NEW CAPABILITIES OF SIS18 AFTER UPGRADE PROGRAM AS FAIR INJECTOR

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Abstract

SIS18, the main synchrotron of the present GSI accelerator complex, will serve as booster for the FAIR facility. Several major and minor upgrade programs were realized since 2008 to improve SIS18 for this purpose. We will report on new capabilities of the synchrotron for present and future user operation, which were not directly attributed to FAIR injector operation. Namely, a spill feedback system to control macroscopic spill shape and optimize spill microstructure during slow extraction. The operation of SIS18 with the new FAIR control system in conjunction with the RF upgrades allows beam operation without restrictions at lower injection energies. Acceleration of two beams consisting of ions with different mass to charge ratios at different revolution frequencies during acceleration are now possible and were successfully demonstrated in 2025. Possible users are medical research and plasma physics. As outlook we describe future plans for beam shaping before fast extraction for medical research.

INTRODUCTION

Due to the requirements of both, the FAIR project [1] and the research on the present campus, many upgrades have been done to GSI's accelerator complex [2, 3]. The priorities were mainly on refurbishing the machine for extended operation as FAIR injector and performance enhancing measures to fulfill the design parameters as injector for the future FAIR facility.

Beside the needed hardware upgrades and refurbishment the existing control system and setting generation software was replaced by a modern system. The established homegrown system was based on old hard- and software standards and most experts were retired, making it impossible to maintain. Moreover new hardware devices were increasingly difficult to implement. The new control system software is an LSA based framework developed together with CERN and will be used to operate all FAIR accelerators [4–6]. It was step-wise rolled out on the existing facility's accelerators. It is right now used to fully operate all machines but the injector linac UNILAC, where it is in the final test phase.

One of the hardware systems, which was completely refurbished and expanded is accelerating RF system. In addition to the two existing ferrite-loaded cavities operating at fourth harmonic (h=4) three new MA-loaded cavities operating at (h=2) have been installed to fulfill the future needs of booster operation for FAIR including dual harmonic operation [7]. The complete low level RF system (LLRF) has been renewed [8].

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The sum of all upgrades mainly aimed at FAIR operation allows us to develop new modes of operation and capabilities beyond the originally intended reach and already offer them to our users at the present campus for tests and research operation.

NEW CAPABILITIES OF SIS18 WITH MODERN HARD- AND SOFTWARE

In the following we will present examples of new modes and capabilities whose development can be attributed as a trade-off of FAIR related upgrades.

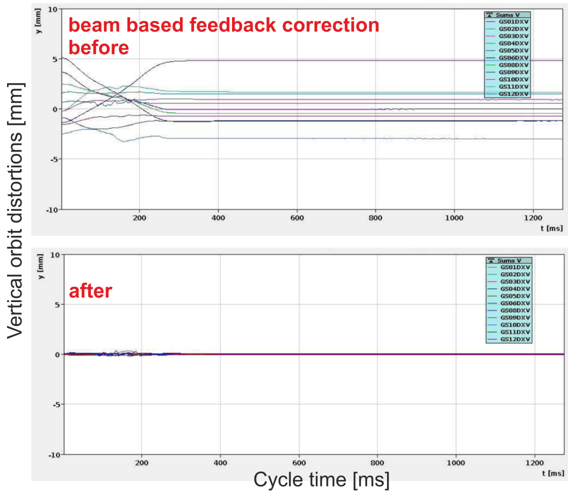

Figure 1: Measurements of the vertical closed orbit distortions (COD) in SIS18 before and after run of the beam based COD feedback prototype presented in Ref. [9]

Beam Based Feedback Systems

The new control software in addition with the refurbishment and upgrades of the existing beam diagnostics systems allows us to integrate beam based feedback systems directly in the control system environment. The main benefit of the new hard- and software are measurement data availability through standard interfaces and constant handling of machine settings over the full accelerator complex. Instead of creating multiple 'black box' feedback system with detector and actor, measurement and feedback can be either fully done in the new environment for slow systems or being integrated, operated and monitored for direct fast feedback systems.

Examples of such systems are presented in Ref. [9, 10]. A result of closed orbit correction prototype is presented in Ref. [9]. Results of a test are shown in Fig. 1. A correction tool for the macro spill structure of a slowly extracted beam has been developed and successfully tested as presented in Ref. [10]. The system was since then used to optimize spill quality for several experiment beam times.

A very successful system which is now evolving from a prototype to a operation's tool is the Spill Optimization System (SOS) [11,12]. It is shaping the macro spill structure with a direct feedback loop and optimizing the micro spill quality via modulation of the RF knock-out signal, by an iterative algorithm. The feedback is either data of a beam diagnostics device or directly from the experiment using the beam. The RF-KO signal is generated by software defined radio. An example of the optimization is shown in Fig. 2

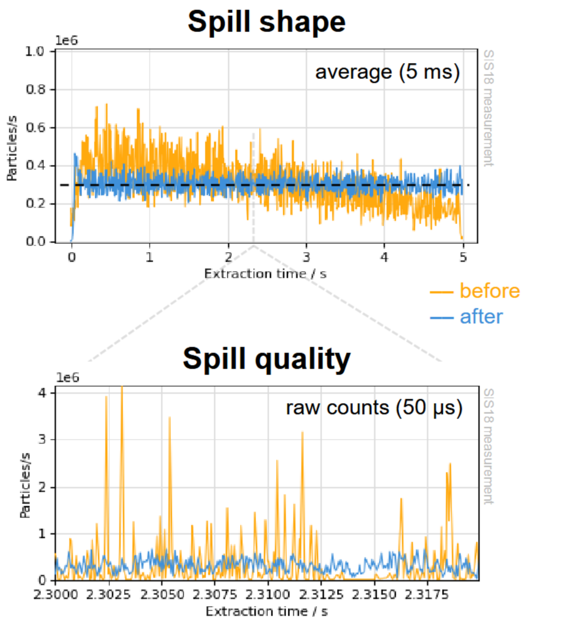

Figure 2: Comparison of the macro spill shape (top) and micro spill structure (bottom) with (blue) and without (orange) SOS system. The prototype system is implemented now for regular operation as reported at this conference by Ref. [12].

New Machine Cycles due to a Flexible RF System

SIS18 is designed to receive beam from UNILAC with a design energy of 11.4 MeV/u. In past operation phases we had to operate at with lower injection energy due to faults or maintenance of the injector's RF system. The lower linac energy leads to a lower revolution frequency at injection than the hardware limit of the cavities at nominal harmonic (h=4) or (h=2). Our standard compensation is to capture the beam at a higher harmonic (h=5) which in return limits us in maximum energy due to upper hardware limit of the accelerating system.

With the new hard- and software we were able to establish a cycle which captures the beam with (h=4) with the low frequency (nominal H=2) cavities. During the ramp the high frequency (nominal H=4) cavities take over as soon as the revolution frequency of the beam is high enough. The synchronization system, designed for dual harmonic operation, allows for a smooth transition during ramping with minimal losses. The amplitude ramps of the RF systems are shown in Fig. 3. This cycle is used in standard operation whenever the injection energy is lower than nominal. If the frequency range of the RF systems are not fitting for the given scenario we can still fall back to a scenario with intermediate flat top, un-bunching, re-bunching with different harmonics and continuation of the cycle. This flexibility can again be attributed to the new hard- and software environment.

We have requirements of users from the medical community for simultaneously extracted mixed beam consisting of Carbon ions for tumor treatment and Helium ions for parallel online monitoring [13]. We could do first tests with such a dual-isotope beam as reported in Ref. [14–16]. In those tests the C and He ions came from a common ion source and were injected and accelerated simultaneously. This lead to contamination of the beam with O ions which was sufficient for experiments but is not acceptable for patient treatment. The uniformity of the He/C Ration over the spill, extracted using the SOS system described above is shown in Fig 4

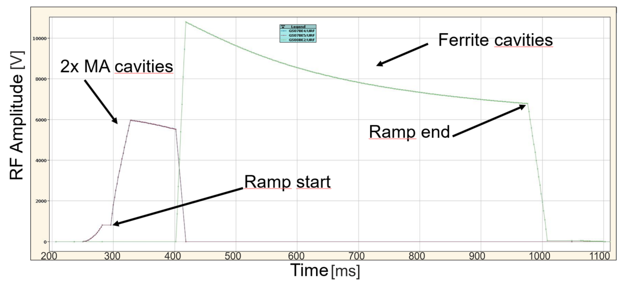

Figure 3: Amplitudes of the new MA and old ferrite loaded cavities for a SIS cycle with lower than usual (about 7 MeV/u instead of about 11 MeV/u) injection energy. If the full injection energy is not available, we compensate for the low revolution frequency during injection by capturing with the MA low frequency cavities (nominal h=2) at harmonic h=4. During acceleration the ferrite cavities take over for further acceleration at nominal h=4. The cycle is used for operation with minimal losses.

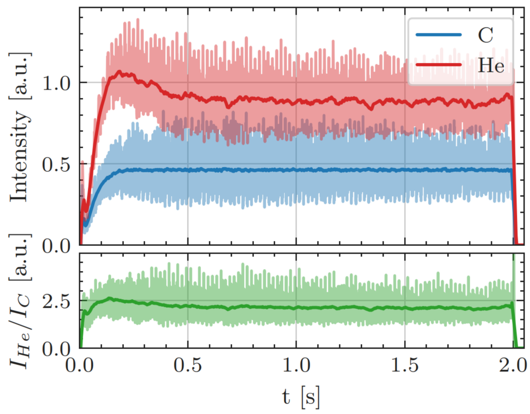

Figure 4: Example of an experiment with mixed He and C beam. Shown are He and C intensities in arbitrary units over the spill duration (top) and the ratio (bottom). Measured with active SOS system and averaged over 20 cycles as reported in Ref. [16].

One option to get a oxygen free mixed beam would be to get two injections from two different sources for He and C prepared with charge states and stripping, to deliver clean beams. Those beams would then be injected subsequently at the same injection energy but at different injection rigidities because they do not have the same mass to charge ratio. We could demonstrate such a cycle recently and it is presented at this conference [17]. There we mixed Fe and Bi, because they were available from different sources at that time. The less rigid beam was injected first and accelerated to an intermediate flattop after RF capture with one RF system. Then the second beam was injected and captured with another RF system and both beams were accelerated at the same magnetic ramp with different revolution frequencies.

This mode of operation might lead to new applications like heating a target with a heavy species for plasma generation while while illuminating it at the same time with He or p for measurements. Alternatively one could provide a light calibration ion (i.g. Carbon) to be mixed with a fragment beam of a heavy ion behind a production target with the right combination of charge states and target thickness.

Systematic Machine Studies with Python Interface

The future operation of GSI's and FAIR's accelerator complex requires the use of automated setup procedures for optimization of the machine setup. The develop and provide such algorithm and machine learning based tools a dedicated python interface to the control software has been established. This was not an original requirement of the specification but the refurbishment offered the needed flexibility to implement it.

It is used regularly for machine studies and a powerful tool to improve our overall performance. Reports on the system and example experiments using the framework can be found in Ref. [18, 19]. New results are presented at this conference by Ref. [20].

Future Plan

Recent research in radiotherapy using ultra high dose rates (FLASH) is considered as a potential breakthrough in cancer treatment [21]. To do FLASH irradiation we provided beam with slowly extracted beam and very short spills in range of 10 ms to 100 ms .

Medical scientists proposed to use even faster beam delivery by fast extraction, which requires a new approach for the dosimetry. With the slowly extracted beam the dose is measured online during irradiation. As soon as the dose limit is reached the beam is shut-off via spill-abort. The new proposal wants to deliver the complete dose via a tumor-conform 3D printed absorber at once. The timescale is about 300 ns , the duration of a fast extraction. That requires to establish the dose via intensity measurement before extraction. The usual cycle to cycle intensity fluctuations during normal operation of about 10% to 20% are considered to high for medical applications.

A possible solution to this problem is, to inject and accelerate the beam normally. On flattop one would establish

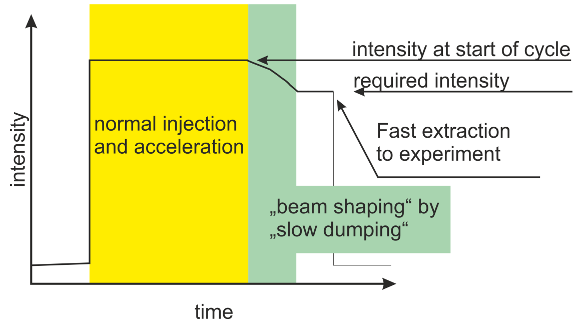

Figure 5: Schematic view of an intensity measurement during a possible cycle for (ultra)FLASH irradiation. After injection and acceleration (orange) the beam is slowly dumped internally via RF KO 'extraction' till the desired intensity is reached and then transported via the fast extraction system to the experiment.

a type of "slow extraction", which is not leading the particles escaping the separatrix into the extraction channel but onto an internal collimator. While doing this 'slow dump' a feedback has to be established on the beam intensity measured with a transformer. As soon as the desired intensity is reached an event is created to abort the 'slow dump' and the initiate the fast extraction towards the experiment as shown schematically in Fig. 5.

This cycle has not been developed and tested but seems feasible with the new flexibility of our present hard-and software. The extraction phase space might even be tailored by adjusting the size of the separatrix during the 'slow dump'. The sextupoles exiting the resonance will be powered down before fast extraction and the working point moved back to nominal values.

CONCLUSION

Changing the complete software system and many hardware components on an established machine is a challenge. Not all capabilities of the 'good old system' might be there from day one. Some things are buggy, some loved old tricks and procedures do not work anymore. We encourage you anyway to dare it if needed. Beside the wanted outcome of better performance due to upgrades, better maintainability and reliability you will get new features you didn't even consider at first place.

After the FAIR upgrades we are now able to provide our users with new beam options and we are still developing more.

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