BEAM LOSS MODELING FOR THE SIS100

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Abstract

In long term storage the dynamic aperture is regarded as the quantity which has to be kept sufficiently large in order to prevent beam loss. In the SIS100 of the GSI future project a beam occupying a large fraction of the beam pipe is foreseen. This circumstance requires a careful description of the lattice magnetic imperfections. The dynamic aperture is estimated in relation with an optimization of the SIS100 working point. For a space-charge-free bunched beam, estimates of beam loss are found to be about 4%. The impact of space charge is discussed, and preliminary results show that the loss is about doubled.

SIS100 NONLINEAR LATTICE

This report describes our progress in dynamic aperture (DA) calculations for the SIS100 using a preliminary lattice and working point [1]. The tools developed here will be applied to an optimized lattice in the near future. In the SIS100 the storage of a beam is foreseen, which fills a good fraction of the beam pipe of semi-axes 55×25 mm [1]. Multipolar expansion of the accelerator magnets is used to model lattice nonlinear components. Usually multipoles b_n, a_n are retrieved by integrating the magnetic field over a reference circle of radius R. The standard calculation of b_n, a_n made with $R \leq 25$ mm leaves uncertain the accuracy of the reconstructed magnetic field in the far region of the magnet aperture. Alternatively, the multipoles can be obtained through a fit [2] of a truncated multipolar expansion with the bending magnetic field map [3]. The best fitting provides the order of the expansion. Table 1 shows the multipoles for an SIS100 dipole at 10% excitation computed with standard [3] and fitting procedure (here $a_n = 0$). In order to improve the convergence between the standard and fit b_3, the magnetic field map has been taken in $|x| \leq 50$ mm. The maximum reconstruction error in the grid magnetic field is $\Delta B/B_0 = 0.38 \times 10^{-4}$. We use

Table 1: Standard and best fit multipoles in units of 10^{-4}.

n	b_n(standard)	b_n(fit)	deviation %
3	1.56	1.65	-5.1
5	-1.11×10^{-1}	-1.41×10^{-1}	-21.4
7	1.40×10^{-2}	2.43×10^{-2}	-42.5
9	6.0×10^{-3}	6.67×10^{-4}	800
11	-4.0×10^{-3}	7.7×10^{-4}	-617
13	4.0×10^{-3}	1.75×10^{-4}	2184

the fit multipoles to describe the nonlinear components in the center of the SIS100 bends. The effect of the sagitta of 8 mm [4] is included through a proper coordinate shift at the location of the bend nonlinearities. The nonlinear components of the quadrupole fringe field are modeled as well [5].

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STABILITY WITHOUT SPACE CHARGE

In Fig. 1a) we plot a cut of the stability domain in the x-y plane. The SIS100 is tuned on the preliminary reference working point [1] of $q_{x0} = 15.9$, $q_{y0} = 15.7$. The stability domain is computed in the x-y section with $\beta_x = 7$ m and $\beta_y = 9.3$ m (injection). Each point in the plot represents the initial condition of test particles with $x' = y' = 0$ which are stable (bounded) during the turns correspondent to its grey scale. In red is plotted the beam pipe in the SIS100 bends. In blue (inner ellipse) is drawn the space section of the beam at 2σ if injected with equilibrated emittances of $\epsilon_{x,rms} = \epsilon_{y,rms} = 8.75$ mm mrad [1]. The DA is defined as the radius (in normalized coordinates) of the largest circle inscribed inside the domain of stable initial conditions [6]. As customary we express the DA in terms of the beam σ, which for equal emittances [1] reads 4.4σ. This result, however, does not account for the imperfections which affect the systematic strength of each magnet nonlinear component. We assume these perturbations are of the same kind for each magnet: with average zero and variance 10% [7] of the systematic strength b_n. By giving each nonlinear component of the SIS100 its perturbed strength, we have formed an error set. For each error set a new DA will be found. We computed the DA for 5×10^4 turns and 97 error sets. These results are shown in the histogram in Fig. 1b). The vertical axes gives the number of sets for which the DA aperture was found to have the value in the correspondent bin in the horizontal axes. Our results for the DA cannot be taken as final values since additional factors need to be taken into account. For a preliminary discussion we assume the suggested reductions (in %) from Ref. [6] and scale in Table 2 the DA-values at 4.4σ accordingly (for the reference working point). We also infer possible beam loss by simply using a Gaussian cut model. The additional safety margin of -20% proposed in Ref. [6] appears to be unacceptable here and needs further consideration.

Table 2: Assumed further reductions of computed DA and accumulated loss.

Source of Uncertainty	Suggestion	DA	% Loss
Sensitivity to initial condition	-10%	3.96	0.3
Time-dependent multipole	-10%	3.65	1.3
Ripple	-10%	3.28	3.6

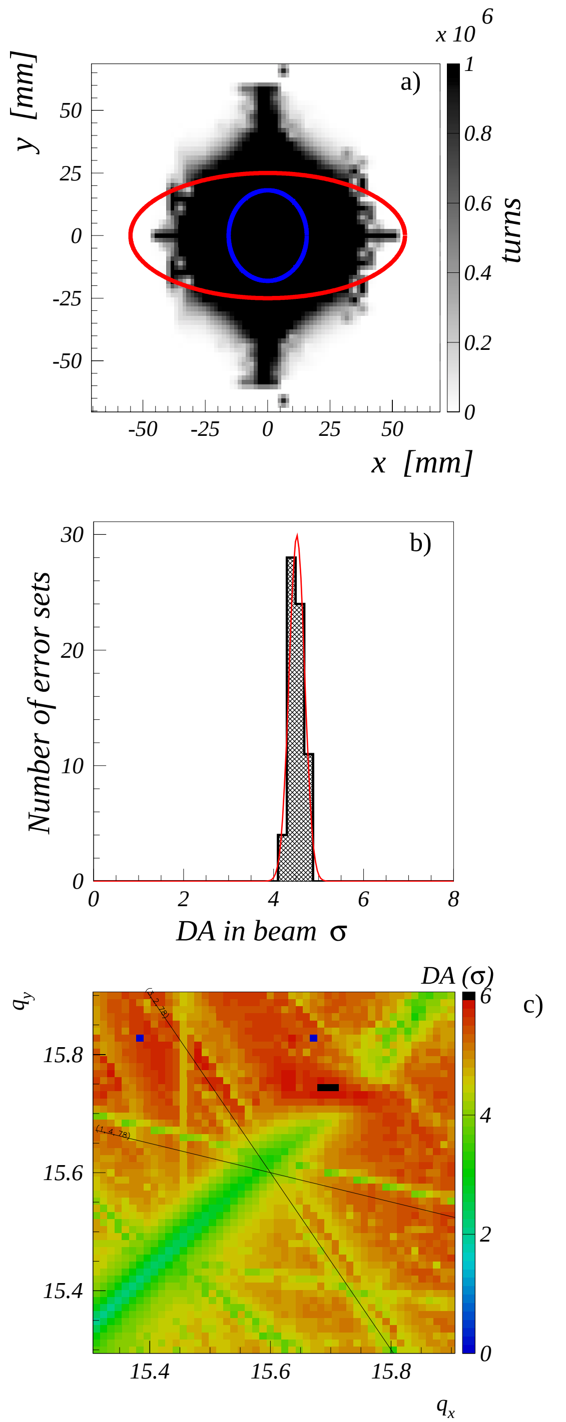

Figure 1: a) Stability domain; b) DA for a beam with $\epsilon_{rms,x,y} = 8.75$ mm mrad as function of bend errors; c) DA versus working point.

EFFECT OF SPACE CHARGE ON LONG TERM BUNCH STORAGE

In the FAIR project [1] it is foreseen that a primary beam U^{28+} is injected into the SIS100 from the upgraded version of SIS18 at 96 MeV/u . There an RF system with harmonic 10 is activated and 8 of the buckets are filled. The total ions stored in the SIS100 is planned to be 10^{12} in 1 second. This storing time corresponds approximately to 10^5 turns. We consider here a reference bunch with unnormalized transverse emittances at 2σ of $\epsilon_x = 50$, and $\epsilon_y = 20$ mm-mrad containing 1.25×10^{11} uranium ions. The momentum spread at 1σ is 2.5×10^{-4}. We consider here a typical frequency of 1000 turns per synchrotron oscillation. In this scenario a high intensity bunch is stored for long time and special attention must be paid to the interplay between lattice nonlinearities and nonlinear space charge forces. In fact it has been recognized in previous studies and experiments that synchrotron motion may reduce beam quality as it induces trapping/detrapping phenomena [8]. Beam emittance increase and particle loss are the final consequences of such a mechanism. The most dangerous effects happens when the bare tune is just above a resonance line as in this case synchrotron motion may induce - through space charge - a periodic crossing of this resonance at large transverse amplitude. Of critical importance for emittance growth and beam loss are the two quantities: 1) the distance of the bare tune from an excited resonance Δq_r; 2) the maximum tuneshift Δq. Extraction of particles may happen when $\Delta q/\Delta q_r$ is sufficiently large. Crucial is also the number of synchrotron oscillations performed during the storage time which has been explored up to 100 synchrotron oscillations. A first inspection of Fig. 1c reveals that the SIS100 reference working point $q_{x0} = 15.9, q_{y0} = 15.7$ is located above the systematic 5th order resonances $q_x + 4\,q_y = 78$, $3\,q_x + 2\,q_y = 78$. In spite of the systematic nature of these resonances one would expect a weak effect due to trapping and detrapping because of the high order of such resonances. It should however be pointed out that in Ref. [8] only one resonance was strongly excited and that here we are in presence of combined nonlinearities of several orders. The overall dynamics is therefore more complex. For a preliminary study of the effect of the synchrotron and space charge induced beam loss we consider two types of bunches.

A) A bunch with moderate space charge, subjected to a tuneshift $\Delta q_y = -0.1$. This tuneshift is consistent with a two harmonics RF system which flattens the bunch profile. For such a tuneshift Fig. 1c shows that apparently no resonance of fifth order is crossed for the above working point.

B) A second type of bunch with stronger tuneshift is considered. For larger tunespread as $\Delta q_y = -0.26$ the possibility of synchrotron induced trapping becomes more serious as $\Delta q_y/\Delta q_r \simeq 2$. The tunespread would cross the resonance $q_x + 4\,q_y = 78$.

The space charge effects are introduced in the tracking through an analytic frozen model of the bunch [9]. The analytic modeling prevents artificial noise effect in the tracking. For these simulations we set 50 space charge kicks per lattice period. The beam pipe is an ellipse of 55×25 mm kept constant along the ring. We consider the SIS100 tuned at the reference working point and tracked 2000 test particles in a bunch for 10^5 turns. In order to model the moderate space charge case we consider an artificially enhanced bunch length of 130 m (1σ), which yields in the bunch center the tuneshifts of $\Delta q_x = -0.068$, $\Delta q_y = -0.1$. The strong space charge case is created with a bunch length at 1σ of 54 m, hence $\Delta q_x = -0.16$, $\Delta q_y = -0.26$. For

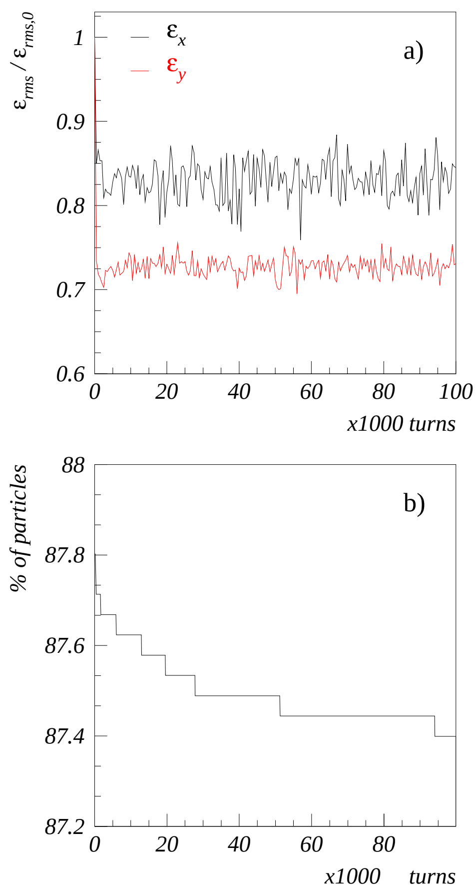

Figure 2: Moderate space charge case results: a) evolution of transverse rms emittances and b) % of initial particles remaining in the bunch.

the moderate space charge bunch Fig. 2 shows the rms x-y emittance evolution normalized to its initial values as well as the percentage of particles survived. The jitter is caused by the low statistics of particles involved in resonance trapping. An initial beam loss is responsible for an emittance drop in x and y. The beam loss after one synchrotron oscillation is 12.5% for the case A) and 12% for the case B). In order to interpret this emittance decrease we repeated the simulation B) without space charge and lattice nonlinearities. We find for this case an initial beam loss of 8.5% and an rms emittance drop to $\epsilon_x/\epsilon_{x0} = 0.75, \epsilon_y/\epsilon_{y0} = 0.88$. These results are consistent with the linear optics. In fact the maximum horizontal extension of the beam is cut by the beam pipe at $2.45\,\sigma$, whereas in the vertical at $2.8\,\sigma$. Hence we interpret the larger reduction of horizontal emittance as major loss of particles in the horizontal plane. This result seems however to contradict the initial decrease found in Fig. 2, as there the bigger emittance reduction happens in the vertical plane. We may question if this is due to pure lattice nonlinearity or from the combined effect of space charge defocusing jointly with the lattice nonlinearities. For the same simulation but now including only lattice nonlinearities we find an initial beam loss of 8.6% and $\epsilon_x/\epsilon_{x0} = 0.77, \epsilon_y/\epsilon_{y0} = 0.92$ after 1 synchrotron oscillation. Again we find a result which seems to contradict Fig. 2. For a simulation including lattice nonlinearities and space charge but keeping the *longitudinal motion frozen* we again find the same results as in the previous case. This allows us to conclude that the synchrotron motion is responsible for particle extraction. The difference of beam loss between the cases with and without *frozen longitudinal motion* suggests that 4% of lost particles are attributable to a periodic crossing of a resonance. The resonance which appears to excite the trapping extraction process could be the 4th order $2\,q_x + 2\,q_y = 63$. This resonance, as shown in Fig. 1c, is located right above the reference working point pushing therefore the ratio $\Delta q_y/\Delta q_r$ to large values as the distance from the resonance Δq_r drops close to zero. The simulations performed in Fig. 2 show also that a small saturating beam loss occurs after the first synchrotron oscillation. For the case A) and B) a 0.5% beam loss is detected during 10^5 turns showing no dependence of long term beam loss on bunch maximum tuneshift.

We finally conclude that for the SIS100 reference working point the beam loss budget is expected to be the extrapolated 3.6% reported in Table 2 plus $\sim 4\%$ induced by space charge effects. More accurate calculations require the complete set of multipolar components b_n, a_n along the ring and misalignment tolerances as well as an increased set of test particles. The reliability of these beam loss predictions has to be tested in dedicated benchmarking experiments.

REFERENCES

[1] C. D. R. http://www.gsi.de/GSI Future/cdr/.

[2] R. Hasse, private comunication.

[3] C. Muehle, private comunication.

[4] K. Blasche, private comunication.

[5] P. Krejcik, (1987), 12th Particle Accelerator Conference (PAC), Washington, DC, 16-19 Mar 1987.

[6] J. P. Koutchouk, 2 (1999), iEEE Particle Accelerator Conference (PAC 99), New York, NY, 29 Mar - 2 Apr 1999.

[7] G. Moritz, private comunication.

[8] G. Franchetti *et al.*, Phys. Rev. ST Accel. Beams **6**, 124201 (2003).

[9] A. Orzhekovskaya and G.Franchetti, these Proceedings.