# HIGH INTENSITY ISSUES AT FAIR

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*Abstract*

The facility for antiproton and ion research – FAIR – will produce secondary beams of unprecedented intensities [1]. In order to produce such intense secondary beams and to provide intense beams for the CBM [2] and APPA [3] collaboration, primary heavy ion beams of highest intensities will be required. The main driver accelerator of FAIR will be the SIS100 synchrotron. The GSI heavy ion accelerator facility will be the injector of ion beams for SIS100. In order to reach the final intensities above $10^{11}$ ions per cycle, the injector chain has to be modified accordingly and the SIS100 has to be tailored to the needs. Therefore an intensity upgrade program of the GSI accelerator facility has been started, which comprises improvements of ion sources, of the injector linacs and of the heavy ion synchrotron SIS18. In addition, high energy beam transport and the SIS100 need to have a dedicated design, in order to handle beam losses. The issues of the upgrade program and of the SIS100 design will be addressed.

## INTRODUCTION

FAIR will provide worldwide unique accelerator and experimental facilities allowing for a large variety of unprecedented fore-front research in physics and applied science. The main thrust of FAIR research focuses on the structure and evolution of matter on both a microscopic and on a cosmic scale – deepening our fundamental understanding of questions of the complex structure of matter. To answer these fascinating and crucial questions, FAIR is being constructed in Darmstadt, Germany. This is a highly sophisticated accelerator complex which will provide high-energy, precisely-tailored beams of antiprotons as well as ions from stable and exotic isotopes. A key feature of the FAIR facility is a highly sophisticated accelerator system that will allow the parallel and versatile production of an unprecedented range of particle beams.

The corresponding four pillars of FAIR physics comprise experiments studying exotic particles that will explore fundamental processes which are thought to have happened in the early phases and still happen in the ongoing evolution of the universe. These processes produced the basic constituents of matter and overall structure we see now in the universe. In addition, a range of experiments will be possible in which different forms of matter are compressed. The experiments will simulate conditions in the early Universe, in ultra-dense stars and at the cores of giant planets like Jupiter. FAIR will explore, in a unique way, the properties of fundamental particles and how they combine into more complex forms of matter under a wide range of astrophysical conditions. The experiments will be truly complementary to those carried out at other future facilities like FRIB [4]. Based on cost estimates and the firm commitments on funding of FAIR Member States, a Modularized Start Version (MSV) has been agreed upon. This version provides for outstanding and world-leading research programmes in all four scientific areas of FAIR. It provides also a unique scientific and technological environment for educating the next generations of students.

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## ACCELERATOR OVERVIEW

The FAIR accelerator facility of the MSV is shown in figure 1. The central part of the FAIR accelerator facility is a synchrotron accelerator ring with maximum magnetic rigidity of 100 Tm – the SIS100. The synchrotron will have a circumference of about 1100. The magnets employed will be new, rapidly cycling superconducting magnets in order to minimize construction and operating costs. For the highest intensities, it is planned to operate the SIS100 at a repetition rate of 1 Hz and therefore with ramp rates of the dipoles up to 4 T/s. The goal is to achieve intense pulsed $U^{28+}$ beams with $4 \cdot 10^{11}$ ions per pulse at 1.5 GeV/u and intense ($2 \cdot 10^{13}$) pulsed proton beams at 29 GeV. For the high-intensity proton beams, as required for antiproton production, a dedicated proton linac delivering 35 mA and 70 MeV protons is needed.

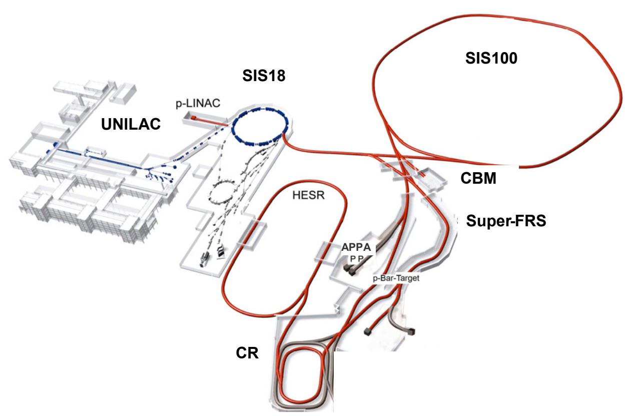


Figure 1: Overview of the FAIR accelerator facility.

The accelerator facility is complemented by a system of storage rings. The collector ring (CR) main task is stochastic cooling of radioactive ion or antiproton beams from the production targets. In addition, this ring offers the possibility for mass measurements of short-lived ions, by operating in isochronous mode. The high-energy storage ring (HESR) is optimized for antiprotons of energy up to 14 GeV. This ring will operate with an internal target and associated detector set-up (PANDA). This unique combination of accelerators and storage rings

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aims for 100 time's higher primary ion beam intensities than present available systems and, in conjunction with the new superconducting Fragment Separator (Super-FRS), for an increase of radioactive beam intensities by a factor of up to 10,000. The Super-FRS will be the most powerful in-flight separator worldwide for exotic nuclei up to relativistic energies. Rare isotopes of all elements up to uranium can be produced and spatially separated within some hundred nanoseconds, thus very short-lived nuclei can be studied efficiently. The Super-FRS is a large-acceptance superconducting fragment separator with three branches serving different experimental areas including the new storage ring complex described above.

## UPGRADE OF THE GSI ACCELERATORS

In order to prepare the injector chain of the FAIR accelerators an upgrade programme comprising the ion sources, the UNILAC and the SIS18. Main goal of the upgrade programme of the UNILAC are higher repetition rate of the high current ion sources, the increase of beam brilliance (beam current / emittance) and the improvement of the beam transmission and therewith the increase of transported beam currents. These measures are seconded by the improved high current beam diagnostic systems [5]. Concerning the heavy ion synchrotron SIS18, main issues are the increase of injection acceptance, the improvement of lifetime for medium-charged U-ions and the increase of beam-intensity per time due to reduction of SIS18- cycle time.

Heavy ion beams are produced by the GSI high current ion sources [6]. The ions are delivered from three different ion source stations. Two high voltage terminals are available for operation of Penning sources and for the high current sources MEVVA and MUCIS. A 14 GHz ECR-source is available at the high-charge injector (HLI), which will be complemented with a 28 GHz SC ECRIS in the near future [7]. An optimization of the high-current source installations in terms of beam transport and transmission is foreseen by installing a new acceleration tube and by a modified beam matching by means of a superconducting solenoid or a plasma lens. In addition, the extraction of ions from the plasma needs to be investigated and optimized, including numerical investigations of the beam formation. The according steps will be investigated at the existing high current test ion terminal (HOSTI). In addition, the setup of a third terminal with a direct injection into the HSI-RFQ is under investigation. Such a so-called 'Compact LEBT' will have the advantage to allow a dispersion free beam injection as no analyzing section is foreseen. In addition the beam has to be collimated, to remove ions, which are not within the acceptance of the RFQ. The ions with the wrong charge state will be not accelerated and lost within the HSI-RFQ. It should be noted, that this additional ion source and transport beam line should be primarily used for enriched material to reduce the abundance of other species that get lost in the RFQ. The low energy beam transport from the ion source towards the linac has to keep the emittance growth low and has to support the optimization of the ion source tune. A collimation channel, which can be adjusted to a certain acceptance, is an ideal tool to optimize the ion source brightness. Through defined apertures and transversal phase space rotation using focusing lenses the outer part of the beam will be scraped away (see fig.3).

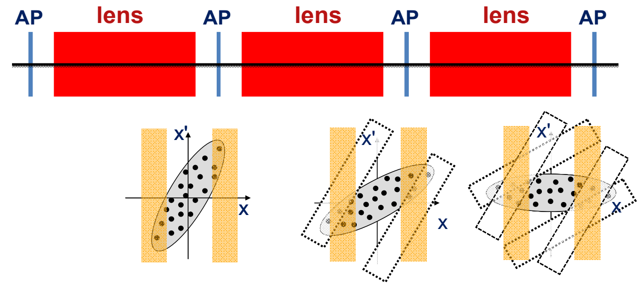


Figure 3: A collimation channel for ion source beam tuning.

The beam brilliance for heavy ions from the UNILAC is not sufficient to reach the requested value for beam injection into the SIS18 in both planes simultaneously. For injection of beams into the SIS18 demands different horizontal and vertical emittances as shown in fig.2. The injection efficiency can in principle be increased if these beams are 'flat' [8], having different emittance values for both lateral directions. However, beams provided from the linear accelerator are in general round, and the horizontal and vertical emittances are usually equal. For the horizontal direction it will be hard to deliver the required brilliance for a round beam. As there is no need for the high brilliance in the vertical direction, keeping the emittances in both direction equal is not required.

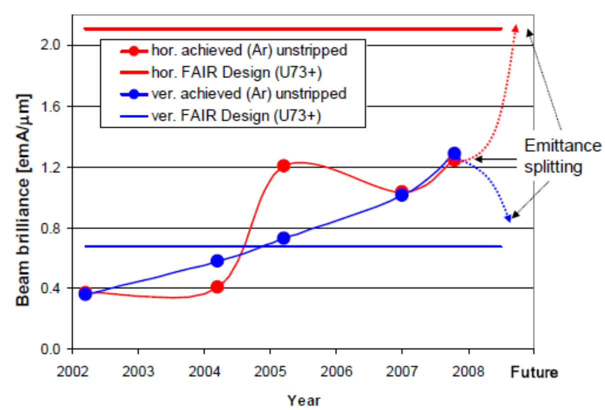


Figure 2: Development of the beam brilliance from the UNILAC over time and improvement of the injection conditions by means of emittance splitting.

Therefore an emittance splitting by a non-symplectic round-to-flat beam transformation would meet the requirements. A new set-up that provides round-to-flat emittance transformation is planned in the beam transfer section the UNILAC and the SIS18 [9].The high intensity operation also means that for the beam diagnostics of the high power ion beam of nearly 1 MW peak power only non beam destructive measurements can be applied. The main components of such diagnostic systems have to be the beam pick-up monitors to determine the beam position. In addition, the newly developed 'Beam Induced Fluorescence' (BIF)-monitors will become important for the UNILAC beam diagnostics. These diagnostics derives information of the beam position and beam width by measuring the photons generated by the excitation of gas molecules due to the beam ions [10].

Another key issue for heavy ion linacs like the UNILAC is related to the charge state stripping technology. The design of charge state stripper for heavy ions is a challenging problem due to the high power deposited in the stripper media by the beam in a small volume. Heavy ion accelerator facilities like GSI or NSCL/MSU established dedicated research and development programmes that include several options. There are carbon or diamond foils, liquid metal films, gas strippers and plasma strippers. The equilibrium charge state of ions is determined by the velocity of the ions, and a higher equilibrium charge state can be obtained when the ions are charge-stripped at a higher velocity. However, space charge effects lead to a considerable emittance growth downstream the stripper, as the higher charge states lead to a beam expansion and broadening. For FAIR the gas stripper is the base option, but higher charge states are envisaged, which could be reached using plasma stripper technologies. A low-atomic-number, highly ionized plasma can yield even higher charge states than a neutral target of the same density (like as gas jet). The effect is in principle attributable to the reduction in the number of available electron-capture channels.

## SYNCHROTRON ISSUES

The primary beam accelerator of FAIR is the 100 Tm synchrotron SIS100. As $U^{28+}$ is the design ion for the SIS100, the goal is the injection of $1.5 \cdot 10^{11}$ $U^{28+}$ ions from SIS18 with a repetition rate of 2.7 Hz at 200 MeV/u into SIS100. Nevertheless within the FAIR project all ion species from Protons to Uranium will be accelerated and delivered to the targets. By eliminating one stripper stage of the existing accelerator complex the ion intensity can be increased by an order of magnitude and the space charge in the resulting beam is significantly reduced. However ions of intermediate charge have significant higher cross sections for charge exchange reactions like impact ionisation or charge exchange. Ions with the wrong charge state get lost on the beam tube and generate due to a rapid change of the local vacuum pressure an avalanche effect called "dynamic vacuum", which limits the maximum intensity in a synchrotron, if it is not carefully controlled [11]. The SIS100 lattice is designed to have a peaked loss distribution for ions undergoing a charge exchange at dedicated positions, where collimators are located and a high pumping speed is established.

Due to the intense heavy ion beams, a number of beam dynamics issues arise in both synchrotrons. Due to the space charge forces, large tune shifts will arise in particular at injection energy level, where the beam has to circulate for a significant time in both synchrotrons. This can lead to crossing of nonlinear resonances, which can cause beam losses and the modification of coherent effects [12]. In addition, the action of fields produced by interaction of the beam with the accelerator materials, on the beam quality, determined as impedances, can lead to coherent instabilities. Passive compensation schemes or active feedback system need to be investigated accordingly to reduce the effects of the wake fields [13]. The strong space charge of the ion beam bunches can build up clouds of electrons, which are created by residual gas ionization or secondary electron emission from the beam tube [14]. The electron clouds can compensate partially the space charge forces (compensation) accordingly, leading to instabilities and incoherent emittance growth. Although the operation of SIS18 does not exhibit any evidence of electron cloud formation yet, but extrapolating SIS18 parameters to those required for high intensity operation as FAIR injector, there is a concern about possible electron cloud build up. The parameters of the future SIS100 operation lead to a concern as well, in particular for coasting beams in the SIS100 during the slow extraction process.

In order to study these processes and their effects on the beam operation on both synchrotrons, numerical models and simulations are essential. In addition the benchmarking and validation of the models by comparison with results from machine experiments are inevitable. However, the modelling of the long term beam loss induced by space charge effects remains very challenging and needs according computing power for systematic investigations by parameter scans.

Materials used in intense heavy ion accelerators undergo irradiation due to beam losses. Therefore investigations of radiation damage and resulting failure mechanisms of FAIR accelerator materials are an issue to be addressed. Those investigations are required to estimate the lifetime of FAIR components and to determine the application of innovative materials for the extreme conditions in the FAIR accelerators. For instance, the critical dose for the break down voltage of insulating materials after irradiation is an important parameter, as expensive components need to be exchanged after a certain operation time. Thus, intense ion beams with high brilliance are mandatory to keep beam losses low in high current injector accelerators like those planned for FAIR.

## OUTLOOK

The FAIR project is now moving forward as funding is available. First procurement of mayor components of SIS100, HEBT and CR and of common systems items has been started in 2012. The preparation of the test facilities for the huge number of SC magnets at GSI, in Dubna and at CERN is proceeding. The schedule of the subproject accelerator foresees first beams from SIS100 in 2018.

The civil construction is progressing fast and clearing of the first section of the construction area has been completed, as shown in fig. 4. The preparation of the

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according infrastructure like roads towards the construction area is in progress and the tendering for the site preparation and the massive foundation of the buildings by 60 m deep pillars is in the tendering process. Start of the civil construction will be in 2013, thus leading to completion of the building in 2016 and 2017.

Figure 4: Clearing of the first section of the FAIR construction site.

## ACKNOWLEDGMENT

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## REFERENCES

[1] FAIR Green Paper – The Modularized Start Version, October 2009

[2] B. Friman et al., "The CBM physics Book", Series: Lecture Notes in Physics, Vol. 814, 2011

[3] http://www.fair-center.de/de/oeffentlichkeit/experimenteprogramm/appa-physics.html

[4] R.C. York et al., "FRIB: A New Accelerator Facility for the Production of and Experiments with Rare Isotope Beams", proc. of the PAC2009, MO3GRI03

[5] P. Forck, A. Peters, P. Strehl, "Beam Diagnostic for the upgraded UNILAC at GSI", proc. of the EPAC98, WEP04A

[6] R. Hollinger et al., Rev. Sci. Instrum. **79** (2008) 02C703

[7] G. Ciavola et al., "Status of the Multipurpose Fully Superconducting ECR Ion Source", proc. of the EPAC08, MOPC140

[8] L. Groening, PRST-AB 14, 064201 (2011)

[9] C. Xiao, "Planning for experimental demonstration of transverse emittance transfer at the GSI UNILAC through eigen-emittance shaping.", proc. of the HB2012, MOP207

[10] P. Forck et al., "Beam Induced Fluorescence Profile Monitor Developments", proc. of the HB2010, WEO1C03

[11] P. Spiller, "Towards the High Intensity Limit in the FAIR Project – present Status and Future Challenges", proc. of the HB2010, MOIC01

[12] G. Franchetti, "Effect of Self-consistency on Periodic Resonance Crossing", proc. HB2012, WE01C01

[13] V. Kornilov, O. Boine-Frankenheim, I. Hofmann, Phys. Rev. ST Accel. Beams 25 (1997) 56

[14] J.M. Jimenez et al., "Electron Cloud with LHC-type Beams in the SPS: a Review of Three Years of Measurements,"Proc. ECLOUD'02 workshop, CERN, CERN-2002-00, (2000) pp. 17–28.