Abstract
The planned heavy ion synchrotron SIS100 will provide unique conditions for heavy ion plasma physics experiments at FAIR. However, the generation of compressed, high energetic beams with the desired intensity requires significant innovations in the accelerator design and technology. The envisaged major increase in heavy ion beam intensity can only be achieved by accelerating ions with medium charge instead of highly charged ions that are currently being used. Over the past two years, experiments in the heavy ion synchrotron SIS18 have shown the tremendous complication with this goal. The significantly shorter life time of the ions, together with the dynamic vacuum effect requires new concepts for the synchrotron design. In order to match the high intensity beam to the plasma physics target further major technical effort will be required in SIS100. A powerful low frequency MA-loaded compression system is being designed for the generation of short, single bunches. Essential progress has been achieved within the frame of the SIS18 bunch compressor project with improving the material properties of the MA-load.

1. Introduction
SIS100 is the first stage of the two stage synchrotron complex SIS100/300, which will be built within the FAIR (facility for antiproton and ion research) project [1] at GSI. SIS100 will be optimized for fast acceleration (dB/dt = 4T/s) of uranium and proton beams, but shall also provide beams of all other ions species. The heavy ion synchrotron SIS18 is going to be upgraded for the operation as a fast ramped booster synchrotron (dB/dt = 10 T/s) for SIS100. Including the UNILAC, most of the existing GSI accelerator facility will be used in the injector chain for SIS100.

The proposed experiments for the plasma physics community [2] and also the experiments planned at the Super-FRS (super FRagment Separator) are the main users for the maximum intensity of heavy ion beams. Furthermore, both experiments need short compressed bunches for a proper matching to the target. While plasma physics experiments care for an optimum energy deposition and heating of the target, Super-FRS experiments worry about the energy variation of the produced secondary beams. Both experiments justify the investment of a powerful bunch compression system in SIS100.

Already at the beam parameters which will be achieved after the SIS18 upgrade program, a dedicated rf system for bunch compression is needed for the plasma physics experiments. The double gap compression system which is under development for this purpose, uses MA-ring cores as inductive load and serves as a prototype for the large compression system of SIS100. In order to achieve the highest possible number of particles per cycle, SIS18 and SIS100 need to be operated with intermediate charge state heavy ions, e.g. U^{28+}. So far, highly charged uranium ions, e.g. U^{73+} are used for acceleration in SIS18. The main intensity limitation is given by the incoherent tune spread at injection energy (11.4 MeV/u) of SIS18. Several measures are planned to increase this limit to finally 2.7x10^{11} uranium ions per cycle. Four SIS18 batches will be accumulated in SIS100, leading to 10^{12} U^{28+}-ions per SIS100 cycle.
2. Synchrotron Design for the Acceleration of Medium Charge State Ions

a) Beam Life Time and Dynamic Vacuum

Several beam lifetime measurements have been performed in SIS18 over a wide range of energy for ions with different atomic number and charge state. At injection energy of 11.4 MeV/u, the 1/e-beam life time of highly charged U^{73+} was measured to be 25s while the life time of medium charged U^{28+} was only 5s. It was observed that the measured life time of uranium beams with medium charge state can be easily effected by pressure variations. Therefore a precise interpretation of the life times requires a parallel fast pressure and mass spectrum verification. The static average gas pressure along the SIS18 circumference is typically in the order of 4x10^{-11} mbar. A mass spectrum measured with the new quadrupole mass spectrometers is shown in figure 1 [3].

Figure 1 : Measured residual gas composition in SIS18.

At injection energy of SIS18, the mechanism that determines the life time of U^{28+} is ionization by collisions with the rest gas while for U^{73+} the capture cross sections are dominating. Unfortunately, the cross sections for ionization of U^{28+} are much higher than for electron capture of U^{73+}.

Meanwhile significant progress has been made with the intensity of the heavy ion beams accelerated in UNILAC. Beams with currents of 1.7 mA of U^{73+} and 2.7 mA of U^{28+} could be provided for injection into SIS18. Although more than 10^{10} U^{28+}-ions have been injected, the maximum number U^{28+}-ions which could be accelerated in SIS18 was only 3x10^9.

The driving reason for the observed U^{28+}-losses is the high sensitivity against the status of the residual gas pressure and its mass spectrum, in connection with strong gas desorption from the beam pipe induced by impacting ions. Due to gas desorption processes, the rest gas pressure behaves strongly dynamic under beam load. Figure 2 shows the residual gas pressure development in SIS18 in a static situation (left) and under beam load (right).

Figure 2 : Residual gas pressure development in a static situation (left) and under beam load (right).

As seen from figure 2, the gas pressure variations may reach up to one order of magnitude within the integration time of the pressure gauges. The amount of gases which is desorped from the beam pipe, scales with the injected number of particles.

b) Charge Separator Lattice and Pressure Stabilization

In order to avoid such pressure variations in SIS100 and to minimize the additional load to the UHV system, a new synchrotron design concept will be used. The concept is based on the fact that the loss position of stripped U^{28+}-ions (U^{29+}) can be well determined by ion optical calculations. Therefore the most important design criteria for the SIS100 lattice structure is actually the function of each lattice cell as a charge separator providing a sufficient separation of the stripped beam from the reference beam. No beam losses shall appear in the dipole magnets and no overlap of the stripped beam and the reference beam shall take place at the loss position. The stripped ions can be caught by a dedicated collimator which shall furthermore be able to control the desorption gases [4]. Such a concept is feasible if the probability for multiple ionization is very low. Multiple ionization would lead to a wide distribution of the losses behind the dipole magnets and would not allow an efficient
collimation. However, recent atomic physics collision studies and extrapolations from measurements have confirmed that single ionization of U\(^{28+}\) is the most probable stripping mechanism at rest gas collisions at beam energies beyond 100 MeV/u (injection energy of SIS100) [5]. Several lattice structures have been investigated with respect to the efficiency of collimation of ionized particles. One goal of the lattice optimization is to provide a maximum displacement of the stripped beam such that the collimators do not create any further restrictions of the acceptance. The synchrotron acceptance is normally defined by the injection- and extraction elements. The collimators shall be positioned at maximum distance from the beam edge, providing 100% efficiency for collimation of stripped ions.

Studies have shown, that within the CDR triplet lattice at maximum a collimation efficiency of only 98% can be achieved and a large number of collimators (11) per arc would be required (figure 5). The lattice was optimized with respect to the charge separation function. Figure 6 shows the collimation efficiency for both structures. The doublet lattice reaches almost 100% collimation efficiency up to rather large distances from the beam edge and provides in addition an acceptance \(A_{h,v} = 190 \times 46 \text{ mm mrad}\) which is in the horizontal plane a factor of 1.8 larger than the CDR lattice (figure 5).

Figure 3: SIS100 lattice structure as proposed in the CDR.
Figure 4: SIS100 doublet structure with three dipoles per cell.
Figure 5: Collimation efficiency of the CDR triplet and an alternative doublet lattice structures. The collimation efficiency of the doublet structures reaches almost 100% with a smaller number of collimators. The collimation efficiency keeps high up to rather large distances from the beam edge.

c) Loss Control and Collimation Technology

A new concept for a dedicated “desorption collimator” was proposed for SIS18 [4]. A prototype of the proposed collimator has been build and installed in front of the injection septum. The collimator shall catch and control the stripped ions before their impact on the surface of the beam pipe. Since gas desorption will also appear on the surface of the collimator, a special geometrical arrangement has to be chosen. The collimator consists of a wedge, with a surface which points in opposite direction to the optical axis. The wedge is completely enclosed by a secondary chamber where the desorped gases are captured. Only a small low conductivity port opens the secondary chamber for the incoming beam. The SIS18 “desorption collimator” has two huge pumping ports which are equipped with cryopumps. In SIS100 the collimator will be included in the cryostat. In order to avoid additional load to the cryosystem and to avoid freezing out of rest gas on the surface, the collimator will be operated at intermediate temperature (~80 K) and will not be in mechanical contact with the walls of the secondary chamber. The surrounding secondary chamber shall act as a cryopump for the desorped gases and will therefore be connected with the magnet cryosystem and operated at a low temperature (~5 K).

Figure 6: Scheme of the collimation system for stripped ions using a wedge dump which is surrounded by a cryogenic secondary chamber.

3. Bunch Compression

a) MA-Core Developments and Compression Systems
The bunch compression project for SIS18 has always suffered from the restricted drift space in SIS18. The length of one compressor cavity has been limited to 0.8 m. The space limitation was one of the driving reasons to design a cavity with a maximum voltage per meter length and thereby high driver power requirements. Similar conditions with respect to the available drift space are expected for SIS100. In order to minimize the power requirements of such a short system, a specific level of MA-core performance is needed.

The core performance is described by the so called \((\mu Q_f)\) product which is often used as a figure of merit for MA and ferrite materials. For our purposes, the \((\mu Q_f)\) value should be much larger than 3.6 GHz at 800 kHz (SIS18). So far, such a ring core performance was not available on the market. In order to improve the ring core performance particularly with regard to the SIS100 project, we have launched a research program in collaboration with Honeywell (USA), Vakuumschmelze (Germany), Hitachi (Japan) and the Radiotechnical Institute in Moscow (MRTI). Using different annealing techniques, various core materials with reduced losses were produced and tested. In order to reduce the costs of the R&D program considerably, the dimensions of the test ring cores were scaled down by a factor of five (keeping the width of the ribbon at 25 mm). The scaled ring cores were tested at GSI with a realistic level of energy density and a corresponding power level of 10 kW. As a result of this effort the \((\mu Q_f)\) values for amorphous ring cores could be increased from 3.6 to 4.6 GHz and for nanocrystalline ring cores from 3.6 to 4.6 GHz. This was achieved by different measures, including the reduction of the ribbon thickness, the increase of the filling factor and last but not least the improvement of the manufacturing techniques.

Meanwhile, the double gap SIS18 bunch compressor cavity is being constructed. 40 ring cores have been ordered, 20 amorphous ring cores from Vakuumschmelze (Vitrovac 6030 F) for one gap and 20 nanocrystalline ring cores from Hitachi (Finemet FT-3L) for the other gap. For the Vitrovac 6030 F ring cores, Vakuumschmelze has guaranteed a \((\mu Q_f)\)-value larger than 3.8 GHz while Hitachi has guaranteed for the Finemet FT-3L ring cores a \((\mu Q_f)\)-value larger than 4.0 GHz. Since measurements with small 1:5 cores have shown a \((\mu Q_f)\)-value of 4.6 GHz, it was expected that especially the Finemet FT-3L ring cores will exceed these specifications. An additional loss of 0.2 – 0.3 GHz was considered for a full scale ring core compared to a 1:5 core. So far we have received 17 full-scale Finemet FT-3L ring cores from Hitachi, three of them could be measured at GSI. The test results have been very interesting: The first ring core has obtained a \(\mu Q_f\)-value of 4.4 GHz, the second 4.7 GHz and the third 5.5 GHz. These values have exceeded our highest expectations. The obtained values will have significant impact on the technical layout and design of the SIS100 bunch compression system.

b) SIS100 bunch compression and peak power optimization

The final bunch length on target determines which fraction of the beam energy will be converted into target energy density. Furthermore, the achievable bunch length defines the size of a matched final focal spot. At the present project status the decision for an appropriate magnet technology of the final focusing system needs to be prepared. Therefore studies on the longitudinal compression process and the achievable bunch length are required.

It is planned to install 26 compression cavities in SIS100 which will provide a total voltage of 1MV at a frequency of 465 kHz \((\pm 70 \text{ kHz}) \ (h = 2)\). Depending on the final beam energy, the system was specified to generate short single bunches with a length between 25ns \((2.7 \text{ GeV/u})\) and 90ns \((400 \text{ MeV/u})\).

Before the final compression, a single bunch must be generated and pre-compressed. The desired final compression mechanism is a phase space rotation initiated by a fast jump in rf voltage. In the linear regime the final bunch length is proportional to the square root of the
ratio between the final and initial voltage $\tau_f \propto \sqrt{V_i/V_f}$. Thus in case pre-bunching and compression is performed by the same rf system a low pre-bunching voltage would lead to very short bunches after compression. Unfortunately, at low pre-bunching voltages the compression process is no longer linear for the full bucket area. Although the large difference in synchrotron frequencies in the bucket may generate a certain level of tails around the bunch core, the peak power will still be enhanced. The method was tested in SIS18 during a plasma physics experiments performed in December 2003. A beam pulse with a length of only 124 ns (FWHM) and 5x10⁹ uranium ions could be generated for target experiments (figure 7). The pre-bunching voltage was only 1 kV while the final voltage of 24 kV was given by the maximum voltage of the two SIS18 cavities. Earlier tests with pure linear compression have only lead to bunches of a length of 350 ns.

**Figure 7**: Nonlinear compressed uranium bunch with 5x10⁹ ions and a FWHM length of 124 ns generated for plasma physics experiments.

Systematic parameter studies have been performed for the SIS100 compression assuming different levels of pre-bunching amplitudes in a harmonic bucket at $h=2$. It was assumed that the beam is pre-bunched from a barrier bucket with a DC longitudinal profile throughout half of the circumference. The energy distribution was Gaussian with a 2σ value of total energy of approximately 52MeV (assuming dp/p_{FWHM} =10⁻³ of nominal value after injection into SIS12/18 at 11.4MeV/u and consequently no emittance growth thereafter up to the start of bunch compression in SIS100). The pre-bunching makes use of an iso-adiabatic ramp keeping the emittance growth to better than a few percent (adiabaticity coefficient kept at 0.5). Upon reaching the intermediate gap voltage, the rf underwent a fast jump (over ~10us) of up to 1MV in amplitude. Figure 8 shows the peak power and pulse length (FWHM) with respect to the pre-bunching voltage at low intensity as well as to the direct space charge included. The same initial beam phase space distribution was used to simulate both these cases. The time taken during bunch rotation at 1MV to reach the maximum pulse compression length is approximately constant and is on average ~100µs.

Under the expected maximum intensities in SIS100, in order to reach pulse lengths of ~50ns or better, feedback or feedforward systems may have to be applied to the bunch compressor systems. It must be stated here that only the direct (capacitive) space charge impedance was considered. For a more thorough treatment, calculations are in progress which include realistic cavity impedances, resistive wall and others which are at present undetermined.

**Figure 8**: Effect of the pre-bunching rf voltage amplitude on the FWHM pulse length and the peak power in the pulse, for U²⁸⁺ at 1GeV/u. Two cases are compared here: with and without, the inclusion in the model of direct (capacitive) space charge.

**References**:

[2] N. Tahir et. al., this proceedings
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   “Electron stripping cross section for fast, low charge state uranium ions”, this proceedings
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Figure 7: Nonlinear compressed uranium bunch with $5 \times 10^9$ ions and a FWHM length of 124 ns measured in the GSI plasma physics cave.
**Figure 8**: Effect of the pre-bunching rf voltage amplitude on the FWHM pulse length and the peak power in the pulse, for $^{28+}$ at 1GeV/u. Two cases are compared here: with and without, the inclusion in the model of direct (capacitive) space charge.