Status of the FAIR project

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Area North is under construction.

Tunnel SIS100:
• concrete works for ground slabs
• concrete works for walls and columns
• concrete works for ceilings
• sealing and backfill works
October 2019

FAIR project: civil construction

V. Kornilov, 4th Workshop on Space Charge, Nov 4-6, 2019, CERN, CH
Four scientific pillars of FAIR:

- **APPA.** Atomic & Plasma Physics
- **CBM** Compressed Baryonic Matter
- **NUSTAR** Nuclear Structure Astrophysics and Reactions
- **PANDA** Antiprotons
UNILAC is modeled using simulation codes section by section

<table>
<thead>
<tr>
<th>section</th>
<th>features</th>
<th>code</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEBT</td>
<td>multi-q, partial sc-compensation</td>
<td>PARTRAN</td>
</tr>
<tr>
<td>RFQ</td>
<td>multi-q, sc, bunches</td>
<td>TOUTATIS (part of TraceWin)</td>
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<tr>
<td>MEBT</td>
<td>sc, bunches</td>
<td>TraceWin</td>
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<tr>
<td>IH-DTL</td>
<td>sc, bunches, KONUS beam dynamics</td>
<td>TraceWin</td>
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<tr>
<td>gas stripper</td>
<td>multi-q, sc, partial sc-compensation, bunches, dipoles</td>
<td>TRACK, TraceWin</td>
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<td>Alvarez DTL</td>
<td>sc, bunches</td>
<td>TraceWin</td>
</tr>
<tr>
<td>transfer channel</td>
<td>sc, bunches, dipoles</td>
<td>TraceWin</td>
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</table>
**SIS18 as the booster for FAIR**

<table>
<thead>
<tr>
<th></th>
<th>Protons</th>
<th>Uranium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of ions per cycle</td>
<td>$5 \times 10^{12}$</td>
<td>$1.3 \times 10^{11}$</td>
</tr>
<tr>
<td>Space charge tune spread</td>
<td>Up to 0.5</td>
<td>Up to 0.5</td>
</tr>
<tr>
<td>Initial beam energy</td>
<td>70 MeV</td>
<td>11 MeV/u</td>
</tr>
<tr>
<td>Final beam energy</td>
<td>4.5 GeV</td>
<td>200 MeV/u</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>2.7 Hz</td>
<td>2.7 Hz</td>
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</table>

**Extensive upgrade program for the beam intensities as the booster for FAIR**

The major challenge: life time of $U^{28+}$ and the dynamic vacuum
SIS18 Intensity Limits

Lower charge state: an order of magnitude higher intensity due to the space charge limit

Space charge limit for lower charge state ions

Space charge limit for high charge state ions

(e.g.:  $\text{Ar}^{18+} > \text{Ar}^{10+}$
$\text{U}^{73+} > \text{U}^{28+}$)
Heavy-ion synchrotrons

The Dominating Intensity Limitation for Heavy Ion Beams in Synchrotrons is the Interaction with the Residual Gas and thereby generated Charge State Changes. Due to Desorption Processes at High Beam Intensities the Static Residual Gas Pressure becomes the so-called Dynamic Vacuum. Ionization in the Dynamic Vacuum is the dominating beam loss mechanism which appears much below the space charge limit.

Ionisation loss drives pressure bumps which itself accelerates the ionisation process.
> Dynamic vacuum instability

- SIS100 ion catcher system optimized for $^{28+}U \rightarrow ^{29+}U$
  - >99% catching efficiency
  - all charge exchange loss is controlled by cryocatcher
World Intensity Record for Low Charge State Heavy Ions

- $3.2 \times 10^{10} \ U^{28+}$ accelerated and extracted successfully
- further upgrade program
- still a factor of 6 in intensity is missing
The present working point • and the space charge tune spread (schematic)

Search for high-current working points \( (Q_v > 3.5?) \):
Injection efficiency is an issue (presently, the multiturn injection in the horizontal plane)
$Q_x + 2Q_y = 11$

non-structure, sextupole, normal

G. Franchetti, et.al., IPAC2015

Figure 3: Beam survival for a bunched beam stored for 1 second as function of $Q_y$. The blue curve is obtained for the partially compensated third order resonance, whereas the red curve is measured for the naked machine.
SIS100: the main accelerator of FAIR

**SIS100**
- C: 5 x SIS18 = 1 083.6 m
- Ions H−U.
- $U^{28+}$ 0.2→1.5 GeV/u
- $p^+$ 4→29 GeV
- High-intensity, low-loss operation
- Coherent instabilities
- Space charge tune spread up to 0.3
- Under construction, commissioning 2025.
The SIS100 synchrotron

- Fast ramping superferric magnets (4 T/s) with “cool” and thin beam pipe.
- Cycle rates of up to 1 Hz (1 s accumulation after injection)
- Slow extraction (over seconds) or fast extraction (single compressed bunches)
SIS100 Reference Cycle: U$^{28+}$ fast extraction

200 MeV/u  200 MeV/u  1.5 GeV/u  1.5 GeV/u

Accumulation  Ramp  RF Manipulations

C = 1083.6 m

1100 ms

6.5×10$^{10}$

270 ms

70ns

5×10$^{11}$

Fast extraction

V. Kornilov, 4th Workshop on Space Charge, Nov 4-6, 2019, CERN, CH
SIS100 Reference Cycle: protons

C = 1083.6 m

4 GeV 4 GeV 4 GeV 29 GeV

Accumulation

RF Manipul.

Ramp

Transition Crossing (or Shift)

Fast extraction

50ns

2 × 10^{13}

1100 ms
Accumulation

260 ms
RF Manipul.

430 ms
Ramp

5 × 10^{12}

\text{V. Kornilov, 4th Workshop on Space Charge, Nov 4-6, 2019, CERN, CH}
Strong effects of space charge for SIS100 beams:
U: 0.3 (injection), 0.07 (after ramp)
p: 0.14 (injection), 0.03 (after ramp)

\[ f_{\text{longitudinal}} \approx 1.5 \text{ kHz} \]
\[ (T \approx 600 \text{ us}) \]
\[ f_{\text{transverse}} \approx 5 \text{ MHz} \]
\[ (T \approx 0.2 \text{ us}) \]

Particles cross different resonances while performing synchrotron oscillations.
Errors + Space-charge: a key aspect for SIS100 beam dynamics

\[ U^{28+} \text{ fast extraction} \]
Fast-ramp (4 T/s) superconducting dipol magnets, under series production. Presently, more than a half (54) is delivered and tested.
Series B field measurements:
• Rotation coil $R=30$ mm
• 5 positions along the magnet
• Coil on the axis (curved magnet, 3.33°)
B field measurements for the First of Series (FoS) magnet revealed an insufficient field quality (2014) → the origins in the mechanic precisions were found, technology was improved (lamination stamping, welding, …)
SIS100 Dipole Magnets

An example for the field measurements for one of the series magnets (data by F. Kaether, et al)

Multipole coefficients of the field errors

\[ B_y + iB_x = (B_n + iA_n) \left( \frac{x + iy}{r_0} \right)^{n-1} \]

- \( B_n \) normal ; \( A_n \) skew
- \( B_1, A_1 \) dipole
- \( B_2, A_2 \) quadrupole
- \( B_3, A_3 \) sextupole
- \( B_4, A_4 \) octupole

\( r_0=30\text{mm}, \) 1 unit = \( 10^{-4} \)
The strongest error component: sextupole.
Very systematic.
The total bending field $B_1L$ from the 49 series magnets. Very systematic. SIS100 Closed Orbit correction system covers at least 40 units.
Distribution of the total bending field $B_1L$ from the 49 magnets. Red line: Gaussian.
SIS100 Dipole Magnets

Distribution of the $B_3$ and $A_2$ errors from the 49 magnets. Red line: Gaussian.

Normal sextupole

Skew quadrupole
Assumptions for the magnet model:

1. Only the allowed \((B_3, B_5, B_7)\) systematic components are nonzero
2. The random errors = sample standard deviations
   \[ r_0 = 30 \text{mm} \]

Plot: \( \pm 2\sigma \) bars
1 unit = 10\(^{-4}\)

The field measurements of the dipole series provide the model of the dipole magnets for particle tracking simulations.
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1. Only the allowed ($B_3$, $B_5$, $B_7$) systematic components are nonzero.
2. The random errors = sample standard deviations
   
   \[ r_0 = 30\text{mm} \]
   
   Plot: $\pm 2\sigma$ bars
   
   1 unit = $10^{-4}$

Fixed values are the systematic components.

The bars show the random components, i.e. the amplitude of the Gaussian distribution among magnets.

$B_n$ normal; $A_n$ skew

$B_2$, $A_2$ quadrupole

$B_3$, $A_3$ sextupole

$B_4$, $A_4$ octupole

The model used in simulations, from the half of the series magnets.
The production of SIS100 main quadrupole sc magnets (166) starts at JINR, Dubna.

Measurements of the B-field for a FoS magnet.

Assumptions for the magnet model:

1. Only the allowed ($B_6$) systematic components are nonzero
2. The random errors $= \text{from the measurement (conservative model)}$

$r_0=40\text{mm}$
Plot: $\pm 2\sigma$ bars
1 unit = $10^{-4}$

<table>
<thead>
<tr>
<th>$I$ [kA]</th>
<th>$L_{off}$ [mm]</th>
<th>$G$ [T/m]</th>
<th>$aa*10^4$</th>
<th>$bb*10^4$</th>
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</thead>
<tbody>
<tr>
<td>0.9</td>
<td>1243.53</td>
<td>2.687</td>
<td>-0.5</td>
<td>-0.6</td>
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<tr>
<td>1.2</td>
<td>1243.37</td>
<td>3.584</td>
<td>-0.5</td>
<td>-0.6</td>
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<tr>
<td>1.5</td>
<td>1243.22</td>
<td>4.400</td>
<td>-0.5</td>
<td>-0.6</td>
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<tr>
<td>3</td>
<td>1242.64</td>
<td>8.957</td>
<td>-0.5</td>
<td>-0.6</td>
</tr>
</tbody>
</table>

A. Shemchuk, M. Shandov,
Report 2018-02-16
Particle tracking simulations using the code Elegant


- Nominal U$^{28+}$ bunch during the 1 sec accumulation at the injection energy
- 6D particle dynamics in the complete SIS100 lattice
- Systematic and random errors in the magnets, closed-orbit distortion
- High intensity: frozen nonlinear space-charge model
- Multi-core simulations on the Green IT Cube at GSI

Other code developments for SIS100 (MADX, SixTrackLib with pyHEADTAIL): Talk V. Chetvertkova on Tuesday, talk A. Oeftiger on Monday.

Other simulation developments at GSI: Talk G. Franchetti on Tuesday, talk I. Hofmann on Monday
Nonlinear space charge for a Gaussian bunch

\[ \Delta x' = \frac{K_{sc}Le^{-z^2/(2\sigma_z^2)}}{2\sigma_z\sqrt{\sigma_x^2 - \sigma_y^2}} \text{Im} \left[ w \left( \frac{x + iy}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}} \right) - e^{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}} w \left( \frac{x\sigma_y + iy\sigma_x}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}} \right) \right] \]

\[ \Delta y' = \frac{K_{sc}Le^{-z^2/(2\sigma_z^2)}}{2\sigma_z\sqrt{\sigma_x^2 - \sigma_y^2}} \text{Re} \left[ w \left( \frac{x + iy}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}} \right) - e^{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}} w \left( \frac{x\sigma_y + iy\sigma_x}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}} \right) \right] \]

- Dependence of \( \Delta Q_{sc} \) on the transverse amplitudes
- Effect of the longitudinal profile on \( \Delta Q_{sc} \): variation along the synchrotron oscillation
- Effect of the transverse beam size (but not profile)
“elegant” simulations: Tune Scans

Every square: beam loss (color, 1 is 100%) after tracking a bunch for 20,000 turns

With space charge

No space charge
There is a good tune area. Longer simulations confirm low losses.

An example for the RIB cycle (1 sec, 4 inj × 2 bunches):
first 2 bunches 9% Loss → 5.5% Total Beam loss
160 000 turns = 1 sec.
Correctors in SIS100

12 Corrector Quadrupoles (B2)
0.75T/m, 0.75m

No skew Quadrupoles (A2)

42 $\xi$–Sextupoles (B3)
350T/m$^2$, 0.5m
(plus 6 Resonance Sextupoles)

12 Corrector Skew Sext (A3)
50T/m$^2$, 0.75m

12 Corrector Octupoles (B4)
2000T/m$^3$, 0.75m
Also for Landau damping!
Without $\gamma_t$-jump: small $\eta$ ($|\eta| < 2.5 \times 10^{-3}$) for 30 ms.
With $\gamma_t$-jump: small $\eta$ for 0.5 ms.

Effects of longitudinal, and transverse space charge for high-intensity proton bunches around transition ($T_c=4.5\text{ms}$)
RF manipulations for protons:

Effect of longitudinal space charge: simulations for the longitudinal emittance preservation and RF scenarios with the high-intensity effects: pyORBIT code (Y. Yuan, GSI, TU Darmstadt).

15Qs (9030 turn)

15 Qs

30 Qs
Effect of cavity impedance on the bunch rotation:

magnetic alloy (MA) loaded rf cavities with total: 360 kV (400 kHz)

Large transverse space charge

$\Delta Q_y^{sc} \approx -0.5$

(during the last turns)

Fast bunch rotation for 70 ns bunch production:

3D space charge problem

O. Boine-Frankenheim PRSTB 13, 034202 (2010)
Summary

• Large-scale civil construction and component procurement for the FAIR project at GSI in Darmstadt. All components are specified.

• The B-field data from the half of the SIS100 dipole magnets demonstrate a sufficiently good field quality

• The target is as complete as possible knowledge of the SIS100 magnet errors

• In SIS18 and SIS100, space charge is a key aspect of beam dynamics and possibly a beam intensity limitation

• Space charge in SIS100: the 1 sec accumulation, ramp, RF manipulation, transition crossing, short bunch generation (3D)

• Simulation developments using different codes