FAIR Challenges
Facility for Antiproton and Ion Research

Ralph J. Steinhagen

EuCARD², Beam Dynamics meets Diagnostics, 4-6 November 2015
Convitto della Calza, Florence, Italy
Facility for Anti-proton and Ion Research
Satellite View

14 km to Frankfurt Airport

7 km to Darmstadt
Main Physics Programme

Nuclear Physics & Physics with Hadrons
- Nuclear Reaction from lowest to highest Energies
- Super-heavy Elements
- Compressed Baryonic Matter
- Anti-matter Research
  - new: PANDA (QCD)

Atomic Physics
- Atomic Interactions
- Precision Spectroscopy of highly charged Ions

Bio-Physics and Bio-Medical Applications
- Radiobiological effects of ions
- Cancer therapy with ion-beams

Material Science
- Ion-Condensed-Matter Interactions
- Nano-structures using ion-beams

Plasma Physics
- Hot dense Plasmas
- Ion-Plasma Interactions

Accelerator Technology
- Linear accelerators
- Synchrotrons and Storage Rings
Modularised Start Version 2020 (MSV0-3)
Total area > 200 000 m²
Concrete for FAIR ~ 600 000 m³
(for reference: 3x more than SPS & LHC, ¼ of Hoover Dam)
Substructure: 1350 pillars, up to 65 m deep (finished)
High Energy Beam Transfer (HEBT) – Civil Construction & Integration
FAIR – First Stage (MSV0-3)
Primary & Secondary
Rare Isotope Beams (RIBs)

SIS18:
main limitations:
Ion-sources, space-charge,
dyn.-vacuum, beam-control
SIS100 ~ 4.8 x SIS18

Super-FRS:
est. rate per primary ion:
- 1.e-1
- 1.e-3
- 1.e-5
- 1.e-7
- 1.e-9
- 1.e-11
- 1.e-13
- 1.e-15

Accelerator Challenges

Diagnostic and XHV at highest intensities

Superconducting Magnets

SIS 100

SIS100 EH

Super - FRS

Beam Cooling
(stochastic + e-beam)
# FAIR Ring Accelerator Parameters

<table>
<thead>
<tr>
<th></th>
<th>SIS18</th>
<th>SIS100</th>
<th>CR</th>
<th>HESR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference [m]</td>
<td>216</td>
<td>1083</td>
<td>215</td>
<td>575</td>
</tr>
<tr>
<td>Max. beam magnetic rigidity [Tm]</td>
<td>18</td>
<td>100</td>
<td>13</td>
<td>50</td>
</tr>
<tr>
<td>Injection energy of protons or anti protons [GeV]</td>
<td>0.07</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Final energy of protons or antiprotons [GeV]</td>
<td>4</td>
<td>29</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>Injection energy of heavy ions [GeV/u]</td>
<td>0.0114</td>
<td>0.2</td>
<td>0.74</td>
<td>0.74</td>
</tr>
<tr>
<td>Final energy of heavy ions U(28+) [GeV/u]</td>
<td>0.2</td>
<td>2.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final energy of heavy ions U(/73+/92+) [GeV/u]</td>
<td>1</td>
<td>11</td>
<td>0.74 (92+)</td>
<td>0.2-4.9 (92+)</td>
</tr>
</tbody>
</table>

- **Max. beam intensity for protons or antiprotons /cycle**
  - SIS18: $5 \times 10^{12}$
  - SIS100: $2 \times 10^{13}$
  - CR: $10^8$
  - HESR: $10^{10}$

- **Max. beam intensity of $^{238}$U-ions /cycle**
  - SIS18: $1.5 \times 10^{11}$
  - SIS100: $5 \times 10^{11}$
  - CR: $10^8$
  - HESR: $10^8$

- **Required static vacuum pressure [mbar]**
  - SIS18: $< 10^{-11}$
  - SIS100: $< 5 \times 10^{-12}$
  - CR: $< 10^{-9}$
  - HESR: $< 10^{-9}$

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**Main FAIR challenges:**

- Control of highest proton and (unprecedented) uranium ion intensities
- Excellent XHV vacuum conditions
Challenge: Control of Dynamic Pressure

\[ U^{28+} + X \rightarrow U^{29+} + X + e \ & \text{Electron-Capture} \]

\[
\frac{dE}{dX} \propto \frac{Z_{\text{ion}}^2}{\beta^2} \cdot \frac{Z_{\text{gas}}^*}{A_{\text{gas}}^*}
\]

Dynamic pressure:

\[
\frac{dP}{dt} = \frac{P - P_0}{\tau_p} + \alpha \eta_{\text{loss}} NP
\]

H. Kollmus et al., J. Vac. Sci. (2009)
SIS18 Dynamic Vacuum Control
SIS-18 Hardware Upgrades

- Intense primary heavy-ion beams:
  RIB production (NuSTAR) and plasma physics

  
  
<table>
<thead>
<tr>
<th>SIS-18 (today/required)</th>
<th>SIS-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference primary ion</td>
<td>$^{28+}$U</td>
</tr>
<tr>
<td>Reference energy</td>
<td>200 MeV/u</td>
</tr>
<tr>
<td>Ions per cycle</td>
<td>$3 \times 10^{10}$ / $1.5 \times 10^{11}$</td>
</tr>
<tr>
<td>cycle rate (Hz)</td>
<td>1 / 2.7</td>
</tr>
</tbody>
</table>

  primarily limited by U-ion source

  
  SIS-18 upgrades for SIS-100 injection:
  - new injection system (larger aperture)
  - NEG coating of vacuum pipe
  - Combined pumping/collimation ports behind dipoles
  - reduction of multi-turn injection loss (ongoing)
  - fast ramping with 10 T/s (ongoing)
  - dual RF system (ongoing)

P. Hülsmann, P. Spiller, O. Boine-Frankenheim et al., IPAC 2010
- U^{29+} loss positions in SIS100 are peaked (by design) at the cryo-aborbers (collimators)

- **Doublet focusing structure:**
  - Dipoles act as a charge state separator
  - 'de-focusing' →'focusing' quadrupole order
  - over-focussing assures beam reaches cryo-absorber

- Dyn. vacuum requires **huge pumping speed:**
  - cryogenic vacuum chambers
    - *N.B. principal reason why SIS100 is cold* → super-conducting dipole/quad. Magnets
    - NEG-coating of most warm vacuum chambers

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May have to accept minimal amount of losses
( primary ion-gas interactions, not intercepted by vacuum system or absorbers)
→ need instrumentation to detect, tell-the-difference and to mitigate the other loss-mechanisms
SIS18 Multi-Turn Injection (H-Phase-Space Painting)
P. Spiller, Y. El-Hayek, U. Blell et al., IPAC'12, 2012

From a linac
e.g. SIS-18, CERN PSB
courtesy Mike Barnes

Simulation: without space charge
Simulation: with space charge

Injection losses → dynamic vacuum pressure rise
(highly complex: easy to simulate ↔ hard to measure/tune with beam)
looking forward to: injection steering (BPMs) & turn-by-turn profiles (IPMs)
SIS100 Ion and Proton Lattices

<table>
<thead>
<tr>
<th>Ion Lattice</th>
<th>Proton Lattice</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{h}/Q_{v}$</td>
<td>$Q_{h}/Q_{v}$</td>
</tr>
<tr>
<td>18.88 / 18.80</td>
<td>21.78 / 17.40</td>
</tr>
<tr>
<td>$\gamma_t$</td>
<td>$\gamma_t$</td>
</tr>
<tr>
<td>15.4</td>
<td>45.5</td>
</tr>
<tr>
<td>$D_{\text{max}}$ [m]</td>
<td>$D_{\text{max}}$ [m]</td>
</tr>
<tr>
<td>1.8</td>
<td>3.0</td>
</tr>
<tr>
<td>$\epsilon_{h}/\epsilon_{v}$ [mm mrad]</td>
<td>$\epsilon_{h}/\epsilon_{v}$ [mm mrad]</td>
</tr>
<tr>
<td>25 / 10</td>
<td>4 / 2</td>
</tr>
<tr>
<td>0.4 – 2.7</td>
<td>29.0</td>
</tr>
</tbody>
</table>

- Symmetric doublet lattice (14 x DF)
- Symmetry broken to shift $\gamma_t$ (6 x DF$_1$, 8 x DF$_2$)
- Vertical plane only weakly affected

D. Ondreka, S. Sorge, V. Kornilov

optics uncertainties $\rightarrow$ uncertainties on collimation, MTI, slow-extraction
$\rightarrow$ requires excellent control of the machine optics
(N.B. gradual proton optics changes from injection $\rightarrow$ extraction over $\sim$ 200 ms)
Slow Extraction from SIS-100
Intense Heavy-Ion Beams for NuSTAR & CBM

<table>
<thead>
<tr>
<th>Ion</th>
<th>Energy</th>
<th>N/s</th>
<th>spill</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{28+}\text{U}$</td>
<td>1.5 GeV/u</td>
<td>5E11</td>
<td>&gt; 1 s</td>
<td>10 kW</td>
</tr>
</tbody>
</table>

Optics, $Q/Q'(\ldots')$ drive uncertainties on slow-extraction performance
→ remedy: control of the machine optics, $Q/Q'$, linearisation prior to s.e., ...
(highly complex, a lot of work ongoing)

Tracking simulations:
5 % (approx. 500 W) loss in the septum wires
$^{92+}\text{U}$ beam loss in warm magnet > 5 W/m

Non-trivial machine protection:
protection of septa wires
down-stream absorbers setup
activation minimisation

Ion Energy N/s spill Power
$^{28+}\text{U}$ 1.5 GeV/u 5E11 > 1 s 10 kW

SIS18 Septum wires: Ø 0.1 mm
(W-Re alloy, mounted under tension)

(radiation resistant warm magnets)
Field errors:
- 2D/3D static calculations
- Measurements
  (prototype magnet)

as indicated before:
Optics, Q/Q’ drive
uncertainties on collimation,
MTI, slow extraction
performance
→ remedy: control of the
machine optics, Q/Q’, control
of non-linearities, ...
(highly complex, a lot of work
ongoing)
1. **Activation**: loss of 'hands-on-maintenance' → '1 W/m criteria'\(^1\)
   - important primarily for localised losses e.g. during slow extraction

2. **Ion-induced desorption**: increase of vacuum pressure
   - primary reason for SIS100 being a cryogenic machine → beam loss control/particle stability
   - distributed combined collimation/pumping system for 'stripping' losses in SIS-100

3. **Machine Protection**: ion-induced damage → \(\sim 10^{10}\) of \(^{238}\text{U}\) considered to be “safe”
   (assumes typically beam spot sizes and energies in SIS100/HEBT)
   - energetic ions cause higher damage than protons

**Beam Loss Budget** in SIS100

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### Collimation of protons (4 GeV)

- **Halo collimators**
- **Cryocatchers**
- **SIS100 lattice**

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<table>
<thead>
<tr>
<th>Beam</th>
<th>Loss criteria (injection)</th>
<th>Loss criteria (extraction)</th>
<th>Tolerable losses (injection)</th>
<th>Tolerable losses (extraction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>1 W/m</td>
<td>1 W/m</td>
<td>10 %</td>
<td>5 %</td>
</tr>
<tr>
<td>(^{40}\text{Ar}^{18+}) ions</td>
<td>2 W/m</td>
<td>1 W/m</td>
<td>30 %</td>
<td>6 %</td>
</tr>
<tr>
<td>(^{238}\text{U}^{92+}) ions</td>
<td>4 W/m</td>
<td>2 W/m</td>
<td>20 %</td>
<td>10 %</td>
</tr>
</tbody>
</table>

**Caution**: '1 W/m' is only indicative!
existing operation, shielding and radiation permit limits instantaneous proton losses to <3% @ 29 GeV and nominal intensities!
→ should aim to be significantly below that limit (ALARA)

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*for comparison: CERN-PS: 4-8% losses achieved (data courtesy R. Steerenberg, 19\(^{th}\) March 2012)

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\(^{1}\) N.V. Mokhov and W. Chou, *The 7\(^{th}\)* ICFA Mini-workshop on High Intensity High Brightness Hadron Beams, USA, 1999.
Sensitivity to Beam Loss
Energy Deposition in Coils vs. IC-type BLM Signals

Quench prevention analysis:
(S. Damjanovic)

- sufficient BLM sensitivity:
  - '5·10^4 ions/s' vs. '5·10^{11} ions/cycle'
  - Most-likely loss locations: Primary (Halo-) collimator, secondary collimator, cryo-absorber, warm magnets (extraction)

cannot assume loss-less Ion operation:
primary ion-gas interactions, slow-extraction, ...
A) plan to use relative BLM signal to freeze operation around best-case loss reference
B) attempt to define 'acceptable losses'
Gretchen Frage: “What are of 'As-Low-As-Reasonably-Achievable' losses" (in a less precisely known high-intensity ion operation territory)
“when you have excluded the obvious, whatever remains, however improbable, must be the truth.”
→ exhaust reasonable operational practices of controlling parameter known to induce particle loss

Low-intensity beams:

A. Extraction/Injection Matching
   • first-turn trajectory steering (BPMs),
   • energy matching (BPMs & Schottky),
   • coarse collimation (IPMs) (removing excessive tails at low energy before propagating)
   • bunch-length to bucket-space matching (FCTs)

B. Closed-Orbit Cycle-to-Cycle Feedback (BPMs)
   • aperture optimisation (coarse, circulating beam)

C. Tune & Chromaticity Correction (BPMS, BBQ)
   • optimises space charge, ΔQ spread, dyn. aperture, beam stability

D. Emittance (blow-up) Monitoring (IPMs, FCTs)
   • frequent cause for loss changes

→ 'acceptable losses' := losses remaining after having performed above steps

High-intensity beams:

E. Optics Correction
   ● Inj./extr. mismatch (Δβ, Δμ) correction (ε-blow-up optimisation)
   ● ring beta-beat correction (aperture opt. & linearises/restores symmetry of the optics → suppresses driving terms)
   ● detailed aperture optimisation (tune β bottlenecks)

F. Detailed Collimation (e.g. 2-stage for protons)
   • see Ivan Strasik's talk @ HIC4FAIR'2015

G. Quantitative slow-extraction optimisation
   • eval. 'Hardt condition', step-width measurement, …

H. ...

Beam Instrumentation & Diagnostics Tools will be vital for day-to-day FAIR operation! – not mere 'nice to have' features –
Modularised Start Version 2020 (MSV0-3)
Super-FRS Example: $^{238}\text{U} \rightarrow ^{233}\text{Th}$ Degrader
– or how to find a needle in a hay stack

Achromatic in velocity, but dispersive in mass and charge

Degrader angle and thickness steers optics for the second spectrometer part
Super-Fragment-Separator (Super-FRS)
Rare Isotope Beam Production (RIB)

Remote Handling
Target
Local Cryogenics

SC Dipoles

SC Multiplets

Radiation Resistant Magnets

Driver Accelerator
CR, HESR, ESR & Cry Storage Rings
Experiments tightly intertwined with Accelerator Operation

CR

circumference 221 m
magn. rigidity 13 Tm
acceptance $\varepsilon_{x,y} = 240 \text{ (200)} \text{ mm mrad}$
$\Delta p/p = \pm 2.7 \text{ (1.5)} \%$
**SIS 100 RF: BCMS**

**Bunch Compression & Merging Scheme**

### Single bunch formation

- **1.5 GeV/u**
  - 8 bunches
  - ‘bunch merging’
  - pre-compression
  - rotation
  - extraction

\[ \Delta Q \approx -0.6 \]

### SIS-18 bunch compressor loaded with 20 MA cores

### Table: Concept & Parameters

<table>
<thead>
<tr>
<th>Concept</th>
<th>#cavities</th>
<th>Voltage [kV]</th>
<th>Frequency [MHz]</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression</td>
<td>16</td>
<td>600</td>
<td>0.4-0.5 (h=2)</td>
<td>MA (low duty cycle)</td>
</tr>
</tbody>
</table>

### Final bunch parameters:

<table>
<thead>
<tr>
<th></th>
<th>Particles/bunch</th>
<th>bunch length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 GeV/u U^{28+}</td>
<td>$5 \times 10^{11}$</td>
<td>60 ns</td>
</tr>
<tr>
<td>29 GeV protons</td>
<td>$2 \times 10^{13}$</td>
<td>25 ns</td>
</tr>
</tbody>
</table>
FAIR Storage Rings
Particle-Stacking & Beam Cooling

- Circulating, cooled beam
- rf-Barriers
- Creation of a gap for injection of additional particles
- New injected bunch
- Cooling

Less beam dynamics and more a technology & machine operation challenge

→ Need good longitudinal diagnostics to tune and orchestrate (SIS100: 20+) RF cavities
HESR Prototyping @ COSY

Pellet Target

WASA

Barrier Bucket Cavity

Stochastic Cooling

Residual Gas Profile Monitor

2 MeV e-Cooler

D. Prasuhn et al.
• **GSI facility**
  - 2 + 1 accelerators (FAIR: 8 → 11++)
  - 20 experimental areas

• **Parallel operation**
  - UNILAC, SIS18, ESR independent
  - 3 different ion species
  - 5 parallel experiments

• **Experiments demand high flexibility**
  - Variation of beam parameters (daily)
    - energy, intensity
    - extraction type
    - number of bunches
  - Change of beam sharing (daily)
  - Switching of ion species (weekly)
  - Adjustment of schedule (monthly)
Periodic beam patterns, dominated by one main experiment – change every two weeks, some run for 2-3 days only:

**Unilac**
- **SIS18**
- **SIS100**

**AP** + **RIB ext. target** ($U^{28+}$) + **Biomat**

**Unilac**
- **SIS18**
- **SIS100**

**CBM** + **RIB ext. target** ($U^{73+}$) + **AP (LE)**

**FAIR Operational Challenge:**
- **presently:** 2 shifts for setup of 2 accelerators → **FAIR target:** 1-2 shift(s) for setting up 5 accelerators + tighter loss control
- **Main strategy/recipe** to optimise 'beam-on-target':
  - quasi-periodic cycle operation: limit major pattern changes by construction ↔ beam schedule planning (tools)
  - minimise overhead of context switches → smart tools, procedures & semi-automation, e.g. beam-based feedbacks, sequencer, …
Summary
FAIR Challenges vs. Remedies

- SIS18
  - Multi-turn injection optimisation → injection matching (BPMs: x, x', y, y', ..) & turn-by-turn IPMs
  - space-charge limit & dynamic vacuum → passive absorbers, vacuum pumping capacity, beam-loss optimisation
  - control of beam loss and beam parameter quality for high intensities → cycle-to-cycle Orbit-FB & Q/Q' Control
  - factor of 10 for heavy ions → ion source optimisations, multi-turn, beam-stability/space-charge opt. → optics, Q/Q'

- SIS100
  - Slow Extraction → K.O. excitation-based method, faster initial Q/Q' setup
  - Bunch-to-Bucket Injection → extraction/injection steering and fast trans./long. intra-bunch feedbacks
  - Control of beam loss and beam parameter quality for high intensities → cycle-to-cylce Orbit-FB & Q/Q' Control
  - Beam loss budget: activation, dynamic vacuum, machine protection → intensity ramp-up procedures, transmission monitoring & interlocks, BLMs

- CR, HESR, ESR & Cry-Ring
  - accumulation/cooling of primary/secondary beams → BCMS, short bunches → long. diagnostics & online tomography

- FAIR accelerator facility – Operational Challenge
  - fast turn-over → change of experiment about every two weeks, some run for 2-3 days only
  - presently: 2 shifts for setup of 2 accelerators → FAIR target: 1-2 shift(s) for setting up 5 accelerators + tighter loss control
  - Main strategy/recipe to optimise 'beam-on-target':
    - quasi-periodic cycle operation: limit major pattern changes by construction ↔ beam schedule planning (tools)
    - minimise overhead of context switches → smart tools, procedures & semi-automation, e.g. beam-based feedbacks, sequencer, ...
      N.B. also liberates operators from tedious task to focus on error (pre-)diagnosis and facility optimisations
... can we do it?

Yes, we can!

... backed by beam instrumentation, diagnostics and procedures for tuning FAIR ...