

SPACE CHARGE EFFECTS DURING MULTITURN INJECTION INTO SIS-18

Stefan Paret, Oliver Boine-Frankenheim, GSI, Darmstadt, Germany

Abstract

For the FAIR [1] project, the intensity of heavy-ion beams in SIS-18 has to be increased by an order of magnitude. In order to achieve the design intensities, the efficiency of the multiturn injection from the UNILAC has to be optimized for high beam currents. This is especially important for the operation with intermediate charge state heavy-ions, where beam loss during injection will lead to pressure bumps and to a reduced lifetime of the beam. An analytic model exploring the limits of lossless injection without collective effects is discussed. The multiturn injection into SIS-18 is studied by virtue of 2D particle tracking simulations using an extended version of the computer code PATRIC. The impact of space charge and image currents on the efficiency of the injection process is analyzed.

INTRODUCTION

GSI's UNILAC and SIS18 are being upgraded in order to increase the beam intensity to the ambitious design parameters for the booster operation for FAIR [2]. For U^{28+} the goal is to accumulate effectively a current of 15 mA for 15 turns in SIS18, corresponding to 2.3×10^{11} particles. For these beam parameters, collective effects are expected to affect the multiturn injection (MTI). The impact of space charge and image currents on the injection efficiency and the particle distribution needs therefore to be investigated.

Furthermore, endeavors are being made to reduce the horizontal emittance in UNILAC [3], which is a key quantity for the MTI. However, investigations are needed to specify the maximal acceptable emittance. For this reason, the injection efficiency and effective particle accumulation are studied as a function of the beam emittance and the particle distribution. The results of the numerical studies shall serve as reference for planned experiments in SIS18.

The particle tracking code PATRIC was modified enabling it to simulate the MTI. In the first section the implementation of the MTI is described. Then an analytic model helping to find good injection parameters is discussed. Finally simulation results without and with space charge are shown. The phase-space distribution, losses and particle accumulation are discussed. An outlook on planned experiments and numerical studies is given.

MTI IN PATRIC

Over the years, PATRIC has been developed at GSI for numerical studies of various kinds of collective effects (see e.g. [4]). So far it was applied to accumulated beams in a ring in storage mode only. In order to investigate the MTI,

the sources of the code were modified.

The most important aspect is the introduction of a time dependent local orbit bump to adjust the orbit to the incoming beam. PATRIC is able to read the sector-maps produced by a MAD-X [5] script which provide the transport matrices around the synchrotron. At the position of the 4 bumpers generating the local orbit bump, markers were inserted as place holders into the file providing the SIS18 beam optics. Hence MAD-X is used to calculate the sector map without injection bump. The bump is added by PATRIC by virtue of horizontal kicks at the markers representing the bumpers. The corresponding elements of the kick vector (K), provided by the sector-map file, are changed to deflect the particles. The deflection angles are adapted turn by turn, until the bump disappeared.

Another change concerns the generation of the particle distribution. Instead of initializing the beam once at the beginning of a simulation, this procedure is repeated at the beginning of the loop until the injection finished. The particles are transported using the transport matrices from MAD-X and the modified kick vectors. If space-charge effects are to be included, Poisson's equation is solved on a 2D transverse grid and momentum kicks corresponding to the local field strength are applied. The boundary conditions can be set to represent the (perfectly conducting) beam pipe or empty space. Thus the impact of image currents can be separated from that of direct space charge.

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.

LOSSLESS INJECTION

An injection scheme without losses allowing the longest injection is looked for as first step. The beam lattice functions at the end of the injector are assumed to be matched to the synchrotron. The beam cross section is presumably elliptical. The bumper ramp is linear and the ramp rate constant. The position of the septum and the injection angle are taken from SIS18. What remains to be optimized for a given emittance and working point are the height of the orbit bump and the angle of the bumped orbit with respect to the incoming beam, as well as the ramp rate of the orbit bump.

First the phase space after a single turn injection is considered. The position of the incoming beam in the horizontal phase space is parameterized as depicted in Fig. 1. The horizontal coordinate x of the beam's barycenter is decomposed into the bump height x_{r0} and the offset \tilde{x} . Due to

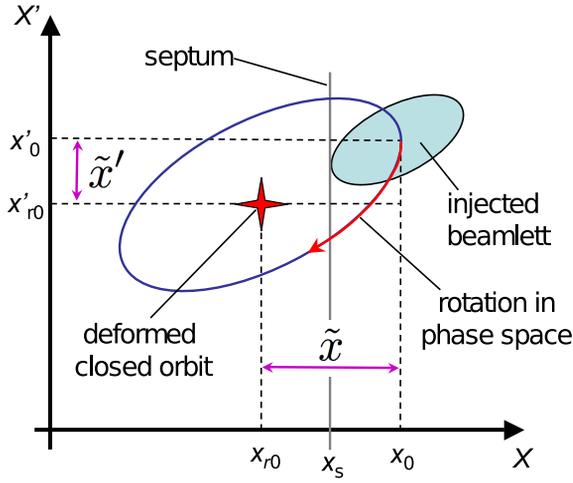


Figure 1: Position of the incoming beam.

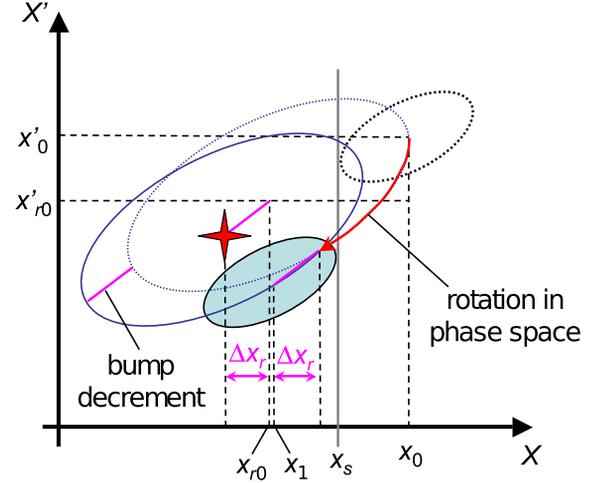


Figure 2: Injected beam after one turn.

the offset the beam moves around the orbit on an ellipse of which the orientation and shape depend on the Twiss parameters α and β . Therefore it is convenient to express \tilde{x} by means of a phase φ and a constant of motion $\hat{x} = \sqrt{\hat{\epsilon}\beta_i}$,

$$\tilde{x} = \hat{x} \cos \varphi. \quad (1)$$

\hat{x} depends on the one-particle emittance of the barycenter given by $\hat{\epsilon} = \gamma_i^2 \tilde{x}'^2 + 2\alpha_i \tilde{x} \tilde{x}' + \beta_i \tilde{x}^2$ and the Twiss parameters at the injection point. The phase of the beam be φ_0 upon injection and φ_m after m revolutions. The phase advance per revolution is equal to $2\pi Q_f$, where Q_f is the fractional part of the horizontal tune. Thus we have

$$\varphi_m = \varphi_0 + 2\pi Q_f m. \quad (2)$$

In addition the beam is shifted synchronously with the orbit due to the reduction of the bump with the decrement Δx_r per turn in x direction. The resulting location of the first injected beam after m turns then writes

$$x_m = x_{r0} + \hat{x} \cos \varphi_m - \Delta x_r m \quad (3)$$

until the injection finished. Afterwards the last term in the equation vanishes.

The most compact filling of the horizontal phase space without losses is achieved by letting the surface of beam touch the septum from the one side when coming in and from the other side after one turn. This means that

$$x_0 = x_s + a + d_s \quad (4)$$

and

$$x_1 = x_s - a, \quad (5)$$

where x_s is the position of inner side of the septum and d_s the septum thickness, as displayed in Fig. 2 The small wires forming the last part of the septum can be neglected with respect to the beam diameter in good approximation.

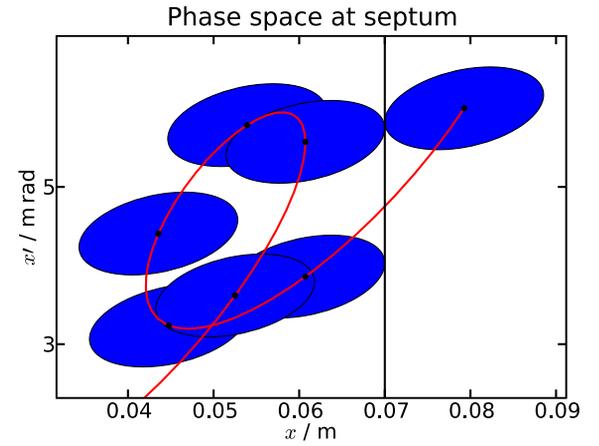


Figure 3: Beam at the septum during successive turns.

After the first turn the beam moves away from the septum before it comes closer to the septum again after a few turns. The closest approach will happen close to the turn $n \approx 1/Q_f$, when one revolution in the transverse phase space is about complete. Particle loss is avoided if the bump was decremented enough to yield

$$x_n = x_s - a. \quad (6)$$

For any smaller x_n the injection efficiency would be reduced.

The injection parameters x_{r0} , x'_{r0} and Δx_r can be adjusted such that x_n corresponds to the largest offset the beam assumes after the first turn. Figure 3 shows the position of the beam during consecutive turns. The red line shows the time continuous interpolation of Eq. 3,

$$x(t) = x_{r0} + \hat{x} \cos \left(\varphi_0 + 2\pi Q_f \frac{t}{T} \right) - \Delta x_r \frac{t}{T}, \quad (7)$$

where T is the revolution period of the beam.

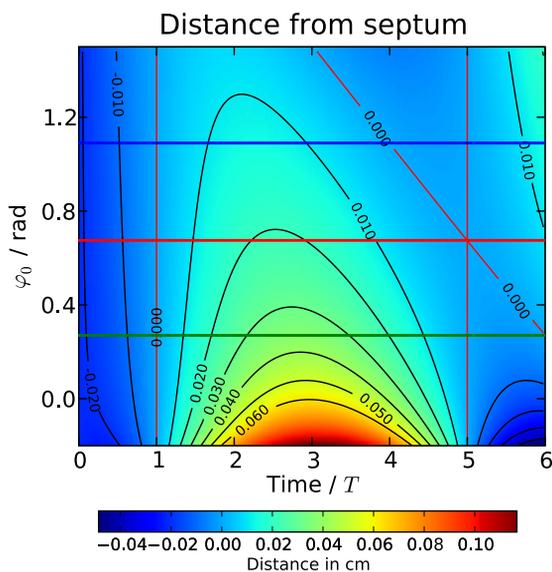


Figure 4: Distance of the beam to the septum for $Q_f = 0.17$, $n = 5$ and $a = 9.3$ mm. The special cases highlighted by the horizontal lines are explained in the text.

More general, applying Eq. 4 to Eq. 6, allows the injection parameters to be expressed as functions of the initial phase φ_0 . Whether the beam suffers particle loss can be determined considering the distance of the outer edge of the beam $d(t) = x(t) + a$ from the septum. Negative values correspond to at least a part of the beam being behind the septum. Particles are lost if $d(mT) < 0$ for $m > 0$. For other times negative values can be tolerated. The distance of the beam from the septum as a function of t and φ_0 is visualized in Fig. 4.

The distance assumes negative values some time after $t = T$ for any phase except $\varphi_0 = 0.67$ rad. This setting actually corresponds to the afore discussed case that the offset becomes the largest after $n = 5$ turns. In Fig. 4 the horizontal red line highlights this situation. For $0.27 < \varphi_0 < 1.09$ negative values do occur, but not while the beam passes the septum. Hence there is no particle loss in this range of phases. Starting with the smallest possible phase, the beam touches the septum after 5 and 6 turns, while with the largest allowed value this happens after 4 and 5 turns. The green and blue horizontal lines in the same figure indicate these limiting cases.

Figure 4 also reveals that smaller phases imply larger distances after 3 turns from which follows that a larger volume of the phase space is occupied. Phases closer to 1.09 rad are hence favorable under ideal conditions. This setting seems to more prone to losses due to imperfections like lattice errors or collective effects, though.

The injection ends when $x_r = 2a + d$. The maximal number of turns available for the injection is consequently

$$n_{max} = \frac{x_{r0} - 2a}{\Delta x_r}. \quad (8)$$

Table 1: Parameter Sets Used in the Simulations

ϵ (rms) / mm mrad	distribution
1.325	KV
1.325	semi-Gauss (SG)
2.0	KV

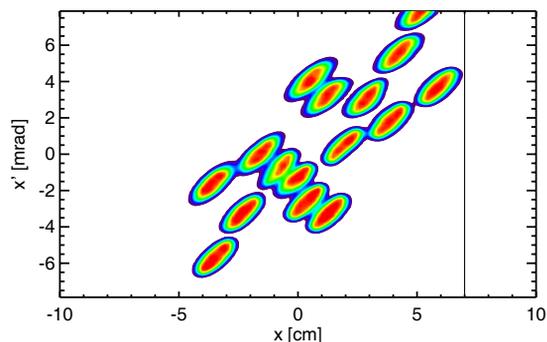


Figure 5: Phase space after 20 turns without collective effects.

With the beam parameters assumed for the booster operation follows that maximal 11 turns can be used for the injection. The targeted 15 effective turns can therefore only be injected accepting losses. The optimal setting for a lossy injection is currently investigated [7].

SIMULATION RESULTS

Numeric simulations were performed with PATRIC. x_{r0} and x'_{r0} were determined as discussed in the previous section. In order to inject more particles than possible without losses, the ramp rate was adapted to the given number of injections according to

$$\Delta x_r = \frac{x_{r0} - 2a}{n_{max}}. \quad (9)$$

The beam deflection to be caused by the four bumpers was evaluated as in Ref. [6].

Three scenarios are highlighted in this section. The variable parameters are summarized in Tab. 1. ϵ_1 corresponds to the design emittance for the booster operation. A KV and a more realistic semi-Gauss (SG) transverse particle distribution are compared. In order to assess the consequences of a larger emittance, simulations were accomplished with ϵ_2 . Always a Gaussian longitudinal momentum distribution with $\sigma_p = 5 \times 10^{-4}$ was used. The longitudinal position is meaningless as only the transverse dynamics is studied. All particles are therefore put into one disc. The set tune was $Q_{hor} = 4.17$.

The horizontal phase space at the septum after 20 turns of which 16 were used to inject the beam, is shown in Fig. 5 without collective effects and in Fig. 6 with space charge and image currents. The smearing out of the particle distribution due to space charge is obvious. Close to the center individual beamlets even cannot be distinguished. The

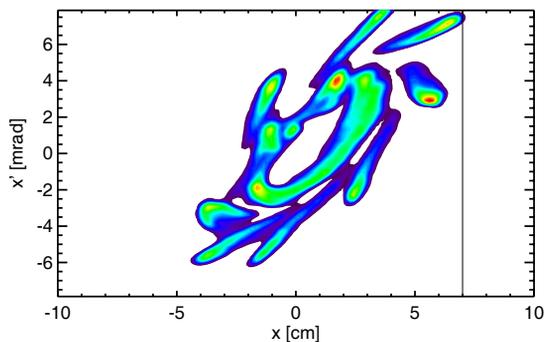


Figure 6: Phase space after 20 turns with space charge and image currents.

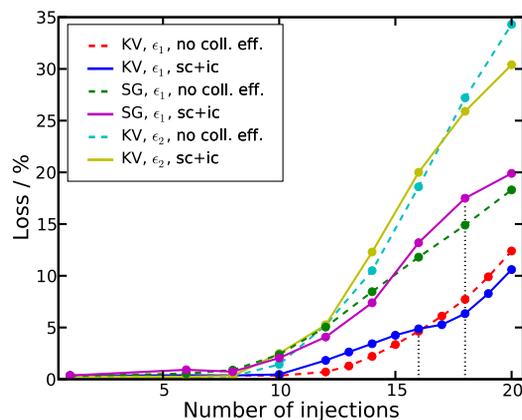


Figure 8: Losses during injection.

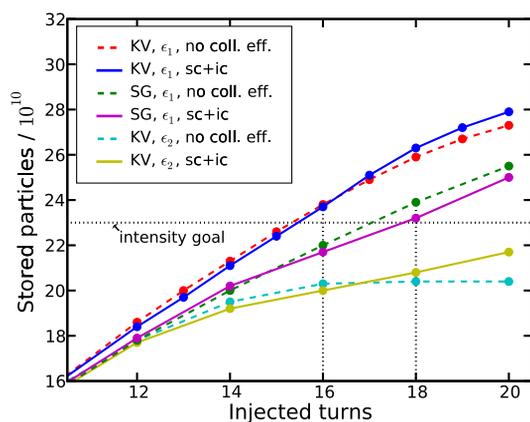


Figure 7: The number of stored particles depending on the length of the injection for the three beams with the parameters given in Tab. 1.

outer beamlets differ by position, though all injection settings were equal. This observation is attributed to the tune shift.

The number of particles accumulated in SIS18 as a function of the injection length is displayed in Fig. 7. 16 turns of the beam with the smaller emittance and KV profile suffice to reach the intensity goal. There is only a marginal difference between the simulation with and without space charge and image currents. For the SG profile, 18 turns are needed. The impact of space charge is slightly higher. Finally, for the larger emittance, the goal is not reached within 20 turns.

The corresponding losses are shown in Fig. 8. The loss rate to be accepted for the smaller KV beam is 5 % only, but 18 % for the SG profile when space charge is taken into account. For the larger beam, the losses are significantly higher, independent of whether collective effects are included or not. The impact of the image currents was found to be negligible compared to space charge so the discussion of direct space-charge effects without image currents is omitted here.

CONCLUSIONS

An injection scheme to evaluate the bump parameters for an efficient and lossless MTI was elucidated. However, it does not allow to inject enough particles to reach the design intensity for FAIR. Hence losses have to be accepted during the injection. Numerical simulations of the MTI were performed and indicated that the targeted rms emittance of 1.3 mm mrad at injection, permits to reach the demanded beam intensity with moderate losses. An rms emittance of 2 mm mrad is too large to fulfil the requirements. Space charge and image-current effects strongly change the particle distribution but only moderately affect the losses.

OUTLOOK

First simulation results have been obtained, but systematic studies are still to be done. A more realistic loss consideration has to include errors in the lattice. For a lossy injection scheme, the local orbit bump can possibly still be improved. Better injection schemes, possibly with a non-linear ramp [7] or coupling to transfer emittance to the vertical phase-space [8] are considered. Also the dependence of the injection efficiency on the tune is of interest.

Finally, measurements in SIS18 are planned to confirm the simulation results. An ionization profile monitor with turn-by-turn time resolution to be installed in SIS18 [9] will allow us to track the phase-space evolution.

ACKNOWLEDGEMENT

The authors thank D. Ondreka and Y. El-Hayek for useful discussions about the injection in SIS-18.

REFERENCES

- [1] FAIR Baseline Technical Report, GSI, 2006, <http://www.gsi.de/fair/reports/btr.html>
- [2] P. Spiller, Towards the High Intensity Limit in the FAIR Project - Present Status and Future Challenges, These proceedings

- [3] W. Barth, The injector systems of the FAIR project, LINAC08, 2008
- [4] O. Boine-Frankenheim and V. Kornilov, Implementation and Validation of Space Charge and Impedance Kicks in the Code PATRIC for Studies of Transverse Coherent Instabilities in FAIR Rings, ICAP06, 2006
- [5] W. Herr and F. Schmidt, A MAD-X primer, Technical report, CERN-AB-2004-027-ABP, CERN, 2004
- [6] C. J. Gardner, Multiturn injection of heavy ions into the booster, Booster technical note no. 197, Brookhaven National Laboratory, 1991
- [7] Y. El-Hayek, GSI, priv. communication
- [8] G. Franchetti, Optimizing multiturn injection with space charge and linear coupling, EPAC00, 2000
- [9] M. Schwickert, P. Forck, P. Kowina, T. Giacomini, H. Reeg and A. Schlörit, Beam diagnostic developments for FAIR, DIPAC09, 2009