# THE FAIR ACCELERATORS: HIGHLIGHTS AND CHALLENGES

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*Abstract*

The FAIR accelerator project at GSI should increase the intensity of primary proton and heavy ion beams by up to two orders of magnitude, relative to the existing GSI facility. In addition to the design of the new synchrotron SIS-100 and the storage rings, the intensity upgrade of the SIS-18 synchrotron plays a key role for the FAIR project. Recently a new record beam intensity for intermediate charge state uranium ions has been achieved in the SIS-18. Still several challenges related to beam intensity effects and phase space conservation have to be mastered in order to reach the beam parameters required for the injection into SIS-100. In SIS-100 beam loss control and machine protection are of major concern. Lost energetic heavy ions can cause a more severe damage of accelerator components than the corresponding amount of protons. Cures and protection measures together with the results of beam dynamics studies will be summarized.

## INTRODUCTION

The Facility for Antiproton and Ion Research (FAIR) in Darmstadt will provide worldwide unique accelerator and experimental facilities allowing for a large variety of forefront research in physics and applied science. The four scientific pillars of FAIR are

- Atomic and plasma physics, and applied sciences in the bio, medical, and material sciences (APPA)
- Physics of hadrons and quarks in compressed nuclear matter (CBM)
- Structure of nuclei, nuclear astrophysics and radioactive ion beams (NuSTAR)
- Physics with anti-proton beams (PANDA)

After the official launch of the project on 7 November 2007, in order to enable an expeditious start of the FAIR construction, a modularized start version was defined [1]. This start version (Fig. 1) consists of the modules 0-3:

0. The 100 Tm heavy-ion synchrotron SIS-100
1. Experimental halls for CBM and APPA
2. The Super-Fragment Separator for NuSTAR
3. The CR collector ring and the HESR antiproton storage ring for PANDA

The modularized start version is based on recent cost estimates and the commitments on funding of the FAIR member states. This modularized start version already provides for an outstanding research program in all four scientific areas. The modules 4 and 5 include additional storage rings for heavy ions and antiprotons. These modules are obvious upgrades of the modularized start version that will further increase the intensity of accumulated antiprotons and radioactive beams. The CBM program will start using beams from SIS-100. As a long term prospective the installation of the SIS-300 (module 6) is foreseen in order to further increase the beam energies for heavy ions. All

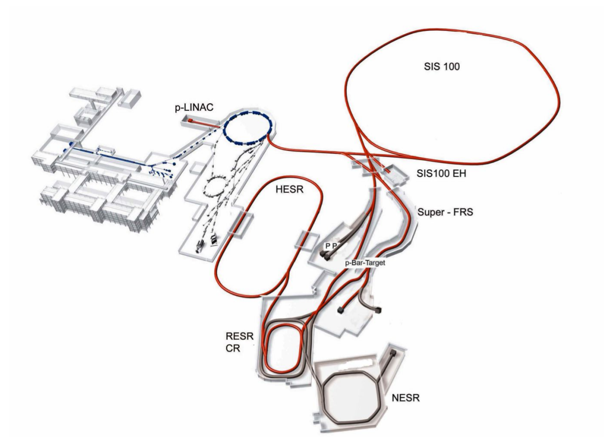


Figure 1: Sketch of the FAIR facility. The modules 0-3 that are part of the modularized start version are indicated in red. The existing GSI facility with the UNILAC linac and the SIS-18 synchrotron is in blue.

the FAIR research programs rely crucially on the performance of the SIS-100 which, together with the upgraded UNILAC/SIS-18 GSI injector facility, should provide intense and high quality beams of protons and heavy-ions. Together with the upgraded SIS-18 the new SIS-100 should provide an intensity increase of a factor of 100 for energetic uranium beams compared to the present facility. The expected final SIS-100 beam intensities are given in Tab. 1. The proton beams are for the production of anti-protons (PANDA). Intense $U^{28+}$ beams, compressed to a single short bunch or as a slowly extracted beam, are the reference case for the production of radioactive ions (NuSTAR) and for plasma physics experiments (APPA). High energy, slowly extracted $U^{92+}$ beams will be used for CBM. This

Table 1: Expected Final SIS-100 Beam Intensities

| Ion | Energy [GeV/u] | N/cycle | rep. rate [Hz] | extraction |
|---|---|---|---|---|
| p | 29 | $2 \times 10^{13}$ | 0.1 | single, short (50 ns) bunch |
| $U^{28+}$ | 1.5 | $4 \times 10^{11}$ | 0.5/0.25 | short bunch (70 ns)/ slow ext. (50 % duty ) |
| $U^{92+}$ | 11 | $1 \times 10^{10}$ | 0.1 | slow ext. |

contribution will focus on challenges related to high beam intensities in SIS-18 and SIS-100. In the HESR standard measures will be implemented to keep the amount of ions trapped in the antiproton beam below the level for instabilities or for beam quality degradation. Recently detailed studies of the accumulation and the cooling of the antiproton beam in the HESR have been completed [2]. These studies demonstrate the possibility to fill the HESR directly from the CR, without the addition storage ring (RESR), that will be added later as part of module 5.

## SIS-18 UPGRADE

The SIS-18 intensity upgrade program has been partially completed. The vacuum chamber has been NEG coated and the beam lifetime for intermediate charge state heavy ions has been improved considerably. At the injection energy of 11.4 MeV/u the projectile stripping cross section for the low charge state ions is large. Because the desorption yield for lost beam ions is high, a challenge for the SIS-18 operation is the control of the residual gas dynamic pressure. For the FAIR reference ion $U^{28+}$ the lifetime at low beam currents and at injection energy increased from previously $\tau \approx 3$ s (Ref. [6]) to $\tau \approx 11$ s. In order to control the dynamic vacuum pressure the multi-turn injection from the UNILAC as well as the orbit correction system were optimized for low beam loss [3]. As a consequence the number of uranium ions accelerated to 200 MeV/u could be increased to $10^{10}$ with only moderate beam loss and reasonably stable residual gas pressure conditions. This intensity is still an order of magnitude below the expected transverse space charge limit of $\Delta Q_{sc} \approx -0.4$ in the SIS-18. The SIS-18 design beam intensities for SIS-100 injection are given in Tab. 2 together with the achieved intensities. Figure 2 shows the space charge tune shifts achieved in SIS-18 at injection energy for different ions. For lighter ions the achieved intensities are already close to the expected space charge limit. In order to reach the space charge limit also for the heavy ions the challenge will be to increase the beam current injected from the UNILAC, but to still limit the losses during multi-turn injection as well as the space charge induced beam loss during rf capture. A still outstanding important upgrade measure is the installation of a new MA-loaded rf cavity operating at harmonic $h = 2$. Together with the existing rf cavities ($h = 4$) the new rf system will generate a dual rf bucket and a corresponding flattened bunch profile. This will reduce the space charge tune shift for a given number of ions in the bunch. In addition the bucket area will be larger by a factor 1.5 relative to the present situation. Presently the bucket area is too small for heavy ions and fast ramping with 2.7 Hz. Especially for heavy ions the conservation of the bunch quality during the rf ramp will be crucial in order to reduce longitudinal beam losses.

## BEAM LOSS BUDGET IN SIS-100

In SIS-100 four batches from SIS-18 will accumulated over roughly 1 s. Afterwards the bunches will accelerated and extracted. Beam losses are expected during the long 1 s injection plateau, during the rf rebunching [4] or during slow extraction [5]. The expected maximum beam power of $\approx 10$ kW from SIS-100 for $U^{28+}$ ions is still rather moderate when compared to fast cycling proton synchrotrons. Also the total beam energy of $\approx 20$ kJ is moderate compared to modern high energy proton storage rings. However, damage or activation of SIS-100 accelerator components might occur for systematic and localized losses as for example during slow extraction. In the following we summarize the main effects caused by lost energetic heavy ions.

**Activation and damage:** The beam loss budget for residual activation caused by energetic heavy ions is higher compared to proton beams. For 1 GeV proton beams the experience showed that uncontrolled beam losses uniformly distributed along the beam pipe of 1 W/m can be accepted as a threshold for the hands-on maintenance. For heavy ion beams recent simulation [8] studies indicated thresholds of 5 W/m at 1 GeV/u, 12 W/m at 500 MeV/u and 60 W/m at 200 MeV/u for uranium beam impinging on stainless steel targets. The higher tolerances result from the higher electronic energy loss of heavy ions relative to protons. On the contrary the higher energy deposition can result in structural damage of organic magnet components, like kapton cable insulation or Epoxy used in magnet coils [9].

**Desorption yield:** Experimental studies of the ion-induced

Table 2: SIS-18 Beam Intensities (Present and Design)

| Ion | Energy [GeV/u] | N/cycle (design/status) | rep. rate [Hz] (design) |
|---|---|---|---|
| p | 4 | $5 \cdot 10^{12}$/- | 2.7 |
| $Ar^{18+}$ | 1.5 | $2 \cdot 10^{11}/7 \cdot 10^{10}$ | 2.7 |
| $U^{28+}$ | 0.2 | $1.5 \cdot 10^{11}/2 \cdot 10^{10}$ | 2.7 |
| $U^{73+}$ | 1 | $2 \cdot 10^{10}/3 \cdot 10^{9}$ | 1.0 |

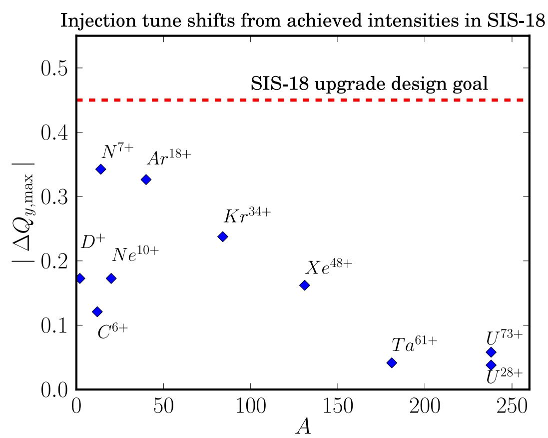


Figure 2: Space charge tune shifts achieved in the SIS-18 at injection energy (11.4 MeV/u).

desorption yield $\eta$ for energetic ions on stainless steel at room temperature [7] indicated a scaling law $\eta \propto (dE/dx)^\alpha$ where $dE/dx \propto Z^2/A$ is the electronic energy loss, $Z$ is the charge number and $A$ the mass number. In the energy range of 5-100 MeV/u and for perpendicular incidence $\alpha \approx 3$ and 2 where obtained for uranium and argon ions, respectively. The measured desorption yields at 100 MeV/u were $\eta \approx 100$ for uranium and $\eta \approx 4$ for argon. Due to the large ionization cross section for $U^{28+}$ ions stable vacuum pressures in the $10^{-11}$ mbar region with a low fraction of heavy residual gas components are required. As a consequence, especially at injection energy, uncontrolled beam loss has to be limited to a few percent in order to avoid pressure bumps due to heavy-ion induced desorption.

**Other beam loss induced effects:** Electrons produced from beam loss induced secondary emission at the wall can contribute to electron cloud driven beam instabilities in SIS-100 [10]. Measurements of secondary-electron yields for low energy ions incident on stainless-steel surfaces were presented in [11]. The emission yield $\gamma_e$ is found to be proportional to $dE/dz \cos^{-1}(\theta)$ where $\theta$ is the angle of incidence. For uranium ions in the energy range of 10-1000 MeV/u there is no experimental data available so far. From [11] one can interpolate yields $\gamma_e > 1$ for 1 GeV/u uranium and perpendicular incidence ($\theta = 0$). However, the electrons originating for collimators could be suppressed by a retarding potential. In summary we expect that uncontrolled beam loss in SIS-100 has to be minimized to a few percent in order to avoid desorption and to maintain the low vacuum pressure. For ionization losses a combined collimation/pumping system (Ref.[12]) will minimize the desorbed gas entering the beam pipe. For other beam loss mechanisms due to space charge and resonances dedicated collimation systems still have to be designed. For localized beam loss, e.g. during slow extraction of heavy ion beams, activation and damage of accelerator components is an issue and requires protective measures.

## LONG-TERM BEAM LOSS DUE TO MAGNET ERRORS AND SPACE CHARGE

In SIS-100 nuclotron-type, fast ramping, superferric dipole and quadrupole magnets will be used [13]. Compared to the magnets used in the Nuclotron synchrotron at JINR the dipole magnet development program for SIS-100 focuses on improvements of the AC loss during ramping with 4 T/s and of the field quality. Field quality measurements performed at the full length prototype dipole gave a good agreement with the field errors obtained from simulations. As a next step a curved dipole prototype magnet with a modified, single layer coil will be build and measured. The SIS-100 machine aperture together with the magnet field errors are checked using particle tracking studies [14]. In addition the simulations account for random fluctuations of the field errors (30 %), as well as for the expected residual closed orbit errors ($\approx 1$ mm) and the induced feed-down. Figure 3 shows the obtained DA together with the aperture and the beam envelope at injection. At injection (200 MeV/u) the uranium beam in SIS-

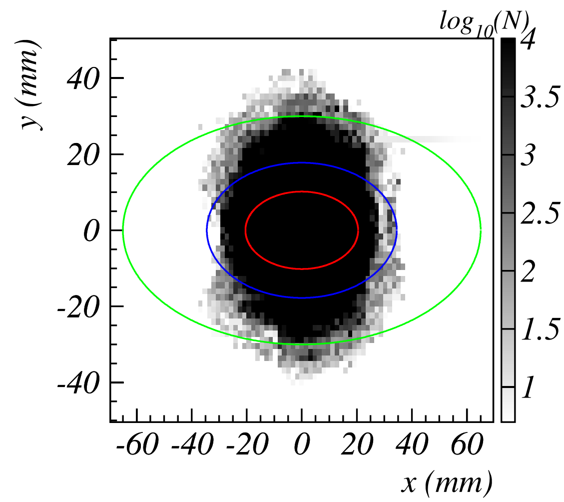


Figure 3: The area of stability (black) in SIS-100 at injection (200 MeV/u) together with the pipe in the dipoles (green ellipse), the aperture (blue ellipse) and the beam envelope (red ellipse).

100 will fill about 1/2 of the available machine aperture. The DA is at $\approx 3.5\sigma$, which is slightly smaller than the available machine aperture. A scan of the DA is shown in Fig. 4. The cluster of resonance lines just below the working point represents a main concern once chromatic and space charge spreads are introduced. At injection en-

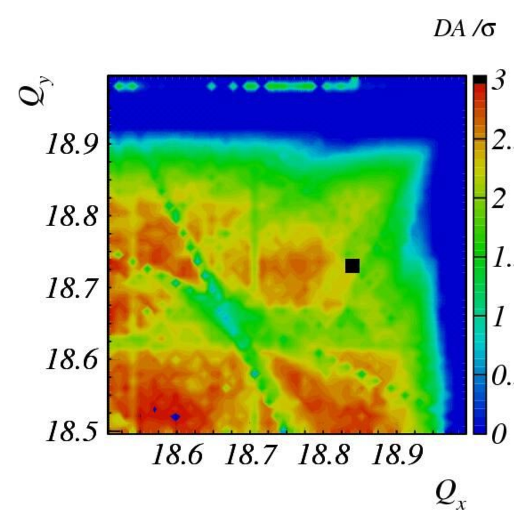


Figure 4: Result of a DA scan for SIS-100 injection energy. The proposed working point is indicated as a black square.

ergy space charge plays an important role and must be included in beam loss simulations. During the 1 s accumulation period the expected transverse space charge tune shift in the bunch center will be $\Delta Q_{sc} \approx -0.3$. The periodic crossing of transverse resonances due to the synchrotron oscillation [15] can lead to a gradual beam loss on the injection plateau. Starting from a realistic beam distribution and including a 'frozen' space charge force, our simulation studies indicate losses exceeding the tolerable 10 % for the design intensities. The challenge in SIS-100 will be to minimize and control the space charge induced losses for heavy-ion beams. Ongoing studies focus on the identification and possible compensation of the driving resonance. Flattened bunches or barrier bucket accumulation are other measures to lower the space charge tune shift. In parallel concepts for 'halo' collimators are also being studied in order to localize the residual space charge induced losses and to limit the resulting gas pressure increase.

## COHERENT INSTABILITIES DRIVEN BY THE RESISTIVE WALL IMPEDANCE

In SIS-100 transverse coherent instabilities can be driven by the large resistive wall impedance. The challenge in SIS-100 will be to damp these instabilities in the presence of the strong transverse space charge force. In coasting beams strong space charge, like in SIS-100, will suppress Landau damping of dipole oscillations. Octupoles are an option to stabilize transverse instabilities in SIS-100 [16], but they will also lower the DA [17]. The expected transverse impedance spectrum in SIS-100 is shown in Fig. 5. Shown is the contribution from the kickers (see also Ref. [18]). The dominant contribution to the transverse impedance spectrum is expected to come from the thin, stainless-steel beam pipe [20]. The design of the beam pipe plays a key role for SIS-100. In order to reduce the effect of eddy currents the pipe can only be 0.3 mm thick [19]. For the revolution frequency at injection ($f_0 = 150$ kHz for $U^{28+}$) the skin depth is $\delta_s \approx 1.5$ mm.

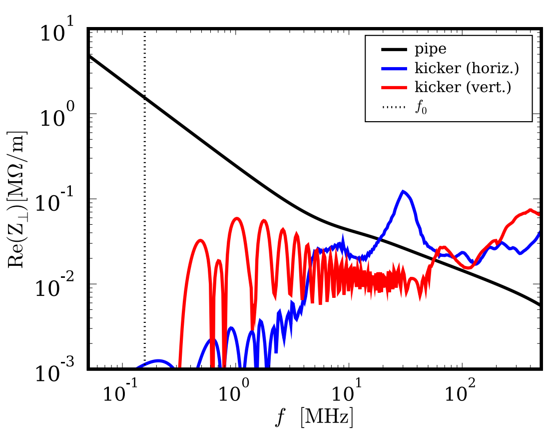


Figure 5: Expected transverse impedance spectrum in SIS-100. Shown are the real parts of the pipe and the kicker impedances. The revolution frequency $f_0$ is indicated.

The wall is basically transparent for frequencies below 3 MHz. Therefore we presently study the impedance contribution of structures directly behind the pipe, like the helium tubes that should cool the pipe in the dipoles to 20 K in order to actively pump gas molecules. Our estimates showed

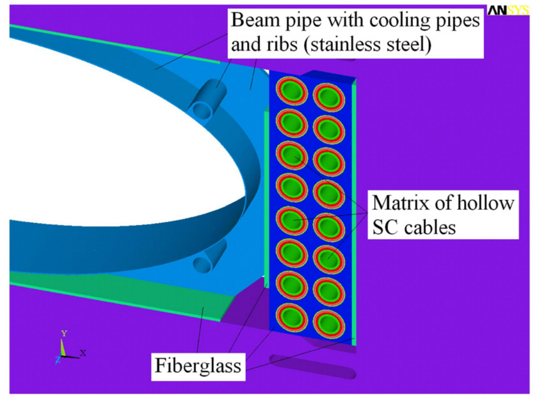


Figure 6: The SIS-100 dipole magnet and thin beam pipe cross section.

that the single bunch head-tail instability will be the dominant transverse instability in SIS-100. During the long 1 s injection plateau the $k = 4$ head-tail mode will the most unstable one, with a growth time of $\tau \approx 70$ ms for the uranium bunches. Even larger growth rates are expected for the proton bunches. Recent simulation studies focused on the effect of transverse space on the growth rate and on the damping of head-tail modes. The important space charge parameter for head-tail modes the given through $|\Delta Q_{sc}|/Q_s$, where $\Delta Q_{sc}$ is the space charge tune shift in the bunch center and $Q_s$ is the synchrotron tune. The values obtained for the bunches at SIS-100 injection are given in Tab. 3. For protons the beam parameters in SIS-100 will

Table 3: Expected SIS-100 Beam Parameters at Injection Energy. $N_b$ is the number of ions per bunch, $M$ the number of bunches, $\Delta Q_{sc}$ the space charge tune shift in the bunch center, $Q_s$ the synchrotron tune and $z_m$ the bunch half-length.

| **Ion** | $N_b$ | $M$ | $-\Delta Q_{sc}$ | $Q_s$ | $z_m$ (m) |
|---|---|---|---|---|---|
| p | $2 \cdot 10^{13}$ | 1 | 0.2 | 0.006 | 20 |
| $U^{28+}$ | $0.6 \cdot 10^{11}$ | 8 | 0.25 | 0.015 | 25 |

be very similar to the CERN PS at the injection plateau. For many years, a horizontal head-tail instability driven by the resistive wall has been observed at the CERN Proton Synchrotron during the long 1.2 s injection flat-bottom [21]. Measurements of the head-tail growth rates indicated an agreement with Sacherer's theory, although the space charge parameter is large (> 100). Recent analytical [22] and simulation studies [23] showed that in the limit of strong space charge the head-tail growth rates do not depend on space charge anymore, which is consistent with the

CERN PS results. In the CERN PS the head-tail instability is damped by linear coupling. This could be an option for the proton bunches in SIS-100. Octupoles are another option to damp head-tail modes in SIS-100. Compared to the PS the instability growth rate will be large, because of the larger 'thin' wall impedance and of the higher bunch currents. Therefore detailed simulation studies of the head-tail stability limit with strong space charge will be performed for SIS-100, including octupoles and other damping mechanisms. For the expected maximum $U^{28+}$ bunch intensities in SIS-100 the space charge parameter will still be moderate ($\approx 16$). For moderate space charge the variation of the space charge tune shift along the bunch causes an 'intrinsic' Landau damping of head-tail modes [24, 23]. In Fig. 7 the Landau damping rates obtained from simulation studies [23] for different head-tail modes $k$ are shown. With increasing mode number $k$ the range of the space charge induced damping increases. Simulation studies of the head-tail instability in SIS-100 for moderate space charge indicate that $U^{28+}$ bunches are sufficiently stabilized by the 'intrinsic' damping.

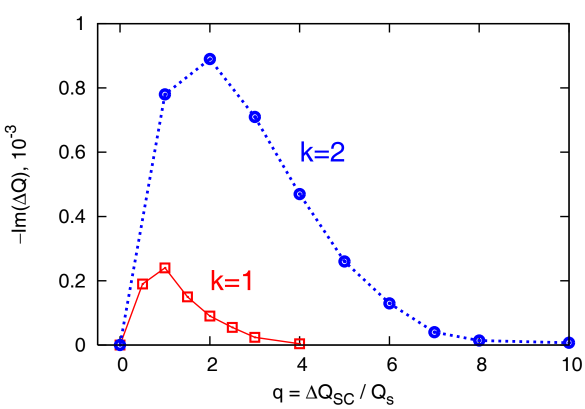


Figure 7: Landau damping of head-tail modes due to space charge.

## CONCLUSIONS

As a consequence of the partially completed SIS-18 upgrade a new record intensity for uranium beams has been reached recently. The remaining challenge will be to further increase the intensity of uranium beams to the predicted SIS-18 space charge limit. In SIS-100 the challenges are related to the operation with intense, 'thick' heavy-ion beams and the expected tight beam loss tolerance due to heavy-ion beam induced desorption and due to the possible local damage or activation. Elaborate experimental and simulation studies are being performed in order to understand and finally minimize the different intensity related beam loss sources, which are the periodic space charge induced resonance crossing in bunches and collective instabilities driven by the resistive wall or by electron clouds. We expect that the space charge induced losses can be reduced by further improving the magnet field quality and by resonance compensation. Flattened bunches or barrier rf buckets could be employed to lower the space charge tune shift. Halo collimators should localize the residual loss. Also we assume that transverse instabilities in SIS-100 can be damped by octupoles or by the 'intrinsic' Landau damping caused by space charge. More detailed results from different simulation studies are still on their way. In addition the optimization of the intrinsic beam loss during the slow extraction of intense beams is an important subject of ongoing work. However, many of the measures related to the control of intensity effect can still be implemented after commissioning.

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