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# RECOMMISSIONING OF SIS18 AFTER FAIR UPGRADES

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*Abstract*

The synchrotron SIS18 of the GSI facility has recently resumed beam operation after a long shutdown, during which major upgrades for the operation of SIS18 in the FAIR facility were realized. This signifies a major milestone for the mission of GSI and FAIR. On one hand, the scientific program of GSI depends strongly on beam from SIS18, including the very important developments of detectors for FAIR experiments. On the other hand, large parts of the existing GSI accelerator facility, including SIS18, are now operated with the FAIR control system, demonstrating its suitability for control of a large scale accelerator facility. Commissioning of the new control system started during the shutdown with a series of dry runs, which proved very useful to establish basic functionalities. Recommissioning of SIS18 was further facilitated by the fact that the machine model of SIS18, implemented in the modeling framework LSA [1, 2], had already been tested with beam several years before the shutdown. Thus, all operation modes of SIS18, including multi-turn injection, electron cooling, as well as fast and slow extraction could be successfully commissioned during the first weeks of operation. Other commissioning activities concerned the operation of new devices installed during the shutdown. These devices, mostly installed to prepare SIS18 for the operation with FAIR design parameters, open new possibilities in the standard operation of SIS18. An unusual challenge for the operation of SIS18 is posed by ground motion due to groundwater lowering for the nearby FAIR construction site. Surveys revealed that SIS18 subsided by several centimeters during one year. Even though the machine was realigned prior to recommissioning, the dynamics of the ground motion will continue to affect operation of SIS18.

## INTRODUCTION

Since 1990, the heavy ion synchrotron SIS18 has been the workhorse of GSI's experimental physics program with heavy ions in the energy range of several hundreds of MeV per nucleon. During the last decade, a series of upgrades to the machine has been completed aiming at satisfying the more demanding requirements of operation within the FAIR facility [3]. More recently, buildings and infrastructure pertaining to SIS18 were upgraded to support operation with the FAIR design intensities, requiring heavy construction work to improve radiation protection by increasing shielding and tightening the tunnel, to establish a new power grid connection, and to modernize the fire protection systems [4]. Those activities were executed during a long shutdown lasting from end of 2016 to mid 2018.

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A major challenge to recommissioning SIS18 after the long shutdown was posed by the switch to the new FAIR control system [5], which affected all parts of the GSI accelerator facility except the linear accelerator UNILAC. Though ultimately unavoidable for integration of SIS18 into the FAIR facility, this proved a difficult step even though the new control system had already been used since 2016 to operate CRYRING, a small storage ring with its own injector [6]. Many issues associated with peculiarities of SIS18 needed to be resolved during the shutdown. The transition was facilitated, though, by the fact that the SIS18 machine model, used to create settings for devices from physics parameters, had largely been implemented and verified with beam in parallel to the operation with the previous control system [7]. Only the electron cooler model was realized later during the shutdown but worked smoothly right from the start of commissioning.

To cope with the uncertainties of operation with the new control system, a commissioning strategy was devised which focused on establishing the proper functioning of the hardware and testing its integration into the new control system as early as possible. Beam commissioning was then performed with priority on verifying the operation modes required for the experiments scheduled in the first physics run.

The remainder of this article gives an overview over the operation modes of SIS18 and the recommissioning experience after the long shutdown.

## SIS18 LAYOUT AND OPERATION MODES

### Machine Layout

The basic SIS18 lattice consists of twelve identical cells, each comprising two bending magnets and a quadrupole triplet. Notably, the optical settings change during the SIS18 cycle: at injection, a triplet optic is applied to maximize the horizontal acceptance for multi-turn injection; during the ramp, the third quadrupole is adiabatically switched off while keeping the tune constant, resulting in a doublet optic. The doublet optic provides larger horizontal beta functions at the extraction elements reducing their required strengths. Despite the increase of the horizontal beta function, the beam size always shrinks due to the stronger adiabatic damping of the horizontal emittance.

SIS18 has a maximum magnetic rigidity of 18.5 Tm. The maximum energy depends on the ion species, ranging from 200 MeV/u for the FAIR reference ion $U^{28+}$ up to 2 GeV/u for light ions and 4.7 GeV for protons. The maximum repetition rate is about 3 Hz, determined by the maximum ramp rate of the main dipole power converter. The practical limit on the longest cycle time is about twenty seconds.

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SIS18 has two different RF systems for acceleration: two ferrite cavities providing a total 28 kV at harmonic number $h = 4$ and three MA loaded cavities delivering a total 40 kV at $h = 2$. The latter were installed as part of the SIS18 upgrade for FAIR [8]. While the standard acceleration scheme today still employs only the ferrite cavities, the reference scheme for FAIR will be dual harmonic operation with $h = 2$ and $h = 4$ using both cavity types. The dual harmonic RF scheme helps to increase intensities by reducing transverse space charge through bunch lengthening.

Finally, SIS18 contains an electron cooler for cooling at injection, which can be employed to create beams with very small transverse beam size and to accumulate beam from the UNILAC for ion species delivered in very low intensities.

Table 1 summarizes the main machine parameters of SIS18.

Table 1: SIS18 Machine Parameters

| | |
|---|---|
| Circumference | 216 m |
| Number of cells | 12 |
| Transverse acceptance | 150 µm × 50 µm |
| Inj. mom. spread ($\sigma$) | $5 \cdot 10^{-4}$ |
| Maximum rigidity | 18.5 Tm |
| Maximum ramp rate | 10 T/s |
| Working point | 4.3, 3.3 |
| Nat. chromat. (triplet) | -1.0, -1.7 |
| Nat. chromat. (doublet) | -1.5, -1.3 |
| Transition $\gamma$ (triplet/doublet) | 4.9 / 5.6 |
| Injection energy | 11.4 MeV/u |
| Extraction energy | 100 – 4700 MeV/u |
| Revolution frequency | 0.2 – 1.4 MHz |
| Max. RF voltage ($h = 2/4$) | 40 kV / 28 kV |
| Maximum cooler voltage | 35 kV |
| Standard cooler field | 0.06 T |
| Standard cooler current | 0.3 A |

### *Injection*

SIS18 is filled horizontally by painting the phase space over several turns with a single pulse delivered by the injector linac (UNILAC). This process, called *multi-turn injection* (MTI), is facilitated by four fast bumper magnets creating a time-dependent horizontal local orbit bump at the electrostatic injection septum. The amplitude of the bump is reduced to zero over several ten turns, corresponding to a time of about 200 µs. An electrostatic chopper installed in front of SIS18 can be used to cut out the desired part of the pulse delivered by the UNILAC, thus avoiding unnecessary losses of particles outside the acceptance of SIS18.

By utilizing SIS18's electron cooler, MTI can be repeated several times to accumulate beam from the UNILAC. This is achieved by alternating MTI with cooling, which effectively clears the injected phase space again. This procedure, referred to as *multiple multi-turn injection* (MMI), increases intensity at the cost of longer cycle time due to the required few hundred milliseconds of cooling time per MTI step.

### *Extraction*

The main extraction mode of SIS18 is *slow extraction*, providing experiments with a continuous spill extended over times ranging from a second to about twenty seconds. A set of six independent sextupoles is excited to create a third-order resonance at $Q_h = 13/3$. Two local orbit bumps are formed to move the closed orbit towards the electrostatic and magnetic extraction septa. Two extraction methods are available: *quadrupole driven extraction* and *transverse knock-out (KO) extraction*. Quadrupole driven extraction employs two extraction quadrupoles to shift the horizontal tune towards the resonance, shrinking the separatrix to render particles unstable. KO extraction uses band-limited pseudo-random noise to blow up the beam horizontally, pushing particles outside the static separatrix. In both methods, a fast spill abort is possible by swiftly switching off the extraction quadrupoles, forcing the tune away from the resonance. KO extraction also supports interruption and resumption of slow extraction by switching the excitation off and on. Extraction of both coasting and bunched beams is possible, the choice depending on experimentalists' requirements on the time structure.

*Fast extraction* within one turn can be realized by firing a set of fast kicker magnets. At higher rigidities, a local orbit bump towards the magnetic septum is required due to limited kick strength. The number of bunches can be changed by performing RF manipulations prior to extraction. When a single bunch is created, it can be longitudinally compressed by applying a fast bunch rotation using a dedicated cavity.

### *RF Techniques*

Several RF techniques are available for manipulating the longitudinal phase space in SIS18. For single bunch creation, a series of *bunch mergings* is applied if the number of bunches equals a power of two. Otherwise, the beam is debunched and rebunched at $h = 1$. With respect to FAIR requirements, the most important RF technique is *dual harmonic acceleration*. The new control system supports this technique in SIS18 for arbitrary main harmonic numbers as long as frequency ranges stay within the cavities' limits. Occasionally, the UNILAC will deliver beam at a lower than the standard injection energy. In that case, upper limits on cavity frequencies can prevent acceleration to highest energy with a single group of cavities. Therefore, a technique has been developed to hand over the beam during the ramp from the MA cavities to the ferrite cavities.

## RECOMMISSIONING

Recommissioning of SIS18 after the long shutdown proceeded in several steps. Toward the end of the shutdown, dry runs were regularly performed to test hardware and control system readiness, followed by commissioning with beam to establish the basic operation modes of SIS18 with particular emphasis on those modes required for the first physics run, which was then successfully completed during this spring.

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### *Dry Runs*

Close to the end of the long shutdown, more and more devices of SIS18 became available for powering and cycling tests. Therefore, a series of eight dry runs was scheduled, roughly one per month with a duration of about three days. During these runs, the control system was used to power and run all available devices with the twofold aim of establishing the proper functioning of the hardware after more than a year of shutdown and verifying the control system features required to operate and monitor the devices.

A significant milestone was reached when the big power converters of main dipoles and quadrupoles were operated synchronously at highest possible ramping speeds, which was part of the site acceptance test of the dipole power converter upgrade for FAIR. For those tests essentially the full control system stack was required and operated successfully.

A notable exception concerned the functionality of the timing system required to request and inject beam from the UNILAC, which was verified in the last dry run before the start of beam commissioning, when the UNILAC was available for testing.

### *Commissioning Runs*

SIS18 recommissioning with beam started in June 2018. Once all devices worked as expected, the basic procedures of injection, acceleration as well as fast and slow extraction were established within two days. However, progress successively slowed down because the control system was still lacking essential monitoring and tuning functionality. Also, in retrospect the learning curve for working with the new control system had been underestimated despite significant training effort prior to beam commissioning. In any event, commissioning was interrupted shortly after by an unforeseen incident in the UNILAC which precluded SIS18 beam operation for several months.

Beam commissioning was resumed by November 2018 with a greatly improved control system. The aim of this so-called engineering run, which lasted four weeks, was to establish all operation modes required for the physics run scheduled for this spring. This lead to the successful demonstration of all operation modes except MMI, which was not required for the physics run. Given the difficulties, expected and unexpected, accompanying the transition to the new control system, this strategy proved very useful, because it helped to reveal and eliminate obstacles as well as to create optimized settings for later reuse in the physics run.

The commissioning runs included also dedicated machine beamtime, part of which was used to continue hardware commissioning of the new MA cavities installed as part of the SIS18 upgrade for the operation as FAIR injector. After a careful phase calibration, dual harmonic acceleration using MA and ferrite cavities was successfully performed. A small number of technical issues with the MA cavities need to be resolved, however, before they can be used in routine operation.

### *Physics Runs*

During this spring, SIS18 completed its first eight week physics run after the long shutdown. Thanks to the previous engineering run, beam commissioning at the beginning of the physics run went very smoothly.

A major part of the physics run was used for the HADES fixed target experiment requiring slowly extracted beam at highest rigidity with an optimal duty cycle to maximize statistics. To achieve these goals, SIS18 was operated for the first time ever with an extraction time of twenty seconds. The spill duty factor was optimized by means of a new technique applying an artificial current ripple at a few kilohertz to one of the main quadrupole power converters. For quadrupole driven extraction, this leads to a significantly smoother spill micro structure [9]. The macroscopic spill shape, on the other hand, was optimized by improving the parametrization of the tune ramp. Further optimization is possible by employing a cycle-to-cycle feedback based on the HADES spill monitors and acting back on the tune ramp. Such a system was successfully demonstrated though not yet used in production due to its prototype state.

The other experiments could be mostly served to their requirements with beam from SIS18. Where requirements could not be met, the reason was more often related to beam physics issues than to shortcomings of the control system. All in all, the FAIR control system proved to be sufficiently advanced to support a smooth SIS18 physics operation, even though significant latencies during the manipulation of settings remain an issue to be solved. Further control system developments for SIS18 will now focus on beam-based tools for a more efficient and reproducible set-up of the machine as well as tools for improved monitoring and analysis of machine and beam performance [10–12].

Ground motion caused by groundwater lowering at the nearby FAIR construction site poses another challenge for the operation of SIS18. In particular, in the three months between engineering run and physics run the SIS18 tunnel had subsided by several millimeters on average. Even though the motion corresponds roughly to a tilt of the SIS18 plane, deviations from this plane are non-negligible. The residual misalignments may explain the observed limitations in the horizontal orbit correction at highest rigidity, where available corrector strengths were insufficient to achieve full correction. Due to the generally low beam intensities requested by experiments during the physics run, this effect could, however, be compensated by adjusting settings without adverse impact on the beam performance.

## CONCLUSIONS

After a long shutdown of almost two years, during which major upgrades to the infrastructure were executed, SIS18 was successfully recommissioned in 2018 with the new FAIR control system. Essentially all operation modes could be reestablished during beam commissioning. In spring 2019, SIS18 served several experiments reliably during a physics run with good beam performance.

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