EFFECT OF SELF-CONSISTENCY ON SPACE CHARGE INDUCED BEAM LOSS

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Abstract

In long term storage space charge driven incoherent effect may lead to a slow beam diffusion that causes emittance growth and beam loss. However, when beam loss are relevant the full mechanism cannot be understood only driven by an incoherent effect. In this proceeding the issue of the self-consistency is discussed, and its impact presented for simplified examples and for the SIS100.

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 and the present study shows the predictions for a better modeling of the lattice, and discusses a modeling of the self-consistency.

BEAM LOSS AT THE INJECTION

In the reference scenario, in SIS100 the nonlinearities are given by standard multipoles in sc dipoles [5, 6] now optimized with respect to those in Ref. [7], and by the multipoles for sc quadrupoles [8]. 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 [9]. Skew components, where missing, are introduced of the same rms strength as the corresponding normal. We also include random gradient errors in quadrupoles. Also unavoidable residual closed orbit distortion (RCOD), after correction are included. 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 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.

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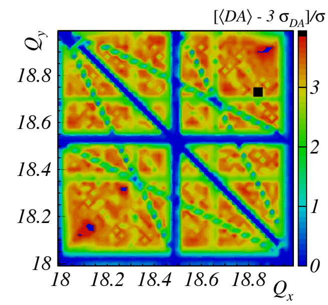

Figure 1: Statistical results of DA scan, the black marker shows the working point.

The bunched beam is modeled 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). The bunched beam has 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).

Among these seeds a "reference error case" has been selected, which yields the slightly pessimistic beam survival of $99.5\% \pm 0.2\%$ in absence of space charge for a larger test beam with emittances $\epsilon_{x/y} = 50/20$ mm-mrad. This error seed is used throughout all next simulations.

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, in the beam center of mass, with a *frozen model* [7]. 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. Tests made over 1.57×10^5 turns confirm that in absence of space charge beam loss are absent. In Fig. 2 b) the first bunch survival is shown for the intensities: $0.625, 0.5, 0.375, 0.25, 0.125 \times 10^{11}$ ions/bunch. As shown by Fig. 2 a), the SC dominated loss may be a result of the periodic crossing of: the second order resonances $2Q_y = 37, Q_x + Q_y = 37$; the third order resonances $2Q_x + Q_y = 56, Q_x + 2Q_y = 56$.

However, the validity of the frozen model simulations is doubtful for beam loss of 90% because of the lack of some space charge update in the code. Nevertheless, the problem of beam survival can be addressed simply with regard of its source that in this case is the presence of machine resonances. Therefore as first approach we compensate to some extent the resonances in order to see what happen to the beam survival.

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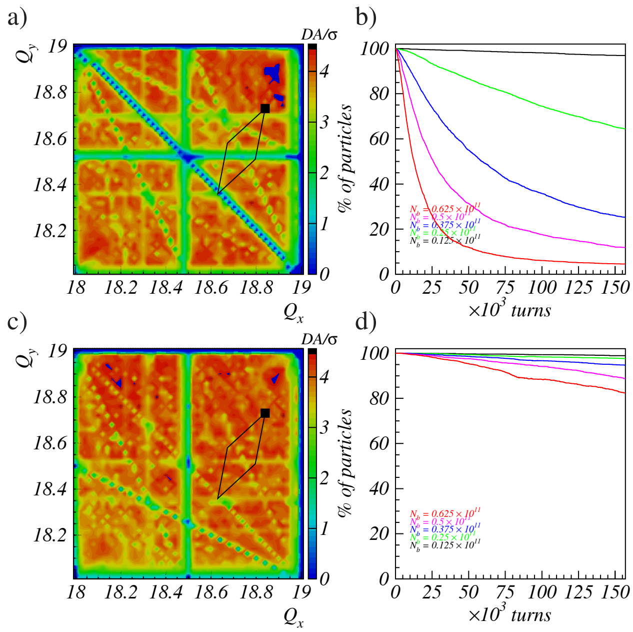

Figure 2: Simulations for SIS100: on the top pictures are simulated the working diagram (left), and beam survival for several intensities (right). In the bottom pictures: same simulations but with the resonances overlapping the tune-spread compensated.

Beam Loss Mitigation

We considered a resonance compensation scheme to reduce and control the the strength of the 2nd order resonances $2Q_y = 37, 2Q_y = 38, 2Q_x = 38, Q_x + Q_y = 37$. We also compensate/control the 3rd order resonances $3Q_x = 56, 2Q_x + Q_y = 56, Q_x + 2Q_y = 56, 3Q_y = 56$.

We computed the driving term of the reference error seed, and those created by each of 12 dedicated corrector quadrupoles and sextupoles. These elements are an "ad hoc" compensation system, still with correcting element located in the actual position of those foreseen in SIS100.

The compensation strategy is to cancel the total driving term of the resonance $n_xQ_x + n_yQ_y = N$ at the tunes specified in Table. 1.

Table 1: Tunes and resonances of control of the resonance driving term.

Q_x	Q_y	n_x	n_y	N
18.5	18.5	0	2	37
18.8	19	0	2	38
19.	18.7	2	0	38
18.5	18.5	1	1	37
18.667	18.667	3	0	56
18.667	18.667	2	1	56
18.667	18.667	1	2	56
18.667	18.667	0	3	56

The requirement is to cancel the total driving term leaving un-affected the dynamic aperture. After applying the correction scheme a new DA scan (see Fig.2c) confirmed the effectiveness of the resonance compensation: the resonances in the tune-spread are compensated leaving other resonances un-excited and the DA remains unaffected. The corresponding beam survival is comforting (Fig. 2d) as the beam loss appears significantly mitigated. However, it is not clear if the effect of the self-consistency is of relevance or not to this prediction.

MODELING SELF-CONSISTENCY

In the simulations here presented the space charge was computed with a frozen model. Particle in cell algorithms (PIC) are not used because the inherent noise that this method produces may create artificial emittance growth [10]. The consequences of this artifact on long-term tracking is difficult to assess especially in a regime of space charge induced resonance crossing. The noise in simulations arises from particle fluctuations in a PIC cell δN_c, which scales as $\delta N_c/N_c = 1/\sqrt{N_c}$, with N_c the number of macro-particles per PIC cell. Therefore a large number of macro-particles would mitigate the problem, however, it is difficult to assess the optimal number of macro-particles on a beam dynamics so complex as for the periodic resonance crossing. For this reason in the studies carried out till now (see for example Ref. [4]) the Coulomb force has been computed by assuming a beam distribution frozen, which yields a space charge noise free force. This approach assumes that beam loss don't exceed $\sim$ 10%. For larger beam loss, simulation predictions are not reliable because missing the feed-back of the beam intensity, and beam size (self-consistency).

Although benchmarking experiments had verified/confirmed the underlying mechanism and provided some confidence on code predictions [11, 7], the study of the effect of self-consistency is relevant for the assessment of effective beam loss, crucial quantity in the discussion on the nonlinear components in magnets, residual closed orbit distortion as well as in the resonance compensation strategy.

An intermediate approach toward the self-consistency has been proposed in [12]. *At each integration time step in frozen model only the intensity is updated leaving unchanged the frozen bunch emittances and frozen particle distributions.* This approach assumes that particles are lost from everywhere inside the beam and creates a "Markovian" process as it creates a loss of memory.

From a simulation point of view this procedure still requires enough macro-particles to allow the description of the continuous beam loss process. The results shown Fig. 2bd are obtained by splitting the work load among 750 processors each of them tracking 4 differently seeded macro-particles for a total of 3000 macro-particles tracked. Each beam intensity curve in Fig. 2bd is obtained as average of all the 750 beam surviving curves obtained from each single simulation. If we apply the Markovian update to a single processor simulation tracking only $N_{sp} = 4$ macro-particles, we certainly cannot expect a smooth beam loss process as a loss of one macro-particle corresponds to an abrupt change of 25% of simulation beam intensity.

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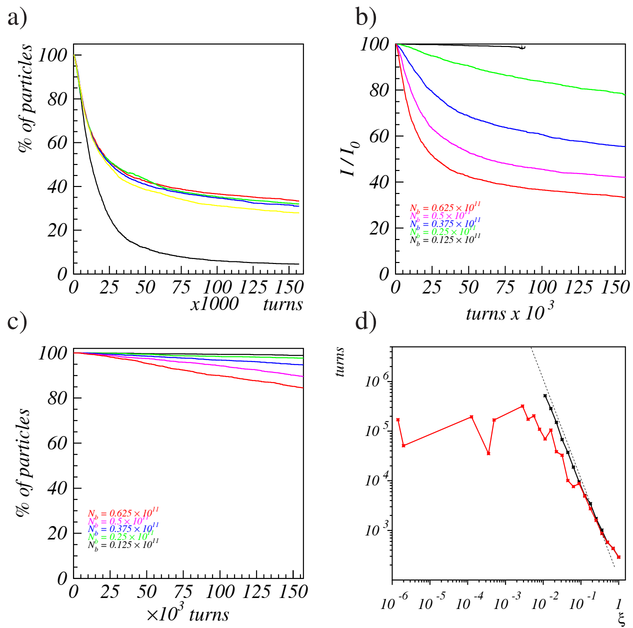

Figure 3: a) Effect of intensity update as function of single processor macro-particles. The black curve shows the beam survival obtained with the frozen space charge. b) Beam survival for the reference scenario; c) Beam survival for the reference scenario with resonance compensated. d) Impact of an artificial noise on the beam loss.

In Fig. 3a we show the results of a series of simulations for the case of the maximum intensity of SIS100 (i.e. 0.625×10^{11} ions/bunch). We studied the Markovian update simulations for $N_{sp} = 4$ (yellow), 10 (blue), 20 (green), and 100 (red) macro-particles, with a number of processors consistent to a total tracking of 3000 macro-particles. Surprisingly the beam survival curves for the several cases bundle together almost regardless N_{sp}.

Based on this finding we applied this algorithm to the scenario of SIS100 in which the resonances were uncompensated/compensated and use $N_{sp} = 4$ for a total of 3000 macro-particles tracked. The result is shown in Fig. 3bc.

The beam survival in SIS100 at maximum intensity is found $\sim 35\%$, which contrarily to the previous $\sim 5\%$ obtained with a frozen model. Instead the beam loss for the compensated resonance scenario keep the beam loss unchanged (compare Fig. 2d with Fig. 3c). This un-sensitivity to the intensity feed-back is due to the small beam loss (max $\sim 15\%$). Therefore for the reference scenario reference seed we find over 8 bunches an overall injection efficiency of 90%. Improved simulations with statistical error-bar will be performed from data of magnet measurements available in future studies.

EFFECT OF NOISE IN SIMULATIONS

We preliminarily also investigate the effect of a random noise on a constant focusing lattice. The effect of the noise introduced by a PIC code is modeled here by adding to the space charge force $F_{sc,x/y}$ a random component $\delta F_{sc,x/y} = K(z)\xi\Lambda \exp[-r^2/(4\sigma_r)]$, where: $K(z)$ is the z-dependent perveance; ξ is a parameter that control the strength of the noise; Λ is a random Gaussian variable of unitary standard deviation; $r^2 = x^2 + y^2$, x, y the particle coordinates; σ_r the average beam size. The coefficient in the exponential is $1/4$, hence it is taken the root square of the particle density, which is proportional to the particle fluctuation in a cell of a PIC code. The interpretation of ξ is the following: for $r < 1\sigma_r$ at the particle amplitude $r = 2\xi$, in good approximation, the standard deviation of the noise equals the space charge force. The parameter ξ is a function of the details of a PIC solver and these dependences and modeling are not discussed here. By exploring the dependence of the beam survival on ξ we attempt to decouple the mechanism of noise production (PIC algorithms) from the mechanism of emittance growth (the periodic crossing of resonances). For simplicity we consider the case of a constant focusing lattice subject to a 3rd order resonance (the same used in Ref. [12]), take a round beam, set a pipe at $4.5\sigma_r$, and take 101 integration steps per betatron wavelength and considered the SIS18 as test machine for a detuning of $\Delta Q_x = 0.15$. We compare the discrepancy of the beam survival between simulations with noise strength ξ with the correspondent noise-free. and mark at which turn the simulation with noise is 5% off the noise-free one. In this way we find a threshold of usage of a code with noise with strength ξ in this type of scenario. The result is shown in Fig.3d. The black curve refers to a tracking at the working point $Q_x = 4.37$, $Q_y = 3.25$, out of the beam loss stop band. The red curve shows the threshold for $Q_x = 4.345$, $Q_y = 3.25$, inside the beam loss stop band. These results suggest that out of the resonance a noise with $\xi < 0.01$ is compatible with tracking of 2×10^5 turns, whereas inside the resonance the noise seems always to have a deteriorating effect. The interpretation and consequences of these results is subject of future work.

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