# ACCELERATION OF INTERMEDIATE CHARGE STATE HEAVY IONS IN SIS18

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*Abstract*

After partially completing the upgrade program of SIS18, the number of intermediate charge state heavy ions accelerated to the FAIR booster energy of 200 MeV/u, could be increased by a factor of 70. The specific challenge for the SIS18 booster operation is the high cross section for ionization of the intermediate charge state heavy ions, in combination with gas desorption processes and the dynamic vacuum pressure. The achieved progress in minimizing the ionization beam loss underlines that the chosen technical strategies described in this report are appropriate.

## INTRODUCTION

In order to reach the desired FAIR [1] intensities for heavy ions, SIS18 has to be operated with intermediate charge states [2,3]. 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. The upgrade program dedicated to the goal of minimum ionization beam loss [4] and stable residual gas pressure conditions has been defined in 2005. So far, a major part of this upgrade program has been succesfully realized, with the result of a significantly increased number of accelerated intermediate charge state heavy ions.

## SIS18 UPGRADE PROGRAM

Six major tasks of the upgrade program have been summarized and are realized in the frame of an EU FP6 funded construction program [5]. The tasks and their present status are listed in Table 1.

Table 1: The Six Upgrade Tasks of 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, profile grid and scrapers [6]. | Completed |
| New NEG coated dipole and quadrupole chambers for strong distributed pumping. | Completed |
| Catcher system for ionized beam ions to minimize the gas desorption [7] (see figure 1) with NEG coated chamber and anti-chamber for strong local pumping. | Completed |
| New h=2 acceleration cavity for fast acceleration with 10 T/s in a two harmonic bucket. | Ongoing |
| TK stripper for high charge state s. | Completed |
| Fast residual gas profile monitor for turn by turn beam profile measurements. | Ongoing |

The new acceleration cavity and the planned upgrade of the dipole power converters are required for fast acceleration of $U^{28+}$ beams with 10 T/s up to 18 Tm. Since the ionization cross sections decrease with beam energy, high ramp rates are significantly contributing to the minimization of ionization beam loss and the stabilisation of the dynamic residual gas pressure. The first step towards faster ramping has been completed in 2006. A new power grid connection for the GSI pulse power network has been built up. The new connection via a 110 kV power line to a 220 kV transformer which is only used by GSI, allows ramping without constraint. The use of the former power grid connection (via a 110 kV line in series with the town Darmstadt) was restricted to 5 MW and a ramp rate of 1.3 T/s.

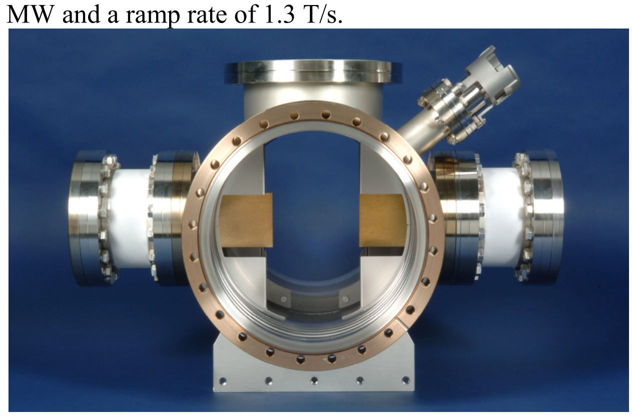

Figure 1: The ion catcher chamber with two blocks made of low desorbing gold coated copper catchers. The catcher on the inner side of the synchrotron covers ionization and the opposite catcher capture loss. The beam current on the catchers can be measured and indicates (folded with the cross sections for the relevant charge exchange process) the strength of the residual gas pressure dynamics.

## HIGH INTENSITY OPERATION WITH INTERMEDIATE CHARGE STATES

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 2). Fast pressure bumps generated by initial systematic beam loss drove strong residual gas pressure variations which in turn amplified this process. Meanwhile, the ionization beam losses were significantly reduced and acceleration and extraction of more than $10^{10}$ ions has been demonstrated with $U^{28+}$, $U^{27+}$ and $Ta^{24+}$ ions. Figure 2 shows the intensity profile in acceleration cycles with $U^{28+}$ and $U^{27+}$ beams in 2001, 2009 and 2010. Acceleration of $2x10^{10}$ intermediate charge state Uranium ions is at present world wide unique. The following measures have contributed to this progress:

- Injection at higher energy (11.4 MeV/u instead of 7.1 MeV/u with lower ionization cross section.
- Acceleration with higher ramp rates (4 T/s instead of 1.3 T/s) and correspondingly shorter cycle times.
- Set-up of a charge catcher system, consisting of two catchers behind each dipole group (one for ionization and one for capture loss). The catchers are made of low desorbing gold coated copper blocks.
- Replacement of all magnet chambers by new, NEG coated chambers.
- Careful optimization of the acceleration cycle in terms of systematic beam loss at multi turn injection and Rf capture loss.

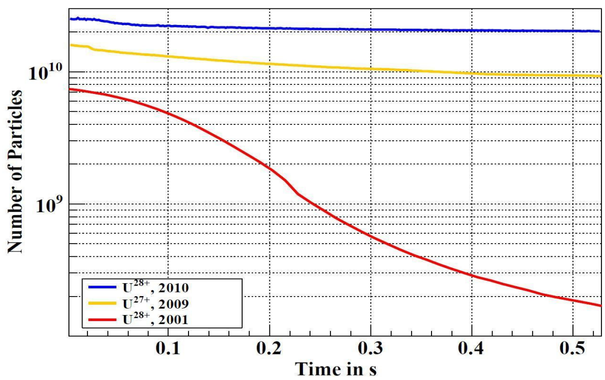


Figure 2: Acceleration cycle with $U^{28+}$ ions in 2010, 2009 and 2001. Beam loss by ionization, which is by far the dominating loss mechanism, could be significantly reduced compared to 2001 and the number of extracted ions increased by a factor of 70.

Further improvement has been achieved in the time averaged number of accelerated heavy ions. The progress for the number of accelerated Ta-ions per cycle could only be achieved with breaks of 9 seconds in between the cycles, where the UHV system could recover the pressure bumps. In the Uranium run, these breaks could be removed completely, indicating the effective suppression of the gas desorption by means of the new catcher system and the significantly higher local and distributed pumping power after the installation of the NEG coated magnet chambers and the ion catcher system.

The static life time at 11.4 MeV/u of $U^{28+}$ ions measured in the last machine experiments was 11 seconds. Compared to the best values measured in 2001, the life time could be increased by a factor of 2.5.

The time averaged residual gas spectrum has been monitored during the machine experiments. As shown in Figure 3, at high current operation the spectrum is strongly affected by the desorbed gases. In the time gap between 21:00 (9 pm) and 9:00 (9 am), the intensity has been significantly reduced. The left and right sides of the plot show the situation at high current operation. Atoms and molecules with mass numbers which are not existent in the background (static) residual gas are generated. The total density of the desorbed gases is comparable to the background gas. Subtracting the average static residual gas spectrum from the combined one (Figure 3) provides the spectrum of the desorbed gases (Figure 4) [8].

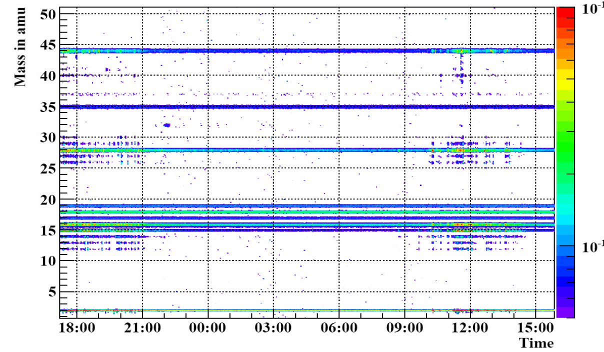


Figure 3: The residual gas spectrum is changed by the desorbed gases. During high current operation (left and right), additional components appear with a comparable density as the background components. The gap in between indicates the time of low intensity operation.

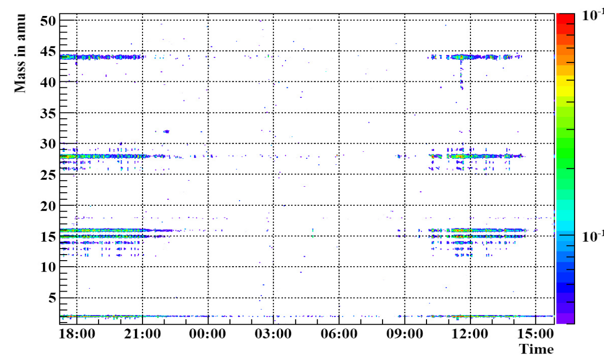


Figure 4: After subtracting the background spectrum (static) the spectrum of the desorbed gases is achieved.

Meanwhile, measurements of the beam currents on the different ion catchers have indicated that the major pressure rise is localized around the injection region. The reason for this localized pressure increase is that, the strongest initial systematic beam loss is created at the multiturn injection process on the backside of the injection septum in section S12. Furthermore, the pressure in the injection section S12 is enhanced by its connection to the transfer channel from the UNILAC. This channel can not be baked-out and is typically operated with residual gas pressures two orders of magnitude higher. The control of the ionization beam loss in section 1 and 2 by the new catcher system and the locally enhanced pumping speed by the NEG coatings of the catcher chambers prevents the pressure rise to develop over the full circumference.

Another source of pressure bumps which has been identified is high voltage breaktdowns in the electrostatic injection septum. For the injection of intermediate charge state, heavy ions at the reference injection energy of 11.4 MeV/u, a new electrostatic septum has been developed and installed. For the electrically stiff intermediate charge state heavy ions, the electrostatic septum must be operated at voltages of more than 220 kV. Although the entrance aperture of the septum is defined by two scrapers, the beam may graze the septum electrodes at large emittances or non appropriate set values. Any beam loss in the tight injection channel generates a volume of enhanced pressure by gas desorption in between the septum electrodes. The generated pressure increase and the free electrons may cause high voltage breakdowns. The high voltage breakdowns are typically delayed by a few milliseconds with respect to the beam injection. Thus, the number of injected ions is not affected and the origin of the disturbed intensity profiles (see Figure 5) is not obvious at first. However, a breaktdown generates an immense pressure increase in the overall septum chamber. The revolving intermediate charge state beam which is exposed to this local pressure cloud, is subject to a fast ionization process with strong beam loss in the following section S1 (see Figure 5).

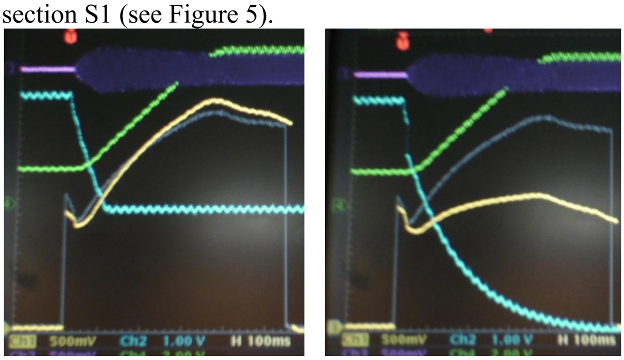

Figure 5: High voltage breakdowns in the electrostatic injection septum create strong local pressure bumps which ionize the revolving intermediate charge state beam and lead to significant beam loss within the cycle. The oscilloscope pictures show the following lines: blue line - high voltage of the injection septum, green line - magnet ramp, yellow line - beam current. The left graphs show the acceleration process without high voltage breakdown. The right graph shows the situation with breakdown.

## SIS18 BOOSTER OPERATION

Different to the present machine experiments, in the booster mode, SIS18 has to be operated with a repetition frequency of 3 Hz. Four SIS18 cycles are needed to fill SIS100 within one second. In the present machine experiments, the repetition rate is typically only 1 Hz. At fast repetition, the pressure rise created in the first cycles affects the later cycles. Even in the most optimistic cases, assuming low initial, systematic beam loss and high distributed and local pumping power, the degradation of the later cycles in terms of ionization beam loss can not be avoided. By means of the further developed STRAHLSIM code [9], the intensity and pressure evolution over the four booster cycles has been simulated again. The latest code extension considers the real loss distribution (origins of pressure bumps) and the vacuum conductivity between the pumps and these positions. In the former version of the code, no special resolution was implemented and the pressure and vacuum conductivity was averaged over the circumference. For the simulation of the ionization beam loss and dynamic pressure evolution, the residual gas composition summarized in Table 2 has been used.

Table 2: Gas Composition Used for the Simulations

| Residual gas component | Fraction for outgassing | Fraction for desorption |
|---|---|---|
| Hydrogen | 88 % | 40 % |
| Nitrogen | 0 % | 0 % |
| Oxygen | 0 % | 0 % |
| Argon | 1 % | 0 % |
| Water | 4 % | 0 % |
| CO | 2 % | 25 % |
| $CO_2$ | 1 % | 10 % |
| Methane | 4 % | 25 % |

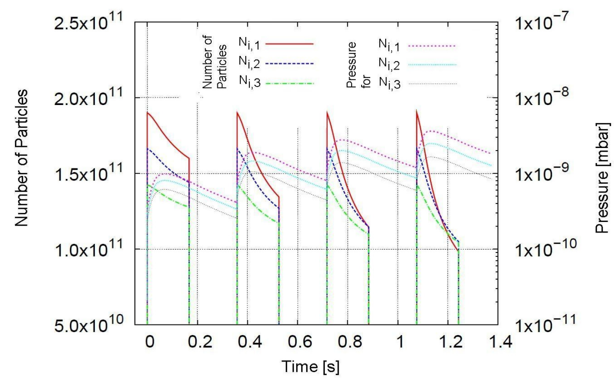


Figure 6: Intensity and pressure profiles for the SIS18 booster mode. Four SIS18 cycles are performed with a 3 Hz repetition frequency. The later cycles suffer from the increased residual gas pressure and correspondingly enhanced ionization beam loss.

Figure 6 shows the calculated intensity profiles and the corresponding pressure profiles for the four booster cycles at fast repetition. The initial systematic beam loss was assumed to be 5%. The simulations were done for different numbers of injected ions. As can been seen, the growing residual gas pressure in the later cycles, causes an increasing ionization beam loss and a decreasing number of extracted ions. However, the new STRAHLSIM simulations, which account for the influence on enhanced local pumping power, as given by the NEG coating of the ion catcher chambers, show for the first time that the goal of $1.5x10^{11}$ particles per second averaged over the four cycles can be reached.

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