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SIS18 OPERATION WITH U^{28+}

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Abstract

In SIS18 U^{28+} is used to reach highest heavy ion beam intensities for FAIR-operation. The medium charge state avoids losses during stripping processes and shifts the space charge limit to higher number of particles. Nevertheless, these ions are subjected to ionization loss in collisions with residual gas particles. Via ion impact induced gas desorption a feedback between vacuum quality and beam emerges, yielding in a beam intensity limitation. The installation of charge exchange collimators is one of the several upgrade measures which have been performed to shift this limit. They are equipped with a current measurement system to detect charge exchanged ions, which is routinely used during machine experiments.

In this proceeding we present different beam based measurements showing dynamic vacuum effects. The non-linear dependence of the extraction intensity on the number of injected particles, ramp rate, and brake-time for vacuum relaxation will be shown. Stored heavy ion beams were used for charge exchange current measurements. They allow conclusions on the vacuum conditions and are presented as well.

INTRODUCTION AND MOTIVATION

SIS18 will be used as injector synchrotron for FAIR. In order to reach highest heavy ion beam intensities, medium charge states, i.e. U^{28+} will be used instead of high charge states like U^{73+}. The medium charge state avoids losses by stripping processes and shifts the space charge limit to higher number of particles. One drawback are high cross sections for charge exchange in collisions with residual gas particles. These cross sections increase with the gas particles atomic number and decrease with beam energy. Charge exchanged ions are separated from the circulating beam and get lost. At the position of impact to the beam vacuum chamber, via ion impact induced gas desorption, adsorbed residual gas is released into the beam volume. This leads to a local increase of the residual gas density. Such, a feedback between vacuum quality an beam intensity emerges. This is called dynamic vacuum and limits the maximum intensity.

SIS18 UPGRADES FOR U^{28+}

In the past decade, various technical upgrade measures were carried out to reduce the issue with dynamic vacuum [1, 2]. They are based on the fundamental understanding of the dynamic vacuum process:

- The new injection septum allows for a higher injection energy at reduced ionization cross sections.
- NEG-coating of vacuum chambers reduces the residual gas pressure and thus charge exchange processes.
- The ion catcher system reduces the gas desorption and such the dynamic vacuum.
- New acceleration cavities and upgraded magnet power supplies allow for faster acceleration, which means less time at high ionization cross sections.

These various improvements, as well as improvements at the injector-linac UNILAC resulted in an increase of maximum number of heavy ion particles, that could be accelerated in a single cycle in SIS18 [3, 4]. Figure 1 shows the highest achievable intensity curves during SIS18 acceleration cycles in recent years.

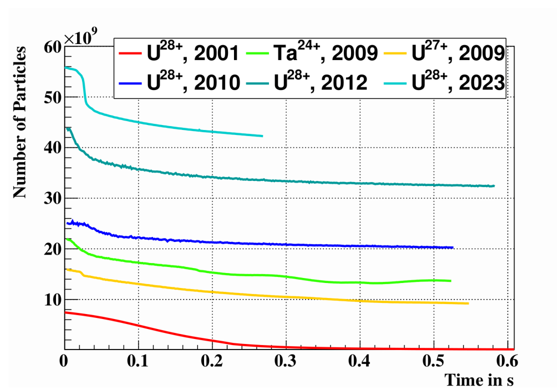

Figure 1: Historic evolution U^{28+}-ions during acceleration cycles in SIS18. Different ramprates yield in different cycle lengths. Large losses at the beginning are caused by the rf capture process and ramp start, further losses due to ionization processes. Ta^{24+} has very similar cross sections to U^{28+}.

MEASUREMENTS

The most recent machine experiments at SIS18 wit U^{28+} were carried out in December 2023. This campaign was dedicated to highest Uranium intensities, which were bred by dedicated, coordinated shifts at the ion source, the injector linac UNILAC and SIS18. One result is the new intensity record, shown in Fig. 1. In 2023, a ramping rate of up to 9.6 T/s could be used, which is why the recorded record cycle for this year is shorter than previous ones with lower ramping rates.

Ramping Rate

One measurement was dedicated to the dependency on the ramping rate. With up to 10 T/s, SIS18 is one of fastest

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controlled ramping heavy ion synchrotrons. During the measurement for Fig. 2, the ramping rate and the beam intensity provided by the UNILAC was varied. The intensity provided by the injector is sufficient to reach the maximum accelerable intensity in SIS18 for low ramping rates. Here, increasing the injector intensity yields in reduction of extraction intensity. Simulations of dynamic vacuum predicted the existence of such maxima [5]. The maximum gets shifted towards higher intensities, as the ramping rate is increased.

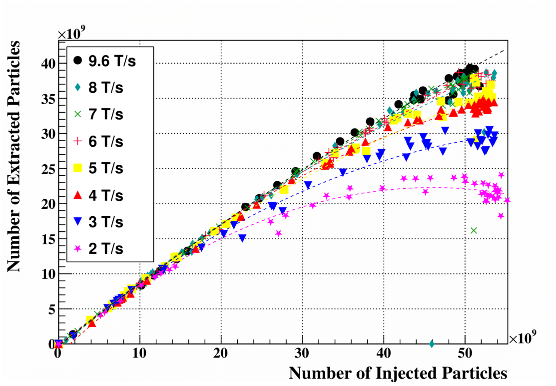

Figure 2: Number of extracted particles over number of injected particles for different ramping rates. For low ramping rates, the extraction intensity reaches a maximum. This maximum gets shifted towards higher number of particles for higher ramping rates. Dashed lines are parabolic fits to guide the eye.

In order to identify a clear dependence on the ramping rate, cycles with an injected intensity higher than $4.6 \cdot 10^{10}$ were taken for Fig. 3, which shows the beam intensity before extraction over the ramping rate. Additionally to the individual points, the average and root-mean-square (RMS) values for each ramping rate are shown. The saturation above 6 T/s is due to the intensity limitation by the Unilac, the maximum accelerable intensity in SIS18 is not yet reached, as it can bee seen in Fig. 2.

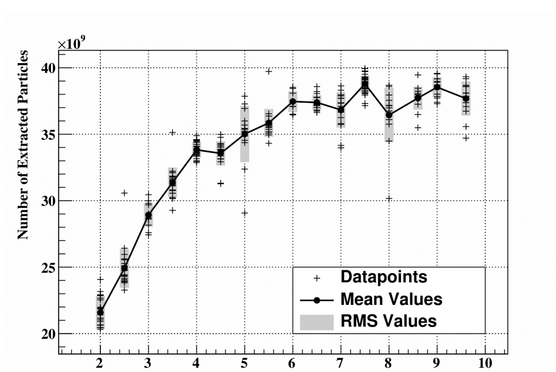

Figure 3: Number of extracted particles as function of the ramping rate. Only cycles with an injection intensity higher than $4.6 \cdot 10^{10}$ particles were taken.

The complete intensity curves and the injection process were recorded for each cycle. This makes it possible to analyze the different losses during acceleration in detail, see Fig. 4. Injection losses are the ratios between the integrated and not necessarily flat UNILAC-pulse and the stored intensity in SIS18 after the injection process. As the electrostatic chopper was our of order, the amount of injection loss is quite high, but constant as a function of ramping rate in the first order. The average amounts to 37.5%. Right after the injection process, the beam gets stored for a few milliseconds to prepare the rf-capture process, called "Injection Storage". In Fig. 1 this is the small area in front of the the step. The storage time causes in average 5% of beam loss. The step itself gets summarized as "RF Capture". This type of beam loss scales roughly linearly with the ramping rate $\dot{B}$ and follows

$$0.4\%\,\mathrm{s/T} \cdot \dot{B} + 5\%.$$

All remaining loss is summarized as "Ramp + Flattop". Here, ionization losses play the dominant role. The data can be described by a shifted exponential decay function:

$$118.6\% \cdot e^{-\dot{B}/1.93\,\mathrm{s/T}} + 12.6\%.$$

The shift term can be understood as contribution by unavoidable processes, like extraction preparation on flattop. For disappearing ramping rate, i.e. stored beam, the beam will get lost completely. In between, the loss function follows an exponential decay. Higher ramping rate yields in fewer losses.

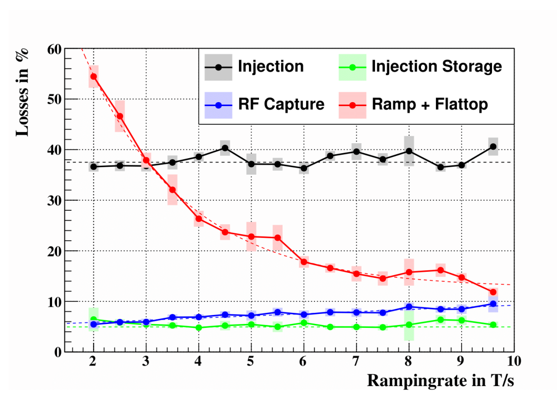

Figure 4: Comparison of different losses for different ramping rates. Only cycles with an injection intensity higher than $4.6 \cdot 10^{10}$ particles were taken. Points represent mean values, colored boxes the corresponding statistical error. Dashed lines represent fit functions, which are explained in the text.

Brake-Times

Varying the brake time between cycles does not yield in such a clear result, as for the ramping rate, see Fig. 5. It has to be noted, that with 0 ms additional brake time, a repetition rate of roughly 1 Hz was achieved. Hereof only 300 ms include sequences with beam, the remaining 700 ms are required for ramp down (~200 ms), preparation time and synchronization times. SIS18 was not operated in the so called "booster mode", which allows for maximum repetition rate. This measurement only shows 3% increase of extracted

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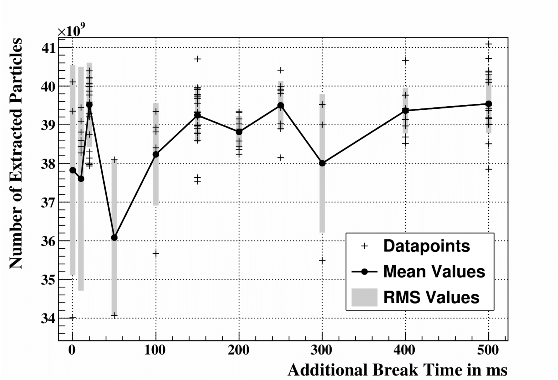

Figure 5: Comparison of different additional break times between the cycles. Only cycles with an injection intensity higher than $5.2 \cdot 10^{10}$ particles were taken.

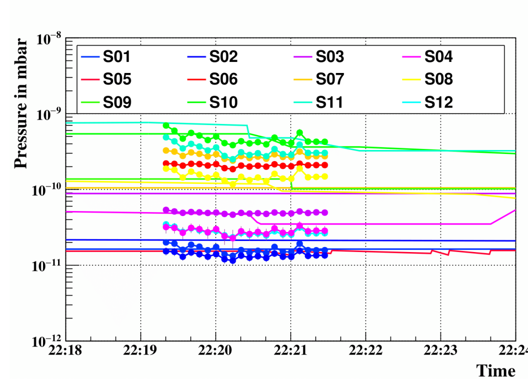

Figure 7: Average normalized collimator currents (dots) compared to pressure measurements (lines) in the corresponding sections.

particles, as the existing brake time is already sufficient for the vacuum to stabilize.

Collimator Currents

The technique to measure ionization loss in SIS18 using the ion-catcher blocks has been explained in details in [6]. Measured collimator currents are normalized to the beam intensity during analysis. Figure 6 shows normalized collimator currents for an arbitrary cycle with medium intensity stored beam. The presentation and the beam intensity is the same as in [6], but with recent data. Now, higher normalized currents are visible, hinting to a pressure increase since 2012.

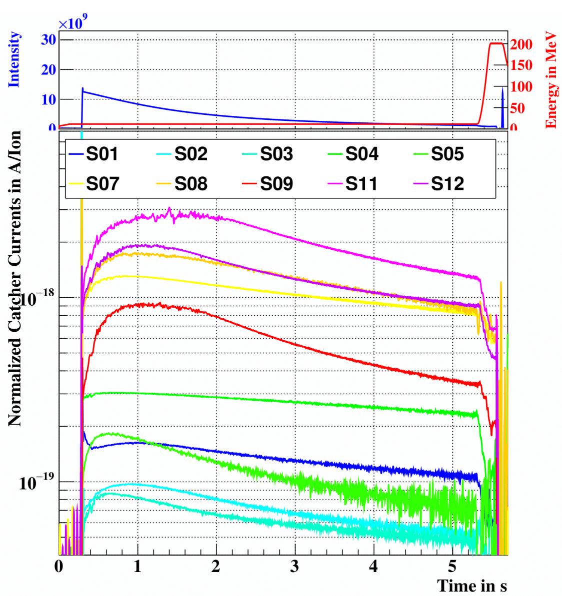

Figure 6: A cycle with stored medium intensity beam and normalized ion catcher currents for electron loss.

Several cycles of stored beam were recorded. The average normalized value around 1 s was taken and scaled by an arbitrary, but constant factor $4 \cdot 10^{7}$. This factor transforms the normalized catcher currents into the UHV-measurement range. Figure 7 shows these determined values together with recorded pressure data. The colors of the collimator currents correspond the pressure measurements, i.e. pressure measurement of S01 is now compared to collimator currents in S02. It is remarkable, that both measurements cover the same dynamic range. Also the order is comparable.

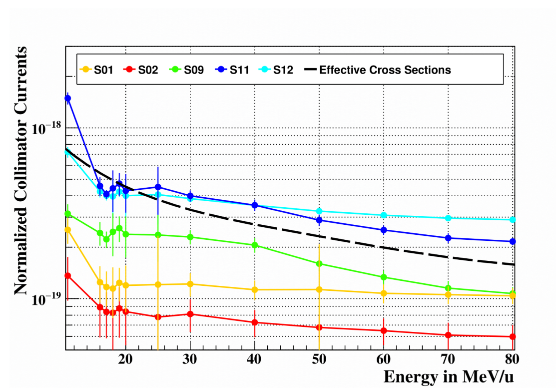

Figure 8: Normalized average collimator currents for different energies, including the scaling of theoretical cross sections for an assumed residual gas composition.

In the last presented measurement, the beam was stored at different energies on an intermediate flattop to record collimator currents. As the ionization cross sections decrease with energy [7], also a decrease of ionization current can be observed, see Fig. 8. The scaled cross section depends on the unknown average gas composition.

SUMMARY AND OUTLOOK

The recent machine experiments yielded in a new intensity record of Uranium beams in SIS18. The high ramping rate of up to 10 T/s successfully helps minimizing ionization loss. Structured measurements show, that SIS18 would be capable for even more intensity. Collimtor current measurements can help to identify regions with high pressure, which need further attention. They can be used successfully to measure vacuum dynamics during a cycle.

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