Non-Linear Tracking for the CLIC Damping Ring

E.Levichev, P.Piminov, D.Shatilov

BINP, Novosibirsk, Russia

LER Workshop, CERN, January 12-15, 2010

Preamble

We performed computer simulations to study nonlinear beam dynamics of particles during the process of damping in the CLIC Damping Ring.

The results reported below were obtained about one year ago and now they are out of date. Since then many parameters have been changed and DA was enlarged significantly.

We did not perform all corresponding simulations for the new set of parameters yet, but the phenomena considered in our “old” studies may have considerable importance for the current configuration as well.

We also discuss the peculiarities of simulation technique, its limitations and imperfections, and the ways how they can be overcame.

List of Main Parameters

	v. 44 May 2005	v. 6.7 Dec 2009
Energy (GeV)	2.424	2.86
Circumference (m)	357.5	493.2
Compaction factor	$6.76 \cdot 10^{-5}$	$6.49 \cdot 10^{-5}$
Betatron tunes [x / y]	73.894 / 33.866	59.384 / 13.416
Synchrotron tune	$3.1 \cdot 10^{-3}$	$6.0 \cdot 10^{-3}$
Natural chromaticity [x / y]	-100 / -141	-172 / -64
Particles per bunch	$2.6 \cdot 10^{9}$	$4.1 \cdot 10^{9}$
Energy loss per turn (MeV)	2.074	5.75
Damping times [x / y / z] (ms)	2.79 / 2.79 / 1.39	1.62 / 1.64 / 0.82
Horizontal emittance [inj / extr] (nm)	$18.0 / 8.0 \cdot 10^{-2}$	$11.26 / 8.04 \cdot 10^{-2}$
Normalized hor. emittance [inj / extr] (nm)	$8.54 \cdot 10^{4}$ / 379.5	$6.3 \cdot 10^{4}$ / 450
Coupling ($\varepsilon_y/\varepsilon_x$) [inj / extr]	0.0172 / 0.01	0.0238 / 0.011
Energy spread [inj / extr]	$7.0 \cdot 10^{-3} / 1.26 \cdot 10^{-3}$	$5.0 \cdot 10^{-3} / 1.4 \cdot 10^{-3}$
Bunch length [inj / extr] (mm)	10.0 / 1.5	10.0 / 1.0

Note: emittances, energy spread and bunch length at extraction are shown with account of IBS.

Nonlinear Beam Dynamics

Low emittance requires strong focusing lattice with large value of natural chromaticity and, as a consequence, strong sextupole magnets to compensate it. In addition, damping wigglers produce essential nonlinearities in the vertical direction. All these factors affect the dynamic aperture, energy acceptance and nonlinear tune-amplitude dependence.

⇩

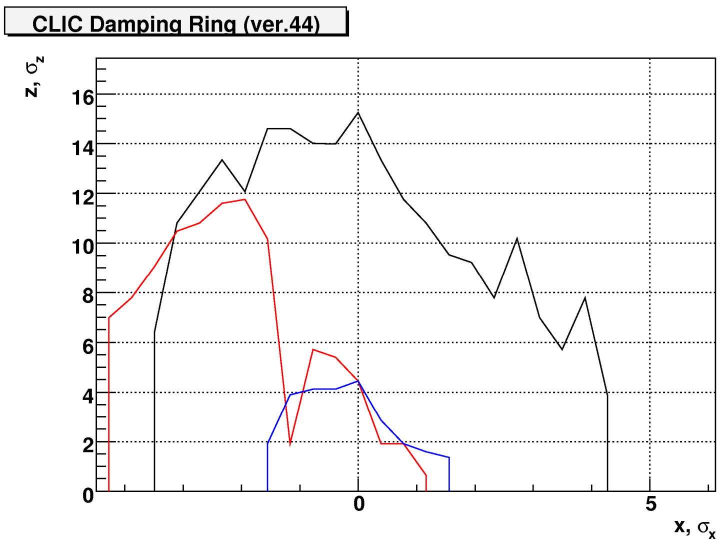
- **The emittances and energy spread at injection can be too large, as compared to DA and energy acceptance, so some part of the beam will be lost in the very beginning.**
- **Due to the tune-amplitude dependence, when the betatron amplitudes shrinks, particles cross the resonances and can be trapped or lost. This can cause the beam intensity loss and emittance blowup.**

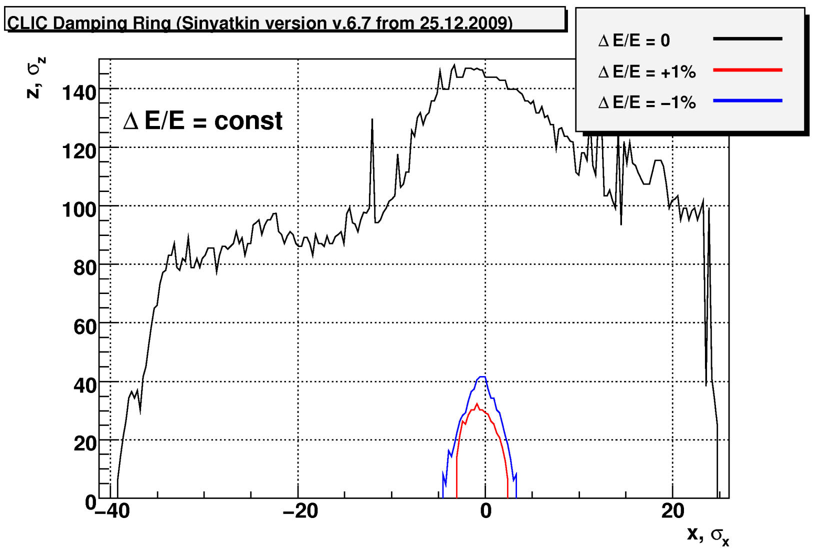
During damping the charge density in the beam increases, so the space charge effects become important. The space charge tune shift can achieve the values of 0.1÷0.2.

⇩

- **Additional tune spread (involve more working resonances).**
- **Combined effect of space charge and tune-amplitude dependence can increase or decrease the speed of crossing the resonances, that is important for the outcome.**

CLIC DR Dynamic Aperture



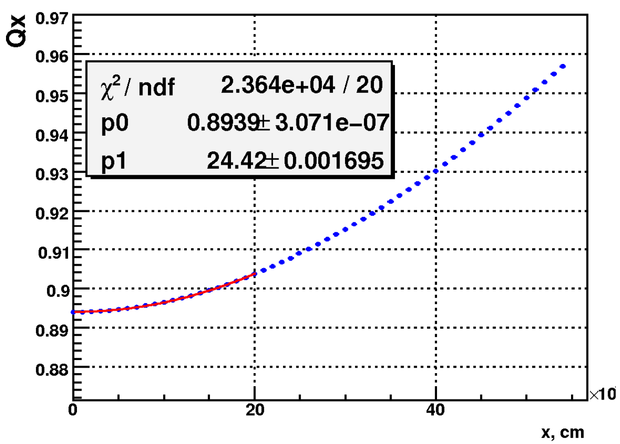


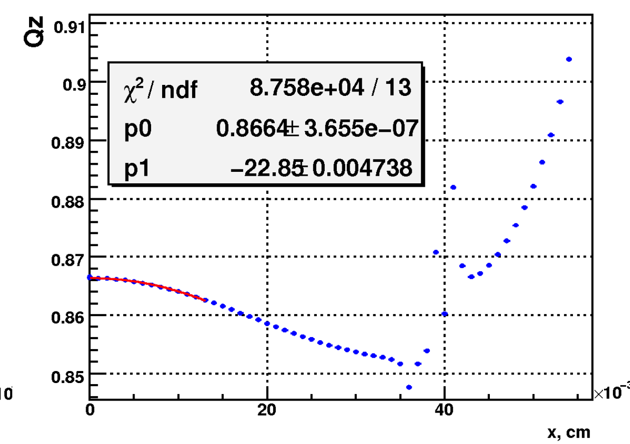
Scales are in sigmas at injection, dE/E = [**−1**, **0**, **+1**]%

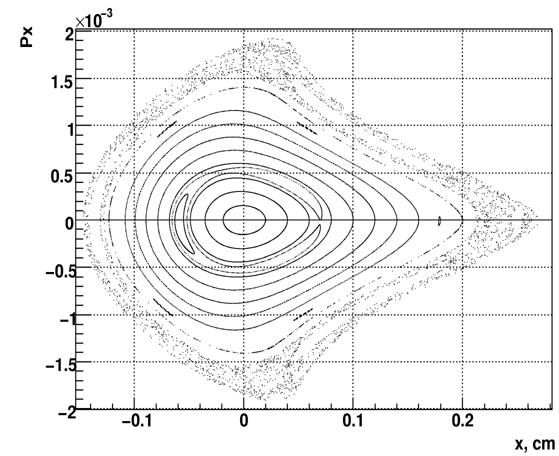
In the current version 6.7 the 4D Dynamic Aperture is very large, but for off-energy particles it shrinks. Reason: the transport matrix between arcs becomes not equal to $\mathbb{I}$ for dE/E ≠ 0. Some additional optimizations are required to eliminate chromaticity of this section connecting the arcs.

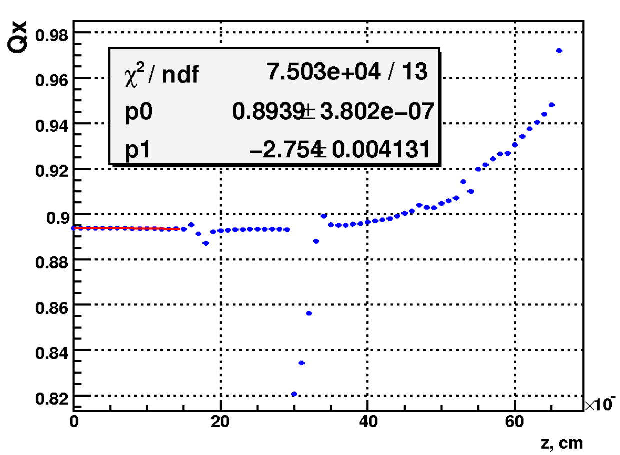
More info about DA can be found in S.Sinyatkin's presentation.

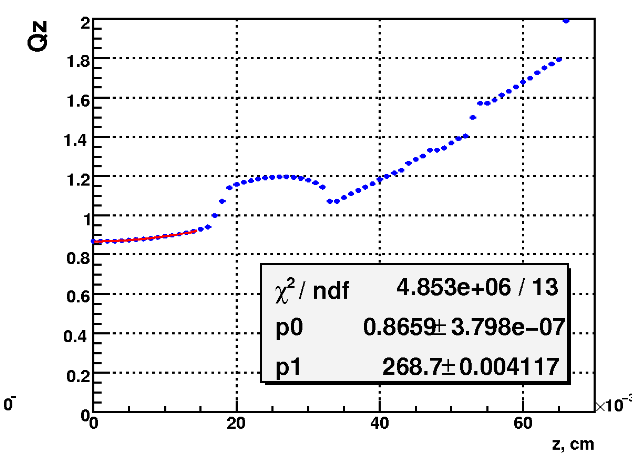
Tune-Amplitude Dependence

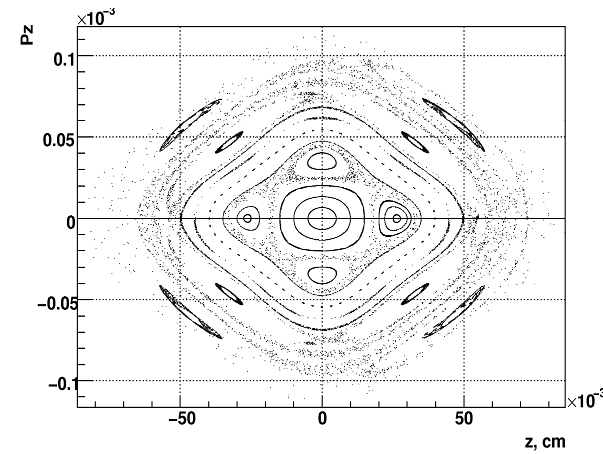












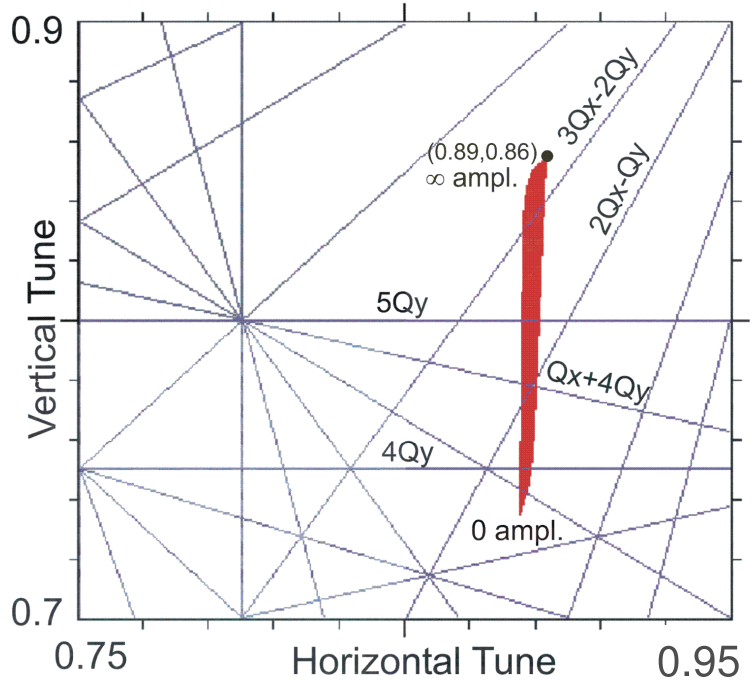
Note how strong resonances affect the $\nu(A)$ dependence.

Space Charge

Tune shift due to space charge (u=x,y): $$\Delta\nu_u = -\frac{r_e\lambda}{2\pi\gamma^3}\oint\frac{\beta_u(s)}{\sigma_u(s)\left(\sigma_x(s)+\sigma_y(s)\right)}ds$$

The effect becomes important at the end of damping process, when the beam density increases. At extraction time the tune shifts become rather large: $\Delta\nu_x$=−0.008, $\Delta\nu_y$=−0.134.

Similar to beam-beam effects, the space charge tune shifts depend on betatron amplitudes, and the footprint can cross several strong resonances.



Simulation Tools

- We combined two tracking codes to simulate bunch of particles in the process of damping: ACCELERATICUM and LIFETRAC. The first one tracks a single particle through nonlinear lattice, including the space charge effects. The second one (actually, it is a beam-beam tracking code) applies damping and noise, and performs data gathering and analysis.

- Number of simulated particles can vary in the range of 10^3 to 10^6 (usually 10^4). The tracking time is divided into steps, usually 100 turns per step. The statistics obtained during tracking is averaged over all particles and all turns for each step. So, we get a sequence of “frames” (10^6 particle-turns) representing evolution of the initial distribution.

- The initial 6D distribution of macro-particles can be either Gaussian (by default), or read from a separate text file. Besides, the macro-particles may have different weights. This allows representing the beam tails more reliably with limited number of particles: the ones initially located in the core region have larger weights while the tail particles with smaller weights are more numerous.

- When ACCELERATICUM performs a particle tracking for its own needs (DA calculation) it calls exactly the same subroutines and uses very same lattice files, that ensures an agreement between the combined code and ACCELERATICUM itself.

Simulation of Damping, Noise and IBS

- We simulated radiation effects in a simplified variant – diagonal damping matrix and diagonal noise matrix (without correlation of noises) inserted at one point in the ring.
- When the beam sizes shrink, the IBS contribution to the emittances becomes significant. For the given beam intensity the equilibrium emittances with account of IBS are about 3 times larger than the normal radiative ones!
- To account the IBS contribution we artificially increased the radiation noise amplitude in order to get the correct equilibrium emittances with the given damping decrements.
- In the early stages, when the beam sizes are large, such noises are incorrect, but actually they do not matter – damping is much stronger, so we can neglect the noises at all. When the beam is damped the noises become more important, and they asymptotically become “correct”.

Imperfections of this simplified approach:

- IBS is not a normal Gaussian noise, it has a specific spectrum (long tails) and can cause a particle loss.
- IBS strongly depends on the particle coordinates, in contrast to the radiation noise.
- The extraction is planned after about 3 damping times, but when both excitation processes (SR and IBS) are represented by the single one (SR), the beam damps to the corresponding emittance later – after about 8 damping times.

Now we are working on the correct implementation of IBS in the tracking code.

Simulation of Space Charge

- Space charge force is similar to beam-beam, so in the first approximation we can use the same formulae to calculate the corresponding transverse kicks. The transverse beam sizes depend on the azimuth where the kick is applied, and the beam linear density depends on the particle longitudinal coordinate.
- The kicks are applied in some number of points distributed over the ring. After some numerical study we found that the best results we have when the vertical betatron phase advances between these points are approximately the same and small.
- To get the necessary number of points we use the following criterion. When doubling the number of points the results should not change much – it means we have enough points to converge. When we half the number of points, the results *should* change – it means we have not too many points. So, in our particular case we have about 1500 points where the space charge kicks were applied.

Imperfections:

- The beta-functions used to calculate beam sizes are unperturbed, while the space charge itself affects them, as it changes the betatron tunes.

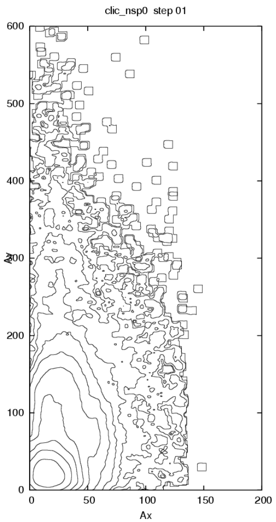
The next step (will be implemented soon):

Use the matrix of 2nd order momenta (or Σ-matrix) to get the beam sizes at any azimuth. Such a matrix at the observation point can be obtained by tracking, and then easily transported to any other point (in linear approximation). In this approach we don't need the beta functions at all, and can use even more complicated lattices with strong coupling.

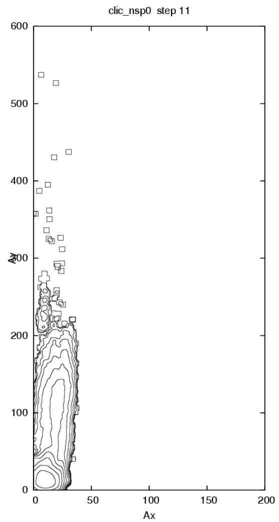
Damping without Space Charge

About 30% of the particles are lost during the first 400 turns. The main reason is the lack of energy acceptance: if we decrease the initial energy spread by a factor of 2, no particle is lost.

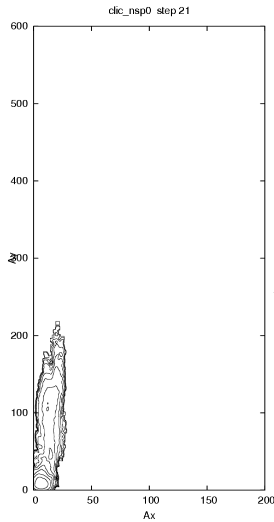
Scale is 200×600 rms beam size at extraction



100 turns

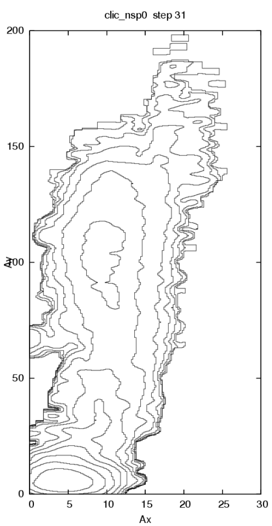


1,100 turns

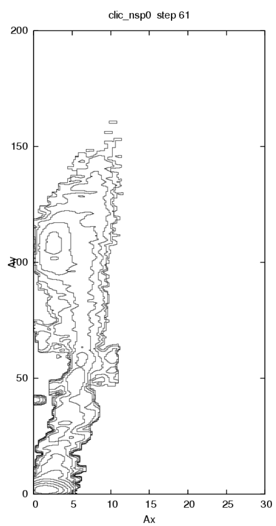


2,100 turns

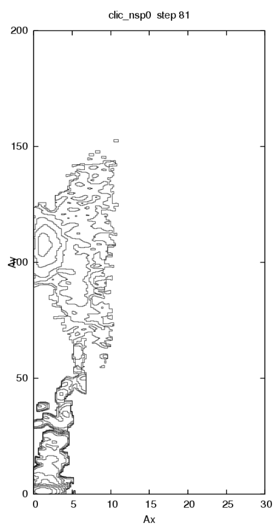
Scale is 30×200 rms beam size at extraction



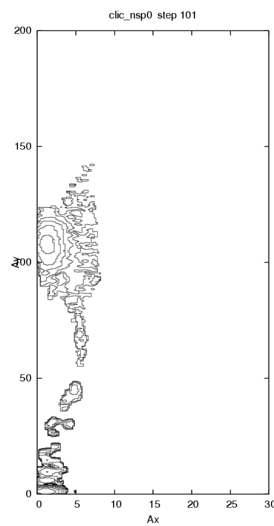
3,100 turns



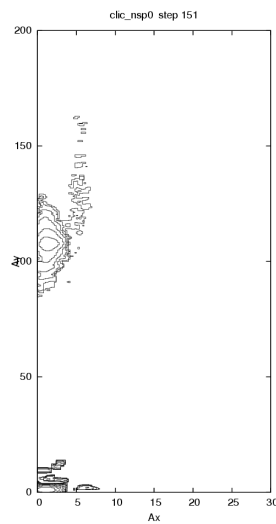
6,100 turns



8,100 turns

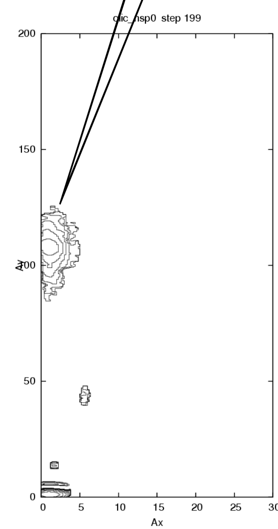


10,100 turns



15,100 turns

1%



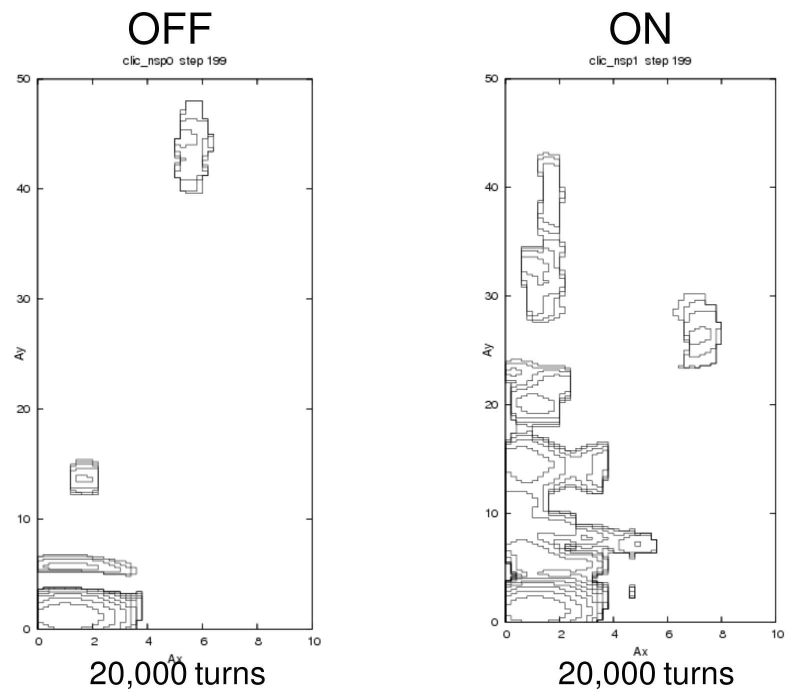
20,000 turns

Effects of Space Charge

Taking into account ~30% intensity losses we increase number of particles in the bunch to have correct value of the space charge at extraction.

When the beam is not damped to extremely low size, the results of the simulation do not differ much from these without the space charge.

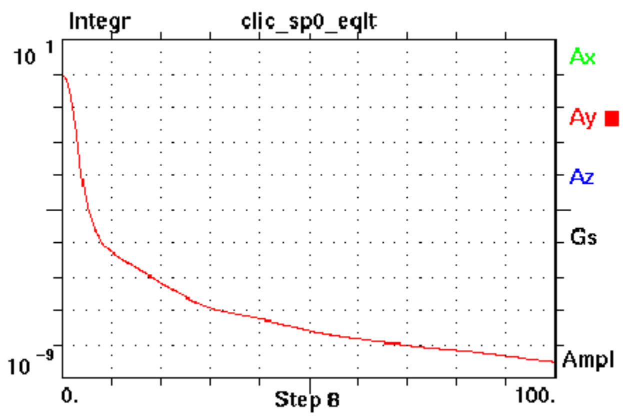
At the final stage of the damping the effects of space charge are clearly seen.



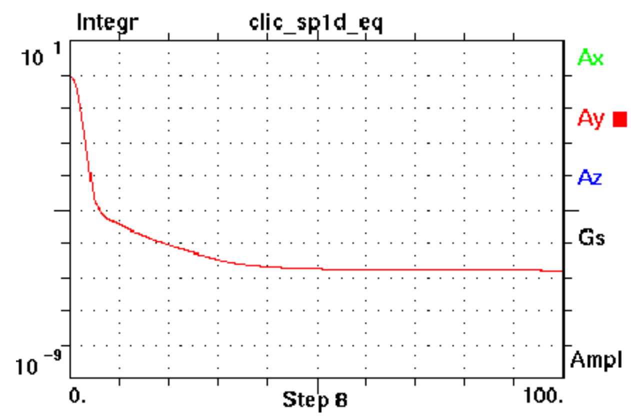
One more test: equilibrium initial emittances

Here we start from the Gaussian distribution with equilibrium emittances. The resulting equilibrium distribution is shown below.

OFF



ON



Fraction of particles (vertical axis, Log scale) located behind the vertical amplitude indicated in the horizontal axis. Without (left) and with the space charge effects.

The fraction of particles on large amplitudes is rather small: 10^{-8} without and 10^{-6} with the space charge. **When crossing the resonances due to damping, this fraction becomes 10^{-2}.**

Summary

- The dynamic aperture and energy acceptance of the CLIC DR lattice v.44 is not enough to accommodate required particles distribution, so that about 30% loss of beam intensity occurs during the first few hundred turns.

- Trapping of the particles into resonance islands produced by the lattices nonlinearities was demonstrated. Space charge effects can strongly affect the process.

- In the present lattice v.6.7 the Dynamic Aperture is large enough for on-energy particles, but for off-energy particles it shrinks. Further optimizations are required.

- A tracking code for nonlinear beam dynamics is updating in order to improve IBS and space charge simulations.