SIS18 – INTENSITY RECORD WITH INTERMEDIATE CHARGE STATE HEAVY IONS

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Abstract

A new development direction towards ultimate heavy ion beam intensities is being pursued at GSI for FAIR. So far, most of the heavy ion synchrotrons have been operated with high charge state heavy ions. In order to reach intensities of more than 10^{11}/U-ions per cycle [1, 2], SIS18 and SIS100 must be operated with intermediate charge state ions [3, 4]. Such a high intensity operation with intermediate charge state heavy ions has never been demonstrated elsewhere. A major upgrade program is being conducted since ten years to prepare the desired booster operation of SIS18. The specific problems coming along with the intermediate charge state operation are strong charge exchange processes by collisions with residual gas atoms, pressure bumps by ion induced desorption and corresponding self amplifying beam loss. These processes appear far below the typical space charge limits. Thus, new design concepts and new technical equipment addressing these issues had to be developed and realized. The upgrade program of SIS18 aiming for minimum ionization beam loss [5] and stable residual gas pressure conditions has been defined in 2005. Meanwhile, the fraction of this upgrade program which has been realized has resulted in a world record in accelerated number of intermediate charge state heavy ions.

INTERMEDIATE CHARGE STATE HEAVY ION OPERATION

Table 1: Existing and proposed heavy ion 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+}

Table 1 shows the presently running and planned synchrotrons using intermediate charge state heavy ions. The strength of 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].

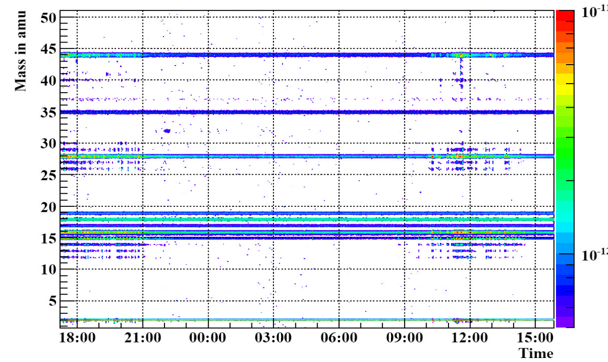

Figure 1: The residual gas spectrum in a synchrotron is changed by the desorbed gases. During high current operation (left and right), additional components appear with a density comparable with the static background spectrum. The gap in between indicates the time of low intensity operation.

The cross sections depend significantly on the target ion, or in other words the residual gas composition in the accelerator. Therefore, 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) (see figure 1). The mass spectrum of the desorbed gases can be determined by subtracting the mass spectrum during intense beam operation (dynamic) from the mass spectrum in the beam-off phase (static) [8].

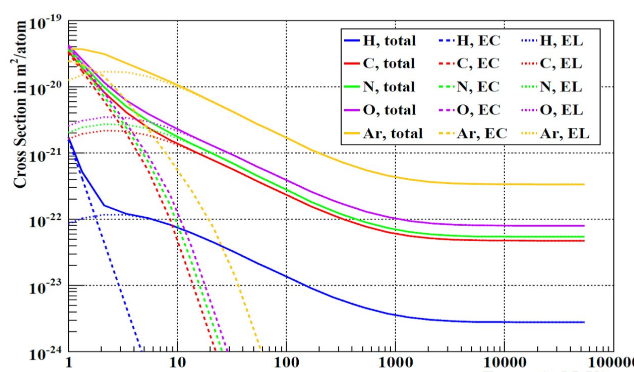

Figure 2: Calculated cross sections for ionization and electron capture of U^{28+}-ions as a function of beam energy for various target (residual gas) atoms.

Figure 2 shows the calculated cross sections for U^{28+}-ions over a large energy range for different target atoms. 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. 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 desired fast ramping for the FAIR synchrotrons. The power converters of SIS18 will be upgraded for acceleration with 10 T/s, while the key issue for SIS100 is the development of fast ramped superconducting magnets.

DEVELOPMENT OF HIGH INTENSITY 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 3). Initial systematic beam loss, e.g. at multiturn injection, may drive fast local pressure bumps and via the ionization process an inflating pressure dynamics with a spatial evolution involving several machine sectors. The enhanced pressure situation in turn amplifies the charge exchange and consequently the beam loss process.

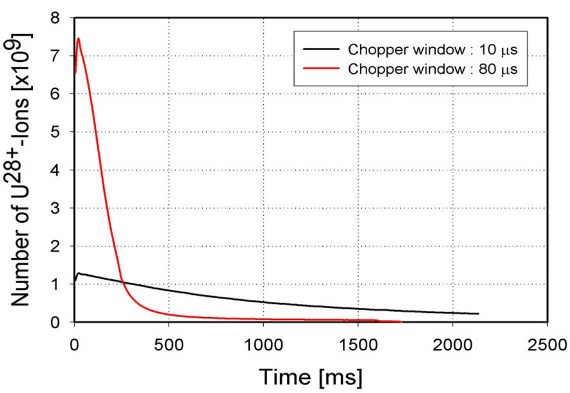

Figure 3: First experiments with U^{28+} in SIS18 in the year 2001. Ionization processes in sections where the pressure was enhance by ion induced desorption, caused an almost complete loss of the beam.

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 developed for the stabilization of the residual gas pressure during high intensity operation. A strategy with major work packages involving most of the technical equipment have been summarized at an early stage of the project and has been realized in the frame of an EU FP6 funded construction program. Furthermore, due to the new power grid connection of the GSI pulse power network, which has been completed in 2006, ramping of SIS18 with a ramp rate of 4 T/s (instead of the 1.3 T/s) has become possible.

Table 2: Work packages of the SIS18 upgrade 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 [9]	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 [10]	Completed
New h=2 acceleration cavity for fast acceleration in a two harmonic bucket	Ongoing

As a result of the various upgrade stages, the beam lifetime could be continuously increased. Figure 4 shows the measured lifetimes of intermediate charge state, heavy ions for different stages of the UHV system upgrade.

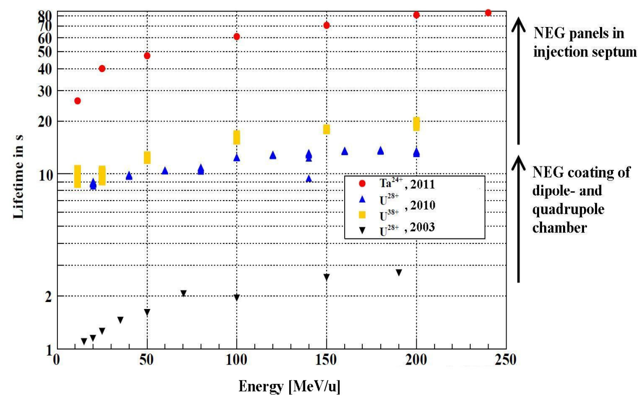

Figure 4: Measured lifetimes of intermediate charge state, heavy ions after NEG coating of the dipole- and quadrupole chambers and after inserting NEG panels in the injection septum.

After the recently completed insertion of NEG panels in the electrostatic injection septum, a perfect agreement of the single particle beam lifetime predicted by STRAHLSIM, with the measured life time as a function of energy has been achieved.

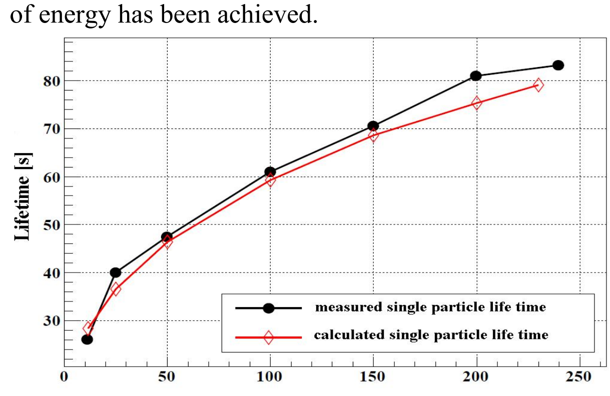

Figure 5: After the installation of NEG panels in the injection septum, a perfect agreement has been achieved between the measured and expected beam lifetime and its energy dependence.

Before the pumping power in the injection septum has been increased, the local pressure in the injection septum has defined the overall average pressure of the machine. Thus, the beam lifetime was always restricted by this enhanced pressure zone. At high intensity operation, the halo ions which are scraped of in the injection channel have a high potential for generating high voltage break downs. High voltage break downs generate strong pressure bumps in the injection septum tank. Even with the support of NEG panels, the recovery of the beam lifetime after a high voltage break down takes 6 minutes.

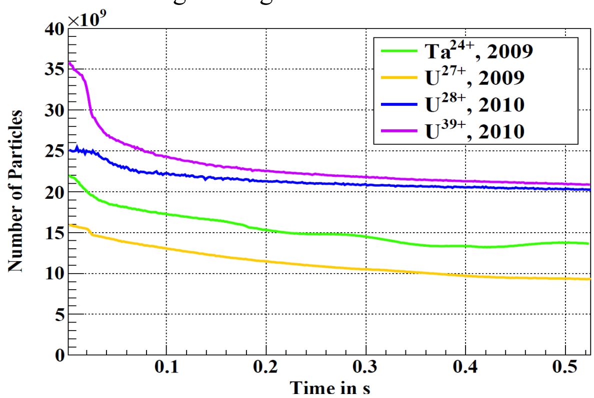

Figure 6: SIS18 acceleration cycles with intermediate charge state Uranium ions in 2009 and 2010. Beam loss by ionization, which is by far the dominating loss mechanism, could be significantly reduced and the number of extracted ions increased by a factor of 70.

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 several times (figure 6). It has been shown that the intensity level reached represents the actual machine performance defined by its technical status and the partial completion of the upgrade program.

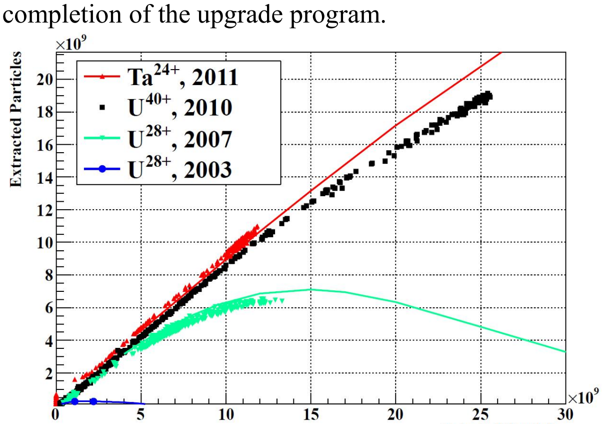

Figure 7: Dependence of the extracted versus the injected number of ions for various stages of the SIS18 upgrade program (measurements and simulations).

Saturation (e.g. green curve) indicates that strong dynamic vacuum effects limit a further increase of extracted number of ions. The graph extracted intensity over injected intensity shows the limit of the machine performance determined by the technical development status of the machine. Figure 7 shows the measured data and a STRAHLSIM extrapolation for higher number of injected ions. A linear dependence indicates that the extracted intensity is not yet defined by dynamic vacuum effects in the synchrotron and the extracted number of ions is still depending on the injected (UNILAC) beam current. Saturation by dynamic vacuum effects limited the maximum number of extracted ions in the year 2007 to 7×10^9 ions, while for the present situation the limit is expected at 5×10^{10} ions.

OUTLOOK

Aiming for the missing factor of ten needed for the FAIR booster mode, a number of additional technical measures are foreseen and under preparation. 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 another 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. 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 8 [11].

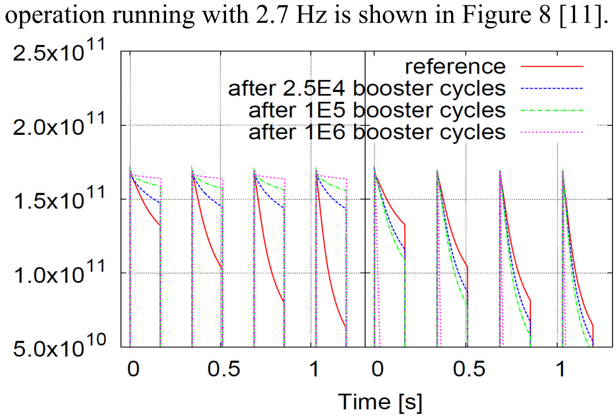

Figure 8: Results of STRAHLSIM simulations for the desired SIS18 booster mode with low initial beam loss. The gas desorption driven vacuum dynamics generates strong charge exchange beam loss. Beam scrubbing (left) may improve the long term behaviour significantly.

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