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SIS18 OPERATION AND RECENT DEVELOPMENT

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Abstract

GSI's existing synchrotron SIS18 will be used as booster for FAIR's main synchrotron SIS100. In addition it provides a wide variety of ions from Protons to Uranium for users directly at GSI and FAIR.

An upgrade program to enhance the overall performance for the booster operation has been carried out.

Part of the upgrade program for booster operation was a complete overhaul of the control system including data supply and timing system. In addition a new magnetic alloy cavities have been installed for h=2 operation and dual harmonic acceleration in conjunction with the existing h=4 cavities. The main power supplies have been upgraded to allow reduced cycle times.

Further upgrades and machine studies have been performed to enhance available beam parameters and provide new features for the users.

We will report about machine studies and recent operation for FAIR Phase 0 experiments utilizing various upgrade measures to enhance overall machine performance.

SUMMARY OF COMPLETED UPGRADES

SIS18 has been upgraded to serve as injector for the FAIR project [1, 2]. The design ion is U^{28+}, which is the most abundant charge state after the first striper stage of injector UNILAC [3]. The higher rigidity at injection energy of 11.4 Mev/u compared to ions stripped in the second stripper stage (for example U^{73+}) required an upgrade of the injection system [4]. To achive the intensity goals for FAIR the SIS18 has to run with a repetition rate of about 3 Hz. The power supply and the RF system [5] have been upgraded to meet this goal. The new magnetic alloy cavities work at harmonic number h=2 and were successfully tested with dual-harmonic operation in conjunction with the existing (h=4) ferrite cavities [6].

A new ionization profile monitor (IPM) was installed [7] and tested, but is at present not fully commissioned for routine operation.

The expected higher average intensities during FAIR booster operation and new safety and radiation protection regulations required a complete overhaul of the SIS18 building. The shielding has been significantly improved and the complete infrastructure in the accelerator building refurbished [8].

The operation of SIS18 with heavy ions of intermediate charge state requires a significant improvement of the vacuum system [9, 10]. All dipole and quadrupole chambers have been NEG-coated [11] to improve the overall static vacuum conditions.

The main obstacle in reaching the required intensities for booster operation is the control of dynamic vacuum effects. The maximum intensity in the cycle is limited by the control of initial and vacuum-induced beam-losses. The loss mechanisms have been studied in detail [12] and a dedicated simulation code named *StrahlSim*, combining ion optics, beam losses and vacuum condition has been deveolped [13, 14]. To overcome the dynamic vacuum instability a complete set of measures has been developed and implemented [15]. Notably a dedicated ion catcher system has been installed to migrate the unavoidable beam losses to surfaces with low desorption coefficients [16]. Machine studies were performed to confirm the suitability of upgrades [17].

Due to the combination of the upgrades' effects, the intensity of accelerated and extracted U^{28+} ions per cycle was increased by approx. a factor of 70 to about 2 to $3 \cdot 10^{10}$ [18]. The transfer of initial losses from the synchrotron into the injection channel to improve the dynamic vacuum effects were successfully tested [19].

SIS18's control system has been upgraded and SIS18 is now routinely operated with a LSA-framework-based software [20, 21].

ADDED FLEXIBILITY BY THE NEW FAIR CONTROL SYSTEM

Following a long shutdown from 2016 to 2018, mainly attributed to the civil construction activity, SIS18 was successfully recommissioned with the new control system [22]. All capabilities of the old control system could be reestablished with the exception of routines for medical tumor irradiation. Patient treatment is no longer planned at GSI.

A reduced set of capabilities for the bio-physics community is developed with a lower priority.

Besides establishing and testing the software foundation for the future FAIR accelerator complex at the existing GSI machines, the new software offers additional flexibility for machine experiments and operation.

During recent operation phases SIS18's injector could not deliver ions at full injection energy (11.4 MeV/u) due to varying reasons. Normally this leads to the situation, that the RF system cannot capture the beam at nominal harmonic number h=4, because the revolution frequency of the ions is too low. As compensation the ions can be accelerated with h=5 up to the upper frequency limit of the accelerating cavities limiting the maximum extraction energy available for experiments.

With the upgraded RF- and control- system it was possible to establish an accelerator cycle, where the ions are captured with h=4 by the low frequency MA cavities. After part of the acceleration ramp, the ferrite cavities take over with h=4 at nominal frequency. In Fig. 1 the RF amplitudes

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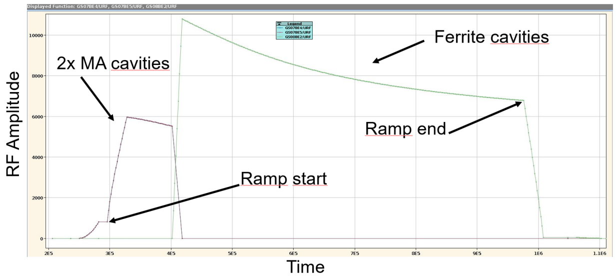

Figure 1: Combined RF cycle of both MA and ferrite RF systems to compensate for low injection energy. Both system work at harmonic number h=4. The MA cavity with a nominal h=2 frequency-swing capable of capturing the ions at low revolution frequency with h=4 and the ferrite cavities taking over during the ramp to finish the acceleration process. This was routinely used for experiment operation with minimal losses showing the performance of the new control system, RF system and RF synchronization.

for this mode of operation are shown. Beginning and end of the ramp are indicated. This cycle was routinely used with minimal losses during experiment operation. It is a convincing demonstration of the capabilities of both, the refurbished and upgraded RF system, the cavity synchronization and the machine modeling.

Beam-based feedback systems developed for FAIR are benefiting SIS18 experiment operation now. A prototype to form the macro spill structure of slowly extracted beams [23] could already be used to significantly optimize the duty factor for experiments with long extraction times and thus increasing the average statistics. A similar beam-based system to correct the closed orbit during the acceleration ramp was successfully tested at SIS18 [24].

SLOW EXTRACTION PERFORMANCE

Most experiments using SIS18 today require slowly extracted ions. Even during full FAIR operation SIS18 is foreseen to deliver slowly extracted beams to fixed-target experiments.

Already in the first report on SIS18 operation in 1990 stated two main problems with the slow extraction [25]: (1) The slow extraction efficiency at highest rigidities and (2) a very strong micro spill structure modulation.

Slow Extraction Efficiency at High Rigidities

The first problem was recently solved. The extraction efficiency was satisfactory (over 80%) if the electrostatic septum could be operated at higher than nominal extraction angle of 2.5 mrad. The best efficiency was achieved with angles of 3.5-4 mrad which is in agreement of the findings from the first operation report cited above. During recent dedicated studies on slow extraction, the power supply's voltage was measured independently of the devices own instrumentation by X-ray spectroscopy of the septum [26]. Figure 2 shows a clear indication that the voltage delivered was too low by a factor of about 1.6. The number is consistent with the measured angles. With proper voltage setting the transmission for high rigidity beams could be significantly improved.

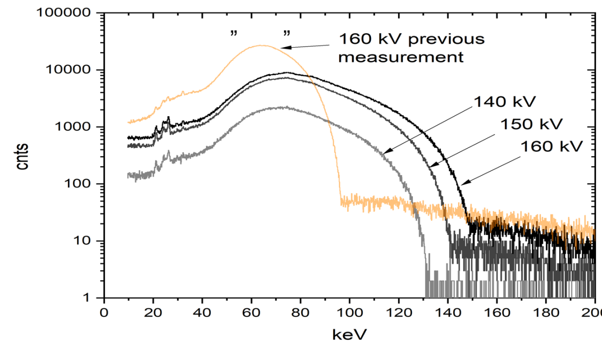

Figure 2: X-ray spectrum of the electrostatic extraction septum [26] with "broken" power supply (orange) and exchanged power supply. Clearly visible is that the old power supply's voltage (which should be 160 kV) is off by about a factor of 1.6.

The old mystery is only partially solved. In the 30 years of operation the electrostatic septum and it's power supply were both exchanged, yet the problem persisted. It is still unclear why the replaced power supply, from a another manufacturer, should have the same mistake with the same severity as the original one.

Improvements of Micro Spill Structure

The fluctuations of spill intensity over the spill significantly hamper fixed target experiments due to pileup in their detectors or data acquisition systems. Extracting bunched beam improves the situation for those experiments, which can cope with the 4 MHz structure imprinted on the spill by h=4 bunching.

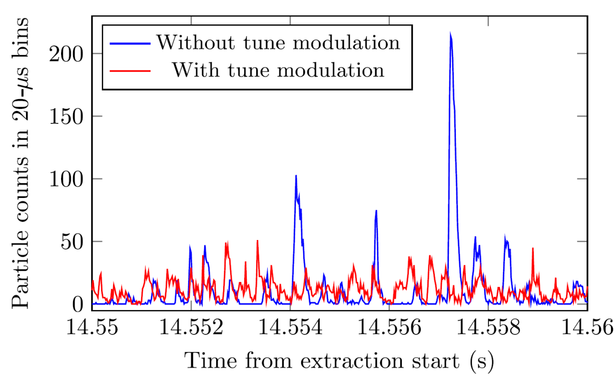

Figure 3: Spill fluctuations with and without tune wobble as described in [27]. The red curve shows a significant smoothing of the particle counts over time which could as well be measured in average statistics of experiments using this method. The tune wobble is available for operation.

For experiments requiring slowly extracted coasting beam a method using a high frequency (kHz range) "tune-wobble" on the main quadrupoles could be established [27]. This

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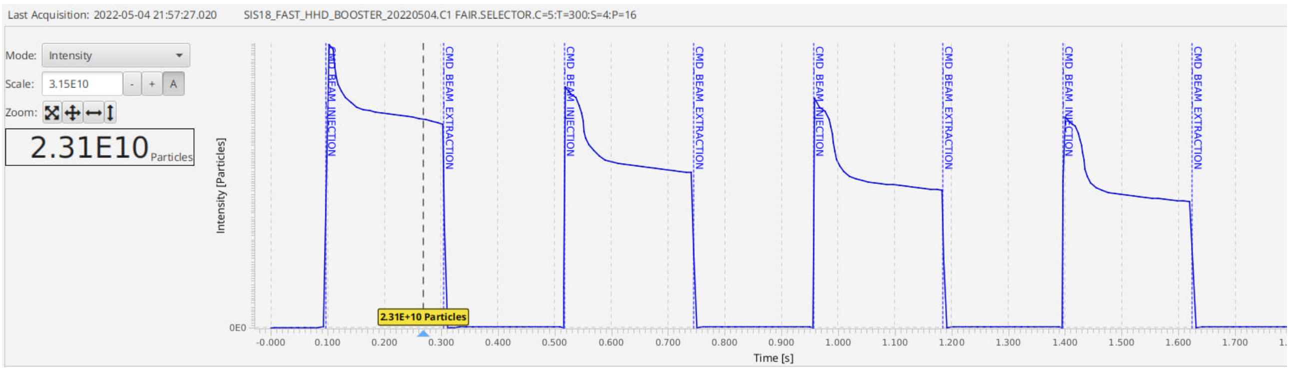

Figure 4: Beam current transformer measurement of a SIS18 booster cycle. About $2 \cdot 10^{10}$ U^{28+} ions per cycle could be extracted in four cycles in about 1.3 s (nominal 1s). That mode of operation was demonstrated for the first time in 2022.

significantly increases the statistics for fixed-target experiments using slow extraction (see Fig. 3). The wobble is implemented and fully operational and can be set up for any experiment, as long as they can provide the required signals for optimization to the main control room.

Planned machine studies will use a 80 MHz VHF cavity from UNILAC which is adapted to SIS18 needs now. It will be experimentally used as an alternative method for longitudinal spill smoothing by high frequency bunching or empty bucket channeling.

RECENT AND PLANNED DEVELOPMENTS

The booster operation of SIS18 for FAIR injection was demonstrated for the first time in machine studies in 2022. Nominal four cycles should be extracted in one second which corresponds to 2.7 Hz operation. 2.4 Hz was successfully demonstrated (see Fig. 4).

Beside the described SIS18 upgrades, this effort required significant developments on control system, timing system, UNILAC and ion sources. The electrostatic septum was damaged during this experiments and the investigation of the cause is presented at this conference [28].

Figure 4 shows a degradation of the cycles which is expected due to worsening initial vacuum conditions. In the near future the conventional vaccuum pumps will be replaced and improved to add more pumping power.

Studies to improve the overall vacuum in SIS 18 by cryo inserts are performed [29–32]. The SIS18 residual gas is now dominated by Hydrogen and already on a very low level. Further improvements most likely require cryo pumping.

To further reduce dynamic vacuum limitations on the beam intensity in SIS18 the overall losses in the cycle have to be reduced. Beside the already demonstrated transfer of losses from the ring into the transfer channel, better beam control and stability by active beam feedback systems [33, 34] or improved machine setup routines by machine learning [35], are under investigation.

For lighter ions the intensity limitation is dominated by space charge effects. To actively reduce space charge instabilities we investigate the possibility to compensate the space charge effects by a dedicated electron lens [36].

CONCLUSION

The originally defined upgrade program of SIS18 as FAIR booster has been concluded. Significant performance increase has been demonstrated and SIS18 proven ready as injector for FAIR commissioning.

Many improvements are beneficial for present physics runs at GSI (FAIR Phase 0) and future early FAIR experiments using SIS18 beam at FAIR's Super-FRS.

Further measures to reach full FAIR intensity and better user operation with direct beams from SIS18 have been started.

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