SKEW QUADRUPOLE EFFECTS ON MULTI-TURN INJECTION EFFICIENCY IN THE SIS18*

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Abstract

One goal of the SIS18 upgrade scheme is concerned about improving the multi-turn injection (MTI) efficiency, in order to reach the required intensities at the targets and in the same time to minimize beam loss which can spoil the vacuum. There were successful attempts in this direction at AGS and PS boosters by using the skew injection scheme and later it was suggested for the SIS18. We studied the effects of introducing a controlled linear coupling on the MTI by simulation using the GSI code PARMTRA.

INTRODUCTION

The MTI is an injection scheme, where the UNILAC beam is injected during the first few microseconds of the machine cycle into different regions of the synchrotron horizontal phase space. In order to inject heavy ion beam from a linear accelerator to a synchrotron, the incoming beam must be aligned on the equilibrium orbit. This is achieved by using a magnetic deflector and an electrostatic septum, which deflect the particles into the synchrotron horizontal acceptance together with orbit bump magnets, which are used to deform the closed orbit. At the start of the MTI, the closed orbit is deformed so that it is near the septum. From this moment onwards, the displacement of the closed orbit will decrease linearly or exponentially with time until it returns back to the initial equilibrium position far away from the septum. Then the MTI process is terminated as the horizontal acceptance limit is reached. The main injection loss happens on the septum from inside, although using orbit bump because its speed is limited in favor of better accumulation. To overcome this limit, the beamlet oscillation can be damped via energy exchange from the horizontal to the vertical plane controlled by applied skew quadrupole magnet.

MULTI-TURN INJECTION SIMULATION

In the MTI process, there are many parameters that should be optimized, like the incoming beam twiss functions, the horizontal fractional tune and the lattice geometry. Using PARMTRA [4], our simulations were carried out with ${}^{40}Ar^{18+}$ ions at injection energy $E_{\text{inj}} = 11.4$ MeV/u. We used the SIS18 lattice but with the linear elements only. The lattice consists of 12 identical periods, each one has triplet quadrupoles (FDF) and two first order bending magnets. The horizontal and vertical acceptances at injection are $A_x = 0.0196$ cm.rad and $A_y = 0.0051$ cm.rad, respectively and the average transverse betatron functions for both planes are $\bar{\beta}_x = R/\bar{Q}_x = 800$ cm/rad and $\bar{\beta}_y = 1000$ cm/rad. The incoming beam was assumed to have a Gaussian transverse distribution with initial RMS transverse emittance $\epsilon_{x0,y0} = 0.0002$ cm.rad. The simulations were performed for upright incoming beamlet with $\alpha_x = 0.003$ rad and $\beta_x = 464.5$ cm/rad so its size is given by $X_{\text{RMS}} \approx X_{\text{max}}/4 = 0.30$ cm. Any coupling between the transverse and the longitudinal motion was ignored. The MTI process starts when the UNILAC beamlet reaches the septum from the outside. The septum blade is defined as an asymmetrical aperture limitation, which divides the horizontal phase space into two regions: incoming and circulating beam. The distance between the center of the incoming beam x_{bi} and the outer edge of the septum x_{sep} is given by Δ, see Fig. 1. According to the beamlet ellipse parameters at injection point the setting for Δ was optimized so the loss on the septum shadow is minimum with good filling of the horizontal acceptance in the same time [1],

$$\Delta = x_b - x_{\text{sep}} = X|_{\text{inj}} = \sqrt{\epsilon_{xi}\beta_{xi}} \qquad (1)$$

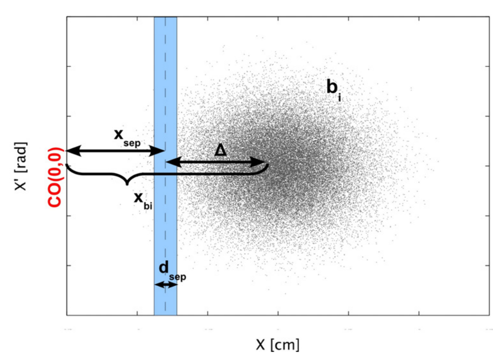

Figure 1: Optimization of the incoming beam parameters for the Multi-turn injection.

With each new beamlet injection, the closed orbit must be shifted with an optimum amount Δ_{bump}. The best step of this shift is given by,

$$\Delta_{\text{bump}} = \frac{1}{4}\left(2\Delta + d_{\text{sep}}\right) \qquad (2)$$

where d_{sep} is the septum thickness, which was assumed to be equal to 0.01 cm as it is the case in the SIS18. This setting allows filling the synchrotron acceptance with a maximum number of injected turns because the interspacing between two subsequently injected beamlets in the transverse

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phase space is the minimum, which is equal to the septum thickness $d_{\rm sep}$. Due to shifting the closed orbit, the beamlet will oscillate in the xx' phase space around the new orbit. Depending on the horizontal fractional tune Q_{xf}, the beamlet will return back to its original position at the septum after number of machine revolutions $N_{\rm rev} = 1/Q_{xf}$. This means that without orbit bump, the Q_{xf} will decide how many turns can be injected. The early beamlets will perform small amplitude oscillations for many turns, whereas the later beamlets will perform large amplitude oscillation for few turns before terminating the injection process. Each beamlet was tracked up to the relevant turns and the loss due to hitting the septum was recordered. Without considering space charge effects, it was possible to inject 21 beamlets whereas 13 beamlets were the effective number. The number of survived particle after the final turn of each beamlet was evaluated to obtain the efficiency curve for different Q_{xf} keeping Q_{yf} fixed on 0.29, see the pink curve in Fig. 5b. The MTI efficiency is defined as, $eff = (N_{\rm final}/N_{\rm initial}) \times 100\%$, where $N_{\rm initial}$ is the initial number of injected particles and $N_{\rm final}$ is the number of survived particles.

SKEW INJECTION OPTIMIZATION

By introducing a controlled linear betatron coupling to the MTI, the injected beamlet oscillation in the horizontal plane will be damped in an energy exchange process to the vertical plane so the particles are moved away from the septum. The turn by turn transverse emittance exchange theory and simulation was given and discussed in [3, 2]. The disadvantage of this scheme is the increase of the beam emittance in the vertical plane, which has usually smaller aperture. This will lead to particles loss if the coupling is too strong. A good optimization implies the exchange to take place partially and just before the return of the beamlet back to its initial position at the septum. The strength of the skew quadrupole $k_{\rm sq}$ should be optimized together with the horizontal fractional tune Q_{xf}, the difference in the horizontal to the vertical tunes δ, the incoming beam parameters and taking into account the geometrical limitation of the SIS lattice.

In order to optimize the usage of the skew quadrupole for MTI process, we simulated the dependance of the transverse emittance exchange amplitude on the skew quadrupole strength for different detuning δ values. In Fig. 2 the maximum emittance exchange amplitude is plotted versus the skew quadrupole strength for the corresponding detuning values. The exchange amplitude for $\epsilon_{x0} > \epsilon_{y0}$ is given by $A = |\epsilon_{x0} - \epsilon_{x\rm min}| = |\epsilon_{y0} - \epsilon_{y\rm max}|$, where the initial transverse emittances were $\epsilon_{x0} = 0.002$ cm.rad and $\epsilon_{y0} = 0.0002$ cm.rad. The maximum exchange amplitude, exactly on the resonance at $\delta = 0$, is $A = |\epsilon_{x0} - \epsilon_{y0}| = 0.0018$ cm.rad where $\epsilon_{x\rm min} = \epsilon_{y0}$. The emittance exchange amplitude is proportional to the skew quadrupole strength and inversely proportional to the detuning; $A \propto k_{\rm sq}$ and $\propto 1/\delta$. For the weakest skew quadrupole $|C| \to 0$ and $\epsilon_{x,y} \to \epsilon_{x0,y0}$. In this case and for $\delta \neq 0.0$, there is no significant emittance exchange, since almost all the working points are outside the stop band width. However, for the strongest skew quadrupole $|C| \gg \delta$ and $\epsilon_{x,y} \to \frac{\epsilon_{x0}+\epsilon_{y0}}{2}$, the coupling strength is large enough where all the tested working points are pushed inside the stop band width so they approach the case $\delta = 0.0$ and $A \to |\epsilon_{x0} - \epsilon_{y0}| = 0.0018$ cm.rad. We found that for effective use of the skew quadrupole, its strength $k_{\rm sq}$ and the detuning δ together with the initial emittance ϵ_{x0} of any beamlet should be set so the exchange will not exceed the vertical acceptance limit. Then, in order to control

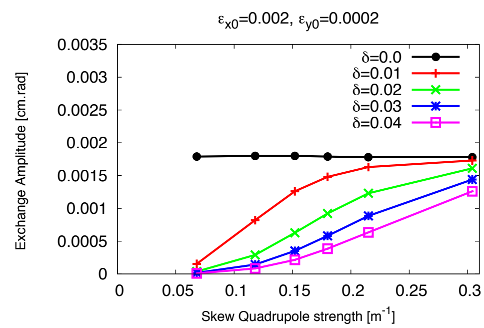

Figure 2: Emittance exchange amplitude versus skew quadrupole strength for different detuning.

the loss on the septum, the dependance of the exchange turns number on the skew quadrupole strength was simulated. The number of turns that is needed to reach the first maximum exchange, where $x = x_{\rm min}$ and $y = y_{\rm max}$, is given by $N_c = 1/2\sqrt{\delta^2/4 + |C|^2}$. The optimum usage of the skew quadrupole implies that the emittance exchange reaches the first maximum when the particles return to their initial phase and position at the septum; $N_c = N_{\rm rev}$. In Fig. 3 the emittance exchange turns number N_c is plotted versus the skew quadrupole strength for the corresponding detuning values. The black line corresponds to $\delta = 0.0$, where $N_c = 1/2|C|$ and $|C| \propto k_{\rm sq}$. With increasing $k_{\rm sq}$ the exchange becomes faster.

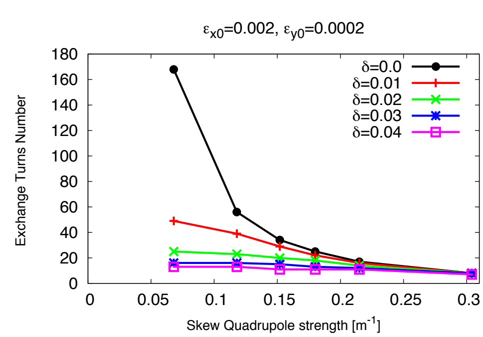

Figure 3: Emittance exchange turns number versus skew quadrupole strength for different detuning.

The bump speed effect with and without skew quadrupole

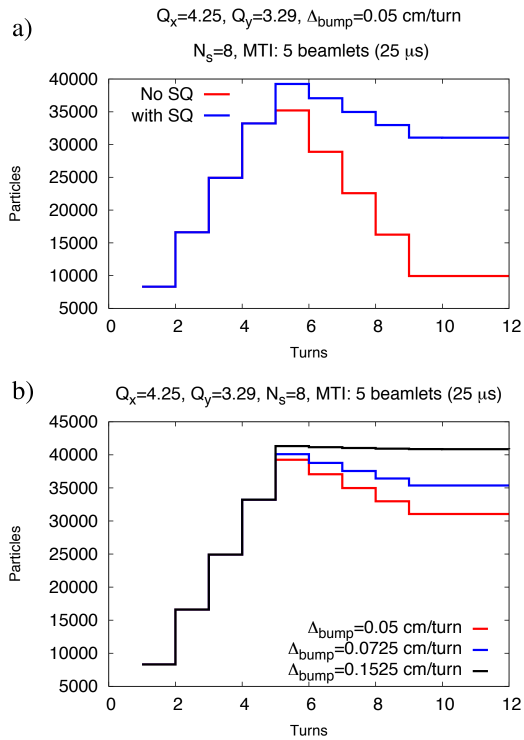

Figure 4: Bump speed optimization for one test working point with and without skew quadrupole.

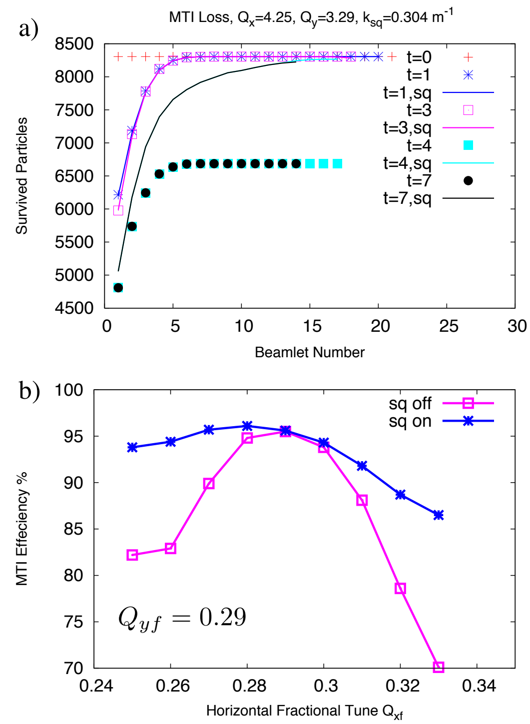

Figure 5: Skew quadrupole effect on a) beam loss and b) multi-turn injection efficiency.

was tested, see Fig. 4a. We set the horizontal fractional tune Q_{xf} on 0.25, which corresponds to $N_{\text{rev}} = 4$, and the detuning was $\delta = -0.04$. The skew quadrupole strength was $N_c = 8 \equiv k_{\text{sq}} = 0.3\ \text{m}^{-1}$. The results were compared with a previous measurement [2]. We tested different bump speeds on these settings and the significant improvement was found for $\Delta_{\text{bump}} = 0.1525$ cm/turn, see Fig. 4b. Finally, we examined the skew quadrupole effect on the MTI efficiency. We repeated the previous simulation in the first section using a skew quadrupole with strength equivalent to $N_c = 8$. As we expected, it is found that the skew quadrupole can improve the MTI efficiency for later beamlets and for working points where the loss comes from later machine revolution turns, see Fig. 5a. The skew injection efficiency is given in Fig. 5b (the blue curve). For $\delta = 0.0$ the improvement is around 2% since the coupling is total so the latest beamlets suffer loss due to the vertical acceptance limitation. Meanwhile, for $|\delta| = 0.04$ the improvement is around 12% since the coupling is partial and just enough to remove the particles from the septum without reaching the vertical acceptance limit.

CONCLUSION

For the purpose of improving the MTI efficiency, the strength of one applied skew quadrupole is optimized together with the horizontal tune, the difference in horizontal to vertical tunes, the incoming beam parameters taking into account the SIS18 acceptance at injection. We found from simulation that the skew injection scheme efficiency depends on the working point. For an effective usage of the skew quadrupole, the criteria is: the detuning must be smaller than the stop band width but different than zero so the exchange amplitude is enough just to damp the beamlet oscillation and move the particle from the septum. The strength of the skew quadrupole in terms of exchange turns number should be the same as the revolutions turns number that the beamlet will perform until its return back to its original position at the septum. Further test of the skew injection scheme needs to be done for the SIS18 high intensity working point including space charge effects.

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REFERENCES

[1] C. J. Gardner, Booster Technical Note, No. 197, Brookhaven National Laboratory, 1991.

[2] W. daqa, I. Hofmann, V. Kornilov, J. Struckmeier and O. Boine-Frankenheim, IPAC'10, Kyoto, Japan, May-June 2010, TUPD004, p. 1922 (2010), `http://www.JACoW.org`.

[3] K. Schindl and P. van der Stok, CERN/PS/BR 76-19 (1976).

[4] J. Struckmeier, GSI-ESR-87-03, GSI-Darmstadt.