MACROPARTICLE SIMULATION STUDIES OF THE LHC BEAM DYNAMICS IN THE PRESENCE OF ELECTRON CLOUD

A. Romano* CERN, Geneva and Technische Universität Darmstadt, Germany
K. Li, G. Iadarola, G. Rumolo, CERN, Geneva, Switzerland

Abstract

Beam quality degradation caused by the Electron Cloud (EC) effects has been identified as one of the main performance limitations for the high intensity 25 ns beams in the Large Hadron Collider (LHC). When a proton bunch passes through an EC, electrons are attracted towards the transverse center of the beam resulting into an increasing electron density within the bunch. The effects driven by the interaction of the electrons with the bunch have been studied with macroparticle simulations in order to evaluate, in different operational scenarios, the threshold for the coherent instabilities as well as the incoherent tune spread. This contribution will summarize the main findings of the simulation study and compare them with the available experimental observations.

MAIN LHC OBSERVATIONS IN 2015-2016

In the LHC the build-up of EC can pose important challenges to the machine operation with trains of closely spaced bunches. As observed during the 2015-2016 run with 25 ns beams, one of the first consequences of operating in a strong EC regime is the difficulty to ensure the beam stability and a good beam quality from injection to collision. In 2015 the beam stability at injection could be guaranteed only with high settings of chromaticity and octupoles ($Q'_{H,V}$=20 units, I_{oct}=40 A) and with the full performance of the transverse damper. Nevertheless, these settings, together with the detuning induced by the EC, created a quite large tune footprint which reached the third order resonance Q_y=.33. [1]. For this reason the working point at injection had to be slightly lowered in order to avoid incoherent beam losses and improve the beam lifetime [2].

In order to confirm that the EC is the main driver of the observed instabilities tests at injection energy were performed with the so-called "8b+4e" bunch pattern. It consists of short trains of eight bunches with 25 ns spacing, separated by four empty slots, for which the EC formation is largely suppressed [1]. Figure 1 shows the comparison of the bunch-by-bunch horizontal emittance measurements for two test fills performed with the "8b+4e" bunch pattern and with the standard 25 ns configuration respectively. The behavior in the vertical plane is very similar. The "8b+4e" beam could be injected using low chromaticity and octupole settings ($Q'_{H,V}$=5 units, I_{oct}=6.5 A) without observing any sizable emittance blowup (see Fig. 1 - top). When injecting the standard 25 ns beam using the same settings, a strong instability developed right after injection, leading to an emittance blow up both in the horizontal and in the vertical plane. A clear reduction of the emittance growth was reached by increasing the chromaticity and octupoles settings, reaching a satisfactory emittance preservation when approaching the operational values.

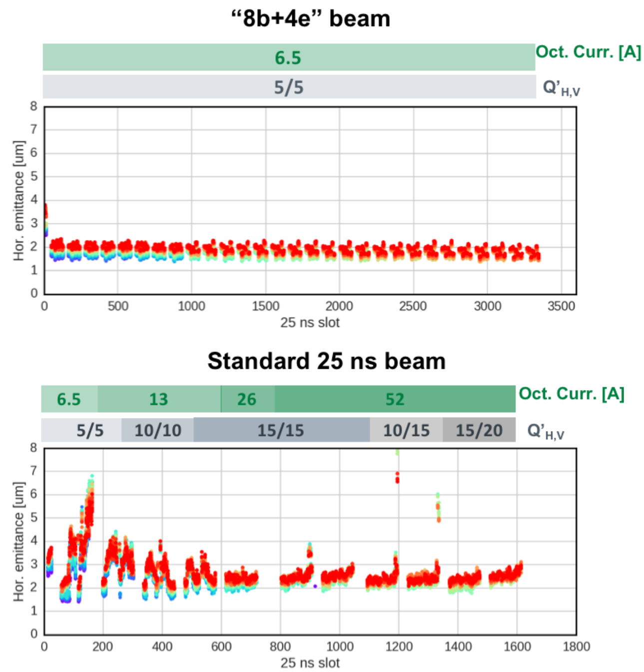

Figure 1: Comparison of the bunch-by-bunch horizontal emittance measurements between the "8b+4e" scheme (top) and the standard 25 ns beam (bottom). The octupoles and chromaticity settings at the moment of the injection of each batch are reported on top of each plot.

Pinning down the beam dynamics effects associated with the EC is crucial to explain the underlying mechanism of these observations and evaluate the threshold for the coherent instabilities as well as the incoherent tune spread.

THE PYECLOUD-PYHEADTAIL SIMULATION SETUP

The understanding of the beam behavior in the presence of EC relies on numerical simulations performed with a PyECLOUD-PyHEADTAIL interface recently developed at CERN. In these simulations both the beam and the EC are modeled with macroparticles and their dynamics is computed making extensive use of Particle-In-Cell (PIC) solvers. This kind of simulations is very consuming in terms of time and computing resources. In order to be able to study the effects observed in the LHC, a significant effort had to be put in the development of the simulation tools in order to speed up the computation. In particular a multi-grid PIC

* annalisa.romano@cern.ch

ISBN 978-3-95450-182-3

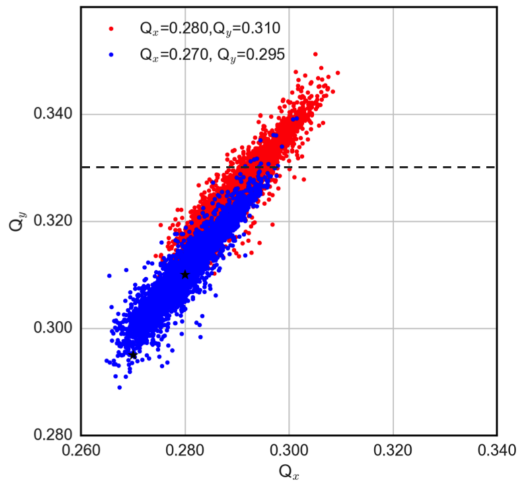

Figure 2: Tune footprints evaluated for a LHC bunch at injection including the effect of octupoles powered at 26 A, Q'$_{x,y}$ at 15 units, and EC in dipole and quadrupole magnets. The dashed line represents the third order resonance Q_y=.33.

algorithm was introduced to resolve the very small size of the LHC beams while still being able to simulate the full beam chamber and a new layer (PyPARIS) was developed in order to profit from parallel computing resources. More information on our simulation toolkit can be found in [3].

A typical instability simulation study requires hundreds CPU cores organized in jobs using 8-16 cores each. Computing times of 3-4 weeks are needed to simulate 10^4 turns, which is the timescale of the instability rise-time experimentally observed. The INFN-CNAF cluster in Bologna has been extensively used for this purpose.

A simplified model can be used to study the incoherent effects. In this case, the forces due to the EC-bunch interaction at each Interaction Point (IP) are calculated only once, during the first bunch passage through the EC, and then stored. On the following turns, the recorded forces are applied when the bunch returns to the same IP. In order to avoid artificial emittance growth [4], in the following simulations, the effect of the EC has been lumped in 15 IPs.

INCOHERENT EFFECTS

Figure 2 shows the tune footprints estimated for the LHC design fractional tunes (Q_x=.28, Q_y=.31) and for the tunes used operationally in 2016 (Q_x=.27, Q_y=.295). In both cases the tune spread has been computed assuming a chromaticity of 15 units in both planes, an octupole current of 26 A and the effect of the EC in dipole and quadrupole magnets. It is clearly visible that the operation at optimized working point is needed to accommodate the large tune spread and avoid the third order resonance Q_y=.33.

TRANSVERSE INSTABILITIES

Simulations have been performed to investigate the impact on the beam stability of the EC in the dipole and quadrupole magnets. Here we will present the main results for the injection beam energy and in the absence of octupoles and chromaticity. Studies covering the impact of octupoles and chromaticity, as well a systematic analysis on the impact of beam energy are presently ongoing. Preliminary results can be found in [5].

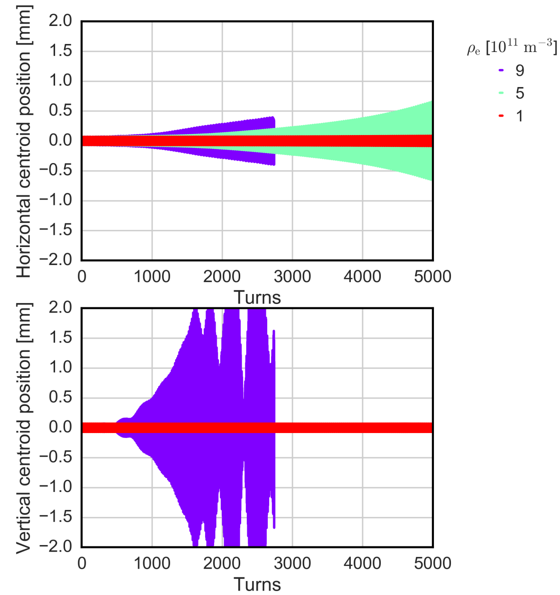

Figure 3: Evolution of the horizontal (top) and vertical (bottom) position of the bunch centroid for different EC densities in dipoles. The instability thresholds in the horizontal and vertical plane are $5 \cdot 10^{11}$ and $9 \cdot 10^{11}$, respectively.

Effect of the EC in Dipoles

We considered a typical LHC bunch at injection (450 GeV/c, $1.1 \cdot 10^{11}$ p/b, 2.5 μm transverse r.m.s normalized emittance, 1.25 ns bunch length – four sigmas) interacting with the EC in the dipole magnets, covering 65% of the total machine circumference. Simulations have been initialized with a uniform electron distribution within the dipole chamber, corresponding to the electron density at the beam location. This was found to be a good approximation in the presence of a dipolar magnetic field [6].

Figure 3 shows the evolution of the transverse position of the bunch centroid for initial electron density scanned from $1 \cdot 10^{11} e^-/m^3$ to $9 \cdot 10^{11} e^-/m^3$ (the electrons are assumed at rest before the bunch passage). The behavior in the two planes is strongly asymmetric, as the presence of a dipolar magnetic field forces the electrons to move along the magnetic field lines. The horizontal instability has a lower threshold electron density but, above threshold, the vertical instability has a much faster rise-time. The nature of the instability in the two planes is also very different. Figure 4 shows the intra-bunch oscillations both in the horizontal and in the vertical plane, over 200 consecutive turns when the instability starts to develop. In the horizontal plane the signal reveals a mode 0-like bunch oscillation (all particles oscillate in phase), while in the vertical plane higher order intra-bunch modes are excited. The bunch motion in the horizontal plane is expected to be detected and suppressed by the bunch-by-bunch transverse feedback system [7] as

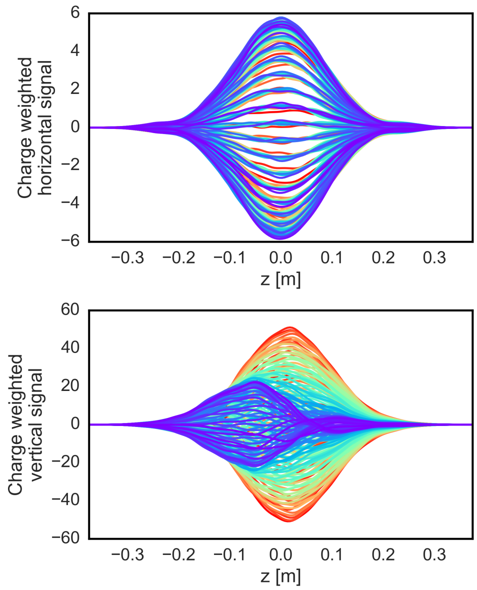

Figure 4: Simulated intra-bunch oscillations in the horizontal (top) and vertical (bottom) plane for an EC density in dipoles of $9 \cdot 10^{11}$ e-/m^3.

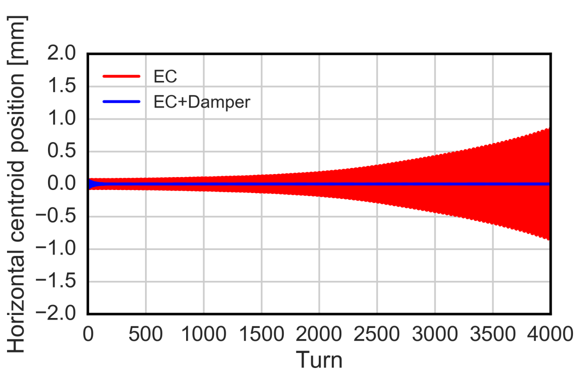

Figure 5: Evolution of the horizontal bunch centroid position with and without the transverse feedback system. The EC density in dipoles has been assumed equal to $9 \cdot 10^{11}$ e-/m^3.

confirmed by the simulations shown in Fig. 5. Therefore, when the feedback is active, the EC in the dipole magnets is not expected to cause horizontal instabilities. By using PyECLOUD buildup simulations, the central density in the LHC dipole magnets in the present conditioning state is estimated to be below the identified density threshold. Therefore, even with chromaticity and octupoles set to zero, the EC in the dipoles is not expected to excite vertical instabilities. The situation changes significantly for lower bunch intensity, for which the electron density at the beam location can become significantly larger. Simulations have shown that in these conditions the EC in the dipoles can trigger vertical instabilities even at 6.5 TeV, in spite of the significantly increased beam rigidity [5] and large tune spread from beam-beam.

Effect of the EC in Quadrupoles

In order to assess the underlying mechanism of the observed instabilities (especially in the horizontal plane), the role of the EC in quadrupoles alone has been also investigated. The quadrupole magnets constitute about 7% of the total length of the LHC. Due to trapping effects from the quadrupole gradient the EC pinch dynamics is very sensitive to the initial phase space distribution of the electrons [8]. For this reason, we initialize the simulations using macroparticles coordinates and velocities imported directly from PyECLOUD buildup simulations. These were saved right before the bunch passage, with the EC in the saturation regime and for a maximum Secondary Electron Yield (SEY) of 1.20. With the EC density fixed according to the SEY, sensitivity studies have been performed by changing the weight of the EC kick, i.e. the fraction of the LHC circumference occupied by quadrupoles .

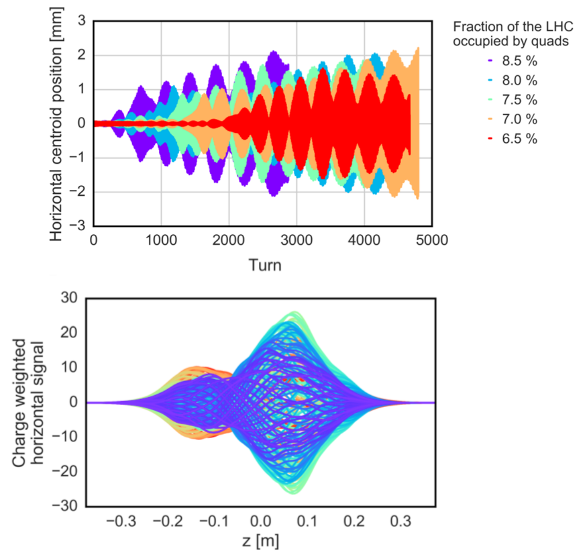

Figure 6: Top: evolution of the horizontal bunch centroid position for different fraction of the LHC circumference occupied by quadrupoles. Bottom: simulated horizontal intra-bunch signal for the realistic total length of quadrupoles. The behaviour in the vertical plane is very similar.

The evolution of the horizontal bunch centroid is plotted in Fig. 6 (top). The instability threshold is found at a value below the effective total length of quadrupoles. The behaviour in the vertical plane is very similar as the presence of a quadrupolar magnetic field does not cause a strong asymmetry between the two planes. This type of instability cannot be damped by the transverse feedback system because it excites high order intra-bunch modes (see Fig. 6 - bottom). This indicates that, in the absence of octupoles and chromaticity, the quadrupoles alone are indeed able to drive instabilities at injection.

ACKNOWLEDGEMENTS

The authors would like to thank the INFN-CNAF institute in Bologna (Italy) for providing support and access to their computing facilities, and G. Arduini, L. Carver, D. Cesini, E. Belli, L. Mether and E. Métral for their important support to the presented studies. Research supported by the HL-LHC project.

ISBN 978-3-95450-182-3

REFERENCES

[1] G. Iadarola et al., in *Proceedings of the 2015 Evian workshop on LHC beam operation, Evian, France , December 15-17, 2015*, CERN-ACC-2015-376, pp. 101-109, 2015.

[2] E. Métral et al., in *Proceedings of the 57th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams, Malmö, Sweden, July 3-8, 2016*, ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams No. 57, pp. 254-259, doi:10.18429/JACoW-HB2016-TUAM2X01, 2016.

[3] G. Iadarola, E. Belli, K. Li, L. Mether, A. Romano and G. Rumolo, "Evolution of Python Tools for the Simulation of Electron Cloud Effects", presented at IPAC'17, Copenhagen, Denmark, May 2017, paper THPAB043, this conference.

[4] E. Benedetto, CERN-THESIS-2008-096, 2008.

[5] A. Romano, G. Iadarola and G. Rumolo, "Electron Cloud Instability Studies for the LHC", presentation at the Electron Cloud Meeting 40, https://indico.cern.ch/event/605497/, 31 March 2017, CERN, Geneva.

[6] H. Bartosik, W. Höfle, G. Iadarola, Y. Papaphilippou, and G. Rumolo, in *Proc. of ECLOUD'12*, Isola d'Elba, Italy, June 5-9, 2012, Yellow Report CERN-2013-002, pp.211-217.

[7] W. Höfle, in *Proc. of the Chamonix 2012 workshop on LHC performances*, Chamonix, France, February 6-10, 2012, CERN-ATS-2012-069, pp. 157-162.

[8] G. Iadarola, A. Axford, H. Bartosik, K. Li, and G. Rumolo, in *Proc. of IPAC'15*, paper MOPJE051, pp. 409-411, 2015.