnet limits the source potential,  $U_{ex}$ , to a maximum 1.2 kV for  $\text{Ga}^+$  ions. The extractor plate, taken to be the point of ion emission, has voltage labelled  $U_{em}$ , and for tests at the magnet laboratory, this ranged between -1 and -3 kV. Together  $U_{ex}$  and  $U_{em}$  create a strong electric field in the ion extraction region which allows for a Taylor cone to form and therefore field evaporation and a singly charged ion beam to occur. Finally,

the einzel lense voltage is labelled  $U_{ei}$ .

The above settings ranges were determined by the available equipment at the iThemba LABS facilities, and could only produce lower energy ions, as will be shown in this chapter. The electrical considerations were changed drastically when the LMIS assembly was set up with the ESIS test-bench at JINR, Dubna, where the extractor plate,  $U_{em}$ , still ranged through negative values, but with a larger available range, between -2 and -6 kV. The LMIS potential,  $U_{ex}$ , was more than double than that used at iThemba LABS, with values between 2 and 3 kV during most investigations. A value of  $U_{ex} = 2.4$  kV on the LMIS became standard for initial tests at JINR. Higher energy beams from the LMIS would prove to have smaller beam widths in the investigations in Chapter 5, which is a good quality for successful injection into the port of the ESIS. However, lower velocity injected ions are preferred in order to increase interaction probability with the electron string, thus the potential was lowered further to 1.7 kV for the injection of  $\text{Ga}^+$  into ESIS.

Other initial electrical considerations include: 1) Negative biasing on the extractor plate for creating an extracting and accelerating electric field for the evaporated  $\text{Ga}^+$  ions, and 2) Positive bias on the einzel lenses for focusing the beam before it reaches the electric quadrupole switch-yard. The einzel lens bias,  $U_{ei}$ , is typically between 50% and 60% the value of  $U_{ex}$  for the most narrow beam focusing.

#### 4.4.3 Adjustable parameters

During operation, all potentials,  $U_{ex}$ ,  $U_{em}$  and  $U_{ei}$  can be controlled. When off-line and removed from vacuum, the distance,  $d$ , can be adjusted via exchanging washers of varying heights, bringing the LMIS needle further or closer to the emitter aperture on the negatively charged electrode plate at voltage  $U_{em}$ .

### 4.5 Testing the system

Much was learned about the operation of an LMIS during the testing period at iThemba LABS, and the results from the various experiments conducted point toward optimum configurations for the LMIS assembly for future uses. Limitations were also discovered and noted, and were dealt with accordingly to improve the design for the next stage of development.

The experiments were performed in the magnetic laboratory at iThemba LABS (see Figure 4.15). The test bench consists of the LMIS assembly, a bending magnet and two Faraday cup charge collectors, dubbed FC1 and FC2, before and after the bending magnet. FC1 is switchable via a pneumatic arm. The entire bench was pumped to vacuum conditions of  $10^{-7}$  Torr prior to experiments, see Figure 4.16.

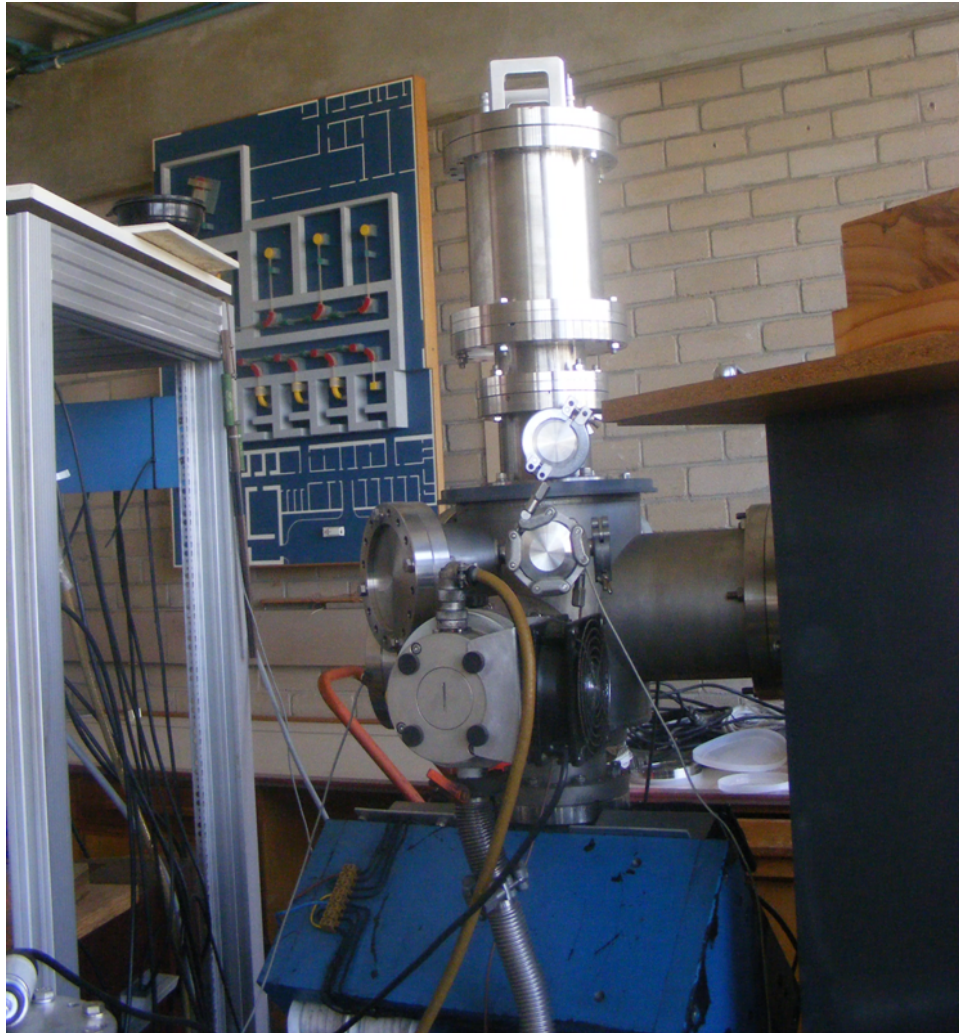


**Figure 4.15:** Test facility for first LMIS experiments in the Magnet Laboratory at iThemba LABS. The LMIS assembly is positioned atop the test bench, and aimed down at the bending magnet, which is in blue housing at the bottom of the picture.

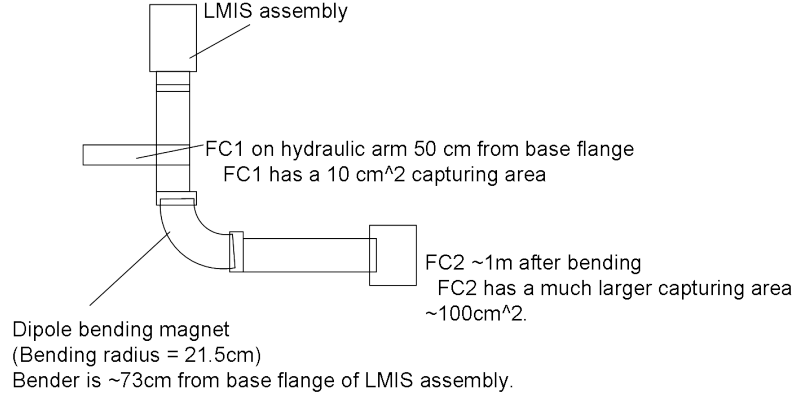


**Figure 4.16:** Diagram of the magnetic laboratory test bench: The ions are produced in the LMIS assembly, which focuses them toward the dipole bending magnet. Ion current can be measured before and after this bender at Faraday cups FC1 and FC2.

Throughout the experiments, it was favoured to observe lower ion currents around 1.2-1.5  $\mu\text{A}$ . The charge capacity of the electron string is 12-15 nC for about 50% neutralization, therefore pulses of 10 ms at this current are enough to fully compensate the space-charge of the ESIS. Even smaller currents are better as fewer atoms would be highly charge-bred: if  $n$  is the desired charge state, for 10ms pulses, an ion current of  $(1.2/n) \mu\text{A}$  is all that is necessary.

Three different values for  $d$  were investigated during these experiments. In the first case,  $d = 0.3 \pm 0.1$  mm was investigated. The actual distance was difficult to measure, but by eye the LMIS needle tip looked like it was just touching the electrode plate. This distance was investigated with the first of the three  $\text{Ga}^+$  LMIS sources, which depleted after a very long heating cycle and extreme potential conditions in the following experiments. The second LMIS was positioned so that the needle protruded a tiny distance into the aperture, with  $d = -0.3 \pm 0.1$  mm roughly. Finally a larger  $d = 0.5 \pm 0.1$  mm was studied.

The following results briefly cover the initial calibration experiments of the LMIS ion delivery system that were performed at iThemba LABS.

#### 4.5.1 Validation of $\text{Ga}^+$ ions

It is possible for an LMIS to produce molecular ions if the extraction field is much larger than 1 V/nm. It is also known that an LMIS can produce a small amount of 2+ ions [65].

Therefore a test was conducted using the dipole bending magnet to ensure that singly charged ions were being produced by the LMIS.

A dipole bending magnet of strength,  $B(I)$ , which is dependent on solenoid current,  $I$ , will cause a rotational orbit through a radius,  $r$ , for a charged particle. For protons of mass  $m$  charge  $q$ , and extraction voltage  $U_{ex}$  this relationship is:

$$B(I) = \frac{\sqrt{2U_{ex}m/q}}{r} \quad (4.1)$$

The extraction voltage of LMIS  $\text{Ga}^+$  ions was recorded when the maximum ion current was measured at FC2. The dipole bending magnet current,  $I$ , was also recorded.

Comparing this recorded data to the proton calibration curve using Equation 4.1, it was seen that the curves overlap should gallium mass be substituted in place of proton mass.

It was clear from this fact that the ion charge was equivalent to the single charge of a proton, and that  $\text{Ga}^+$  ions were indeed being produced.

#### 4.5.2 Stability

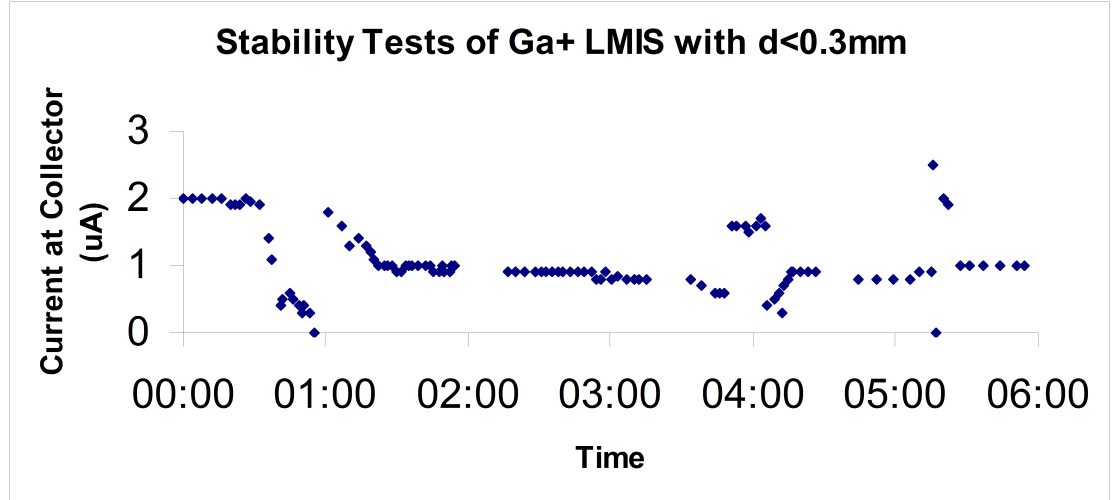


**Figure 4.17:** Stability test of LMIS after a heating cycle. Although there was near stability for almost over 2 hours of continuous operation, the potentials  $U_{ex}$  and  $U_{em}$  had to be ramped to keep consistent ion current. These occasions are indicated by the sudden increase in current after a decrease. Ion current was measured at FC1. It is clear that continuous operation of the LMIS is limited. Short pulsing of  $U_{ex}$  improves this drastically. The error in current measurements was about 5% (instrument rating).

Ion beam stability is vital to the smooth running of future injection experiments into

the ESIS, for both pulse and continuous modes of operation. Stability measurements were done regularly as experiments proceeded. For stability, ion currents measured at FC1 should not fluctuate over the course of more than an hour and longer, although no perfectly stable beam was observed for more than one and a half hours. Shorter stability checks were suitable enough to continue with other measurements of current, while longer stability checks were performed each time a new  $d$  position was configured. The data shown in Figure 4.17 represents one of the best cases of stable ion current.

It was found that often, especially after a heating cycle, the ion current could take more than half an hour to gain stability, and often not at the initial measured current, but at a lower value after stabilizing. On other occasions this stability was reached as lower ion currents grew to higher currents. This can be explained by the wetting of gallium on the LMIS needle tip not being stable either, and something that would eventually be corrected by using the LMIS in a pulse-mode of operation. However, for these initial tests at the magnetic test laboratory, only continuous mode ion production was explored at first.

In cases where current diminished rapidly after setting up field conditions, by ramping  $U_{ex}$  or  $U_{em}$  the current could be returned to a higher value, but never quite the same (see Figure 4.17). The larger the difference in  $U_{ex}$  and  $U_{em}$  values, the greater the electric field in the region before the aperture, and hence higher current output. It was observed, however, to drop back down minutes later.

Stability of  $\text{Ga}^+$  from the LMIS depends upon the electric field conditions forming the Taylor cone which is the zone of ion production at a microscopic level at the tip of the LMIS needle [66]. At lower current, the ion current is likely to fluctuate periodically or entirely cease flowing, while at higher currents, gallium depletes faster and charged mass of a molecular nature could form bubbles or jets from the LMIS instead of ions. Therefore there is an optimal range of ion currents that such a device should be operated under [67]. The electric field giving rise to the formation of a stable Taylor cone depends upon the adjustable parameters,  $d$ ,  $U_{ex}$  and  $U_{em}$ .

The stability of the LMIS in continuous mode was maintained for longer than 2 hours. The gallium wetting on the LMIS needle would be expected to diminish over time during operation. This effect will be remedied by pulsing the potential on the LMIS or emitter plate, which should replenish the Taylor cone by re-wetting the LMIS needle.

### 4.5.3 Electrode biasing for ideal ion current

Measurements of  $U_{ex}$  and the current at FC1 were performed for several  $U_{em}$  values for each of the  $d$  settings. The largest set of data obtained for the most  $U_{em}$  settings was taken for  $d = 0.3$  mm, which, being the closest but still non-protruding distance, was the most attractive according to simulations.

A plot of these potentials and how much ion current was yielded gives insight into the

optimum configuration for producing a given ion current. See Figure 4.18.

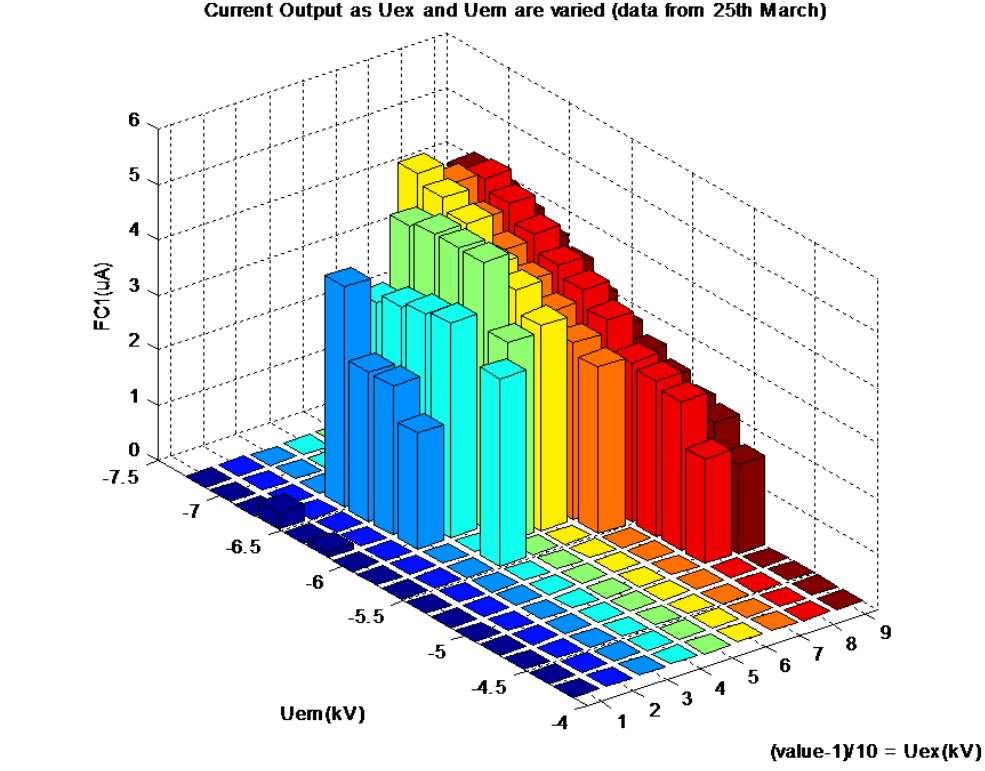


**Figure 4.18:** Electrode biasing effect on  $\text{Ga}^+$  current. A threshold for  $U_{ex} > 0.6$  kV for low  $U_{em}$ , and  $U_{em} < -5.5$  kV for low  $U_{ex}$  is observed for the production of ion current. Maximum current ( $5 \mu\text{A}$ ) was also observed around  $U_{ex} = 0.5$  kV and  $U_{em} = -7.0$  kV. The error in both current and voltage measurements was about 5%.

#### 4.5.4 Ion current loss between FC1 and FC2

Beam quality is of vital importance in transmitting ions from this LMIS assembly into the ESIS. Unfortunately, no apparatus were available to measure the beam emittance directly. However, a comparison of current arriving at FC2 after bending with the current measured at FC1 before bending reveals how much current loss occurs between the two points. This was sufficient as a first test to study the transmission efficiency of the beam transport between the two Faraday cups<sup>1</sup>.

<sup>1</sup>Both the Faraday cups at the iThemba LABS magnet laboratory were equipped with electrostatic secondary electron suppression. In front of each cup is an electrode biased to -300 V. This prevents

During these tests, the einzel lenses were always adjusted when measuring current at FC1 and FC2 to maximize the current arriving there by effectively increasing or decreasing the beams focal distance. Current at FC2 was measured only after both the magnet current and einzel lens were set as to maximize this current.

Figure 4.19 shows that there is a region around  $U_{ex} = 0.6$  to  $0.7$  kV where the transmission is close to 100% and that the first LMIS configuration for  $d = 0.3$  mm investigated has the highest yields. Values of transmission greater than 100% occur due either to current fluctuations during measurements, or because of a smaller FC1 current collection area. Current measurements at FC1 may also be higher due to singly charged molecular ions ( $n\text{Ga}^+$ ), which undergo equivalent paths to  $\text{Ga}^+$  ions in electric fields; however these do not arrive at FC2 due to there being different masses in the magnetic field. Actual  $\text{Ga}^+$  transmission is therefore possibly greater than measured.

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secondary electrons from escaping the cup

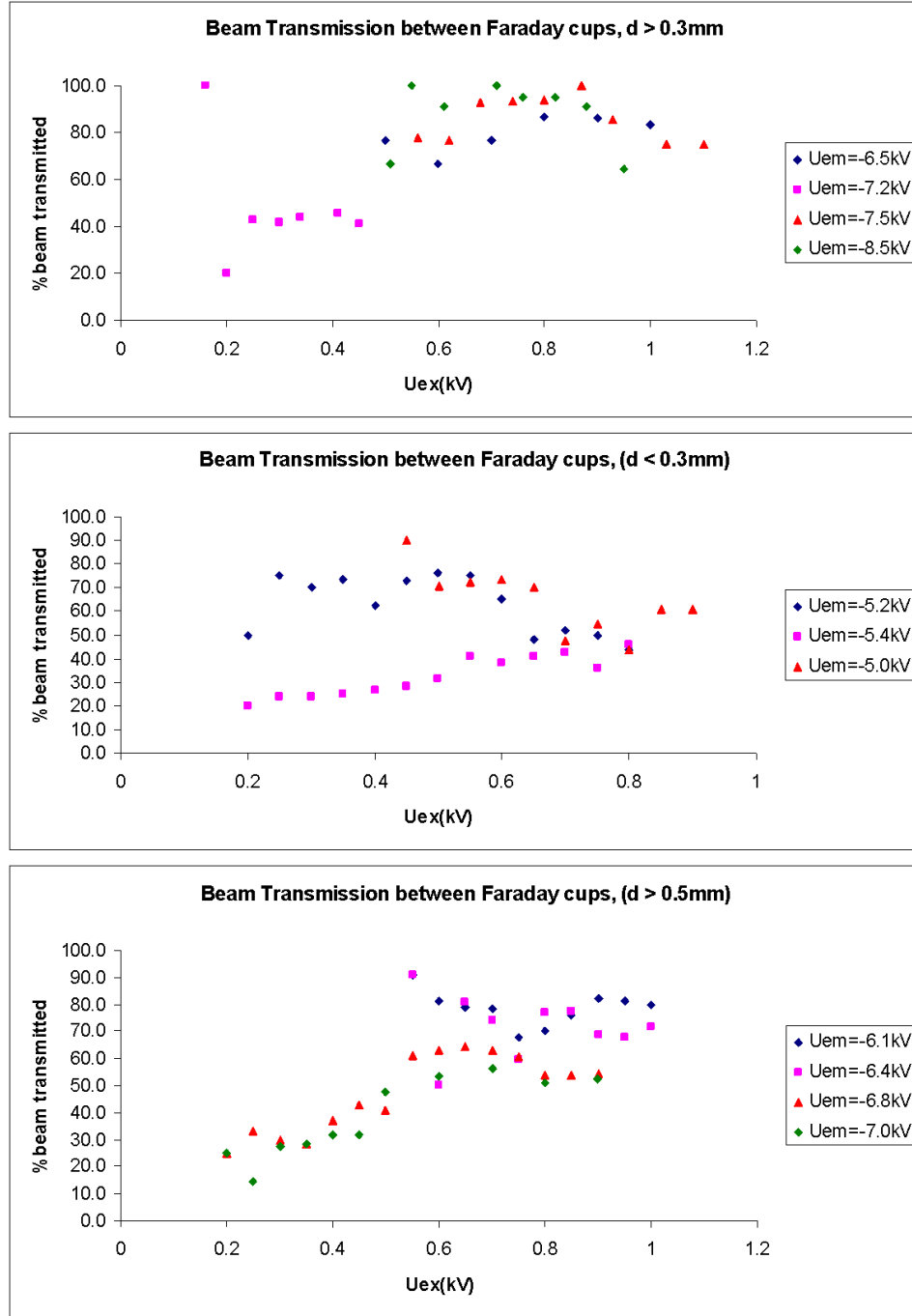
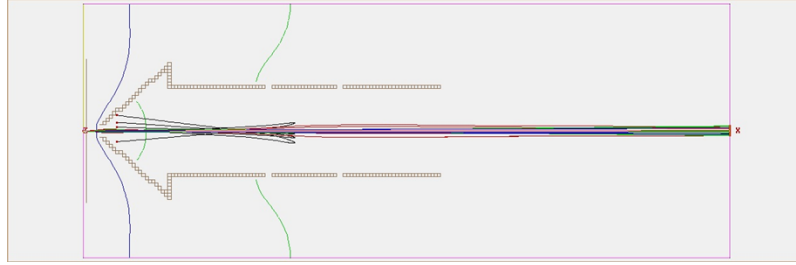


**Figure 4.19:** The data in the above graphs were calculated via  $100 \cdot 100 \cdot (\text{FC2} - \text{FC1}) / \text{FC1}$ . There is poor transmission for  $U_{ex} < 0.5\text{ kV}$

**Box 4.2: Simulating the LMIS with differing ion energies,  $U_{ex}$ :**  $\text{Ga}^+$  ions travelling through the prototype LMIS assembly have been simulated via SIMION.  $U_{ex} = 600$  V,  $U_{em} = -6.2$  kV and  $U_{ei} = 240$  V:



**Box Figure 4.2:** Excellent focusing of ions with half angle  $< 50^\circ$ , einzel lenses control focus, and reflect those ions with lower x-direction energies due to higher initial half angles (black trajectories with  $50^\circ$  initial half angle are mostly reflected). Ion energy is 0.6 keV as given by  $U_{ex}$ .

The  $\text{Ga}^+$  LMIS is expected to have a forward arc of ion production supplying ions with initial half angles of no greater than  $30^\circ$  [9]. The real LMIS should therefore operate similarly to these simulations.

According to these simulations, larger distances like  $d > 0.3$  mm or greater (Box Figure 4.2) show the most parallel beams which give rise to best beam transmission. There is ample electric field in the same direction as the beam axis. This quality diminishes the closer  $d$  is to zero or negative (protruding through aperture) which also gives rise to a loss of  $\text{Ga}^+$  ions.

#### 4.5.5 Optimum tip-to-plate distance, $d$

For each distance,  $d$ , configuration there were conditions for  $U_{ex}$  and  $U_{em}$  that led to more stable ion current than others. From the trends in the data, throughout all  $d$  investigations, it was observed that ion current was only produced when  $U_{em}$  was sufficiently big the larger  $d$  was, and as such,  $U_{ex}$  would have a threshold value for lower  $U_{em}$ , around 0.50 to 0.60 kV. At higher  $U_{em}$ , it was possible to reduce  $U_{ex}$  down to 0.15 kV in the best of cases, which yielded only around  $0.1 \mu\text{A}$  of ion current. Here  $U_{em}$  was -7.0 kV or larger in magnitude.

The best ion current transmission was observed for  $d = 0.3$  mm, which agrees with simulations of beam trajectories - although the current that was measured might have been too large for 100 ms pulses of  $1.2 \mu\text{A}$ . Here the detected current was around 3 to  $5 \mu\text{A}$ .

Finally, the einzel lenses,  $U_{ei}$ , were shown to be most effective when they were biased to about 60% of the ion beam energy,  $U_{ex}$ .

### 4.5.6 Design improvements

The initial testing experiments revealed what should be improved in the design. The future experiments that were performed at JINR incorporated an improved LMIS ion delivery system after the following upgrades were implemented:

#### Electrical Considerations

The electric wires and feed-throughs for heating and powering the LMIS potential  $U_{ex}$  were put under higher electrical tension than they could tolerate and this led to sparking and the electrical breakdown of this port on the 150 mm base flange.

The design was improved by using cables tolerant for 3 A, as well as higher tensions up to 3.0 kV.

For the design to be more robust, the base flange was also re-designed to include an extra high potential feed through for the LMIS  $U_{ex}$ . An extra port for electrical feeds was added to the base flange for future polarity reversing of the ion optics as well, if necessary.

#### Adjusting $d$

Precision cut washers made out of vesconite are used to adjust the distance between the needle tip and electrode aperture. The drawback here is that the whole system must be taken off-line, vacuum broken, and then manually configured for a new distance  $d$  with these washers. Then cleaning, followed by vacuum pumping, must occur before experiments can begin again.

Some form of an external screwing system, perhaps contained in a bellows, may prove innovative such that  $d$  can be adjusted from the exterior of the base-flange outside, by a rotational control which can raise or lower the LMIS carriage within.

#### Voltage pulsing

The ESIS requires an over barrier injection current of around  $1.2 \mu\text{A}$  for 100 ms for a space-charge compensation within the ESIS of around 50%. Thus stable current is required for each injected pulse over lengthy periods of time. Prior to the ESIS, singly charged ions pass through and are deflected by an electrical quadrupole switch-yard into the ESIS. The switch-yard is then powered off when extraction of charge-bred ions from the ESIS occurs, only to be powered back on for the next singly charged ion injection pulse from the LMIS.

There are then two options here: Firstly, the LMIS itself could be pulsed, which means that  $U_{em}$  is the most likely control for this pulsing, as  $U_{ex}$  should not be pulsed and

should be constant, as it characterizes the ion energy. However, current stability will not be uniform without some form of a modulating circuit that knows just how much to ramp  $U_{em}$  by in order to maintain the same current in every pulse [68].

Another option would be pulsing on the quadrupole switchyard itself. If the ion current proves to be stable for hours on end (also perhaps modulated via some control circuit on  $U_{em}$ ), then the switchyard could just deflect the ions continually streaming through it for an injection pulse in the ESIS.

#### 4.5.7 Conclusions for ion assembly prototype tests

The prototype testing of the  $\text{Ga}^+$  LMIS assembly proved successful in creating stable ion beams of up to two hours or more, of ion currents suitable for injection into the ESIS. Beam emittance properties were not obtained, however, from transmission of current between two Faraday cups, beam quality was shown to be best for  $d = 0.3\text{mm}$ .

The extractor voltage,  $U_{ex}$ , was shown to directly characterize ion energy with a small spread of energies around this point, most likely due to thermal and hydrostatic considerations, which is no greater than 5 V per ion.

The  $\text{Ga}^+$  LMIS from AP-TECH and others, including those from the FEI Company are all made with similar dimensional specifications, and the design of this LMIS assembly is capable of fitting what are known as JEOL bases. Thus future tests involving  $\text{Ga}^+$  and  $\text{Au}^+$  ions in Dubna were easy to commence with the improved assembly.

### 4.6 The DRE-EBIT Quadrupole Switch-yard

The inclusion of a switch-yard beam-line component in the transport system, similarly to the work by A, Thorn *et. al* [29], is justified for the purpose of having both injection and extraction of ions on the same transport system. Essentially, the injection/extraction line becomes a 2-way street, with pulsed traffic controlled by the pulsing on the switch-yard electrode biases. During injection, the switch-yard should be powered and allow the singly charged ions from the LMIS assembly to be bent  $90^\circ$  into the injection line and then into the ESIS. After charge-breeding, the switch-yard must then be un-biased for the extracted HCIs to fly past it for use in further experiments.

A cut-away drawing of the switch-yard is shown in Figure 4.20. This component was also supplied with a vacuum chamber with six flanges, ample for the electrical and vacuum pumping connections, and together installed onto the transport system at the Laboratory for High Energy Physics (LHEP), at JINR, Dubna, Russia (Figure 4.21).

The installation and optimization of a singly charged ion beam through the switch-yard constitutes the second leg of the beam-line transport system development.



**Figure 4.20:** Image of the switch-yard from the Dre-EBIT website [30]. The vacuum chamber is shown at the bottom with the four electrodes which are powered with opposite biases up to  $\pm 25$  kV. The two power supplies and their protective casings are connected above the switch-yard.

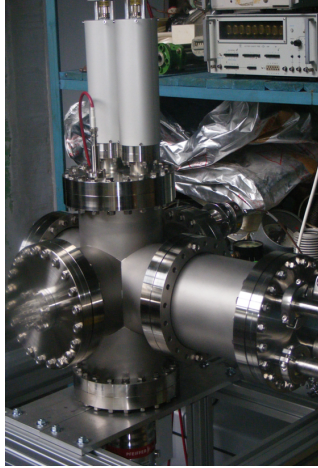


**Figure 4.21:** In the above photograph the LMIS assembly (right) has been connected to the Dre-EBIT quadrupole switch-yard (centre) at the Laboratory of High Energy Physics, JINR.

## 4.7 Optimizing the ion injection transport system

The electrical quadrupole switch-yard can be biased on its opposite electrodes up to  $\pm 25$  kV. The switch-yard can also be pulsed with a 30 Hz switching frequency [30].

Two main beam-current investigations were performed in the initial tests using the singly charged ion beam passing through the switch-yard: 1) Measuring ion current bent  $90^\circ$  compared to direct (quadrupole un-biased) measurements, and 2) Pulse-mode studies.

### 4.7.1 Ion current measurements: straight vs bending directions

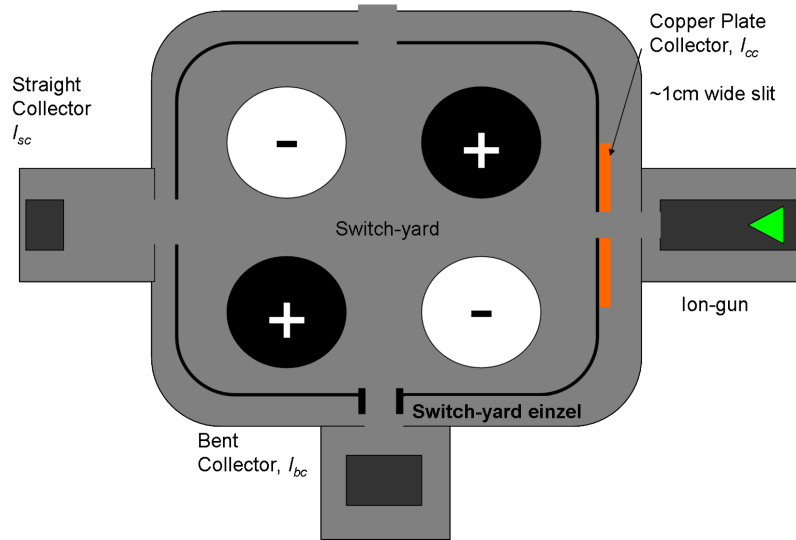


**Figure 4.22:** Current measuring diagnostics are shown: There are two Faraday Cups for each of the straight and bending directions. Current measured here is denoted  $I_{SC}$  and  $I_{BC}$  respectively. Additionally, a copper plate/foil with a small 1 cm wide aperture is included before entry into the switch-yard for collimation, as well as to measure current loss,  $I_{CC}$ .

$\text{Ga}^+$  current was measured on Faraday cups; one positioned across the quadrupole directly opposite the LMIS focusing assembly,  $I_{SC}$ , and the other directly after the  $90^\circ$  bend,  $I_{BC}$ .

The aim for this preliminary optimization was to ensure that enough current was being produced by the LMIS, and to ensure that the entire amount could be deflected by the switch-yard.

Bending through the switch-yard was first successful using 6.0 keV ions and biasing the bender to  $\pm 5.5$  kV which almost matches this ion energy. In this regime a large amount of ion current ( $2.0 \mu\text{A}$ ) was measured in the straight direction and  $2.6 \mu\text{A}$  in

the bending direction. Additionally, a copper foil with a 1 cm wide circular aperture was placed in front of the switch-yard (Figure 4.22), in order to both collimate the beam, and to serve as a current collector for un-focused beam,  $I_{CC}$ . In this test, 3.1  $\mu\text{A}$  was measured on the foil  $I_{CC}$ . Therefore there must have been current loss in the straight direction, as more beam is measured in the bent direction. This could be due to a small collection area on the straight direction Faraday cup, or the possible dipole focusing of the quadrupole switch-yard on the beam. Simulations will show that dipole focusing is indeed a possibility in Box 4.3.

The settings used to achieve this are summarized in Table 4.1. Note that the switch-yard einzel lens, which is positioned on the exit of the switch-yard after bending, was slightly biased to achieve maximum transport efficiency. This lens is used either to focus the beam on entry into the switch-yard, or to focus the beam leaving the switch-yard. Another important note is that the biasing on the switch-yard is dependent on the ion energy, and for the first successful bending measurements, the value  $U_{bend} = \pm 5.5$  kV matched the incoming ion energy of  $U_{ex} = 6.0$  keV. In later tests at different ion energies, the switch-yard biasing is adjusted accordingly.

**Table 4.1:** Electrode Settings for First Successful Ion Beam Bending

| Electrode/Ion-Optics | Symbol        | Biasing (kV) |
|----------------------|---------------|--------------|
| LMIS                 | $U_{ex}$      | +6.0         |
| Emitter Plate        | $U_{em}$      | -1.0         |
| Einzel Lenses        | $U_{ei}$      | +4.0         |
| Switch-yard          | $U_{bend}$    | $\pm 5.5$    |
| Switch-yard einzel   | $U_{bend,ei}$ | 1.2          |

In future experiments, it was possible to reduce the ion energy and still have almost 100% efficient bending once more einzel lenses were included on the LMIS assembly. However, several experiments were performed with  $U_{ex} = 6.0$  kV due to the fact that higher beam energies yield greater ion current and lower un-normalized emittance.

#### 4.7.2 Pulse-mode

A pulse generator was produced and installed at the test bench at JINR. This device was used for initial pulsing tests, and could modulate negative potentials on the emitter plate  $U_{em}$  up to around -1.0 kV.

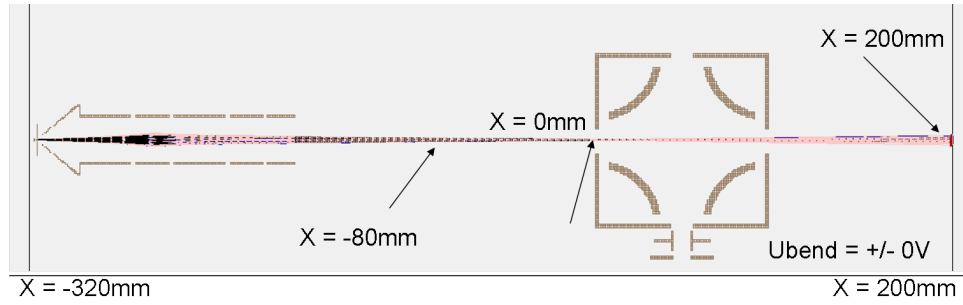
Ion current pulses of 2.6  $\mu\text{A}$  were measured for square pulse lengths of 10 ms, which meet the requirements for ESIS operation in the over-barrier injection mode [32].

The negative potential on the emitter electrode plate,  $U_{em}$ , was pulsed from 0 to -1300 V while the LMIS tip  $U_{ex}$  was held at 6.0 kV. The potential difference required to form an ion current is triggered in this range, with zero ion current being produced

and admitted while  $U_{em} = 0.0$  V. This implies that pulsing on the plate is suitable for controlling ion production.

In improved experiments covered in Chapters 5 and 6, the LMIS,  $U_{ex}$ , was pulsed instead of the emitter plate,  $U_{em}$ . It was shown that pulsing on the LMIS is good for the restoration of the liquid-metal wetting, and this leads to even better long term stability. Using the LMIS continuously leads to the drying out of the LMIS tip, and hence to lower currents and the need for more heating-cycles. The ion energy was also be lowered in later experiments to between 1.4 and 2.0 kV, and therefore the ion-optical settings were optimized and adjusted for such energy in later chapters.

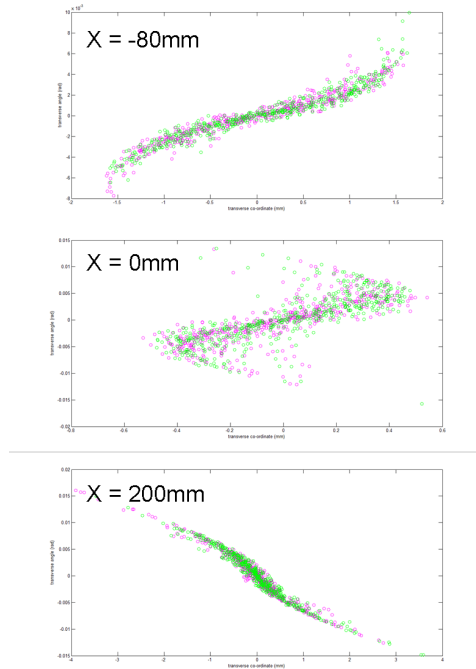
**Box 4.3: Emittance study of beam with and without bending** An improved ion delivery system (with more lenses) and the quadrupole switch-yard are simulated together in order to understand the effect of bending on the beam emittance. The following simulations compare statistical emittance in the straight direction to the 90° bent direction. In each case, 500 ions are initialized with half angles between 0° and 30°, an energy spread of 5 eV and with  $U_{ex} = 5.0$  kV,  $U_{em} = -7.0$  kV and  $U_{ei} = 4.0$  kV.



The 90% 2rms-transverse emittance is calculated at the indicated locations on the principle X-axis via:

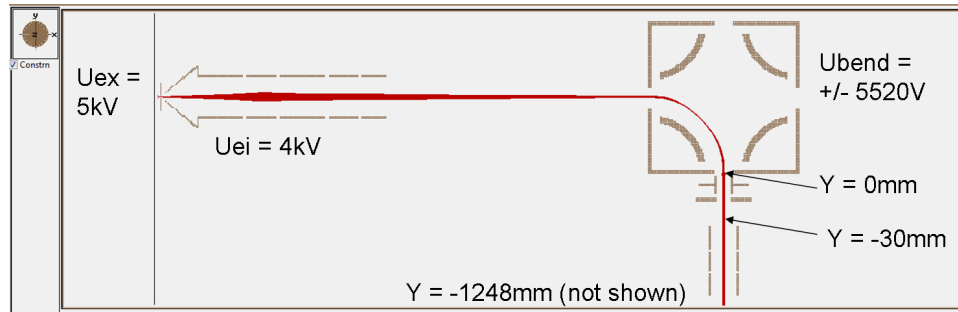
$$\epsilon_{2RMS} = 4\sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x \cdot x' \rangle^2} \text{ mm} \cdot \text{mrad}$$

where  $x'$  is the angle with respect to either transverse direction, in this case Y or Z. The phase-spaces are plotted below (green data = Z, magenta data = Y)

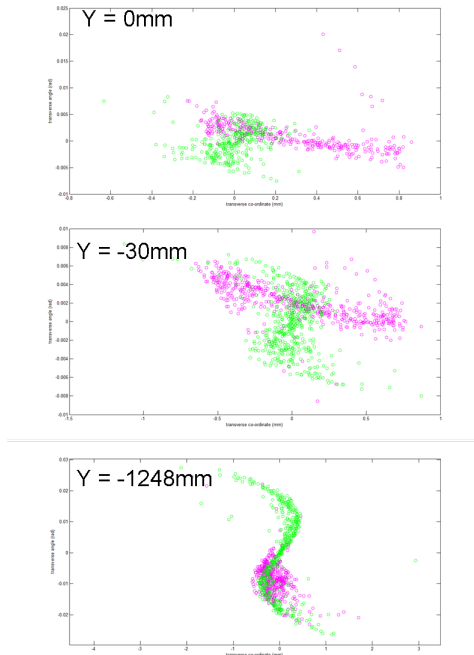


Firstly it is important to note that due to the use of negative co-ordinate values in these calculations, the above graphs show ellipses that are sloped in the opposite direction than would be expected. The beam is originally converging at  $X = -80$  mm (note the data in the graphs should be mirrored across the y-axis). It focuses at  $X = 0$  mm where it is narrowest. Eventually at  $X = 200$  mm, it diverges.

Similarly, with  $90^\circ$  bending from  $X$  into  $Y$ , emittance and phase-spaces were calculated at the indicated  $Y$ -values:



The phase-spaces on the new axis are plotted below (green data =  $Z$ , magenta data =  $X$ )



It is very clear the green phase-space (un-bent,  $Z$  direction) continues to grow as per drift space, where the magenta data reflects that some dipole aberration has affected the  $X$  phase-space.

The transverse rms-emittance values are calculated and compared:

| Distance in X (mm) | $\epsilon_z$ ( $\pi$ .mm.mrad) | $\epsilon_y$ ( $\pi$ .mm.mrad) |
|--------------------|--------------------------------|--------------------------------|
| -80                | 2.45                           | 2.22                           |
| 0                  | 3.12                           | 2.80                           |
| 200                | 3.43                           | 3.55                           |

| Distance in Y (mm) | $\epsilon_z$ ( $\pi$ .mm.mrad) | $\epsilon_x$ ( $\pi$ .mm.mrad) |
|--------------------|--------------------------------|--------------------------------|
| 0                  | 0.89                           | 3.06                           |
| -30                | 2.17                           | 4.31                           |
| -1248              | 20.55                          | 28.46                          |

The tables of simulation results are shown above. It is expected that for an ion beam propagating through a drift space with no external forces acting on them, the emittance is fixed. Each result above came from a separate simulation, so although the environment is the same in each case, random variations between results which should be the same are expected.

In the straight direction (upper table) the emittance in grows very slightly in each transverse direction.

In the bending direction however, the transverse X emittance is always much greater than the Z emittance. The Z transverse direction should be treated as per a drift space, as there are no forces from the switch-yard acting in this direction.

The values taken at Y = -1248 mm are also subject to discretion, as there were a few additional focusing lenses that were not shown on the diagram above that might have caused the emittance growth.

It should therefore be concluded that correcting steerer type electrostatic lenses be included immediately after the switch-yard in order to improve the X-emittance after bending.

Finally, it should be noted that the statistical emittance values obtained via SIMION analysis should not be compared to real emittance values found in measurements. This is because the characterization of the beam in SIMION can never truly match the real beam profile and initial angular distribution of ions from the LMIS. However, these simulated emittance values are useful when compared to one another as in the above case.

## 4.8 Completion of Injection System

The LMIS assembly, which consists of the LMIS and focusing system, electrostatic lenses and the quadrupole switch-yard, including the beam diagnostics, constitute the first important components of the injection/extraction system for use with the ESIS.

Several improvements have been made on this system in order to deliver a more focused beam of ions, limiting ion loss at the extractor electrode plate.

### 4.8.1 The Next Phase

Ions have been produced, using the LMIS in pulse-mode operation, and successfully deflected  $90^\circ$  through the switch-yard. At this stage in the research no measurements of beam parameters other than the current and transport efficiency had yet been made.

Beam profiling was performed during the final phases of the development to ensure that the ion beam met the requirements for ESIS injection. The profilometer was not yet available in the early development of the injection system covered in this chapter [70].

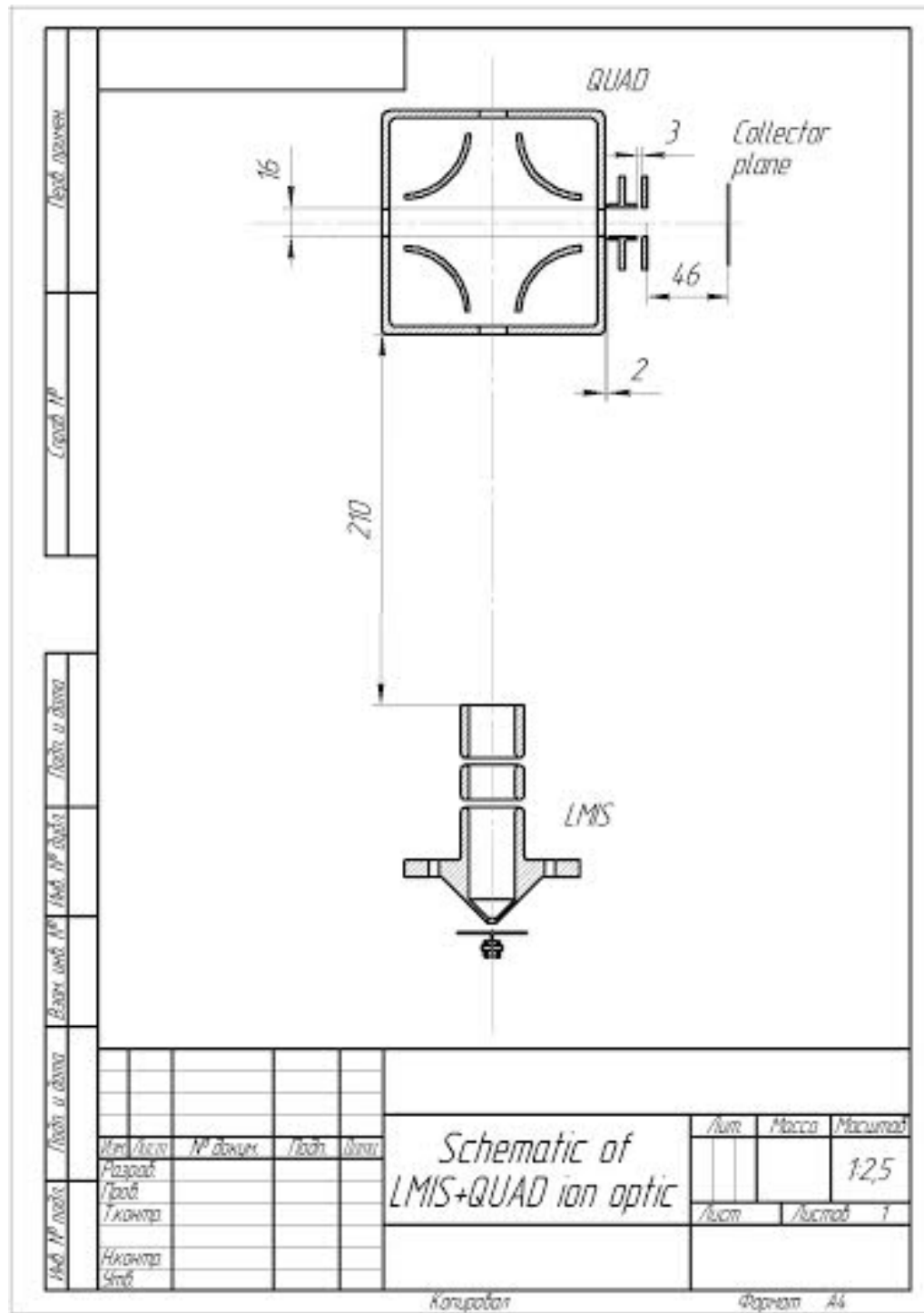


**Figure 4.23:** Technical drawing of the LMIS assembly connected to the Dre-EBIT quadrupole switch-yard.

## Chapter 5

# Singly Charged Ion Beam Measurements

In Chapter 4, the development of an ion-assembly capable of emitting singly charged ions was shown and discussed. The LMIS, followed by a system of electrical lenses for focusing the beam had already undergone initial tests and measurements, revealing that singly charged gallium ions were being produced, at currents up to  $6.0\ \mu\text{A}$ . Various regimes of voltage biasing were investigated and an example of such a regime yielding  $3.1\ \mu\text{A}$  of ion current was shown in Table 4.1.

The DRE-EBIT quadrupole switch-yard proved to be successful in deflecting the beam by  $90^\circ$ . The total ion current measured by Faraday cups in the forward direction matched the total ion current bent by  $90^\circ$ .

These first tests investigated quantities of ion current measured at two or more different locations where Faraday cups were placed. These proved to be useful initial tests to calibrate the system, however, nothing about the beam shape, emittance and other properties could be investigated using these rudimentary techniques. Therefore several methods were employed to study the beam shape before and after bending. The initial methods included the use of photographic and x-ray paper to get a measurement of the beam spot size after a given duration of impact upon the paper. More in depth investigations were made once a harp beam profilometer was used for beam diagnostics. The harp profilometer is capable of measuring beam shape and current at varying distances along the beam's principal axis, from which beam properties such as half-width and emittance can be obtained.

Beam profiling was performed using the harp before and after bending in order to optimize the voltage biasing on the ion optics for each ion optical element from the LMIS to the final destination in the ESIS (for injection). The above processes will be explained and discussed in detail this chapter.

A replica ESIS front port (the injection/extraction port of the ESIS) was built and added to the transport system in order to estimate the quality of injected beam into the ESIS before the real injection experiments which will be covered in Chapter 6. Experiments with this replica ESIS port are included and discussed in the latter part of this chapter, however the method of ion-beam profiling used to obtain beam parameters will be covered first.

## 5.1 Initial Ion Beam Analysis

Two rudimentary techniques were employed to determine beam properties of the ion beam before the harp multi-wire beam profilometer was used to obtain detailed beam profiles. Firstly, photographic paper, and then x-ray paper were placed as targets for the beam.

Secondly, a multi-plate charge collector was built in the workshop at JINR and this was employed briefly to gauge the beam symmetry and current distribution. The multi-plate charge collector was positioned in place of the Faraday cup usually measuring  $I$ .

Both the x-ray and multi-plate methods were limited;

- The measurement, or picture, could only be taken at a single distance along the principle axis. In order to estimate emittance, one would require measurements taken at successive positions of the beam.
- Exposure time: The beam spot on the photographic or x-ray paper will grow in size while it is exposed to the ion beam. Therefore, the ion beam should only be incident on these materials for a few milliseconds - the duration of what might be expected from an injection pulse - to yield the realistic beam-width. Ion current distribution over the cross-section is also difficult to accurately deduce.
- In the case of the multi-plate charge collector, secondary electrons were observed to cascade from the one plate to another, which led to erroneous measurements of very low or even negative current on adjacent plates.
- The resolution of the beam is only as good as the smallest measuring increment, so the multi-plate method could only be justified if the beam current was symmetric and well-centred, while the x-ray method yields no information about ion current at all.

## 5.2 Beam Profile Measurements

A beam diagnostic device known as a harp beam-profilometer was constructed by electrical engineers at JINR, and was used to make accurate measurements of ion beam

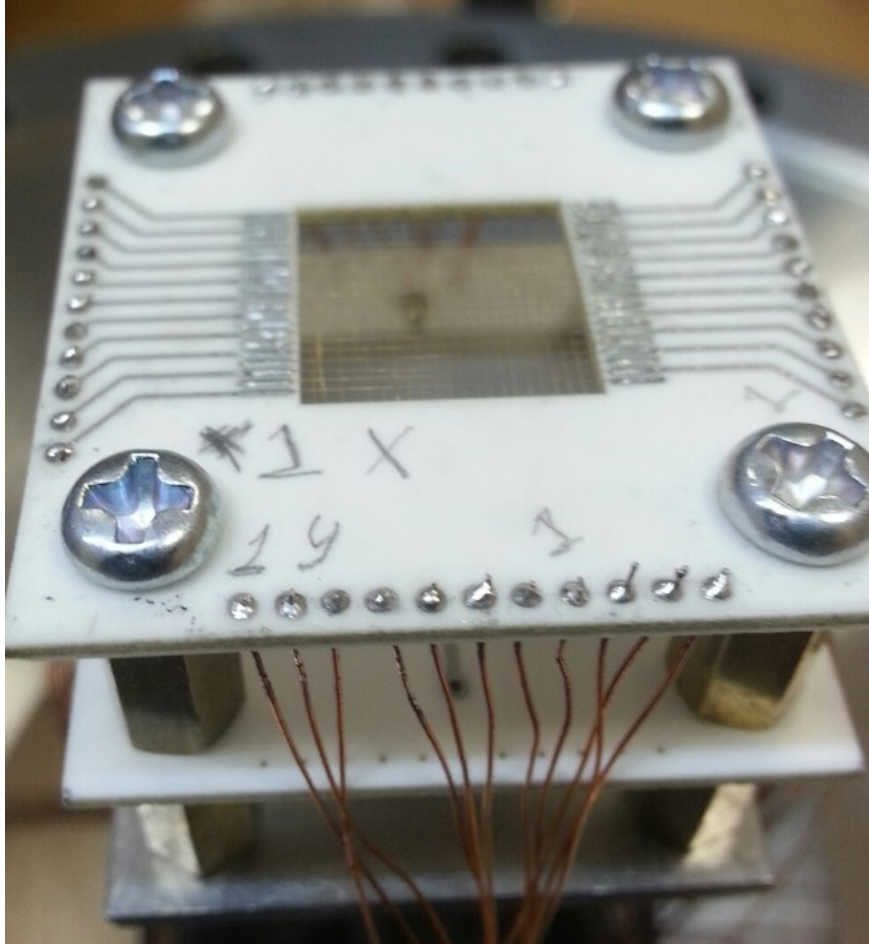


**Figure 5.1:** Harp Beam Profilometer

profiles. These profiles were in turn used to determine emittance and other beam parameters. The harp used is shown in Figure 5.1.

### 5.2.1 The Harp Beam Profilometer

The harp multi-wire profilometer is so called the resemblance to a musical harp as can be seen in Figure 5.1.

The harp consists of two grids made of very fine gold wires 0.1 mm in diameter. Each grid has 21 wires, each 0.5 mm apart. The grids are perpendicular to each-other and separated by 0.5 mm of ceramic. Thus if aligned to a beam, the horizontal wires measure current arriving in the vertical direction, and vice-versa, with a resolution of  $0.5 \pm 0.05$  mm. The two grids cover a square centimetre, and positioned behind both is a  $1 \text{ cm}^2$  collecting plate that measures the bulk of the current focused onto the detector.

Additionally, the harp-profilometer has a screw - adjustable distance setting. The harp profiler unit can be moved in the direction of the beam axis from 0 cm to 2.4 cm. This is particularly important for using multiple profile measurements taken at different locations to obtain the transverse emittance of the beam.

### 5.2.2 KRION 6-T ion injection and extraction components

For the first harp profiling experiments, the injection and extraction line consisted of the LMIS assembly, the DRE-EBIT Electrical Quadrupole switch-yard, and vacuum chambers for beam diagnostics.

#### Switch-yard biasing

Previous measurements had shown that for maximal current on bending, the quadrupole switch-yard should be biased to  $\pm 5.0$  kV for 6.0 keV  $\text{Ga}^+$  ions [70][69]. At lower ion energies, the biasing on the quadrupole can vary between 60 and 90% of the ion beam energy. A rectangular einzel lens is positioned at the bending exit of the switch-yard. The biasing on this lens helps focus the beam after bending and this is also dependent on quadrupole biasing strength at lower ion energies. The vertical positioning of the electrical quadrupole can act to focus or defocus the beam in the horizontal plane and does not act strongly in the vertical plane - essentially allowing the beam to diverge due to space-charge in the vertical transverse direction. A balance between biasing on the quadrupole and the built in switch-yard einzel lens is therefore required for adequate focusing in both directions after bending. This lens is biased between 50 and 60% of the ion energy when used.

#### Entire setup for harp profiling

A schematic for the injection and extraction process is shown in Figure 5.2. A pulsing scheme was tested and would be used for the injection and extraction of ion beam. The injection pulse with activated bending quadrupole is 2 ms within a 2 s repetition time. This pulsing method is suitable for over-barrier injection and extraction for charge-breeding with the ESIS [35].

At least one vacuum chamber would be placed between the ESIS and switch-yard with more focusing lenses, with biasing switchable between injection and extraction cycles. This lens system, and a mock-up of the ESIS entry port had not been installed at this stage, and this will be discussed in the next section.

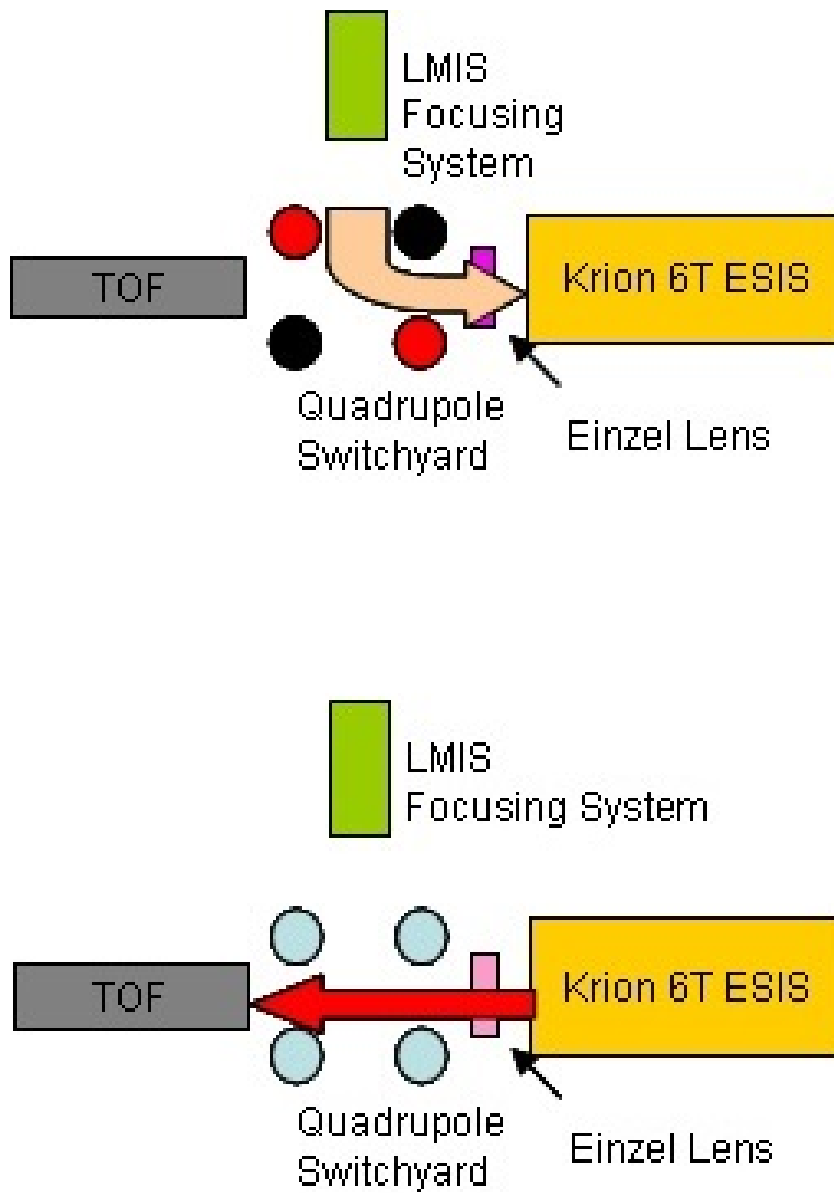


**Figure 5.2:** Working cycle for charged ion injection, breeding, and extraction from ESIS through the electric quadrupole switch-yard.

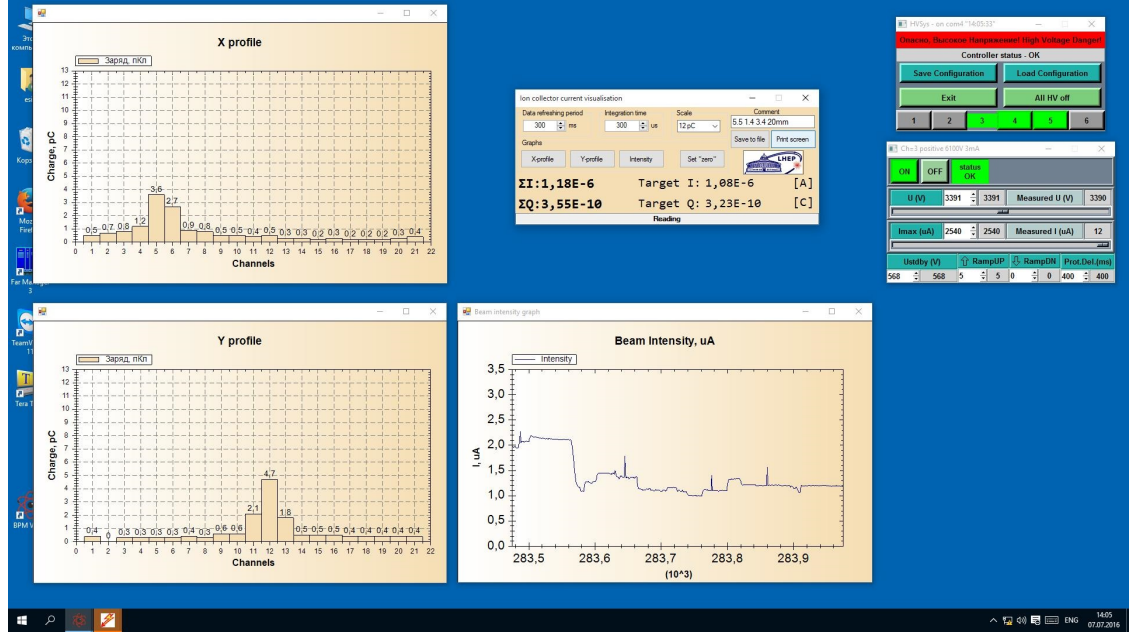


**Figure 5.3:** Example screen capture of data acquisition gui, as well as power supply control panel.

### 5.2.3 Data acquisition

A data acquisition program was written for the harp profilometer.

The total current received by each wire in each grid is plotted into an immediate profile, the summed current arriving at all wires plus background plate is shown<sup>1</sup>, and the fluctuation of this with time, which shows beam stability, is also plotted while the harp was on-line measuring the ion beam, see Figure 5.3. Integration time for recording the current and profiles with the programme can be adjusted, as well as the refresh rate for the displayed data. The scale of the current profile graphs can also be adjusted for smaller or larger beam current. These parameters were always set to yield the most clearly resolved beam profiles possible.

A screen-shot can be taken for each measurement such as in Figure 5.3. The profile information can then be saved to a notepad file for further analysis. This file contains the total current measured, as well as the individual integrated charge collected by each wire and it's corresponding number between 1 and 21. Each number represents a wire position from -5.0 mm to 5.0 mm, each 0.5 mm apart, covering a centimetre.

The output notepad data files were then subjected to extensive analysis in MATLAB to

<sup>1</sup>The total current of the two grids of wires and the back plate is recorded and displayed on the data acquisition GUI. The harp wires measure current in the pA range while the back plate receives most of the current in the  $\mu$ A range. The loss between the harp wires and back plate is therefore close to zero at  $< 0.001\%$ , implying that ion transmission efficiency through the harp is basically 100 %.

obtain further beam information such as transverse emittance and beam-widths at the focal-point. A single experiment utilized three or more locations of the harp along the principal beam axis in order to calculate parameters such as emittance, and therefore three or more beam profiles at different distances were analysed per experiment.

#### 5.2.4 Calculation of transverse emittance and beam-width

A MATLAB code called *HIBA.m* was written to extract beam parameter information from harp output. A flow-chart showing how this code works is shown in Figure 5.4.

Output notepad files containing profile information are input into the code, together with the distance setting on the harp detector. For a given transverse direction,  $x$  or  $y$ , the profile is analysed. The code immediately displays the percentage of total current given by the median of the profile, plus half of the current in the two columns neighbouring the median. This is a good first look at how much of the current is within a single central square millimetre in the centre of the ion beam.

The profile distributions are then used as statistical weightings and when multiplied by the total current this yields ion current profiles. Each  $x$  and  $y$  profile pair is then combined in quadrature to approximate what the beam spot and current density distribution may look like per given harp distance in an experiment, see Figure 5.5 for an example of this immediate output.

The MATLAB code then uses a sub-routine to fit a Gaussian (see Figure 5.6) over the beam profile and calculates the corresponding standard deviation,  $\sigma$ , which is the equivalent beam half-width. It does this for three or more harp distances,  $d$ , and using this set of half-widths and distances, emittance and narrowest beam half-widths in a transverse direction can be calculated. Note that the harp data acquisition system had a built in background subtraction, and the background seen in 5.6 is due to the beam halo containing the more eccentric ion orbits. The errors in the data points are taken as the square-root of the charge data.

#### Calculating emittance

Emittance is essential for knowing if a particle beam will be suitable for injection into a beam-line component of a given acceptance. For injection to succeed, transverse beam emittance must be equal to or less than the entry acceptance of the ESIS.

Beam transformation between points on a beam line can be given by equations 5.1 and 5.2, where  $\sigma$  is the 2x2 beam matrix containing half-width squared,  $\sigma_{11}$  and half-angle squared  $\sigma_{22}$  as well as the cross-terms  $\sigma_{12} = \sigma_{21}$ , which give the correlation between the other two terms[71]. These values are related to the Twiss-Parameters which describe the ellipse made by the beam in phase-space [72].

Flowchart of Harp Ion Beam Profilometer Data Analysis  
 MATLAB (*HIBA.m*) Programme by M. Segal

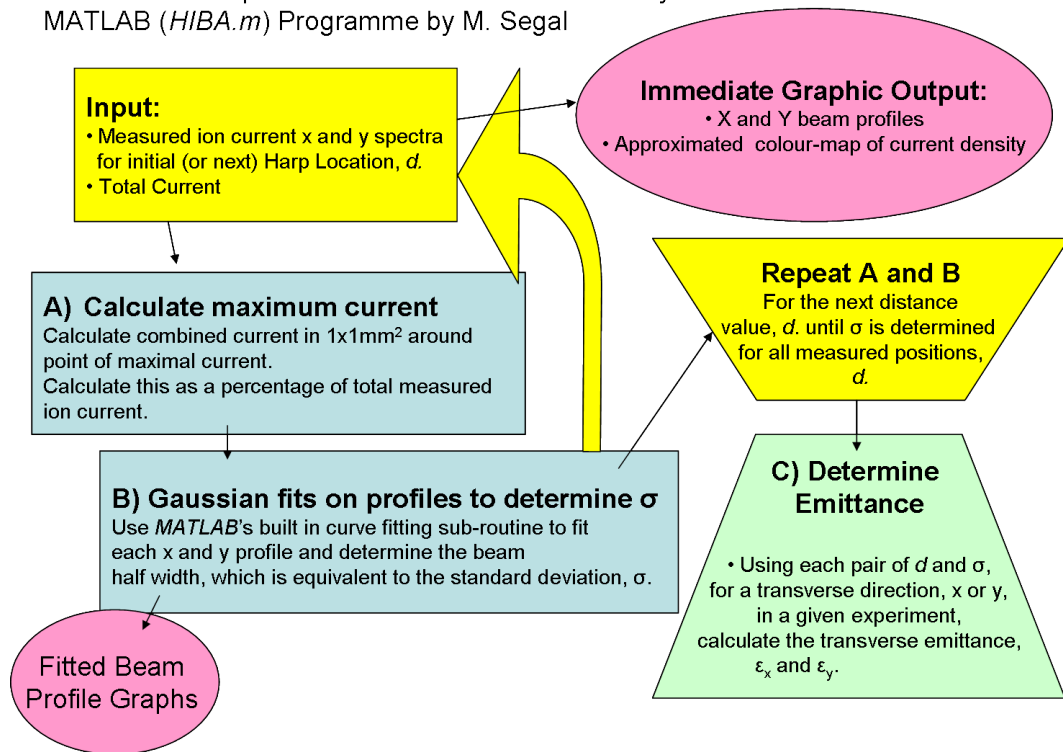


**Figure 5.4:** Computational process to determine beam parameters from beam profile measurements with the Harp Profilometer.

Beam Profiles for specific Harp location,  
d=6.8cm from LMIS gun to Harp (5keV ions)

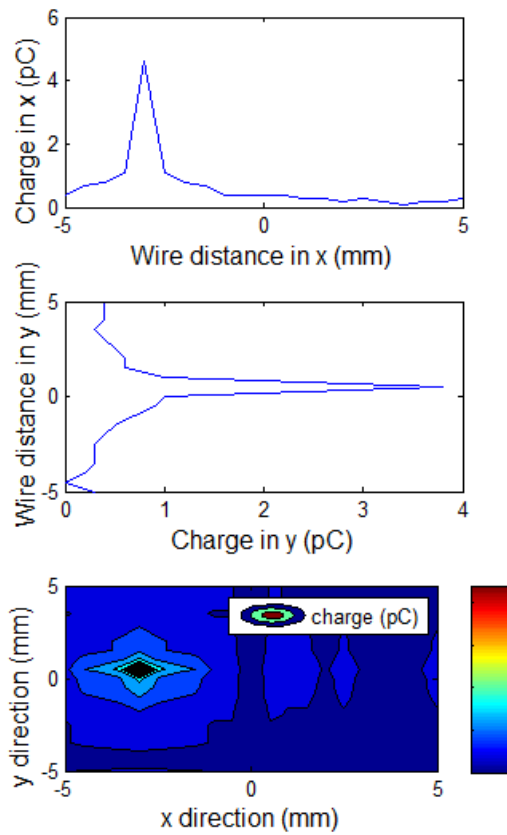


**Figure 5.5:** Immediate graphical output when executing HIBA.m. The density map is approximated by combining data from the x and y charge distributions in quadrature.

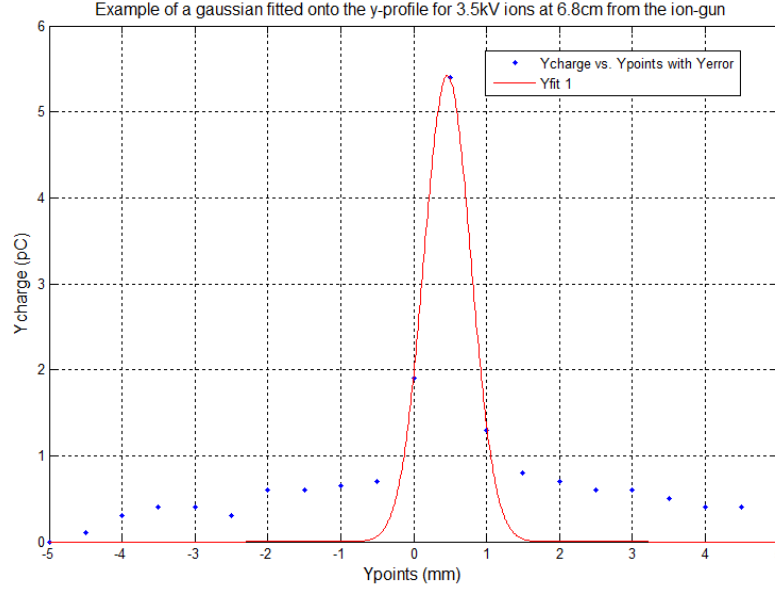


**Figure 5.6:** Example of the MATLAB Gaussian-fitting sub-routine. From such fits, beam half width incorporating 68% of the beam - which is the standard deviation,  $\sigma$  - is determined.

$$\mathbf{R} = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix} \quad (5.1)$$

$$\sigma^1 = \mathbf{R} \sigma^0 \mathbf{R}^T \quad (5.2)$$

The transformation matrix,  $\mathbf{R}$ , depends on the beam-line elements, and is simple for a translational transformation in a drift-space of length,  $L$ .

$$\mathbf{R}_L = \begin{pmatrix} 1 & L_1 \\ 0 & 1 \end{pmatrix} \quad (5.3)$$

Using this and solving Equation 5.2 for the translated beam yields:

$$\sigma_{11}^i = \sigma_{11}^0 - 2L_i \sigma_{12} + L_i^2 \sigma_{22} \quad (5.4)$$

In Equation 5.4 the squared half-width at the reference point, is  $\sigma_{11}^0$ . A drift-length,  $L_i$ , is chosen for another half-width measurement. This half-width squared is  $\sigma_{11}^i$ . Both half-angle squared,  $\sigma_{22}$ , and cross-terms,  $\sigma_{12}$ , are unknown, yet constant for a drifting beam - so a system of these equations are used to solve for them using multiple

half-width measurements at distances,  $L_i$ , from the reference half-width position::

$$\begin{pmatrix} \sigma_{11}^1 \\ \sigma_{11}^2 \\ \sigma_{11}^3 \end{pmatrix} = \begin{pmatrix} 1 & -2 L_i & L_i^2 \\ 1 & -2 L_i & L_i^2 \\ 1 & -2 L_i & L_i^2 \end{pmatrix} \begin{pmatrix} \sigma_{11}^0 \\ \sigma_{12} \\ \sigma_{22} \end{pmatrix} \quad (5.5)$$

$$\begin{pmatrix} \sigma_{11}^0 \\ \sigma_{12} \\ \sigma_{22} \end{pmatrix} = \begin{pmatrix} 1 & -2 L_i & L_i^2 \\ 1 & -2 L_i & L_i^2 \\ 1 & -2 L_i & L_i^2 \end{pmatrix}^{-1} \begin{pmatrix} \sigma_{11}^1 \\ \sigma_{12}^2 \\ \sigma_{22}^3 \end{pmatrix} \quad (5.6)$$

The transverse 2rms-emittance was calculated for beam data from simulations in Chapter 4.7 via:

$$\varepsilon_{2RMS} = 4\sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2} \quad (5.7)$$

Un-normalized transverse emittance is calculated in a similar way. The beam width squared is both  $x^2$  and  $\sigma_{11}^0$ , the half-angle squared is  $x'^2 = \sigma_{22}$ , while the cross term  $xx' = \sigma_{12}$ . The multiple of 4 represented 95 % of the beam. Excluding the multiple of 4 in the 2rms-emittance, the un-normalized emittance is determined:

$$\varepsilon = \sqrt{\sigma_{11}^0 \sigma_{22} - (\sigma_{12})^2} \quad (5.8)$$

At least four harp profile measurements corresponding to the reference point and three drift lengths,  $L_i$ , must be made to make a single calculation for emittance using the system of three equations in 5.6. Having additional half-width measurements at different drift-lengths causes the system of equations to be over-solved. With more half-width measurements at different drift lengths, multiple arrangements of the equations can be made and therefore several calculations of emittance can be done, and an average with standard uncertainty determined. With four measurements, a statistical error is not available and a larger error on the emittance can be assumed. For the purpose of this work where only four half-widths were used, a 50 to 100 % uncertainty is applied.

The un-normalized emittance given in Equation 5.8 is taken from half-widths that were determined by the widths of fitted Gaussian curves. This means this emittance corresponds to 68 % of the beam and should be multiplied by 4 to correspond with 95 % of the beam. Emittance results in Chapter 5 are quoted for 68 % of the beam, while those in Chapter 6 are more accurate due to larger data sets and are taken for 95 % of the beam.

### Normalized emittance

Emittance values can only be compared with one another if they are normalized. The normalized emittance is calculated using,

$$\varepsilon_N = \varepsilon \beta \gamma \quad (5.9)$$

Where the relativistic factor,  $\gamma$ , is basically unity for the ion energy range used, and the dependence on the relativistic velocity factor,  $\beta$ , can be taken as the square-root of ion energy in  $\sqrt{MeV}$ :

$$\varepsilon_N \approx \varepsilon \sqrt{U_{ex}} \quad (5.10)$$

Unless specified together with the ion energy, emittance can only be compared across experiments with ion-sources if they are normalized with respect to the energy.

### Approximating Beam-Width

The half-width of the beam-waist is another important parameter. This is the smallest dimension the beam spot can reach with the given settings of an experiment, and as such, this value should be smaller or of the order of the dimensions of the ESIS drift-tubes, which are 0.8 mm in diameter.

Profiles were measured over a range of 0 to 24 mm on the principal beam axis (z-axis) as the harp profilometer allows. The half-widths of such profiles were found to increase, decrease, go through a minimum turning point if the focal point was within the detector range, or be very erratic and have a maximum turning point - which is evidence of error in measurement, as a beam cannot diverge then converge within the drift length, such as in Figure 5.7.

In the case of a minimum turning point, a method involving the fitting of a parabola to the  $(d, \sigma)$  data was used to determine the turning point and the position on the beam axis. This was used as an approximation of the beam waist.

In the other cases, the smallest measured value was simply quoted with its measuring location,  $d$ , to be the smallest beam width. Of course the smaller this number, the better, as the real beam-waist would have to be even smaller still.

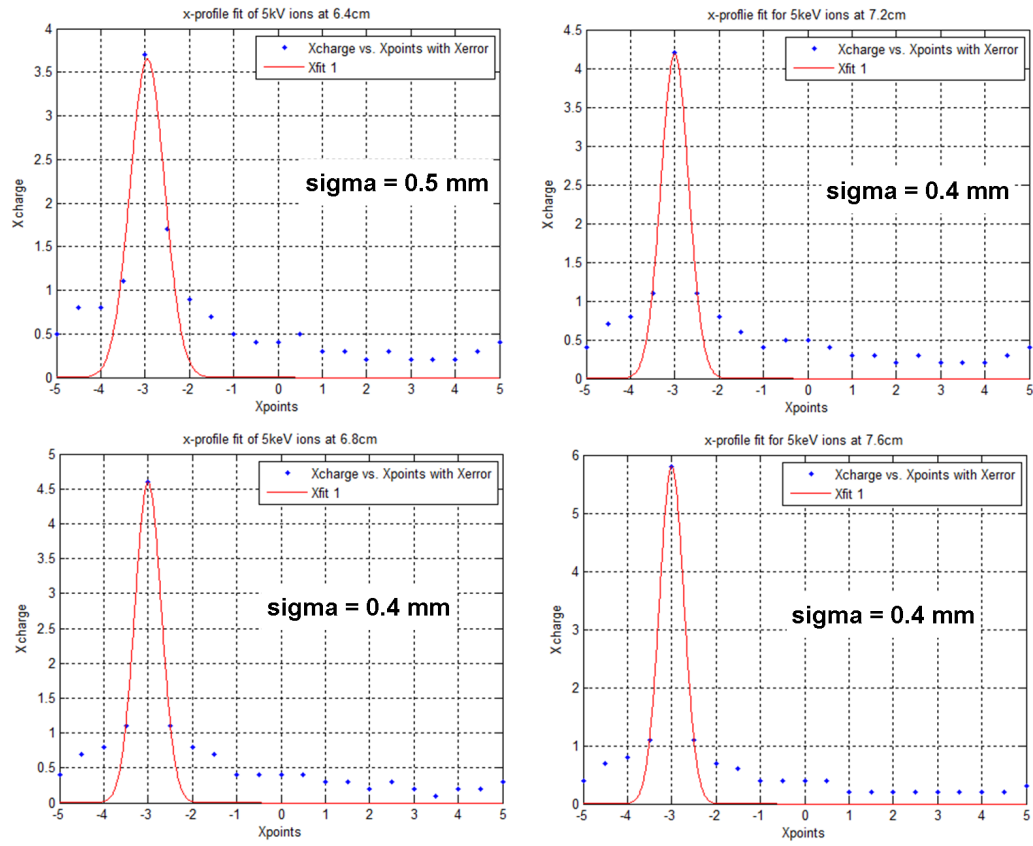


**Figure 5.7:** X (or Y) emittance and minimum beam width determination requires usage of several profiles measured at different distances,  $d = 6.4, 6.8, 7.2$ , and  $7.6$  cm, from the LMIS, in this case for 5 keV  $\text{Ga}^+$  ions.

### 5.3 Harp Beam Profiling: Initial Experimental Results

Three broad investigations were performed using the harp beam profilometer in order to calibrate and optimize the transport system more thoroughly. In all prior cases, rough beam analysis techniques were used in addition to the study of ion current arriving at Faraday cups. This was the first attempt at improving the beam transport with the more accurate beam profiling device: the harp beam profilometer.

All of the three experiments discussed in this section were performed in the CW (continuous wave) mode of operation, as no pulse-timing schemes were utilized on any of the ion optics or the ion source. Pulse modes of operation will be studied in depth in section 5.4. This current section and results therein can be considered a first calibration of the post-bending transport optics, using only a continuous beam of ion current.

Firstly, direct characterization of the LMIS-assembly was performed by placing the harp profilometer on the other end of the vacuum chamber, facing the LMIS directly. With this setup, the profilometer's location on the z-axis could be adjusted from 6.4 cm at the closest distance to the last lens of the LMIS-assembly, to 8.6 cm at the farthest.

Two of three experiments were performed in this configuration;

- A beam profile study for narrow beam widths and increasing energy from 1.4 keV to 6.0 keV, and,
- A study of settings for increased beam current at lower energies between 2.0 keV and 3.5 keV. Lower energy is better for over-barrier ESIS injection, increasing the probability of rapid electron-ion collisions in the electron string, while the energy should still be high enough for efficient transport and low emittance for ESIS injection.

Bending measurements were performed with the profilometer set with its closest distance approximately 1.4 cm from the switch-yard einzel lens, and ranging up to 3.6 cm away. An aluminium plate with a 3 mm diameter aperture was positioned just before the quadrupole switch-yard as a means to measure transport efficiency through the bender. If focusing before the switch-yard was well configured, most of the beam would fit through the aperture. If not, the aperture would act as a beam collimator. In this case there were narrower beams of lower current. Unfortunately the ion current on the aluminium plate could not be measured due to a technical fault.

The third of these experiments was the first harp profilometer study of focusing after bending using the switch-yard einzel lens for beam energies between 2.0 keV and 3.0 keV. This was also the last experiment in this phase of ongoing optimization for ion injection.<sup>1</sup>

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<sup>1</sup>The third of three LMIS that had been used since 2014 for various tests of the beam-line was exhausted during experiment C. The LMIS ion output becomes erratic and unstable when it is close to depletion, and this may be reflected in the results for experiment C, which have been kept in their chronological order.

### Experiment A: On-axis beam profiling with increasing beam energy

The calculated transverse emittance values are shown in Table 5.1. Emittance variation for both transverse directions is presented in Figure 5.8, while beam width variation with energy is shown in Figure 5.9.

Normalized emittance,  $\varepsilon_N$ , was estimated by multiplying the emittance values by the square-root of the ion energy in MeV as shown in Equation 5.10[73]:

The normalized emittance values shown in Table 5.1 are low and comparable to values measured by Alton *et. al.*, [73], which is expected for a gallium LMIS. Alton *et. al.*, measured normalized emittance for Ga LMIS to be less than  $7 \pi \cdot \text{mm} \cdot \text{mrad} \cdot \sqrt{\text{MeV}}$  for beams of 31 keV.

The trends in the data shown in Figure 5.8 for un-normalized emittance show that the emittance is inversely related to beam energy. The expected relationship is  $\varepsilon \propto 1/\sqrt{U_{ex}}$ , which has an exponent of -0.5. When linearized, the plots in Figure 5.8 show exponents of -3 in the x-direction and -3.5 in the y-direction. This difference from -0.5 is most likely due to the LMIS property of having increasing transverse energies with beam current. According to Alton *et. al.*, [73], the emittance grows proportionally to the square-root of current as well:  $\varepsilon \propto \sqrt{I_{max}}$ . This effect is more pronounced at lower beam energies, which would cause the larger negative exponents observed in Figure 5.8. Uncertainties in Figure 5.8 are taken as 5% of the emittance value. Due to there being only 3 or 4 beam-profiles per energy value studied, statistical uncertainty in emittance could not be obtained.

In Table 5.1, the maximum total current measured is presented; this is the summed ion current collected by the harp and the back-plate. On average, it was observed that between 40% and 60% of this current was concentrated in the central  $1 \text{ mm}^2$  of the beam.

It was observed that the principal beam axis was centrally positioned in the y-direction, yet offset by 2.5 mm in the x-direction. This 2.5 mm offset was constant for every distance,  $d$ , of the harp. This means the offset is a systematic misalignment of the LMIS assembly with the harp, that is, one or both devices are slightly shifted in the offset direction. This constant offset also implies that the LMIS assembly and harp were directly in line with each other, and that there was no angular deviation or increase when comparing the beam measured at a closer distance with the same beam at a farther distance. Thus it is a relatively simple problem to fix, and the results could easily be shifted to the new central point. This shifting was already performed in the fitting of Gaussian curves during data extraction with *HIBA.m*.

The graph in Figure 5.10 shows the measured half width of the beam at each harp measuring location in the x transverse dimension. The shape of the beam envelope can be seen within a degree of experimental uncertainty. The beam widths in the y-direction show a similar trend but tended to be up to 0.5 mm wider. Since the harp

**Table 5.1:** Experiment A: Un-normalized and normalized transverse emittance results with increasing beam energy

| Ion Energy<br>(keV) | $\varepsilon_x$<br>( $\pi$ .mm.mrad) | $\varepsilon_y$ | $\varepsilon_{N,x}$<br>( $\pi$ .mm.mrad. $\sqrt{MeV}$ ) | $\varepsilon_{N,y}$ | $I_{max}$<br>( $\mu A$ ) |
|---------------------|--------------------------------------|-----------------|---------------------------------------------------------|---------------------|--------------------------|
| 2                   | 231                                  | 210             | 10                                                      | 101                 | 1.25                     |
| 3                   | 77                                   | 64              | 4.2                                                     | 18                  | 1.21                     |
| 3.5                 | 313                                  | 31              | 19                                                      | 17                  | 0.99                     |
| 4                   | 8                                    | 6               | 0.5                                                     | 0.5                 | 0.86                     |
| 5                   | 11                                   | 9               | 0.7                                                     | 1.0                 | 1.10                     |
| 5.5                 | 18                                   | 9               | 1.3                                                     | 1.2                 | 1.19                     |
| 6                   | 9                                    | 124             | 0.7                                                     | 12                  | 1.59                     |

strings are only 0.5 mm apart, this limits the resolution of beam half width, such that if a beam half width value is less than  $0.5 \pm 0.05$  mm, then it can be said that the half width is at most 0.5 mm.

The half-width should either monotonically increase or decrease with distance in the case of a diverging or converging beam, or go through a turning point if the focal point is within the harp measuring range. Any shapes that do not behave as such probably have been determined from bad data or have large statistical error.

### Experiment B: On-axis beam profiling for higher ion current

Table 5.2 contains the results for higher currents at lower energies. Here the total current measured varied from 2 to 3  $\mu A$  compared to 1  $\mu A$  used in Experiment A. Also shown are the electrode-plate and einzel lens configuration potentials. It can be seen, that for the same energy of 3.1 keV, the biasing settings can greatly influence un-normalized transverse emittance and current.

Entries on this table can also be compared with the equivalent energies in Table 5.1 - especially between 2.0 keV and 3.5 keV - in order to obtain optimal current and emittance conditions for ESIS injection.

The beam half-widths that were measured at different harp locations,  $d$ , were compared with Experiment A. These were found to be slightly larger than those observed in Experiment A, since greater current was preferred over beam focusing in this experiment.

### Experiment C: Quadrupole post bending focusing

The results in Table 5.3 show chronologically the final measurements taken after  $90^\circ$  bending with the quadrupole. The LMIS depleted at the end of these investigations, and the instability of the LMIS is reflected in the later results of Experiment C, as the

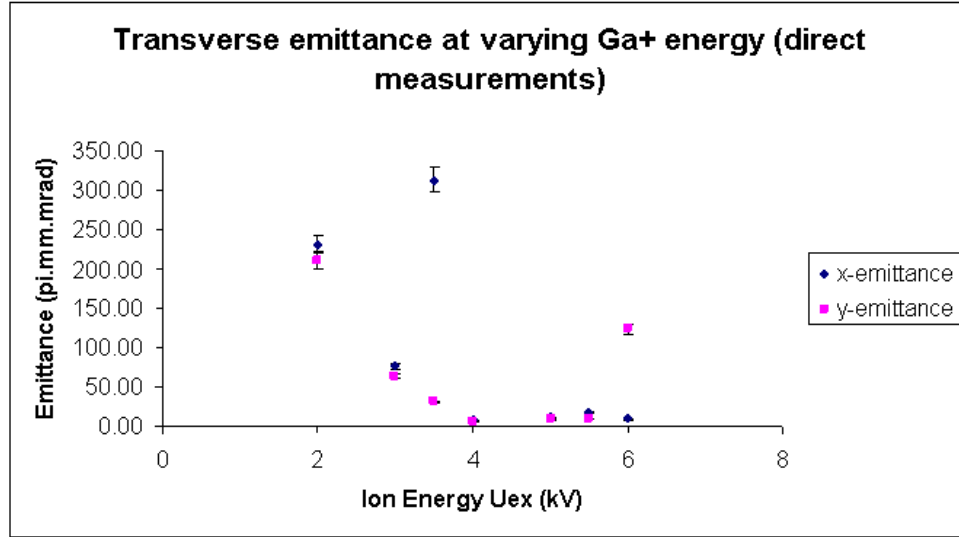


**Figure 5.8:** Experiment A: Un-normalized emittance calculated for each transverse direction. It can be seen that this emittance is inversely proportional to ion energy, see Table 5.1. Errors were estimated at 5% of the emittance values. Statistical error could not be obtained per data point due to too few profile measurements.

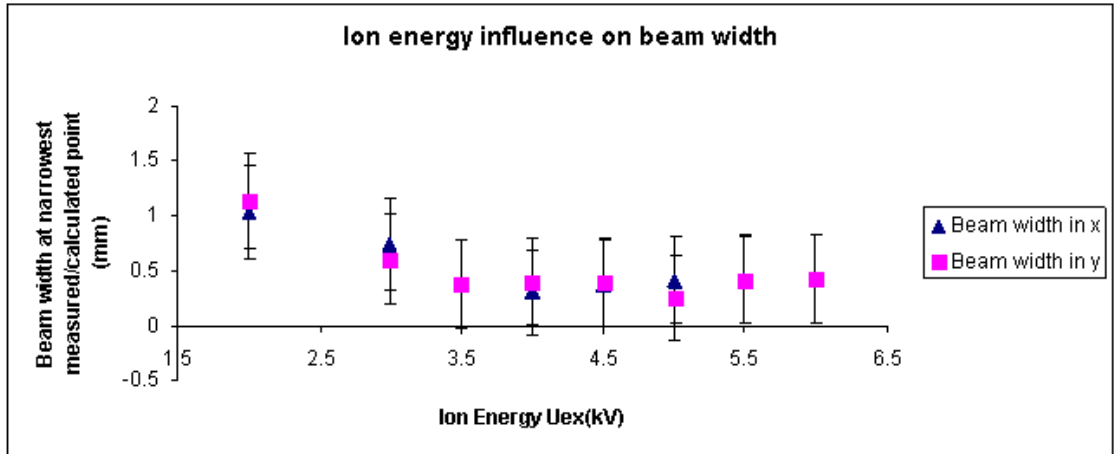


**Figure 5.9:** Experiment A: Minimum beam-width is calculated for each transverse direction. The resolution of the harp profilometer is 0.5 mm, which means that values calculated that are lower than this have great uncertainty, and 0.5 mm can be considered a lower bound for attainable beam-widths. The error in half-width is calculated via the standard uncertainty for an analogue scale.

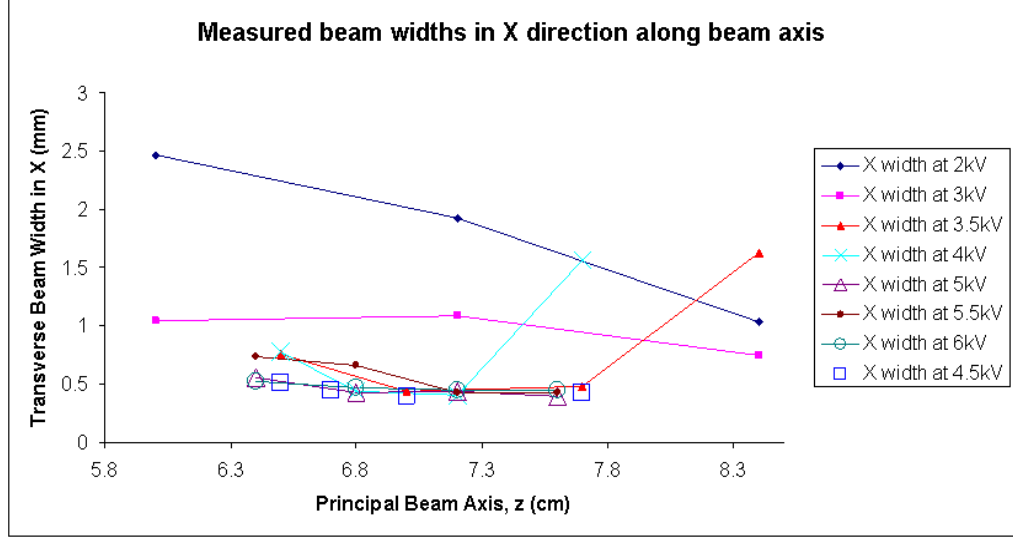


**Figure 5.10:** Experiment A: Beam half widths in x calculated in *HIBA.m* at their measurement locations. Graphs with turning points indicate the focal point was within the measurement range.

**Table 5.2:** Experiment B: Transverse emittance results for higher total ion current, at higher beam-widths.

| Ion Energy<br>(keV) | $\varepsilon_x$<br>( $\pi \cdot \text{mm} \cdot \text{mrad}$ ) | $\varepsilon_y$<br>( $\pi \cdot \text{mm} \cdot \text{mrad}$ ) | $\varepsilon_{N,x}$<br>( $\pi \cdot \text{mm} \cdot \text{mrad} \cdot \sqrt{eV}$ ) | $\varepsilon_{N,y}$<br>( $\pi \cdot \text{mm} \cdot \text{mrad} \cdot \sqrt{eV}$ ) | $U_{em}$<br>( $\mu\text{A}$ ) | $U_{ei}$<br>(kV) | (kV) |
|---------------------|----------------------------------------------------------------|----------------------------------------------------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-------------------------------|------------------|------|
| 2.0                 | 116                                                            | 119                                                            | 5                                                                                  | 41                                                                                 | 3.03                          | -6.4             | 0.8  |
| 2.6                 | 55                                                             | 46                                                             | 3                                                                                  | 11                                                                                 | 2.42                          | -6.6             | 1.0  |
| 3.1                 | 34                                                             | 14                                                             | 2                                                                                  | 3                                                                                  | 2.18                          | -6.7             | 1.3  |
| 3.1                 | 31                                                             | 11                                                             | 2                                                                                  | 2                                                                                  | 1.66                          | -4.4             | 1.6  |

**Table 5.3:** Experiment C: Transverse emittance results after 90° quadrupole bending, at lower ion current.

| Ion Energy<br>(keV) | $\varepsilon_x$<br>( $\pi$ .mm.mrad) | $\varepsilon_y$<br>( $\pi$ .mm.mrad) | $\varepsilon_{N,x}$<br>( $\pi$ .mm.mrad. $\sqrt{eV}$ ) | $\varepsilon_{N,y}$<br>( $\pi$ .mm.mrad. $\sqrt{eV}$ ) | $I_{max}$<br>( $\mu$ A) | $U_{em}$<br>(kV) | $U_{ei}$<br>(kV) | $U_{bend}$<br>(kV) | $U_{bend,ei}$<br>(kV) |
|---------------------|--------------------------------------|--------------------------------------|--------------------------------------------------------|--------------------------------------------------------|-------------------------|------------------|------------------|--------------------|-----------------------|
| 1.4                 | 5                                    | 9                                    | 0.2                                                    | 0.3                                                    | 1.02                    | -6.6             | 0.86             | 1.1                | 0                     |
| 1.6                 | 6e+03                                | 114                                  | 246                                                    | 5                                                      | 0.11                    | -6.6             | 1.1              | 1.3                | 0                     |
| 2.0                 | 533                                  | 941                                  | 24                                                     | 42                                                     | 0.08                    | -6.0             | 1.2              | 1.8                | 0                     |
| 2.0                 | 3e+06                                | 6                                    | 2e+05                                                  | 0.3                                                    | 0.07                    | -6.0             | 1.25             | 1.9                | 0                     |
| 2.5                 | 182                                  | 21                                   | 9                                                      | 10                                                     | 0.10                    | -6.0             | 1.36             | 2.1                | 0                     |
| 3.0                 | 219                                  | 12                                   | 12                                                     | 0.7                                                    | 0.14                    | -5.6             | 1.6              | 2.5                | 0                     |
| 3.0                 | 49                                   | 13                                   | 3                                                      | 0.7                                                    | 0.19                    | -5.8             | 1.44             | 2.33               | 0                     |
| 3.0                 | 66                                   | 11                                   | 4                                                      | 0.6                                                    | 0.20                    | -6.5             | 1.4              | 2.1                | 1.56                  |
| 3.0                 | 104                                  | 15                                   | 6                                                      | 0.8                                                    | 0.20                    | -6.5             | 1.33             | 1.96               | 1.5                   |
| 2.0                 | 14                                   | 282                                  | 1                                                      | 13                                                     | 0.11                    | -7.0             | 01.1             | 1.6                | 1.5                   |

liquid metal ion source started to sputter instead of delivering continuous current at the end of its lifetime.

A range of lower ion energies was investigated, and as already mentioned, maximum current was much lower due to the aluminium plate and small 3 mm aperture prior bending. Listed on Table 5.3 are all the biasing settings that were used on each electrical optical component. The switch-yard einzel lens,  $U_{bend,ei}$ , was not used at first, and it was clear that focusing in the y-direction, which was horizontal in this investigation, was far better than focusing in x (or vertical). This is probably due to the dipole-focusing caused by the electrical quadrupole in the horizontal plane.  $U_{bend,ei}$  was switched on for the final few measurements, and it was observed that focusing in the vertical improved drastically, at the expense of focusing in the horizontal. Therefore there exists a middle ground limit where both directions can be adequately focused without defocusing in the other dimension.

### 5.3.1 Analysis and discussion: Harp beam profiling

The harp-profilometer allowed for excellent beam profile measurements which had not been done before in this experimental work [69]. The beam profiles measured and analysed yielded several results which lend insight into the beam-line optimization problem. The MATLAB code, *HIBA.m*, has been successful in extracting and interpreting data, and perhaps can be useful if a form of this program is used on-line during measurements and data acquisition.

## Experiments A and B

The direct profile measurements and subsequent analysis showed that both very low half-widths, within the limit of experimental uncertainty, can be achieved, at currents up to 3  $\mu$ A in CW-mode. Transverse emittance was shown to behave as expected

with increasing energy in Figure 5.8, emittance being inversely proportional to the square-root of beam energy.

An analysis of the energies in the 2 keV to 3.5 keV range shows that emittance is decreased (improved) at higher currents too, yet beam width increases. When comparing 3.1 keV beams in Table 5.2, it is seen that a lower setting on  $U_{em}$  gives better emittance, but less total current. Wider beams with more current can also be made by reducing the strength on the LMIS assembly einzel lens system,  $U_{ei}$ .

The axial offset, an example of which can be seen in the x-profile in Figure 5.3, can easily be fixed by shifting the harp or LMIS so that they are properly aligned. The data does not suffer, as this offset is simply taken to be the centre point of the principal axis since it is a systematic shift of the same 2.5 mm in every profile.

## Experiment C

The un-normalized emittance values listed in Table 5.3 were subject to the most statistical error, and therefore some of the values measured were extremely large. Especially in the unfocused direction, which would sometimes yield very flat profiles which correspond to massive beam half widths and huge emittance. This could be due to the aforementioned lifetime end of the LMIS. Never-the-less, some of the data were very good, such as in the case of 3 keV beam with  $\pm 2.5$  kV quadrupole biasing. After beam focusing improved emittance measurements in x (compare the bottom 3 values of  $\varepsilon_x$  with the top values in Table 5.3), while also improving y emittance at 3 keV. This is a very positive observation. Of course,  $\varepsilon_y = 408 \pi \cdot \text{mm} \cdot \text{mrad}$ , which was obtained from the final profiling measurements, reflects the end and instability of the LMIS.

The 3 mm diameter aperture in the aluminium plate before bending could have improved the collimation and therefore emittance and width of the beam after bending, however, its presence reduced the overall ion current reaching the harp. The plate was removed in the next phase of experiments. If the LMIS-assembly focusing system has been well configured, then one might hope to expect improved emittance and beam width together with increased ion current.

### 5.3.2 ESIS injection considerations

The aim for over-barrier ion injection into the ESIS is at least  $1.2 \mu\text{A}$  of beam, and at lowest possible energies available in order for the ions to be sufficiently trapped. Therefore ion energy between 2.0 keV to 3.5 keV has been studied primarily in this section, however lower energies around 1.4 to 1.7 keV will be better suited for over-barrier injection and this is discussed in Chapter 7. The acceptance of the ESIS injection port is about  $10 \pi \cdot \text{mm} \cdot \text{mrad}$ , with an entrance diameter of 3.2 mm, meaning half-widths of no greater than 1.6 mm are required. In these experiments, such numbers were not obtained, yet some results were very close. Any beam half width less than 0.5 mm

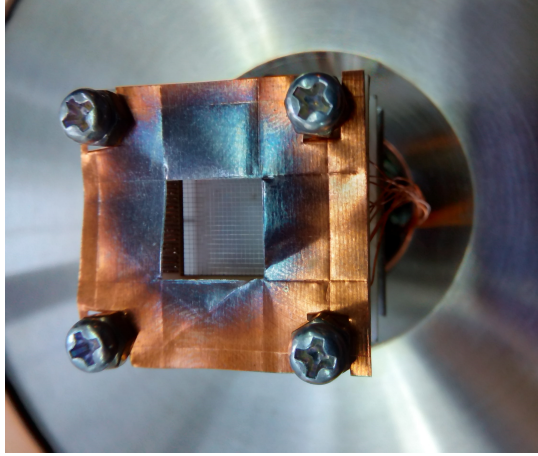


**Figure 5.11:** Harp Beam Profilometer after some use measuring  $\text{Ga}^+$  beam. The copper foil was used as an additional means to collect current. The gallium halo can be seen clearly on the copper foil, and the translational offset of about 2.5 mm off the principal beam axis is clear.

may be reasonable, and many of the minimum half widths measured were found to be of this size. For greater half-widths, a much smaller fraction of the ion beam would be able to enter the ESIS. At lower energy, the smallest half-widths in both transverse directions were found in Experiment A, for 3.5 keV ions. The best emittance in both directions were found in Experiment B, for 2.6 keV ions (yet larger beam width), and in Experiment C, for 3 keV ions and  $\pm 2.5$  kV quadrupole biasing, with an un-powered switch-yard einzel lens.

This emittance result was the closest to the ESIS acceptance, with  $\varepsilon_x = 14 \pm 9 \pi \cdot \text{mm} \cdot \text{mrad}$  which agrees with experimental uncertainty, and  $\varepsilon_y = 29 \pm 12 \pi \cdot \text{mm} \cdot \text{mrad}$  which very nearly agrees within experimental uncertainty. However, the beam half width of this in the unfocused vertical direction was 1.5 mm, while it was less than 0.5 mm in the horizontal, which is satisfactory.

The next section will cover beam profiling experiments that were performed to optimize the ion optics and switch-yard bias again for beam energies around 2.0 keV with pulsed biasing on the LMIS, switch-yard and harp.

The results in the above investigations focused on only CW-mode of ion beam operation, with no pulse-timing analysis. Therefore this was a limitation as a pulsing scheme is required for ESIS injection and extraction cycles. Pulsing schemes will be presented in detail in the investigation in Section 5.4.

## 5.4 Experiments for Optimizing Pulsed Beam Bending

In Experiment C, covered in the previous section, the first beam profiles were measured using the harp for CW-mode beams after  $90^\circ$  bending by the switch-yard. Beam parameters could be attained via analysis of these profiles. However, there was only one set of results for Experiment C and no analysis of pulse-timing. The results from experiment C were also limited due to the time frame in which the investigation was performed. The  $\text{Ga}^+$  LMIS that was in use also depleted, which brought the end to this phase of tests.

The next phase of experiments that is covered in this section deals with the improvement of beam after bending by making extensive use of the harp profilometer, and therefore improving upon the results discovered in the previous section. The following investigations were also more in depth and served to finalize the calibration of transport system parameters. The results from these tests fix the voltage bias required on all the ion-optics to their optimal configuration for the investigated beam energies, and also set the pulse-timing conditions for maximal beam current transmission, narrowest beams, and lowest transverse emittance. Obtaining beam profiles with the harp while adjusting harp on-time was yet to be investigated and was studied for the first time in the following experiments.

A total of 26 experiments were performed during this optimization phase. These investigations included:

- Beams at lower energies and the effect of beam energy on the transmitted beam parameters. Optimal biasing settings were obtained for each energy studied.
- Beam energy was fixed at 2.0 keV. The biasing on the LMIS was pulsed. The switch-yard bias and harp detector on-time were pulsed with similar periods to the LMIS. Slightly adjusting the delay or pulse lengths on these factors changed the quality of beam profiles recorded.
- The delay on the harp profilometer was calibrated for the optimum pulse-settings: first at a single profilometer distance to ascertain beam profile quality dependence on the delay, and secondly at several profilometer distances from which transverse emittance was calculated.

Included in this analysis are only the highlights of these experiments with the most notable results mentioned and discussed.

All of the profiles were measured with the same technique introduced in Section 5.3. Beam parameters were obtained using the *HIBA.m* MATLAB data processing code.

The schematic of this set-up that was used in this investigation is shown in Figure 5.12.

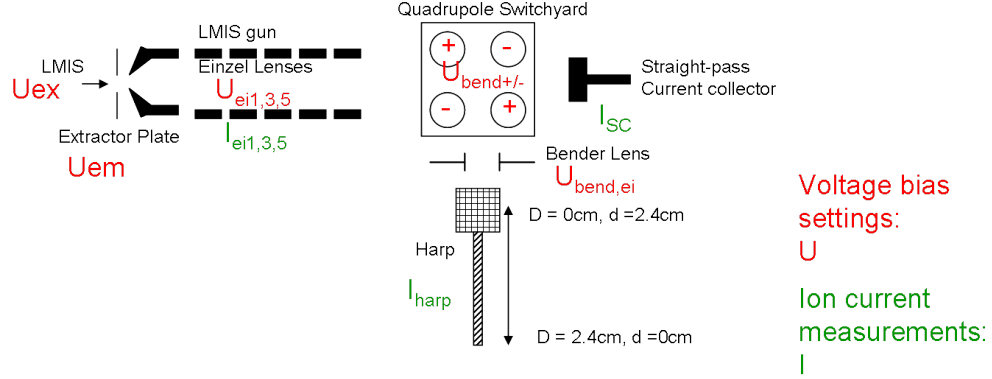


**Figure 5.12:** Schematic of existing transport system post 90° bending by the quadrupole switch-yard, for beam profiling via harp.

#### 5.4.1 Optimizing ion optics for lower energy beams, with pulse-mode

9 beam profiling investigations were performed using  $\text{Ga}^+$  ions of energies from 1.0 keV to 2.5 keV. The quadrupole switch-yard bias,  $U_{bend}$  and quadrupole switch-yard einzel lens,  $U_{bend,ei}$ , were set in order to obtain maximum possible beam current transmission in the bending direction. The settings displayed in Table 5.4 for the quadrupole biasing were those that yielded the most current after a few initial sweeps of the voltage bias settings.

The harp was positioned farthest away with  $d = 0$  mm, and brought closer for each measurement. Profiles were recorded for  $d=0, 8, 16$  and  $20$  mm. These profiles were used to estimate emittance and the width of the transported ion beam.

The beam produced from the LMIS was pulsed on  $U_{ex}$ , the switch-yard potentials,  $U_{bend}$ , were also pulsed to emulate the injection phase of ions into ESIS. The harp on-time was also pulsed. Pulse settings for this experiment were kept constant, with 4 ms pulses on the LMIS, switch-yard and harp. The harp also had a 2 ms delay before it's on-time. The overall repetition period was 1 s.

Ion current was measured at the harp, and un-bent beam current was also recorded on the straight collector plate,  $I_{SC}$ .

The voltage bias settings are listed in Table 5.4, and the beam parameter results are highlighted in Table 5.5.

In Table 5.5 the average current at the harp,  $I_{harp}$ , the average un-normalized transverse emittance,  $\varepsilon^1$ , and half-widths,  $\sigma$ , in both transverse directions were recorded. These averages were calculated over each measurement position,  $d$ , of the profilometer.

<sup>1</sup>Here the beam, after bending, is propagating in the z-direction, so the transverse direction, x, is the dimension in which the switch-yard deflected the beam, while the transverse direction, y, has been unaffected by the quadrupole switch-yard.

**Table 5.4:** Ion-optics settings for optimal beam bending with varying beam energy given by  $U_{ex}$ 

| $U_{ex}$<br>(kV) | $U_{em}$<br>(kV) | $U_{ei}$<br>(kV) | $U_{bend}$<br>(kV) | $U_{bend,ei}$<br>(kV) |
|------------------|------------------|------------------|--------------------|-----------------------|
| 1.0              | -6.0             | 0.60             | $\pm 1.60$         | 0.83                  |
| 1.4              | -4.8             | 0.90             | $\pm 0.89$         | 0.29                  |
| 1.6              | -5.0             | 1.00             | $\pm 1.07$         | 0.59                  |
| 1.8              | -4.8             | 1.20             | $\pm 1.30$         | 0.67                  |
| 2.2              | -3.0             | 0.90             | $\pm 1.92$         | 1.09                  |
| 2.4              | -4.2             | 1.00             | $\pm 1.72$         | 0.90                  |
| 2.4              | -4.2             | 1.00             | $\pm 1.60$         | 0.83                  |
| 2.5              | -2.8             | 1.20             | $\pm 1.95$         | 0.99                  |
| 2.5              | -3.2             | 1.10             | $\pm 1.94$         | 1.11                  |

**Table 5.5:** Results for optimal beam bending with varying beam energy

| Beam Energy<br>(keV) | $I_{SC}$<br>( $\mu$ A) | $I_{Harp}$<br>( $\mu$ A) | Transmission<br>% | $\varepsilon_{N,x}$<br>( $\pi$ .mm.mrad. $\sqrt{MeV}$ ) | $\varepsilon_{N,y}$<br>( $\pi$ .mm.mrad. $\sqrt{MeV}$ ) | $\sigma_x$<br>(mm) | $\sigma_y$<br>(mm) |
|----------------------|------------------------|--------------------------|-------------------|---------------------------------------------------------|---------------------------------------------------------|--------------------|--------------------|
| 1.0                  | 0.85                   | -                        | -                 | -                                                       | -                                                       | -                  | -                  |
| 1.4                  | 0.70                   | 0.33                     | 47                | 11                                                      | 36                                                      | 5.1                | 9.0                |
| 1.6                  | 0.70                   | 0.50                     | 71                | 5                                                       | 28                                                      | 246                | 5                  |
| 1.8                  | 0.80                   | 0.53                     | 66                | 10                                                      | 23                                                      | 4.9                | 7.7                |
| 2.2                  | 0.62                   | 0.45                     | 73                | 0.2                                                     | 0.04                                                    | 1.4                | 0.7                |
| 2.4                  | 1.15                   | 0.99                     | 86                | 2                                                       | 0.8                                                     | 2.7                | 1.8                |
| 2.4                  | 1.15                   | 0.73                     | 63                | 2                                                       | 1                                                       | 2.0                | 2.3                |
| 2.5                  | 0.70                   | 0.33                     | 47                | 0.2                                                     | 0.2                                                     | 1.2                | 0.6                |
| 2.5                  | 0.75                   | 0.67                     | 89                | 1.0                                                     | 0.6                                                     | 1.6                | 1.7                |

**Table 5.6:** Optimal bias settings on extractor plate and einzel lenses prior switch-yard for maximum current delivered in the straight pass direction  $I_{SC}$ 

| Beam Energy<br>(keV) | Extractor Plate, $U_{em}$<br>(kV) | Einzel Lenses, $U_{ei}$<br>(kV) | Max. Ion current, $I_{SC}$<br>( $\mu$ A) |
|----------------------|-----------------------------------|---------------------------------|------------------------------------------|
| 2.4                  | -4.2                              | 1.0                             | 1.2                                      |
| 2.5                  | -3.2                              | 1.1                             | 0.9                                      |

Transmission of the  $90^\circ$  deflected beam was calculated by taking the ratio  $I_{harp}/I_{SC}$ . It is assumed that the full ion current from the LMIS is being recorded at the straight-collector, as the ion-optical biasing settings focus the beam entirely through the copper-plate aperture (and  $I_{copper} = 0 \mu\text{A}$  always),  $I_{SC}$ , while a portion is lost while bending.

Low values for emittance and beam half-width, and high values of current at the harp (and therefore high total transmission) were favoured results. Lower beam energies between 1.0 and 1.8 keV yielded the worst results, with no suitable profiles - only noise for the 1.0 keV beam.

The best results were found for beam energies of 2.2 keV and higher. Comparing the two results for 2.4 keV, one can see there is trade-off between current transmission and beam-width or emittance. This is because narrower beam profiles were recorded when there was lower current transmission - and hence lower emittance values were calculated. This trend can also be observed between the two sets of results for 2.5 keV ion beams.

### Optimizing $U_{em}$ and $U_{ei}$

The 2.4 keV and 2.5 keV experiments were also used to calibrate the ion-optical bias of all the electrodes in use, and for each of these beam energies, both the extractor plate,  $U_{em}$ , and einzel lens,  $U_{ei}$ , biasing ranges were swept through while the straight collector current,  $I_{SC}$ , was measured with no bending. When  $I_{SC}$  was maximum, the bias settings on  $U_{em}$  and  $U_{ei}$  were recorded and used throughout all future experiments. See Figures, 5.13, 5.14, 5.15 and 5.16. Once the best setting of extractor-plate potential,  $U_{em}$ , for maximum current was obtained, this was used to get the best einzel bias  $U_{ei}$ , for highest current measured at the straight collector,  $I_{SC}$ .

These optimum settings on  $U_{em}$  and  $U_{ei}$  for these beam energies are summarized in Table 5.6. A similar investigation was performed in Chapter 4 in the original construction of the Ion-Gun system, but only lower beam energies ( $U_{ex} < 1.1 \text{ kV}$ ) were investigated. The results shown here are more valid for beam energy around 2.4 keV and these voltage settings will be used throughout later investigations.

A beam energy of 2.4 keV will be favoured in future investigations as higher ion current and better beam parameters were measured at this energy setting. This is perhaps

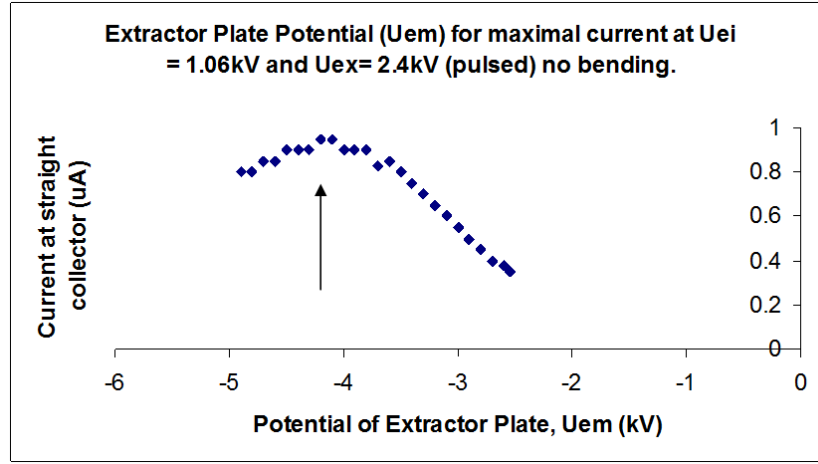


**Figure 5.13:** Optimization of extractor plate potential  $U_{em}$  for maximum current transported to straight detector,  $I_{SC}$  for 2.4 keV beam. Optimum  $U_{em} = -4.2$  kV.

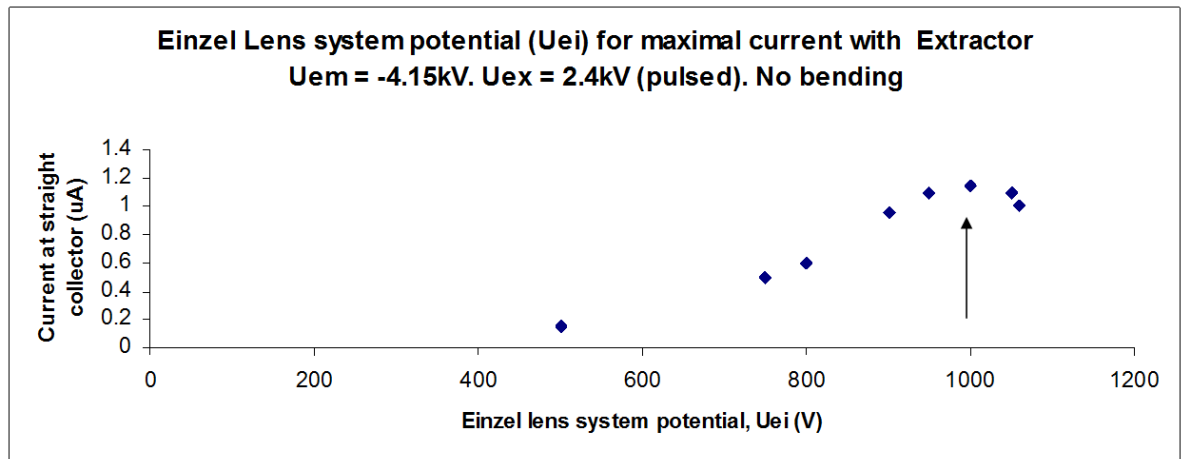


**Figure 5.14:** Optimization of einzel lens potential  $U_{ei}$  for maximum current transported to straight detector,  $I_{SC}$  for 2.4 keV beam. Optimum  $U_{ei} = 1.0$  kV.

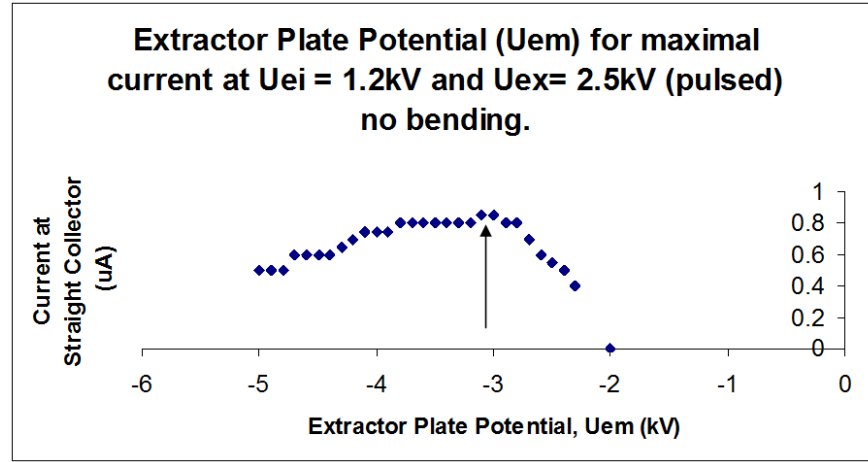


**Figure 5.15:** Optimization of extractor plate potential  $U_{em}$  for maximum current transported to straight detector,  $I_{SC}$  for 2.5 keV beam. Optimum  $U_{em} = -3.2$  kV.

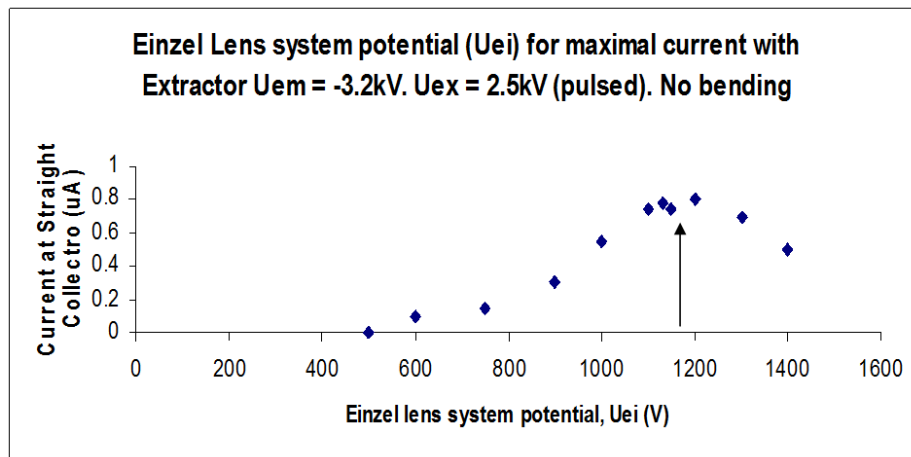


**Figure 5.16:** Optimization of einzel lens potential  $U_{ei}$  for maximum current transported to straight detector,  $I_{SC}$  for 2.5 keV beam. Optimum  $U_{ei} = 1.1$  kV.

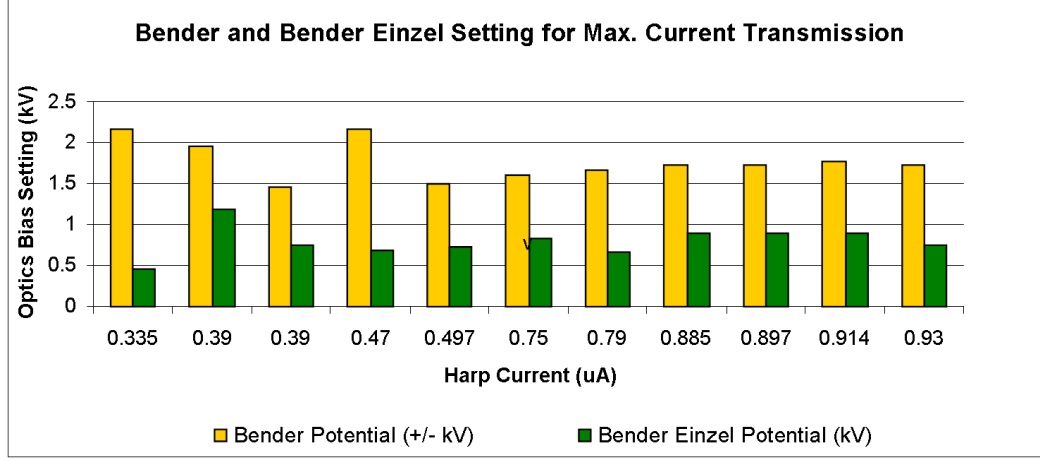


**Figure 5.17:** Optimization of quadrupole switch-yard biasing,  $U_{bend}$ , and switch-yard einzel lens biasing  $U_{bend,ei}$ , for 2.4 keV beam. The maximum harp current recorded was  $0.9 \mu\text{A}$  for  $U_{bend} = \pm 1.8 \text{ kV}$  and  $U_{bend,ei} = 0.8 \text{ kV}$ .  $I_{SC} = 1.15 \mu\text{A}$  was recorded on the straight pass collector through-out.

the lowest beam energy for a good beam: lower energies are favoured for ESIS charge-breeding allowing for more interaction time with the electron string, but the beam must also pass the injection criterion of the ESIS, and 2.4 keV ion beams are currently the best candidate judging from the results thus far.

### Optimizing $U_{bend}$ and $U_{bend,ei}$

The quadrupole switch-yard bias on both the quadrupole electrodes as well as the switch-yard einzel lens, were swept through as in the above investigation of  $U_{em}$  and  $U_{ei}$ . Ten such measurements were recorded for 2.4 keV ions with the ion-optics settings shown in Table 5.6 in use. The results are shown in Figure 5.17.

According to the results shown in Figure 5.17, the bias settings on the switch-yard which yield maximum  $90^\circ$  deflected beam current were  $U_{bend} = \pm 1.8 \text{ kV}$  and  $U_{bend,ei} = 0.8 \text{ kV}$ .

### Further observations and conclusions

- The highest current output occurred for  $U_{ex} = 2.4 \text{ kV}$  at  $I_{SC} = 1.15 \mu\text{A}$ , rather than  $U_{ex} = 2.5 \text{ kV}$  as might be expected. There is a sweet-spot here after which ion current yield drops as  $\Delta V$  (voltage difference between  $U_{ex}$  and  $U_{em}$ ) increases, which has been shown in previous results.
- A beam energy of 1.0 keV had yielded ion current, but no beam profiles that could

be fitted by a Gaussian were measured. Only noisy and chaotic profiles with no distinct shape.

- Due to high  $I_{harp}$  and  $I_{SC}$  and better emittance values than the other experiments, the first experiment with  $U_{ex} = 2.4$  kV seemed to be most successful at determining potential bias settings for future experiments. However the beam widths measured were not as small as those measured the experiments with  $U_{ex} = 2.5$  kV. This is a useful data, and will be improved upon as these beam energies are studied further.
- The y-direction is less coupled to the bending direction which is in the x-z plane, yet higher emittance was measured compared to the x-direction. This shows the necessity of requiring an after bending focusing or x/y correction optics.
- Beam widths in y were much smaller for the higher energy ions and the beam widths in x were consistently larger and more diffuse after bending.

**Table 5.7:** Constant ion-optics biasing for pulse-timing investigations of 2.0 keV beam

| Ion-optics    | Bias (kV) |
|---------------|-----------|
| $U_{em}$      | -4.3      |
| $U_{ei}$      | 0.9       |
| $U_{bend}$    | $\pm 1.6$ |
| $U_{bend,ei}$ | 0.9       |

#### 5.4.2 Pulse-timing settings and harp delay

Beam profiles were recorded and analysed to study the effect of voltage pulsing on the LMIS, the quadrupole switch-yard and harp profilometer.

The quality of a beam profile can be improved upon by pulsing the harp on and off so that it receives an ion pulse from the LMIS without a front or tail. Depending on the delay or advance time on the pulsed harp, only the front or tail of the pulse can be recorded as well.

The harp pulsing and delay time also allow insight into the formation of the Taylor-Cone on the LMIS during operation, and it is also possible that the LMIS lifetime increases and pulsed current is more stable while operated in pulse-mode due to the constant re-wetting of the LMIS needle.

The form of beam profiles measured with these harp-delays can be compared with those found in CW-mode. In the investigations which follow, optimal pulsing and delaying is sought after for narrowest and brightest ion beams.

In this investigation, the transport system had constant voltage bias settings, while pulse-settings were varied. Beam energy of 2.0 keV was used, and the voltage bias settings are listed in Table 5.7. Although this beam energy of 2.0 keV was not investigated previously, the pulse-timing settings would still prove useful to later experiments with beams between 2.0 and 2.5 keV.

Once again, a total repetition period of 1s was used, with 4 ms pulses on the LMIS bias,  $U_{ex}$ . A 2 ms delay had been used on the harp as well, which essentially means it is only powered and operating when the majority of a beam pulse is impacting the harp. These settings were varied and observations were made.

#### Pulsing and advancing the switch-yard

Maximal ion current was measured when the switch-yard was pulsed at the same rate as the LMIS - which is the trigger rate. There is room for a slight shift due to the time difference made by the ion beam but this is negligible when compared to millisecond range, as time-of-flight of 2.0 keV ions is in the microsecond range for this transport

system. However, due to the deceleration caused by positive einzel lens biasing, the ion flight time is slightly lengthened.

Should the LMIS be advanced or delayed, the switch-yard and harp would need be equally advanced or delayed, with the switch-yard at least 2 ms more advanced to maintain maximal ion current detection. This is revealed in a more detailed survey of harp delay times.

### Delaying the harp pulse

The harp delay, which is analogous to the open or closed gate time of the ESIS, is an important factor in obtaining good beam profile results, and later, adequate beam pulses injected into the ESIS.

To investigate the effect of harp delay in detail, the trigger pulse length, LMIS, switch-yard and harp were all pulsed at 8 ms instead of 4 ms in a 1.6 s total cycle. A 0.4 ms advance was placed on the switch-yard to avoid ion current passing through the straight direction, and this also accounts for much more than the travel time of the beam.

Figures 5.18 and 5.19 show a collection of results from which the effect of delaying the harp can be seen when profiles are measured at a fixed distance of the harp. In Figure 5.18, one can observe a constant plateau of beam widths between around 2.5 and 7.5 ms. In Figure 5.19, the same could be said for ion current recorded by the harp. There is very little beam arriving at the harp at earlier times and the detector would be recording the front of the beam pulses in this case. Correspondingly, the beam pulse has all but passed when the detector is turned on at times greater than 8 ms, so delays beyond 7 ms are recording the tail end of the ion beam pulse. In Figure 5.18, the very large beam-widths at 1 ms and 8 ms are due to flat and noisy profiles at these lower ion currents.

The range of harp delay values just after 1 ms to 2 ms were investigated with more resolution: several harp-delays were recorded at three different positions of the harp in order to calculate emittance and relate this to the harp delay.

### Observations on harp delay

Figure 5.20 shows the effect of harp delay on the beam half-widths at different distances along the beam axis. For all cases, the beams observed appeared to be converging due to their negative slopes. Smaller half widths can be measured at lower delay times as also observed in Figure 5.18.

The beam current was also found to increase with wider half-widths as expected, which in turn increased due to longer delay time. After 2 ms both current and half-widths are constant until the pulse closes (in this case, at 8 ms).

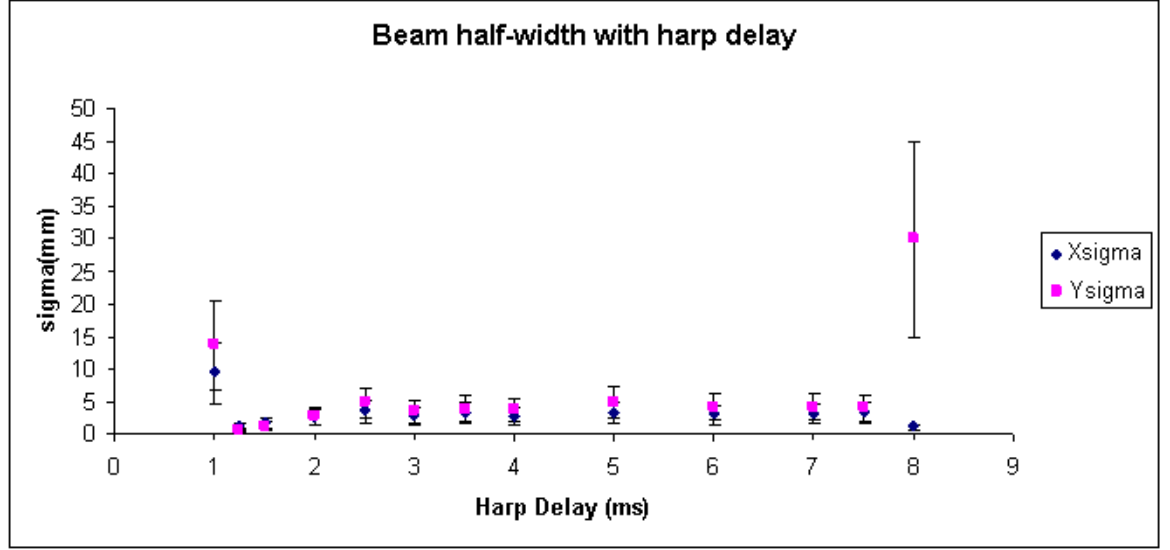


**Figure 5.18:** The effect of delaying the pulse on the harp. Large values for  $\sigma$  at 1 ms and 8 ms are calculated due to the flat profiles measured, yielding very large half-widths when the flat profile data is fitted with a Gaussian. The error-bars are half the size of the half-widths.

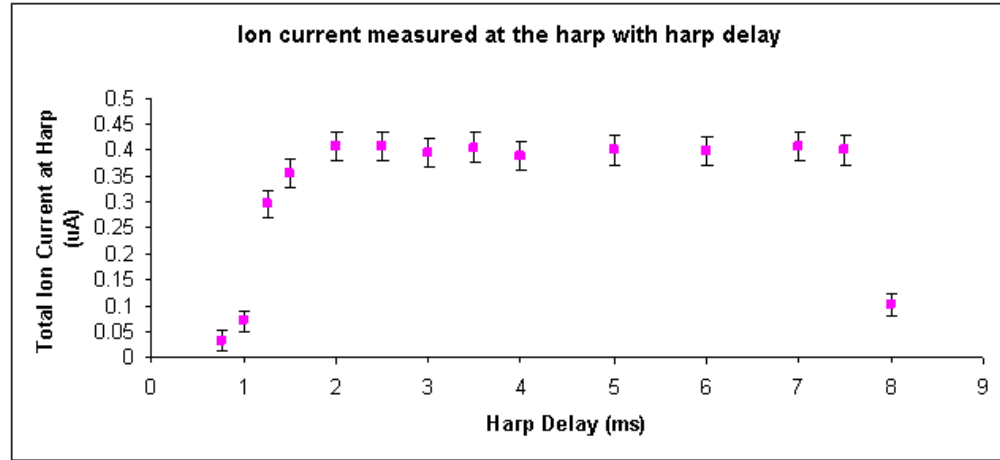


**Figure 5.19:** Effect of harp delay on current measured by the harp,  $I_{harp}$ . A 5% tolerance uncertainty is shown in the error-bars.

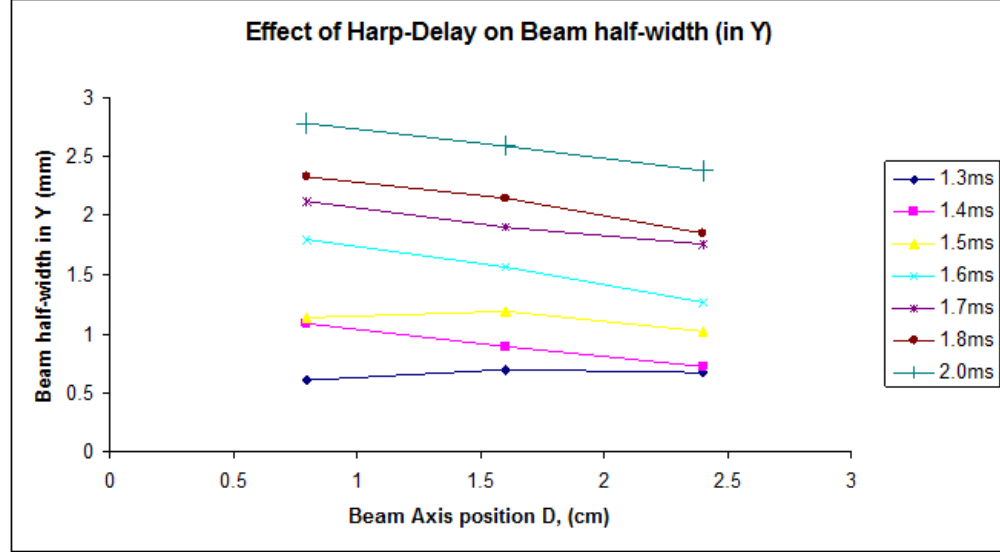


**Figure 5.20:** Effect of harp delay on beam half-widths in y, at three locations of the beam. The width approaches a constant value for delays greater than 2.0 ms. This implies that the front of the beam pulse is narrow and grows transversally in time.

Emittance was also derived using the three harp positions in this investigation, and results are presented in Table 5.8. Note that no error could be estimated for these emittance values, as five or more positions are required to make multiple estimates of emittance, where the average with its standard deviation may be found. Instead, the error here can be estimated as the standard deviation of all the harp-delay measurements, which is  $\pm 7 \pi \text{ mm.mrad}$ .

Delaying the harp on-time as done in these experiments shows a picture of the beam's longitudinal nature, with the shortest and longest delays corresponding to the front and tail of the ion pulse respectively.

An interesting trend is observed in the range of emittance values calculated and shown in Table 5.8; emittance is small for the delay time of 1.3 ms corresponding to smaller beam half-widths. The emittance values then increase as delay time is increased, but then decreases again at the threshold delay time of 2.0 ms. It has already been observed that a delay time of 2.0 ms or more is required to measure the entire size of the pulse, and these delays give maximal current at the cost of beam width. This trend is evident in the x transverse direction, but due to not knowing the uncertainty in emittance, the values are only comparable with the standard deviation of this data set, which is  $\pm 7 \pi \text{ mm.mrad}$ . The 1.4 ms values are outliers likely due to fluctuating LMIS current output. It is more probable that the emittance for a 1.4 ms harp delay is between 5 and 15  $\pi \text{ mm.mrad}$  for both transverse dimensions. Taking more profile measurements at other harp distances should reveal a smaller emittance here and allow for error estimation. Note that the normalized emittance for all these values can be obtained

**Table 5.8:** Investigating emittance for varying harp-delay times

| Harp Delay Time<br>(ms) | $\varepsilon_x$<br>( $\pi$ .mm.mrad) | $\varepsilon_y$<br>( $\pi$ .mm.mrad) |
|-------------------------|--------------------------------------|--------------------------------------|
| 1.3                     | 11                                   | 10                                   |
| 1.4                     | 58                                   | 56                                   |
| 1.5                     | 15                                   | 5                                    |
| 1.6                     | 28                                   | 16                                   |
| 1.7                     | 32                                   | 31                                   |
| 1.8                     | 36                                   | 35                                   |
| 2.0                     | 10                                   | 5                                    |

approximately by multiplying the emittance by  $\sqrt{2kV}$ , which is constant throughout as  $U_{ex} = 2.0$  kV is fixed for this investigation.

Although an exceptional unnormalized emittance was measured for 1.3 ms delay time of  $\varepsilon_x = 11 \pi$ .mm.mrad, and  $\varepsilon_y = 10 \pi$ .mm.mrad, the current measured here only averaged around  $0.4 \mu\text{A}$  which is far below the ESIS injection criterion of  $1.2 \mu\text{A}$ . The small and growing front of the beam is measured at earlier delay times. Both current and half-width increase together over the first 2 ms of delay, after that they plateau until the beam is switched off. The end of the pulse (the beam's tail), can be measured by harp-delay lengths equivalent to the beam on-time, and can be observed as a decrease in both current and beam width. This is shown for beam-width in Figure 5.18, and current in Figure 5.19.

The harp-delay is useful for measuring well defined profiles on the harp - which gives a longitudinal time profile of the beam. However, delaying on the harp should not have any direct bearing on real ESIS injection experiments, and is primarily useful for understanding the ion beam shape evolution in time.

## Chapter 6

# Ion Transport System Tests with Replica ESIS Entry-Port

The design for the entire ion transport system is shown in Figure 6.1. This system was first tested without using the Krion 6T ESIS, and instead, a replica of the ESIS entrance port was constructed and included in the beam-line, with the harp profilometer positioned such that the ion beam entering the ESIS through this port can be measured and analysed. This process ensures the best quality beam, meeting all appropriate parameters and conditions for the best possible ion injection.

### 6.1 Design of Complete Ion Transport System

The full schematic of the injection system coupled with replica ion-optics of the ESIS axial entrance port is shown in Figure 6.1. With reference to the schematic, the following elements have already been discussed:

- **The LMIS assembly**, consisting of LMIS, Extractor plate and Einzel Lenses. Earlier diagnostics were performed by measuring ion current (or better, the lack thereof) on the Einzel lenses,  $I_{ei,1,3,5}$ . Note that there has been an extension to the number of lenses used, and lenses marked 1,3 and 5 are those positively biased to about 60% of the LMIS bias,  $U_{ex}$ , while evenly spaced lenses are on ground.
- **The Quadrupole Switchyard**, with copper foil collimator (with 1cm diameter) aperture for beam diagnostics and current measurement before entry on  $I_{copper\,foil}$ . The switch-yard also includes an entrance Einzel lens with bias  $U_{bend,ei}$ , and the bending electrodes, with potentials  $U_{bend\pm}$ . The straight pass current collector is aligned directly opposite the incoming ion beam and is used for beam transmission diagnostics throughout all experiments.

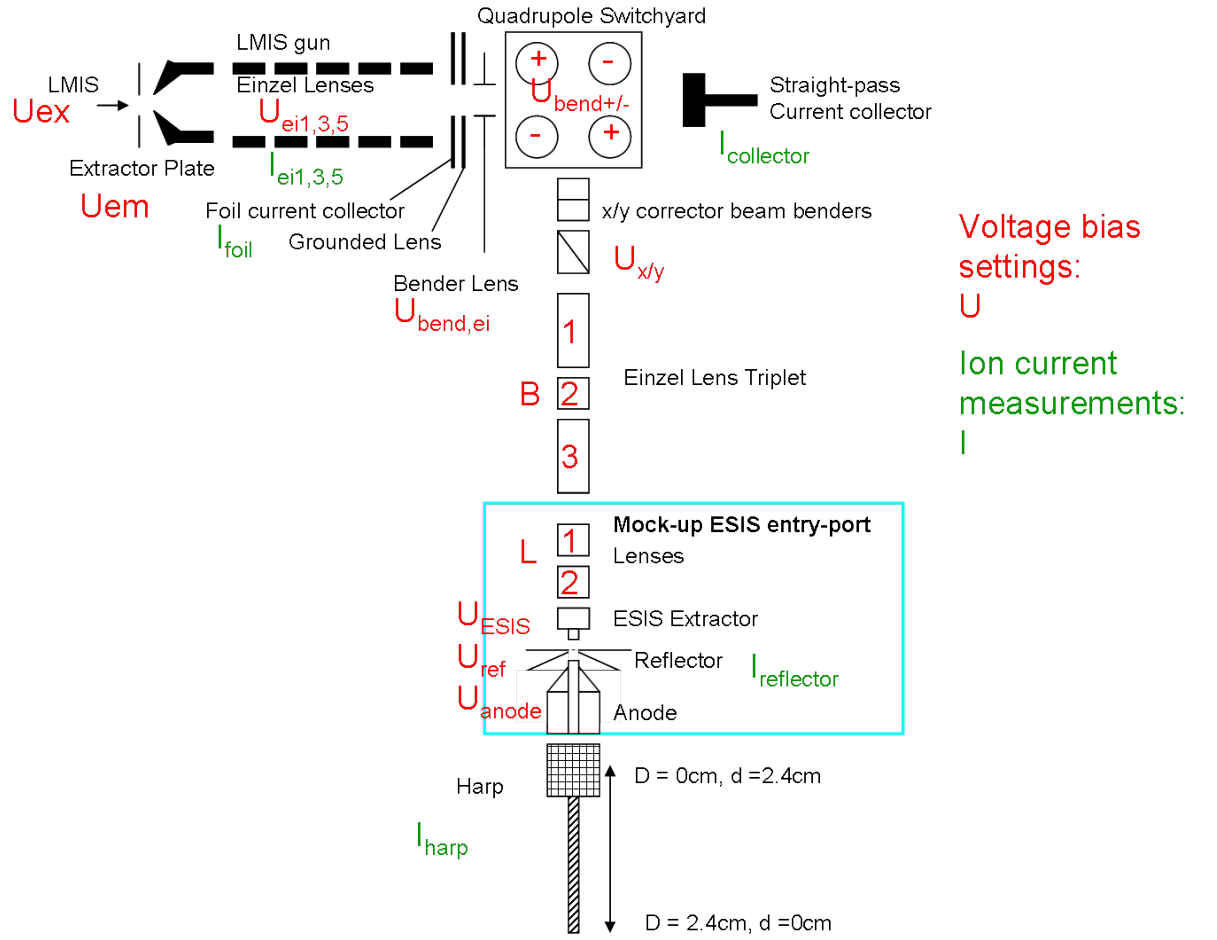


**Figure 6.1:** Complete transport system with replica ESIS entrance port. All ion-optics shown with voltage bias labels,  $U$ , in red, and current collector/ beam diagnostics with labels,  $I$ , in green.

The transport system was extended to incorporate several new elements post bending, in order to ensure the delivery of the ion beam to the ESIS:

- **X/Y correction steerers** were now included to fix the beam shape immediately after bending, in order to reduce dipole aberrations in the beam, and deliver a beam that is well focused in both transverse dimensions. This was achieved by having slightly different biasing on each of the deflectors semi-circular tubes making the corrector benders. The first bender corrects deflections in the vertical (y) direction, and the second corrects horizontal, left/right offset, the potentials given by  $U_{x/y}$ . In the first few experiments with this device, it was also operated as a set of focusing lenses post bending, by having all of the electrodes biased to the same voltage.
- **Einzel Lens Triplet B**, also called the long-lenses for short-hand and to distinguish from the other einzel lenses used. These were necessarily included to focus the beam into the ESIS, and is the final part of the system that is not part of the ESIS (or replica entrance) itself. Early tests also utilized this long-lens system for beam diagnostics and current measurement, as will be explained in the next section.

The ESIS mock-up, or replica entry-port, which is shown in Figure 6.1 in the blue square, was included for the final beam transport optimization tests:

- **Focusing lenses**,  $L_1$  and  $L_2$ , which are essential for the final focusing of the beam into the ESIS. The potential of the second lense,  $U_{L2}$ , was positively biased while  $U_{L1}$  was held at ground for optimal focusing.
- **The ESIS Extractor**. This electrode,  $U_{ESIS}$ , is usually negatively biased during the extraction of ions after charge breeding in the ESIS. During optimization, it was also sometimes negatively biased to improve ion injection into the ESIS.
- **The Electron Reflector** is also an important component in the working ESIS, as this is what allows the electron-string to form. In the first calibration experiments, the potential of the reflector,  $U_{ref}$ , was often biased to the same as that of the extractor,  $U_{ESIS}$ .
- **Anode**. Ions are trapped inside of the ESIS due to the strong axial magnetic field, as well as the electrostatic trap caused by two anodes; one on the electron-gun side of the trap area, and the other on the extraction end which was emulated on the replica. The biassing on this anode,  $U_{anode}$ , is lowered when HCIs are extracted. In the following experiments with the replica entry-port, this element has been left on ground potential.

Ions that have been transported by this system to the ESIS anode and beyond, have definitely been injected into the ESIS at this point. Therefore the harp-profilometer was positioned just beyond the anode, and because of the ability to measure beam profiles for a range of distance values, it can measure the ion beam evolution within the ESIS. The harp positions represent locations already well inside the vicinity of the electron-string.

A photograph of the full setup as discussed above is shown in Figure 6.2.

## 6.2 First ESIS Injection Measurements with Replica Entrance Port

Several step-by-step measurement processes were required to ensure that the ion beam was incident on the harp after successful transport through the system.

Before these processes - which involved using the ion-optical elements such as the corrector lenses (biased  $U_{X/Y}$ ), the long lensed (biased  $U_{B2}$ ), and the ESIS focusing lenses, (biased  $U_L$ ) as beam current diagnostics - rough measurements were made to ensure that ESIS injection would be possible.

The refinement process will be covered in the next subsection where the best beam parameters are obtained for ESIS injection. The following is a summary or highlight of the very first ESIS replica injection results.

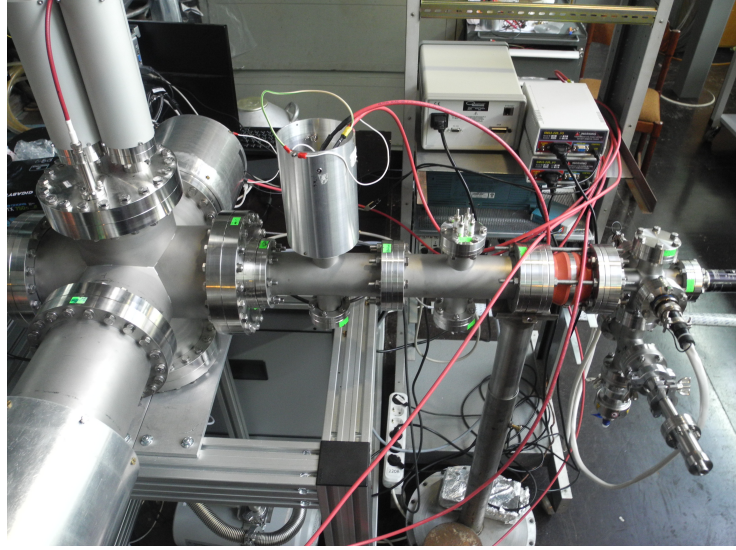


**Figure 6.2:** A photograph taken of the full transport system with injection into the replica ESIS port and harp-profilometer. The LMIS-assembly vacuum chamber is on the bottom left, the switch-yard middle-left, and the final post-bending line into replica ESIS and harp is central, from left to right. Behind this setup one can see HV power supplies and the control and data acquisition system.

### 6.2.1 Experimental parameter settings

In the following investigations, the harp-delay was modified between three trials. These delays were 1.3 and 1.5 ms. Harp delays of less than 2 ms were chosen in this case as these values give cross-sections at the front of the beam pulse in time. As was seen in the last chapter, this also yields lower emittance and smaller beam-widths at the expense of ion current.

The ion current was recorded on the copper collector when it was not being deflected,  $I_{copper}$ . When deflected, this current was measured on the ESIS reflector/extractor combined  $I_{ESIS/ref}$ , and on the harp,  $I_{harp}$ . Using the reflector/extractor current and the measured total harp current as the total amount of deflected current, the transmission efficiency,  $\eta\%$ , of beam into the ESIS can therefore be obtained using:

$$\eta\% = 100 \frac{I_{harp}}{I_{ESIS/ref} + I_{harp}} \quad (6.1)$$

The collector current ( $I_{copper}$ ) was often less than the combined current measured after deflection ( $I_{ESIS/ref} + I_{harp}$ ), implying that the copper collector did not collect all the ion beam current in the straight direction, as higher current was always measured in the deflected direction.

**Table 6.1:** Ion optics biasing and pulse settings for first replica injection tests. Voltages not mentioned here were varied between the trials, and harp delay times for each trial were 1.5 ms, 1.3 ms and 1.5 ms again, respectively for Trials 1, 2 and 3.

| Ion-optics | Bias (kV) | Pulse settings | Time (ms) |
|------------|-----------|----------------|-----------|
| $U_{ex}$   | 2.4       | Period         | 1000      |
| $U_{em}$   | -5.0      | LMIS           | 4.0       |
| $U_{ei}$   | 0.8       | Switch-yard    | 4.0       |

The ion-optics biasing were different for each investigation, those for the most successful of the trials are listed later. Those kept constant throughout are displayed in Table 6.1 alongside the pulse-timing settings used throughout.

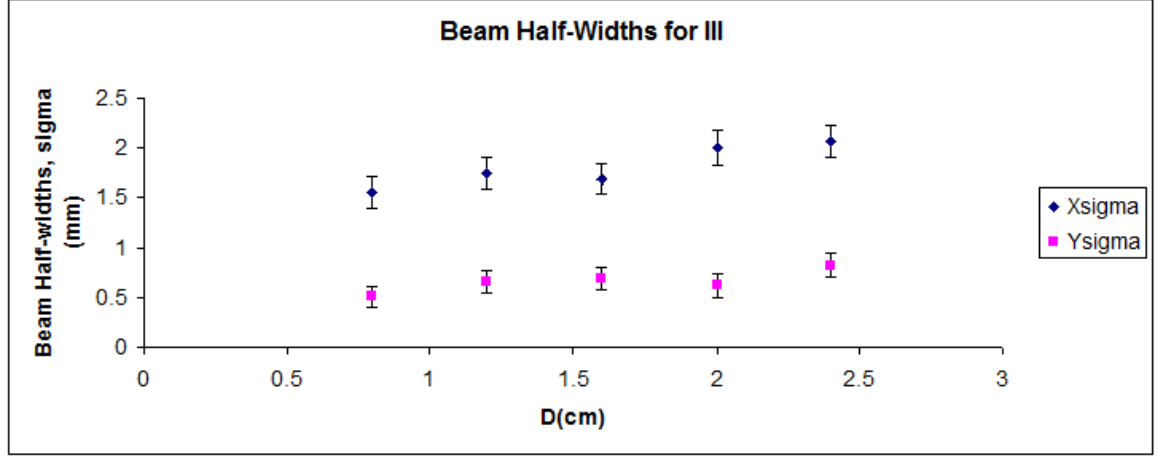


**Figure 6.3:** Beam half-widths calculated from harp profiles, plotted for each harp position. Trial 3.

### First replica injection results

Beams of 2.4 keV  $\text{Ga}^+$  ions were studied over three trials. The ions were transported through the entire system, and focusing into the replica ESIS post bending was achieved by varying the settings on the newly installed ion optics,  $U_{X/Y}$ ,  $U_B$ ,  $U_L$  and  $U_{ref/ESIS}$  shown in Figure 6.1. The switch-yard potentials were also adjusted to obtain the best beam.

Three beam parameters were investigated using the harp-profilometer:

- **Beam half-width**,  $\sigma$ . In Trial 1, only three harp positions were measured. Results were improved in Trials 2 and 3 by using five harp positions.
- **Beam offset**, each beam offset from the principle axis.
- **Current transmission**, the percentage of current arriving at the harp was compared to that arriving at the straight-pass collector. See Table 6.2.

The unnormalized emittance was also calculated for each trial, the results of the best of these three trials is summarized in Table 6.2.

#### 6.2.2 Measurements of beam half-width

The most narrow half-widths are desired for a well focused beam. In Figure 6.3, half-widths obtained by fitting Gaussian curves to the measured harp profiles are plotted for Trial 3 (Trial 1 and 2 showed similar results). The error-bars in these plots are calculated by combining the uncertainties in the measurement: 5% assumed tolerance, scale uncertainty of minimum 0.5 mm - a triangular distribution function is used for

analogue measurement, and finally the root-mean-square error obtained as a goodness-of-fit parameter during Gaussian fitting.

Trial 2 and 3 were better than Trial 1, and the beam width in the y-direction for these trials was small, less than 1.5 mm. However there was still work to be done in narrowing the beam in the x-direction.

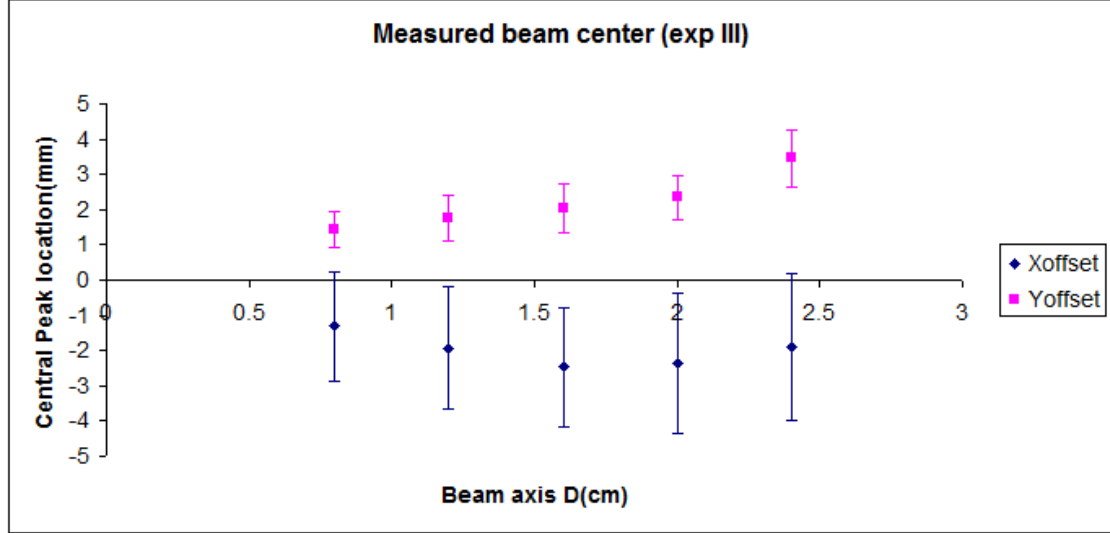


**Figure 6.4:** Beam offset calculated from harp profiles, plotted for each harp position. Trial 3.

### 6.2.3 Measurements of beam axial offset

The beam offset for the third trial is shown in Figure 6.4. The deviation off axis indicates that better focusing and alignment would be required to improve the results. Error-bars here are given by the beam-half widths,  $\sigma$ .

The beams observed in Trials 2 and 3 are parallel, and nearly on axis in the x-direction, within experimental uncertainty, however the y-direction is not parallel and the beam appears to be badly aimed in this direction.

### 6.2.4 Best results

Trials 2 and 3 both led to good results; Trial 2 showed promise in terms of beam focusing on axis and current transmission, while Trial 3 yielded slightly worse x-emittance but better y-emittance values than Trial 2, with narrower profiles and smaller half-widths. The comparison of these results is shown in Table 6.2, and the voltage bias settings that led to these results are shown in Table 6.3.

Note that the ion current incident on the ESIS extractor and reflector were also recorded as this beam is almost incident on the harp, but unfortunately is not focused into the ESIS anode aperture which is 3 mm in diameter.

An important diagnostic is the measurement of current at the reflector/anode of the ESIS replica. The biasing on all of the newly installed elements were adjusted to maximize the current measured here first, before maximizing the current measured by the harp.

**Table 6.2:** Comparison of results between initial ion-injection test Trials 2 and 3.

|                                                         | Trial 2 | Trial 3 |
|---------------------------------------------------------|---------|---------|
| Harp Delay (ms)                                         | 1.3     | 1.5     |
| $I_{harp,max}$ ( $\mu\text{A}$ )                        | 0.43    | 0.38    |
| $I_{collector}$ ( $\mu\text{A}$ )                       | 0.5     | 0.5     |
| $I_{ref/ESIS}$ ( $\mu\text{A}$ )                        | 1.3     | 1.2     |
| $\eta\%$                                                | 23.5    | 24.0    |
| $\varepsilon_x$ ( $\pi.\text{mm.mrad}$ )                | 10      | 30      |
| stdev in x ( $\pi.\text{mm.mrad}$ )                     | 5       | 15      |
| $\varepsilon_y$ ( $\pi.\text{mm.mrad}$ )                | 35      | 30      |
| stdev in y ( $\pi.\text{mm.mrad}$ )                     | 20      | 20      |
| $\varepsilon_{N,x}$ ( $\pi.\text{mm.mrad}.\sqrt{MeV}$ ) | 0.5     | 1.5     |
| $\varepsilon_{N,y}$ ( $\pi.\text{mm.mrad}.\sqrt{MeV}$ ) | 1.7     | 1.5     |

**Table 6.3:** Ion-optics biasing for Trials 2 and 3.

| Ion-optics bias     | Trial 2 | Trial 3 |
|---------------------|---------|---------|
| $U_{bend,+}$ (kV)   | 1.09    | 1.10    |
| $U_{bend,-}$ (kV)   | 1.05    | 1.10    |
| $U_{bend,ei}$ (kV)  | 0.39    | 0.42    |
| $U_{X/Y}$ (kV)      | 0.10    | 0.95    |
| $U_B$ (kV)          | -3.0    | -2.9    |
| $U_{L2}$ (kV)       | 0.77    | 0.72    |
| $U_{ref/ESIS}$ (kV) | -7.0    | -4.6    |

In these tests, the X/Y corrector was not used as a corrector, but rather as a single focusing lens, which is very useful for focusing after the ion beam is bent by the switch-yard.

The settings listed in Table 6.3 provided a starting point for more exact measurements whereupon the transmission of beam into the replica ESIS was improved, in addition to the other beam parameters<sup>1</sup>. The following section details the process of refining these voltage bias settings and show-cases several excellent beams that can be used for over-barrier injection into the ESIS.

### 6.3 Refined ESIS Injection Measurements with Replica Entrance Port

The previous test-trials, with results summarized in Table 6.2, showed that ESIS injection was possible. However, beam transmission was very poor between the straight-pass collector and the harp, as the recently added ion-optical elements had only a few calibrations based on simulations in SIMION.

A method using each of these ion-optical elements as Faraday-cup/current-collectors was employed to improve the beam focus into the ESIS considerably. This process will be discussed briefly.

#### 6.3.1 Refining beam alignment and focusing onto the harp

Each ion-optical element between the quadrupole switch-yard and the replica ESIS port were utilized as current collectors to ensure that maximal beam is transported.

Starting with the beam-line element closest to the switch-yard, current was measured for different settings until those yielding maximum current were obtained. This was the same approach that was used to ensure that the maximum beam current was being transported from the LMIS into the switch-yard in the first leg of the ion journey.

For example, a plot is shown in Figure 6.5 showing this process for optimizing the X/Y corrector,  $U_{X/Y}$  and also finding a range of settings for  $U_{bend,+/-}$  where measured current on the long lens B2,  $I_{B2}$ , is largest.

These maximal settings were then kept constant and used as the next diagnostic lens, L2, was employed as a charge-collector in a similar way. Following L2, the ESIS reflector and anode were used, and finally the harp.

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<sup>1</sup>The positive and negative quadrupole bias do not have to be identical for deflection by 90° to occur, and often high current was measured when there was an offset. For convenience however, symmetrical biassing was preferred, as in the case of Trial 3.

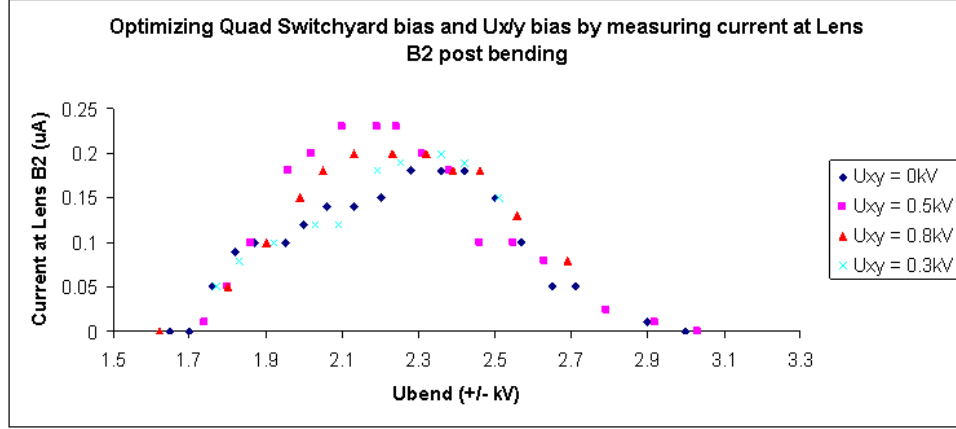


**Figure 6.5:** Example plot of beam refinement process. Here Lens B2 is used as a current collector to find maximal current at different switch-yard and x/y corrector biasing. The switch-yard provides most current transmission with value  $\pm 1.8$  kV and  $\pm 2.4$  kV. Larger  $U_{X/Y}$  values focused more beam onto B2, and will be set at values around 1.8 kV after several calibrations.

### 6.3.2 Refined Beam Measurements

After this refinement process, results from 5 replica-ESIS injection experiments with slightly different biasing and pulse settings are presented. In each measurement, the harp-profilometer was positioned at six different positions,  $D$ , on the bent-beam axis: 4, 8, 12, 16, 20 and 24 mm. Each experiment was the average of three trials, i.e. three sets of measurements were taken, adjusting the harp from 4 to 24 mm, then back again, and then forward again. This served to reduce random error, one of which was the unstable, fluctuating ion current output from the LMIS. For the purposes of ion injection into the ESIS, narrow beams  $< 3$  mm in diameter with current around  $1.2 \mu\text{A}$  in the transmitted, central part of the beam, are required. For the purpose of ion reflection experiments, which is discussed in the next section, wider and divergent beams give rise to better reflection, and were preferred. The MATLAB code, HIBA.m, was used to extract beam half widths, estimated (fitted) amplitudes and offsets via fitting Gaussian curves to the measured harp profiles.

Another MATLAB code was used to visualize each beam in two ways: 1) Overall side view of the beam by aligning profile colour-maps, and 2) cross section slices containing current density information at each measured distance.

### 6.3.3 Replica ESIS Injection Results

Five investigations of beam profiles were performed using the aforementioned method. The beam energy was kept constant for each at 2.5 keV. In each case, there were only slight variations between ion-optic biasing and pulse-timing settings. All five of

**Table 6.4:** Ion-optics biasing for best replica ESIS injection results. All values listed are in kV.

| Ion-optics bias               | Symbol        | Trial 1 | Trial 2 | Trial 3 | Trial 4 | Trial 5 |
|-------------------------------|---------------|---------|---------|---------|---------|---------|
| Ion Extraction Energy         | $U_{ex}$      | 2.5     | 2.5     | 2.5     | 2.5     | 2.5     |
| Extraction Plate              | $U_{em}$      | -5.0    | -5.4    | -6.0    | -6.5    | -5.4    |
| LMIS-assembly einzel Lenses   | $U_{ei}$      | 1.25    | 1.25    | 1.25    | 1.25    | 1.25    |
| Positive Switch-yard bias     | $U_{bend,+}$  | 2.11    | 2.38    | 1.38    | 2.32    | 2.34    |
| Negative Switch-yard bias     | $U_{bend,-}$  | -1.22   | -1.71   | -1.71   | -1.58   | -2.20   |
| Switch-yard einzel Lens       | $U_{bend,ei}$ | 0.0     | 0.0     | 0.0     | 0.0     | 0.0     |
| Positive Horizontal Corrector | $U_{x,+}$     | 1.79    | 1.79    | 1.79    | 1.79    | 1.79    |
| Negative Horizontal Corrector | $U_{x,-}$     | 1.79    | 1.80    | 1.80    | 1.80    | 1.80    |
| Positive Vertical Corrector   | $U_{y,+}$     | 1.80    | 1.80    | 1.80    | 1.80    | 1.80    |
| Negative Vertical Corrector   | $U_{y,-}$     | 1.80    | 1.80    | 1.80    | 1.80    | 1.80    |
| Long Lens (negatively biased) | $U_{B2}$      | 0.0     | 0.0     | 0.0     | -2.0    | -4.0    |
| ESIS focusing Lens            | $U_{L2}$      | 1.66    | 1.66    | 1.66    | 1.66    | 1.66    |
| ESIS Extractor and Reflector  | $U_{ex/ref}$  | 0.0     | 0.0     | 0.0     | 0.0     | 0.0     |
| ESIS Extractor                | $U_{ESIS/ex}$ | 0.0     | 0.0     | 0.0     | 0.0     | 0.0     |
| ESIS Reflector                | $U_{ref}$     | 0.0     | 0.0     | 0.0     | 0.0     | 0.0     |

these results gave excellent profiles by eye - all narrow with high current density at least within 1.5mm half-width, and also excellent beam current transmission, such that measured  $I_{harp}$  and  $I_{collector}$  current values were similar, which indicates the total beam passing through the un-powered switch-yard in the straight direction is almost completely transported to the harp, which is over 1m away in the bent direction.

The beam-profiling analysis method and software has yet to be implemented for on-line use during beam measurements, so the sets of data obtained were analysed after the experiments were performed.

### Experimental Parameters

The ion-optics biasing settings for each of the five investigations are listed in Table 6.4, while the pulse-timing settings are shown in Table 6.5.

The main differences between the five trials for best injection are the extraction plate biasing,  $U_{em}$ , which increases beam current with increased negative bias, the positive and negative switch-yard potentials,  $U_{bend,+}$  and  $U_{bend,-}$ , which can differ significantly, but still deliver a focused beam on a variety of settings. Trial 4 and 5 also investigated the effect of large negative bias on the long-lens,  $U_{B2}$ .

The other voltage biasing have remained constant, as they were the previously determined optimum values for beam transport, and were configured to focus the 2.5 keV beam through the system. The positive and negative X and Y correctors,  $U_{X/Y}$ , func-

**Table 6.5:** Pulse-mode settings for ion injection into replica ESIS. All values are in milliseconds. Harp integration time was 500  $\mu$ s for Trials 1-4, and 800  $\mu$ s for Trial 5.

| Timing Settings   | Trial 1 | Trial 2 | Trial 3 | Trial 4 | Trial 5 |
|-------------------|---------|---------|---------|---------|---------|
| Cycle Period      | 800     | 800     | 800     | 800     | 800     |
| Trigger Pulse     | 8       | 8       | 8       | 8       | 8       |
| LMIS pulse        | 8       | 8       | 8       | 8       | 8       |
| LMIS delay        | 0       | 0       | 0       | 0       | 0       |
| Switch-yard pulse | 4.0     | 4.0     | 4.0     | 3.5     | 4.0     |
| Switch-yard delay | 2.0     | 2.0     | 3.5     | 0.0     | 2.0     |
| Harp pulse        | 8       | 8       | 8       | 8       | 8       |
| Harp delay        | 2.5     | 2.5     | 2.5     | 2.5     | 2.5     |

tion primarily as einzel lenses as they were all biased to the same potential, however a slight deviation in  $U_{X,+}$  has been shown to provide a good correction to previously seen horizontal off-sets. Similarly to the LMIS-assembly einzel Lenses,  $U_{ei}$ , being constant and at such a value to deliver the full beam into the switch-yard with no current deposited on the prior copper foil,  $I_{copper}$ , the ESIS focusing lens,  $U_{L2}$ , is set to 1.66 kV which was shown to achieve the best possible focusing and beam current to the harp.

The replica ESIS entrance extractor, reflector and anode were all unpowered during this investigation. In real injection experiments, a positive barrier potential should be present for the electrostatic trap during over-barrier injection. Therefore these results represent direct injection into the ESIS with no barrier present - which would serve to focus the positive beam onto the electron string. Additionally the ions entering the ESIS will also experience the negative potential of the electron-string which should cause additional focusing of the beam as it enters the electrostatic trap. Thus, the results obtained from the harp profiles, which were measured within the trap area of the replica ESIS, could be assumed to be improved upon in the presence of the electron-string and barrier potential.

The pulse-timing settings shown in Table 6.5 are chosen for maximal current in the measured profiles. It had already been observed that low harp-delay gives profile measurements of the narrow part of the beam at expense of current, so a value of 2.5 ms was chosen for this, which is in the plateau of maximal expected current shown previously in Chapter 5. In most trials, a time window was used when the switch-yard was powered on, hence the 4.0 ms pulses with a 2.0 ms delay, which allowed for forward current to be measured by the straight collector in the first and last 2 ms of the LMIS pulse, while the ion beam was deflected 90° by the switch-yard in a window between 2.0 and 6.0 ms of the total 8.0 ms trigger pulse. These choices for switch-yard pulsing and delay were useful to obtain and compare current measurements, but they had no bearing on the results obtained.

### Replica Injection Results: Raw Profile Data

The beam profiles of each experimental trial were measured, and this data was analysed to obtain further beam parameters. A raw plot of each profile taken at each harp position,  $D$ , was obtained before any further data analysis and these plots reveals the beam behaviour - whether it was converging or diverging - as the beam profiles evolve through six measurement positions.

Each trial was repeated three times, obtaining three profiles of the beam for a specific harp location, and these three profiles were summed. The form of this final profile is a better average for the ion beam over time. Such data is presented in the graphs in Figures 6.6 to 6.10.

**Figure 6.6:** Summed beam profiles for Trial 1.

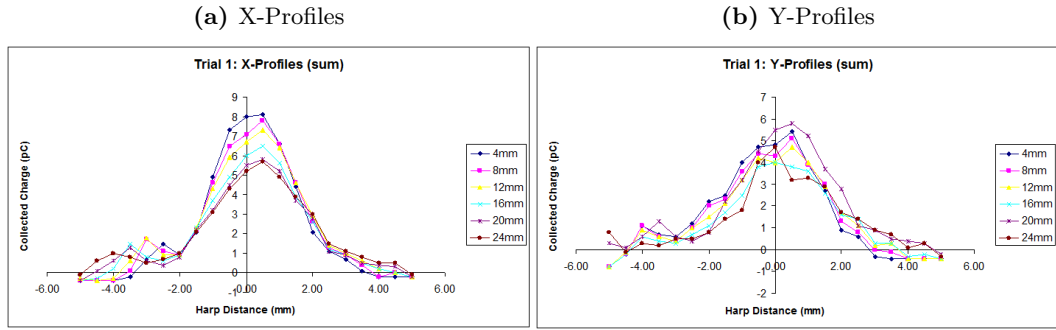
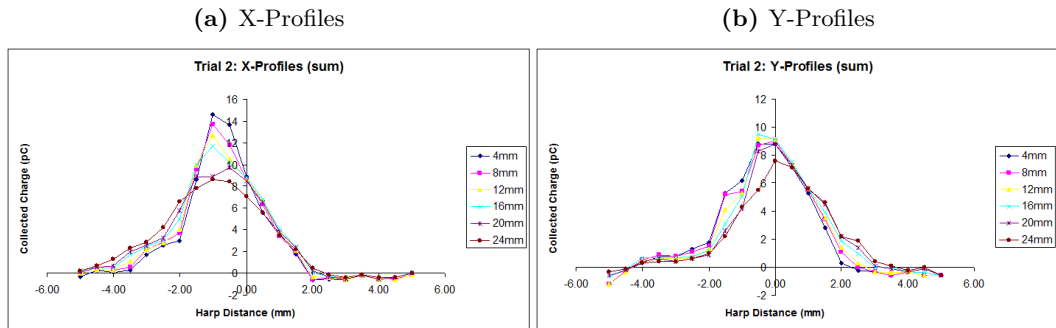


**Figure 6.7:** Summed beam profiles for Trial 2.



### Replica Injection Results: $\text{Ga}^+$ Current

The ion current measured by the harp was recorded with each profile at each of the six measurement locations, with  $D = 4$  mm being closest to the harp. In each trial, more than  $1.2 \mu\text{A}$  was measured for each harp position. In Trial 3, the potential difference

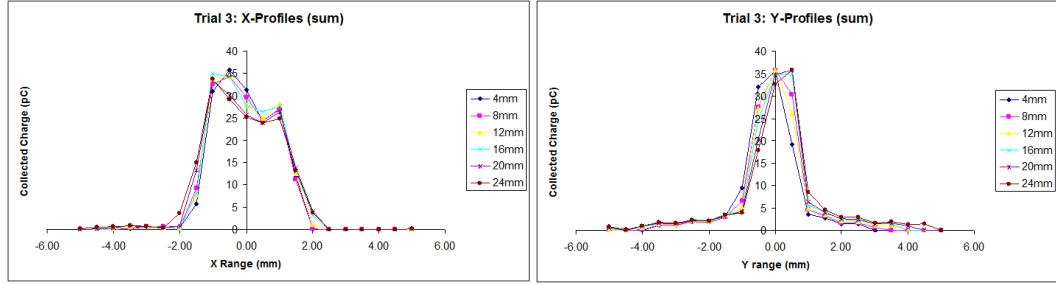
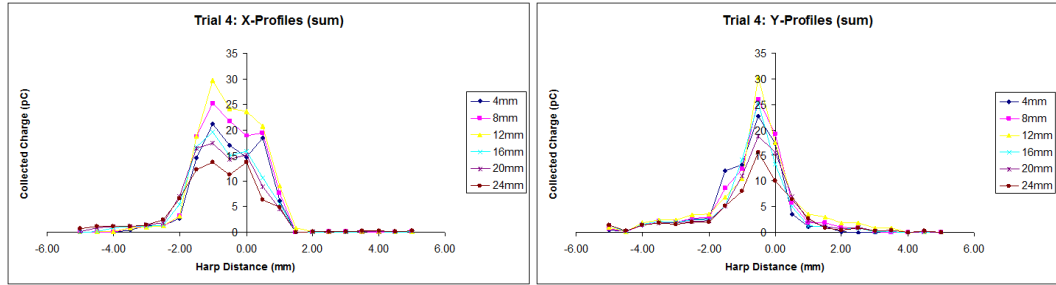
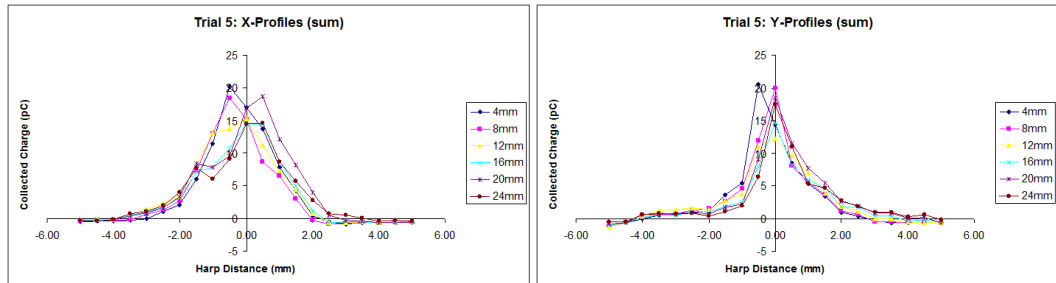
**Figure 6.8:** Summed beam profiles for Trial 3.**(a)** X-Profiles**(b)** Y-Profiles**Figure 6.9:** Summed beam profiles for Trial 4.**(a)** X-Profiles**(b)** Y-Profiles**Figure 6.10:** Summed beam profiles for Trial 5.**(a)** X-Profiles**(b)** Y-Profiles

**Table 6.6:** Beam transmission between quadrupole switch-yard and harp profilometer. Harp current at closest position ( $D = 0.4$  cm) is compared to straight collector current while switch-yard is un-powered.

| Current Measured                           | Trial 1 | Trial 2 | Trial 3 | Trial 4 | Trial 5 |
|--------------------------------------------|---------|---------|---------|---------|---------|
| $I_{collector}$ ( $\mu\text{A}$ )          | 1.8     | 2.2     | 3.4     | 2.3     | 1.9     |
| $I_{copper}$ ( $\mu\text{A}$ )             | 0       | 0       | 0       | 0       | 0       |
| $I_{ref/ex}$ ( $\mu\text{A}$ )             | 0.8     | 0.5     | 0.4     | 0.4     | 0.6     |
| $I_{harp}$ ( $D = 4$ cm) ( $\mu\text{A}$ ) | 1.36    | 1.31    | 3.16    | 1.69    | 1.36    |
| Transmission Efficiency                    |         |         |         |         |         |
| $\eta$ (%)                                 | 76      | 60      | 93      | 73      | 72      |

between LMIS and extractor plate was largest and therefore the most ion current of  $3 \mu\text{A}$  was produced and measured. However the harp profiles for this result became over-saturated due to data acquisition current resolution.

The measured current at each of the six harp positions fluctuated only slightly with respect to the average current measured. Variation possibly caused by slightly erratic current out-put from the LMIS was evident, and very little sign of increasing or decreasing current was observed for each trial. This implies that the full beam current was measured beyond the replica ESIS entrance.

Beam current transmission is also calculated by comparing that measured at the harp,  $I_{harp}$ , and ESIS reflector/extractor,  $I_{ref/ex}$ , which is the current that was transported through the full system to the ESIS, with current measured at the copper-foil,  $I_{copper}$ , and in the straight direction without bending,  $I_{collector}$ . These results are shown in Table 6.6. The transmission is calculated by assuming the full current produced by LMIS and entering into the switch-yard is given by  $I_{collector}$ , and by determining the fraction of which became the harp measured current,  $I_{harp}$ .

Table 6.6 shows that Trial 3, although due to over saturated profiles, has the highest transmission with 93%, and Trials, 1, 4 and 5 are all above 70%. 2.5 keV beams also proved to be most efficient at ion transport which was also seen in Section 5.4 (Table 5.6). It is important to note that should the transmission to both the harp and reflector/extractor be calculated, the transmission would be greater than 100%. This implies that all of the current is transmitted to the ESIS replica, however there must have been some current that was not measured by the straight collector as this should represent the total current. This is most likely due to the finite dimensions of the straight collector and that some current was not measured, but lost, in the straight direction when the quadrupole switch-yard is un-powered. One can also note that all of the current produced by the LMIS is entering the switch-yard due to the well calibrated LMIS-assembly system which gives  $I_{copper} = 0 \mu\text{A}$  in all cases.

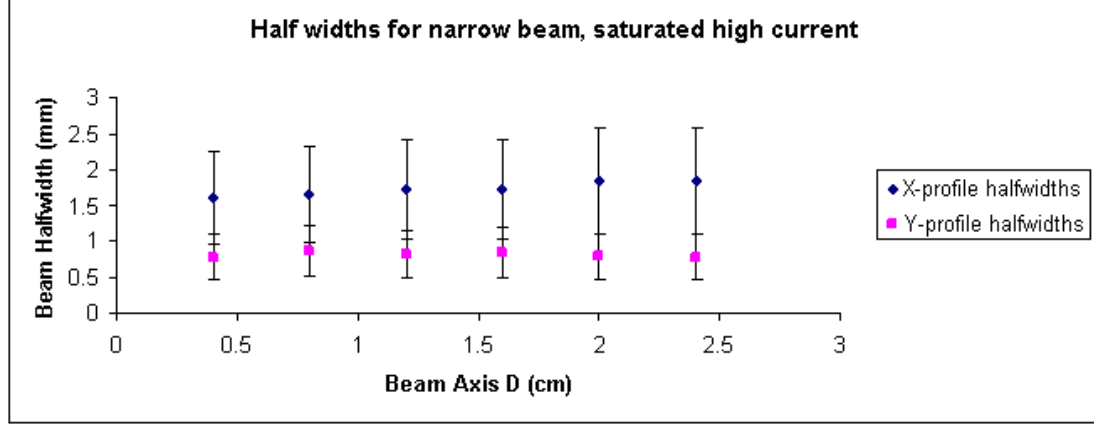


**Figure 6.11:** Beam half-widths determined by HIBA.m for each of 6 profiles measured at different positions for Trial 3. Trial 3 showed the smallest half-widths, but this is likely due to current over-saturation of the harp data acquisition system. The error-bars are given by 40% of the half-width value, due to better statistics obtained from 3 repeated profile measurements per harp distance  $D$ .

### Replica Injection Results: Beam Widths

Beam half-widths were measured via HIBA.m and the Gaussian fitted profiles. The narrowest beam-widths are most desired for maximum ion capture by the electron-string upon injection. The lowest half-widths in both the x and y transverse beam dimensions were found in Trial 3, in which over-saturation of the harp occurred. This was shown to be around 0.7 mm for the y-profile half-widths, but over 1.5 mm in x. See Figure 6.11.

Trial 5 proved to have the smallest half-widths, without the over saturation which occurred in Trial 3. The results from Trial 5 show that these settings are possibly the best for real ESIS injection. The half-widths measured for Trial 5 are shown in Figure 6.12.

Figure 6.12 shows the best half-widths measured for stable current. Once again, the y-profiles were narrow when compared to the x-profiles. The half widths in y, or  $\sigma_y$ , were centred around 0.8 mm, while  $\sigma_x$  were larger than  $\sigma_y$ , but near to or less than the commonly measured 1.5 mm.

### Replica Injection Results: Axial Offset

A negligible axial offset is very important for ESIS injection. The offset measured should be consistently less than 0.5 mm for each harp position during beam-profiling. Ideally, the offset should be zero, or very close to zero for ion beam interaction with the electron string. If the offset is too high, then the magnetic field of the ESIS will

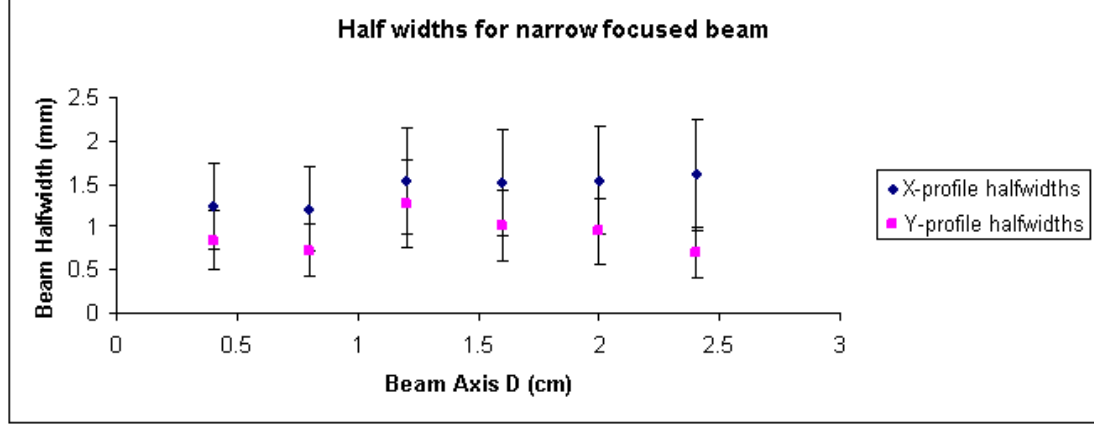


**Figure 6.12:** Beam half-widths determined by HIBA.m for each of 6 profiles measured at different positions for Trial 5. Trial 5 showed small half-widths in both transverse directions. Trial 5 beam parameters should be chosen for real ESIS injection experiments. The error-bars are given by 40% of the half-width value, due to better statistics obtained from 3 repeated profile measurements per harp distance  $D$ .

cause wider radii of ion orbits and this will reduce the chance of ions encountering the electron string as they pass into the ion-trap area of the ESIS.

Another important aspect of axial offset, is consistency. In other words, is the beam parallel with the principle axis even if it is offset? And if so, by how much does the beam deviate from the ideal trajectory? One can assume that should the beam not be parallel, but still focused onto the electron string at some point on the trajectory, there will still be possible electron interactions with the ions, in which electron stripping and hence charge-breeding can occur.

Figure 6.13 shows the offset plotted against each harp location for Trial 1. The error bars in the graph are given by the beam-half widths  $\sigma$ . The error bars all cross the offset = 0 mm axis, which is a positive result, indicating that the beam is well centred within experimental uncertainty. All five of the trials yielded results similar to those shown in Figure 6.13, however some proved to be better aligned than others.

A comparison was made between the trials by analysing the average offsets and the gradient of the measured offset from the centre of the beam from each of the six profile measurements. The standard deviation around the average offset should be small to indicate a very parallel beam in addition to the gradient being equal or close to zero. The average offset value should also be close to zero or actually zero for a well-centered beam. The results from this analysis are shown in Tables 6.7 and 6.8.

The results shown in Tables 6.7 and 6.8 were then used to ascertain which of the five trials gave the most centred and parallel beams for ESIS injection, and by comparing the X-offsets and Y-offsets of each, the following points were determined about each

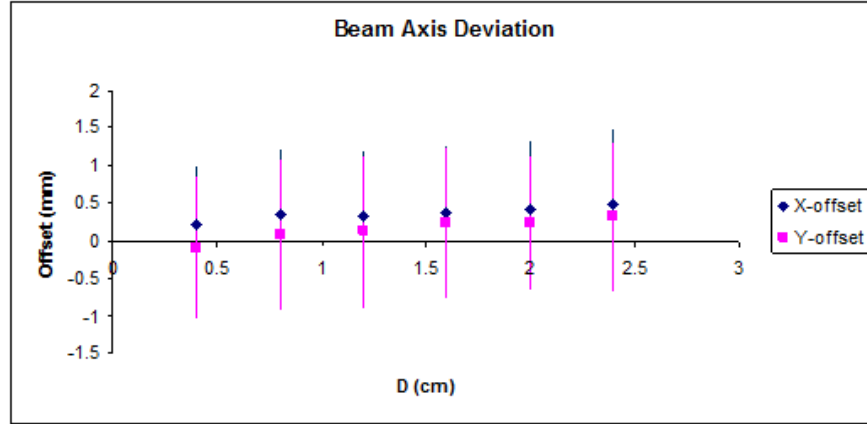


**Figure 6.13:** The axial offset for the beam measured in Trial 1 is shown. The errors come from the beam half-widths,  $\sigma$ . The beam can be considered to be well centred and parallel to the principle axis within the bounds of experimental uncertainty.

**Table 6.7:** Analysis of beam offsets in X-transverse direction for five trials

|                     | Trial 1 | Trial 2 | Trial 3 | Trial 4 | Trial 5 |
|---------------------|---------|---------|---------|---------|---------|
| Average Offset (mm) | 0.361   | -0.764  | -0.171  | -0.618  | -0.085  |
| Error (mm)          | 0.095   | 0.066   | 0.028   | 0.123   | 0.253   |
| Gradient            | 0.012   | -0.006  | -0.003  | -0.015  | 0.028   |
| Intercept (mm)      | 0.196   | -0.679  | -0.125  | -0.413  | -0.471  |

**Table 6.8:** Analysis of beam offsets in Y-transverse direction for five trials

|                     | Trial 1 | Trial 2 | Trial 3 | Trial 4 | Trial 5 |
|---------------------|---------|---------|---------|---------|---------|
| Average Offset (mm) | 0.155   | -0.007  | 0.063   | -0.451  | 0.009   |
| Error (mm)          | 0.146   | 0.171   | 0.138   | 0.059   | 0.165   |
| Gradient            | 0.019   | 0.022   | 0.018   | 0.004   | 0.019   |
| Intercept (mm)      | -0.106  | -0.316  | -0.181  | -0.508  | -0.261  |

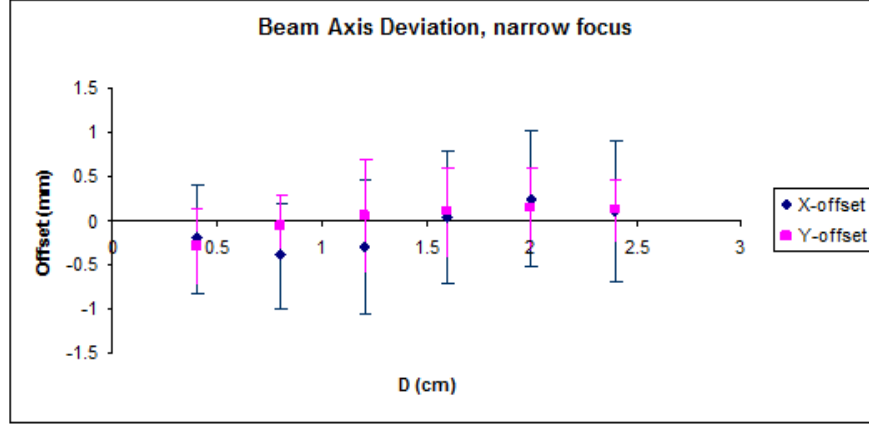


**Figure 6.14:** The axial offset for the beam measured in Trial 5 is shown. The errors come from the beam half-widths,  $\sigma$ . This beam displayed the least overall offset, and although it was not parallel with the principle axis, excellent beam parameters were obtained.

trial:

- Trial 3 had the least amount of offset. The results were from over-saturated profiles however, and too much ion current from the LMIS was being used limiting the lifetime of the ion source.
- Trial 1 was a balanced beam in both transverse directions, consistently well centered (see Figure 6.13).
- Trial 2 had close to zero y-offset, but a very large x-offset.
- Trial 5 had the least average offset, though larger errors than Trial 3. It had the most divergence in the horizontal direction. This was the best trial; only  $2.5 \mu\text{A}$  was produced when compared to the  $3.5 \mu\text{A}$  used in Trial 3 (Table 6.6).

### Replica Injection Results: Transverse Emittance

Transverse emittance was calculated for each of the five trials. The method outlined in Chapter 5 was used, using Equations 5.4 to 5.7, and by using multiple values of the measured half-widths for each calculation, six transverse emittance values were calculated for each transverse direction in each trial. This was made possible by having more harp-profilometer locations,  $D$ , to work with when only three are needed to calculate one value of emittance, six different positions allow for six emittance determinations. The average and standard deviation from these calculations are reported in Table 6.9.

It is clear from Table 6.9, that the measured transverse emittance was lowest in Trial 4, making the settings in Trial 4 the best going forward. The ESIS electron-string is about  $60 \pi \cdot \text{mm} \cdot \text{mrad}$  for 2.5 keV ions (calculated with Equation 2.9) for an electron

**Table 6.9:** 90 % Transverse emittance results for replica ESIS injection Trials 1 to 5.

|                                                      | Trial 1 | Trial 2 | Trial 3 | Trial 4 | Trial 5 |
|------------------------------------------------------|---------|---------|---------|---------|---------|
| $\varepsilon_x$ ( $\pi$ .mm.mrad)                    | 20      | 15      | 20      | 15      | 20      |
| stdev in x ( $\pi$ .mm.mrad)                         | 10      | 10      | 10      | 10      | 10      |
| $\varepsilon_y$ ( $\pi$ .mm.mrad)                    | 30      | 15      | 5       | 5       | 5       |
| stdev in y ( $\pi$ .mm.mrad)                         | 15      | 10      | 5       | 5       | 5       |
| $\varepsilon_{N,x}$ ( $\pi$ .mm.mrad. $\sqrt{MeV}$ ) | 1       | 0.8     | 1       | 0.8     | 1       |
| $\varepsilon_{N,y}$ ( $\pi$ .mm.mrad. $\sqrt{MeV}$ ) | 0.8     | 0.5     | 0.3     | 0.3     | 0.3     |

current density of 620 A/cm<sup>2</sup> and B = 5 T. The emittance of each trial was lower than this acceptance, meaning all the results in Table 6.9 correspond with successful injection into the electron string.

The results from Trial 4 imply  $10^{15}$  ions have been injected into the ESIS. By taking the injected current and dividing by the pulse time, 1.7  $\mu$ A / 8 ms, the injected charge is obtained, which when divided by  $q = 1.6 \times 10^{-19}$  gives the number of singly charged ions successfully injected. The number of injected ions will be lower for smaller pulse-lengths which are more practical for specific accelerator duty-cycles.

Improvement in beam focusing was also required in the x-transverse direction, as parameters were measured to be consistently larger than those in the y-transverse direction.

### 6.3.4 Beam Visualization

#### Beam side-view

The six beam profiles measured for a particular beam at each of 6 harp positions were plotted next to one another in a colour density map to visualize the side-view of the beam, these graphs are shown in Figures 6.15 and 6.16.

#### Beam current density evolution

Density maps from the beam profile measurements of Trial 5 are shown in Figure 6.17.

The MATLAB code uses the beam half-widths and beam offsets to plot an estimated ellipse containing 68% of the ion current at a given harp distance,  $D$ . This ellipse is plotted in green. The outside of the beam (envelope) is estimated where the Gaussian-fit goes to zero, widths and axial offsets are obtained, and a yellow ellipse is plotted which should contain the remaining 32% of the beam. A 3 mm diameter red circle is also plotted as the target drift tube cross section of the ESIS in order to see how centralized and focused the beam was. These three ellipses are plotted on top of a colour-map density plot which is obtained by multiplying, element-by-element, the measured X

and Y profiles, and then normalizing this 2-D distribution to the overall harp current measured. The green, 68% ellipse will always contain the brightest part of these density maps.

Ion beams can thus be compared with each other by eye using these various plots, and one could make a better guess to ascertain which the best candidate beams for ESIS injection would be, before looking at numerical results of the beam parameters.

### 6.3.5 Discussion: Best ESIS Injection Results

The outcome of Trial 4 in this investigation yielded the most promising and practical results for ESIS injection. The transverse emittance values corresponding to 1.6 keV beam energy were  $\varepsilon_x = 15 \pm 10 \pi.\text{mm.mrad}$  and  $\varepsilon_y = 5 \pm 5 \pi.\text{mm.mrad}$ , and both are equivalent to the electron-string acceptance of  $10 \pi.\text{mm.mrad}$ , within the experimental uncertainty. In Trial 5 the beam was found to be less divergent and more parallel, and to be mostly contained in the 3 mm diameter ESIS entrance, when comparing the green and red ellipses in Figure 6.17.

The very saturated results from Trial 3 were still useful and perhaps higher currents might be possible when the lifetime of the LMIS is not an issue, as high current output greater than  $3 \mu\text{A}$  is not recommended with the AP-Tech LMIS. Higher currents can be achieved by ramping the potential on the extraction plate,  $U_{em}$ .

The settings for Trial 5 differed from the other trials primarily because the long lens,  $U_{B2}$ , was biased to -4.0 kV when the others had a smaller magnitude or zero biasing here. Trial 4 yielded poor results although it was also biased with  $U_{B2} = -2.0 \text{ kV}$ . The better focusing and cleaner beam may also be due to the more symmetric choice of switch-yard,  $U_{bend}$ , potentials. In Trial 5,  $U_{bend,+} = 2.34 \text{ kV}$  and  $U_{bend,-} = -2.20 \text{ kV}$ , while in Trial 4,  $U_{bend,+} = 2.32 \text{ kV}$  and  $U_{bend,-} = -1.58 \text{ kV}$ , which were similar settings to the other trials (See Table 6.4).

## 6.4 Conclusions of Replica ESIS Experiments

Singly charged ion injection from LMIS to the ESIS entry-port on a replica system was successful using  $\text{Ga}^+$  ions. Profiles were measured using the harp placed after this entrance aperture of 3 mm diameter, implying that most of the injected beam will enter the ESIS. In terms of current efficiency, it appears 100% of the ion beam was bent by the switch-yard with these settings. In this case,  $2.1 \mu\text{A}$  ion current is produced by the LMIS of which  $1.9 \mu\text{A}$  or 90% is measured by the harp. Transverse emittance has been calculated for the optimized settings for the 1.6 keV beam:

$$\varepsilon_x = 15 \pm 10 \pi.\text{mm.mrad} \text{ and } \varepsilon_y = 5 \pm 5 \pi.\text{mm.mrad}$$

**Figure 6.15:** Side-view obtained from colour-mapping the beam profiles as current density measured by the harp at six locations. Trials 1, 2 and 3.

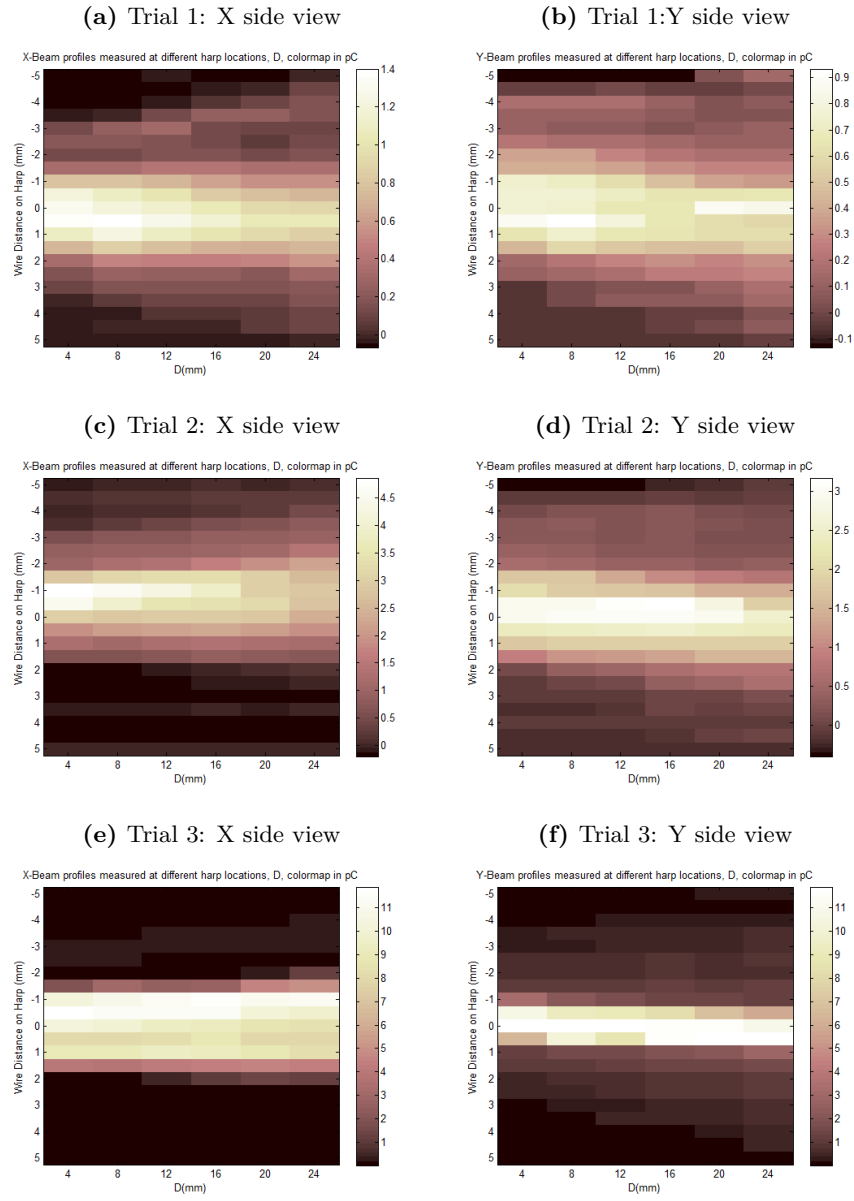


**Figure 6.16:** Side-view obtained from colour-mapping the beam profiles as current density measured by the harp at six locations. Trials 4 and 5.

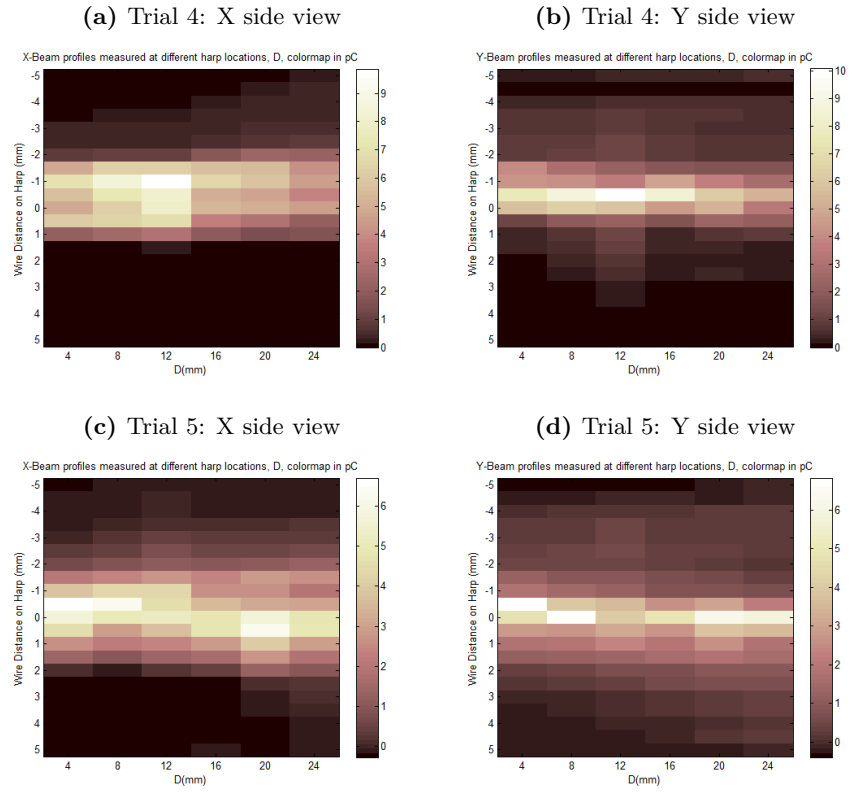
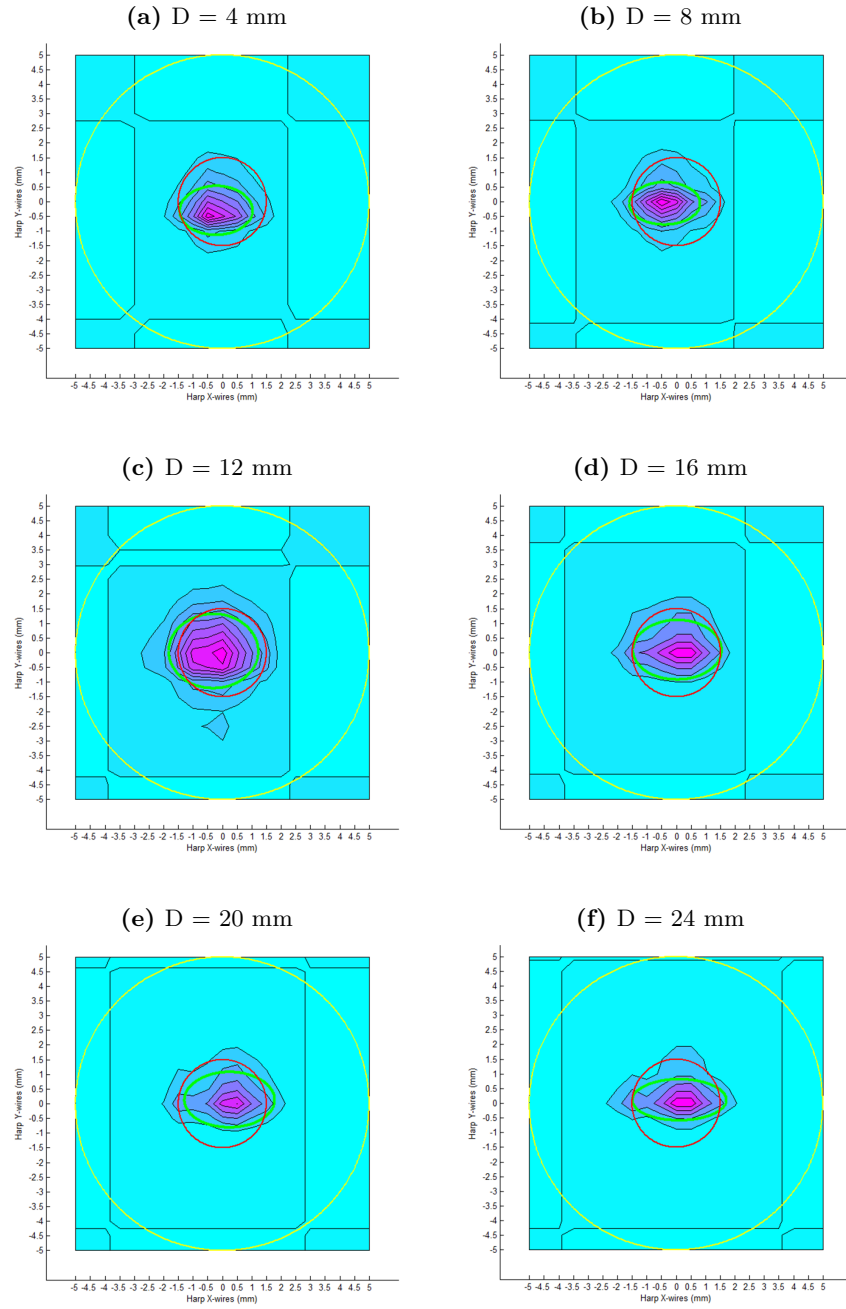


**Figure 6.17:** Beam-density maps at six harp locations. Trial 5.

Trials with differing settings were performed and the emittance values were similar, falling close to or within the above experimental ranges. These results were comparable with the ESIS acceptance limit of  $10 \pi \cdot \text{mm} \cdot \text{mrad}$  required for ion injection into the electron string in the ESIS.

The growth of  $\varepsilon_x$  is most likely from the dipole aberration caused by the electrical quadrupole switch-yard in the transverse direction where bending occurs. This could be mitigated in future by using a less severe bending angle than  $90^\circ$  for bending. However, electrical steerers have been included in the next design in attempt to mitigate this contribution to emittance growth.

## Chapter 7

# ESIS Charge Multiplication from Singly Charged Ion Injection

The ion injection system was connected to the KRION 6T ESIS. The injection of singly charged ions into the KRION could now be attempted, followed by the observation of subsequent charge multiplication of these ions to higher charge-states during confinement in the KRION, which would hopefully be observed during extraction.

Before this could be done,  $\text{Ga}^+$  ion current was first measured on the drift tube structure within the KRION to ensure that transport into the system was possible while no electron string was present. At first, only a small current of  $0.3 \mu\text{A}$  was measured on the drift-tubes, when  $1.2 \mu\text{A}$  was measured across at the straight current Faraday cup,  $I_{\text{straight}}$ , which showed injection was only 25% efficient. This was improved after subsequent experimentation. These measurements were performed in the presence of a 5 Tesla magnetic field which was created a-priori via the KRION superconducting solenoid at liquid helium temperature of 4 K.

The KRION system was modified for the injection of ions through the ion extraction port of the KRION. In order to do this, the entire KRION test-bench was raised to a higher voltage so as to allow for the injection of 1.4 to 1.8 keV  $\text{Ga}^+$  ions at low velocities. Typically, 1.7 keV ions were used and the KRION bench was 200 V lower at 1.5 keV, thus injected ions had lower velocities equivalent to  $T = 200 \text{ eV}$ , which is better for slower ion passes through the KRION, and this also increases the probability of ions interacting with the electron string.

A negative voltage pulse was supplied during injection at the barrier in order to open the way for the injected ion beam. Timing on the injection, charge-breeding, and extraction cycles were configured optimally. The ion optical elements such as the lenses and the quadrupole bender were optimized for injection of 1.7 keV singly charged ions. These were also on a pulse timing regime which powered off the appropriate lenses and the bender to allow for multiply charged ion extraction and their measurement on the

opposite end of the quadrupole bender.

Finally, the electron string was created within the KRION and the injection of singly charged ions into the electron string was achieved, followed by the successful extraction of multiply charged ions after charge breeding.

A Faraday cup,  $I_{FCleft}$ <sup>1</sup>, that collected the extracted ion pulses was positioned on the final side of the quadrupole bender, opposite the KRION extraction port, in order to measure the extracted current. The schematic of the entire system ion injection system linked to the KRION is shown in Figure 7.1.

Charge multiplication states could then be observed by only allowing a small energy band of extracted ions per pulse by means of a voltage chopper. The chopper allowed for a small window of extracted ions to pass, and these ions shared a similar initial energy due to the small chopping time interval, typically 100, 200 or 300 ns. This allowed for a more uniform energy of the extracted pulse, and ions of different charge states would be able to separate more clearly as they traversed through the unpowered transport system to be measured on the left-side Faraday cup,  $I_{FCleft}$ .

The signal on this Faraday cup was amplified, and using the distance from this detector to the KRION, time-of-flight (TOF) spectra were obtained. Although poorly resolved due to the short flight distance of 96 cm, the evidence of various peaks in these spectra proved that different charge states were being produced for different confinement times within the KRION, thus proving that singly charged ion injection is a feasible mechanism for injecting metal ions into the KRION for charge multiplication.

## 7.1 Experiment Setup

### 7.1.1 Ion Transport into KRION 6T ESIS

The ion transport system was connected to the KRION as shown in Figure 7.1. This is an updated version of the rough schematic shown previously in Figure 6.1. A few modifications were necessary to link the ion transport system to the entrance of the ESIS, including a pair of new einzel lenses, and an adaptor flange going from the 15 cm diameter chambers of the ion transport system, to the much larger 40 cm diameter flange of the KRION.

Refer to Figure 7.1 for the final experimental set-up:

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<sup>1</sup>All Faraday cups throughout these experiments were equipped with a nearby negative plate to suppress the production of secondary electrons.

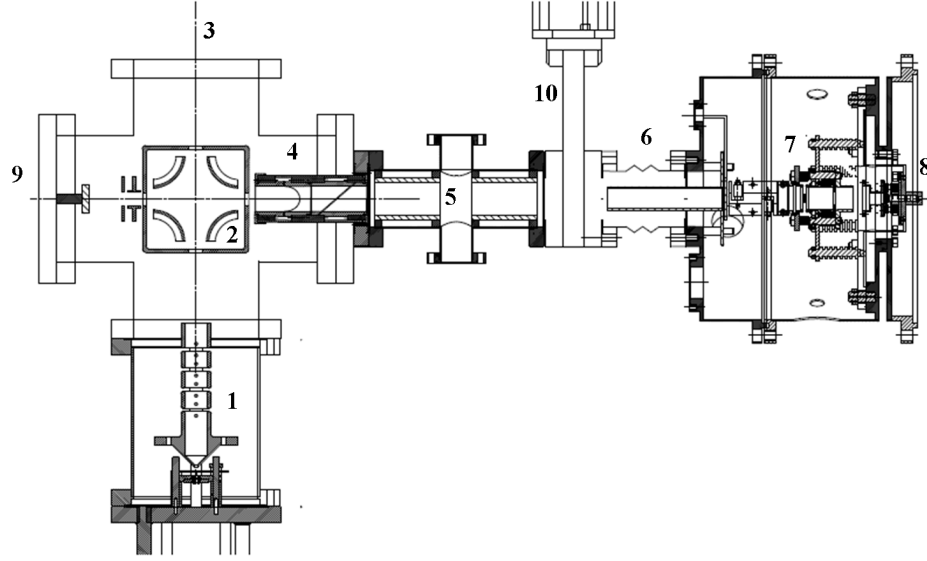


**Figure 7.1:** Schematic of ion transport system coupled with KRION 6T ESIS.

1. LMIS assembly
2. DRE-EBIT Quadrupole Switchyard
3. Faraday cup  $FC_{straight}$
4. Transverse Beam Correcting Deflector lenses
5. Pair of einzel lenses, LA and LC
6. Long einzel lens, L3
7. KRION Entry port, L2, L3, Extractor, Reflector and Anode
8. Drift-Tube structure within KRION
9. Faraday cup  $FC_{left}$
10. Gate valve separating KRION system from LMIS transport system

### LMIS Assembly

The LMIS assembly needs no further explanation as this development constitutes most of the earlier chapters in this thesis. There were no modifications other than the replacement of PVC details with teflon, and replacing the PVC LMIS holder with a stainless steel one. These changes were essential for achieving a better vacuum within the system.

### DRE-EBIT Quadrupole Switchyard

The quadrupole bender was set on a bias comparable to the ion energy. The positive electrode of the bender proved to be unstable in its switching time at this energy, causing the overall injected beam to be non-uniform in ion current delivery into ESIS. The slower switching time could also be a cause of ion injection and extraction losses, however its contribution to the quality of results is minimal. The faulty power supply for this electrode would be replaced in the near future.

### Faraday cup $FC_{straight}$

The pulse timing was set to allow for some ion current to arrive at the Faraday cup positioned opposite the LMIS on the other side of the bender. Ion current was measured here before and after the bender was powered in each cycle. This allowed the experimentalist to measure ion current being produced by the LMIS as a means of ion current verification and quality control. Between 0.5 or 1.2  $\mu A$  was measured depending on the recent heating of the LMIS.

### Transverse beam correcting deflector lenses

The transverse beam correcting lenses were all biased equally in the first investigations of this set-up. The option to uncouple them and supply them with different power supplies could still be performed to aim the beam more completely into the ESIS. In the first tests, these lenses were treated as a single einzel lens, and were positively biased during injection and on ground for multiply charged ion extraction.

### Pair of einzel lenses, LA and LC

A pair of new einzel lenses replaced the replica-system's long lens triplet. LA and LC were positioned in the middle drift space between the LMIS ion transport assembly and the KRION. LC, the left-most of these two lenses was positively biased only during injection, while LA, closer to the KRION, was kept at ground for optimal focusing onto the ESIS entrance port.

### Long einzel lens, L3

Following the long lenses, a third long lens is built on to the system prior to the KRION entry port. This is essential also for ion injection focusing, and is positively biased during injection, and on ground for extraction.

### **KRION Entry port, L1, L2, Extractor, Reflector and Anode**

The KRION entry port, which was emulated in the replica ESIS experiments, remains the same as before. The lenses L1 and L2, and the biasing on the Extractor, Reflector and Anode were controlled by the KRION control system and ideal injection settings obtained. Known settings, typical for the KRION, were used during extraction. The presence of the electron string which is reflected at the Reflector and Anode causes a negative potential drop in that vicinity which was beneficial to the injection of positive ions.

### **Drift-Tube structure within KRION**

The electron string exists within the drift tube structure of the KRION 6T ESIS. A total of 24 drift tubes, each with their own power supply fill the 1.2 m length of the KRION. The first 6 drift tubes are cooled to liquid nitrogen temperature around 70 K, as is the last drift tube. The central drift tubes are cooled to liquid helium temperatures of 4 K.

The magnetic field of the KRION is already present in the entrance port of the KRION where it is 1/20 of the maximum at the position of the reflector and anode. Within the drift tubes, the magnetic field was 5 T.

There is more to be said about the operation of drift tube biasing depending on the type of charge-breeding mode used: two main methods were employed, fast extraction and slow extraction. These will be elaborated on later, however they involve different pulse timing regimes on the biasing of individual drift tubes.

### **Faraday cup $FC_{left}$**

The left hand side Faraday cup was the final diagnostic used to measure extracted HCIs. The biasing on the bender, LA, LC and L3 were all to ground, while that on L2, L1 and the internal components were modified during extraction.

This change in biasing of the transport system allows for the typical ion extraction that is commonly performed with KRION charge-breeding of neutrals. The short distance from the KRION to this FC was about 96 cm and minimal losses occur from extraction to measurement due to well defined, low emittance extraction from the KRION.

This FC was first used to measure the entire bunch of HCIs per period to obtain the full integrated current and the total charge. Later, an amplifier was installed here, and the chopper was configured at the extractor in order to utilize this FC as a low resolution time of flight A/Q analyser.

## Gate-Valve

The LMIS assembly was connected to the KRION system. These two large systems are separated by a high vacuum gate valve. This serves the useful purpose of isolating one system and maintaining the vacuum conditions there, while the other system may need modifications or repairs. Additionally, while pumping to excellent vacuum conditions, the gate valve could be opened to share the turbo molecular pumps throughout both systems and to achieve similar vacuum conditions in each. During ion injection and extraction experiments, the gate valve would be open.

### 7.1.2 Vacuum Conditions

The KRION ESIS has an upper limit on the value of the operable pressure within. This is of the order  $10^{-8}$  mbar. The electron string state in the KRION cannot form at pressures of order  $10^{-7}$  mbar or higher.

Previously, the LMIS assembly vacuum condition could at best reach the  $10^{-7}$  mbar range. Therefore, a larger turbo molecular pump was installed onto the LMIS assembly system, in addition to replacing all PVC parts with Teflon or stainless steel. PVC is a poor material for low pressure systems due to continual outgassing.

The new turbo molecular pump allowed for the required order of magnitude improvement of the vacuum. Additionally, the pumps for both the LMIS assembly and the KRION system are connected when the gate-valve between the systems is open. Hence the pumping power of the KRION system was lent to the LMIS assembly and vice versa.

It is important to mention that each time the LMIS was pulse triggered for injection, the vacuum condition temporarily degraded. This is most likely due to local discharges at the extractor plate and beam loss on the lenses, or from the beam impinging on the Faraday cups. Therefore, the timing on this pulse was chosen to be a small period of around 4 to 10ms, while the overall repetition time was much larger, between 2 s and 10 s, which allowed for the immediate pumping back down to the lowest operation pressure of  $7.5 \times 10^{-8}$  mbar. More rapid cycles or longer LMIS pulses gave rise to a gradually increasing pressure, thus warranting these longer duty cycles and shorter ion pulses.

### 7.1.3 System Configuration for 1.7 keV $\text{Ga}^+$ ions

#### Ion Optics Biasing

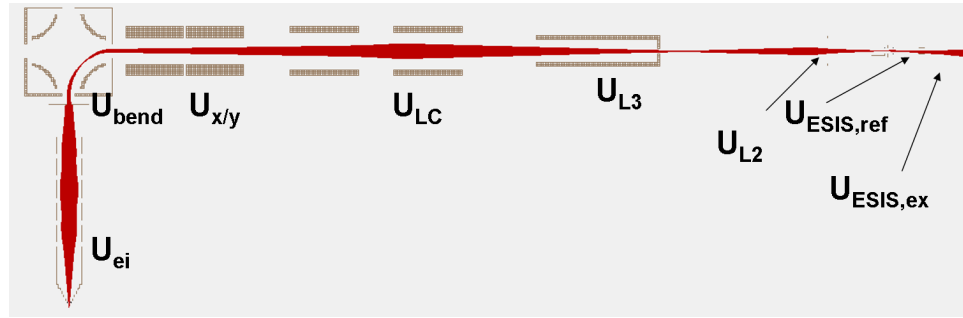
Table 7.1 lists the ion optical bias parameters for 1.7keV ion injection into KRION.

**Table 7.1:** Ion-optics biasing for real ESIS injection experiments.

| Ion-optics bias             | Symbol            | Bias [kV] |
|-----------------------------|-------------------|-----------|
| Ion Extraction Energy       | $U_{ex}$          | +1.70     |
| Extraction Plate            | $U_{em}$          | -5.50     |
| LMIS assembly einzel lenses | $U_{ei}$          | +1.90     |
| Positive Switch-yard bias   | $U_{bend,+}$      | +1.88     |
| Negative Switch-yard bias   | $U_{bend,-}$      | -1.88     |
| Switch-yard einzel lens     | $U_{bend,ei}$     | 0.00      |
| Corrector lenses            | $U_{xyAll}$       | +0.85     |
| Lens LC                     | $U_{LC}$          | +0.50     |
| Lens LA                     | $U_{LA}$          | +0.00     |
| Lens L3                     | $U_{L3}$          | 0.00      |
| Lens L2                     | $U_{L2}$          | +1.78     |
| Lens L1                     | $U_{L1}$          | 0.00      |
| ESIS Extractor              | $U_{ESISextract}$ | -0.58     |
| ESIS Reflector              | $U_{ESISreflect}$ | -7.50     |

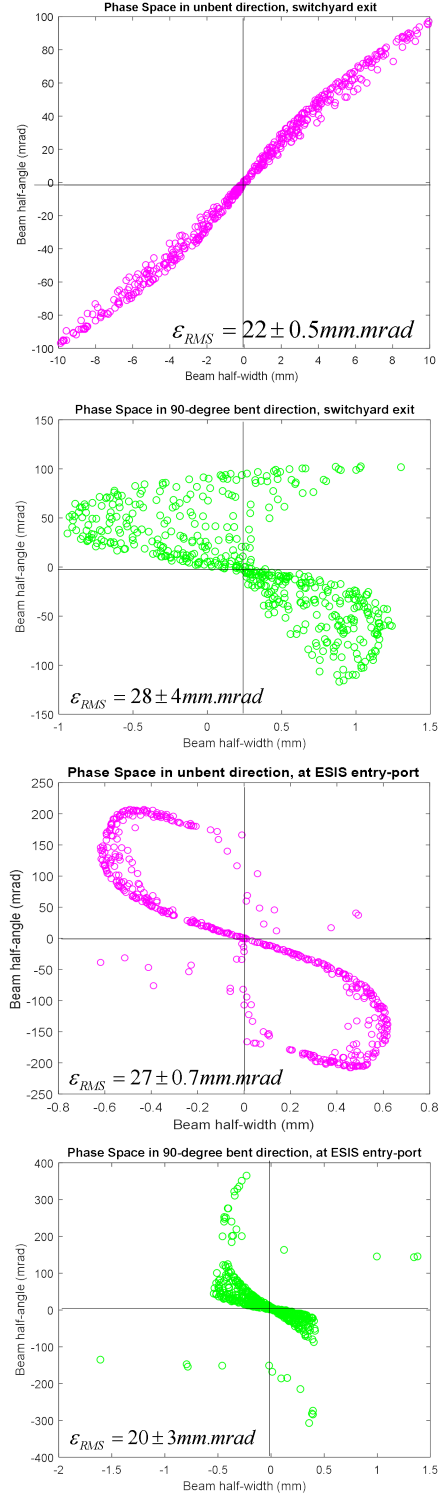
The individual drift tube potentials, of which there are 24, were already configured to standard ESIS extraction modes.

**Box 7.1: Simulating external injection of 1.7 keV  $\text{Ga}^+$  beam** The external injection system was removed from the replica ESIS and installed onto the real ESIS after undergoing calibrations via beam profile measurements and simulations. It was requested that the ion energy be lowered to be between 1.4 to 1.7 keV instead of the 2.2 keV both simulated and tested in previous experiments. This was in order to lower voltage requirements on the ESIS platform and to reduce ion velocities as the beam enters the ESIS. Therefore new biasing on all optics were required - a task first investigated with SIMION. The ion energy used throughout was 1.7 keV.



The ion-optics simulated in the above were set to the values in Table 7.1. The transverse rms-emittance was measured at the exit of the quadrupole, as well as at the entrance to the ESIS. The ions were initiated with a  $5^\circ$  half-angle.

The phase-space plots are shown, first at the switch-yard exit, and second, at the ESIS entrance:



The rms-emittance values are shown on the above plots. The magenta plots show the un-bent, y-direction, while the green plots show the x-direction - the direction into which the beam was bent. The beam is diverging in y as it leaves the quadrupole, but is well focused in x, and converges in both transverse directions within the ESIS. To compare these with experimentally determined emittance values, they should be multiplied by 4 to get 2-rms emittance, accounting for 95% of the beam, and divided by  $\pi$  for the unit. Lastly for normalized emittance, the values should be multiplied by  $\sqrt{U_{ex}}$ , with the ion energy  $U_{ex}$  in MeV. The values are all in agreement with replica experiments within error. The uncertainties are small in the non-deflected direction, indicating particle drift, while in the deflected direction, the beam is asymmetrical indicating the dipole aberrations and strong focusing in the x-direction.

In replica ESIS injection Trial 5, as quoted in Table 6.9, the normalized emittance was  $\varepsilon_{N,x} = 1 \pm 0.5 \pi \cdot \text{mm.mrad} \cdot \sqrt{\text{MeV}}$ , which agrees with the largest normalized emittance from simulations, using the simulation data from the x phase-space exiting the switch-yard shown above:  $\varepsilon_{N,x} = 1.4 \pm 0.2 \pi \cdot \text{mm.mrad} \cdot \sqrt{\text{MeV}}$ .

### Pulse Timing Settings

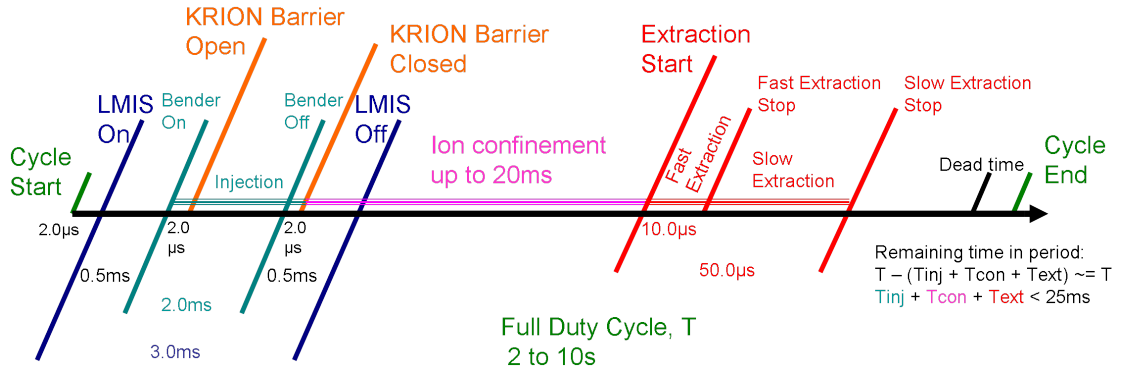


**Figure 7.2:** Timing scheme for the voltage pulsing of beam-line components for injection, confinement and extraction of ions from KRION.

Ion injection,  $\tau_{inject}$ , confinement,  $\tau_{confine}$ , and extraction times,  $\tau_{extract}$ , were all incorporated into the complete duty cycle of the KRION 6T ESIS. Figure 7.2 shows the general voltage bias pulsing scheme for the KRION, with the addition of the  $\text{Ga}^+$  injection period. Confinement time - the duration in which ions are trapped within the KRION - will vary depending on charge state output required, and extraction times can be varied depending on whether slow or fast extraction is being performed. Extraction methods will be discussed in the next section.

Ions enter the ESIS during injection, but may escape while the barrier remains open.

Slower ions have a greater probability of interacting with the electron string while faster ions may be reflected and escape towards the LMIS. Injection and confinement periods should be comparable to each other in duration.  $\text{Ga}^+$  ions have velocities of around 24 km/s at energies of 200 eV, and many will be reflected within around 100  $\mu\text{s}$  from the opposite barrier should they not interact with the string. Closing the injection barrier for confinement should therefore occur at the end of injection time, which is characterized by switching off the quadrupole switch-yard. More ions may already be caught in the negative potential well of the electron string, beginning ionization processes before full trapping in the drift-tube system.

Ion injection, being similar to earlier experiments, required voltage pulsing on the LMIS and the quadrupole switch-yard. The full repetition cycle begins with pulsing on the LMIS for 3 ms. The switch-yard would then be powered after 0.5 ms for a 2 ms injection pulse into the ESIS. The 0.5 ms at the beginning and end of this pulse when the switch-yard is not powered, could be observed on the straight direction FC,  $I_{\text{straight}}$ .

Added onto this injection time, is the beginning of the KRION confinement time,  $\tau_{\text{confine}}$ . The singly charged ions were injected into the KRION over a lowered front barrier potential of 1.5 kV for 1.7 keV ions. This barrier was then raised above the ion energy for the duration of the ion confinement. After  $\tau_{\text{confine}}$  fast or slow extraction is performed, data recorded, and the system waits the rest of the dead time until the end of the duty cycle. The duty cycle period was large compared to the LMIS pulse, between 2 and 10 s, in order to maintain a good vacuum.

Confinement times in the following experiments varied between 0.1 ms to 3.0 ms with larger  $\tau_{\text{confine}}$  values corresponding to higher A/Q ratios observed.

## 7.2 Ion Extraction from KRION

### 7.2.1 Fast Extraction

The KRION, when typically working with the Nuclotron ring at JINR, is configured for fast extraction to match the repetition rate and provide one-turn injection of HClIs into the Nuclotron. The KRION must provide the entire confined population of HClIs into pre-accelerating RFQs and a linear accelerator (linac) before they are injected into the Nuclotron ring, and this is done in such a way to time the pulsed injection with a single turn of the existing ions within the ring - thus this injection time is a short 8  $\mu\text{s}$ , which is also the orbit period of the ions in the Nuclotron.

Pulse biasing is applied to the 24 drift-tubes in the KRION with a steep gradient of biases to expel the confined ions quickly. The drift-tube maximum bias was 2.7 kV above the bench potential of 1.0 kV, and hence 3.7 kV above ground.

Extracting ions using this method allows for the rapid removal of the ions from the KRION, however these ions have a larger longitudinal energy spread, varying between 1.5 to 3.7 keV, which is not useful for obtaining Q/A spectra, where it is important for all the ion charge species to have very similar initial conditions, such as extraction energy.

An advantage of fast extraction is that higher current output is obtained when compared to slow extraction. This is due to the shorter confinement time in the trap - which means that fewer ions escape the trap due to heating effects before extraction.

It is important to note that when the KRION-6T is being used with the Nuclotron injector at JINR, the whole system is on a high voltage platform around 2.5 kV. Therefore extracted ions enter the Nuclotron RFQ system with their energy spread added to the platform high voltage, giving a longitudinal energy spread of 26.5 to 28.7 keV when platform voltage is 2.5 kV for example. This is also standard procedure with EBIS injection systems at other accelerators.

### 7.2.2 Slow Extraction

The pulsed biasing on the drift tubes during slow extraction occurs slowly over 50  $\mu$ s. All drift-tubes are raised simultaneously to the extraction energy which is the same as the injection barrier potential, 1.7 kV. Thus the drift-tube bias is only raised by 0.7 kV above the KRION potential, which is again 1.0 kV above ground, for 1.7 keV extracted ions - these ions leak out of the injection port over the front barrier.

The slowly extracted ions maintain a low longitudinal energy spread, however they were extracted over a larger time. The small energy spread allows one to obtain mass-to-charge spectra via time-of-flight, however, the varying initial departure time of each ion during extraction, between 1.0 and 50  $\mu$ s, means that there can still be confusion in a time-of-flight spectrum due to this time spread.

### 7.2.3 Measuring highly charged ions

Slow extraction allows for similar initial extraction energies, however, there will be a larger spread in initial extraction times. The extraction pulse containing the full allotment of confined ions is not useful in time-of-flight analysis due to this spread in time.

A voltage chopper was used to take only a thin slice,  $\Delta T$ , of extraction time. The voltage chopper is a pulsed potential barrier on the extraction electrode of the KRION. In order to obtain a sample of ions for T.O.F, the barrier was closed during extraction, and opened for  $\Delta T = 100, 200$  or  $300$  ns, and closed again, allowing only a thin slice of the full ion distribution to be extracted, see Figure 7.3. The extracted sample of

ions would now have similar energies, and a very small initial time spread compared to their expected flight times.

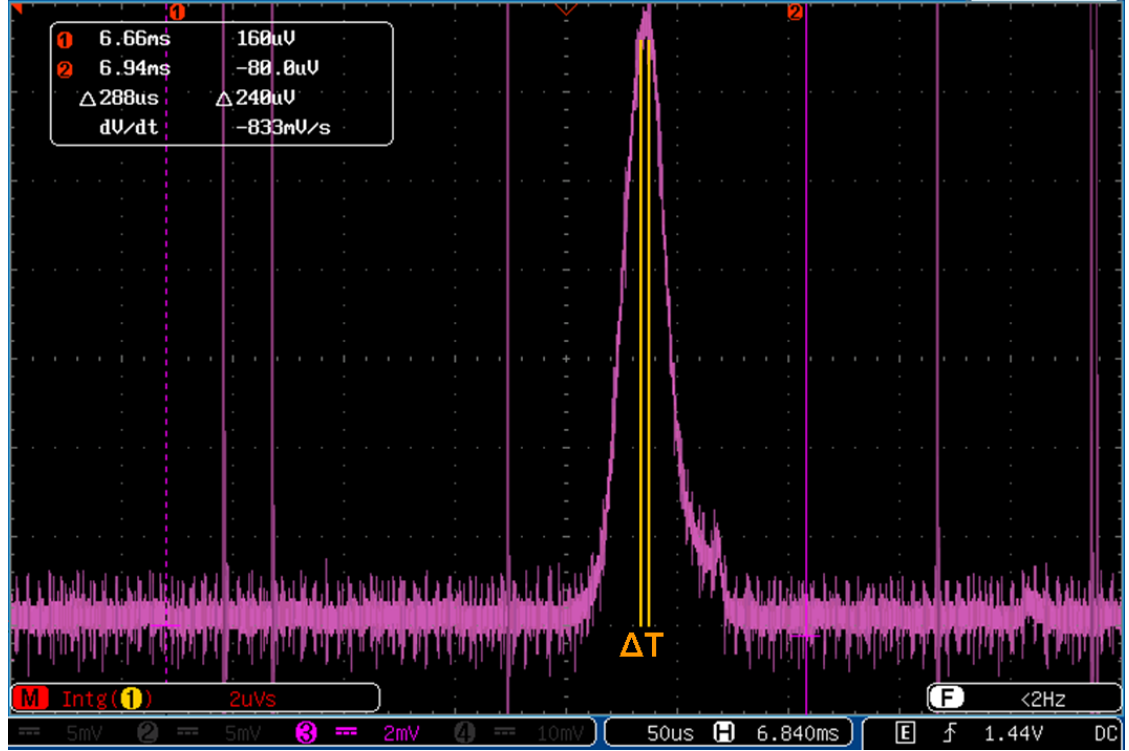


**Figure 7.3:** Extracted HCI pulse containing  $\text{Ga}^{n+}$ ,  $\text{Xe}^{n+}$ , and residual gas  $\text{H}^+$ ,  $\text{N}^{n+}$  and  $\text{O}^{n+}$  as measured on *FCleft*. The yellow lines mark the slice taken using the voltage-chopper - which is exaggerated. The time-scale shown is 50  $\mu\text{s}$  per division - the length of the full extracted pulse.

### Time of Flight A/Q Analysis

The ion extraction was now tailored for T.O.F analysis: longitudinal energy spread was reduced by using slow extraction, and all ions in the sample would start their flights within 50 to 150 ns of each other, which was accomplished by using the voltage chopper.

The left hand side FC, *FCleft*, for detecting the extracted pulse was about 96 cm away from the KRION extraction port. For 1.7 keV ions, one might expect flights in the microsecond range with this small distance. The chopper time spread of 50 to 150 ns will grow over this small distance contributing to the broadening and overlapping of expected peaks. Therefore the full resolution of A/Q peaks was not achieved.

An amplifier was connected to *FCleft* as only a small number of ions were expected per chopped-pulse.

## 7.3 Charge Multiplication

### 7.3.1 Initial tests with xenon

External injection of singly charged ions into the KRION is a feat that has not been accomplished before. Before these attempts were made, the KRION, while connected to the LMIS transport assembly, was operated with neutral injection - in this case xenon gas - in order to test and configure the extraction process. This process is often used with the KRION, and the extraction system of the KRION was already calibrated for this purpose.

Additionally, xenon, as well as residual gas within the system (hydrogen, nitrogen and oxygen), are beneficial as they are used as markers from which to compare A/Q spectra obtained - and to distinguish where possible gallium peaks may be observed in these spectra.

Fast extraction of xenon and residuals yielded between 0.16 to 0.60 nC of charge at  $FCleft$  while slow extraction of the same yielded 1.14 nC for  $\tau_{confine} = 0.3$  ms and 1.30 nC for  $\tau_{confine} = 0.8$  ms in these initial experiments. This result shows that the total charge amount extracted is proportional to the confinement time in the KRION. The oscillogram for the 0.8 ms result is shown in Figure 7.4.

### 7.3.2 $Ga^{1+}$ injection

One final modification to the KRION extraction port was required in order to inject 1.7 keV  $Ga^+$  into the confinement area.

The potential barrier was already on and higher than the  $Ga^{n+}$  energy during the confinement and extraction process, and had to be lowered just enough, at the right moment, to allow for injection. The entire KRION system was already around 2.0 kV above ground, and this needed to be lowered for 1.7 keV ion injection.

Therefore an electronic pulsing module providing a negative drop of  $\Delta V = 700$  V for the injection time was installed to complete the transport system for injection into the KRION during duty cycle.

The operational parameters of the KRION 6T ESIS for these  $Ga^+$  injection are given in Table 7.2.

### 7.3.3 $Ga^{n+}$ results

The initial A/Q time-of-flight spectra obtained had a large amount of contamination from xenon due to the first ion extraction tests. Therefore, xenon was still expected

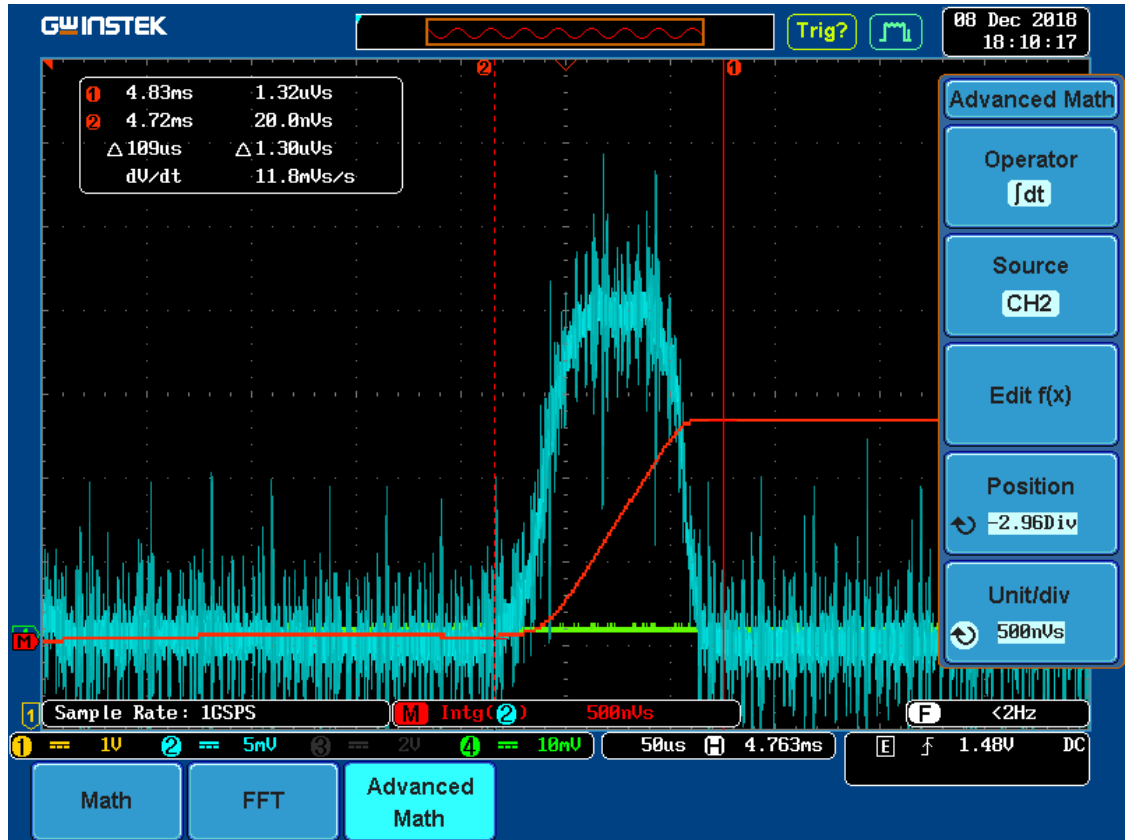


**Figure 7.4:** Extracted HCI pulse of  $\text{Xe}^{n+}$  at  $\tau_{\text{confine}} = 0.8$  ms. The integrated current showing 1.30 nC is displayed on the top left of the figure in units of  $\mu\text{Vs}$ . The signal is rather noisy as the system had not yet been configured for T.O.F, and the amplifier on *FCleft* was also not in use yet.

**Table 7.2:** KRION 6T ESIS settings for  $\text{Ga}^+$  injection

| Parameter                            | Symbol       | Value                    |
|--------------------------------------|--------------|--------------------------|
| Max. solenoidal magnetic field       | $B$          | 5.0 T                    |
| Electron gun energy                  | $E_{e,gun}$  | 4.8 keV                  |
| Mean electron energy                 | $E_{e,ave}$  | 3.5 keV                  |
| Electron current density (estimated) | $j_e$        | 580 A/cm <sup>2</sup>    |
| Injection pulse length               | $\tau_{inj}$ | 4 ms                     |
| Trapping capacity (50% compensation) |              | $10^{10}$ charges        |
| Slow-extraction energy               |              | $1.5 \times Q$ keV       |
| Fast-extraction energy               |              | $2.7 \times Q$ keV       |
| Slow-extraction time                 |              | $\approx 30 \mu\text{s}$ |
| Fast-extraction time                 |              | $\approx 8 \mu\text{s}$  |

among the residual gasses to be present in the A/Q spectra. Such an example is shown in Figure 7.5.

In Figure 7.5, no clear gallium peaks were obtained. This was because the extraction port had not yet been modified for ion injection, and no gallium was yet inside the KRION system. The location for the predicted  $\text{Ga}^{16+}$  or  $\text{Ga}^{17+}$  peaks at this confinement time,  $\tau_{confine}$ , is shown, but they are not present in the spectrum. The extraction port was then modified as mentioned before, using a negative voltage pulser, and shortly afterwards, multiply charged gallium ions were observed.

Pure gallium peaks were obtained by using suitable characteristic  $j_e\tau_{confine}$  (See Chapter 2) that would favour gallium over xenon. There were many attempts at this and several  $\text{Ga}^{n+}$  peaks were observed for various confinement times.

The first result proving that external injection and subsequent HCI extraction is possible is shown in Figure 7.6, and the confinement times required to reach various average charge states are shown in Table 7.3. The expected maximum states (or mixtures of states) of gallium peaks were determined with the CBSIM graph in Figure 7.9.

### 7.3.4 ESIS A/q spectra using CBSIM-Analysis

The simulation software, CBSIM-Analysis [42], was used to obtain the expected charge states for a given electron energy and  $j_e\tau_{confine}$ . A germanium CBSIM graph is shown in Figure 7.9 which was used to determine the charge-states. A brief description on how these graphs were used to determine what ion and charge-species are observed for EBIS was discussed in Chapter 2. At this point in the research, gallium CBSIM graphs intended for use were erroneous<sup>1</sup>. Therefore graphs for germanium were used instead.

<sup>1</sup>These graphs were requested from the CBSIM-analysis group in Germany, but there were errors in their simulations for gallium.

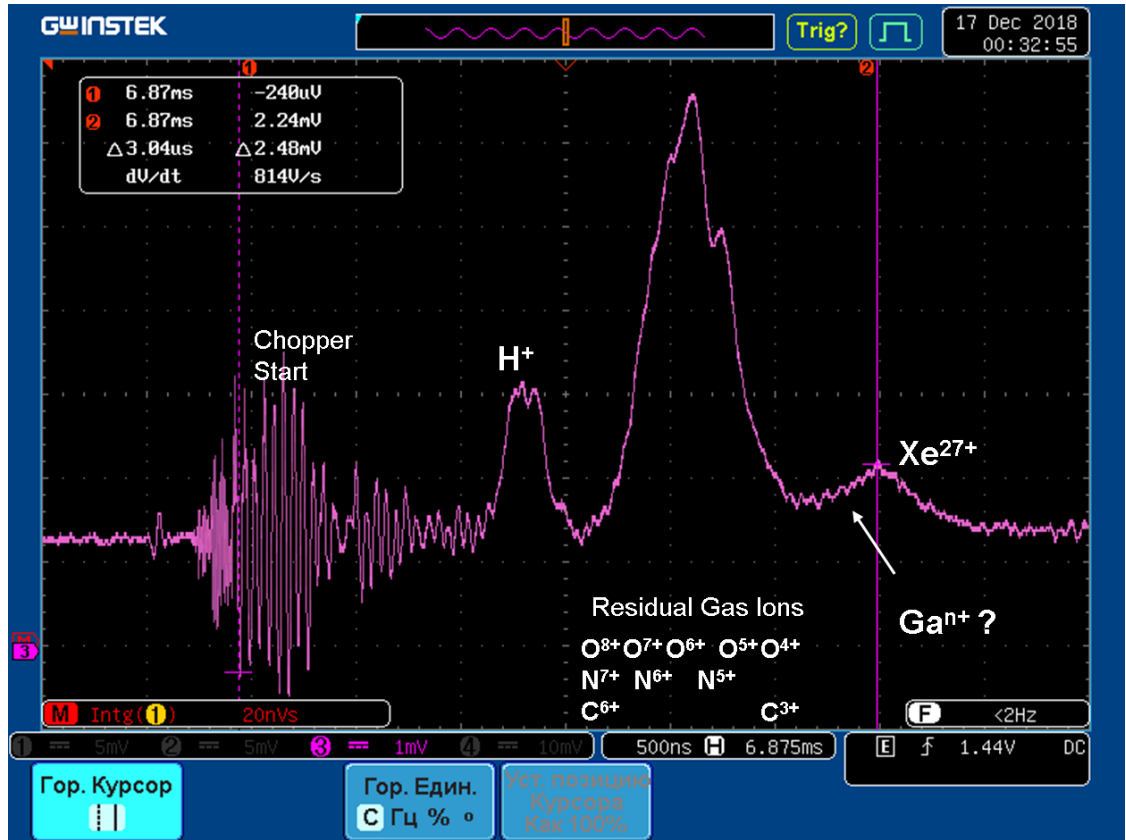


**Figure 7.5:** Extracted T.O.F A/Q spectra containing contaminating xenon and residual gas. It is unlikely high quantities of carbon are present, although it is shown where these peaks are likely to occur. The big unresolved mountain has indications of smaller peaks that could be resolved using a longer T.O.F. The xenon peak which is calculated using CBSIM to be centered on 27+ is shown. In this oscillogram, the spectra was measured with a chopper time of 200 ns, and  $\tau_{confine} = 12.0$  ms.

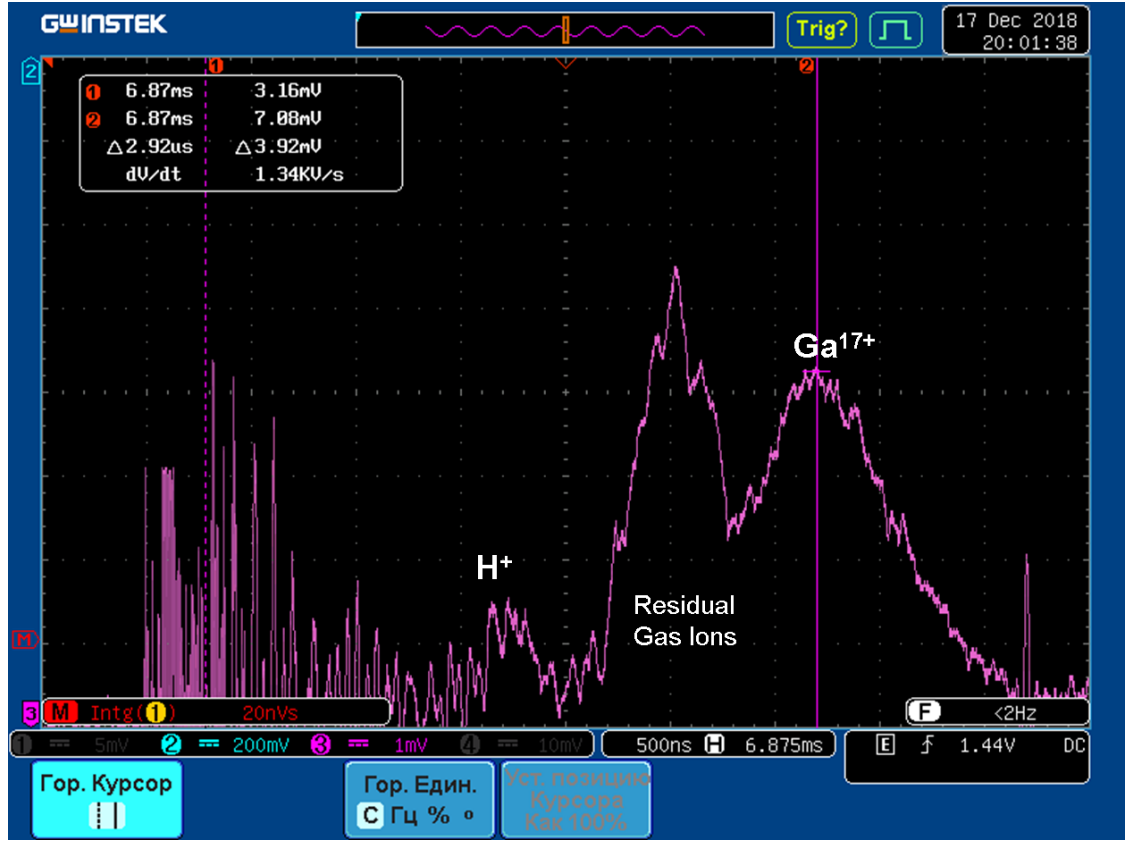


**Figure 7.6:** The first measured peak of multiply charged gallium. The peak was identified using the graph from CBSIM-Analysis software. This is the first evidence that singly charged gallium ions could be injected into KRION, followed by the extraction of multiply charged gallium. No xenon was present as the system had already pumped most of it out. Additionally, with  $\tau_{confine} = 9.30$  ms, there is no chance xenon would appear on this spectrum, as lower charge states of Xe would arrive after the  $Ga^{17+}$  peak. The confinement time is too short to produce high charge state Xe ions.

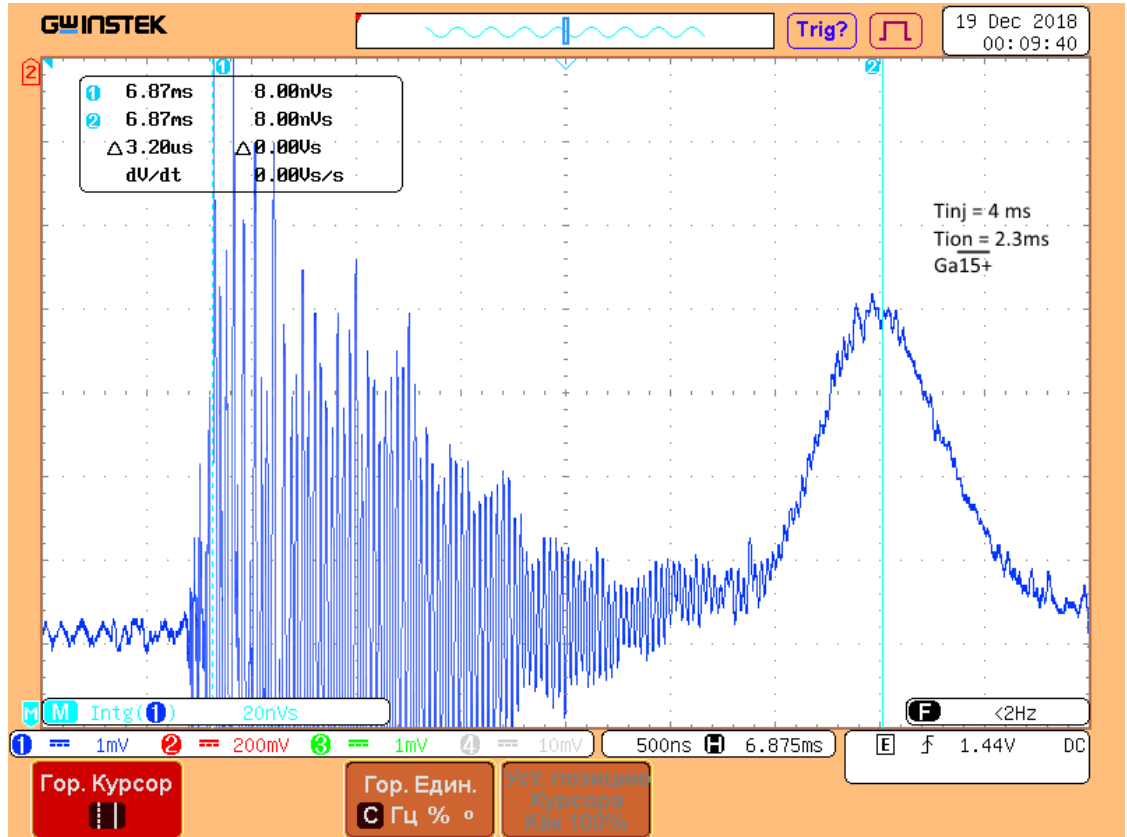


**Figure 7.7:**  $\text{Ga}^{15+}$  peak measured after  $\tau_{confine} = 2.30\text{ ms}$ . Residual gas ions have been suppressed due to long time running of the KRION with external  $\text{Ga}^{1+}$ , thus exhausting these contaminants. Using a 300 ns chopper pulse and having longer confinement times will remove  $\text{H}^{1+}$  due to ion heating losses.

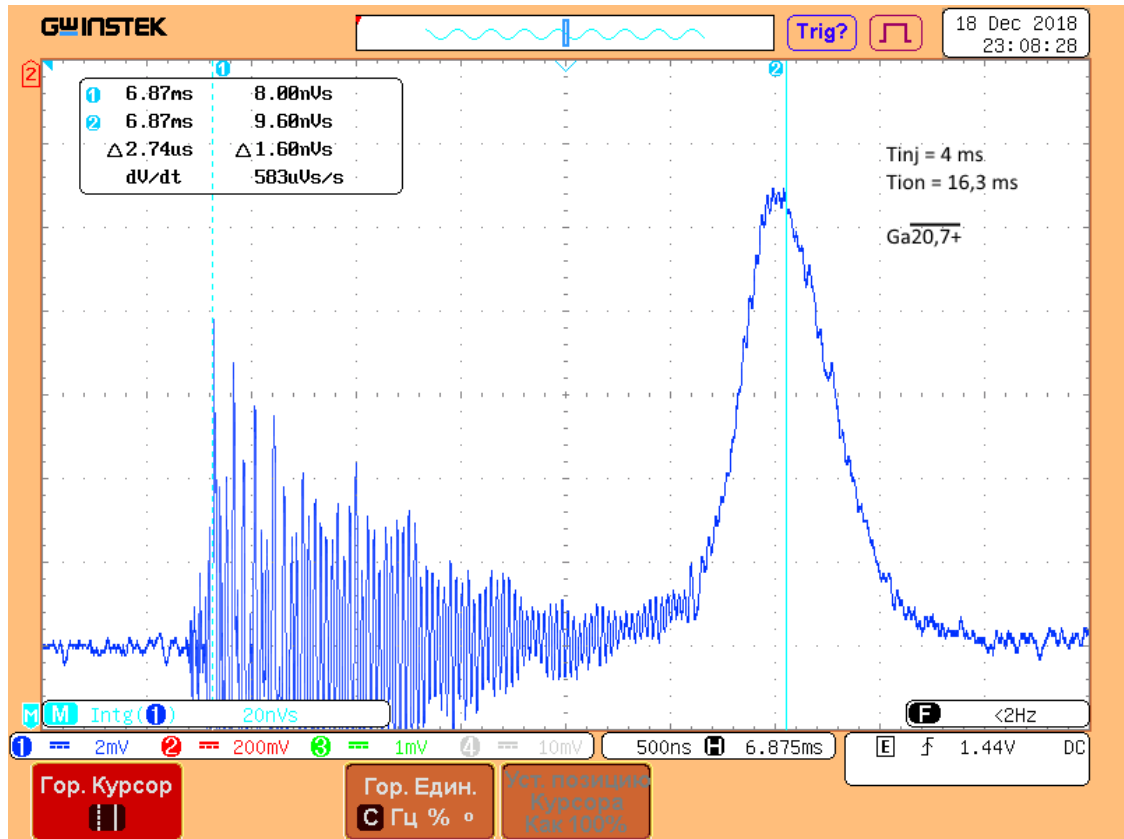


**Figure 7.8:** Neighbouring, unresolved peaks are observed as a mixed peak as in the case of the above spectrum. The charge-state is determined using CBSIM-Analysis. The 20,7+ means there is a mixture of the 20+ and the 21+ state, with 70% of the species being in the 21+ state and 30% in the 20+ state.

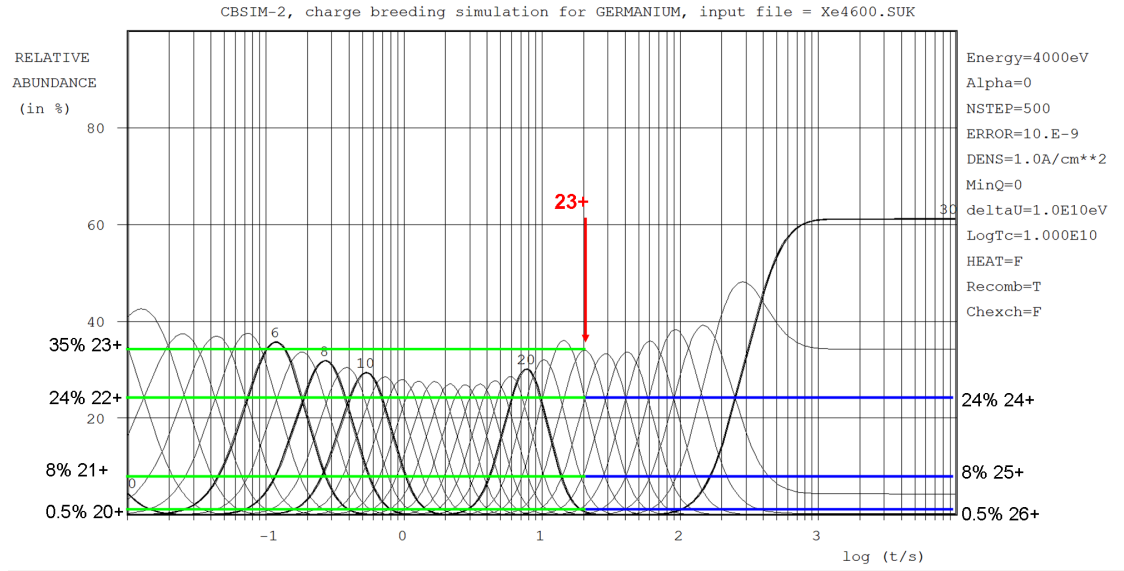


**Figure 7.9:** CBSIM-Analysis graph for the charge-state spectra evolution with confinement time with  $j_e = 1 \text{ A/cm}^2$ . This low current density is used for calibrations to determine the real current density. Usually the x-axis should measure the  $\log(t)$  with time in ms, but due to the low current density, the time is in seconds. The 23+ charge state is highlighted with respective symmetric contributions from 22+ and 24+, and 21+ and 25+ as well. Note that these results were simulated for germanium, which is very much like gallium in electron shell structure, and hence used in place. Gallium graphs could not be obtained from CBSIM-Analysis at this time, so germanium was used instead. The sum of the expected ion species percentage is 100%, as shown on the vertical axis. Green lines indicate lower charge states, while blue lines indicate higher charge states.

**Table 7.3:** Charge states of gallium obtained with increasing  $\tau_{confine}$ .

| Charge State      | $\tau_{confine}$ [ms] |
|-------------------|-----------------------|
| 15                | 2.3                   |
| 17 (60%) 16 (40%) | 4.3                   |
| 19 (30%) 18 (70%) | 8.3                   |
| 20                | 12.3                  |
| 21 (70%) 20 (30%) | 16.3                  |
| 22 (60%) 21 (40%) | 20.3                  |
| 23 (10%) 22 (90%) | 24.3                  |
| 23 (60%) 22 (40%) | 28.3                  |
| 23                | 32.3                  |

Germanium has  $Z = 32$ , while gallium has  $Z = 31$ , so the expected distributions should be alike, as these two elements also share similar ionization energies.

For ESIS, a few extra steps are required to work out the produced charge-states as the electron current density is not known a-priori.

Knowing the electron energy and the expected charge-state for a given confinement time, the current density can be estimated from CBSIM. The maximum charge-state can be estimated from a CBSIM calculation that was performed at the incorrect current density. For example,  $j_e = 1 \text{ A/cm}^2$  was used initially and is shown in Figure 7.9. Matching this with the charge-state allows for the time to be calculated off of the x-axis; for example, the peak corresponding to  $\text{Ga}^{23+}$  in Figure 7.9 yields  $\log(t/s) = 1.3$ . Solving for time gives 19.95 s. That would be the amount of time for the 23+ state to be reached with a low current density. However, it was experimentally determined that the 23+ state occurred after  $\tau_{confine} = 32 \text{ ms}$ . Dividing this time by the actual time yields a more accurate estimate of the current density:  $19.95 \text{ s} / 32 \text{ ms} = j_e / 1 \text{ A/cm}^2 = 623 \text{ A/cm}^2$ .

This exercise was then done for the other expected charge states using the  $j_e = 1 \text{ A/cm}^2$  graphs in Figure 7.9. More estimates for current density could then be obtained:

**Table 7.4:** Estimating ESIS current-density with CBSIM-Analysis

| Gallium charge state | $\tau_{confine}$<br>ms | $j_e$<br>$\text{A/cm}^2$ |
|----------------------|------------------------|--------------------------|
| 23+                  | 32                     | 623                      |
| 22.1+                | 25                     | 565                      |
| 21+                  | 18                     | 555                      |

This was done for all the states recorded in Table 7.3 and an average electron string current density of  $j_e = 580 \text{ A/cm}^2$  was determined. This is the working parameter

shown in Table 7.2.

Note that due to poor resolution of the T.O.F spectra, using the time difference between the H signal and the peak of the gallium distribution, the maximum expected charge-state could be estimated. The data in Table 7.3 reflects the increasing charge state with confinement time. This is shown in Figure 7.10 for some of the charge-state values. In each case, the H peak was always used as a reference point to calibrate further data.

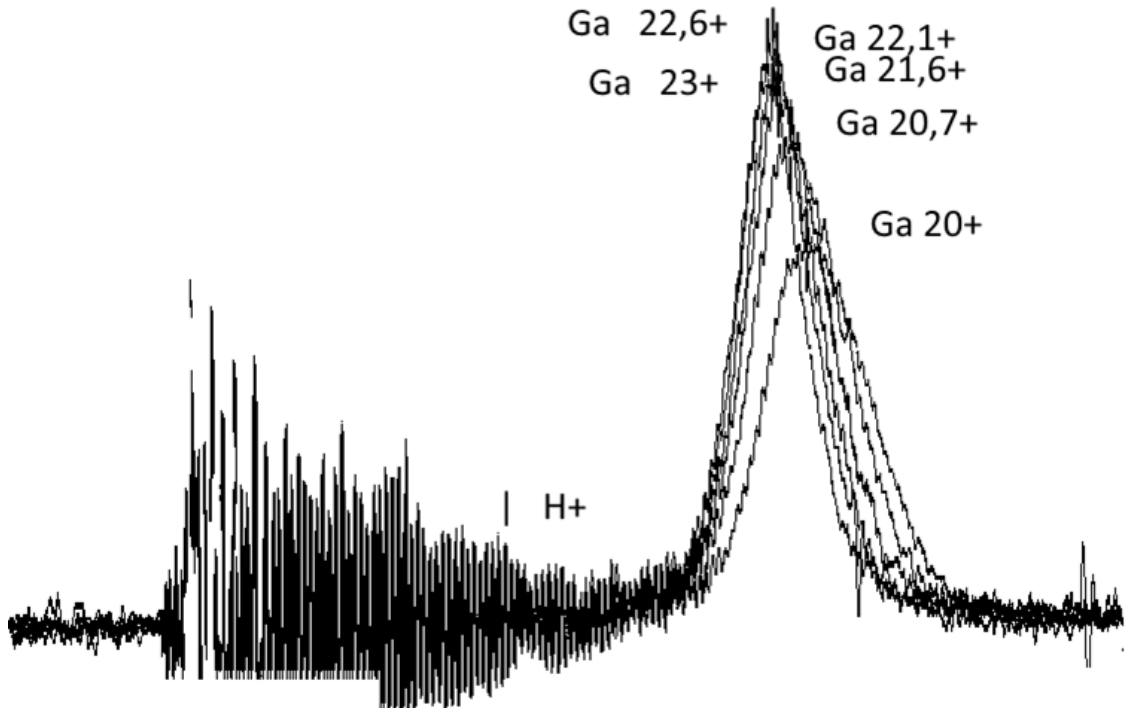


**Figure 7.10:** The above graphs show how the mean charge-state increases with confinement time, as reflected in Table 7.3, but the time-of-flight duration decreases causing the peaks to shift to the left, toward the reference H peak, for higher average charge-states. Note that the amplitudes here do not relate directly to charge quantity, but are shifted due to increasing extraction efficiency with higher charge-states.

Using the calculated current density value, CBSIM calculations were then made at a variety of electron energies. This is the major difference in using CBSIM with ESIS as compared with EBIS. The ESIS, due to reflection of electrons, has a distribution of electron energies within the string given by the values in Table 7.5 [75]:

CBSIM simulations were then made with the above data. The percentage contributions for the mean charge state of  $\text{Ga}^{23+}$  were used to obtain a weighted average for this charge-state. According to Figure 7.9 the abundance of  $\text{Ga}^{23+}$  was 35 %. However, once the weighted average of this charge-state is calculated for the various electron

**Table 7.5:** Electron energies in electron string[75]

| Electron energy<br>keV | Fraction<br>% |
|------------------------|---------------|
| 3.0                    | 15            |
| 3.8                    | 25            |
| 4.2                    | 30            |
| 4.8                    | 25            |
| 5.2                    | 5             |

energies, an abundance of 38 % is determined. Therefore when compared with EBIS, the ESIS has a slightly purer charge-state selectivity.

### 7.3.5 Conclusion of Ion Injection Experiments

It is possible to inject singly charged ions from an external source into the KRION, and subsequently produce HCIs of that ion species. This is an awesome finding, as up to date, the injection of metal atoms or ions into the KRION for charge multiplication had been problematic; such as the use of gas ligands containing metals or using alternative compounds in a gas state for neutral injection.

Injection of the singly charged ion beam into the KRION extraction port had never been performed before, and it is the first time this method has been used with the KRION to produce HCIs of a metal species, although 1+ to n+ charge breeding has been successful using EBIS at various laboratories [36].

The ability to use metallic ion injection into KRION is now an option, and further methods for other metallic injection are ready to be explored. Different primary ion sources could replace the LMIS and without too many additions or changes, it is expected that KRION could produce HCIs of any element via external ion injection.

The injection of singly charged fission fragments into a charge-multiplier like KRION is of interest to iThemba LABS. With a similar transport system, highly charged ions of heavy elements and radioactive isotopes can be created [3].

The repetition time was 10 s. This is very long for the purpose of studying radioactive isotopes. Work should be done to make this overall time shorter, at least in the order of 10 ms, which would be better for studying shorter lived isotopes.

Experiments in the near future will incorporate a dedicated T.O.F analyser, with a long enough length to allow for clear resolution of A/Q peaks in the spectra. Work at JINR continues with the external ion injection facility and the experiment is due to continue using a gold/germanium LMIS, with other external ion species and different primary 1+ ion sources in the future.

## Chapter 8

# Discussion and Conclusion

### 8.1 Charge Breeding Efficiency

High efficiencies for converting singly charged ions into higher charge states is essential in the long term operation of charge-breeders with accelerators. High efficiency, together with a sizeable number of extracted particles, is imperative in studying rare-isotopes with short half-lives. In charge-multiplication from singly charged ions, two types of efficiency can be discussed.

#### Specific charge state efficiency

The number of extracted ions,  $N_n$ , in a specific charge-state,  $n$ , can be calculated by dividing the total extracted charge in that charge-state,  $Q_n$ , by  $n$ , followed by dividing the elementary charge,  $q$ ,

$$N_n = Q_n / qn \quad (8.1)$$

The specific charge-state efficiency is the ratio of extracted ions in charge-state  $n$  to the number of singly charged injected ions, or  $N_n / N_{1+}$ . Since  $N_{1+} = Q_{1+} / q$ , where  $Q_{1+}$  is the measured charge of injected ions, the specific charge-state efficiency can be written in terms of the measured extracted and injected charges:

$$\eta_n = \frac{Q_n}{nQ_{1+}} \quad (8.2)$$

### Overall charge breeding efficiency

The total efficiency over all charge states is given by summing the efficiencies of all specific charge states:

$$\eta = \sum_{n=1}^Z \eta_n = \frac{1}{Q_{1+}} \sum_{n=1}^Z \frac{Q_{n,extracted}}{n} \quad (8.3)$$

Similarly to specific charge-state efficiency, the efficiency over all charge states can only be obtained from a pure A/q spectrum that is ensured to have no contaminants from other atomic species. The ESIS is especially proficient at isolating specific species and limiting contamination of residual gasses especially with medium mass elements [33].

A cumulated extracted current pulse is shown in Figure 8.1.

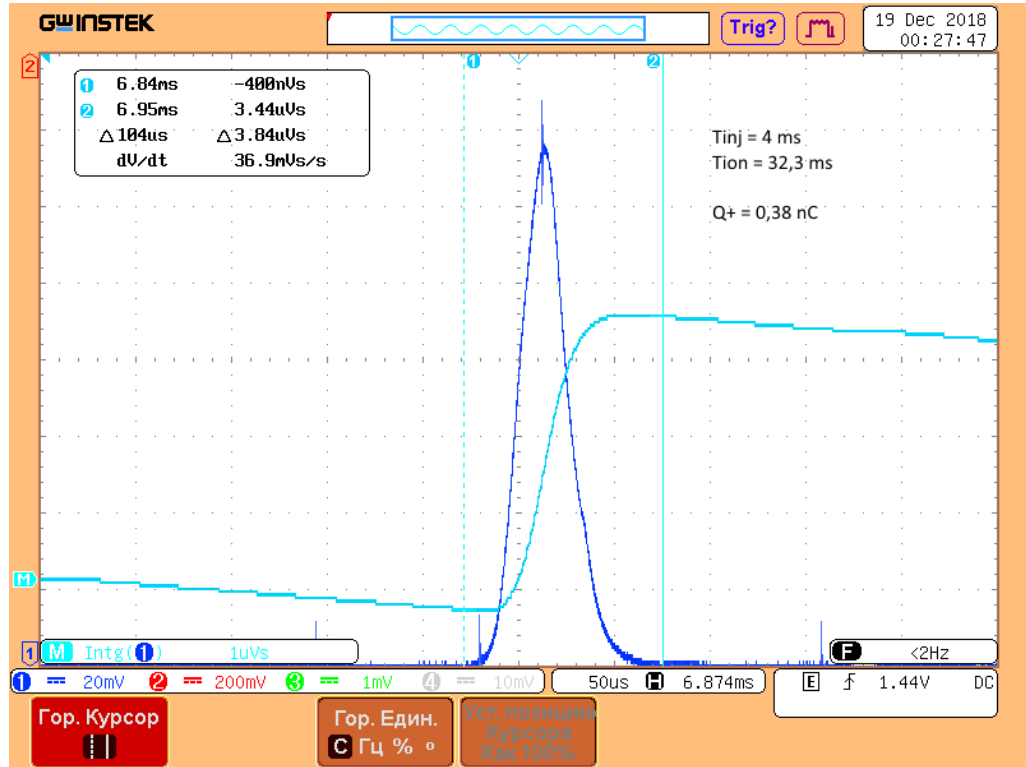


**Figure 8.1:** Oscillogram from  $FC_{left}$  of extracted gallium ions of mixed charge states.

### 8.1.1 Efficiency result and limitations in efficiency measurements

In order to accurately measure both kinds of efficiencies, a moveable Faraday cup should be positioned directly in front of the ESIS entrance. Such a regime would allow for the measurement of the current, and hence the total charge injected. This FC can then be removed during injection and repositioned during breeding, and the full extracted current could then be immediately measured. In practice the amount of time to mechanically move a beam diagnostic is not practical for the small measurement times required, and therefore with the assumption of minimal losses, the current could rather be measured further down the beam line. In the case of the present work, this is done on the Faraday cup after the quadrupole switch-yard,  $FC_{left}$ .<sup>1</sup>

Secondly, it becomes difficult to measure the specific charge state efficiency when  $A/q$  spectra are obtained through the method of "chopping" the extracted beam as explained in Chapter 7. Chopping the extracted pulse was done in order to minimize longitudinal energy straggling and to limit ion velocities so that  $A/q$  spectra could at least be resolved over a short time-of-flight.

### Overall efficiency estimation

With the absence of a Faraday cup immediately before the ESIS, the current measured at  $FC_{straight}$  could be used to obtain an estimate on the lower bound of the transport efficiency and hence the overall charge breeding efficiency. Recall,  $FC_{straight}$  was positioned directly in line with the LMIS assembly, on the other side of the quadrupole switch-yard. This beam diagnostic was used to measure the current going into the direction of the ESIS and to ensure the injection pulse was working as it should be.

The current intended for injection into the ESIS was measured at  $FC_{straight}$  and was typically between 0.7 and 1.0  $\mu A$  using an optimized biasing regime on the beam optics. Assuming, due to losses, that only 0.7  $\mu A$  of  $Ga^+$  is injected over 4 ms, or 2.8 nC of singly charged ions, then using the extracted accumulated current shown in Figure 8.1, which was 0.38 nC, the overall transport and charge-breeding efficiency for these first injection tests is estimated to be greater than 14% via Equation 8.3.

Such calculations were performed for EBIS injection by Beebe *et,al* [79], obtaining 14.5% for low energy singly charged nitrogen injection with 200 ms confinement time - a result very similar to ESIS injection.

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<sup>1</sup>A moveable Faraday-Cup was installed with the LMIS into ESIS injection and extraction line at JINR. However, this device became stuck during the initial operation and had to be removed to continue experiments.

### Specific charge-state efficiency estimation

ESIS charge-breeding is excellent and credited for obtaining very high specific charge state efficiencies after suitably long confinement time. One can refer back to the  $A/q$  spectra shown in Chapter 1 in Figure 1.10 to see this in the charge breeding of  $\text{Ar}^{16+}$ . The  $\text{Ar}^{16+}$  peak contains more than 95% of the extracted ions (Although this makes use of the closed-shell effect of  $\text{Ar}^{16+}$  [34]).

The output given in Figure 8.1 shows the total charge integrated for the confinement period of 32.3 ms without chopping being used. The specific efficiency calculation is made easier by knowing the total output charge integrated over the extraction period, which is not convenient while using a 'chopped' fraction of the total charge. One can expect an average charge state around 23+ using multiple CBSIM results taken for different electron energies as explained in Chapter 7. The presence of the 23+ state accounts for 38% of the spectrum. Multiplying this by the 14% obtained for over-all efficiency, gives rise to a specific efficiency,  $\eta_{23+} = 5.3\%$

## 8.2 Discussion of results

The research presented in this thesis is novel in that no 1+ to n+ charge-breeding of metal ions has ever been performed with an ESIS before. Although metal ligands have been injected into the ESIS through a neutral gas inlet port in the case of charge-breeding iron via ferrocene, and of gold ions through internal surface ionization for the production of gold ions for the Nuclotron, the charge breeding of  $\text{Ga}^+$  with the ESIS marks the first occasion of external ion injection into ESIS.

### 8.2.1 ESIS neutralization during charge breeding

In the results presented in Chapter 7, 0.38 nC of mixed gallium ions was extracted from the ESIS. When related to prior xenon injection experiments, it is known that 7 nC correspond to 90% compensation in the charge-breeder. Applying this ratio to the 0.38 nC measured results in a compensation level of only 6%.

The ESIS is able to reach much higher levels of compensation than this, often with extraction occurring at 50 or 60 % neutralization. Therefore in future experiments it is imperative to improve the beam transport efficiency and overall ion current injected into the ESIS.

### Comparison with EBIS and ECRIS

One cannot calculate 1+ to n+ breeding efficiency with the injection of neutrals due to the difficulties in estimating the number of injected particles. This is easily achieved for

singly charged ions as the injection current can be measured and compared to extraction current.

Therefore, the efficiency of 14% and specific-efficiency of 5.3% mentioned above can only be compared to similar experiments where injected and extracted ion currents were measured in the same way.

Three salient external injection experiments with the EBIS are highlighted: REX-EBIS at CERN [14], Dresden EBIS for BNL, used at RHIC (Relativistic Heavy Ion Collider) [29] and at NSCL in Michigan [86].

Table 8.1 lists some 1+ to n+ efficiency measurements for these similar experiments:

**Table 8.1:** Comparison of Performance Characteristics of Various Charge-Breeders. Normalized emittance values are noted with a \*.

| Charge-Breeder     | $\varepsilon_n[\pi.mm.mrad]$                    | $\eta_n$                                | Extracted Ions                      | Ref. |
|--------------------|-------------------------------------------------|-----------------------------------------|-------------------------------------|------|
| KRION 6T ESIS      | 0.5* (Xe <sub>124</sub> <sup>30</sup> )         | > 5% (Ga <sup>23+</sup> )               | < 10 <sup>8</sup>                   | [84] |
| REX-EBIS           | 7.4 (40 keV)                                    | < 5% (Rb <sub>87</sub> <sup>17+</sup> ) | 10 <sup>6</sup>                     | [40] |
| REX-EBIS (RIBS)    | < 10 (30 keV)                                   | 10% (Cu <sub>90</sub> <sup>19+</sup> )  |                                     | [19] |
| RHIC-EBIS          | 0.1* (Au <sup>32+</sup> )                       | -                                       | 10 <sup>9</sup>                     | [79] |
| CARIBU EBIS        | 0.003*                                          | 20% (Cs <sup>28+</sup> )                | >10 <sup>7</sup>                    | [82] |
| NSCL EBIS          | > 2 (Ar <sub>40</sub> <sup>17+</sup> ) (30 keV) | > 20%                                   | >10 <sup>10</sup> predicted         | [86] |
| NSCL EBIS (RIBS)   |                                                 | 26% (Ar <sub>34</sub> <sup>15+</sup> )  |                                     | [86] |
| ECRIS              | < 26 (few eV)                                   | 8% (Rb <sub>85</sub> <sup>19+</sup> )   | 10 <sup>9</sup> to 10 <sup>13</sup> | [19] |
| ECRIS (RIBS)       |                                                 | 14% (Ba <sub>144</sub> <sup>28+</sup> ) |                                     | [22] |
| Foil/Gas Stripping | n/a                                             | 7% (Sn <sub>132</sub> <sup>23+</sup> )  | n/a                                 | [14] |

The results for ECRIS in Table 8.1 are taken from experiments with the CARIBU ECRIS, which are of the PHOENIX type and used as "boosters" at CARIBU (Californium Rare Isotope Breeder Upgrade), situated at Argonne National Laboratory (ANL) near Chicago in the US. Note that where non-normalized emittance values are listed, the ion energy is quoted in parenthesis, otherwise the normalized emittance is calculated from 2rms-emittance containing 95% of the beam particles. As discussed in Chapter 1, an ECRIS delivers a continuous beam which corresponds to the higher particle counts, although they are at lower charge states. This higher particle output is the main strength of ECRIS, however mass-separation is very necessary to limit contaminants.

The results from the present work are comparable to existing experiments as shown in Table 8.1. The high efficiency for charge-breeding gold at RHIC shows that it is possible to attain excellent charge-breeding with minimal losses. It is expected that efficiency will be lower for rare-isotopes using the ESIS, as is evidenced by the lower values for rare-beams from REX-EBIS. Essentially, the efficiency should remain consistent across

isotopes, including RIBS, but losses may be incurred due to radioactive decay of short-lived isotopes. The radioactive  $\text{Sn}_{132}^{23+}$  is listed to compare charge-stripping via foils and/or gas jets with the charge-breeders.

The KRION 6T has been shown to have a very good extraction emittance as was determined by beam profile analysis using a Pepperpot profiler by S. Barabin, *et. al.*, [84]. This value is around  $0.5 \pi \cdot \text{mm} \cdot \text{mrad}$  and can be expected to be consistent throughout various experiments as it is determined by the ESIS extraction electrodes and their configurations and structure.

Comparing the ESIS results in Table 8.1 to the most significant experiments using EBIS or ECRIS where rare-isotopes have already been tested, such as those shown in Vondrasek *et.al.*, [22] for ECRIS at ANL, and in Lapierre *et.al.*, [86] and Wenander *et. al.*, [19] for EBIS, it is clear that the KRION will be able to deliver similar or even better SCS efficiencies and particle counts. The most important issue that remains is to ensure that larger quantities of the desired  $1+$  ion arrive in the ESIS with minimal losses. The KRION 6T ESIS can then ensure that the specific charge state output required is easily reached by controlling  $j\tau$  effectively, giving an  $A/q$  spectrum with a single or very dominant peak at the required state.

### 8.3 Feasibility of singly charged ion injection into ESIS

The work presented in this thesis has shown that  $1+$  to  $n+$  injection and extraction is possible with the ESIS. This is the first case in history where such a task has been accomplished, and deserves to be highlighted. This fact extends the list of available atomic species to the ESIS, across most of the metals, except perhaps the refractory metals. Any desired species can be injected into the ESIS provided it can be made a singly charged ion from a primary source.

The LMIS was used as a test source in this case, due to its high brightness and current output, and relative ease of use: short heating cycles due to low melting point of gallium, easy to switch and change extraction electrode configurations, and relatively cheap to obtain. Tests with ions from other LMIS or LMIAS such as gold can still be performed. Other primary singly charged ion sources can also now be considered and be installed in place of the LMIS. FEBIAD, MEVVA, laser and surface ionization are all possible candidate methods for providing other metallic and rarer ions to the ESIS. This opens up several possibilities for future tests.

The quick breeding, or confinement times in the ESIS, which are of the order of 10 ms, and a total repetition period in the 100 ms range or less, allows for a wider view of the short lived isotopes. It is envisaged that those isotopes with half-lives greater than a few seconds can be provided to accelerator experiments using the ESIS with  $1+$  ion injection<sup>1</sup>. Such short-lived isotopes are planned to be studied from fission decay

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<sup>1</sup>A few seconds are required for slow diffusing of fragments from the target.

products in the 1+ charge-state.

### 8.3.1 Prospects of ESIS Charge Breeding at iThemba LABS

The lower limit for charge-injection/extraction specific charge-state efficiency was found to be 5.3% for singly charged ion injection into the ESIS. When compared to most ECRIS machines, this value is quite comparable - an upper value for ECRIS efficiency is around 7%, and this is for continuous (cw) mode of ion production.

In practice, ESIS efficiency will be reduced due to the duty-cycle. If a 50% duty-cycle is assumed, the ESIS efficiency would be equivalent to the ECRIS. The 5.3% measured herein is also a lower limit, and after improvements to the injection system for better focusing of singly charged ions into the ESIS, a higher efficiency is expected.

This result means the ESIS is a promising candidate for a charge-breeding ion source for future projects at iThemba LABS where high efficiency charge-breeding is important, such as for the production of RIBS.

## 8.4 Future work with 1+ ESIS injection

The work presented herein has shown that external metallic ion injection is feasible using a LMIS, followed by n+ ion extraction at efficiencies comparable to other world-class charge-breeding facilities.

An estimate of 5.3% specific state efficiency was obtained. Due to technical reasons, an accurate measurement of 1+ ion current arriving at the entrance to the ESIS could not be measured, and instead the un-bent current was used - thus limiting the efficiency estimate. Future experiments should resolve this issue once the move-able Faraday-cup at the ESIS entrance has been fixed, and a better determination of transport and breeding efficiency can then be made.

Gallium-69 has been used as the first test source due mainly to its commercial availability. Gold-germanium liquid metal-alloy ion sources, which have a higher melting point than gallium, will be tested next with the existing system. This should be easy to switch to, as the Au-Ge LMAIS has the same fitting dimensions as the Ga LMIS used in this work.

Other techniques for producing 1+ ions, such as the surface ionization of bismuth, will also be tested with a few modifications to the external injection system. Eventually, such a system should be robust to several kinds of primary 1+ ion sources, including ISOL methods for fission fragment ions - which is of importance to the work being done for SAIF at iThemba LABS.

## 8.5 Future prospects of 1+ to n+ charge-breeding with ESIS

The KRION has essentially been upgraded with the new ability to provide an extended list of species for experimentation. The two main driving factors for achieving this work are the development of the NICA at JINR, Dubna, Russia, and the development of SAIF at iThemba LABS, Cape Town, South Africa [3].

The NICA, or Nuclotron Ion Colliding fAcility, is in the late stages of its completion, and is due for its first experiments in the 2020s [2]. The KRION-N ESIS is currently under development at JINR, which will be a dedicated ESIS for the Nuclotron experiments, providing gold, xenon, argon (as before), as well as whatever myriad elements are called for. Primary singly charged ion injection to deliver the more difficult to obtain elements will be an essential feature on the KRION-N.

SAIF will be of use both as a research centre, and a commercial isotope production facility. The existing separated sector cyclotron will be used to provide a primary beam of 66 MeV protons to the "Low Energy Radioactive Ion Beam" (LERIB) facility. It will produce low-energy 60 keV beams of fission fragments in the 1+ charge state. A front-end test bench for a fission fragment ion source using a uranium carbide target is already under construction at iThemba LABS. It is this ion source that will supply 1+ beams for injection into a charge-breeder for the next stage of SAIF: The Accelerator Centre for Exotic Beams (ACE Beams), which will see the post acceleration of the fission fragment beams.

A map of the existing iThemba LABS cyclotron facility (Figure 8.2) shows where the intended LERIB and ACE-Beams facilities will be situated. Here both an ESIS and an ECRIS will be desired to make use of the pros and cons of either in a given situation. For the production of rare-isotopes, an ESIS is planned to be used to deliver high quantities of pure beam.

The work in this thesis is intended to contribute toward the technical design study for ACE-Beams. This facility may take one or two decades before it is entirely up and running: the development of a dedicated ESIS for the tasks required will be important work in the interim.

## 8.6 Word of thanks

I would like to thank the National Research Foundation (NRF) of South Africa for funding this study. I would also like to thank the Joint Institute for Nuclear Research (JINR) for hosting and accommodating the development of the ion injection system and the experiments required to achieve the aims of this research.

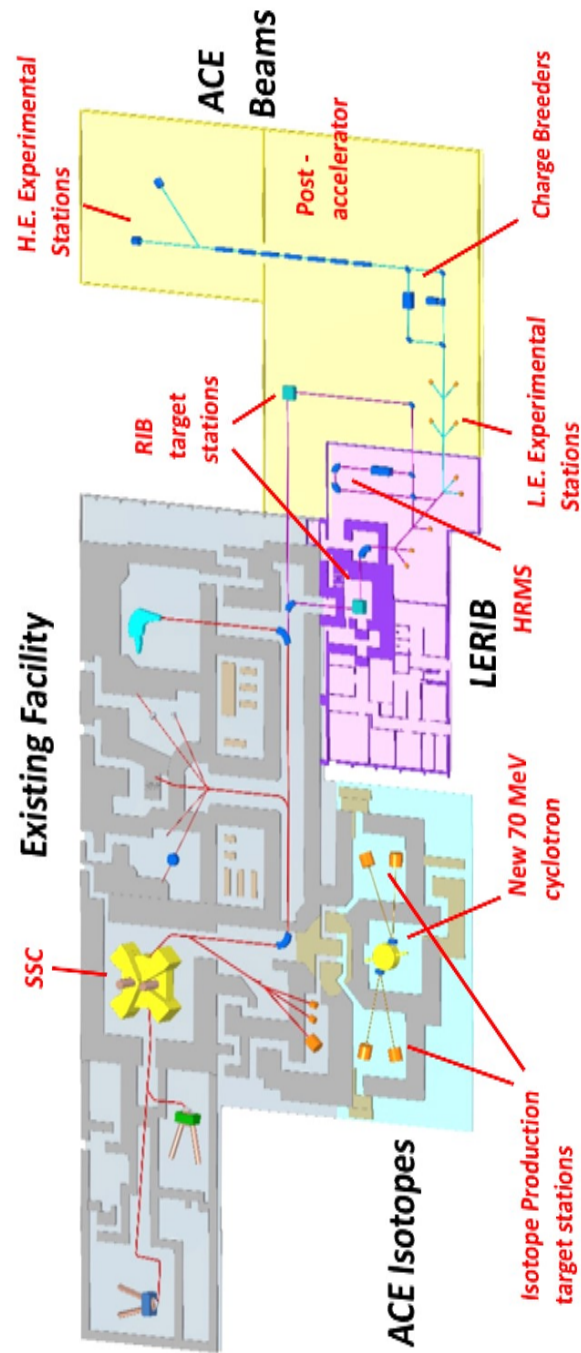


**Figure 8.2:** Proposed floor-plan for South African Isotope Facility (SAIF). Both an ESIS and an ECRIS are proposed to be used in tandem for the production of HCIs of rare-isotopes of all atomic species, barring only the refractive metals.

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