NONLINEAR BEAM DYNAMICS WITH STRONG DAMPING AND SPACE CHARGE IN THE CLIC DAMPING RING

E.Levichev, P.Piminov, D.Shatilov, BINP, Novosibirsk, Russia

Abstract

The beam is injected into the CLIC damping ring with the relatively large emittance and energy spread and then is damped to the extremely low phase volume. During the damping process the betatron frequency of each particle changes due to the space charge tune shift and nonlinear detuning produced by the chromatic sextupoles, wiggler nonlinear field components and by the space charge force. During the damping, the particle cross resonances, which can trap some fraction of the beam, cause the loss of intensity, the beam blow up and degrade the beam quality. In this paper we study the evolution of the beam distribution in time during the damping.

INTRODUCTION

For storage rings with extremely low emittance a study of the dynamical behavior of the beam motion during the damping can be of a great importance. On the one hand, low emittance requires strong focusing lattice with a large value of natural chromaticity and strong sextupoles to compensate it. On the other hand, high current density induces space charge effects, which can be significant (with the space charge tune shift of ~0.1-0.2). In addition, damping wigglers produce essential nonlinearities in the vertical direction.

Typically, the beam is injected into such facilities with the initial emittance that is hundreds of times as large as the final one. During the damping, the charge density in the beam increases and the linear betatron frequency of all particles decreases (incoherent space charge tune shift). At the same time, as the oscillation amplitude A shrinks the betatron frequency of a particle changes according to the nonlinear tune-amplitude dependence $\nu(A)$. The main sources of the nonlinear detuning are strong chromatic sextupoles, damping wigglers and nonlinear part of the space charge potential. Due to the tune changing, particle cross resonances, which can cause the beam intensity loss, emittance blow-up, particle trapping into the resonance islands, and other deteriorations of the beam quality.

Qualitatively, a combined effect of the space charge tune shift and the amplitude damping with strong nonlinearity can be described as follows. During the damping the betatron tune depends on time as

$$\nu(t) = \nu_0 + \Delta\nu_{sc}(t) + \Delta\nu\big(A(t)\big),$$

where the small-amplitude space charge tune shift is inversely proportional to the beam emittance $\Delta\nu_{sc}(t) \sim -\varepsilon^{-1}(t)$ and always decreases the tune with damping while the amplitude dependent part $\Delta\nu\big(A(t)\big)$ may, depending on the sign of the tune-amplitude coefficients, increase or decrease the tune of the particle traveling with some damping amplitude $A(t)$. The result of the resonance crossing depends on the crossing rate: in the adiabatic limit the particles can be trapped in the resonance island (for the stable resonance) or lost during the passing (for the unstable resonance). Meanwhile the crossing rate depends on the sign and value of the nonlinearity. Combination of the linear space charge and nonlinear effects can increase the passing speed or decrease it ensuring adiabatic conditions and beam degrading.

To explore the beam damping process with nonlinear magnetic field and space charge, we have combined two computer codes in a single package. The beam-beam code LIFETRAC was developed for simulation of particle distribution in circular electron-positron colliders with radiation damping and excitation [1]. Another code is ACCELERATICUM [2], which tracks particle in a 6D manner with a realistic path lengthening in all magnetic elements (it is important for a correct simulation of the coupled synchrobetatron motion).

CLIC DR MODEL OVERVIEW

For the simulations we have used the DR lattice version v.44 by Maxim Korostelev dated May, 2005. This is not the freshest lattice version but as the work on the final design of the CLIC DR structure is still in progress we decided to apply our code to the ring lattice that was intensively studied in the past; the detailed description is available in [3]. In our study we pursue the following purposes: (i) establishing and testing the computer simulation approach in order to explore the time evolution of particle distribution in presence of strong damping, space charge and nonlinear lattice; (ii) understanding if all these factors may influence the CLIC DR performance and estimating the value of such influence.

The CLIC DR lattice consists of two arcs with 100 low-emittance TME cells and two long straight sections, which include the damping wigglers (38 wigglers in each section) in the FODO cells. The wiggler parameters are: the peak field is 2.5 T, the period length is 5 cm and the total length of the wiggler magnet is 2 m. Currently, we ignore the wiggler nonlinearities in order to save the processing time. The peak RF voltage is 2.4 MV. For the simulation plots the observation point is in the middle of the zero-dispersion wiggler section with the betatron functions of $\beta_{x0} = 124.5$ cm, $\beta_{y0} = 744.6$ cm.

The main characteristics of the lattice v.44 without the intra-beam scattering are given in Table 1. IBS strongly influences such final beam parameters as emittances, energy spread and bunch length. IBS is not included internally in our simulation software package so we have put by hand in LIFETRAC the initial (at injection) and final (at extraction) beam sizes taking into account IBS together with the relevant damping decrements.

Table 1: Main Parameters of the CLIC DR v.44

Energy	2.424 GeV
Circumference	357.5 m
Compaction factor	$6.758 \cdot 10^{-5}$
Betatron tunes	73.894/33.866
Natural chromaticity	-100.2/-141.0
No of particles in bunch	$2.6 \cdot 10^{9}$
Energy loss per turn	2.074 MeV
Damping times	2.79/2.79/1.39 ms

So the representation of the radiation damping in our simulation is quite correct while both heating mechanisms (quantum fluctuation and IBS) are reproduced by the quantum fluctuation only. The beam parameters before and after the damping are listed in Table 2.

Table 2: Beam Parameters at Injection and Extraction

	Inj/Extr
Hor emittance, nm-rad	13/0.08
Normalized hor.emittance, nm-rad	63000/360
Vertical emittance, nm-rad	$0.32/8\times10^{-4}$
Norm vertical emittance, nm-rad	1500/4
Energy spread, %	0.5/0.13
Bunch length, mm	10/1.5

Fig.1 demonstrates the tune-amplitude dependence for the chromatic sextupoles. This dependence is rather strong and quite complicated because during the damping the particle tune crosses several resonances (see Fig.3), which cause peculiarities on the smooth curve of the tune-amplitude dependence.

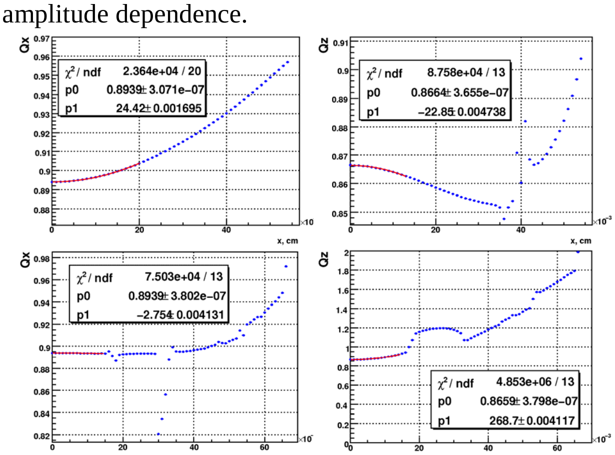

Figure 1: Tune-amplitude dependence for the sextupoles.

The Poincaré plots in Fig.2 show the integer resonance at the horizontal plane and a large fourth-order resonance in the vertical plane. The latter resonance island locating at the amplitude ~$20\div40\times10^{-3}$ cm (~100 vertical sigmas at extraction) is also seen at the tune-amplitude curve in the right-down plot of Fig.1. Besides, one may observe several high-order resonances in the vertical phase portrait. These resonances are stable now but in the presence of the field errors they may cause the dynamic aperture shrink and particle losses.

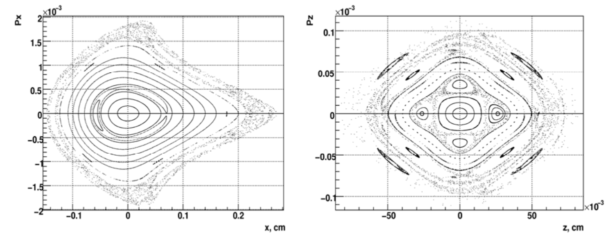

Figure 2: Phase portrait: horizontal (left) and vertical (right).

The space charge also contributes to the tune shift with the linear part estimated as $\Delta\nu_y = -0.134, \Delta\nu_x = -8\cdot10^{-3}$. A nonlinear contribution can be shown at the betatron tunes diagram as the foot-print just like for the beam-beam effect (Fig.3). Due to the space charge, the tune point crosses several resonances in the vertical direction.

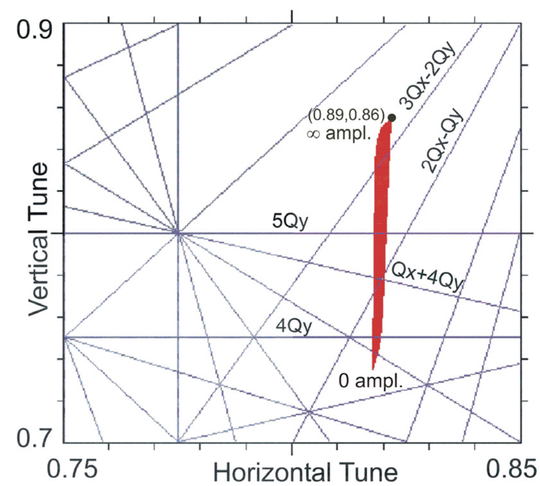

Figure 3: Space charge foot-print.

Of course the picture presented in Fig.3 is not complete because, besides the space charge tune shift, one has to take into consideration the nonlinearity of the sextupole and wiggler field. The sextupole tune shift is included into the simulation below.

BEAM EVOLUTION WITH DAMPING

At first, we simulate the evolution of the particle distribution without the space charge but with the chromatic sextupoles. 1000 particles were distributed by Gaussian law according to the injection parameters given in Table 2 and tracked during 20000 turns relating to ~8 transverse damping times ($\tau_{x,y} \sim 2500$ turns). Actually, the extraction is planned for ~3 damping times but in our simulation, when both excitation processes (SR and IBS) are represented by the single one (SR), the beam damps to

2

the extracted emittance later so the results at ~8τ of our simulation correspond to ~3τ with IBS; and SR is considered separately. An important result is that during the damping about 30% of the particles are lost behind the limit of the dynamic aperture during the first 400 turns! The detailed study has shown that the main reason is the lack of the energy dynamic aperture. The next series of the results relates to the case with the space charge. Taking into account ~ 30% intensity losses we increase the number of particles in the bunch to have a correct value of the space charge potential amplitude at the extraction.

The distribution plots during the damping as a function of the turn number are shown in Fig.4. At the damping time of $2 \div 3\tau_y$, a long vertical tail in particle distribution is formed. The reason is the strong vertical nonlinearity from the chromatic sextupoles producing many resonances as can be seen from the right plot in Fig.2. In Fig.4 at the right plot (19900 turns, ~$8\tau_y$), a chain of the islands is seen with particles trapped inside.

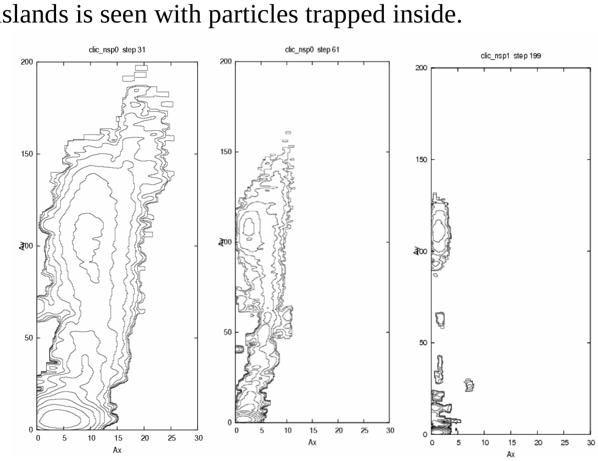

Figure 4: Particle distribution for 3100, 6100 and 19900 turns; scale is 30×200 rms beam size at extraction.

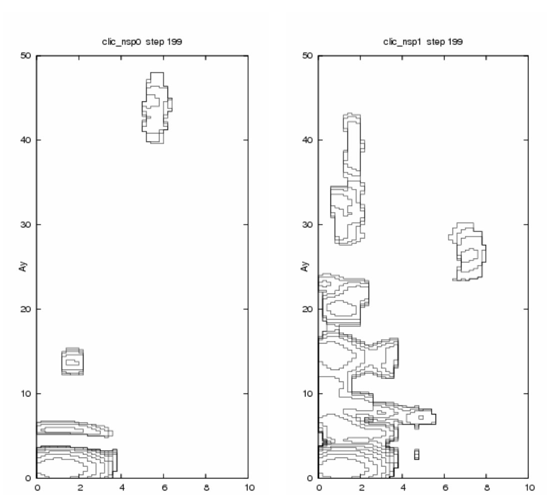

Figure 5: Comparison of the final particle distribution with (right) and without (left) the space charge.

When the beam is not damped to the extremely low value, the results of the simulation with and without the space charge do not differ much.

However, at the final stage of the damping, the difference is clearly seen. Additional nonlinearity of the space charge force (which in the vertical plane is stronger than in the horizontal one) produces additional distortion of the beam in the vertical direction. The detailed particle distribution at the end of the simulation (20000 turns) is demonstrated in Fig.5. A small amplitude (linear) tune shift due to the space charge from the simulation is $\Delta\nu_y = -0.118, \Delta\nu_x = -8.2\cdot 10^{-3}$ (close to that obtained by the estimation).

CONCLUSIONS

Evolution of the particle distribution in the CLIC DR during the damping process is studied with the computer simulation in the presence of the chromatic sextupoles and the space charge effect. The dynamic aperture of the lattice v.44 (May, 2005) is not enough to accommodate the required particle distribution and the 30% loss of the beam intensity occurs during the first hundred turns. Future work on the sextupole arrangement optimization and the dynamic aperture increase is necessary.

Trapping of the particles in the resonance islands produced by the sextupoles and nonlinear space charge potential is demonstrated. The considered nonlinearities do not degrade the ring performance much (the vertical emittance blow up is ~3%) but as the results depend on the particular resonance pattern and on the tune point, the simulation of the beam distribution evolution for the final version of the DR lattice is desirable. As during the damping process particles are captured in the resonance islands and the tail population increases by several orders of magnitude (from ~$10^{-6}\div10^{-8}$ to 1%), the effect may be enhanced via enlarging the CLIC DR bunch intensity and the ring circumference.

Besides, the inclusion of the wiggler nonlinearity (that is again rather strong just for the vertical plane) is also desirable.

REFERENCES

[1] D.Shatilov, Part. Accel. **52**, 65 (1996).
[2] P.Piminov, Master's thesis, BINP, Novosibirsk, 2000 (in Russian).
[3] M.Korostelev, PhD Thesis, CERN, 2006.