Emittance Growth from Electron Clouds Forming in the LHC Arc Quadrupoles

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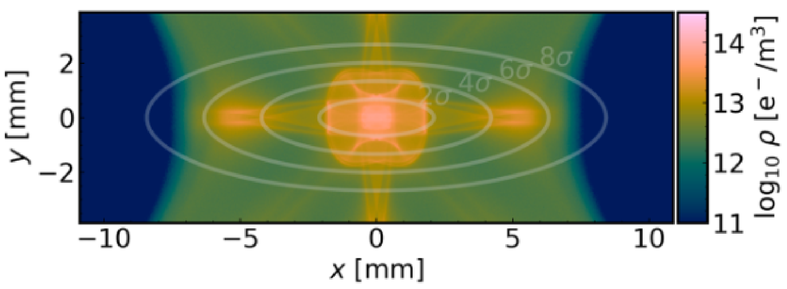
K. Paraschou*[,1], H. Bartosik[1], L. Deniau[1], G. Iadarola[1], E.H. Maclean[1], L. Mether[1], Y. Papaphilippou[1], T. Pieloni[2], J. Potdevin[2], G. Rumolo[1], R. Tomás[1]
[1]CERN, Geneva, Switzerland, [2]EPFL, Lausanne, Switzerland.

Abstract

Operation of the Large Hadron Collider with proton bunches spaced 25 ns apart favours 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 optimising the optics of the lattice can allow the mitigation of such effects.

* konstantinos.paraschou@cern.ch

The electron cloud in an arc quadrupole



Electron cloud (e-cloud)

- Simulated with **PyECLOUD** code,
- **Located in main quadrupoles of LHC arcs,**
- **Time-dependent non-linear forces,**
- Weak-strong approximation,
- Potential obtained on three-dimensional grid → *Tricubic Interpolation* for a symplectic map.

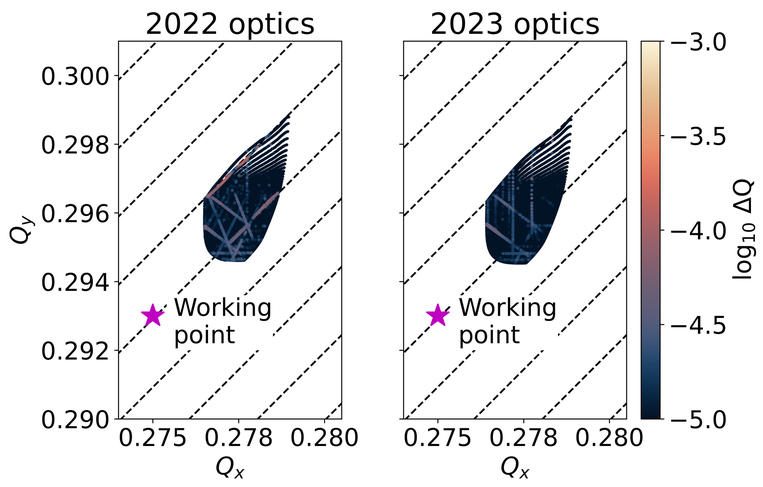
Simulations using XSuite code include:

- LHC lattice modelled with thin lenses,
- Sextupoles for large chromaticity,
- Octupoles for large amplitude detuning.

Optics change in 2023

- Small changes in "trim" quadrupoles,
- Changes phase advance on arc-by-arc basis,
- Corrects $4Q_x$, $2Q_x - 2Q_y$ resonances from lattice octupoles,
- and $4Q_x + mQ_\zeta$, $2Q_x - 2Q_y + mQ_\zeta$ resonances from e-cloud in quadrupoles:
  - same location,
  - negligible longitudinal phase advance.

E-cloud or octupoles?



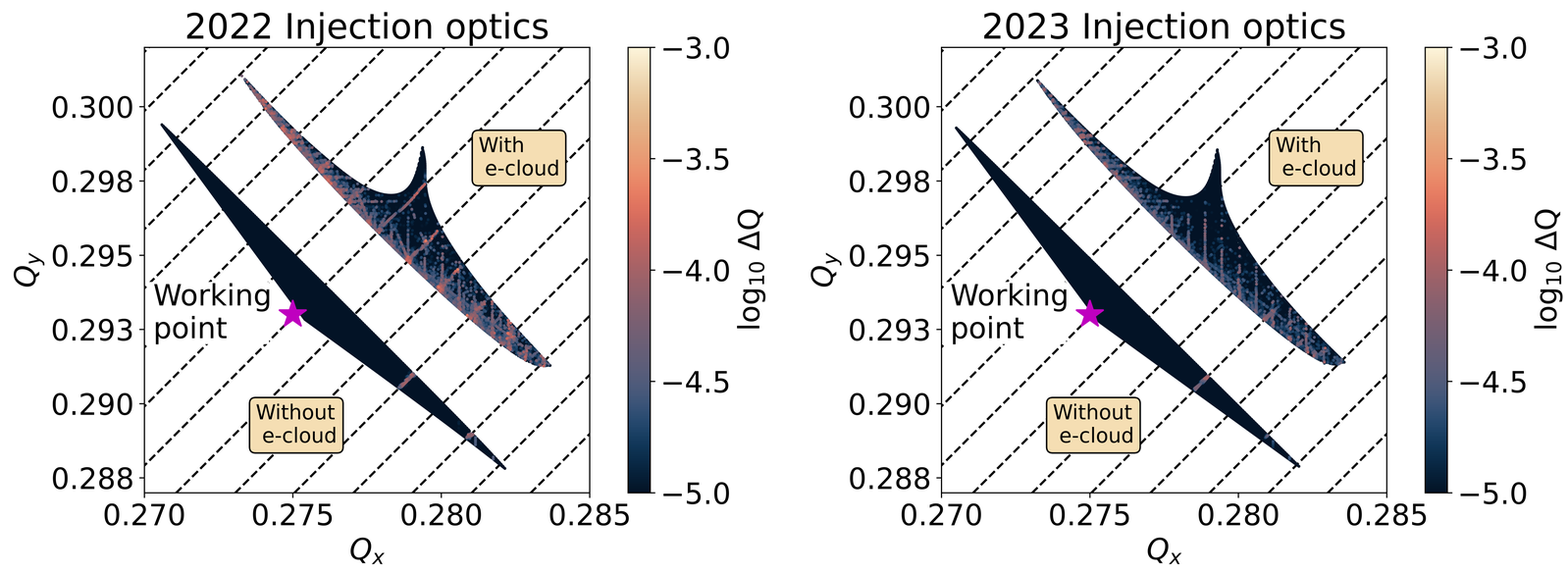
Frequency Map Analysis without octupoles:

- Tune spread is much smaller.
- $2Q_x - 2Q_y + mQ_\zeta = 4$ are still excited in the 2022 optics, but not in the 2023 optics configuration.
- E-cloud's potential is driving the resonance excitation.

Conclusion & Outlook

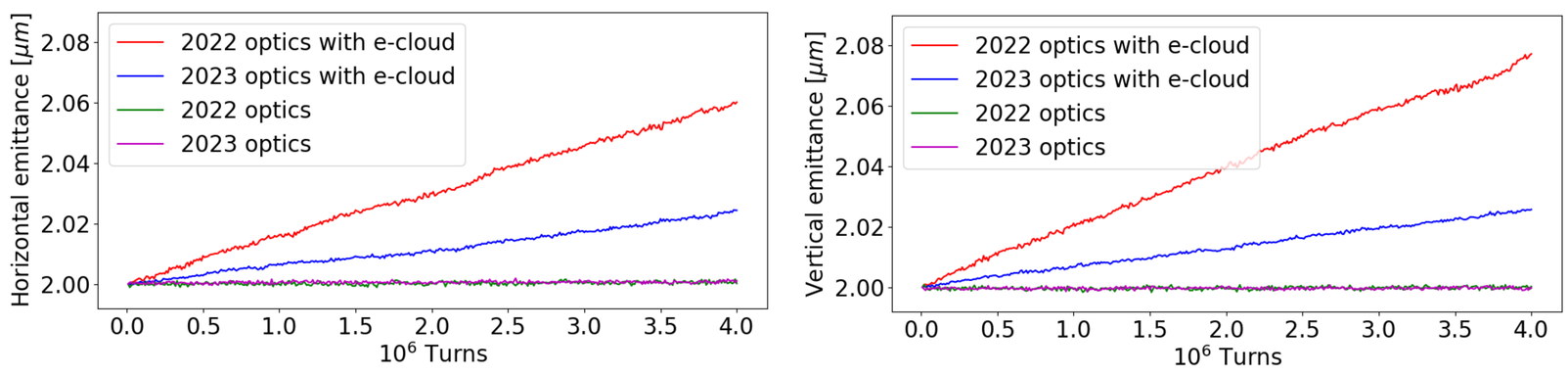
- Simulated emittance growth was reduced through optics optimization (phase advance).
- SEY was approximated as uniform.
- Experimental measurements are pending.
- In the HL-LHC era, beam screen Secondary Emission Yield will change through:
  - Intentional treatment,
  - Unintentional degradation.

Synchro-betatron resonances



- $2Q_x - 2Q_y + mQ_\zeta$ resonances excited strongly with the 2022 optics configuration.
- As expected, $2Q_x - 2Q_y + mQ_\zeta$ resonances are mitigated in the 2023 optics configuration.
- Other high-order resonances become dominant, e.g. $7Q_x + mQ_\zeta$.

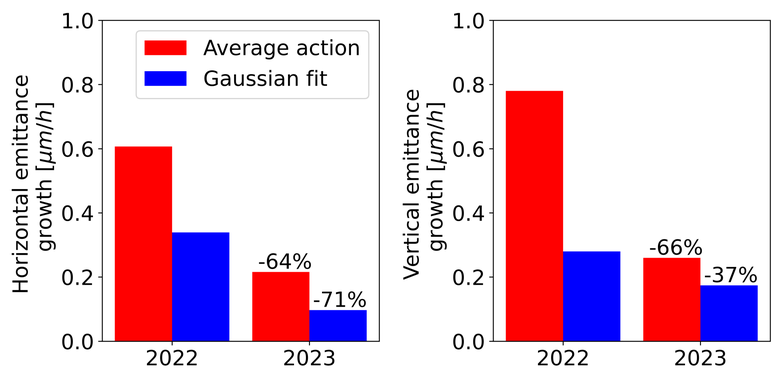
Emittance growth simulations



- Emittance growth is linear.
- No e-cloud → no emittance growth.
- Simulated emittance growth is larger with the 2022 optics than with the 2023 optics.

Defined emittance as:

1. Average (linearized) action over all particles.
2. Gaussian fit on the profile of x and y coordinates.



- Emittance is reduced in both cases.
- Two methods give different growth → tails are being developed in the transverse profiles.

Acknowledgements

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