EMITTANCE GROWTH FROM ELECTRON CLOUDS FORMING IN THE LHC ARC QUADRUPOLES

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Abstract

Operation of the Large Hadron Collider with proton bunches spaced 25 ns apart favors the formation of electron clouds. In fact, a slow emittance growth is observed in proton bunches at injection energy (450 GeV), showing a bunch-by-bunch signature that is compatible with electron cloud effects. The study of these effects is particularly relevant in view of the planned HL-LHC upgrade, which relies on significantly increased beam intensity and brightness. Particle tracking simulations that take into account both electron cloud effects and the non-linear magnetic fields of the lattice suggest that the electron clouds forming in the arc quadrupoles are responsible for the observed degradation. In this work, the simulation results are studied to gain insight into the mechanism which drives the slow emittance growth. Finally, it is discussed how optimizing the optics of the lattice can allow the mitigation of such effects.

INTRODUCTION

Simulations of incoherent electron cloud (e-cloud) effects for the Large Hadron Collider (LHC) in its typical injection energy configuration were described in Refs. [1–3]. The results showed that incoherent emittance growth can be caused by the e-clouds forming in the main quadrupoles. This can be understood from the fact that the e-cloud forming in the main quadrupoles shows a significant electron density at the beam's location. Contrary to that, the e-clouds forming in the dipoles have electron densities that are concentrated at distances far away from the center of the beam.

This contribution is focused on the analysis of the beam dynamics for LHC e-cloud simulations, in order to gain information on the mechanism driving the emittance growth. In the first part of the paper, the effect of synchro-betatron resonances is identified to be present in the dynamics of the protons, through the Frequency Map Analysis (FMA) [4] method. This observation led to an effort to improve the LHC optics through a change in the arc-by-arc phase advance, which minimizes the excitation of fourth-order resonances by the lattice octupoles and of synchro-betatron resonances from the e-clouds [5,6]. In the second part of this paper, long-term tracking simulations are presented, showing that the emittance growth from e-cloud effects improves significantly as a result of the optics modification.

SIMULATION METHOD

The analysis of the beam dynamics is done through turn-by-turn particle tracking simulations using the Xsuite software [7], where the elements of the LHC lattice and the e-cloud interactions are modelled with thin lenses. Strong non-linearities with sextupolar and octupolar magnets are induced on purpose during the typical operation of the LHC. These non-linearities are necessary to prevent coherent beam instabilities caused by the electron clouds themselves. Normally, during the 2022 and the 2023 runs, the sextupole magnets were powered to achieve chromaticity values of $Q'_x = Q'_y = 25$, while the octupole magnets were powered to approximately 40 A, inducing an amplitude detuning characterized by the detuning coefficients $\alpha_{xx} = 0.31\,\mu\text{m}^{-1}$, $\alpha_{yy} = 0.32\,\mu\text{m}^{-1}$, $\alpha_{xy} = \alpha_{yx} = -0.22\,\mu\text{m}^{-1}$ [8].

The effect of the e-cloud is simulated by using a scalar potential that has been generated with the PyECLOUD multipacting simulation code [9], under the effect of a quadrupolar magnetic field (12.1 T/m) and bunches spaced by 25 ns, each with $1.2 \cdot 10^{11}$ protons per bunch, normalized transverse emittances equal to 2 μm and an r.m.s. bunch length equal to 9 cm. The surface of the beam chamber is assumed to have a uniform Secondary Emission Yield (SEY) with a maximum equal to 1.4 and the e-cloud interaction is modelled as a thin-lens following the formalism in Ref. [10]. Moreover, a tricubic interpolation scheme is employed to ensure that the

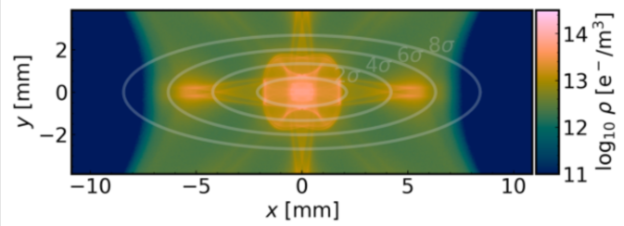

Figure 1: Snapshot of an electron cloud forming in a main quadrupole of the LHC.

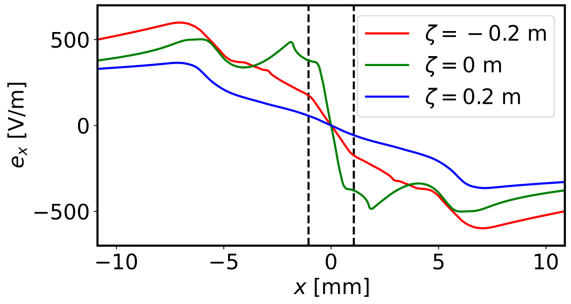

Figure 2: Normalized horizontal force at $y = 0$ for different times during the bunch passage.

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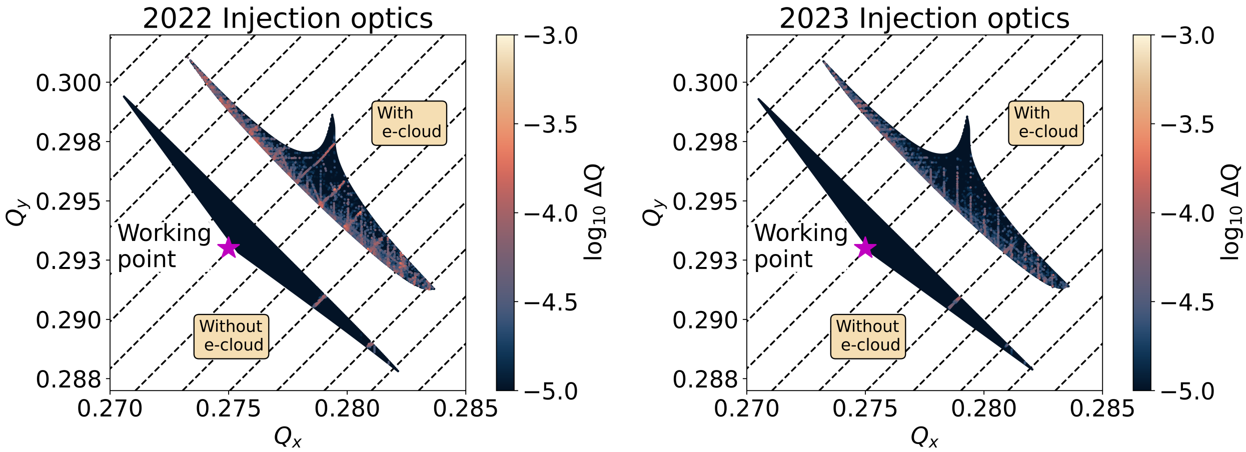


(a) (b)

Figure 3: Frequency map analysis with and without electron cloud effects, with the optics configuration used (a) in 2022 and (b) in 2023. The dashed lines represent the family of $2Q_x - 2Q_y + mQ_\zeta = 4$ resonances.

interaction satisfies the symplectic condition [11]. Finally, a weak-strong approximation is used for the simulation of the incoherent e-cloud effects. This is justified by the fact that all coherent beam instabilities are cured and because the involved changes in the beam distribution are so slow that their impact on the e-cloud dynamics is negligible.

A snapshot of the electron density in the cloud used in this study is shown in Fig. 1, and the (horizontal) normalized forces that are induced by it at $y = 0$ are illustrated in Fig. 2. It is evident that such forces are highly non-linear and strongly depend on the longitudinal coordinate.

To improve the accuracy of the FMA presented in the next section, we reduce the value of chromaticities and octupoles as their absolute strength are not expected to play a major role in the general mechanisms of the beam dynamics.

In the simulations of emittance growth, the parameters of the typical physics operation of the LHC are used. Finally, in the emittance growth simulations, we also power the lattice skew quadrupoles in order to replicate the effect of a small residual uncorrected linear coupling in operation.

SYNCHRO-BETATRON RESONANCES

In our FMA simulation, particles are tracked for 20 000 turns, and the betatron tunes are computed from the turn-by-turn data including the first ($Q_{x,1}$, $Q_{y,1}$) and the last ($Q_{x,2}$, $Q_{y,2}$) 10 000 turns. The distance between the two tunes gives an indicator of chaotic behavior in the particle trajectories, evaluated as:

$$\Delta Q = \sqrt{\left(Q_{x,2} - Q_{x,1}\right)^2 + \left(Q_{y,2} - Q_{y,1}\right)^2}. \qquad (1)$$

The particles being simulated are uniformly spread in the transverse action space J_1, J_2 covering up to three times the transverse r.m.s. beam size in amplitude. In the longitudinal plane, all particles begin synchrotron oscillations with the same initial condition: $\zeta = 0.1$ m and $p_\zeta = 0$, with an oscillation amplitude of $\max(p_\zeta) = 2.78 \cdot 10^{-4}$. The synchrotron tune of the particles is found to be equal to $Q_\zeta = 3.98 \cdot 10^{-3}$.

The results of the FMA simulations are summarized in Fig. 3. Figure 3 (a) shows two FMA simulations, one without and one with e-cloud effects in the LHC 2022 configuration. It is clear that the amplitude detuning that is generated by the lattice octupoles is larger than that of the e-clouds. The strongest effect of the e-cloud appears to be the excitation of resonances. In particular, the $2Q_x - 2Q_y + mQ_\zeta = 4$ family of (synchro-betatron) resonances, represented by the dashed lines in Fig. 3 , appears to be strongly excited.

The same FMA simulations are performed with the 2023 optics configuration, and are shown in Fig. 3 (b). In this case, the $2Q_x - 2Q_y + mQ_\zeta = 4$ resonances are significantly suppressed. This is not surprising since the 2023 LHC injection optics were designed such that both 1) lattice octupoles and 2) e-clouds in main quadrupoles have phase advances to obtain the self-compensation of the resonance driving terms related to the $2Q_x - 2Q_y + mQ_\zeta = 4$ resonances [5, 6].

After correcting the $2Q_x - 2Q_y + mQ_\zeta = 4$ resonances, other families of resonances appear now dominant in the FMA of Fig. 3b. Namely, the excited resonances appear to align with the high-order $7Q_x + mQ_\zeta = 434$ resonances.

To first order perturbation theory, the octupoles are not able to drive the above synchro-betatron resonances. For this reason, another set of FMA simulations are done in order to confirm whether the lattice octupoles are a necessary condition to observe these resonances. In these simulations, shown in Fig. 4, the octupoles are not powered. Once more, the $2Q_x - 2Q_y + mQ_\zeta = 4$ resonances are observed with the 2022 optics configuration, while they are not with the 2023 optics configuration. This confirms the hypothesis that in fact the e-clouds drive these synchro-betatron resonances by themselves.

EMITTANCE GROWTH

The emittance growth observed in the LHC is typically slow, observable only in timescales that span several minutes. For this reason, a large number of turns needs to be

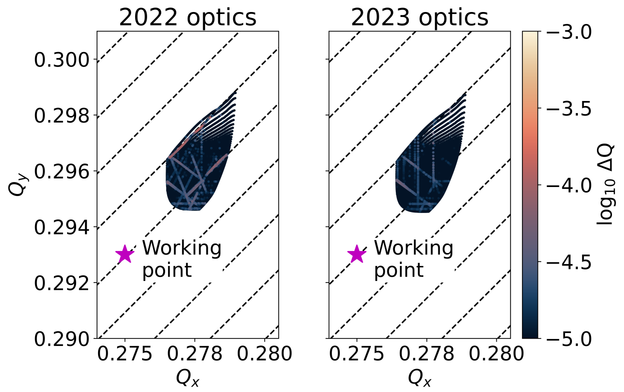


Figure 4: Frequency map analysis with e-cloud effects, without octupole magnets, for the optics configuration used in 2022 (left) and in 2023 (right).

simulated to see an effect in simulations. Here we simulate a distribution of particles for $4 \cdot 10^6$ turns, which is approximately equal to six minutes of beam time.

Two different methods are used to calculate the beam emittance and its growth. In the first method the emittance is defined as the average of the linearized particle actions [12]. In the second method, a Gaussian function is fitted on the transverse profile of the normalized positions. The first method is much simpler and is the typical definition found in literature. On the other hand, the second method is closer to a practical measurement of the emittance in a real accelerator and is useful for comparison with experimental measurements. Nevertheless, if the distribution of particles remains Gaussian in the normalized phase space, the two methods should give the same result.

The emittance growth is simulated for four cases:

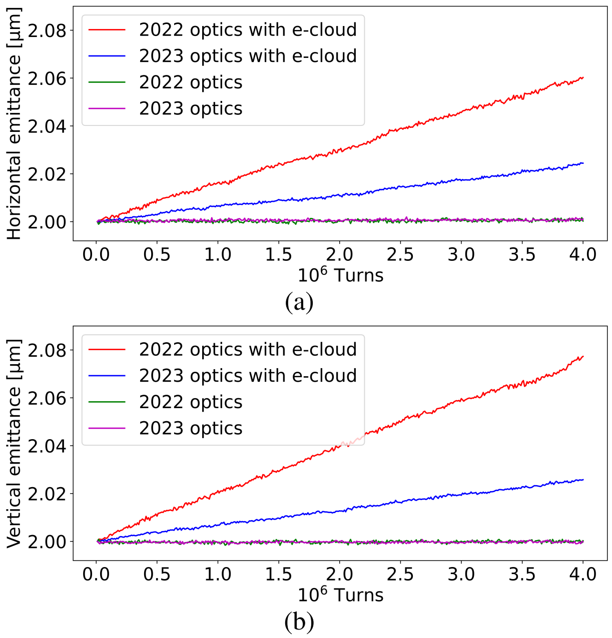
1) with e-clouds, in the 2022 optics configuration,
2) without e-clouds, in the 2022 optics configuration,
3) with e-clouds, in the 2023 optics configuration,
4) without e-clouds, in the 2023 optics configuration.

They are illustrated in Fig. 5, in red, green, blue and magenta, respectively, calculated using the first method. The trend is linear in all cases and the emittance growth is found to be significantly smaller with the 2023 optics configuration compared to the 2022 optics. In the absence of e-cloud effects, there is no emittance growth.

The emittance growth calculated with the two methods and its comparison in the different optics configurations is presented in Fig. 6. It can be noticed that the emittance growth takes larger values when using the average of the particle actions (shown in red) than when fitting a Gaussian profile. This implies that the e-cloud effect evolves the distribution towards one with heavier tails in the transverse profiles.

SUMMARY & OUTLOOK

Simulations show that the new LHC injection optics deployed in 2023 minimizes the excitation of synchro-betatron resonances by the e-clouds forming in the main quadrupoles.



(a)

(b)

Figure 5: Simulations of (a) horizontal and (b) vertical emittance evolution, in the 2022 and 2023 configurations.

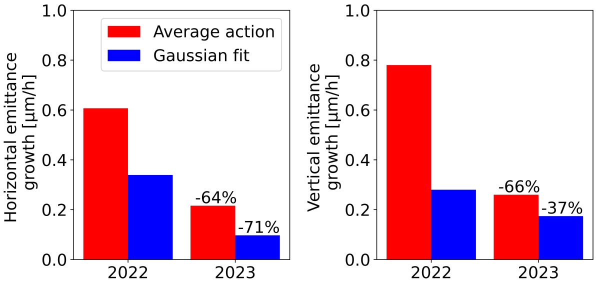


Figure 6: Horizontal (left) and vertical (right) emittance growth computed with different methods and different optics.

By correcting these resonances, a reduction in the emittance growth is also observed in simulations. This study opens up the possibility to use optics modifications in order to combat incoherent effects caused by electron clouds.

So far, it has been assumed that the SEY of the beam chambers is the same across the full length of the LHC. Experimental measurements show that the SEY is different in every single FODO half-cell of the LHC arcs [13, 14]. However, the SEY of the beam chambers in the quadrupole magnets of each half-cell cannot be measured directly. Unfortunately, the experimental measurements to compare the emittance growth driven by e-clouds between 2022 and 2023 optics configuration could not yet take place due to technical issues in the accelerator.

The study of the emittance growth by e-clouds is important for operation after the HL-LHC [15] upgrade. Depending on how the SEY will evolve among the different LHC arc half-cells, whether it is through an unintentional degradation or an intentional treatment of some of the beam chambers, it might be possible to further optimize the optics to reduce the possible impact of incoherent e-cloud effects.

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