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The optimization of the Multi-Turn Injection (MTI) from the UNILAC into the SIS18 is crucial in order to reach the FAIR beam intensities required for heavy ions. The injection efficiency can be increased if these beams are flat, i.e. if they feature unequal transverse emittances. At the GSI UNILAC it is planned to build a transverse emittance transfer section which should transfer the horizontal emittance to the vertical and preserve the product of both [1, 2]. 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 is developed. First simulation results for flat uranium beams including collective effects will be presented.

Introduction

The GSI SIS18 synchrotron and the linac UNILAC are being upgraded in order to increase the beam intensity to the FAIR design parameters. 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 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 [3]. For the FAIR intensities collective effects are expected to affect the MTI.

The MTI efficiency depends on the distance of the beam center to the septum, the slope of the injected beam, the number of the injection periods, the number of betatron oscillations per turn Q, and the emittance of the injected beam. To decrease the beam emittance in one plane - here the horizontal - the proposal is to build a transverse emittance transfer section in the UNILAC [1, 2]. By applying solenoid fringe fields during charge stripping this beam line should transform a round uncorrelated beam ($\epsilon_x = \epsilon_y$) to a flat beam ($\epsilon_x < \epsilon_y$) and preserve the product

$$\epsilon_x \times \epsilon_y = \text{const.} \quad (1)$$

By using Eq. (1) the minimal accessible horizontal emittance is

$$\epsilon_{x,min} = \frac{\epsilon_x \epsilon_y}{A_y} \approx 1.7 \text{ mm mrad} \quad (2)$$

with the vertical SIS18 acceptance A_y of 50 mm mrad, the present UNILAC FAIR design transverse emittances $\epsilon_x = 5.3$ mm mrad and $\epsilon_y = 16$ mm mrad [5, 4]. All emittances in this text are four times the rms emittance following the concept of rms equivalent beams.

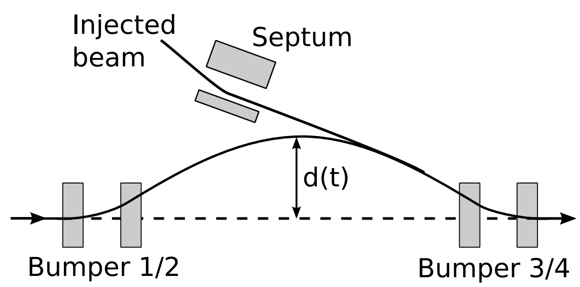

Fig. 1: Layout of the multi-turn injection.

The emittance exchange affects also the space charge tune shift

$$\Delta Q^{sc}_{x,y} = -\frac{2 r_p N g_f Z}{\pi \beta^2 \gamma^3 B_f A} \times \frac{1}{\epsilon_{x,y} + \sqrt{\epsilon_{x,y}\epsilon_{y,x}\frac{Q_{x,y}}{Q_{y,x}}}} \quad (3)$$

in both planes. In the above equation $Q_{y,x}$ is the vertical or horizontal tune, B_f the bunching factor, g_f the form factor, N the number of particles in the whole ring accelerator, r_p the 'classical' proton radius. As Eq. (3) demonstrates for the transformed beams the space charge tune shift in one plane depends inversely on the emittance in the same plane since the product of both emittances is constant. According to the emittance exchange the horizontal space charge tune shift for a single beamlett increases from $\Delta Q_x = -0.06$ to -0.08 and the vertical decreases from $\Delta Q_y = -0.04$ to -0.017.

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 center will have a linear x and an angular x' displacement with respect to the non-deformed closed orbit. After injection the beam will undergo betatron oscillations in the synchrotron or storage ring. 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 larger amplitudes of the betatron oscillation as the orbit bump is reduced. The process goes on until the maximum number of injections is reached. The beam emittance after the injection process is considered as area of the smallest ellipse that contains all injected particles. The phase space dilution during the injection is defined as [6]

$$D = \frac{\epsilon_f}{n_{mti}\epsilon_i} \qquad (4)$$

where ϵ_i is the emittance of the injected beamletts, ϵ_f the emittance of the final beam and n_{mti} the number of injected beamletts. The final beam emittance must be smaller than the machine acceptance. This means, the optimum injection scheme (i.e. time dependence of the orbit bump) has the smallest dilation and the lowest loss at the septum.
For a linear closed orbit the decrease per turn is often proposed as [7]

$$\Delta x = \frac{1}{4}(2a + d_c) \qquad (5)$$

where a is the beam radius and d_c is the septum thickness. This linear decrease minimizes the loss at the septum. Unfortunately, for large beamlett emittances Eq. (5) can imply large dilution factors after several turns, since a small dilution factor requires small closed orbit decreasing steps per turn.

MTI simulation studies

The MTI simulation studies were performed with a modified PATRIC version, which included loss calculation on the septum and on the SIS18 acceptance. In PATRIC an acceptance collimator placed vis-à-vis to the septum filters out all particles with an horizontal emittance larger than 190 mm mrad (horizontal SIS18 acceptance A_x = 150 mm rad plus 25%).
In the simulation we injected U^{73+} KV-beamletts with the present FAIR design current of 5.5 mA. For the simulation with a horizontal betatron tune of $Q_x = 4.17$, the corresponding beta function at the injection point is 12.14 m. In [8] we show that

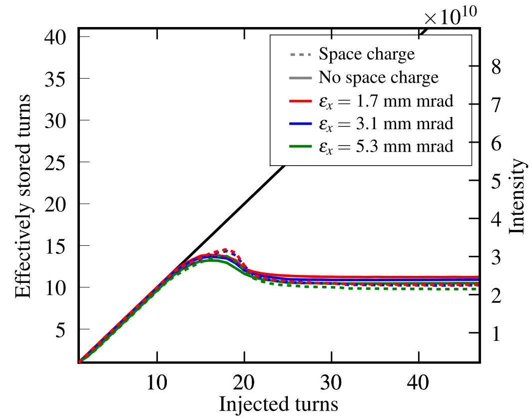

Fig. 2: Number of effective turns versus the total number of turns for Δx = 4 mm per turn and $Q_x = 4.17$.

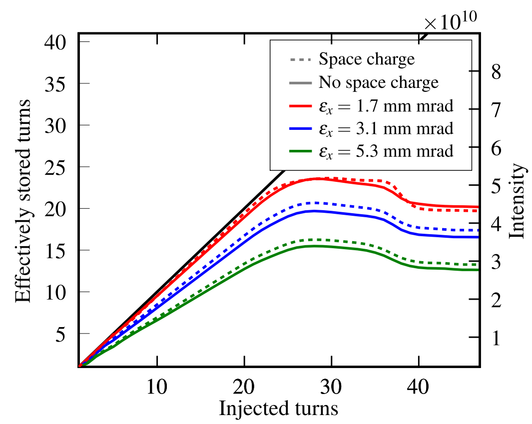

Fig. 3: Number of effective turns versus the total number of turns for Δx = 2 mm per turn and $Q_x = 4.17$.

$Q_x = 4.17$ is the tune for the smallest losses with and without space charge effects. We verified in [8] the beam slope to be 6.5 m and in [9] the optimal beam position in the horizontal plane and maximal orbit amplitude to be $x_c + d_c + 2a$ with the position of the septum of $x_c = 0.07$ m.
Fig. 2 and 3 show the effectively stored numbers of turns versus the total number of injected turns for a faster (Δx = 4 mm per turn, Eq. (5) for ϵ_x = 5.3 mm mrad) and slower (Δx = 2 mm per turn, Eq. (5) for ϵ_x = 1.7 mm mrad) orbit decrease. In both figures the black solid line represents no losses. For the faster orbit decrease, for all three emittances, maximal 15 turns can be stored effectively, also if space charge effects are included. With the slower orbit decrease, for the smallest emittance, effectively 24 turns can be injected and for the largest emittance 18 turns. For the smallest emittance and

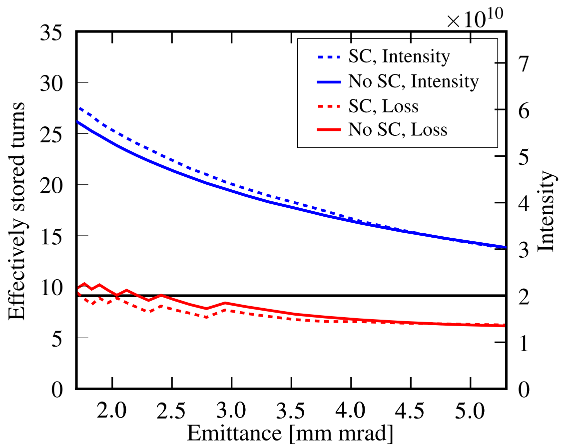

Fig. 4: Number of effective stored turns versus horizontal emittance for $\Delta x = \frac{0.6}{4}(2a + d_c)$ per turn and $Q_x = 4.17$ in blue and the loss in red.

slow orbit decrease (red dashed lines in Fig 3) space charge has detrimental effects, for all other cases beneficial effects.

Until the machine acceptance is reached, the loss is minimal for the fast orbit decrease for all three emittances and for the slow decrease only for the smallest emittance. However the loss for larger emittances and the slow decrease is higher, more turns can be injected than with the faster orbit decrease. Our simulation for the chosen linear closed orbit decrease confirmes $\Delta x = \frac{0.6}{4}(2a + d_c)$ as good compromise for maximal effectively stored turns with tolerable losses.

Fig. 3 shows for all emittances losses after 35 turns due to machine acceptance. To avoid later losses due to the machine acceptance we will stop in following simulation studies the injection of more turns if the horizontal acceptance limitation is reached. As second injection stop condition we will include loss limitations during the injection process.

The effective number of stored turns for different emittances for tolerable losses are shown in Fig. 4. The dashed lines in Fig. 4 indicate simulations with space charge effects (SC), the solid without. Fig. 4 demonstrates that with the smallest emittance related to the present emittance ~ 15 more turns can be stored and space charge can have beneficial effects on the injection efficiency (dashed line).

Conclusions and outlook

A smaller horizontal emittance can improve the MTI efficiency. With the smallest accessible emittance related to the present emittance ~ 15 more turns can be stored also if space charge effects are present. Depending on the emittance and the chosen linear closed orbit decrease space charge can have beneficial and detrimental effects. In all simulations a KV transverse particle distribution has been used. For a more realistic-semi-Gauss distribution larger losses are expected [9].

Unfortunately, the planned testing section for exchange emittance works only for ions, which are stripped in the transfer line. Ions like U^{28+} will be stripped already at the entrance to the Alvarez. For these ions one must foresee a second emittance transfer section or find other injection schemes which can provide lower dilation factors and tolerable losses during injection for larger emittances. Exponential orbit decrease is a candidate.

Acknowledgments

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