High Intensity Issues at FAIR

Oliver Kester
Institut für Angewandte Physik,
Goethe-Universität Frankfurt
and
GSI Helmholtzzentrum für Schwerionenforschung
for the FAIR @ GSI section
Outline

- Introduction
  - The FAIR heavy ion accelerators
  - The injectors at GSI

- FAIR accelerator challenges
  - High current ion sources
  - Linac beam dynamics and cavities
  - FAIR synchrotrons

- Outlook
Requirements to conduct world class experiments

- Beam intensity increase:
  - Primary beams: x 100 – x 1000 (4*10^{11} uranium ions and 2*10^{13} protons per spill)
  - Secondary beams: x 10,000

- Beams:
  - Anti protons
  - Protons to uranium
  - RIBs

- Beam quality:
  - Cooled anti proton beams
  - Cooled, intense RIBs

- Beam pulse structure:
  - extreme short pulses to quasi continuous

Modularized start version
Preparing the Injector Chain
Preparing the Injector Chain

UNILAC upgrade
High power (high intensity), short pulses
- Increase of beam brilliance (Beam current / emittance)
- Increase of transported beam currents
- Improvements of high current beam diagnostics / operation

Exchange of 35 years old Alvarez accelerator
With modern interdigital H-type structures
Higher intensities → 28 GHz ECRIS

SIS 18 upgrade
Fast ramping, enhanced intensity per pulse
- Increase of injection acceptance
- Improvement of lifetime for low-charged U-ions
- Increase of beam-intensity per time due to reduction of SIS18- cycle time
High current ion source issues
GSI high current sources

Filament driven

MUCIS, MUCIS New, CHORDIS

Working material:
Gases

Vacuum Arc driven

MEVVA, VARIS

Metalls and Gases

High Duty factor

PIG

Metalls and Gases

VARIS (Vacuum Arc Ion Source)

- Optimized for Uranium (67% of $^{238}\text{U}^{4+}$)
- Emission current density
  - $170\,\text{mA/cm}^2$
  - $156\,\text{mA} @ 32\,\text{kV}$
  - $55\,\text{mA} @ 131\,\text{kV}$
  - $20\,\text{mA}$ in front of the RFQ
  - $9\,\text{mA}$ behind the RFQ

- Improving the beam quality at plasma extraction
- Improvement of beam transport
- Lifetime of cathodes
- 3 Hz operation
VARIS (Vacuum Arc Ion Source)

- Optimized for Uranium (67% of 238U⁴⁺)
- Emission current density
  170 mA/cm²
  → 156 mA @ 32 kV
  → 55 mA @ 131 kV
  → 20 mA in front of the RFQ
  → 9 mA behind the RFQ

- Improving the beam quality at plasma extraction
- Improvement of beam transport
- Lifetime of cathodes
- 3 Hz operation
Beam transport → compact LEBT

Beam transport from the source to the RFQ was designed for several orders of magnitude lower intensities!

→ New Terminal and direct injection
→ Larger acceptance of LEBT components
ECR – Ion extraction and beam transport studies

\[ \omega_c = \frac{qB}{m} \]

Axial B field

Hexapole (Radial Magnetic Field)

Microwave Injection

Beam Extraction

Beam born in Magnetic field!

\[ f_B = 28 \text{ B}[T] \text{ (GHz)} \]

Plasma electrode 24 kV

Puller electrode -1.5 kV

Beam line potential

SuSI ECR extraction

-24000 V

-1500 V
ECR – Ion extraction and beam transport studies

**simulated beam profiles**

- **flat profile**
- **Hollow profile**

**Matched extraction**

**Mismatched extraction**

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**Plasma electrode** 24 kV
**Puller electrode** -1.5 kV
**Beam line potential**

**SuSI ECR extraction**

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**Graphs:**
- Total current: 99.18 µA
- CG: (-1.16, 1.50)
- RMS: (6.22, 7.67)
- Mask: (1.00, 2.00, 47.00, 45.00)

- Total current: 160.90 µA
- CG: (4.16, 3.87)
- RMS: (8.34, 10.89)
- Mask: (1.00, 2.00, 47.00, 45.00)
Unique tool: transverse beam collimation channel

Goal: Increase beam intensity into a given phase space → examples:
- NSCL - SUSI ECRIS collimation channel (M. Doleans et al.)
- Hahn Meitner Institute (ISL) ECR heavy ion injector (A. Denker et al.)

Use the channel as a tuning tool for optimized ion extraction parameters

- Set the channel at a given acceptance and optimize the beam brilliance

![Graph showing beam current after collimation channel](image-url)
LINAC issues
## 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\textsuperscript{U}^{4+}</strong></td>
<td></td>
<td></td>
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</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 $\pi\cdot$mm$\cdot$mrad</td>
<td>120 $\pi\cdot$mm$\cdot$mrad</td>
<td>120 $\pi\cdot$mm$\cdot$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>±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>258\textsuperscript{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 Ions/100$\mu$s</td>
<td>5.7 emA@567 kW $1.3\cdot10^{11}$</td>
<td>12.6 emA@1221 kW $2.8\cdot10^{11}$</td>
<td>15.0 emA@1453 kW $3.3\cdot10^{11}$</td>
</tr>
<tr>
<td><strong>273\textsuperscript{U}^{73+}</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. Beam Intensity, 11.4 MeV/u, Ionsen/100$\mu$s</td>
<td>2.7 emA $2.3\cdot10^{10}$</td>
<td>4.6 emA $3.9\cdot10^{10}$</td>
<td>3.5 emA $3.0\cdot10^{10}$</td>
</tr>
<tr>
<td>Transv. Emittance (11.4 MeV/u) (90%, tot.)</td>
<td>11.0 $\pi\cdot$mm$\cdot$mrad</td>
<td>5.0 $\pi\cdot$mm$\cdot$mrad</td>
<td>7.0 $\pi\cdot$mm$\cdot$mrad</td>
</tr>
</tbody>
</table>
H-type structures for FAIR

- FAIR-p-linac $\rightarrow$ 325 MHz-CH-prototype, room temperature
- ALVAREZ replacement $\rightarrow$ IH-structures (108 MHz)

Prototyping of a SC 325 MHz-CH structure @ Frankfurt
H-type structures and KONUS

- Negative synchronous phase structure: $\Phi_s = -30^\circ$
drift tubes with integrated quadrupoles

- $\Phi_s = -30^\circ$
Focusing (longitudinal & transversal) and acceleration

- KONUS beam dynamics

  $\Phi_s = -35^\circ$
  Lens
  $\Phi_s = 0^\circ$
  Rebuncher
  Main Acceleration
  $\Phi_s = 0^\circ$
  Lens

  separated sections of transverse and longitudinal focusing
  and of acceleration

  Combined 0-deg synchronous particle structure
H-type structures and KONUS

- KONUS beam dynamics

\[ \Phi_s = -30^\circ \]

- Negative synchronous phase structure:

- KONUS beam dynamics

- Combined 0-deg synchronous particle structure

separated sections of transverse and longitudinal focusing and of acceleration
Charge state stripper for intense heavy ion beams

C-foil stripper
- short lifetime at highest intensities, but highest charge states

Gas stripper
- High intensity capabilities, but lower charge states
- Equilibrium charge state (efficiency)

Unused foil

Edge of the foil before irradiation

Glowing of interaction region

N₂ @ up to 4500 mbar

n⁻238U⁴⁺ n⁻0.13⁻238U²⁺
Alternatives: Liquid Lithium or plasma stripper

**Plasma stripper**
- Need to increase the gas density – plasma window for differential pumping
- Dense plasma channel separated by plasma windows

**Liquid Li-stripper**
- Challenging to established a thin Li-film, stable with time and controllable thickness

MIT Plasma window in a test setup at BNL

Liquid Li stripper system under development at ANL

Heavy Ion Beam

Reminder:

\[ B_{x/y} := \frac{(q/A) \times \text{Current}}{\text{Emittance}_{x/y}} \]

- achieved UNILAC brilliances are similar
- horizontally we are not ok
- vertically we are ok

→ emittance transfer from horizontal to vertical plane should help
→ transfer should preserve \( \varepsilon_x \times \varepsilon_y \)
Emittance transfer

\[ E_x \cdot E_y = \text{const} \]

→ See poster of Chen Xiao (MOP207)
Synchrotron related issues
Requirements to conduct world class experiments

<table>
<thead>
<tr>
<th></th>
<th>SIS-18</th>
<th>SIS-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference primary ion</td>
<td>U^{28+}</td>
<td>U^{28+}</td>
</tr>
<tr>
<td>Reference energy</td>
<td>200 MeV/u</td>
<td>1.5 GeV/u</td>
</tr>
<tr>
<td>Ions per cycle</td>
<td>1.5E11</td>
<td>4E11</td>
</tr>
<tr>
<td>cycle rate (Hz)</td>
<td>2.7</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Protons from SIS-100:** 29 GeV, 2x10^{13}, 1 bunch, 0.2 Hz
Collective effects in the FAIR rings

Incoherent space charge:

→ Tune shift
→ Beam losses and modification of coherent effects

Impedances:
* image currents in the beam pipe
* magnetic/resistive materials: ferrite, magnetic alloy
→ coherent instabilities and feedback requirements

Secondary particles:
electron clouds created by residual gas ionization and secondary electron emission
→ trapping of electrons during slow extraction
two-stream instability.

In the FAIR synchrotrons SIS-18 and SIS-100 different incoherent/coherent effects occur simultaneously.

Numerical models are essential!

→ See talk of Oliver Boine-Frankenheim in TUO1A
Long term beam loss for a intense bunched beam

Example of resonances on SIS100: the space charge tune-spread crosses several resonances

→ Talk of G. Franchetti in session WEO1C
Mitigation strategy

without resonance compensation

compensating the lattice resonances

Ongoing effort for including self-consistency

measurement and control of the tune are mandatory

→ See talk of R. Singh in TUO1C

Bunch distribution is altered due to space charge effects (by wake fields)

→ Potential-well distortion
→ Ion bunch form deformation

Challenges:

➢ Space charge induced voltage reduction
➢ Bunch stability with space charge
➢ Control of bunch deformation by rf-operation

Dual harmonic operation
→ Increase of bucket area
→ Flattened bunch profile

See poster of Monika Mehler today (MOP205)
Dynamic Vacuum effect and collimation

- Projectile-Ionisation
- Target-Ionisation
- Dipole
- Adsorbed Residual Gas
- Desorption
- Desorbed Gas
- Coulomb-Scattering, Intra-Beam-Scattering

→ See talk of Ivan Strasik in WEO3C
Dynamic Vacuum effect and collimation

- Projectile-Ionisation
- Dipole
- Adsorbed residual gas
- Coulomb-Scattering, Intra-Beam-Scattering

See talk of Ivan Strasik in WEO3C

Graph showing number of particles over time for different ions:
- $U^{28+}$, 2001
- $\text{Ta}^{24+}$, 2009
- $U^{27+}$, 2009
- $U^{28+}$, 2010
- $U^{39+}$, 2010

FAIR ‘materials’

Carbon materials for Super-FRS:
- Mechanism of radiation damage, critical dose
- Structural and thermo-mechanical properties degradation

Insulators:
- Critical dose determined
- Breakdown voltage of insulating material after irradiation

Targets and Beam Catchers - Super-FRS

- Investigate radiation damage and failure mechanism of FAIR accelerators materials
- Lifetime estimations for FAIR components
- Innovative materials for extreme conditions

→ Talk of Marilena Tomut in WEO3C
I did not talk about....

Diagnostic and XHV at highest intensities

Superconducting magnets

Rf-cavities

Production - targets

SIS100 and SIS300

UNILAC

p-LINAC

SIS18

HESR

S-FRS

CR

100 m

AI block

Ti window

Target: Ni-rod ($r=0.15\text{cm}$, $l=10\text{cm}$) within graphite cylinder ($r=1\text{cm}$)

air cooling
The FAIR project is moving forward
The FAIR project is moving forward
The FAIR project is moving forward

- German funding available
- Procurement of components for SIS100, HEBT and CR started
- Preparation of the test facilities for the SC magnets at GSI, Dubna and CERN
Acknowledgement

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