SPACE CHARGE AND ELECTRON CLOUD SIMULATIONS

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Abstract

Tracking of high intensity effects for few turns of a circular accelerator is at reach of present computational capabilities. The situation is very different when the prediction of beam behavior is extended to hundred of thousands of turns, where special approaches for the control of computer artifact are necessary sometimes to the expense of a complete physical modeling. The identification of the key physical ingredients helps to the development of computer algorithms capable of treating the long term tracking.

Here we present the latest status of long-term tracking simulations of high intensity bunches for SIS100, and also discuss a more realistic modeling of the incoherent effect of an electron cloud for the LHC.

INTRODUCTION

The motivation of these studies has started with the approval of the FAIR project at GSI. In the SIS100 synchrotron of the FAIR project [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, 4].

The simultaneous presence of space charge and the lattice induced nonlinear dynamics may create a diffusional regime leading to beam loss [5, 6]. The modeling of this unusual beam operation has been subject of studies in the past decade and relies on analytic models [7], which allow the suppression of a characteristic noise of PIC codes [8]. This approach neglects the coherent effects created by the Coulomb force as, for instance, the excitation of unstable modes of the beam [9]. On the other hand in the PIC self-consistent studies in Ref. [10] it is also shown that coherent nonlinear resonances are not of relevance for Gaussian beam distributions. Therefore in all studies for SIS100 it was adopted a modeling of "frozen" type and a quest to understand the dynamics was undertaken.

Over the years a systematic approach has been taken which had a two-fold purpose:

1) Understand the basics of the mechanism (lattice resonance affected by space charge created by a bunched beam) in order to more effectively improve SIS100 performances and to device possible cure for too high beam loss level [7]. Up to now the studies to understand the mechanisms of periodic resonance crossing have been confined to "frozen" algorithms.

2) Benchmarking the code prediction against experiments performed on a real machine. These studies started with an experimental campaign at the CERN-PS in the years 2002-2003 [11]. Few years later a new campaign was made at GSI in the SIS18 [6]. The results of these campaigns have shown that the simulation do not predict correctly the beam loss. The experiments always yield more beam loss of what is predicted with a computer code. The reason for this discrepancy is not fully understood as to the imperfection of the modeling implemented in computers also one has to account an imperfect knowledge of the real machine used for the benchmarking.

In the year 2004-2005 it was suspected that a similar diffusional mechanism could be created by the electron cloud during the electron pinch process driven by the passage of a proton bunch. Studies presented in Ref. [12] have shown that the effect of a resonance crossing is indeed at the base of a slow incoherent emittance growth. The issue of the modeling of the electron pinch is very central for the emittance growth prediction. The complexity of the dynamics of the electrons during the pinch process makes hard to use an analytic modeling. Attempts to investigate the emittance growth with analytic modeling of the electron pinch are reported in Ref. [5]. Differently from the space charge, the benchmarking with a beam experiment is here much more difficult because the knowledge of all electron cloud parameters is very difficult.

It is worth mentioning that the synergy between electron cloud and space charge studies allowed the development of a new theoretical framework which redefines the concept of fixed points for non adiabatic resonance crossing [13].

In these proceedings we report the state of the simulations for the SIS100 and we address recent development in the modeling of electron-cloud incoherent effects for the LHC.

SPACE CHARGE SIMULATION

As result of the studies on the periodic resonance crossing and all the considerations on nonlinear and high intensity effects the working point of the SIS100 was chosen as $Q_{x/y} = 18.84/18.73$. The studies presented in Ref. [5, 6] estimated the SIS100 beam loss, however without clear evidence that periodic resonance crossing is the issue. In recent studies we have found that this is the case.

Modeling of the Dynamics at Injection

Random errors, reference beam, and reference error seed. In SIS100 the nonlinearities are given by standard multipoles in sc dipoles [14, 15] now optimized with respect to those in Ref. [5, 6], and by the multipoles for sc quadrupoles [16]. 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

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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 [17]. 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. 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. 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). For the next simulation we select a "reference error seed" (only MRE). The resonances excited by this seed are shown in Fig. 1 (left).

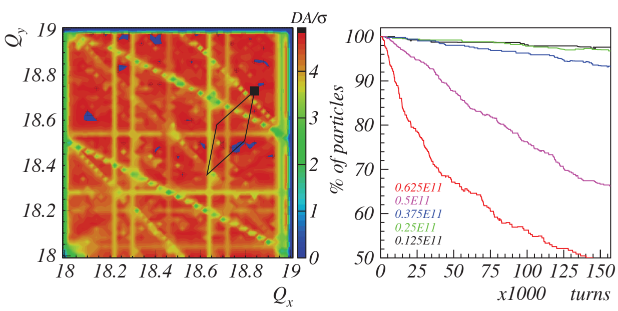

Figure 1: DA scan for the reference error seed and the expected tune-spread (left). First bunch survival evolution for several beam intensities (right).

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 [5, 6]. 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. 1 (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. 1 (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.

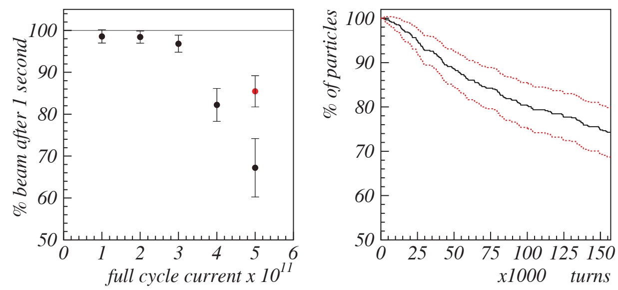

Figure 2: Left) Summary of the beam survival at the end of the cycle. Right) Beam survival of the first injected bunch with 0.625×10^{11} ions for dipoles with all multipoles reduced by a factor of 2.

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. 2 (right), shows a beam survival of $75\% \pm 2\%$ against the previous $\simeq 48\% \pm 2.7\%$ in Fig. 1(left) [error bars are described in Ref. [5, 6]]. In Fig. 2 (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.

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. 3 (left)]. A simulation of the first bunch for the intensity

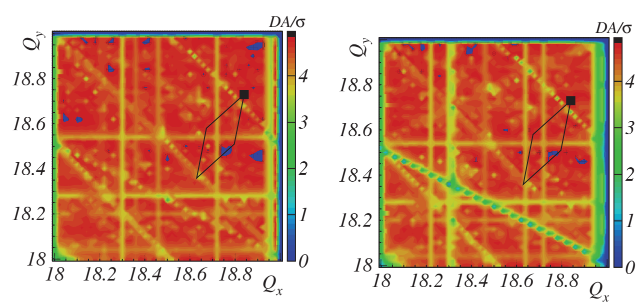

Figure 3: DA scan obtained by removing the 3rd order components in dipoles (left); Right) DA scan obtained by correcting $Q_x + 2Q_y = 56, 3Q_x = 56$.

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.

We then developed a resonance compensation scheme to reduce the strength of the 3rd order resonances $Q_x + 2Q_y =$

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$56, 3Q_x = 56$, which cross the space charge tune-spread [Fig. 1(left)]. This approach was already suggested in Ref. [5, 6], 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 unaffected the dynamic aperture. After applying the correction scheme a new DA scan [see Fig. 3 (right)] confirmed the effectiveness of the resonance compensation: The resonances $Q_x + 2Q_y = 56, 3Q_x = 56$ have been compensated [compare with Fig. 1(left)]. We then repeated the simulation made in Fig. 1 (right) for the maximum intensity case and show the beam survival in Fig. 4 (right): We find that the beam survival rises to $97\% \pm 0.3\%$. Fig. 4 (left) shows the beam survival for the same beam but without resonance compensation [in blue the same curve of Fig. 1(right)].

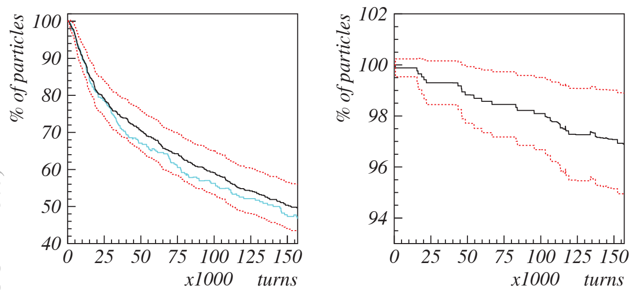

Figure 4: Survival of the first bunch beam for the case 0.625×10^{11} ions, without resonance compensation (left), and with resonance compensation (right).

Modeling of the Acceleration

After the last bunch is injected, the acceleration ramp of 4T/s starts [see Fig. 5]. 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:

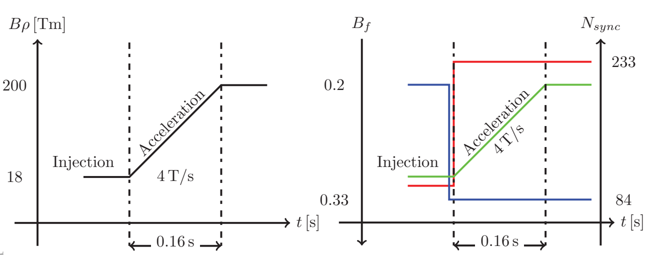

Figure 5: Schematic of the acceleration ramp (left); Change of bunching factor and of the synchrotron tune (right).

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. 5).

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 $B\rho$ [14]; e) We also include the contribution of the eddy current, which we keep constant throughout the acceleration [18];

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. The algorithm used in the code is illustrated in Fig. 6

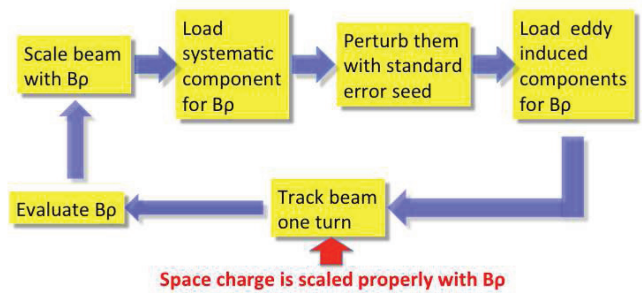

Figure 6: Computer algorithm used for modeling the acceleration dynamics with space charge.

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.

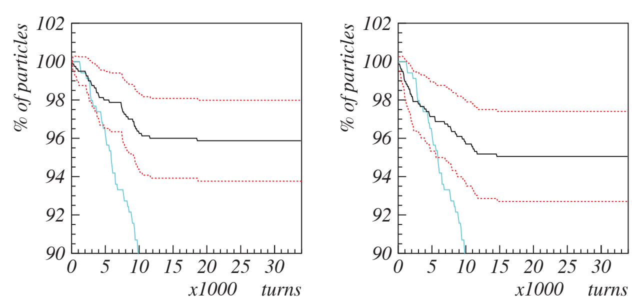

Figure 7: Beam loss during the $4T/s$ ramp without including eddy current (left). On the right picture the systematic eddy current is included. In blue the beam survival at injection plateau (for comparison).

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Conclusion/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.

ELECTRON CLOUD SIMULATIONS

We address here the modeling of the electron cloud incoherent effects which relies on the modeling of the pinch of the electrons. The details of this process are described in Ref. [5] where an ensemble of electrons are tracked and the structure of pinch is obtained. As a first approach, the modeling of the structure of electrons was made by using a simplified model as described in Ref. [5]. There the electron cloud structure has been modeled as a circular sheet with radius function of the position of the proton in the bunch reference frame. This model assumes that the average effect of the electron cloud on a proton of the bunch can be computed assuming the distribution of the electrons to be infinitely long. The resulting electric field has therefore no "z" component. Although the simplicity of the model, the resulting effect on the detuning experienced by a proton is rather complex as shown in Ref. [19]. This model is clean and allows the construction of very clear frequency maps, as shown in Ref. [5]. However, in this model the pinch process is assumed to be the same in each interaction point, which is not the case as the motion of the electrons is strongly influenced by the type of magnetic field created by the accelerator elements present at the location of the electron cloud. This effect was studied for pinch in drift and in a dipole in Ref. [5], but more in general the electron pinch structure becomes more complex for higher order magnetic fields. For example in Ref. [20] a study of the electron pinch in a quadrupolar magnetic field is presented. In particular the symmetry of the electron structure is very sensitive to the transverse position of the proton bunch with respect to the magnetic center of the element in which the electron cloud is located. This dependence is shown in Fig. 8. It is considered a LHC bunch with transverse rms size σ_r of 0.88 mm, an rms bunch length σ_z of 11.4 cm, with a bunch population $N_p = 1.15 \times 10^{11}$ protons, and a beam energy of 450 GeV. The initial electron distribution is uniform in a circle of radius $R = 10\sigma_r$, and it is always considered centered in the vacuum chamber, the number of macro-electrons is $N = 5 \times 10^5$. The left column of pictures show the pinch of electrons when the proton bunch is centered. The right column pictures show pinch process when the beam is shifted horizontally of 3 times the beam transverse radius. From Fig. 8 it is evident that the structure of the electrons cannot be modeled by simple analytic models. A relevant issue for the phenomenon of periodic res-

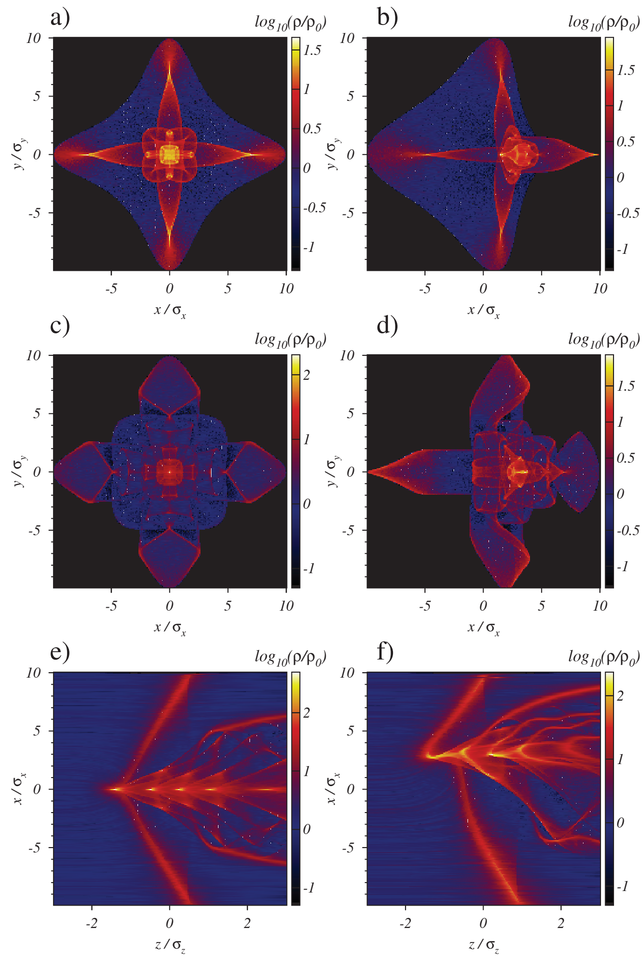

Figure 8: Electron density enhancement for the proton beam on axes (left column), and the same simulation with the beam shifted of $\Delta x_b = 3\sigma_r$ (right column). ab) the $x-y$ plane at $z=0$; cd) the $x-y$ plane at $z=1$; ef) the $z-x$ plane at $y=0$.

onance crossing is to establish what is the maximum tune-shift created by the pinch of the electrons. The larger is the tune-shift the more pronounced is the effect on the proton beam. In a study presented at the ECLOUD'12 workshop it is shown that in a good approximation the maximum tune-shift has to be expected along the closed orbit of the proton bunch [21]. An attempt of characterization of the detuning from a pinch process requires the inclusion in the proton dynamics of the full electron dynamics. To this purpose the following procedure was adopted:

1) We compute the "normalized transverse force" E_x, E_y created by electrons at each location of the bunch. The force is modeled as $\propto 1/r$ with a cut off [21]. By normalized it is meant that the electric field E_x, E_y is computed for a reference charge density assigned to each macro electron. As consequence the realistic force is obtained by re-scaling this force of a proper factor F, proportional to the electron cloud density.

2) The field E_x, E_y is stored as function of x, y, z on a

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$200 \times 200 \times 200$ grid that include the bunch itself. The grid extends to $[-10\sigma_r, 10\sigma_r]$ in both transverse axis, while on the longitudinal axes it extends in the range $[-3\sigma_z, 3\sigma_z]$.

3) The actual force on a proton when it passes through the electron cloud at the longitudinal position z (in the bunch reference frame), is obtained via tri-linear interpolation from the grid data.

4) The previous procedure is applied for a pinch of electrons in a drift, dipole, and a quadrupole. We define in this way 3 new elements "EC kick" which are consistently applied in the neighbor of each element of the circular accelerator structure.

At the moment this procedure remains inconsistent as it does not take into account of the differences in optics at different locations where electron pinch will take place. Clearly these optics differences are responsible of deforming the transverse section of the proton beam which consequently will produce a "deformed" electron pinch. Hence it becomes necessary, but it is left to future studies, to establish if there is a scaling property of the structure of electron cloud with β_x, β_y at the location in which the pinch takes place. In Fig. 9 we show the detuning along the longitudinal axis obtained applying this method for a reference example Ref. [21]. Here the electron cloud density is artificially enhanced for the purpose of testing the algorithm ($n_e \sim 10^{16}\mathrm{m}^3$). The completion of the tests is left for future studies.

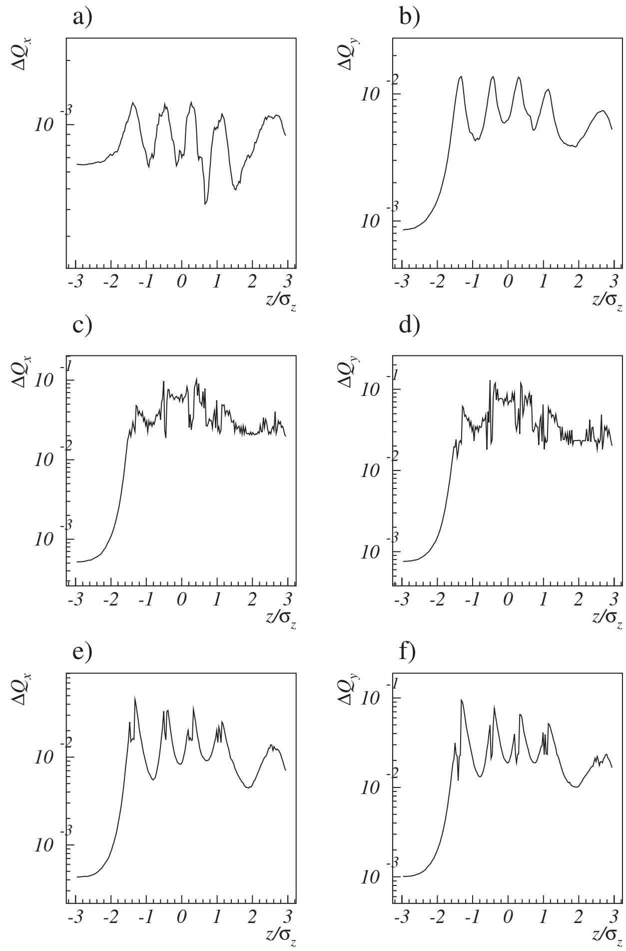

Figure 9: Detuning along the bunch for test particles at transverse amplitude of $0.1\sigma_r$. The right column is the horizontal tune, the left column is the vertical tune. ab) one EC kick in a dipole; cd) one EC kick in a drift; ef) one EC kick in a quadrupole.

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