SIMULATION OF SPACE EFFECTS DURING MULTITURN INJECTION INTO THE GSI SIS18 SYNCHROTRON

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Abstract

The optimization of the Multiturn Injection (MTI) from the UNILAC into the SIS18 is crucial in order to reach the FAIR beam intensities required for heavy ions. In order to achieve the design intensities, the efficiency of the multiturn injection from the UNILAC has to be optimized for high beam currents. We developed a simulation model for the MTI including the closed orbit bump, lattice errors, the parameters of the injected UNILAC beam, the position of the septum and other aperture limiting components, and finally the space charge force and other high-intensity effects. The model is also used to estimate the required proton and heavy-ion beam emittances from the UNILAC and from the projected p-linac. For the accurate prediction of the MTI efficiency a careful validation of the simulation model is necessary. We will present first results of the comparison between experiments and simulation for low and high uranium beam currents.

INTRODUCTION

The GSI SIS18 synchrotron and the linac UNILAC are being upgraded in order to increase the beam intensity to the FAIR design parameter. For FAIR the SIS18 has to work as booster for the new SIS100 synchrotron. One crucial point in the upgrade program is the optimization of the Multiturn Injection (MTI) from the UNILAC into the SIS18. The beam loss during the MTI into the SIS18 must be minimized to avoid an intolerable increase of the dynamic vacuum pressure, which in turn leads to a reduced life-time of intermediate charge state heavy-ions [1]. The main beam loss is expected to occur on the injection septum. For FAIR intensities collective effects are expected to affect the MTI. The impact of space charge and image currents on the injection efficiency are therefore being investigated.

The aim of the present study is the development of a detailed simulation model for the MTI including the closed orbit bump and errors, the parameters of the injected UNILAC beam, the position of the septum and other aperture limiting components, and finally the space charge force and other high-intensity effects. The model can also be used to indicate the required proton and heavy-ion beam emittances from the UNILAC and from the projected p-linac. Before the model can be applied to predict and optimize the MTI for high currents a careful validation with MTI experiments is necessary.

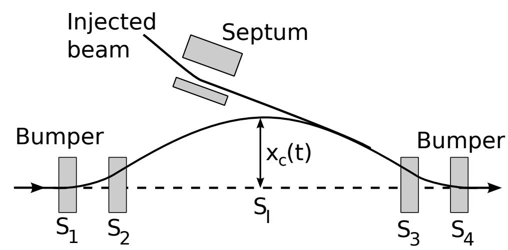

Figure 1: Layout of the multiturn injection.

MULTITURN INJECTION

In the SIS18 the beam is stacked in the horizontal betatron phase space using a closed orbit bump to bring the stacked beam close to the injection septum (See Fig. 1). The incoming beam centre will have a linear x and an angular x' displacements with respect to the undeformed closed orbit. After injection the beam will undergo betatron oscillations. One turn later the beam will come again to the injection point. Due to the betatron oscillation around the closed orbit the beam will avoid the septum. Meanwhile a new beam will be injected. This beam will have a larger amplitude of the betatron oscillation as the orbit bump is reduced. The process goes on until the maximum number of injection is reached. The beam emittance after the injection process is considered as area of the smallest ellipse that contains all injected particles. The dilation during the injection is defined as [2]

$$D = \frac{\epsilon_f}{n_{MTI}\epsilon_i} \quad (1)$$

where ϵ_i is the emittance of the injected beamlet, ϵ_j the emittance of the final beam and n_{MTI} the number of injected beamlets. The final beam emittance muss be smaller than the machine acceptance. This means, the best injection schemes have the smallest dilation and the lowest loss at the septum.

The injection bump is produced by four bumper magnets located in the injection region with positions

$$s_1 < s_2 < s_I < s_3 < s_4 \quad (2)$$

where s_I is the point of injection (See Fig. 1). If we require that the four bumper magnets produce no closed orbit distortion outside the injection region and the horizontal position and angle of the closed orbit x_c, x_c' at the injection position s_I are the degrees of freedom, than the angular kick produced by the bumper magnets are [3]

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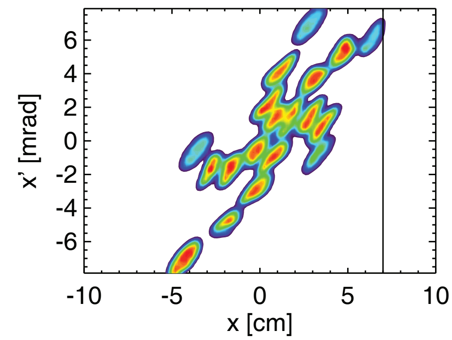

Figure 2: Phase space after 21 turns without collective effects.

$$\varphi_1 = \frac{-b_{41}\phi_2 - b_{42}\phi_4}{b_{43}}, \quad \varphi_2 = \frac{b_{31}\phi_3 + b_{32}\phi_4}{b_{43}}, \tag{3}$$

$$\varphi_3 = \frac{d_{I2}x_c - b_{I2}x'_c}{b_{21}}, \quad \varphi_4 = \frac{-d_{I1}x_c + b_{I1}x'_c}{b_{21}} \tag{4}$$

with

$$b_{ji} = \sqrt{\beta_j\beta_i}\sin(\phi_j - \phi_i), \tag{5}$$

$$d_{ji} = \sqrt{\frac{\beta_i}{\beta_j}}\sin(\phi_j - \phi_i) - \frac{\alpha_j}{\beta_j}b_{ji}. \tag{6}$$

Here α_j, β_j, and ϕ_i are the horizontal lattice parameters at the point s_j.

For simplicity and technical reasons the SIS18 operation control program SISMODI uses an approximation of the described analytic solution for the calculation of the angular kick during injection. With this approximation the two degrees of freedom are being limited to one. For the new control system such limitations are not planned. For fixed horizontal position and angle of the closed orbit at the injection position and several horizontal tunes the angular kicks were calculated and quadratic functions were fitted on these results. By normalizing the angular kick functions with the fixed horizontal position and by multiplying with the desired bump amplitude one can adjust the four functions on each bump amplitude [4].

MTI SIMULATION CODE (PATRIC)

At the GSI accelerator physics department the PATRIC simulation code has been developed over many years for numerical collective effects. In order to investigate the MTI the sources of the code were modified such that a time dependent local orbit bump can be adjusted to the incoming beam [5].

Figure 2 shows a snapshot of a MTI simulation of the horizontal phase space without collective effects at the septum after 21 turns are injected. In the simulation the bump is added by four horizontal kicks at the bumper position on the SIS18 lattice. The deflection angles are adapted turn by turn until the injection orbit bump has disappeared given

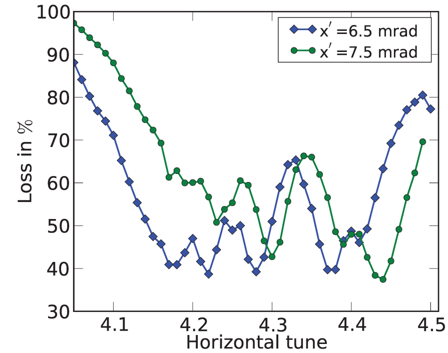

Figure 3: MTI loss as a function of the horizontal tune for a mated and a mismatched beam.

by Eq. 3-6 or calculated by the SIS18 control approximation. Collimators count turn by turn the loss on the septum and on the SIS acceptance. Figure 2 shows that some of the outside beamlets (light-blue) loose particles during the injection at this collimators. If space-charge effects are to be included the Poisson's equation is solved on a 2D transverse grid and momentum kicks corresponding to the local space charge field strength are applied.

The modified version of PATRIC can be employed to study losses, particle accumulation, emittance growth and the phase-space distribution for varying tune, bump settings, injection duration and initial particle distribution, emittance and intensity. Also the effects of a linear or nonlinear ramp, the effect of measured local close orbits deformation caused by lattice errors and the effect of the approximate SIS18 model can be studied.

MTI SIMULATION STUDIES

The MTI efficiency depends on various machine and beam parameters. Some important parameters, like the injected beam parameters, are not precisely known from measurements. In the measurements with the correction devices in the transfer channel and in the injection area in the SIS18 the injected beam slope (divergence angle x') can be modified by $\pm 1 - 3$ mrad and the beam position (x) by $\pm 10 - 20$ mm in respect to the septum position and slope. Unfortunately, it is not possible to measure the beam slope and position during injection [4]. Therefore we study the effect of the mismatched beam slope within the SIS18 injection model.

Figure 3 shows the dependency of the MTI efficiency on the horizontal tune for a mated beam slope of 6.5 mrad and for a mismatched beam of 7.5 mrad. For the mated beam (blue circles) the simulation shown the well known maxima losses at the fractional tunes related to the resonance condition $q_x n = m$ [6]. The smallest loss $\sim 40\%$ is at 4.17. For the mismatched beam (green diamonds) the maxima are shifted to the right. For tunes between 4.0-4.3 the losses are increased by more than 15% and for tunes between 4.4-4.5 the losses is 15% smaller related to the mated beam losses.

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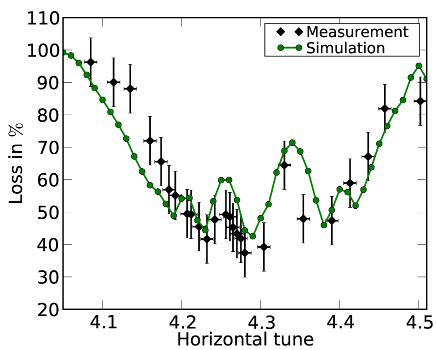

Figure 4: Simulated and measured MTI loss as a function of the horizontal tune. Measurement results provided by [7].

For the comparison between experiments and simulation we used the machine experiments bump fall (orbit amplitude of x_c = 90 mm and bump fall of Δx_c = 2.5 mm per turn), the SISMODI angular kick calculation, measured orbit errors and beamlet emittance. The emittance was measured to $\epsilon_{rms} = 1.625$ mm mrad in the transfer channel to the SIS18 a few meters before the injection point [7]. [7] provided also the loss measurement results after 21 turns of U^{28+} beam with 1.35 mA have been injected. In Fig. 6 the simulated and measured dependence of the MTI beam loss on the tune is shown for low currents. The Figure shows a good agreement between measurements and simulations. Both show that the local beam loss maxima are located at the same fractional tunes. This was possible by setting the beamlet parameters to x = 90 mm (position of septum plus beamlet radius) and x' = 7.9 mrad (variable between 3-9 mrad) in the simulation. The reason for the good agreement is especially the choice of the divergence angle of the injected beam.

The effect of space charge and image currents on the MTI efficiency and particle distribution are considered. Figure 5 shows a snapshot of an MTI simulation with collective effects at the same moment and simulation parameters as Fig. 2. The smearing out of the particle distribution due to space charge is obvious. Close to the center individual beamlets even cannot be distinguished. The outer beamlets differ by position compared to Fig. 2 though all injection settings were equal. This observation is attributed to the tune shift.

Figure 6 shows the injection efficiency as a function of the horizontal tune with and without collective effects. The maxima and minima of the efficiency are shifted. For the injection efficiency the SIS18 high working point q_x = 4.17 is a good choice for high and low currents.

CONCLUSIONS AND OUTLOOK

For low beam currents a good agreement between a simulation model and MTI measurements in the SIS18 is obtained. For the present default settings in the SIS18 the injection efficiency depends very sensitively on the horizontal tune. Further well-controlled measurements at low and high beam currents are required in order to fully validate the model. Other injection schemes for lower loss like a non-linear ramp are considered. Full 3D space charge simulations a planned to understand better the space charge effects and validate the model.

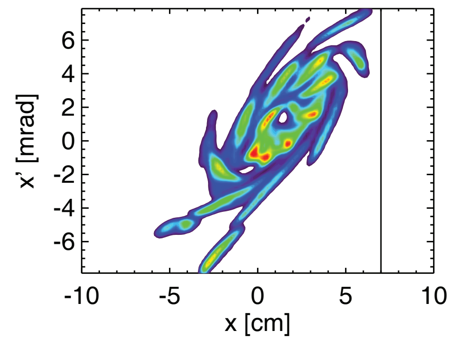

Figure 5: Phase space after 21 turns with collective effects.

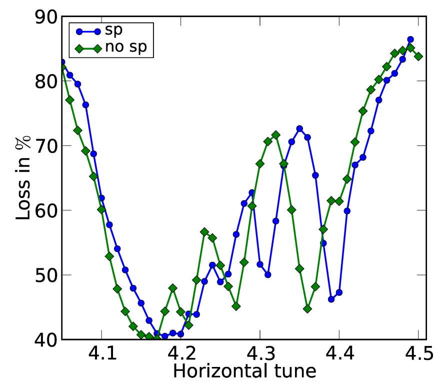

Figure 6: MTI loss as a function of the horizontal tune with and without collective effects.

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