A superconducting cw-LINAC for heavy ion acceleration at GSI

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A superconducting CW-LINAC for heavy ion acceleration at GSI

Winfried Barth, GSI & HIM & MEPhI

1. Introduction
2. Status of the Unilac High Current Performance
3. Cavity Development
4. General linac layout
5. R&D approach
6. Status of demonstrator linac
7. Advanced R&D
8. Summary&Outlook
The GSI **UNI**versal **Lin**ear **AC**celerator

High Charge State Injector (1991)

- MUCIS, MEVVA
- LEBT
- HSI (RFQ, IH1, IH2)
- HLI (ECR, RFQ, IH)
- Poststripper (Alvarez, Cav.)
- Gas Stripper
- TK
- Foil Stripper

High Current Injector (1999)

- PIG
- 36 MHz
- 108 MHz

Alvarez (1975)

- Single Gap Resonators (1975)

1 pμA, $^{48}$Ca (ECR)
1 pμA, $^{50}$Ti (PIG/ECR)
10 emA, $^{238}$U (0.03%, MeVVa)

to SIS 18

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Development of compact, high efficient, (high intensity) heavy ion linac...

How to shorten the lengths of a heavy ion accelerator?

Mar 1983; Particle accelerator conference; Santa Fe, NM (USA):

- Very complex ion sources
- Ion sources to be optimized for high intensity high charge state beams
- Low charge/mass ratio → High field gradient/long accelerating structure
- Stripping losses → intensity requirements
- Highest linac energy → stripping to the highest possible charge state for max. final beam energy
High Power Heavy Ion Accelerator projects → driving force for ion source, accelerator cavity development

...most of planned heavy ion beam injection intensities have not been achieved so far...

NICA / HILAC Au$^{31+}$ 10emA

GSI/FAIR U$^{28+}$ 15emA

RIKEN RIBF U$^{35+}$ 525 eµA

LHC Pb$^{27+}$ 1 emA

FRIB U$^{76+}$ + ... + U$^{80+}$ 700 eµA

MP HIRFL U$^{41+}$ 100 eµA

RAON/Korea U$^{79+}$ 8.3 pµA (200 MeV/u)
Facility for Antiproton and Ion Research

Upgraded existing facility: ion-beam source and injector for FAIR

Primary beams: protons to $^{238}$U

New future facility: ion and anti-matter beams of highest intensities and high energies

Accelerator Components & Key Characteristics

<table>
<thead>
<tr>
<th>Ring/Device</th>
<th>Beam</th>
<th>Energy</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIS 100 (100Tm)</td>
<td>protons</td>
<td>30 GeV</td>
<td>$4 \times 10^{13}$</td>
</tr>
<tr>
<td></td>
<td>$^{238}$U</td>
<td>1 GeV/u</td>
<td>$5 \times 10^{11}$ (intensity factor 100 over present)</td>
</tr>
<tr>
<td>SIS 300 (300Tm)</td>
<td>$^{40}$Ar</td>
<td>45 GeV/u</td>
<td>$2 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>$^{238}$U</td>
<td>34 GeV/u</td>
<td>$2 \times 10^{10}$</td>
</tr>
<tr>
<td>CR/RESR/NESE</td>
<td>ion and antiproton storage and experiment rings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HESR</td>
<td>antiprotons</td>
<td>14 GeV</td>
<td>$\sim 10^{11}$</td>
</tr>
<tr>
<td>Super-FRS</td>
<td>rare isotope beams</td>
<td>1 GeV/u</td>
<td>$&lt; 10^9$</td>
</tr>
</tbody>
</table>

FAIR-design uranium beam parameters at the UNILAC

<table>
<thead>
<tr>
<th></th>
<th>HSI entrance</th>
<th>HSI exit</th>
<th>Alvarez entrance</th>
<th>SIS 18 injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion species</td>
<td>$^{238}$U$^{++}$</td>
<td>$^{238}$U$^{++}$</td>
<td>$^{238}$U$^{28+}$</td>
<td>$^{238}$U$^{28+}$</td>
</tr>
<tr>
<td>Elect. Current [mA]</td>
<td>25</td>
<td>18</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Part./100μs pulse</td>
<td>$3.9 \times 10^{12}$</td>
<td>$2.8 \times 10^{12}$</td>
<td>$3.3 \times 10^{11}$</td>
<td>$3.3 \times 10^{11}$</td>
</tr>
<tr>
<td>Energy [MeV/u]</td>
<td>0.0022</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>$\Delta W/W$</td>
<td>-</td>
<td>$4 \times 10^{-3}$</td>
<td>$\pm 1 \times 10^{-2}$</td>
<td>$\pm 2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\varepsilon_{\text{beam,x}}$ [mm mrad]</td>
<td>0.3</td>
<td>0.5</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>$\varepsilon_{\text{beam,y}}$ [mm mrad]</td>
<td>0.3</td>
<td>0.5</td>
<td>0.75</td>
<td>2.5</td>
</tr>
</tbody>
</table>

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Pushing the limits for uranium beam operation

**High Current Injector**

- **Ion Source:** Applying a multi-aperture extraction system at the VARIS ion source → Increased U⁴⁺-intensity and improved primary beam brilliance

- **Low Energy Beam Transport:** Improved LEBT-performance and RFQ-Matching using high brilliance uranium beam from the VARIS → 70% RFQ-Transmission \((I_{\text{out}} = 9.7 \text{ emA})\)

- **RFQ:** RF optimization by adjusting plunger positions at the HSI RFQ tank and extensive rf-conditioning → Reduction of forwarded rf-power, yielding for reliable high-current uranium beam operation.

- **MEBT:** Optimizing the between RFQ and IH DTL by increasing the transverse and longitudinal focusing strength (3%) → Reduction of beam loss, stable high current operation

- **1.4 MeV/u-Transport Line:** Adapting the quadrupole channel (matching the gas stripper) → 90% beam transmission, U⁴⁺ beam current of 7.4 emA available for heavy ion stripping.
Heavy Ion Stripping

P. Scharrer, et al. @HIAT2015, W. Barth, et al. @IPAC2016, W. Barth, et al. @HB2016

- For high intensive heavy ion beams → Increase of the so called „ionic charge“ by collision with matter (= STRIPPING, Removal of electrons)
  → Reduction of the necessary effective potential for the acceleration of ions.
- Collision of heavy ions with matter → e− capture (∼ Z5) and e− loss (∼ Z4)
- (Pulsed) H2 gas stripping cell with target thickness > 10 μg/cm²

<table>
<thead>
<tr>
<th></th>
<th>N2-gas jet [8]</th>
<th>H2-gas cell (pulsed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back-pressure</td>
<td>0.4 MPa</td>
<td>12.0 MPa</td>
</tr>
<tr>
<td>U28+-current</td>
<td>6.0 emA</td>
<td>7.4 emA</td>
</tr>
<tr>
<td>Stripping charge state</td>
<td>28+</td>
<td>29+</td>
</tr>
<tr>
<td>Stripping efficiency</td>
<td>12.7±0.5%</td>
<td>21.0±0.5%</td>
</tr>
<tr>
<td>Energy loss</td>
<td>14±5 keV/u</td>
<td>60±5 keV/u</td>
</tr>
<tr>
<td>Max. current</td>
<td>4.5 ±10 emA</td>
<td>11.5 ±10 emA</td>
</tr>
<tr>
<td>εx (90%, tot.)</td>
<td>0.76 μm</td>
<td>0.51 μm</td>
</tr>
<tr>
<td>εx (90%, tot.)</td>
<td>0.84 μm</td>
<td>0.96 μm</td>
</tr>
<tr>
<td>Hor. brilliance (90%)</td>
<td>5.32 mA/μm</td>
<td>20.29 mA/μm</td>
</tr>
</tbody>
</table>

Beam Energy Loss:

<table>
<thead>
<tr>
<th></th>
<th>N2-jet (max.)</th>
<th>14±5 keV/u</th>
</tr>
</thead>
<tbody>
<tr>
<td>U28+</td>
<td>Pulsed H2-stripper cell (7.5 MPa)</td>
<td>35±5 keV/u</td>
</tr>
<tr>
<td>U29+</td>
<td>Pulsed H2-stripper cell (12.0 MPa)</td>
<td>60±5 keV/u</td>
</tr>
</tbody>
</table>

@1.4 MeV/u gas stripper section

H2 (pulsed) gas cell

N2 gas jet

Beam energy loss at 1.4 MeV/u gas stripper section

Charge distribution

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Status of the Unilac High Current Performance

- **LEBT**
  - October 14: 16 emA
  - November 14: 12 emA
  - October 15: 12 emA
  - July 16: 8 emA
  - Design: 16 emA

- **HSI**
  - October 14: 12 emA
  - November 14: 8 emA
  - October 15: 8 emA
  - July 16: 4 emA
  - Design: 12 emA

- **U^{28+}**
  - October 14: 16 emA
  - November 14: 12 emA
  - October 15: 12 emA
  - July 16: 8 emA
  - Design: 16 emA

- **U^{4+}**
  - October 14: 12 emA
  - November 14: 8 emA
  - October 15: 8 emA
  - July 16: 4 emA
  - Design: 12 emA
How to use a heavy ion machine for acceleration of high intensity p+-beams?

- ** Ion source**
  - Methan
  - CH$_3^+$ acceleration
    - using HSI heavy ion capability for acceleration of hydrocarbon compounds
  - cracking of compounds + stripping

- C$^6+$ acceleration (6 emA)
- H$^+$ acceleration (3 emA)
High intensity proton beam measurements at GSI-UNILAC

\[
\begin{align*}
    H_3^+ & \rightarrow (3)p^+ \\
    CH_3^+ & \rightarrow (3)p^+ \\
    C_3H_7^+ & \rightarrow (7)p^+
\end{align*}
\]

Ion current [mA]

- LEBT
- RFQ
- HSI
- Gasstripper
- Alvarez
- Single Gap Res.
- TK
- Emittance @TK

- April 14
- May 14
- July 14
- July 16
- October 15

p⁺ - design limit
Requirements for FAIR and the SHE-program

**FAIR requirements:**
- extremely high pulse intensities
- low repetition rate (max. 3 Hz)
- low duty factor (0.1 %) (pulse length for SIS18 only 100 µs)
- (advanced heavy ion species from ECR ion source)

**“Super Heavy Element” requirements:**
- relatively high pulse intensities
- high repetition rate (50 Hz)
- high duty factor (-> 100 %) (pulse length up to 20 ms)
H-type Cavity Developments

HSI 36 MHz@gsi
HLI 108 MHz@gsi
IH 216 MHz@HIT/Heidelberg

Wideröe
Alvarez

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Motivation and Main Design Parameter

- Reactions at coulomb barrier $\rightarrow$ production of SHE

- Operation $\text{cw}$
- Mass / Charge 6
- Beam current $\leq 1$ mA
- Injection energy 1.4 MeV/u
- Output energy 3.5 - 7.3 MeV/u

Production of element $^{288}_{115}$uut, $^{289}_{115}$uut, 30 events

(D. Rudolph, Lund Univ., PRL 111, 112502 (2013))

<table>
<thead>
<tr>
<th></th>
<th>GSI- Unilac</th>
<th>cw-Linac</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam intensity(particle/s)</td>
<td>$6 \cdot 10^{12}$</td>
<td>$6 \cdot 10^{13}$</td>
</tr>
<tr>
<td>Beam on target</td>
<td>3 weeks</td>
<td>2 days</td>
</tr>
</tbody>
</table>
Superconducting CW-LINAC Layout
(S. Minaev, 2009)

- Multigap CH-cavities
- Small number of rf cavities and short cavity lengths (up to 1 m)
- acc. gradient of 5 MV/m $\rightarrow$ compact linac design
- Several cavities, solenoids per cryostat
- Modular construction
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Step 0: CW-LINAC Demonstrator@GSI

Technical challenges:

- Design and production of the sc CH-cavity
- Constant alignment of the components during cool-down
Design of Cryomodule by Cryogenic

Trial Design Aug. 2010

Frame with Cavity and Solenoids

Final Design

Assembly
Delivery to GSI (19.11.15)

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Cryomodule-assembly @ GSI

- Frame with the dummy cavity
- „Dry“ cooling of sc-solenoids
- Special suspension of components preserves alignment during cooldown
First cool down test @ GSI (17.12.15)

- Cryostat installed in cw-bunker
- Temperature is monitored during cooldown
- sc-Solenoids were ramped at 9.3 T
- Standby losses of cryostat 3W
- Drift of components during cooldown +-0.15mm
Cross Bar H-Mode Accelerating Cavity

- Drift tubes are alternating connected to “+” and “-” potential
- Cross bar H-mode cavity → CH-cavity
CH-Cavity for Demonstrator @ 216.8 MHz
(F. Dziuba, Ph. D thesis)

Production @ RI
delivery September 2016

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>0.059</td>
</tr>
<tr>
<td>Frequency</td>
<td>216.816 MHz</td>
</tr>
<tr>
<td>Cells</td>
<td>15</td>
</tr>
<tr>
<td>Length $\beta\lambda$-def (mm)</td>
<td>691</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>409</td>
</tr>
<tr>
<td>Cell length</td>
<td>40.82</td>
</tr>
<tr>
<td>$E_a$ (MV/m)</td>
<td>5.1</td>
</tr>
<tr>
<td>$B_p/E_a$</td>
<td>5.2</td>
</tr>
</tbody>
</table>

- Transverse size & efficiency → $2 \times 108.408$ MHz = 216.816 MHz
Cavity Production @ RI
(Bergisch Gladbach, Germany)

cavity inside

rf-coupler flanges

bellow tuner

cavity with end caps
Quality Factor $Q$ vs $E_a$ for CH-Demonstrator

(F. Dziuba, Ph. D thesis)

- RF-testing is completed
- $Q_0 = 5 \times 10^8$ @5 MV/m (design acc. gradient)
- Demonstrator cavity is in final production step (welding of He-reservoir)
- Accelerating gradient can be increased by high pressure rinsing and Ar-discharge
Transverse Emittance Measurement at cw Demonstrator @ July 2015

- Beam test of the matching line
- Measurement of transverse emittance at side of cw-demonstrator
- Reliable information about transverse emittance at exit of HLI for design of Advanced Demonstrator
Step 1&2: Advanced Demonstrator@GSI

- The standard cryomodule contains 2 cavities and 1 solenoid
- Cavity 2&3 are already in production. Delivery @ Q1 of 2017
- Tendering for cryostat @ Q4 of 2016
- Advanced demonstrator allows first experiment at coulomb barrier for light and medium heavy ions
Infrastructure @ HIM

- Ready to move in
- High Pressure Rinsing (HPR)
- RF testing (warm & cold cavities)
- Cleanroom environment
- Optional: setup for BCP
Recent delivery of components

108 MHz-rebuncher

Clean room upgrade @GSI
(class ISO 5 (required: ISO 6), at FFU unit: class ISO 2 (required: ISO4))

High Power rf coupler
Summary

- Matching line is tested
- Liquid He infrastructure is tested
- Cold test of entire Demonstrator cryostat (incl. dummy cavity)
- sc-solenoids ($B = 9.3$ T) successfully tested
- RF-testing of Demonstrator cavity is completed @GUF
- Demonstrator cavity is in final production step
- 2nd Rebuncher cavity ready for commissioning
- New clean room@GSI available
- 2 Power coupler delivered
- Power coupler test bench in preparation
- Production of two further (short) CH-cavities already started
- Standard cryostat is defined
Schedule of activities 2016

- April&July: First beam tests with cryostat
  - 3D matching
  - sc-solenoids
  - bunch structure monitor
- July: commissioning of local clean room
- >August: delivery of power coupler and rf-conditioning
- September: Commissioning/Rebuncher
- October: rf-test of demonstrator cavity at site
- November: beam test of fully equipped cryostat (CH-cavity+solenoids)
- Next steps:
  - Further Improvement of the demonstrator cavity
  - Ordering of standard cryostats
  - Commissioning of infrastructure @ HIM
  - Delivery of “short” cavity
Further strategy I

2015

2019
Further strategy II

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Further strategy III

**cw-HLI Upgrade**

**cw-RFQ**

@GSI-workshop 2/2009

**GOAL:**
- Higher Charge State → higher energy gain
- Higher Charge State → higher beam intensity without stripping
- Higher heavy ion beam intensity → cw-/ pulse-mode operation
- Compact accelerator → lower cost
Further strategy IV

International collaborations:
- MEPhI (Russia)
- ITEP (Russia)
- JINR (Russia)?
- ANU (Australia)?
- MSU (U.S.A.)?
- TRIUMF (Canada)?
- RISP (Korea)?
- ESS (Sweden)?
- ...

S. Polozov (MEPhI), W. Barth (GSI, HIM, MEPhI), T. Kulevoy (ITEP), S. Yaramyshev (GSI, MEPhI), „cw-LINAC RFQ development“, proc. of HB-2016, Malmö, Sweden, (2016)
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M. Amberg, former HIM

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M. Busch, GUF-IAP
M. Basten, GUF-IAP
D. Mäder, GUF-IAP
U. Ratzinger, GUF-IAP
Thank You for Your attention!
Backup
Loss free (high current) U^{28+}-beam injection into the GSI-synchrotron SIS18

- UNILAC beam measurement at 1.4 MeV/u
- Reduced UNILAC beam brilliance at SIS18 injection
- SIS18-beam intensity to achieve space charge limit (2\times10^{11} part. per pulse)
- SIS18-beam intensity after multi turn injection \( I_{scl} = 187.5 \text{ emA} \)

![Graph showing beam intensity and emittance](image)
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³IAP, Goethe University, Frankfurt, Germany
⁴KPH, Johannes Gutenberg-University, Mainz, Germany
⁵National Research Nuclear University - Moscow Engineering Physics Institute, Moscow, Russia

Recently the Universal Linear Accelerator UNILAC serves as a powerful high duty factor (25%) heavy ion facility for the ambitious experiment program at GSI. Beam time availability for SHE (Super Heavy Element)-research will be decreased, as UNILAC should provide Uranium beams for FAIR (Facility for Antiproton and Ion Research at Darmstadt) with an extremely high peak current but low duty factor. To keep the GSI-SHE program competitive on a high level and even beyond, a standalone superconducting continuous wave (100% duty factor) linac in combination with the upgraded GSI High Charge State injector is envisaged. In preparation for this, the first linac section (financed by HIM and GSI) since 2016 is under tests with beam, demonstrating the future experimental capabilities. Further on the construction of an extended cryo module, comprising two shorter Crossbar-H cavities, is foreseen to be tested until end of 2017. As a final R&D step towards an entire linac, three advanced modules should be built until 2019, serving for first user experiments at the Coulomb barrier.