MITIGATION OF SPACE CHARGE AND NONLINEAR RESONANCE INDUCED BEAM LOSS IN SIS100

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Abstract

Long term beam loss in SIS100, so far, was suspected to be originated by a periodic resonance crossing mechanism although without a direct evidence of it. We prove here that this is indeed the deteriorating mechanism by demonstrating that compensating some relevant resonance intercepting the space charge tune-spread beam loss is significantly mitigated. A short discussion on beam loss during acceleration is addressed as well.

INTRODUCTION

In the SIS100 synchrotron of the FAIR project at GSI [1] bunches of U^{28+} ions are stored for about one second and then accelerated: During this cycle beam loss cannot exceed 10% [2, 3]. The simultaneous presence of space charge and the lattice induced nonlinear dynamics may create a diffusional regime leading to beam loss [4]. The proposed mechanism of periodic resonance crossing was taken into account for the choice of the SIS100 working point $Q_{x/y} = 18.84/18.73$. The studies in Ref. [4] estimated the SIS100 beam loss, however without clear evidence that periodic resonance crossing is the issue. Our new study shows that indeed beam loss at injection is a result of periodic resonance crossing, and develop a strategy to improve SIS100 performance. We also address beam loss during acceleration.

BEAM LOSS AT THE INJECTION

Before presenting the simulation results in presence of space charge, we discuss which model of the machine and of the beam we adopt. We call this the "reference scenario".

The Reference Scenario

Random Errors In SIS100 the nonlinearities are given by standard multipoles in sc dipoles [5, 6] now optimized with respect to those in Ref. [4], and by the multipoles for sc quadrupoles [7]. Chromatic correction sextupoles are ignored. The systematic multipoles yield a short term dynamic aperture (10^3 turns) of 5.3σ for a reference beam of 8.75 mm-mrad rms emittance with the beam magnetic rigidity at injection of 18 Tm. Magnet random errors (MRE) are introduced through a $\pm 30\%$ fluctuation for all computed multipoles of the sc dipoles [8]. Skew components, where missing, are introduced of the same rms strength as the corresponding normal. Also unavoidable residual closed orbit distortion (RCOD), after correction are included. In Fig. 1 (left) we show the statistical dependence of the DA from the rms RCOD and MRE (kept at 30%). For safety we consider a reference vertical RCOD of 1 mm rms (1.6 mm horizontal), which contains 95% of the associated RCOD distribution. The feed down of magnets components for magnets displacement of $d_{x,rms} = d_{y,rms} = 0.32$ mm and MRE yields an average DA of $\simeq 4\sigma$ with a variance of $\simeq 0.2\sigma$, with a minimum at 3.4σ. The possible resonances excited are shown in Fig. 1 (right) by plotting the lower DA of a subset of 30 error seeds (of 1 mm rms RCOD), i.e. $\langle DA\rangle - 3\sigma_{DA}$. This calculation does not include the RCOD contribution. According to the seed of the RCOD and MRE any of these resonances may be excited.

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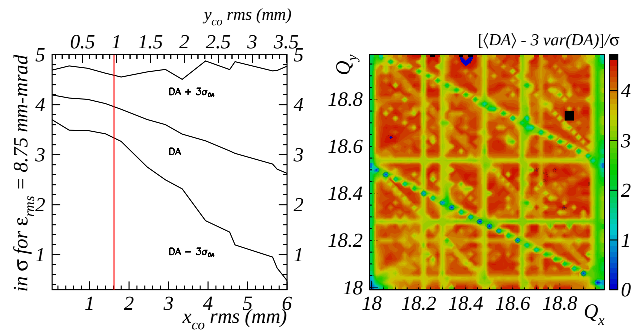

Figure 1: DA vs. COD (left); Statistical results of DA scan (right), the black marker shows the working point.

Reference Beam We model the bunched beam with a Gaussian transverse distribution truncated at 2.5σ in amplitudes as result of a controlled beam shaping during transfer from SIS18 to SIS100. The reference emittances (2σ) are $\epsilon_{x/y} = 35/15$ mm-mrad (edge at $2.5\sigma <$ DA=3.4σ). We will also use a larger probing beam "Beam2" with $\epsilon_{x/y} = 50/20$ mm-mrad (edge at $2.98\sigma <$ DA=3.4σ) for selecting a reference error seed.

Reference Error Seed We used the Beam2 as a probe for selecting a reference error seed. Simulations up to 10^4 turns for each of the 30 seeds (only MRE+RCOD) yield an average beam survival of $99.7\% \pm 0.2\%$. Among these seeds we selected the "reference error case" with the slightly pessimistic beam survival of $99.5\% \pm 0.2\%$. This error seed is used throughout all next simulations. We then evaluated the effect of the chromaticity in the reference bunched beam with rms momentum spread of $\delta p/p = 5 \times 10^{-4}$ consistent with a bunch length of $\pm 90^0$ (bunching factor of 0.33) and linear synchrotron period of 233 turns (RF voltage of 53 kV if SC is ignored). Simulations show a beam survival of $\simeq 99.6\% \pm 0.16\%$. In Fig. 2 (left) we show the resonances excited by the "reference error seed" (only MRE).

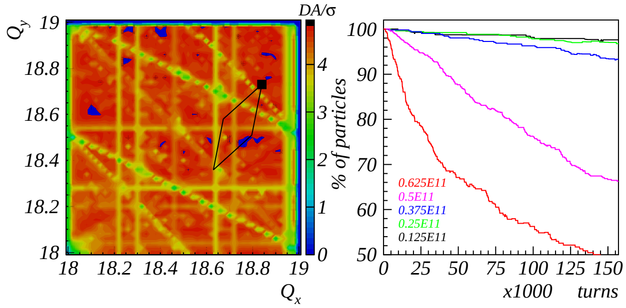

Figure 2: DA scan for the reference error seed and the expected tune-spread (left). First bunch survival evolution for several beam intensities (right).

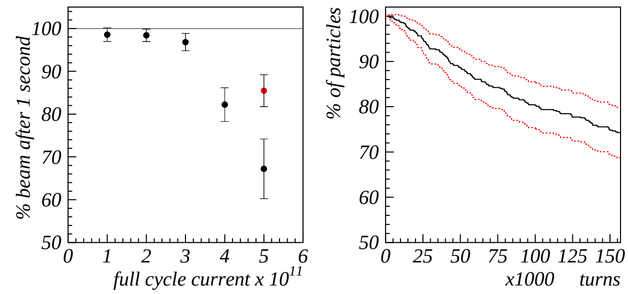

Figure 3: Left) Summary of the beam survival at the end of the cycle. Right) Beam survival of the first injected bunch with 0.625×10^{11} ions for dipoles with all multipoles reduced by a factor of 2.

Space Charge Induced Beam Loss

Simulations with SC are made with MICROMAP including all previously discussed effects for the "reference error case". The SC is computed with a frozen model, which incorporates the local beam size defined by the beam optics [4]. The space charge calculation are performed in the beam center of mass. For the total maximum nominal intensity of 5×10^{11} of U^{28+} in 8 bunches the SC peak tune-shifts are -0.21 / -0.37. In order to make sure that the space charge algorithm does not introduce artifacts we made a simulations in absence of lattice nonlinearities finding no beam loss in 1.57×10^5 turns.

The beam survival at the end of the cycle (8 bunches) $N_T(t_{end})/N_T(inj)$ is obtained from the beam survival of the first bunch $N(t)/N_0$, with N_0 the number of particles in the first bunch, via the formula $N_T(t_{end})/N_T(inj) = 1/4 \sum_{i=1}^{4} N(t_{end}-t_i)/N_0$, with t_i injection time. In Fig. 2 (right) the first bunch survival is shown for the intensities: $0.625, 0.5, 0.375, 0.25, 0.125 \times 10^{11}$ ions. As shown by Fig. 2 (left), the SC dominated loss may be a result of the periodic crossing of: the second order resonance $2Q_y = 37$, the third order resonances $Q_x + 2Q_y = 56, 3Q_y = 56$, the fourth order resonances $2Q_x+2Q_y = 75, 4Q_x = 75$. It should be noted here that the simulation model employed in this study lacks dynamical self-consistency. This is not expected to matter for losses at or below the few percent level. However, for larger losses, as for the cases $0.5, 0.625 \times 10^{11}$ ions, inclusion of full self-consistency (e.g. updating the SC force as a consequence of losses) could easily enhance or diminish the loss rate.

Beam Loss Mitigation

As in absence of lattice nonlinearities no beam loss is found, we first considered ideally improved dipoles. By reducing the nonlinear components of the dipoles by a factor 2 a simulation of the 0.625×10^{11} ions intensity, in Fig. 3 (right), shows a beam survival of $75\% \pm 2\%$ against the previous $\simeq 48\% \pm 2.7\%$ in Fig. 2(left) [error bars are described in Ref. [4]]. In Fig. 3 (left) this is shown over the the full cycle by a red marker. We conclude that: 1) Better dipoles significantly improve the beam survival; 2) This finding does not yet prove that periodic resonance crossing is the underlying beam loss mechanism

Removing the 3rd Order Components A more "realistic" approach, but still simplified, consists in removing only the 3rd order component in the dipoles. We find that, as expected, most of the 3rd order resonances vanish leaving the dynamic aperture unchanged [see Fig. 4 (left)]. A simulation of the first bunch for the intensity 0.625×10^{11} ions shows that the beam survival raise now to $97\% \pm 0.6\%$. This test proves that the third order resonances + space charge are responsible of the long term beam loss.

Resonance Compensation We then developed a resonance compensation scheme to reduce the strength of the 3rd order resonances $Q_x + 2Q_y = 56, 3Q_x = 56$, which cross the space charge tune-spread [Fig. 2(left)]. This approach was already suggested in Ref. [4], but never implemented. We computed the driving term of the reference error seed, and those created by each of 12 dedicated corrector sextupoles. The compensation strategy is to cancel the total driving term at $Q_{x,c} = Q_{y,c} = 18.66$, the interception of the two resonances we intend to mitigate. The requirement is to reduce the total driving term at $(Q_{x,c}, Q_{y,c})$ leaving un-affected the dynamic aperture. After applying the correction scheme a new DA scan [see Fig.4 (right)] confirmed the effectiveness of the resonance compensation: The resonances $Q_x + 2Q_y = 56, 3Q_x = 56$ have been compensated [compare with Fig. 2(left)]. We then repeated the simulation made in Fig. 2 (right) for the maximum intensity case and show the beam survival in Fig. 5 (right): We find that the beam survival rises to $97\% \pm 0.3\%$.

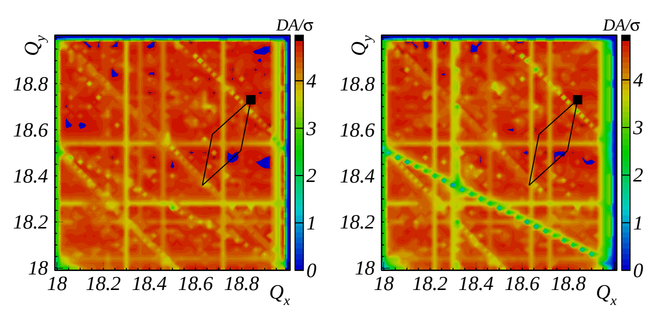

Figure 4: DA scan obtained by removing the 3rd order components in dipoles (left); Right) DA scan obtained by correcting $Q_x + 2Q_y = 56, 3Q_x = 56$.

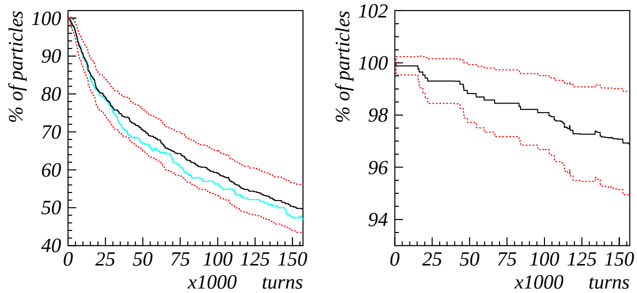

Figure 5: Survival of the first bunch beam for the case 0.625×10^{11} ions, without resonance compensation (left), and with resonance compensation (right).

Fig. 5 (left) shows the beam survival for the same beam but without resonance compensation [in blue the same curve of Fig. 2(right)].

BEAM LOSS DURING ACCELERATION

After the last bunch is injected, the acceleration ramp of 4T/s starts [see Fig. 6]. During acceleration several processes happen simultaneously. We study here the acceleration without any beam loss mitigation scheme (resonance compensation). Our modeling rely on the following approximations/assumptions:

1) The SIS100 modeling is the same as the reference scenario, i.e. chromaticity, dispersion, RCOD, and MRE seed are included.

2) We assume at the beginning of the ramp the beam of the reference scenario. However, the longitudinal distribution is now rms matched to the acceleration bucket (change of bunching factor and synchrotron period, see Fig. 6).

3) The modeling of the acceleration takes into account of: a) The transverse beam emittance shrinking with $\beta\gamma$; b) The reduction of the space charge $\propto \gamma^{-2}$; c) The scaling of the synchrotron tune according to $(\beta^2\gamma)^{-1/2}$ in a linear bucket; d) The dynamic change of the dipole magnets multipole with $B\rho$ [5]; e) We also include the contribution of the eddy current, which we keep constant throughout the acceleration [9];

In order to assess possible beam loss during acceleration and to evaluate the effect of the fast ramping, simulations have been performed for the bucket used at the injection, and the bucket used during the ramp. We also computed the beam loss in presence or absence of the eddy current. The model with the bucket of the storage and no eddy current represents the case of an ideal adiabatic acceleration ramp.

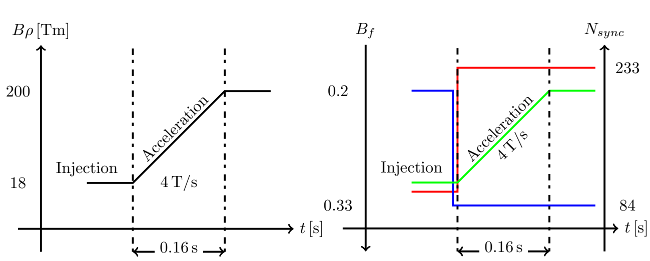

Figure 6: Schematic of the acceleration ramp (left); Change of bunching factor and of the synchrotron tune (right).

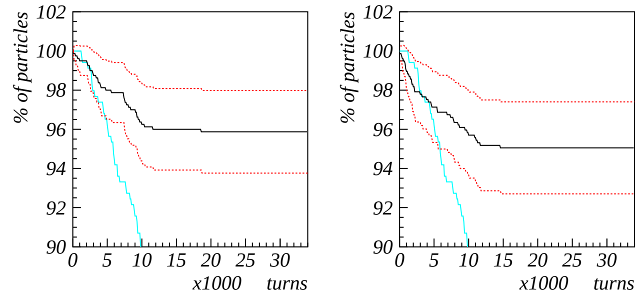

Figure 7: Beam loss during the $4T/s$ ramp without including eddy current (left). On the right picture the systematic eddy current is included. In blue the beam survival at injection plateau (for comparison).

Discussion Simulations show that for the adiabatic ramp beam loss is smaller than 1%, even adding the $4T/s$ eddy current. This is attributed to the fast damping of SC $\propto \gamma^{-2}$. Different is the case when the consistent bucket is used: The short bucket increases the space charge tune-spread $\simeq 60\%$ and 4% beam loss is found in the first 10^4 turns [Fig. 7(left)]. The more conservative case is obtained by the simultaneous presence of a small bucket and eddy current with an increase of beam loss to 5% [Fig. 7(right)]. These results indicate that beam loss for the reference beam should be expected in the level of $5 \pm 3\%$ in the first half of the ramp for the last injected bunch.

CONCLUSION AND OUTLOOK

Our studies confirm that the working regime of SIS100 is subjected to a space charge induced periodic resonance crossing. For the selected "reference scenario" we proved that a proper compensation of the resonances across the tune-spread mitigates the damaging effect to 2.5% beam loss (5 % with safety margin). A preliminary study of the acceleration shows that beam loss of the order of 5% is found ($\sim$ 10% with a safety margin). The robustness of these results to other error seeds and an improved modeling of the beam dynamics during acceleration ramp will be subject of a future work.

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