UNILAC-Upgrade: High Current Development wrt U^{28+}

W. Barth

- Heavy Ion Linear Accelerator UNILAC
- High Current Project (HSI-Upgrade 1999)
- Unilac Upgrade Program (2007)
  - HSI Frontend I
  - Stripper Sections
  - Alvarez Matching
- Status of the Unilac High Current Performance
- FAIR-UNILAC-Upgrade (>2007)
  - HSI-Frontend II
  - charge separator
  - Beam Diagnostics
- End to end simulations
- Outlook
The GSI **UNI**versal **Linear AC**celerator

High Current Injector  Alvarez  Single Gap Resonators
<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec. 98</td>
<td>Last operation-shift with Wideröe injector</td>
</tr>
<tr>
<td>Jan.-Feb. 99</td>
<td>Disassembly of Wideröe and rf, installation of LEBT section</td>
</tr>
<tr>
<td>March 99</td>
<td>Successful commissioning of LEBT</td>
</tr>
<tr>
<td>April-May 99</td>
<td>Mounting IH-RFQ and first acceleration up to 120 keV/u</td>
</tr>
<tr>
<td>June 99</td>
<td>Beam tests with Super Lens, achieving 10 mA Ar⁺ at RFQ exit</td>
</tr>
<tr>
<td>July 99</td>
<td>Assembly of IH1, verification of beam acceleration up to 743 keV/u</td>
</tr>
<tr>
<td>August 99</td>
<td>Completing HSI with IH2 and stripper section</td>
</tr>
<tr>
<td>2. Sept. 99</td>
<td>Proof of acceleration up to 1.4 MeV/u, further on: 80% IH-transmission for highest argon intensities (8 mA)</td>
</tr>
<tr>
<td>October 99</td>
<td>Upgrade of transfer line to SIS and mounting of matching section to Alvarez</td>
</tr>
<tr>
<td>November 99</td>
<td>Establishing three beam operation, complete Alvarez transmission at highest current</td>
</tr>
<tr>
<td>Since Nov. 99</td>
<td>HSI in routine operation</td>
</tr>
<tr>
<td>February 2000</td>
<td>Achievement of the 90%-rf levels, first 1.4 MeV/u U⁺⁺ beam (3 mA)</td>
</tr>
</tbody>
</table>
Intensity Upgrade
(Achievement of the SIS18-space charge limit)

Linac Design Particle Current at 1.4 MeV/u

Fully Stripped Ions into SIS at 11.4 MeV/u

Most Abundant Charge State selected from 11.4 MeV/u Carbon Stripper into SIS

Assumption: 20 turn injection into the horizontal phase space!
Status of the UNILAC High Current Performance (1999)

**Beam Brilliance**

- Ar^{10+}
- Ar^{18+}

**Beam transmission**

- Gasstripper
- Alvarez
- Foil Stripper
- SIS-Injection

- 1 mA
- 6 mA

- 1 mA
- 7 mA
- 10 mA

- 1 mA
- 7 mA
- 10 mA
UNILAC-Upgrade Program I

• MEVVA-Ion Source: Further development, improvement of operation lifetime, beam stability, …
• RFQ-Upgrade: Exchange of RFQ-rods, modified IRM
• Super Lens-Upgrade: Improved rf-performance
• IH 1: New Triplet-Lens
• Investigation of the longitudinal HSI-beam quality
• Increased stripper gas density
• Matching to the ALVAREZ-DTL under space charge conditions
• Reduction of the number of Single Gap Resonators
• Alignment
• High Current Beam Diagnostic
• Machine Investigations: Frontend, Alvarez-matching, transfer line-emittance measurements
RFQ-Upgrade: New RFQ-Rods

After 5 years of operation

New RFQ-rods

After copper-plating

Input rf-Power [kW] vs rf-voltage [V]

Commissioning 1999
February 2003
December 2001
HSI-RFQ-Commissioning (7/2004)

$I = 16 \text{ emA}, (\text{Ar}^{1+})$

Graph showing RFQ Amplitude [V] vs. RFQ Transmission [%] for April and July 2004. The working point is indicated by a dashed vertical line.
Increased Stripper Gas Density

6 emA, $U^{4+} \rightarrow U^{28+}$

stripping efficiency [%] vs. $P_{\text{stripper}}$ [mbar]

- 26+
- 27+
- 28+
- 29+

Valves

Limitation (old) vs. Limitation (new)
Status Quo

![Graph showing horizontal and vertical SIS-acceptance for different stripper devices.](image)
Status Quo

LEBT HSI Gasstripper Alvarez Single Gap Resonators

Foil Stripper SIS-Injection

U^{4+} U^{27+} U^{73+}
# Status of the UNILAC Uranium-Performance

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>Design (1999)</th>
<th>required for FAIR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>( ^{238}U^{4+} )</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. Beam Intensity ( I ), (2.2 keV/u)</td>
<td>16 emA</td>
<td>16 emA</td>
<td>20 emA</td>
</tr>
<tr>
<td>( I_{\text{max}} )@beam power, (1.4 MeV/u)</td>
<td>6.5 emA @587 kW</td>
<td>15 emA@1250 kW</td>
<td>18 emA@1500 kW</td>
</tr>
<tr>
<td>Transv. Emittance (LEBT) (90%, total)</td>
<td>140 ( \pi \cdot \text{mm-mrad} )</td>
<td>120 ( \pi \cdot \text{mm-mrad} )</td>
<td>120 ( \pi \cdot \text{mm-mrad} )</td>
</tr>
<tr>
<td>Macropulse Length</td>
<td>150 ( \mu \text{s} )</td>
<td>150 ( \mu \text{s} )</td>
<td>150 ( \mu \text{s} )</td>
</tr>
<tr>
<td>Reproducibility/Transversal Emittance</td>
<td>±4.5%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Beam loading, 7emA (IH2)</td>
<td>350 kW</td>
<td>590 kW (15 emA)</td>
<td>710 kW (18 emA)</td>
</tr>
<tr>
<td><strong>( ^{28}U^{28+} )</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. Beam Current, (1.4 MeV/u)</td>
<td>6.25 emA</td>
<td>12.6 emA</td>
<td>15.0 emA</td>
</tr>
<tr>
<td>Max. Beam Intensity, 11.4 MeV/u, ( I_{\text{max}} )@beam power Transfer to the SIS18</td>
<td>5.7 emA@567 kW 1.3( \cdot 10^{11} )</td>
<td>12.6 emA@1221 kW 2.8( \cdot 10^{11} )</td>
<td>15.0 emA@1453 kW 3.3( \cdot 10^{11} )</td>
</tr>
<tr>
<td><strong>( ^{73}U^{73+} )</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. Beam Intensity, 11.4 MeV/u, ( I_{\text{max}} )@beam power ( I/\text{ions}/100\mu\text{s} )</td>
<td>2.7 emA 2.3( \cdot 10^{10} )</td>
<td>4.6 emA 3.9( \cdot 10^{10} )</td>
<td>3.5 emA 3.0( \cdot 10^{10} )</td>
</tr>
<tr>
<td>Transv. Emittance (11.4 MeV/u) (90%, tot.)</td>
<td>11.0 ( \pi \cdot \text{mm-mrad} )</td>
<td>5.0 ( \pi \cdot \text{mm-mrad} )</td>
<td>7.0 ( \pi \cdot \text{mm-mrad} )</td>
</tr>
</tbody>
</table>
## UNILAC-Upgrade II (for FAIR)

*(FAIR-Technical Report 2005)*

<table>
<thead>
<tr>
<th>sub-project</th>
<th>aim</th>
</tr>
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<tbody>
<tr>
<td>• High Current test bench → U(^4)+-ion source terminal for the High Current Injector</td>
<td>18 emA, U(^4)+, 1.4 MeV/u</td>
</tr>
<tr>
<td>• U(^4)+-Compact Low Energy Beam Transport</td>
<td></td>
</tr>
<tr>
<td>• HSI-RFQ-Upgrade</td>
<td></td>
</tr>
<tr>
<td>• Gasstripper</td>
<td>13% stripping efficiency for U(^{28})+, 100 % transmission</td>
</tr>
<tr>
<td>• Power Supplies for 178 Alvarez-quadrupoles</td>
<td>(\sigma_0 = 55^\circ), U(^{28})+ (improved beam quality)</td>
</tr>
<tr>
<td>• 11.4 MeV/u charge state separator</td>
<td>charge state separation for a 5 emA U(^{73})+ beam</td>
</tr>
<tr>
<td>• High Current beam diagnostics</td>
<td>Measurement of ion current, transmission, beam profile, position, energy, transverse and longitudinal emittance</td>
</tr>
</tbody>
</table>
HSI-RFQ upgrade (2009)

- Higher transverse acceptance and phase advance (keeping maximum field at the electrode surface)
- New Input Radial Matcher design → improved beam matching
- Improved beam dynamics for gentle buncher optimized for rapid and uniform separatrix filling →
- Resonant frequency shift with increased average radius and reduced electrode thickness can easily be compensated
- Beam dynamics studied with DYNAMION & PARMTEQ-M
- Beam intensity at HSI-RFQ output (18 mA of U⁴⁺ ions) meets the FAIR requirement

<table>
<thead>
<tr>
<th></th>
<th>Final Design</th>
<th>Existing Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage, kV</td>
<td>155.</td>
<td>125.</td>
</tr>
<tr>
<td>Average radius, cm</td>
<td>0.6</td>
<td>0.5245 – 0.7745</td>
</tr>
<tr>
<td>Electrode width, cm</td>
<td>0.84</td>
<td>0.9 – 1.08</td>
</tr>
<tr>
<td>Maximum field, kV/cm</td>
<td>312.0</td>
<td>318.5</td>
</tr>
<tr>
<td>Modulation</td>
<td>1.012 – 1.93</td>
<td>1.012 – 2.09</td>
</tr>
<tr>
<td>Synch. Phase, degree</td>
<td>-90° - -28°</td>
<td>-90° - -34°</td>
</tr>
<tr>
<td>Aperture, cm</td>
<td>0.410</td>
<td>0.381</td>
</tr>
<tr>
<td>Min. transverse phase advance, rad</td>
<td>0.555</td>
<td>0.45</td>
</tr>
<tr>
<td>Norm. transverse acceptance, cm mrad</td>
<td>0.0856</td>
<td>0.73</td>
</tr>
<tr>
<td>Output energy, MeV/u</td>
<td>0.120</td>
<td>≈ 0.1185</td>
</tr>
<tr>
<td>Number of cells with modulation</td>
<td>394</td>
<td>343</td>
</tr>
<tr>
<td>Length of electrodes, cm</td>
<td>921.74</td>
<td>921.74</td>
</tr>
</tbody>
</table>
HSI-RFQ upgrade (2009)

measurement for present RFQ:

- Design
- Transmission / % before upgrade 2004
- Transmission / % after upgrade 2004
- Transmission / % after upgrade 2009

Beam current (mA)

FAIR requirements

- 15 mA
- 8.5 mA
- 7.5 mA

= Max. Measured up to 2008

Tank Voltage / % of Nominal Voltage

(100% = Working Point)

- before upgrade 2004
- after upgrade 2004
- after upgrade 2009

Transv. emittance (cm*mrad)

Hermite output

New RFQ

Existing RFQ

Rf Power [kW]

Fwd new
- Rfl new
- Fwd 3 weeks
- Rfl 3 weeks
- Fwd 9 weeks
- Rfl 9 weeks
- Fwd 1 year
- Rfl 1 year

Tank Voltage [V]
Charge State Separator
High Current operation (Uranium)
New Power Supplies for the UNILAC Alvarez dc-Magnets

- The achieved ratio current / rms-emittance at DTL exit is too low for FAIR
- Design: 15.5 mA / 0.25 µm; Achieved: 4.4 mA / 0.43 µm
- One measure of improvement → reduction of emittance growth along DTL
- Exp. and simulation: possible by increasing DTL quad strengths
High Current Beam Diagnostics: Beam Induced Fluorescence Monitor

Compact chamber with 150 mm insertion:

4.7 MeV/u Ar^{10+} beam
I=2.5 mA equals to 1011 particle
One single macro pulse of 200 µs
Vacuum pressure: p=10^{-5} mbar (N2)

Large beam power → Non-intercepting method:
⇒ Beam Induced Fluorescence BIF
N_2 + Ion → (N_2^+)^+ Ion → N_2^+ + γ + Ion
With single photon detection scheme
⇒ installation of seven BIF-stations
Multi Particle Simulations (LEBT – SIS18-Injection)

- LEBT (PARMILA-Transport)
- RFQ (PARMTEQ)
- IH-Section (LORAS)
- 1.4 MeV/u-Stripper Section (PARMILA-Transport)
- ALVAREZ (PARMILA)
- Single Gap Resonators (PARMILA-Transport)
- Transfer Line (PARMILA-Transport)
- 11.4 MeV/u-Stripper Section (PARMILA-Transport)
- Matching SIS 18 (PARMILA-Transport)

no further upgrade measures considered!
Space Charge Forces (for high current uranium beams) ...
Transversal Emittance (90%)

Normalized UNILAC Emittance [$\pi\cdot$mm*mrad]

- Horizontal
- Vertical
- Horizontal (l=0)
- Vertical (l=0)

no further upgrade measures considered!
Outlook

Transversal Emittance (90%)

Normalized UNILAC Emittance \( \pi \cdot \text{mm} \cdot \text{mrad} \)

Transmission [%]

Horizontal, \( \varepsilon \) verkl.

Horizontal (Gauss)

Transmission

end to end

16.5 mA (U\(^{4+}\))

3.9 mA (U\(^{73+}\))
Backup
RFQ-Upgrade: Modified Input Radial Matcher

Matching 1999

Matching 2004
HSI-LEBT Upgrade

Upgrade 0
- High Current test stand measurements

Upgrade I
- Switching magnet with increased aperture
- Quadrupole quartet (matching to the RFQ) with increased apertures

Upgrade II (Compact LEBT)
- Beam line with direct injection to the RFQ (integrated into the existing layout)

Previous simulations: Compact LEBT + New RFQ → 20 mA behind RFQ!
Beam commissioning of the Charge State Separator system

**Charge Separation**

40AR^{18+}-Beam Emittances (90 %)

<table>
<thead>
<tr>
<th></th>
<th>high current</th>
<th>low current</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4 \cdot \varepsilon_{\text{rms}} \ [\mu m])</td>
<td>hor.</td>
<td>vert.</td>
</tr>
<tr>
<td>behind D II</td>
<td>9.0</td>
<td>17.6</td>
</tr>
<tr>
<td>SIS injection</td>
<td>5.5</td>
<td>8.1</td>
</tr>
</tbody>
</table>

**Beam Dynamics**

**High Current Emittance Growth**

- D I + D II
- D III + D IV
- foilstripper
- charge separation
Reduction of Mismatch

• new algorithm used to rms-match a (measured) initial distribution to periodic DTL
• test of matching by re-measuring emittance growth

• significant reduction of emittance growth by rms-matching including space charge