Electron Cloud Instability Simulations for the LHC

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Abstract

We present results of simulations of transverse single bunch instabilities for the LHC and LHC Upgrade scenarios and in particular first results with electron cloud in the dipole regions. The possibility to use the code HEADTAIL below the threshold of the fast instability is under study and we here discuss a possible way to distinguish numerical noise from true physics.

INTRODUCTION

The instabilities induced by electron cloud are a concern for LHC and for the future upgrades of the collider, especially at injection energy. Simulations have been done with HEADTAIL [1, 2, 3]. The code models transverse, single bunch instabilities, assuming that the interaction between the electron cloud and the bunch happens at a finite number of locations around the ring. The electrons and the protons are represented by macroparticles and the bunch is divided into slices. A PIC module compute the interaction between the 2D cloud and each slice. In the following section we show first results of modelling the real distribution of the electrons in dipole field regions. Then some prediction for LHC upgrade scenarios are discussed. Finally, the last section is devoted to the study of the emittance growth below the threshold of the fast head-tail instability and its dependance on the number of interaction points per turn.

ELECTRON CLOUD IN THE DIPOLES

It has been observed that in the SPS the electron cloud is mainly concentrated in the dipole regions. The electrons populate stripes at a certain distance from the beam, depending on the bunch intensity. We suppose that this will be valid also for the LHC and, since the nominal bunch intensity will be the same, we can assume (from SPS measurement [4]) that the stripes will be at about 14 mm from the axis, with an rms size of $\sigma_{str} = 8$ mm. In these simulations, 10% of the electrons are distributed uniformely inside the chamber and the other 90% are populating the stripes, which have a uniform profile, $4\sigma_{str}$ wide. Figure 1 shows the projection of the electron cloud density onto the horizontal axis (the chamber is elliptical) and the electron cloud density evolution in the vertical plane. It is evident that the electrons pinch toward the center during the passage of the bunch in the vertical plane, while in the horizontal plane they do not move because of the strong magnetic field approximation, which freezes their motion perpendicular to the field lines.

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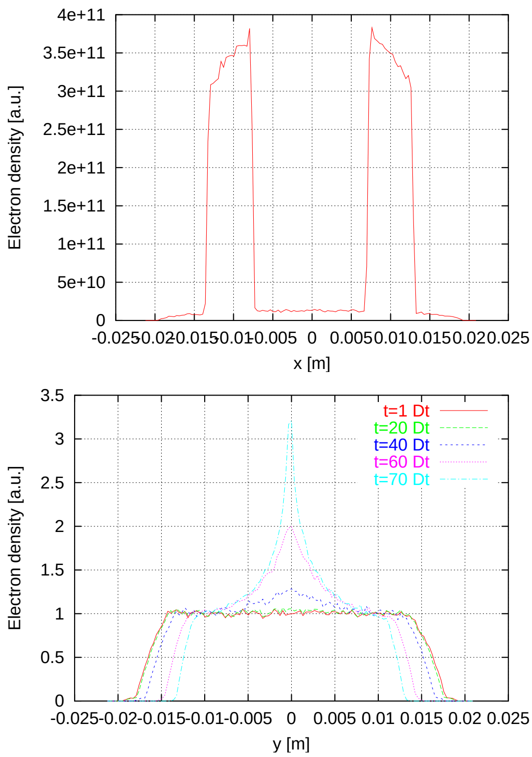

Figure 1: Projection of the electron cloud density on the horizontal (top) and on the vertical axis (Dt correspond to the passage of one slice)(bottom), for the LHC at injection. The total lenght of the bunch $(/pm2/sigma_z)$ is divided into 70 slices.

The emittance growth (Fig. 2) is very low and even for high average cloud density we are below the threshold of the fast head-tail instability. If the electrons are really concentrated in stripes, far from the beam axis, an average density higher than the one predicted for uniform distribution seems to acceptable, even at injection. However there are a lot uncertainties in the electron distribution and, moreover, the stripes position is not fixed, but varies with the beam parameters.

ELECTRON CLOUD SIMULATIONS FOR THE LHC UPGRADE

Simulations for LHC upgrade scenarios have been done pessimistically assuming that the electron cloud is uniformly distributed in the transverse plane (no magnetic field and no stripes).

In Fig. 3 the emittance growth vs. time is shown for the different scenarios, whose parameters are listed in Table 1. The electron cloud density is $\rho_e = 1.2 \times 10^{12}$ m^{-3}. Even

Table 1: Parametres for the nominal LHC and for LHC Upgrade Scenarios

parameter	nominal LHC (ultimate)	Short bunch	Piwinski
cloud density, $\rho_e[\mathrm{m}^{-3}]$	1.2×10^{12}	-	-
bunch population, N_b	$1.1 \times 10^{11}(1.7 \times 10^{11})$	1.7×10^{11}	3.0×10^{11}
beta function, $\beta_{x,y}[\mathrm{m}]$	100	-	-
rms beam size, $\sigma_{x,y}[\mathrm{mm}]$	0.884	-	-
rms bunch length, $\sigma_z[\mathrm{m}]$	0.13	0.0806	0.214 (uniform profile)
rms momentum spread, δ	4.68×10^{-4}	7.71×10^{-4}	1.40×10^{-4}
longitudinal emittance, $\epsilon_z[\mathrm{eVs}]$	1.25	1.25	0.625
synchrotron tune, Q_s	0.0059	0.0188	0.00128
momentum compact fact, α_c	3.47×10^{-4}	-	-
circumference, $C[\mathrm{m}]$	26659	-	-
nominal tunes, $Q_{x,y}$	64.28, 59.31	-	-
chromaticity, $Q'_{x,y}$	2,2	-	-
dispersion, D [m]	1.5	-	-
magnetic field	no	-	-
relativistic factor, γ	479.6	-	-
cavity voltage, V [MV]	8	21.5	3
harmonic number, h	35640	106920	3564

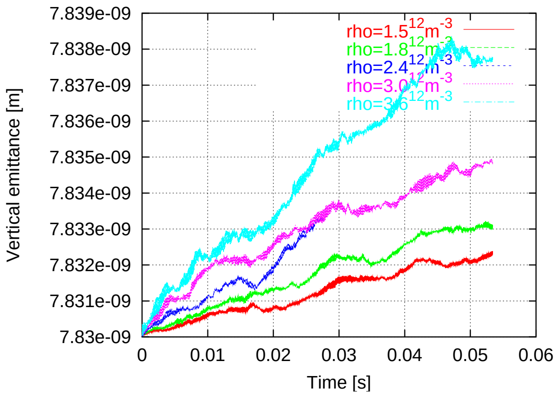

Figure 2: Emittance growth vs. time, with different average electron cloud densities, for LHC at injection

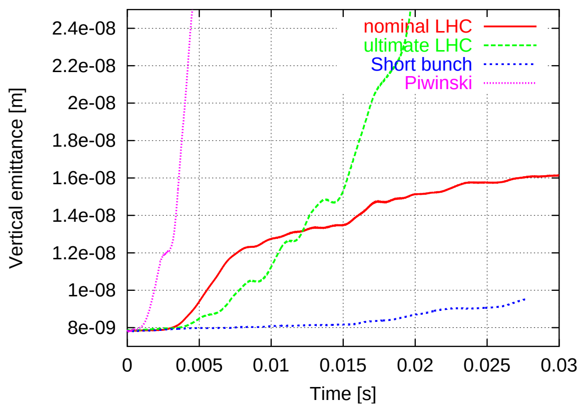

Figure 3: Vertical emittance growth vs. time for the different LHC scenarios, at injection energy.

for the nominal LHC a strong instability would develop, if the cloud distribution was uniform. Assuming this electron cloud density for all cases, we can compare the different scenarios and it seems that the "short bunch" option would be the most favorable, due to the fact that the synchrotron motion mixes head and tail protons more quickly. On the other side, the "Superbunch", or "Piwinski" configuration, is the most unstable one (here ignoring that the real electron density may be much lower for this case).

SLOW TERM EMITTANCE GROWTH

Figure 2 shows that even below the threshold of the fast head-tail instability, a slow, long-term emittance growth is still present, which depends on the electron density and seems to be linear in the time. Studies are ongoing to understand how much the simulation parameters (number of macroparticles, grid size, number of points of interaction between the beam and the cloud) influence the results in this regime [5, 6]. We here discuss the dependance on the number of kicks per turn. A scan on the number of interaction points has been done, assuming the nominal LHC parameters, and a low electron density of $\rho_e = 2 \times 10^{11}$ m^{-3}, in order to stay below the fast headtail instability threshold. Figure 4 shows the relative emittance growth rate vs. the number of interaction points along the ring. No clear convergence is seen. This is probably due to the fact that when we set the number of kicks per turn, we change the effective phase advance between the interaction points and the strength of the kick itself. The plot (Fig. 5) of the emittance growth rate (multiplied by the number of kicks) vs. the fractional part of the tune divided by the number of kicks shows the possibility of hitting some resonances.

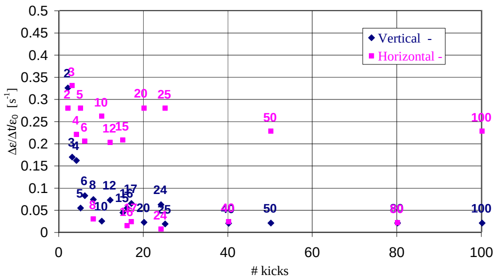

Figure 4: Relative emittance growth rate vs. number of kicks per turn, below the threshold of the fast-instability ($\rho_e = 2 \times 10^{11}$ m^{-3} ; $Q' = 2$)

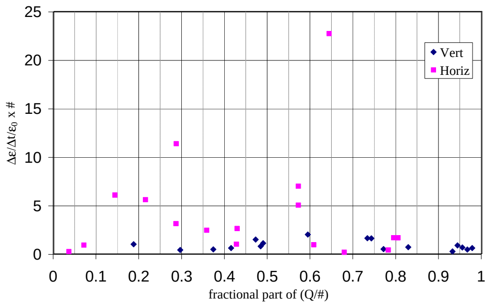

Figure 5: Relative emittance growth rate vs. the fractional part of the tune divided by the number of kicks

A tune scan was done, with one kick per turn, for an electron cloud density of $\rho_e = 4 \times 10^{10}$ m^{-3} in order to stay in the slow emittance growth regime. Figure 6 clearly reveals the presence of a resonance pattern. Anyway, understanding which resonance is responsable for a larger emittance growth rate is quite difficult. In Fig. 7 the scanned working points are superimposed on the resonance tune diagram. Shown in red are the points which correspond to larger emittance and in black some of the low-emittance ones. It is not clearly evident whether these points lie on resonance lines or not. In addiction, due to the interaction with the electron cloud, the working point can change. In orange, we plot the 'effective tune' corresponding to cases of larger emittance growth, computed via an FFT of the bunch centroid. Only in one case, corresponding to the third order resonance line $Qx = 0.666$, the nominal and the effective point agree, but normally the effective tune is shifted. Figure 8 shows an example of the FFT of the horizontal and vertical bunch centroid motion, from which the effective tune was obtained.

CONCLUSIONS AND OPEN QUESTIONS

The electrons will presumably be concentrated in the dipole field regions of the LHC ring and they will mainly populate stripes, whose distance from the axis depends on the bunch intensity. If they are far from the beam, the induced emittance growth will be lower than for the uniform

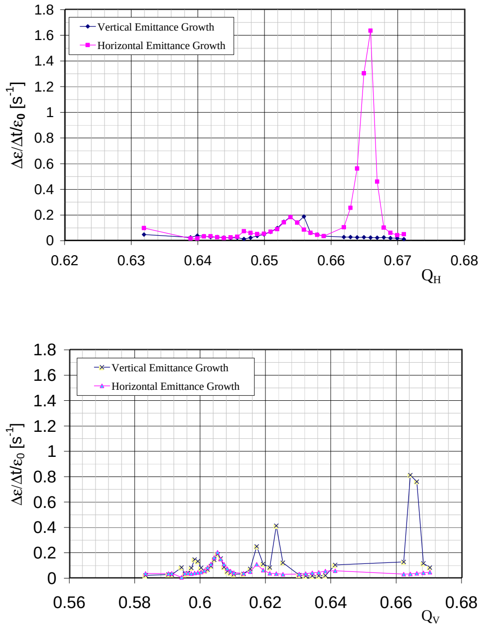

Figure 6: Tune scan with $\rho = 4 \times 10^{10}$ m^{-3}, 1 kick/turn): relative emittance growth rate vs. tune. Top: $Q_h = 0.6318, ...0.6708$, $Q_v = 0.5931$. Bottom: $Q_h = 0.6418$, $Q_v = 0.5931, ...0.6701$.

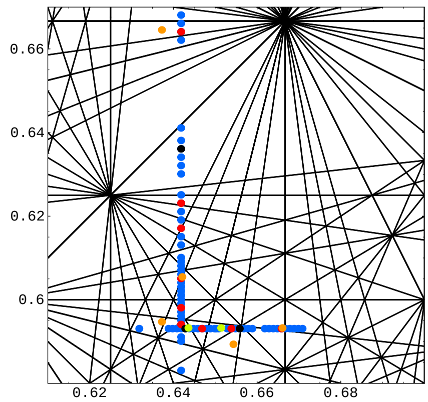

Figure 7: Resonance diagram, up to the 10th order lines, whith the working points from the scan. RED: points corresponding to larger emittance, ORANGE: corresponding points obtained from FFT of the bunch centroid, BLACK: low-emittance points, GREEN: corresponding effective tunes.

distribution. First results for the LHC underline the need to take into account and model the real electron distribution around the ring. Benchmarking with experiments in the SPS is in progress. The simulations for LHC upgrade scenarios have been done assuming a constant electron cloud distribution. This is quite a pessimistic assumption, but it gives an idea of differences between the scenarios. Studies are ongoing on the possibility to use HEADTAIL code

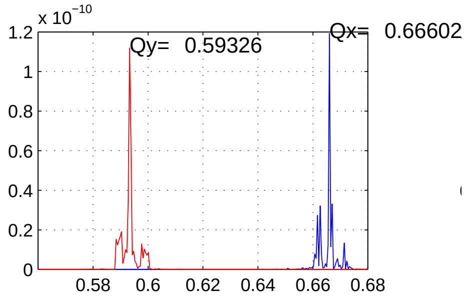

Figure 8: FFT of the bunch centroid, corresonding to simulation with nominal tunes of (0.6661,0.5931). In BLUE the horizontal spectrum obtained via the FFT, in RED the vertical.

below the threshold of the fast instability and to distinguish numeric noise from true physics. We should be aware that some effects in the emittance growth are due to hitting some resonance excited by the placement of the interaction points. The problem raises whether this is just an artifact of the simulations or whether we have to take into account the cloud modulation along the ring. Once more, we feel the need to model the real distribution of the electrons and for this pourpose in a collaboration with USC, we are implementing in the quasi-continuous plasma code QuickPIC the characteristics of both the beam and the electron distributionfor the individual magnets elements of the ring. In this way we suppress artificial resonances and may observe true ones.

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