Development of the UNILAC towards a Megawatt Beam Injector

W. Barth, GSI - Darmstadt

1. GSI Accelerator Facility – Injector for FAIR
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Future Internationale Accelerator Facility at GSI: FAIR (Facility for Antiproton and Ion Research)

Status Quo

UNILAC

Linac Upgrade for SHE

p-linac

HITRAP

FAIR

Linac Upgrade for SHE
Development of the UNILAC towards a Megawatt Beam Injector, W. Barth

Future Internationale Accelerator Facility at GSI: FAIR (Facility for Antiproton and Ion Research)

Status Quo

Beams now:
Z = 1 – 92
(protons to uranium)
up to 2 GeV/nucleon

FAIR

Beams in the future:
100 – 1000 fold intensity
Z = -1 – 92
(protons to uranium plus anti-matter, i.e. anti-protons)
up to 35 - 45 GeV/nucleon
Development of the UNILAC towards a Megawatt Beam Injector, W. Barth
Multi Particle Simulations (LEBT - SIS-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)
Space Charge Forces (for high current uranium beams) ...

\[ SCP \sim I_{\text{part}}^q q^2 \beta^{-1} (XYZ)^{-1} \]

- \( \text{U}^{4+} \) 15 emA
- \( \text{U}^{28+} \) 12.6 emA
- \( \text{U}^{73+} \) 3.9 emA
## SIS 18 – Intensity Upgrade Program and requirements for FAIR

(a twentyfold mutiturn injection is supposed)

<table>
<thead>
<tr>
<th>ION SPECIES</th>
<th>HSI entrance</th>
<th>HSI exit</th>
<th>Alvarez entrance</th>
<th>SIS 18 injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}^{4+}$</td>
<td>$^{238}\text{U}^{4+}$</td>
<td>$^{238}\text{U}^{28+}$</td>
<td>$^{238}\text{U}^{28+}$</td>
<td></td>
</tr>
<tr>
<td><strong>El. Current [mA]</strong></td>
<td>16.5</td>
<td>15</td>
<td>12.5</td>
<td>8.4*</td>
</tr>
<tr>
<td><strong>Part. per 100µs pulse</strong></td>
<td>$2.6 \cdot 10^{12}$</td>
<td>$2.3 \cdot 10^{12}$</td>
<td>$2.8 \cdot 10^{11}$</td>
<td>$1.9 \cdot 10^{11}$*</td>
</tr>
<tr>
<td><strong>Energy [MeV/u]</strong></td>
<td>0.0022</td>
<td>1.4</td>
<td>1.4</td>
<td>11.4</td>
</tr>
<tr>
<td><strong>$\Delta W/W$</strong></td>
<td>-</td>
<td>$\pm 4 \cdot 10^{-3}$</td>
<td>$\pm 2 \cdot 10^{-3}$</td>
<td>$\pm 2 \cdot 10^{-3}$</td>
</tr>
<tr>
<td><strong>$\varepsilon_{n,x}$ [mm mrad]</strong></td>
<td>0.3</td>
<td>0.5</td>
<td>0.75</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>$\varepsilon_{n,y}$ [mm mrad]</strong></td>
<td>0.3</td>
<td>0.5</td>
<td>0.75</td>
<td>2.5</td>
</tr>
</tbody>
</table>

* in SIS-acceptance, as expected from multiparticle calculation
Unilac-Measures (since 2002)

- 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 (S. Yaramishev, MOP08)
- Reduction of the number of Single Gap Resonators
- Alignment
- High Current Beam Diagnostics (A. Peters, MO202)
## MUCIS- & MEVVA- Ion Sources

### HSI-INJECTION DESIGN

<table>
<thead>
<tr>
<th>Ion</th>
<th>HSI-INJECTION</th>
<th>DESIGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_3^+$</td>
<td>1.0 mA</td>
<td>0.8 mA</td>
</tr>
<tr>
<td>D$_3^+$</td>
<td>2.0 mA</td>
<td>1.6 mA</td>
</tr>
<tr>
<td>$^{12}$C$^+$</td>
<td>7.0 mA</td>
<td>3.2 mA</td>
</tr>
<tr>
<td>$^{14}$N$^+$</td>
<td>4.0 mA</td>
<td>3.8 mA</td>
</tr>
<tr>
<td>$^{18}$O$^+$</td>
<td>5.0 mA</td>
<td>4.8 mA</td>
</tr>
<tr>
<td>$^{20}$Ne$^+$</td>
<td>5.5 mA</td>
<td>5.4 mA</td>
</tr>
<tr>
<td>CO$^+$</td>
<td>6.0 mA</td>
<td>8.1 mA</td>
</tr>
<tr>
<td>Ar$^{1+}$</td>
<td>19.0 mA</td>
<td>10.8 mA</td>
</tr>
<tr>
<td>Kr$^{2+}$</td>
<td>8.0 mA</td>
<td>11.6 mA</td>
</tr>
<tr>
<td>Xe$^{2+}$</td>
<td>0.75 mA</td>
<td>17.4 mA</td>
</tr>
</tbody>
</table>

### MUCIS (Multi Cusp Ion Source)

- Emission Current Density $\leq$ 150 mA/cm$^2$

### MEVVA (MEtal Vacuum Vapor Arc Ion Source)

- Emission Current Density $\leq$ 150 mA/cm$^2$

### Development of the UNILAC towards a Megawatt Beam Injector, W. Barth
RFQ-Upgrade: New RFQ-Rods

After 5 years of operation

New RFQ-rods

After copper-plating

Development of the UNILAC towards a Megawatt Beam Injector, W. Barth
**RFQ-Upgrade: Modified Input Radial Matcher**

Matching 1999

NP1 = 1  
NP2 = 9  

80.00 mm (Horiz) 30.0 Deg (Long.)  

Length = 2722.65 mm

Matching 2004

NP1 = 1  
NP2 = 9  

80.00 mm (Horiz) 30.0 Deg (Long.)  

Length = 2722.65 mm
Test Bench Measurements in the HSI-LEBT (8 emA, U⁴⁺)

Emittance Growth: -19 % (3 %)
Transmission: 70 % (84 %)

before Quadrupole Quartet

1999

2004
HSI-RFQ-Commissioning (7/2004)

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

**Graph:**

- **X-axis:** RFQ-Amplitude [V]
- **Y-axis:** RFQ-Transmission [%]

- **Legend:**
  - Red circles: April 2004
  - Blue diamonds: July 2004

- **Data Points:**
  - April 2004: 
    - 3.0 V: 10%
    - 4.0 V: 20%
    - 5.0 V: 30%
    - 6.0 V: 40%
    - 7.0 V: 50%
  - July 2004: 
    - 3.0 V: 20%
    - 4.0 V: 30%
    - 5.0 V: 40%
    - 6.0 V: 50%
    - 7.0 V: 60%

- **Working Point:**
  - April 2004: 6.0 V, 50%
  - July 2004: 6.0 V, 60%

**Development of the UNILAC towards a Megawatt Beam Injector, W. Barth**
IH 2: Longitudinal Mismatch

\[ U_{IH2} = 8.15 \text{ V} \]

\[ U_{IH2} = 8.25 \text{ V} \]

\[ U_{IH2} = 8.45 \text{ V} \]
Increased Stripper Gas Density

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

$P_{\text{stripper}}$ [Torr]

- $I_{\text{analyzed}}$ [emA]
- 90%-emittance [mm*mrad]

- beam emittance
- beam brilliance

- $I$ (analyzed)
Alvarez-Matching

Emittance Measurement before the DTL, 3.5 emA U²⁺

Betafunction (before Matching)

Alvarez DTL-Transmission: 92 % (before) 99 %. (after)

Betafunction (after Matching)

(S. Yaramishev, MOP08)
Status of the UNILAC High Current Performance

**Beam Brilliance**

- \( \text{Ar}^{10+} \)
- \( \text{Ar}^{18+} \)

**Beam transmission**

- \( \text{Ar}^{-} \text{-Transmission} \% \)

Development of the UNILAC towards a Megawatt Beam Injector, W. Barth
Status of the UNILAC Uranium-Performance

DEVELOPMENT OF THE UNILAC TOWARDS A MEGAWATT BEAM INJECTOR, W. BARTH

Development of the UNILAC towards a Megawatt Beam Injector, W. Barth
## Status of the UNILAC Uranium-Performance II

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>Design</th>
<th>required for FAIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}^{4+}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. Beam Intensity, (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 @545 kW</td>
<td>15 emA @1250 kW</td>
<td>16 emA @1500 kW</td>
</tr>
<tr>
<td>Transv. Emittance (LEBT) (90%, total)</td>
<td>140 $\pi \cdot \text{mm} \cdot \text{mrad}$</td>
<td>120 $\pi \cdot \text{mm} \cdot \text{mrad}$</td>
<td>120 $\pi \cdot \text{mm} \cdot \text{mrad}$</td>
</tr>
<tr>
<td>Macropulse Length</td>
<td>150 $\mu$s</td>
<td>150 $\mu$s</td>
<td>150 $\mu$s</td>
</tr>
<tr>
<td>Reproducibility/Transversal Emittance</td>
<td>$\pm 4.5%$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Beam loading, 6emA (IH2)</td>
<td>300 kW</td>
<td>590 kW (15 emA)</td>
<td>710 kW (15 emA)</td>
</tr>
<tr>
<td>$^{238}\text{U}^{28+}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. Beam Current, (1.4 MeV/u)</td>
<td>5.0 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>4.5 emA @440 kW $1.0 \cdot 10^{11}$</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>$^{238}\text{U}^{73+}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. Beam Intensity, 11.4 MeV/u, Ions/100$\mu$s</td>
<td>2.0 emA $1.7 \cdot 10^{10}$</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>10.0 $\pi \cdot \text{mm} \cdot \text{mrad}$</td>
<td>5.0 $\pi \cdot \text{mm} \cdot \text{mrad}$</td>
<td>7.0 $\pi \cdot \text{mm} \cdot \text{mrad}$</td>
</tr>
</tbody>
</table>
Further Upgrade Measures (2005-2009)

- High Current Test Bench for the investigation of the Ion Source (Post acceleration)
- Dedicated U$^{4+}$-High Current-Frontend (Compact-LEBT@RFQ)
- Further investigation of the high current matching to Alvarez-DTL
- Increased zero current phase advance in the Alvarez-DTL
- High Current Beam Diagnostics in the whole UNILAC
- Compact Charge Separator for the separation of U$^{73+}$ under sc-conditions
- Further development of simulation tools
- Extended High Current UNILAC machine experiments
Main Upgrade Measures (2005-2009)

**Alvarez-Upgrade (new Power Supplies)**

- $\Delta \Phi_0 = 39^\circ$
- $\Delta \Phi_0 = 51^\circ$

**Dedicated U$^{4+}$ Frontend-System**

**High Current Beam Diagnostics**

**Compact Charge Separator**

Development of the UNILAC towards a Megawatt Beam Injector, W. Barth
Example of UNILAC 3-Beam Operation

MEVVA
$^{238}\text{U}^{4+}$: 1 Hz / 0.3 ms

ECR
$^{12}\text{C}^{2+}$: 50 Hz / 5.0 ms

PIG
$^{208}\text{Pb}^{9+}$: 50 Hz / 5.0 ms

20 ms

1000 ms

Mixed Mode Poststripper

Development of the UNILAC towards a Megawatt Beam Injector, W. Barth
Upgrade of the UNILAC for Super Heavy Element Production

- 50% duty factor (presently: 25%, $A/\xi \leq 8$)
- intensity-gain factor $x2$

New rfq-tank:
- gain of the duty factor
- higher injection energy
- increased acceptance

Additional 28 GHz-ion-source:
- intensity gain of factor two
- higher charge states for increased duty factor

LEBT – Laminated magnets:
- redundancy for ion sources
- preparation for future pulse to pulse operation

10 Single gap resonators

Alvarez
## Proton Linac

### Source
- **H⁺, ECR, 95 keV, 110 mA**

### LEBT
- 2-solenoid focusing
- 95 keV, 100 mA, 0.3 µm*

### RFQ (4-rod or 4-windows)
- 3 MeV, 90 mA, 0.4 µm*
  *(norm., rms)*

### DTL – Section
- rel. momentum spread
- rf pulse length
- beam pulse length
- max. repetition rate
- 352.21 MHz, rt,
- 11 CH-structures
- 70 MeV, 70 mA, 2.8 µm**
- ± 5 ·10⁻⁴
- 250 µs
- 100 µs
- 5 Hz
  ***(norm., tot)***

### Output Power
- **W_{out} = 70 MeV**
- **I = 70 mA**

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L. Groening, MOP06
R. Tiede, MOP12
Z. Li, MOP20
A. Schempp, THP11
**Development of the UNILAC towards a Megawatt Beam Injector, W. Barth**

**Decelerator for the Heavy Ion TRAP**

<table>
<thead>
<tr>
<th>HITRAP Section</th>
<th>Energy [MeV/u]</th>
<th>ΔT/T</th>
<th>$\varepsilon_{x,y} (= \varepsilon_{x,y})$</th>
<th>$\varepsilon_x (= \varepsilon_y)$</th>
<th>total Transmission</th>
<th>particles/spill</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESR</td>
<td>5.0</td>
<td>4.8 $\times$ 10^{-4}</td>
<td>0.093</td>
<td>0.9</td>
<td></td>
<td>1 $\cdot$ 10^{6} measured</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>2 $\times$ 10^{-4}</td>
<td>0.1</td>
<td>1.0</td>
<td>100%</td>
<td>(6 $\cdot$ 10^{5}) estimated</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>2 $\times$ 10^{-4}</td>
<td>0.06</td>
<td>0.7</td>
<td></td>
<td>2 $\cdot$ 10^{5} measured</td>
</tr>
<tr>
<td>Entrance Prebuncher</td>
<td>4.0</td>
<td>4.8 $\times$ 10^{-4}</td>
<td>0.2</td>
<td>2.2</td>
<td>100%</td>
<td>6 $\cdot$ 10^{5}</td>
</tr>
<tr>
<td>Entrance IH</td>
<td>4.0</td>
<td>$\pm$ 1.3 $\times$ 10^{-2}</td>
<td>0.2</td>
<td>2.2</td>
<td>28%</td>
<td>1.7 $\cdot$ 10^{5}</td>
</tr>
<tr>
<td>Exit IH / Entr. RFQ</td>
<td>0.5</td>
<td>$\pm$ 2 $\times$ 10^{-2}</td>
<td>0.24</td>
<td>7.3</td>
<td>28%</td>
<td>1.7 $\cdot$ 10^{5}</td>
</tr>
<tr>
<td>Exit RFQ</td>
<td>0.006</td>
<td>$\pm$ 7 $\times$ 10^{-2}</td>
<td>0.37</td>
<td>100</td>
<td>26%</td>
<td>1.5 $\cdot$ 10^{5}</td>
</tr>
<tr>
<td>LEBT, entrance of trap</td>
<td>0.006</td>
<td>$\pm$ 7 $\times$ 10^{-2}</td>
<td>0.37</td>
<td>100</td>
<td>21%</td>
<td>1.2 $\cdot$ 10^{5}</td>
</tr>
</tbody>
</table>
Summary

- An extended upgrade program in the UNILAC in combination with machine investigations resulted in a seven times higher uranium beam intensity offered for the injection into the synchrotron SIS 18. 2.0 emA (73+), 4.5 emA (28+) → 0.45 MW beam power

- Mainly the improved ion source performance, an upgrade of the HSI-structures, the increased stripper gas density, the optimization of the Alvarez-matching, and the use of various newly developed beam diagnostics devices were responsible for the successful development program.

- FAIR-requirements: The UNILAC-upgrade will be continued with the investigation of a new front end for U⁴⁺, stronger power supplies for the Alvarez quads, a charge state separator system and beam diagnostics devices, sufficient for the operation with megawatt heavy ion beams.

- Primary proton beam intensities will be increased by a new proton linac (to be commissioned in 2007).

- The decelerator for the HITRAP should be ready for operation in 2008.

- Advanced SHE experimental program: Improvement of the average target luminosity for medium heavy ions in the MeV/u-range (linac development program 2005-2009).