# TOWARDS THE HIGH INTENSITY LIMIT IN THE FAIR PROJECT – PRESENT STATUS AND FUTURE CHALLENGES

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## INTRODUCTION

In order to reach the desired intensities of heavy ion beams for the experiments of FAIR [1, 2], SIS18 and SIS100 have to be operated with intermediate charge states [3, 4]. Operation with intermediate charge state heavy ions at the intensity level of about $10^{11}$ ions per cycle has never been demonstrated elsewhere and requires a dedicated upgrade program for SIS18 and a dedicated machine design for SIS100. The specific problems coming along with the intermediate charge state operation in terms of charge exchange processes at collisions with residual gas atoms, pressure bumps by ion induced desorption and corresponding beam loss appears far below the typical space charge limits. Thus, new design concepts and new technical equipment addressing these issues are developed and realized with highest priority.

The upgrade program of SIS18 addressing the goal of minimum ionization beam loss [5] and stable residual gas pressure conditions has been defined in 2005. A major part of this upgrade program has been successfully realized, with the result of a world record in accelerated number of intermediate charge state heavy ions.

## INTERMEDIATE CHARGE STATE HEAVY ION OPERATION

In order to minimize the required magnetic and electrical field strengths, so far heavy ion accelerators made use of highly charged ions where ever possible. For the generation of highly charged ions, stripper stages made of supersonic gas jets or foils have been installed at suitable positions (energies) along the accelerator. Even the major intensity loss resulting from the selection of one charge state out of the generated charge state distribution has been accepted.

Table 1: Existing and proposed heavy ions synchrotrons operated with intermediate charge state heavy ions.

| | | |
|---|---|---|
| AGS Booster | BNL | $Au^{32+}$ |
| LEIR | CERN | $Pb^{54+}$ |
| NICA Booster | JINR | $Au^{32+}$ |
| SIS18 | GSI | $U^{28+}$ |
| SIS100 | FAIR | $U^{28+}$ |

With the aim for higher intensities and consequently increasing space charge effects and intensity restrictions, the charge state of heavy ions must be reduced. However, there are only a small number of heavy ion synchrotrons world-wide operating or designed with such intermediate charge state heavy ions. Table 1 shows the presently running and planned synchrotrons using intermediate charge state heavy ions.

The strength of the charge exchange processes in a machine cycle depends on the cross sections for ionization and electron capture as a function of the beam energy. The atomic physics models used for the calculation of these cross sections have been improved in the last ten years significantly and extended to relativistic energies [6]. Various experiments have been conducted, e.g. with the internal gas target of the ESR at GSI, to benchmark the predicted cross sections [7].

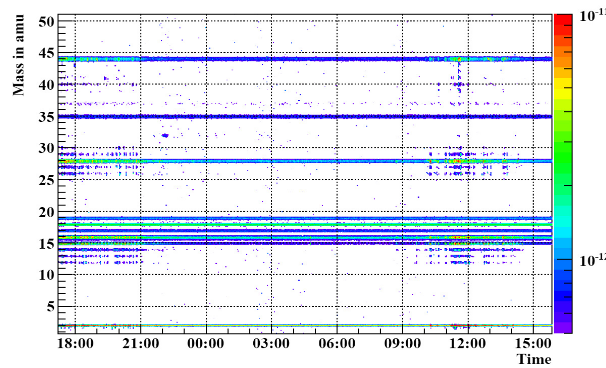


Figure 1: The residual gas spectrum in a synchrotron is changed by desorbed gases. During high current operation (left and right), additional components appear with a density comparable with the background components. The gap in between indicates the time of low intensity operation.

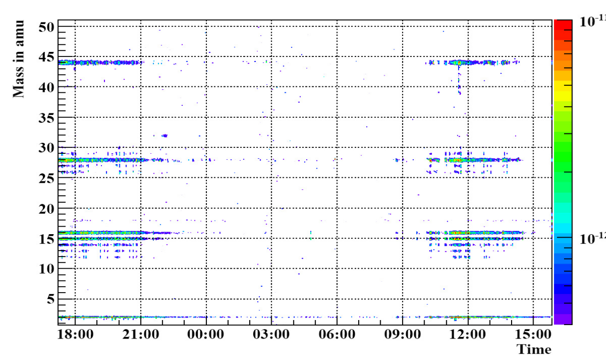


Figure 2: After subtracting the background spectrum (static case) the spectrum of the desorbed gases is obtained.

The cross sections depend significantly on the target ion, or in other words the residual gas composition of the accelerator. Here, it must be considered that the mass spectrum differs significantly in the dynamic case (with beam in the machine) from the static situation (without beam). The mass spectrum is strongly influenced by the gases which are desorbed from the walls by the impact of ions. Figures 1 and 2 show the mass spectrum measured in SIS18 in phases with and without beam. Figure 2 shows the spectrum of the desorbed gases which is achieved by subtracting the spectrum in the dynamic from the static case.

Figure 3 shows the calculated cross sections for $U^{28+}$-ions over a large energy range for different target atoms [8]. In comparison with highly charged ions, as they are for instance accelerated since 20 years in SIS18, the cross sections of the intermediate charge state ions are typically two orders of magnitude higher.

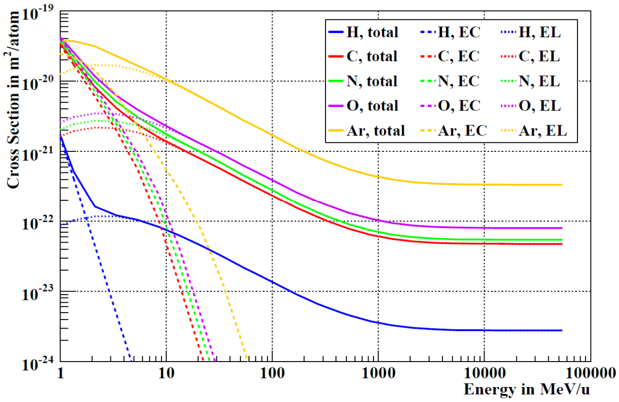


Figure 3: Calculated cross sections for ionization and electron capture of $U^{28+}$-ions as a function of beam energy for various target (residual gas) atoms.

However, the real strength of the charge exchange processes is strongly linked with the realistic machine cycle. Since the cross sections for ionization are significantly decreasing with energy, long term operation at low energies (e.g. injection plateaus) should be avoided, while fast acceleration with high ramp rates is desirable. This rule is the reason for the aim for fast ramping within the FAIR project. The power converters of SIS18 are upgraded for acceleration with 10 T/s, while the key issue for SIS100 is the development of fast ramped superconducting magnets.

An important parameter for the comparison of different machines is the integral cross section times the number of ions per cycle. The integral cross section is achieved by integrating the energy dependent cross section over the realistic machine cycle. Table 2 shows a comparison of this product for the machines listed in Table 1.

As can be seen, the product for the FAIR SIS100 is exceeding by far all other synchrotrons and, although the beam energy is compared with SIS18 higher, is even an order of magnitude stronger than for SIS18. The reason is the four times higher beam intensity in SIS100, and the longer cycle time with a long plateau of 1s for injection. Since the N x $\sigma_{int}$-product indicates the total amount of beam loss by charge exchange, the operation of SIS100 with intermediate charge state heavy ions is most demanding and requires a dedicated machine design [9].

SIS100 is in terms of charge exchange beam loss the most demanding synchrotrons. However, in the following the developments and achievements for the synchrotron SIS18 are described. SIS18 is an existing test bed where the basic understanding of the mechanisms related to the intermediate charge state operation and the predictions and expectations made for to technical upgrade measures can be benchmarked.

Table 2: Comparison of the integrated cross section for charge exchange times the number of particles per cycle for different synchrotrons

| Accelerator | Ion species | Total integ. cross section | Number of ions | N x $\sigma_{int}$ |
|---|---|---|---|---|
| AGS Booster | $Au^{31+}$ | $4.5\times10^{-21}$ | $5\times10^{9}$ | $2.2\times10^{-11}$ |
| LEIR | $Pb^{54+}$ | $5.5\times10^{-20}$ | $1\times10^{9}$ | $5.5\times10^{-11}$ |
| NICA Booster | $Au^{32+}$ | $4.9\times10^{-21}$ | $4\times10^{9}$ | $1.9\times10^{-11}$ |
| SIS18 | $U^{28+}$ | $8.7\times10^{-22}$ | $1.5\times10^{11}$ | $1.3\times10^{-10}$ |
| SIS100 | $U^{28+}$ | $1.8\times10^{-21}$ | $6\times10^{11}$ | $1.1\times10^{-9}$ |

## DEVELOPMENT OF THE SIS18 BOOSTER OPERATION WITH INTERMEDIATE CHARGE STATE HEAVY IONS

First experiments with high intensity, intermediate charge state heavy ion beams have been performed in 2001. At this time, most of the injected $10^{10}$ $U^{28+}$-ions have been lost by ionization in the residual gas within a few hundred milliseconds (Figure 4). Fast pressure bumps initiated by initial systematic beam loss generated a strong residual gas pressure dynamics, which in turn amplified the charge exchange process.

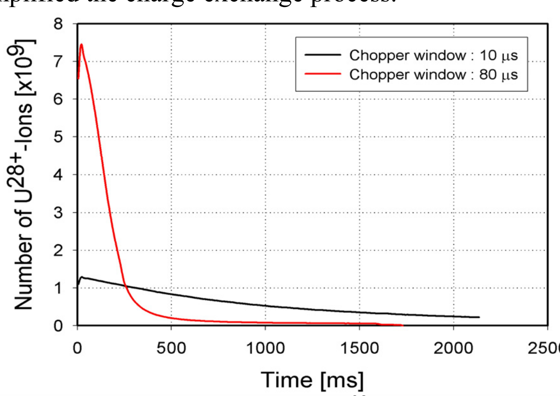


Figure 4: First experiments with $U^{28+}$ in SIS18 in the year 2001. Ionization of the beam ions in local enhanced pressure regions which were created by ion induced desorption caused an almost completed loss of the beam.

In 2009, the ionization beam loss could be significantly reduced and stable acceleration and extraction of more than $10^{10}$ $U^{28+}$-ions has been demonstrated for the first time. This major progress has been achieved by the completion of dedicated upgrade measures aiming for a stabilization of the residual gas pressure during high intensity operation.

Six major technical projects of the upgrade program have been summarized and were realized in the frame of an EU FP6 funded construction program.

Table 3: Upgrade projects within the EU FP6 funded SIS18 construction program and their present status.

| | |
|---|---|
| New injection system for injection of $U^{28+}$ beams at 11.4 MeV/u with larger acceptance, diagnostics and protection equipment [10] | Completed |
| New NEG coated dipole and quadrupole chambers for strong distributed pumping | Completed |
| Ion catcher system for ionization beam loss to minimize the effective gas desorption [11] | Completed |
| New h=2 acceleration cavity for fast acceleration in a two harmonic bucket | Ongoing |

Furthermore, the new power grid connection of the GSI pulse power network, which has been completed in 2006, enables ramping of SIS18 with higher ramp rates. As described before, high ramp rates are significantly contributing to the goal of minimizing the ionization beam loss and stabilising the dynamic residual gas pressure at intermediate charge state operation.

The machine development program towards highest intensities of beams with intermediate charge state heavy ions has been continued in 2010. Several runs have been performed with various (heavy) ion species and charge states. The major intensity step achieved in the year 2009, with more than $10^{10}$ ions per cycle could be repeated (Figure 5). It has been shown that this intensity level represents the actual machine performance achieved by partial completion the technical measures summarized in the SIS18 upgrade program [12].

The latest progress in operation with intermediate charge state heavy ions has been achieved by a slight increase of the charge states ($U^{39+}$ instead of $U^{28+}$). The new charge state could be produced by replacing the gas stripper in the UNILAC by a foil stripper [13]. Since the second stripper stage in the transfer channel (normally used to generate highly charged ions) has been bypassed, the intensity of the $U^{39+}$-beam was comparable with the intensity of the $U^{28+}$-beams. Thus, also for the $U^{39+}$-beam the number of accelerated ions exceeded the level of $10^{10}$ ions (see Figure 5). However, the increased charge state enables acceleration to a higher final energy (350 MeV/u instead of 200 MeV/u) which is of particular interest for the running experimental program at GSI.

Predictions made with the STRAHLSIM code [14] for the life time of the $U^{39+}$ beam could surprisingly not been confirmed by the corresponding measurements. According to the applied capture and ionization cross sections it was expected, that the life time of $U^{39+}$-beams is significantly longer than of the $U^{28+}$-beams and the charge related beam loss and its consequences for the dynamic vacuum were supposed to be correspondingly lower.

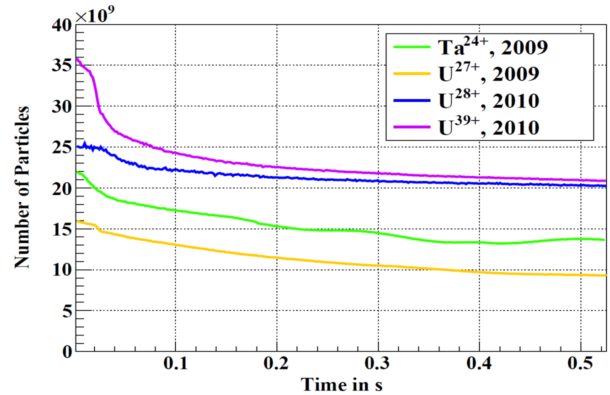


Figure 5: SIS18 acceleration cycles with intermediate charge state Uranium ions in 2009 and 2010. Beam loss by ionization, which is by far the dominating loss mechanism, could be significantly reduced and the number of extracted ions increased by a factor of 70.

In order to confirm the measured life times, the measurement method itself and its dependence on various parameters (e.g. intensity, tune etc.) have been investigated [15]. By measurements and STRAHLSIM simulations, it could be shown, that the dynamics vacuum affects the results of the life time measurements down to intensities of the order of a few $10^8$ ions (Figure 6).

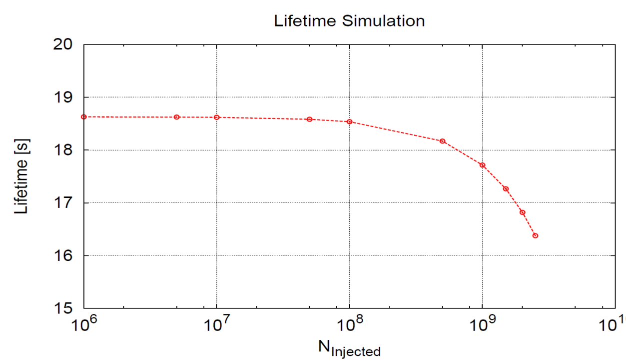


Figure 6: Calculate dependence of beam life time as a function of the beam intensity for $U^{39+}$-ions.

The selection of the charge state plays an important role for an appropriate design concept of a future linac replacing the existing ALVAREZ section of the UNILAC. Therefore, a measurement campaign has been conducted to determine the life time for several charge states of Uranium beams under comparable conditions (Figure 7). The dependence of the life time from the charge state can be clearly noticed. Unfortunately, the transition to the life time of charge state 28+ could not yet been measured. However, it is known from previous measurements that the trend which can be seen in the plot, does not continue down to charge states around 28+.

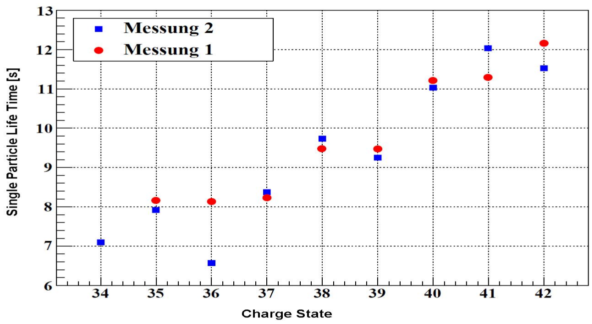


Figure 7: Life time of various Uranium beams with different charge states at 11.4 MeV/u in the SIS18.

## OUTLOOK

The SIS18 upgrade program will be continued with the installation of a new h=2 MA-loaded acceleration cavity and a new dipole power converter. Both systems will enable an increase of the ramp rate from now 4 T/s to 10 T/s. A precondition for the acceleration of intermediate charge state heavy ions are vanishing initial beam loss. Uncontrolled initial beam loss may drive pressure bumps which determine the pressure and beam loss evolution over the whole cycle. The present synchrotron operation of SIS18 is determined by the initial pressure bumps generated by beam loss during multi turn injection. Therefore, systematic studies have been launched to remove these beam loss by means of a three stage collimation system from the synchrotron into the transfer channel. The collimators are used to a) generate a sharp edge beam in the injection septum and b) to optimize the efficiency of the multi turn injection process.

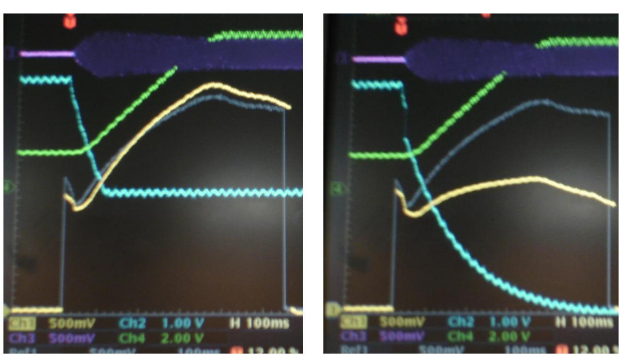

Figure 8: Beam current (yellow) over a machine cycle in SIS18. The blue line shows the voltage of the electrostatic injection septum. The green curve indicates the magnetic field cycle. In the right picture, a high voltage brake down has generated a strong local pressure bump just after injection. The locally enhanced pressure creates major beam loss by charge exchange over the whole cycle.

How strong the charge exchange rate can be increased by a local pressure cloud is impressively demonstrated with Figure 8. It turn out that the high voltage stability of the electrostatic injection septum is challenging. The lower charge state of the heavy ions requires a significantly higher electrical field - the septum is operated with voltages up to 220 kV. In addition, grazing particles from halo of the high intensity beam desorb gas from the electrodes which increases the pressure in the septum. The enhanced pressure is potentially leading to high voltage brake down with a spark over generating an additional strong pressure bump. Figure 8 shows how the local pressure bump in the injection septum (the spark happened after injection) generates beam loss by charge exchange of almost 50 % within the cycle. As counter measure, NEG panels are actually installed under the septum electrodes.

If beam loss can not be avoided, it must be dumped on dedicated ion catcher systems which are equipped with low desorption materials and coatings. The predicted beam survival with an assumed uncontrolled initial beam loss of less than 5 % in the SIS18 booster operation running with 2.7 Hz is shown in Figure 9.

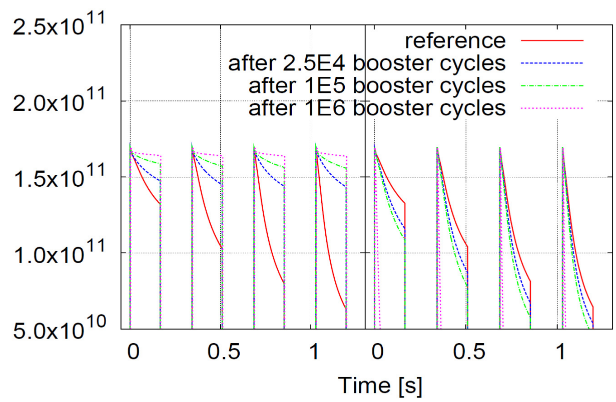


Figure 9: Results of STRAHLSIM simulations for the SIS18 booster mode with low initial beam loss. The gas desorption driven vacuum dynamics generates strong charge exchange beam loss. Beam scrubbing (left) may improve the situation significantly after ten thousand cycles.

## ACKNOWLEDGEMENT

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