OPTIMIZATION OF THE SIS18 INJECTOR OPERATION FOR FAIR

D. Ondreka, H. Liebermann, B. R. Schlei, GSI, Darmstadt, Germany

Abstract

In the FAIR accelerator complex, the existing synchrotron SIS18 will serve as an injector, supplying intense beams of heavy ions and protons for further acceleration in the synchrotron SIS100. In order to satisfy the intensity requirements for FAIR, SIS18 has to be operated routinely at the space charge limit. Particularly demanding requirements arise from the operation with medium charge state heavy ions due to the dynamic vacuum created by ions lost through charge exchange reactions. It is therefore crucial to avoid losses in SIS18 as much as possible while confining unavoidable losses onto low desorption surfaces. In this contribution we report on the ongoing activities related to minimizing the losses by means of a better quantitative understanding and control of the beam. This includes the development of more accurate theoretical models, benchmarked with machine experiments, as well as the practical integration of the models into the control system, using beam instrumentation data in the calculation of set values whenever possible.

INTRODUCTION

The synchrotron SIS18, after 25 years of successful operation in the GSI facility, faces new challenges with the upcoming FAIR project, where it will mainly serve as an injector to the synchrotron SIS100. The FAIR design goals ask for an increase in beam intensity by an order of magnitude at a three times higher repetition rate. To overcome the space charge limit, SIS18 will be operated for FAIR with medium charge state heavy ions. This places strong demands on the vacuum system, because medium charge state ions are very susceptible to charge exchange reactions with residual gas in the beam pipe at low energies. Through a series of upgrade measures, an impressive increase of the intensity of the design ion U^{28+} from 10^9 to 3×10^{10} particles per cycle has been achieved in the last years [1]. At present, this number is limited by the current from the injector.

However, simulations and measurements of the dynamic vacuum indicate that, when increasing intensities further, particle loss on all but low desorption surfaces must be strictly avoided [2]. Since the losses at the beginning of the cycle presently are on the order of 10 to 30 per cent, there is no guarantee that with more current from the injector the number of particles extracted from SIS18 will increase.

Therefore, the focus shifts to a better quantitative understanding of the loss mechanisms with the aim of mitigating them by an improved operational control. Ultimately, the control system should let the operator in create optimized settings by adjusting the parameters of an adequate machine model, supported by the integration of beam instrumentation data in the settings generation process.

This contribution reports on the activities relating to the operation of SIS18 in the FAIR injector mode.

CONCEPTS

The main sources for losses in SIS18 are well known: MTI is susceptible to producing losses on the septum when optimizing for intensity; particles in the tails of the momentum distribution get lost from the buckets at the beginning of acceleration; orbit distortions limit the acceptance and amplify non-linearities; for a large space charge tune spread, particles can get lost on resonances.

The losses during MTI are routinely decreased by collimating the injected beam in the injection line when operating with U^{28+}. Still, the residual losses on the septum need to be reduced further. Therefore, a theoretical model for the optimization of MTI under high intensity conditions is presently being developed [3]. The model makes predictions for the optimal injection parameters as a function of the emittance. This model shall be benchmarked with the machine soon.

Under high intensity conditions, it is difficult to clear the tails of the momentum distribution, since these are created by the action of longitudinal space charge in the ring. However, the particle lost from the buckets can be captured on a low desorption collimator. This requires a precise control of the orbit at the beginning of acceleration. Since a stable and flat orbit improves the performance of the machine anyway, efforts are taken to correct the orbit over the complete cycle: An application for orbit control will be available soon. In addition, a B-train system is being developed to correct the mean orbit deviation.

Finally, losses due to resonances should be avoided by compensating the resonances. Collimation of these losses is difficult, because the loss position can in general not be controlled. Machine experiments for resonance compensation are in preparation, and an integration into the settings generation system is foreseen.

SETTINGS GENERATION

One of the most important operating tools is the settings generation system for the creation and modification of the set values used to control the devices of the accelerator. The settings generation system for FAIR will be based on the CERN LSA framework [4]. Its core is formed by the machine model, representing the accelerator by a hierarchy of parameters from physics to hardware and implementing the algorithms for the calculation of all parameters. Applications allow the user to display and modify the parameters of the model at all levels of the hierarchy. Since 2012, the system, though still in a prototype state, can be used to control SIS18 during machine experiments. In the following, the features of the new settings generation system related to the FAIR injector operation are described.

MTI in SIS18 is realized using a time dependent orbit bump created by four magnets. For matching the theoretical model against the real machine, the settings generation

system must provide a parameter for modifying the orientation of the bump in horizontal phase space, including the strong dependence on the working point. The bumper model has been implemented accordingly and is now available for parameter studies.

One of the essential ingredients in the FAIR injector operation is the implementation of a dual harmonic acceleration scheme in SIS18, employing three MA cavities operated at $H = 2$ together with two ferrite cavities at $H = 4$. Dual harmonic acceleration will lower the transverse space charge significantly due to the lower peak intensity of the bunches compared to single harmonic operation. On the other hand, single harmonic acceleration will not necessarily be given up completely. Consequently, the machine model for SIS18 was designed to support both single and dual harmonic acceleration. The model is parametrized by physics parameters (bunch area, filling factor, ramping speed, etc.) and derives from these the RF amplitude and phase ramps, including effects of longitudinal space charge.

Finally, the FAIR injector mode for protons is currently being implemented. Protons need to be treated specially because their final energy may exceed the transition energy of SIS18. To avoid transition crossing, the transition energy must be shifted by means of an optics distortion. As a consequence, the extraction parameters need to be calculated in a different way. The new model takes this into account.

Of course, development of the machine model will be continued until FAIR is in routine operation. Meanwhile, effort is put in the development of applications coupling the results of analyzed beam instrumentation data back into the settings generation system. As an example, an application for orbit correction on the ramp based on direct readout of the beam position monitors is presently being prepared. With a stable orbit during acceleration, the performance of SIS18 is expected to increase significantly. This kind of software feedback shall be used whenever a sufficiently accurate model cannot be implemented with a reasonable amount of effort.

MACHINE EXPERIMENTS

During the first half of this year, the new settings generation system was used extensively both to check its validity and to provide settings for the commissioning of new hardware and new operation modes. The flexibility of the new settings generation system proved extremely helpful in the first commissioning of the new MA cavity with beam, which went very smoothly. Apart from that, a number of further experiments involving the RF system were supplied with settings.

The improved model for MTI was successfully commissioned. Originally, it was planned to use the new model directly for systematic studies of MTI. Unfortunately, these experiments could not be performed because the performance of SIS18 was severely hampered by an obstacle in the beam pipe. While this obstacle could be evaded by introducing a local orbit bump, the nominal machine performance could

not be established. Therefore, the MTI studies had to be deferred to the second half of the year, when the obstacle will have been removed. For the same reason, intensity dependent features of the model, like the space charge correction in the calculation of the set values for the RF, could not be tested so far.

Despite this limitation, two important machine experiments for the development of the FAIR injector mode could be performed. The results are presented in the remainder of this section.

Dual Harmonic Acceleration

Owing to an extensive upgrade program of the low-level RF system of SIS18 performed by the GSI RF group in the last years, the precise phase control and synchronization of the cavities required to establish dual harmonic acceleration are now available. The feasibility of this scheme had already been demonstrated earlier using the ferrite cavities. The recent installation of the first MA cavity allowed to test dual harmonic acceleration in the FAIR scheme, albeit with a lower ramping speed. This experiment, conducted primarily by the RF group to test the synchronization mechanisms of the low-level RF systems [5], served at the same time as a test of the algorithms for dual harmonic acceleration implemented in the new machine model.

The experiment was performed with a beam of Kr^{33+} at different extraction energies, with intensities of up to 2×10^9 particles per cycle. A low ramping speed of $1\,T/s$ was chosen in order to minimize spurious effects from a high ramping speed. Figure 1 shows the ramps for amplitude and phase of the two RF cavities used during the experiment. The new MA cavity was operated at the main harmonic $H = 2$, while one of the two ferrite cavities was operated at $H = 4$.
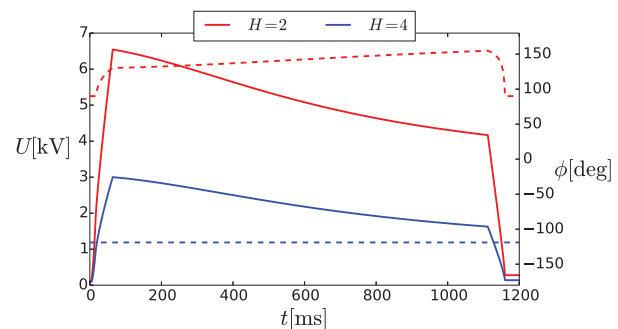

Figure 1: Amplitude (solid) and phase (dashed) ramps of the two RF systems operating at $H = 2$ and $H = 4$ during dual harmonic acceleration.

After fine tuning the global phase offset of the MA cavity using the settings generation system, flat-topped bunches were observed over the whole ramp.

Figure 2 shows bunch profiles recorded during this experiment by the RF group (see also [5]). Similar results were obtained for operation with $H = 4/8$ using the two ferrite cavities. These results validate the machine model for dual harmonic acceleration in the low intensity case.
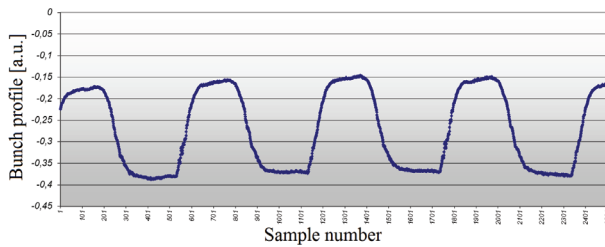
Figure 2: Bunch profiles recorded by the RF group during the $H = 2/4$ dual harmonic acceleration experiment.

Fast Ramping

The injector mode requires the operation of SIS18 at a ramping speed of $\dot{B} = 10\,\mathrm{T/s}$. Since SIS18 is not routinely operated at this ramping speed, an experiment was performed to check the machine performance under these conditions. For highly charged ions, the ferrite cavities provide enough voltage to allow acceleration at high ramping speeds. Using a beam of Ni^{26+} with intensities of about 5×10^8 particles, acceleration at ramp rates from $3.6\,\mathrm{T/s}$ to $9\,\mathrm{T/s}$ was studied. The extraction energy was chosen to match the present current limit of the dipole power converter for fast ramps. Figure 3 shows the corresponding dipole cycles. In this experiment, a new mode for creating the total RF voltage was employed, switching the cavities on sequentially instead of distributing the voltage equally. This mode minimizes the cavity impedance at low voltages and will become important for the operation with high intensities.
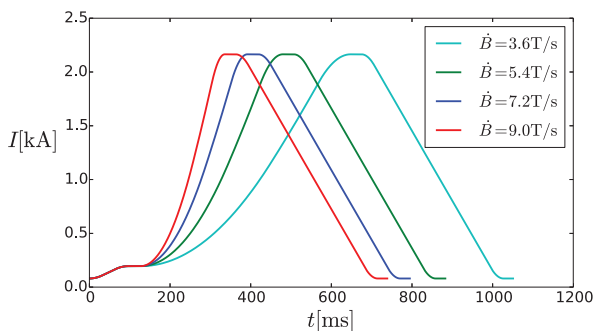

Figure 3: Dipole current cycles used in the experiments with fast ramps for different ramping speeds.

As indicator for the machine performance the losses as a function of $\dot{B}$ were used. Figure 4 shows the number of particles over time, normalized to the value N_0 at injection. The dashed line indicates the start of acceleration, which is the same for all ramping speeds. The losses at the beginning of the cycle can be attributed to the difficult operation conditions due to the obstacle in the beam pipe. Even though there is some particle loss during acceleration, the data show no significant increase of particle loss with increasing ramping speed. Since the bucket area had to be chosen to match the bunch area quite tightly to reach $\dot{B} = 9\,\mathrm{T/s}$, this result indicates the correctness of the ramping speed dependence implemented in the machine model. It also demonstrates the

capabilities of SIS18 to accelerate particles at the ramping speed required for the FAIR injector operation.
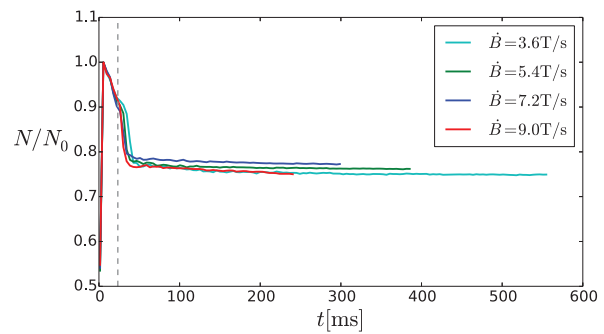

Figure 4: Number of particles normalized to the value at injection for different ramping speeds.

In addition to the particle number, the position of the beam was recorded, showing a systematic drift during the ramp caused by eddy current field drag in the main dipoles. A machine experiment in the next beam time will be dedicated to reducing this drift by modifying the current set value for the main dipoles.

CONCLUSIONS

The development of SIS18 towards the injector operation for FAIR has made considerable progress thanks to a series of technical upgrade measures. The focus shifts now to improving the operation of SIS18 with the major goal of reducing uncontrolled losses to avoid degradation of the dynamic vacuum. Corresponding operational concepts are being developed and tested. The new settings generation system has already proven a versatile and valuable tool in the commissioning of new hardware and new operation modes, long before the new control system for FAIR will be ready for operation. During the rest of this year, the system will be used to perform further machine experiments, with special emphasis on the study of intensity dependent effects, before the operation of SIS18 will be shut down until 2017 to reinforce its radiation shielding.

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