ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPJE051

EFFECT OF ELECTRON CLOUD IN QUADRUPOLES ON BEAM INSTABILITY

G. Iadarola* A. Axford, H. Bartosik, K. Li, G. Rumolo, CERN, Geneva, Switzerland

Abstract

Both simulations and machine experience at the CERN Super Proton Synchrotron (SPS) and Large Hadron Collider (LHC) have shown that the electron cloud has a lower build up threshold in quadrupoles than in dipoles and field free regions. As a consequence, while beam induced scrubbing can efficiently suppress the electron cloud in both dipoles and field free regions, a residual electron cloud can still survive in the quadrupoles and potentially degrade the beam quality. To study this effect, a PyECLOUD module for electron tracking in quadrupole fields including effects of secondary emission at the vacuum chamber has been implemented in PyHEADTAIL. With this module, the effect of the electron cloud in quadrupoles on beam stability and beam quality preservation can be assessed, as well as its impact on future LHC and HL-LHC operation.

INTRODUCTION

Electron cloud (EC) effects have been observed at the SPS throughout the years in which this machine has been prepared to become injector for the LHC, and at the LHC itself during the first three years of beam operation (Run 1, 2010–2012), becoming more and more severe while reducing the bunch spacing [1].

At the SPS, the EC has been identified as a main performance limitation since the early years of 2000. At that time a severe pressure rise was observed all around the machine together with transverse beam instabilities, significant losses and emittance blow-up on the trailing bunches of the train. Since 2002, scrubbing runs with 25 ns beams were carried out almost every year of operation in order to condition the inner surfaces of the vacuum chambers and therefore mitigate the EC. Since 2011, no important beam degradation due to EC can be observed on the cycle timescale for four batches of 72 bunches with $N \approx 1.35\times10^{11}$ p/b and normalized transverse emittances of about 3 μm (r.m.s.). However, for higher intensities, an EC driven transverse instability is observed after the injection of batches beyond the first one, leading to emittance blow up and particle losses on the trailing bunches of the injected trains. This can be due to a recrudescence of the EC both in the regions with dipole field (because of the stripes moving to out to unscrubbed regions) and in quadrupole regions, where the threshold for EC build up becomes lower due to the higher bunch intensities. Pinning down the main origin of these instabilities is crucial to decide on the future strategy of coating some parts of the SPS with low Secondary Electron Yield (SEY) material [2]. This depends not only on the multipacting thresholds in the different chambers and magnetic field configurations, but

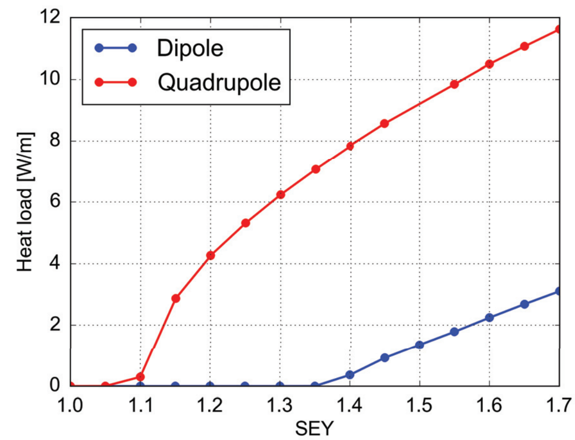

Figure 1: Heat load in the dipole and quadrupole magnets in the LHC arcs as a function of the SEY of the beam screen.

also on how much they individually contribute to render the beam unstable.

At the LHC, the EC effects could be successfully mitigated with 50 ns beams through beam induced scrubbing. This bunch spacing could be used for most of the integrated luminosity production with 7–8 TeV Center of Mass (CoM) energy in 2011–12. After the long shutdown 1 (LS1) the LHC will be able to run at 13 TeV CoM energy and the design bunch spacing of 25 ns will be used to reach the design luminosity within the pileup limits accepted by the LHC experiments. In the test runs on 2011 and 2012, the 25 ns beam, due to its significantly lower multipacting threshold, suffered from strong EC effects [1]. Thanks to the scrubbing effect, a decrease of the SEY resulted in a substantial reduction of the heat load in the cryogenic sections and of the dynamic pressure rise in the warm regions. Heat load measurements from the cryogenic system showed that up to 80% of the energy lost by the beam was deposited on the beam screens of the cryogenic arcs. Since in the LHC arcs each beam screen cooling circuit extends over a full half cell (three 15 m long dipoles and one 3 m long quadrupole plus multipoles), the individual contributions of the different magnets to the heat load cannot be disentangled. However, simulations carried out with the PyECLOUD code [1] show that the multipacting threshold in the arc quads is much lower than in the dipoles, as illustrated in Fig. 1. For SEY of 1.35, the EC can be suppressed in the arc dipoles, but not in the quadrupoles,which have a multipacting threshold of 1.1. This suggests that, even after significant scrubbing, the quadrupoles are likely to remain important contributors to the integrated EC along the LHC. Measurements from the Stand Alone Modules (SAM), which are magnets equipped with dedicated cryostats for which heat load detection is available, confirmed that the quadrupoles exhibit a much

* Giovanni.Iadarola@cern.ch

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPJE051

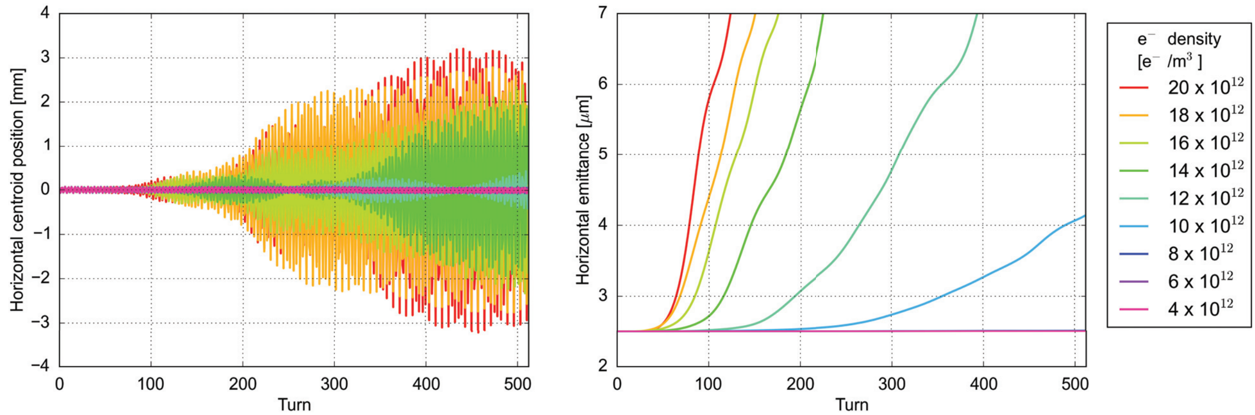

Figure 2: Evolution of the horizontal position of the bunch centroid and of its horizontal transverse emittance for different initial EC densities in the LHC arc quadrupoles (the behavior in the vertical plane is very similar).

larger specific heat load compared to the dipoles after the 2012 Scrubbing Run [1]. To understand the beam degradation after beam induced scrubbing, it is therefore crucial to correcly model the impact of the EC in the LHC quadrupoles on the beam dynamics.

THE PyECLOUD-PyHEADTAIL SIMULATION SETUP

PyHEADTAIL is a code for beam tracking through macroparticles, which includes the effects of collective beam interactions. It is the evolution of HEADTAIL [3], mostly written in Python language with cython extentions for the computationally intensive parts. PyHEADTAIL can be used in combination with PyECLOUD to simulate EC induced effects on beam dynamics, e.g. EC driven instabilities. Following the general philosophy of PyHEADTAIL, PyECLOUD can be used to generate EC objects with a tracking method. Within the PyHEADTAIL simulation, the EC object receives as an input the set of macroparticles representing the beam, moves the electrons (initialised uniformly in the beam chamber or using an output distribution from PyECLOUD, see next section), calculates and applies the transverse kicks felt by the beam macroparticles from the forces induced by the updated electron distributions. This approach has several advantages with respect to the old HEADTAIL:

- The evolution of the EC is simulated by PyECLOUD, widely benchmarked in the different configurations of magnetic field;
- The boundary conditions on the chamber (both electromagnetic and in terms of secondary emission) are taken into consideration;
- Magnetic field configurations previously unavailable for simulations become directly usable (combined functions, quadrupoles);
- Scenarios such as long bunches with trailing edge multipacting or bunch train instabilities can be simulated with this module (still to be tested).

The electron pinch for the simple case of an SPS bunch through a uniform EC in a dipole or field-free region has been successfully benchmarked against the old model both in terms of electron motion and kicks on the beam particles. The instability behaviour (with centroid motion and emittance growth) known from previous analyses is also recovered with the new module. Simulations of the effect of the EC in quadrupoles can be therefore carried out using this new tool.

SIMULATION RESULTS FOR THE LHC AT 450 GeV

PyHEADTAIL has been used with the PyECLOUD module to simulate the effect of the EC in the quadrupoles in the LHC for the nominal beam and assess the threshold for the onset of the coherent instability. We considered a typical LHC bunch at injection (450 GeV/c, 1.25×10^{11} p/b, 2.5 μm transverse r.m.s normalized emittances, 1.35 ns bunch length - four sigmas) interacting with an EC over a fraction of 5% of the total machine circumference (27 km), which is approximately the fraction of the ring covered by quadrupoles. The initial EC density has been assumed uniform and its value has been scanned from 4 to $20{\times}10^{12}$ e^{-}/m^3 (the electrons are assumed at rest before the bunch passage). The interaction of the bunch with the EC was lumped in 79 interaction points with $\beta_{x,y} \approx 90$ m. In Fig. 2 the evolution of the horizontal centroid (left plot) and horizontal emittance (right plot) is plotted for different initial electron densities (as labeled). The behaviour in the vertical plane is very similar, as, unlike in dipoles, the presence of the quadrupolar magnetic field does not cause a strong asymmetry between the two transverse planes. The instability threshold is found at around 10^{13} e^{-}/m^3.

The EC build up in an arc quadrupole has been then simulated with the PyECLOUD code to check which value of the SEY would be such as to excite a coherent instability. Figure 3 shows the central density, i.e. the electron density at the beam location just before a bunch passage, as a function of the SEY. It is clear that only for values of SEY above 1.7,

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPJE051

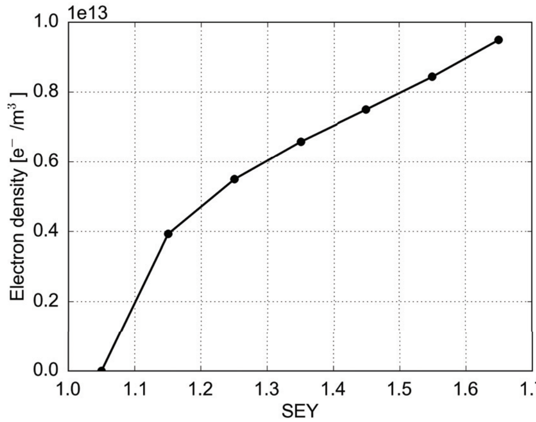

Figure 3: Electron density at the beam location as a function of the SEY of the beam screen of the LHC arc quadrupoles.

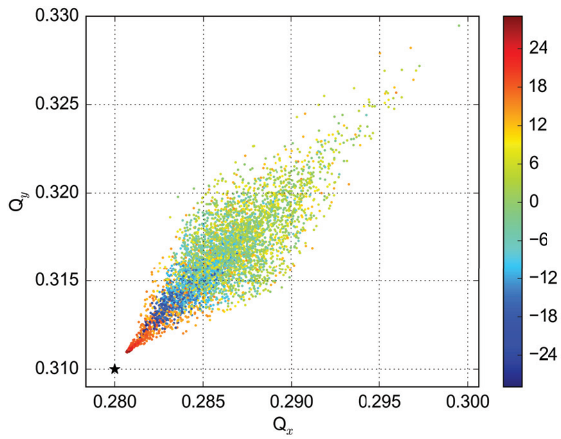

Figure 4: Tune footprint due to the EC in the LHC arc quadrupoles for SEY=1.2, computed from uniform initial electron distribution.

the quadrupoles alone would be able to to drive an instability. From heat load measurements on the SAMs, it could be inferred that SEY is about 1.2 in the LHC quadrupoles. This means that, if the dipoles could be fully scrubbed, the remaining EC in the quadrupoles would be not sufficient to make the beam unstable. Nevertheless, the incoherent effects of the EC in the quadrupoles still need to be considered. For this purpose, we first estimate the beam tune footprint. Assuming no (or slow) changes in the bunch distribution, the electron motion during the bunch passage is recorded once and applied at the different turns/kicks. The synchrotron motion is also frozen. The result for a uniform initial distribution is shown in Fig. 4. The same exercise has been done using an electron phase space distribution taken directly from a PyECLOUD simulation at saturation (as shown in Fig. 5, upper plot). The result is shown in Fig. 5, lower plot. It is clear that in both cases there is a correlation between the tune shift and the longitudinal position of the particles along the bunch. Particles sitting at the bunch head suffer the lowest tune deviation because the pinch has not yet started, while particles in the middle of the bunch are most shifted due to the pinch focusing. Besides, the tune footprint for the case of realistic electron distribution has a smaller extension, because the pinch is attenuated by the fact that electrons trapped along the magnetic field lines do not move towards the beam.

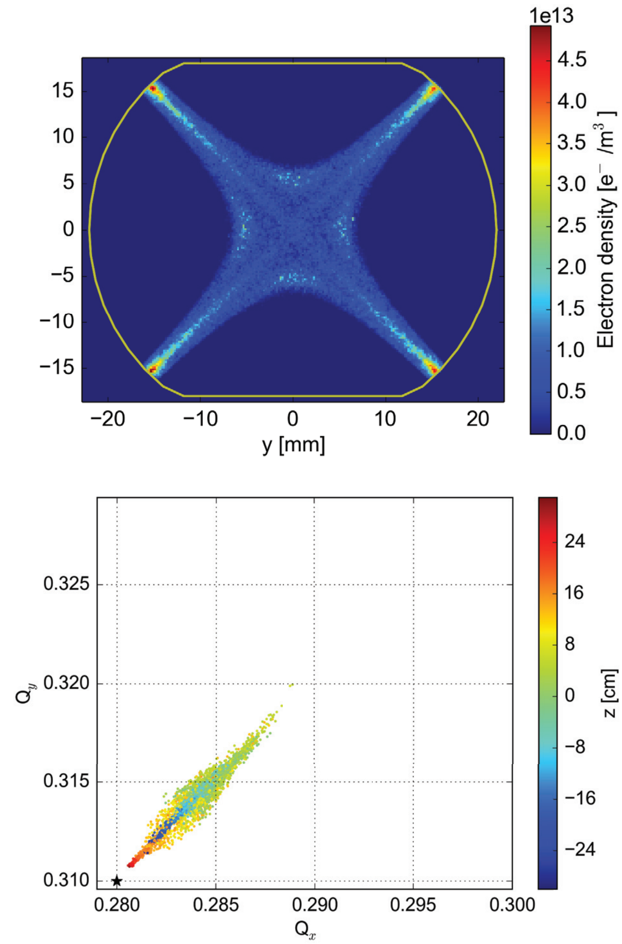

Figure 5: Electron distribution in an LHC arc quadrupole, right before a bunch passage, with the EC in the saturation regime (upper plot) and tune footprint due to the EC in the LHC arc quadrupoles for SEY=1.2 using realistic macroparticles coordinates from a PyECLOUD buildup simulation (lower plot).

ACKNOWLEDGMENTS

Research supported by EU FP7 HiLumi LHC - Grant Agreement 284404.

REFERENCES

[1] G. Iadarola, "Electron Cloud studies for CERN particle accelerators and simulation code development", CERN-THESIS-2014-047 and references therein.

[2] G. Iadarola *et al.*, "Detailed Studies of Beam Induced Scrubbing in the SPS", these proceedings

[3] G. Rumolo and F. Zimmermann, "Practical User Guide for HEADTAIL", CERN-SL-Note-2002-036-AP, 2002