Slow Beam Degradation due to Electron Clouds at the LHC: Observations and Modelling

Konstantinos Paraschou[1,2], Giovanni Iadarola[1]

[1]Accelerator and Beam Physics group, Beams department, CERN
[2]Physics department, Aristotle University of Thessaloniki, Greece

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Outline

1. Introduction to electron clouds

2. Observations in LHC during Run 2

3. Progress in simulations
   a) Description of e-cloud interaction
   b) Simulation results

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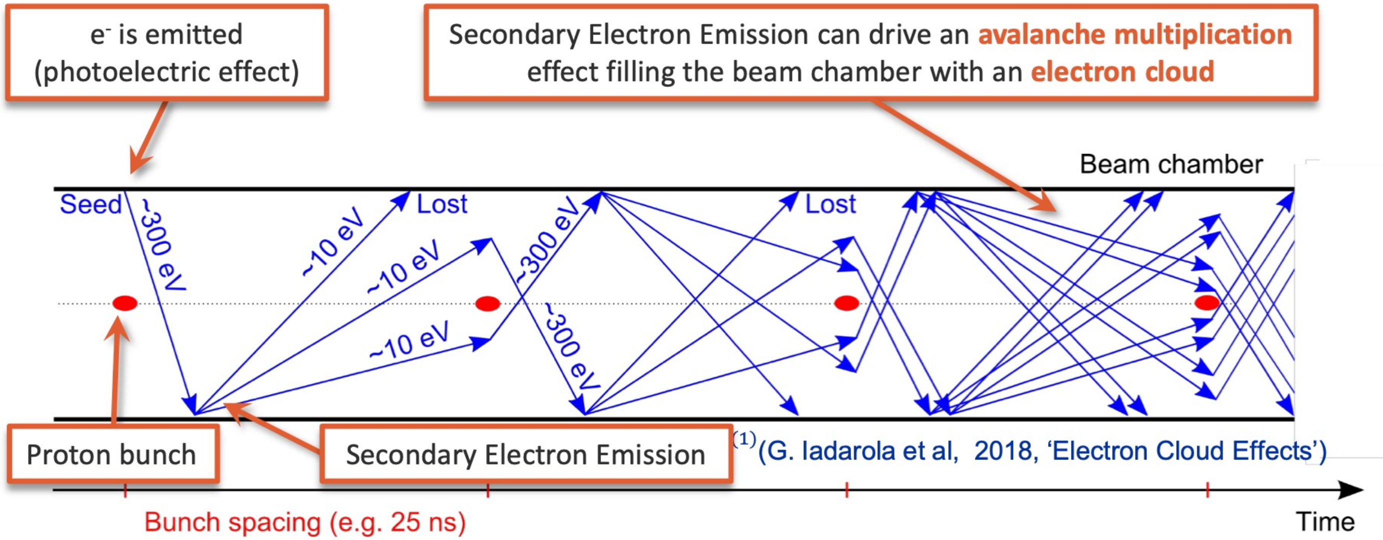
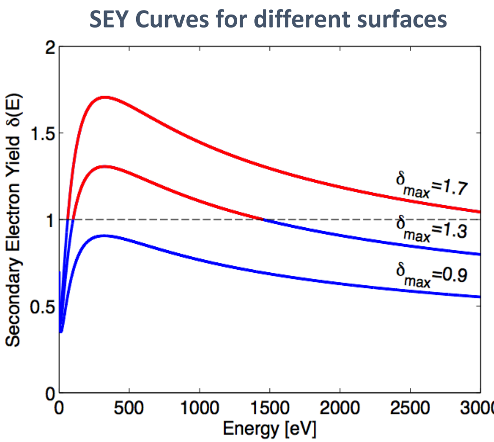
Electron clouds



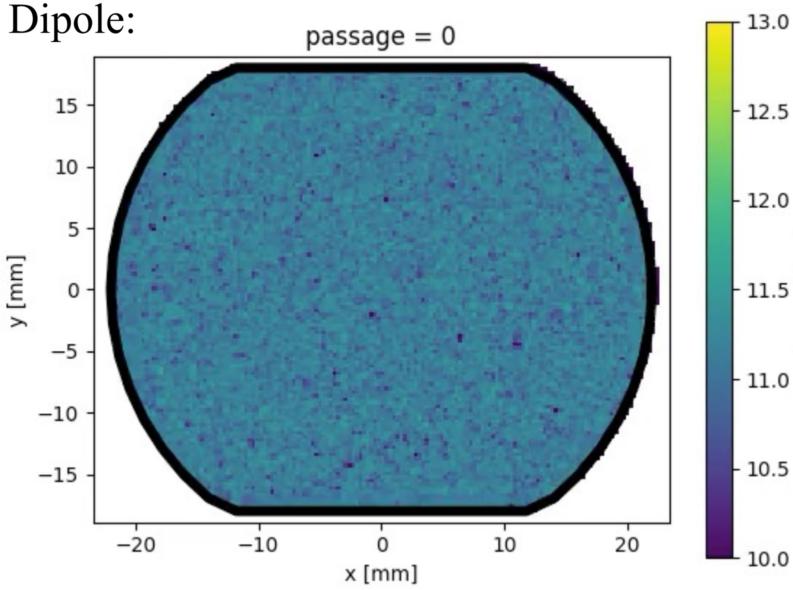
1. Electrons are introduced into the beam chamber (residual gas ionization / synchr. rad. + photoelectric effect)
2. Electrons are accelerated by passing bunches and impact on beam chamber.
   - Depending on energy of electron and **Secondary Emission Yield** of surface, electrons can be emitted.

If conditions allow, **electrons multiply exponentially!**

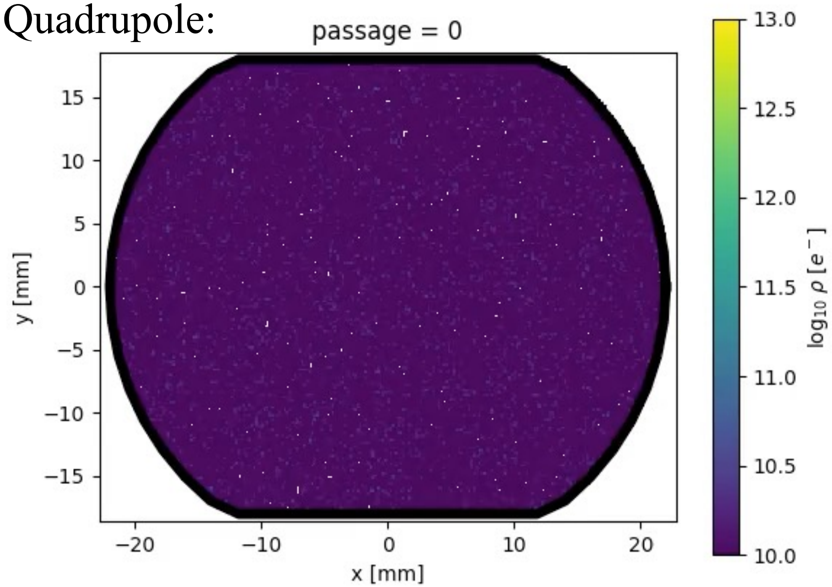


Electron clouds

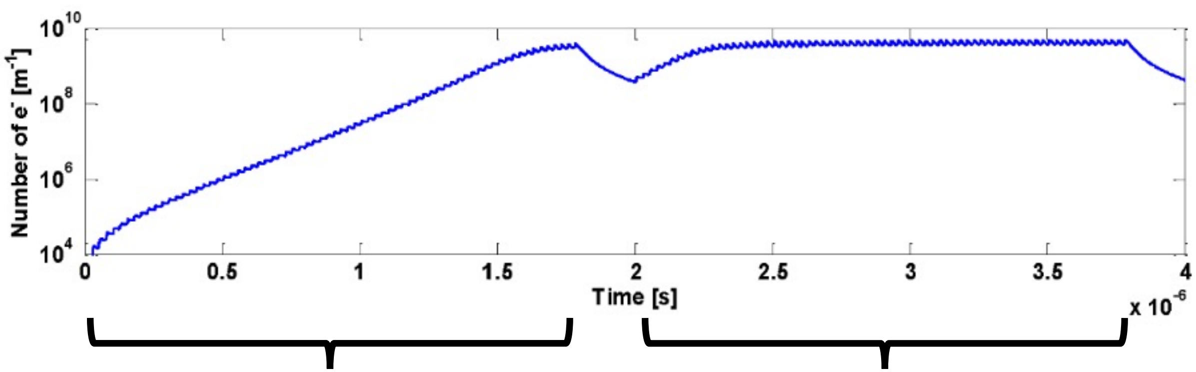
Dipole:



Quadrupole:

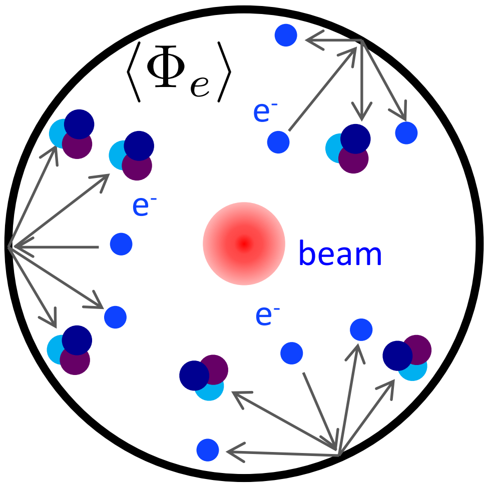


- Electrons multiply until a saturation is reached.
- Number of electrons quickly decays when bunches are not passing.
- Magnetic fields strongly affect the e-cloud.



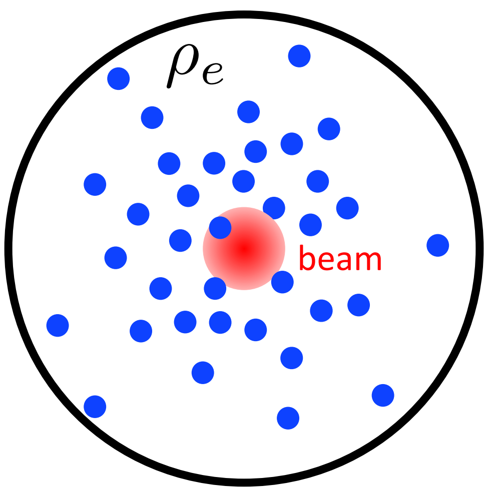
72 bunch passages 72 bunch passages

Electron cloud effects



The electron flux to the wall is responsible for

- Dynamic pressure rise
- Heat deposition
- Spurious signal for beam instrumentation



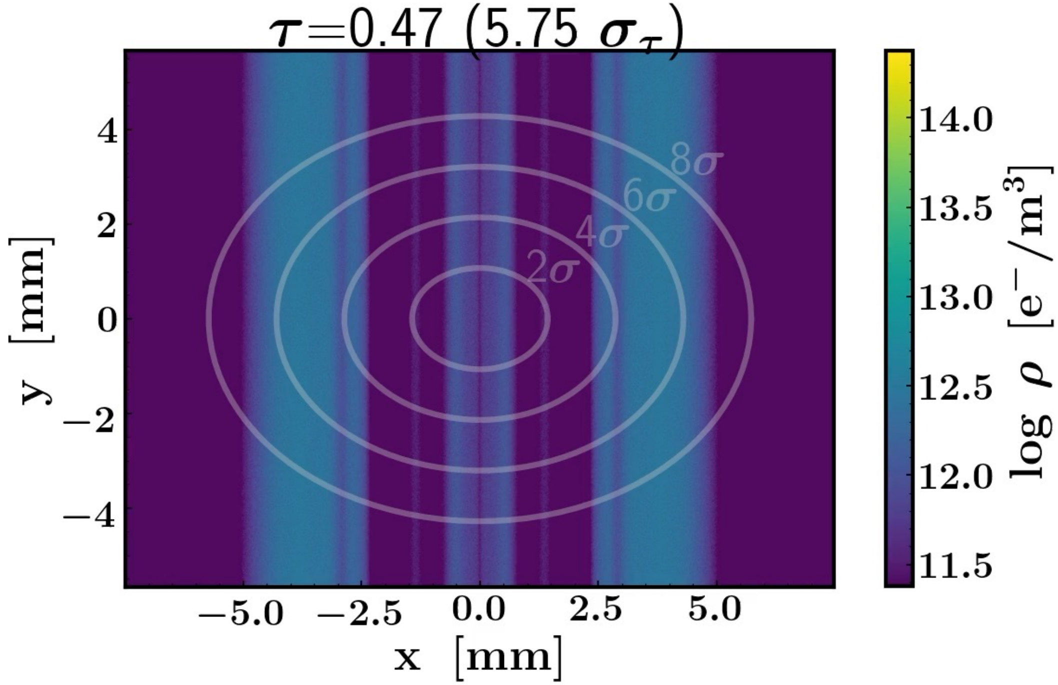
[G. Rumolo]

The electron density inside the chamber causes:

- Tune shift along the bunch train
- Synchronous phase shift along bunch train.
- Coherent beam instabilities (single and coupled bunch)
- **Incoherent effects** (beam lifetime degradation and slow emittance growth)

Electron cloud pinch

Incoherent electron cloud effects concern the motion of single particles under the influence of the non-linear forces induced by the electrons.



- Motion of electrons is very complex → Complex electron densities → complex induced forces.
- Protons from the beam are "moving" within these complex forces due to:
  - Betatron oscillations: up-down, left-right
  - Synchrotron oscillations: back-forth in "time"

→ Increase of proton oscillation amplitude → losses + emittance growth.

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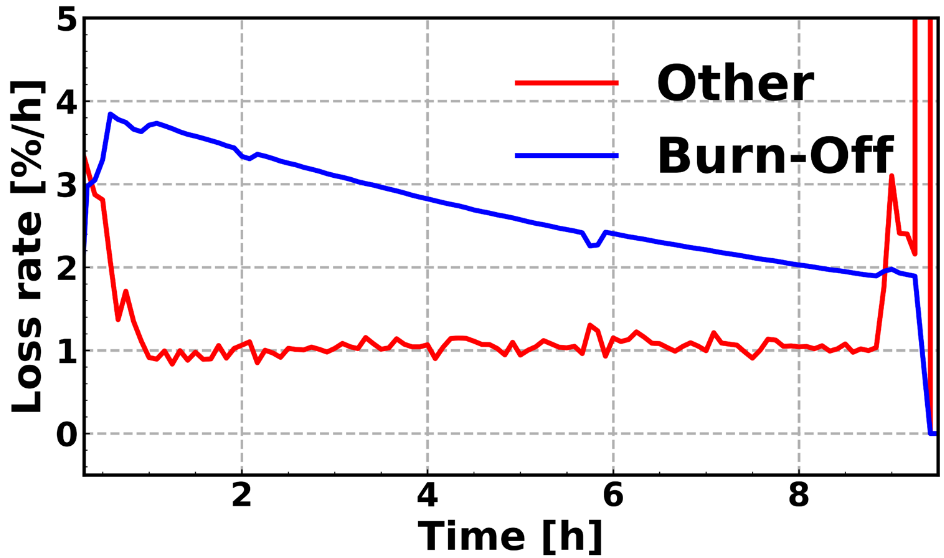
LHC observations during a typical fill

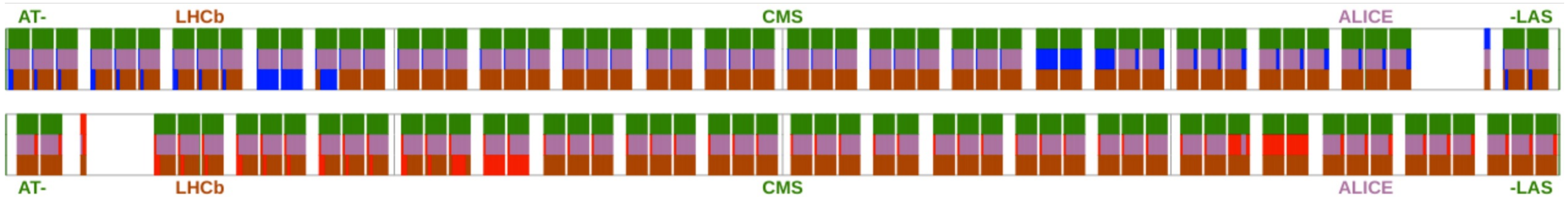


Losses come from:

- Luminosity burn-off that decreases gradually.
- Continuous rate of additional losses.

$$\left(-\frac{dI}{dt}\right)_{\mathrm{other}} = \underbrace{\left(-\frac{dI}{dt}\right)_{\mathrm{total}}}_{\text{Total loss rate (Fast Beam Current Transformer)}} - \sigma_{\mathrm{inel.}} \cdot \overbrace{\mathcal{L}}^{\text{Luminosity (ATLAS + CMS)}}$$

Filling scheme

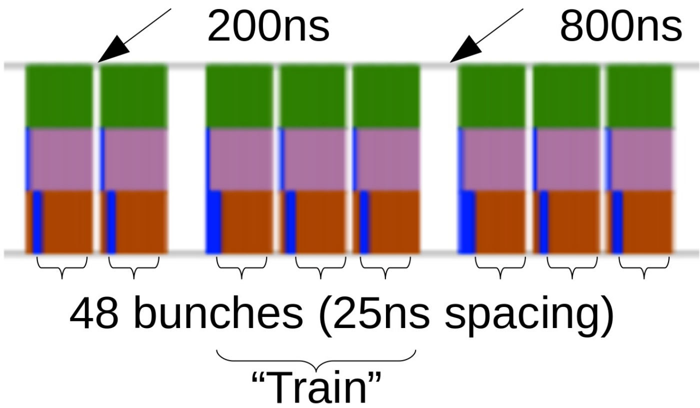


Standard 2018 Physics filling scheme (2556 bunches) [lpc.web.cern.ch]

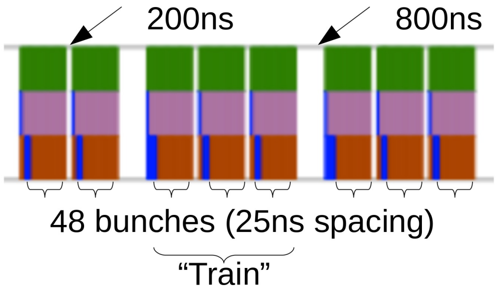
Beam is composed of repeating patterns (trains):

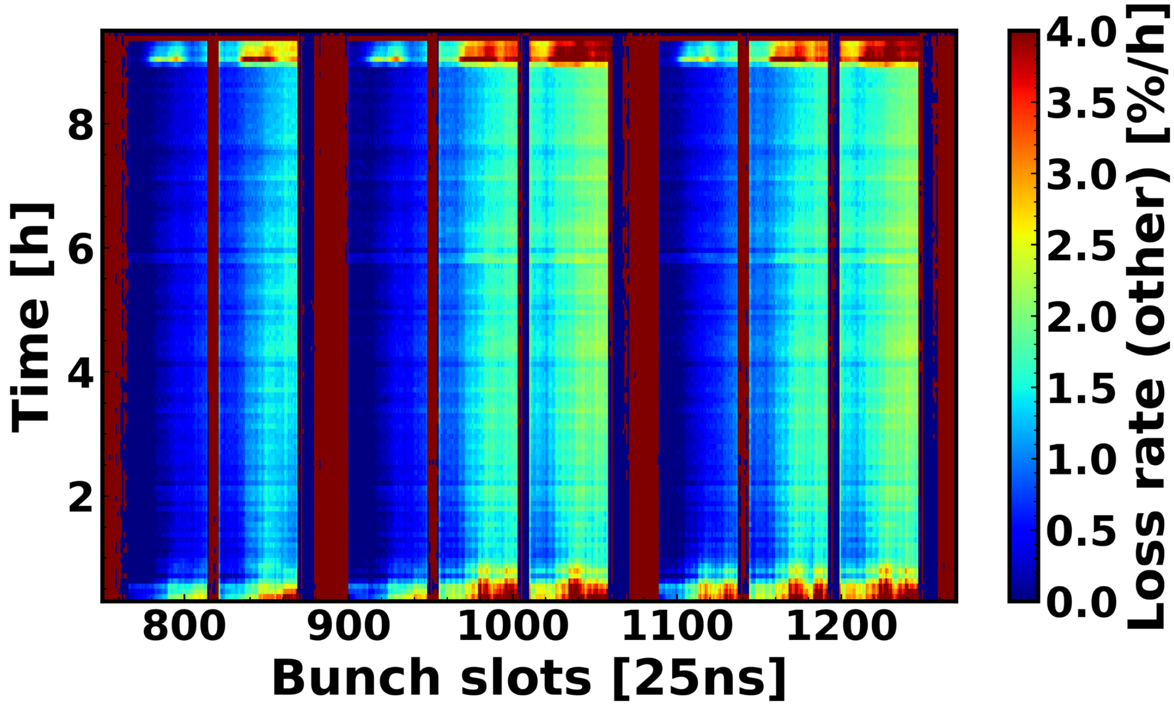
- 2x48 bunches,
- 3x48 bunches.

Magnification:



All bunch-by-bunch losses



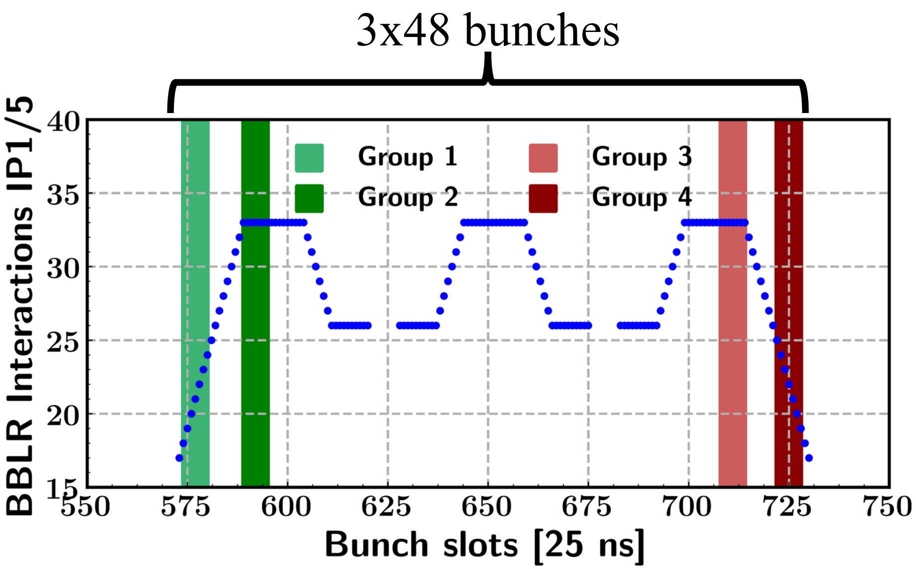


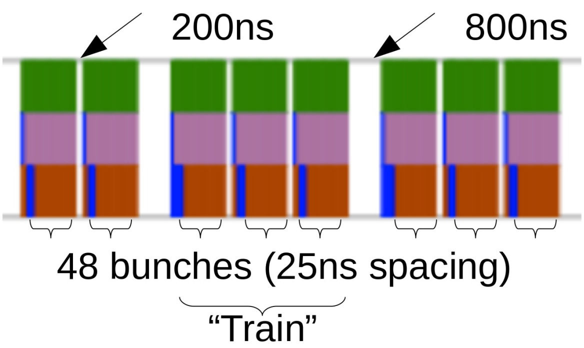
Global picture: Fairly constant loss rate (Corrected for burn-off).

- Grows from head to tail of each train

Number of BBLR interactions

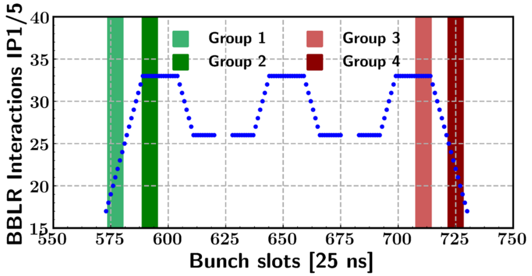
The only other non-linearities that depend on the bunch position are the Beam-Beam Long-Range (BBLR) interactions.
Number of long-range encounters changes for each bunch in the filling scheme.

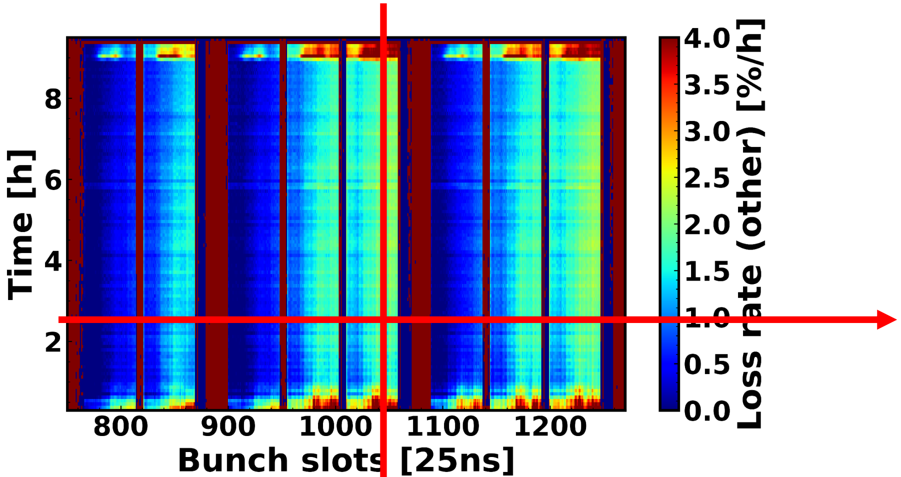


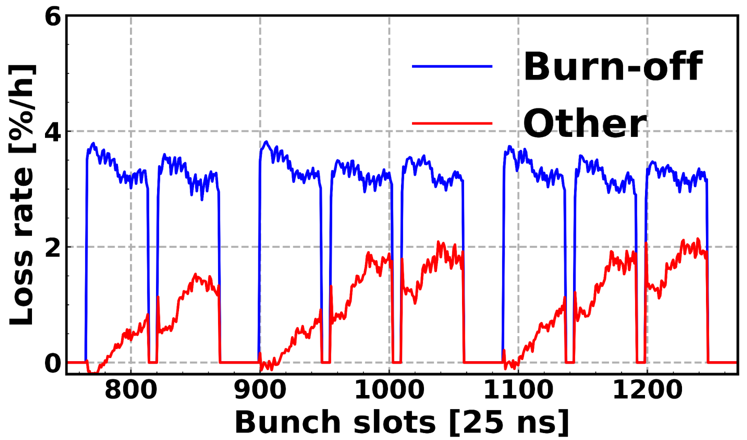


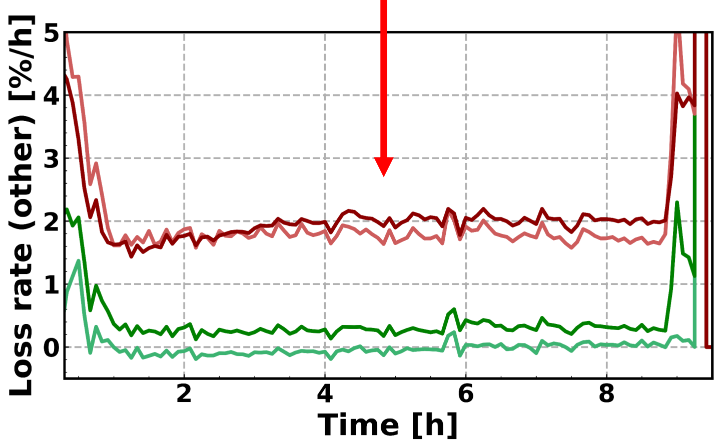
- **Group 1**: Few BBLR, reduced e-cloud effects
- **Group 2**: Max BBLR, reduced e-cloud effects
- **Group 3**: Max BBLR, stronger e-cloud effects
- **Group 4**: Few BBLR, stronger e-cloud effects

Example #1: Physics fills



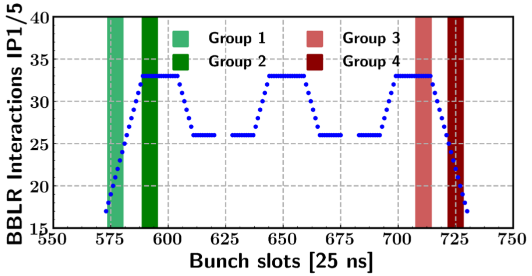




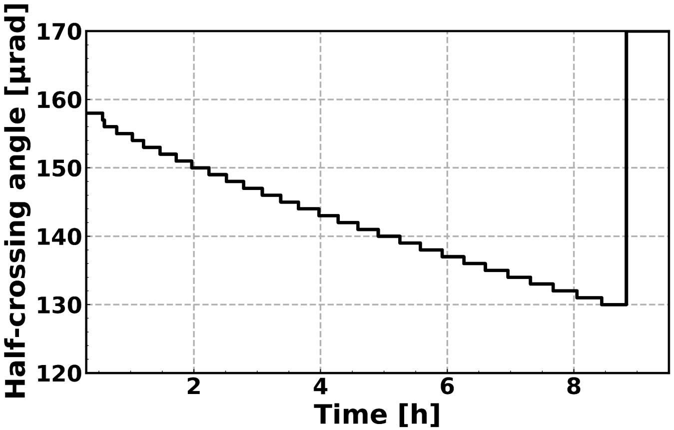


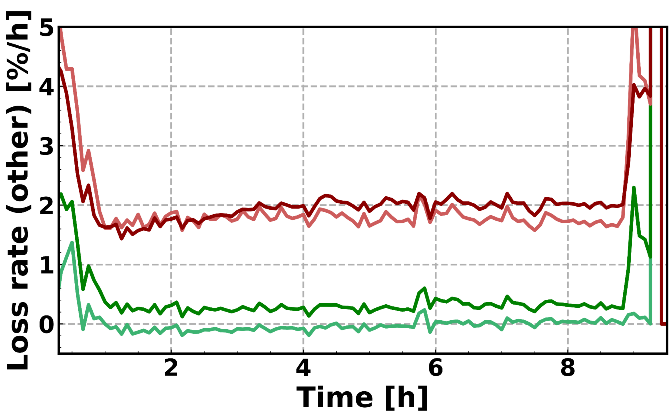
- Bunch-by-bunch pattern emerges
- Consistent with e-cloud buildup behaviour.
- Beam-beam effects alone cannot explain behaviour

Example #2: Crossing angle

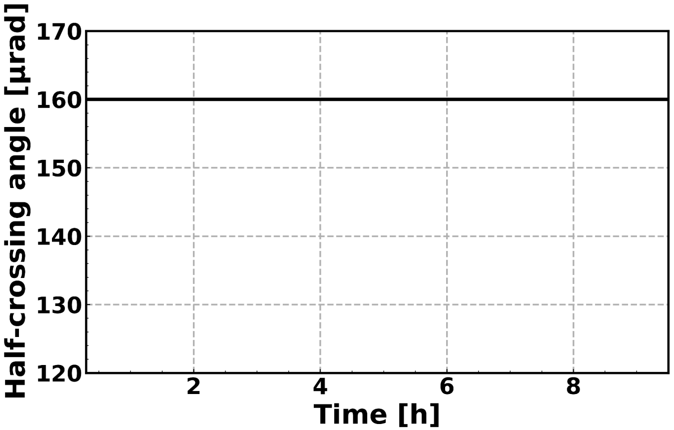


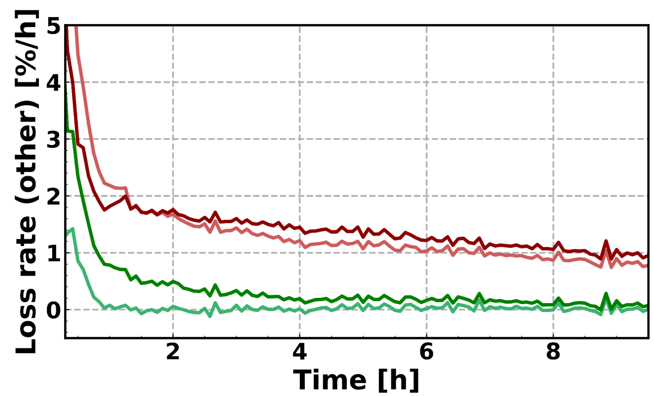
Typical physics fill:





Special test:

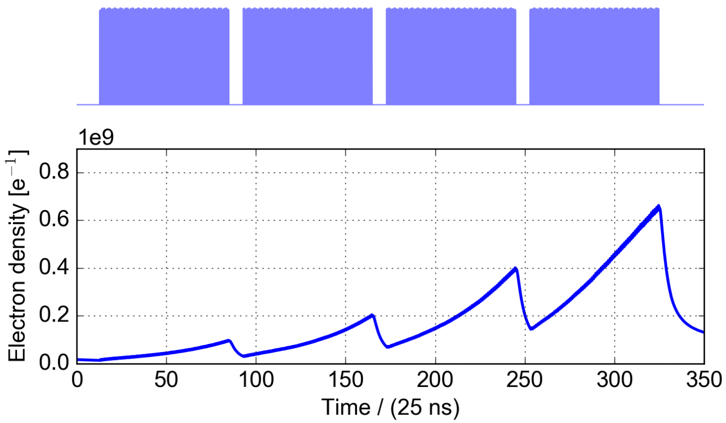




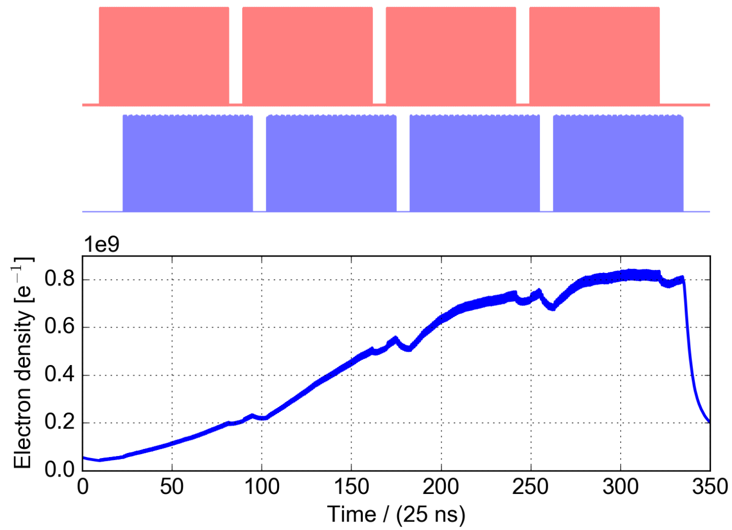
- A reduced crossing angle typically enhances BBLR interactions.
- In this case, it enhances the e-cloud pattern losses.

Example #3: Buildup simulations in Inner Triplet quadrupoles

One beam:



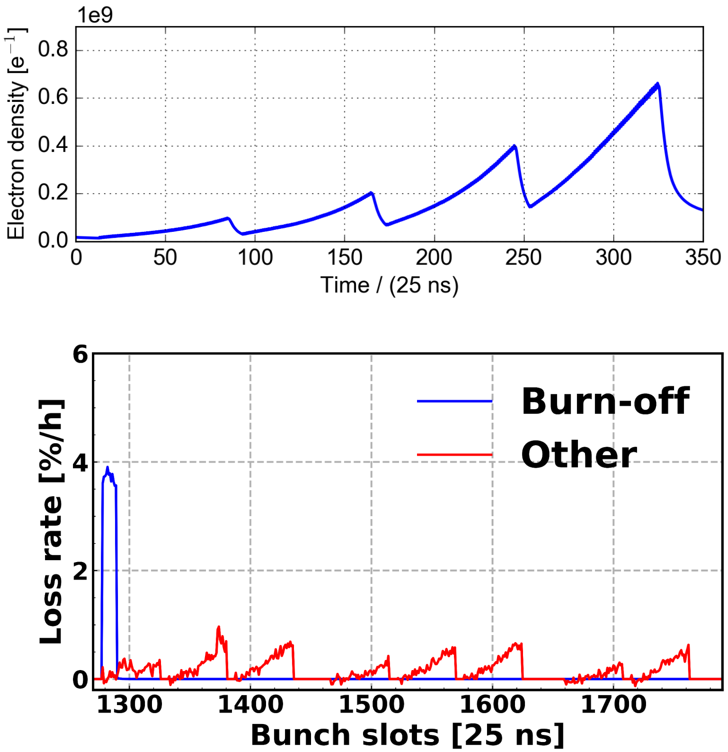
Two beams:



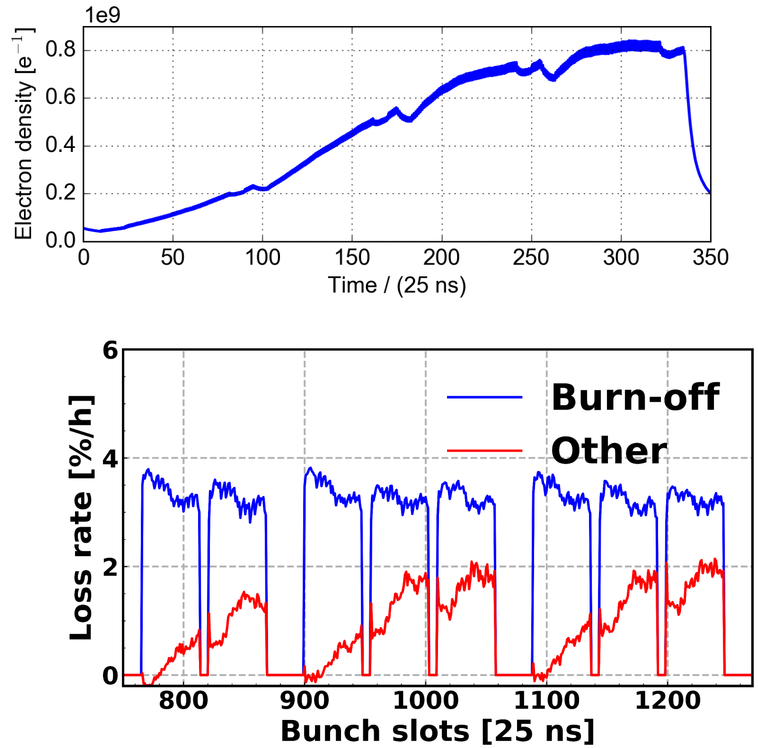
- One beam: In the small 200 ns between batches, the electron cloud decays significantly.
- Two beams: Beams are not synchronized and the e-cloud does not decay.

Example #3: Buildup simulations in Inner Triplet quadrupoles

One beam:



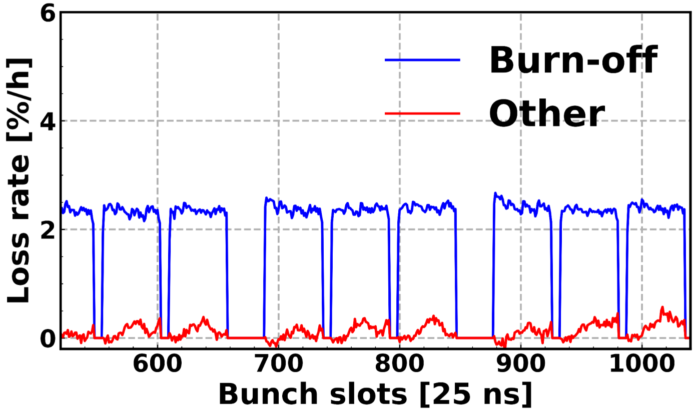
Two beams:



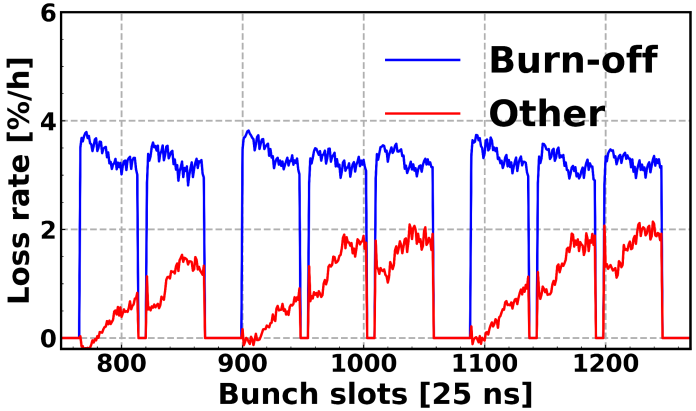
The bunch-by-bunch pattern of the losses resembles the e-cloud buildup simulations of the Inner Triplet quadrupoles.

Example #4: Measurements with different betatron functions

β* = 65 cm, φ = 120 μrad
Large ATS telescope[1] →
→ enhancement of arc beta functions



β* = 30 cm, φ = 150 μrad
Moderate ATS telescope



- Decreasing β in the inner triplet quadrupoles should reduce effect of the e-cloud in the inner triplet.
- Increasing β in arcs should enhances e-cloud effect:
  no significant losses.

[1]For more details, see S. Fartoukh: https://indico.cern.ch/event/772189/contributions/3209049/

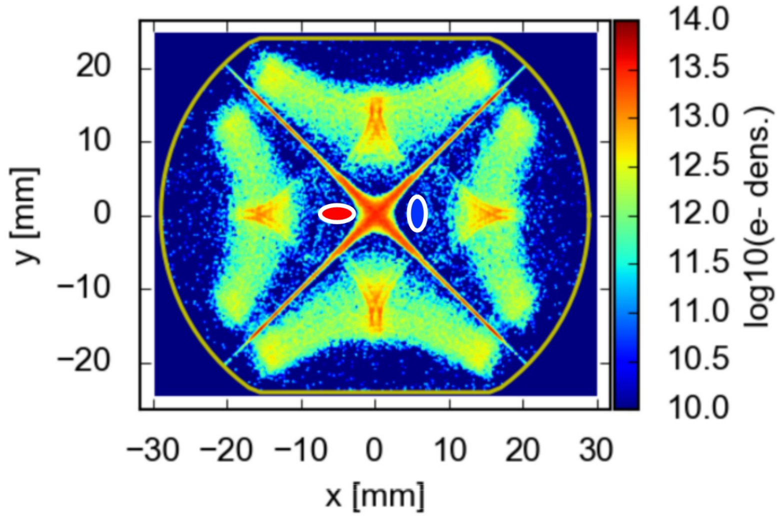
Summary - Observations

Electron cloud related losses are enhanced when:

1. reducing β* (increasing β in IT)
2. reducing crossing angle (changes closed orbit in IT)
3. Two beams are present (enhanced buildup in IT)

but not when:

4. Increasing β in arcs



All observations point to the Inner Triplet Quadrupoles.

Good news: HL-LHC Inner Triplet will have a-C coating to suppress e-cloud.

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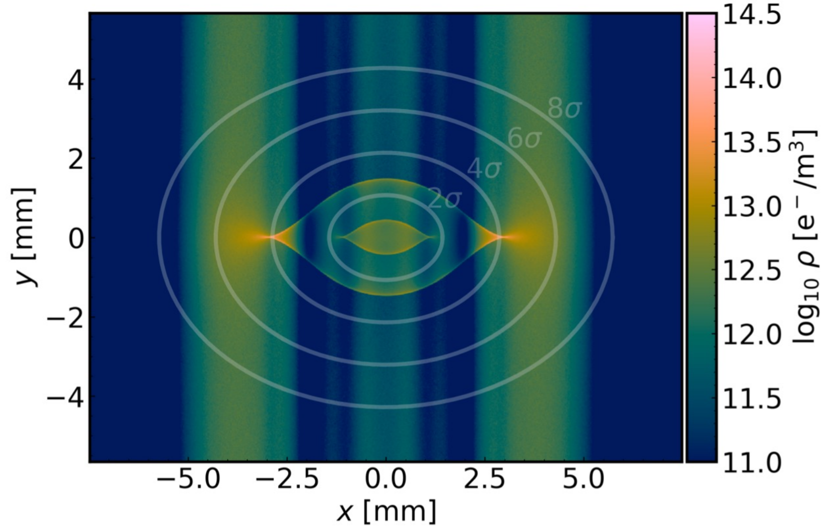
Introduction to simulations

[G. Iadarola, CERN-ACC-NOTE-2019-0033]



$$x, y, \tau \mapsto x, y, \tau$$

$$p_x \mapsto p_x - \frac{qL}{\beta_0 P_0 c} \frac{\partial \phi}{\partial x}(x, y, \tau)$$

$$p_y \mapsto p_y - \frac{qL}{\beta_0 P_0 c} \frac{\partial \phi}{\partial y}(x, y, \tau)$$

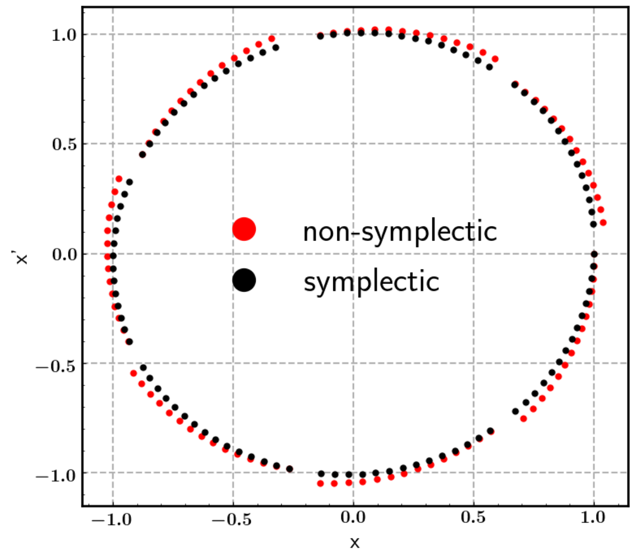
$$p_\tau \mapsto p_\tau - \frac{qL}{\beta_0 P_0 c} \frac{\partial \phi}{\partial \tau}(x, y, \tau)$$

$$\rho \to \phi \to \frac{\partial \phi}{\partial x} \dots$$

- Complex time-dependent e-cloud density → complex time-dependent forces
- Slow incoherent effects → e-cloud can be re-used = weak-strong approximaton (no self-consistency)
- **But:** e-cloud potential (PIC) is defined on a 3D grid. Needs to be interpolated.

Symplecticity

- Numerical methods in solving Hamiltonian systems can break the symplectic condition, making them less accurate at long timescales. (Millions of turns)
- Typically important to preserve symplecticity, even at the expense of accuracy.



- Interpolation scheme should guarantee symplecticity.

In our case, symplecticity: $$\frac{\partial^2 \phi}{\partial x \partial y} = \frac{\partial^2 \phi}{\partial y \partial x}$$

$$x, y, \tau \mapsto x, y, \tau$$

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$$p_y \mapsto p_y - \frac{qL}{\beta_0 P_0 c} \frac{\partial \phi}{\partial y}(x, y, \tau)$$

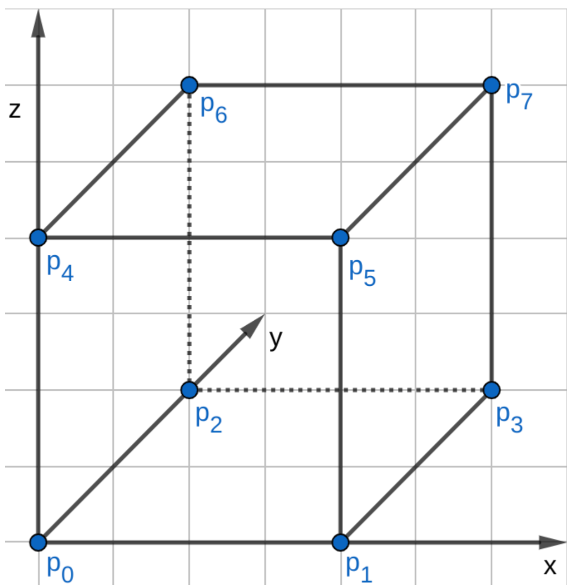
$$p_\tau \mapsto p_\tau - \frac{qL}{\beta_0 P_0 c} \frac{\partial \phi}{\partial \tau}(x, y, \tau)$$

- Linear interpolation is not symplectic.

Tricubic interpolation

Given a regular 3D grid of any function f^{ijk}, we interpolate locally in a way that the following quantities are continuous globally.

$$\left\{ f, \frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}, \frac{\partial^2 f}{\partial x \partial y}, \frac{\partial^2 f}{\partial x \partial z}, \frac{\partial^2 f}{\partial y \partial z} \right\}$$



Lekien and Marsden* proved that it is possible to meet this condition by using a tricubic interpolation scheme.

$$f(x,y,z) = \sum_{i=0}^{3} \sum_{j=0}^{3} \sum_{k=0}^{3} a_{ijk} x^i y^j z^k$$

The coefficients a_{ijk} change from cell to cell but required quantities stay continuous across the cells.

- Analytical derivatives for interaction.

*F. Lekien and J. Marsden, "Tricubic interpolation in three dimensions". https://doi.org/10.1002/nm2.1296

Small digression

Demonstration of symplecticity violation/preservation

Consider the Hamiltonian: $$H = \frac{p_1^2}{2} + \frac{p_2^2}{2} + \phi(q_1, q_2) \quad \text{with} \quad \phi(q_1, q_2) = e^{q_1 - q_2}$$

These quantities are conserved:
(along with the Hamiltonian)

$$J_1 = (p_1 - p_2)^2 + 4e^{q_1 - q_2},$$

$$I_1 = \frac{p_1 - p_2 + \sqrt{J_1}}{p_1 - p_2 - \sqrt{J_1}} \exp\left(\sqrt{J_1}\,\frac{q_1 + q_2}{p_1 + p_2}\right)$$

We can numerically solve the equations of motion with the method:

$$q_1^f = q_1^i + p_1 \cdot \Delta t$$

$$q_2^f = q_2^i + p_2 \cdot \Delta t$$

$$p_1^f = p_1^i - \frac{\partial \phi}{\partial q_1}(q_1^f, q_2^f) \cdot \Delta t$$

$$p_2^f = p_2^i - \frac{\partial \phi}{\partial q_2}(q_1^f, q_2^f) \cdot \Delta t$$

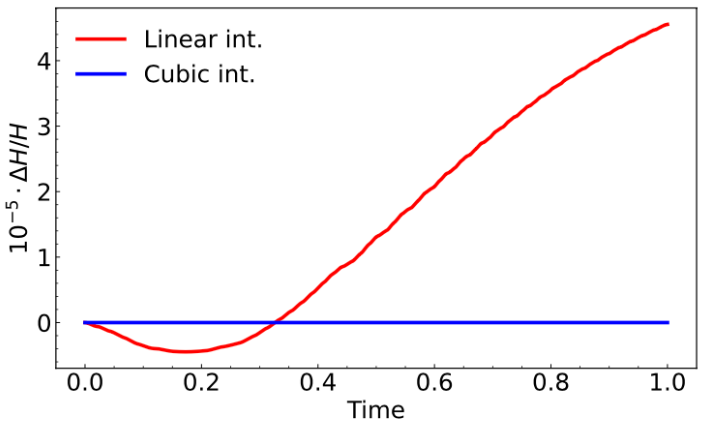
- The potential is discretized on a grid and the two interpolation methods are used.

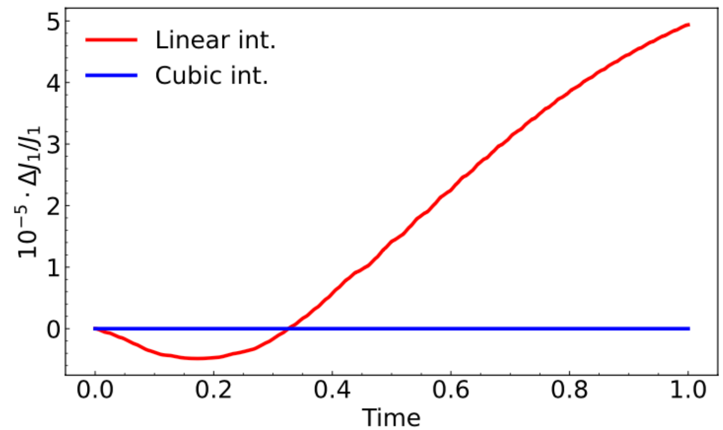
1. Linear interpolation
2. Cubic interpolation

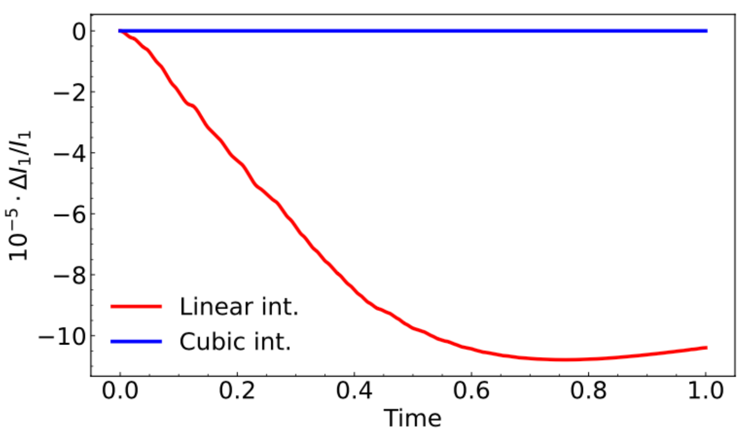
Demonstration of symplecticity violation/preservation

Non-symplectic method: Use (bi)linear interpolation on the derivatives of $\phi(q_1, q_2) = e^{q_1 - q_2}$.

Symplectic method: Use (bi)cubic interpolation on $\phi(q_1, q_2) = e^{q_1 - q_2}$.





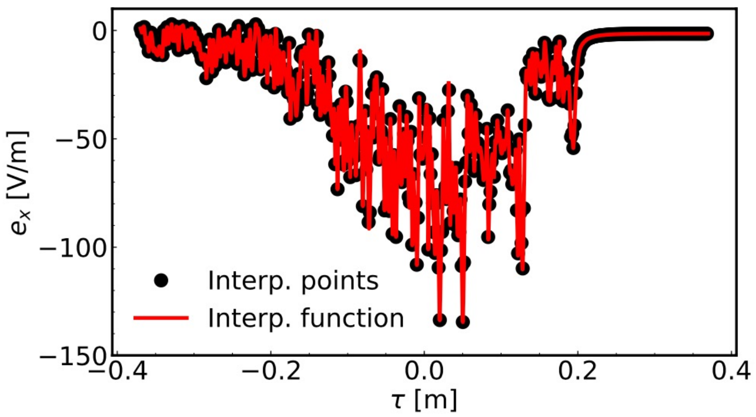


- The relative error on the integrals of motion does not grow with a symplectic method,
- While it grows for non-symplectic methods.

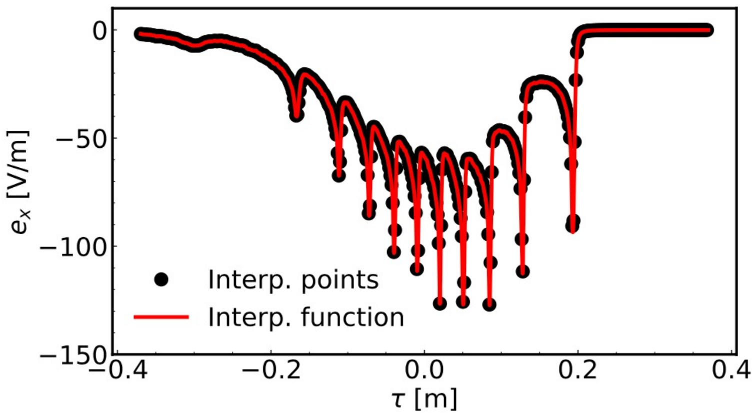
End of digression

Issue with PIC potential

One simulation



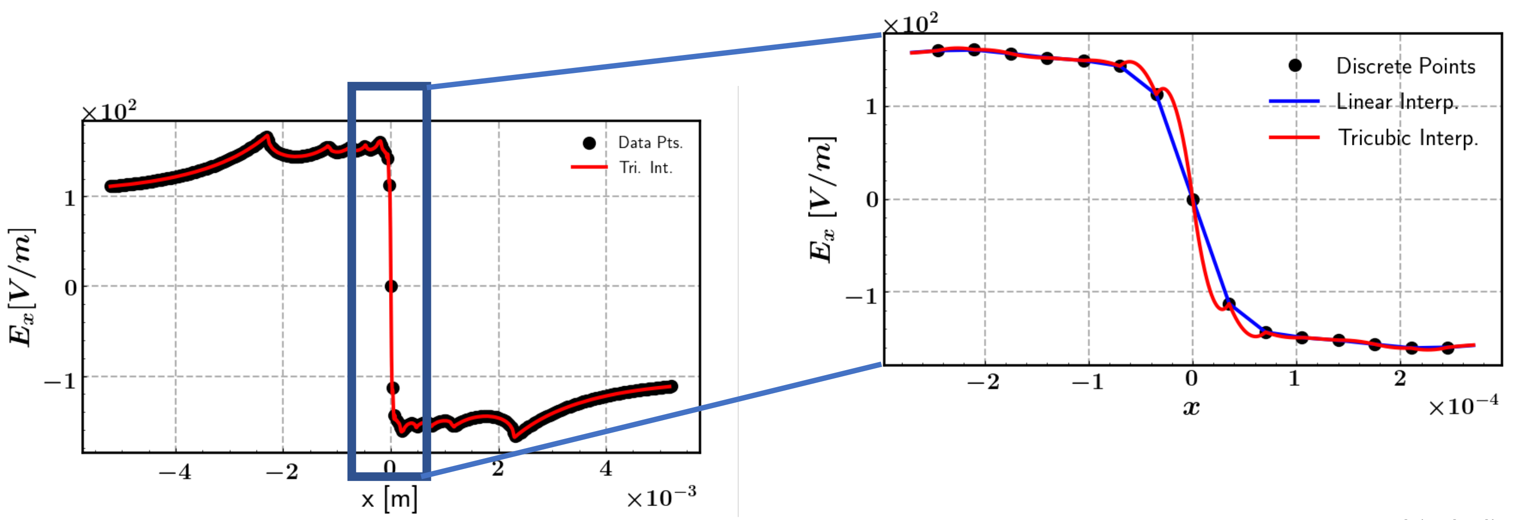
4000 simulations



- PIC simulation suffers from macroparticle noise.
- Can be reduced by averaging many simulations.

Averaging 4000 reveals the physical structures in the induced forces.

Issue with cubic interpolator



[zoom of left figure]

- Close look reveals irregularities from Tricubic interpolation.
- Inaccuracies are correlated with **discontinuity of second derivative accross cells**.

$$\mathcal{E}_x^{ijk} = \left.\frac{\partial e_x^{\mathrm{int}}}{\partial x}\right|_{x \to x_i^+} - \left.\frac{\partial e_x^{\mathrm{int}}}{\partial x}\right|_{x \to x_i^-} = -2\frac{\partial^3 \phi}{\partial x^3}(x_i, y_j, \tau_k)\,\Delta x + O\left(\Delta x^3\right)$$

Refinement of potential

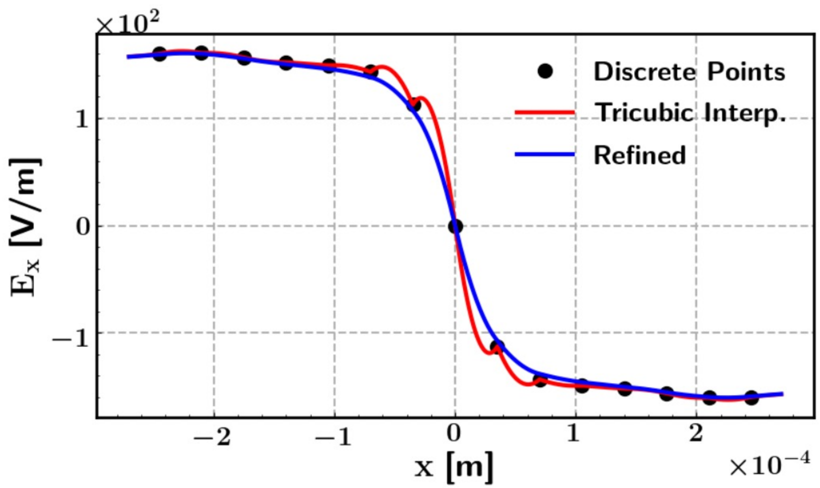
We found that we can treat our potential by:

1. Interpolate charge density on an auxilliary finer grid (by factor h).
2. Recalculate φ and derivatives in the finer grid.
3. Store recalculated φ and derivatives on original grid.

$$\Delta x_{\text{refined}} = \frac{\Delta x}{h}$$

Minimal expense on memory and speed (performed during pre-processing)
Proved analytically that error becomes:

$$\mathcal{E}^{ijk}_{x,\text{refined}} = -2\frac{\partial^3 \phi}{\partial x^3}(x_i, y_j, \tau_k)\frac{\Delta x}{h^2} + O\left(h^{-4}\Delta x^3\right)$$



Complete mitigation of the irregularities.

Quick recap

- Analytical form of e-cloud kick.
- Used a high-order interpolation scheme (tri-cubic) to preserve symplecticity everywhere in phase space.
- Averaged multiple Particle-In-Cell e-cloud simulations to reduce macroparticle noise in the interpolated data.
- Solved Poisson's equation in a finer auxiliary grid (**done only once**) to improve performance of the interpolation scheme.

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$$p_\tau \mapsto p_\tau - \frac{qL}{\beta_0 P_0 c} \frac{\partial \phi}{\partial \tau}(x, y, \tau)$$

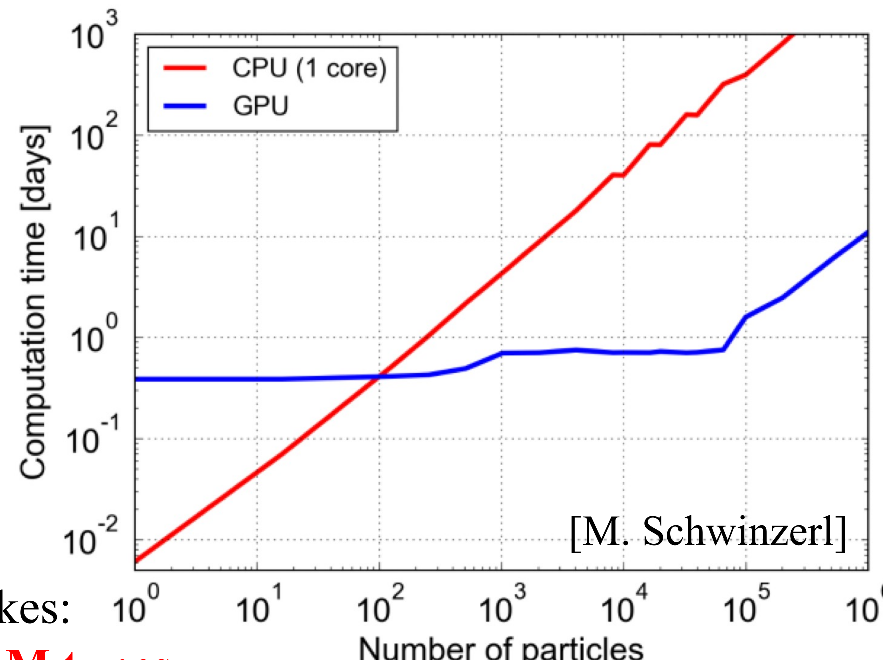
Next:

- Direct tracking simulation results of the **incoherent effect of electron clouds in the main dipole and quadrupole magnets of the LHC at injection energy**.
- Interaction was implemented in SixTrackLib/XSuite software to use GPUs and including the **full lattice model** of the LHC.
- SixTrackLib/XSuite simulates beam particles through each element of the lattice using symplectic (non-linear) maps.

Graphics Processing Units

Realistic e-cloud simulation studies were made possible only through access to modern Graphics Processing Unit hardware.

Two orders of magnitude gained in computation time compared to a CPU.



- Simulations are still very heavy.
- Simulation using a V100 GPU takes:
  1 week / 20 000 particles / 10 M turns.

Following studies used several GPUs available from:

- CERN IT batch service
- INFN-CNAF in Bologna (through HL-LHC collaboration)

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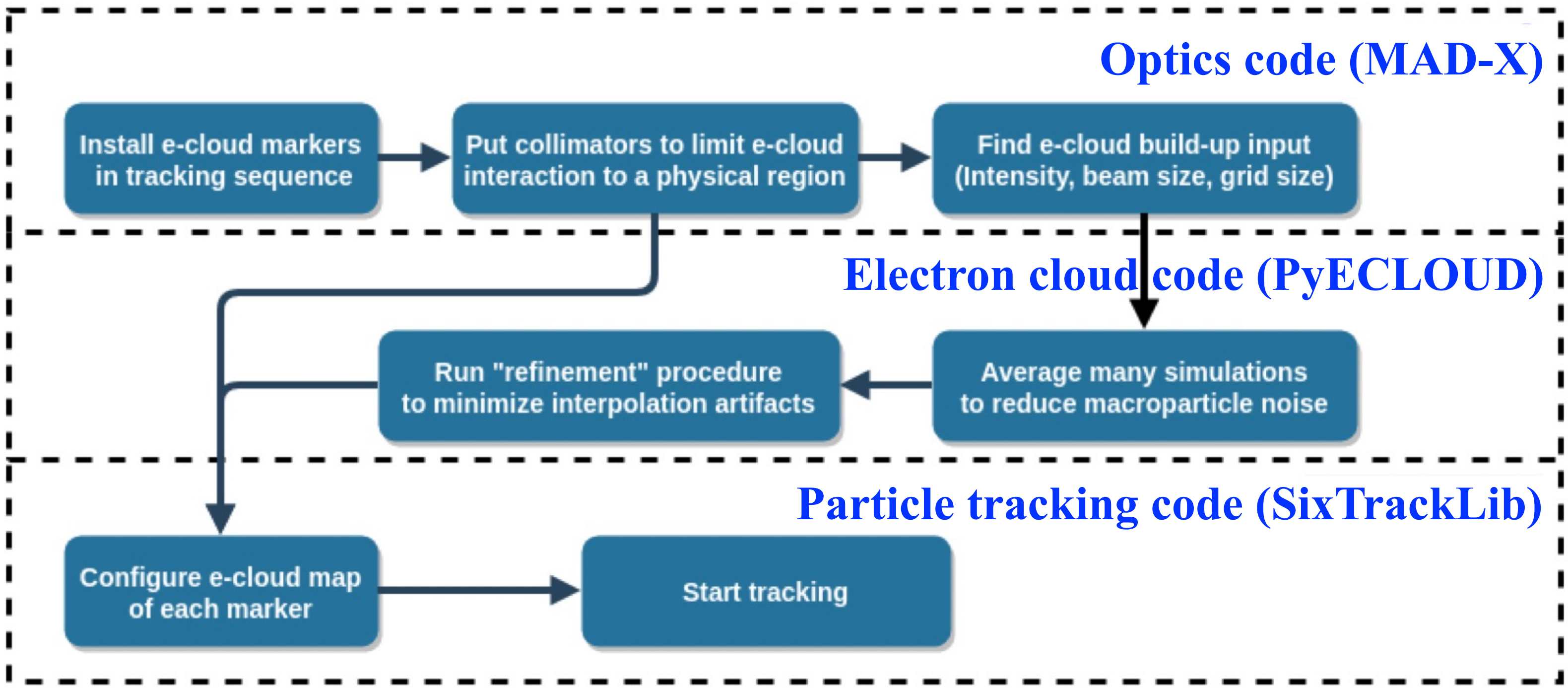
1. Introduction to electron clouds

2. Observations in LHC during Run 2

3. Progress in simulations
   a) Description of e-cloud interaction
   b) Simulation results

General procedure for the simulation



Examples:

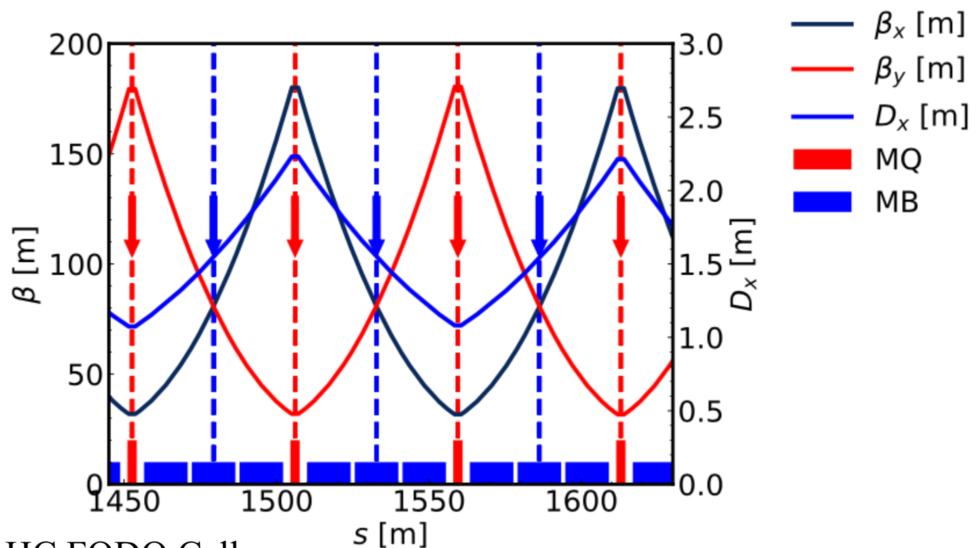
- Dynamic aperture tune scan to optimize accelerator's configuration.
- Dynamic aperture (SEY, bunch intensity): qualitative characterization of e-cloud effect, tolerances/intensity reach.
- Frequency Map Analysis for insight on the mechanism.
- Long-term simulations for estimations of losses and emittance growth.

E-cloud setup

E-cloud exists across the full length of the LHC beam pipe.
Different magnetic fields lead to completely different e-clouds.
Most significant contributors:

1. E-cloud in arc dipoles (MB) (66%)
2. E-cloud in arc quadrupoles (MQ) (7%)

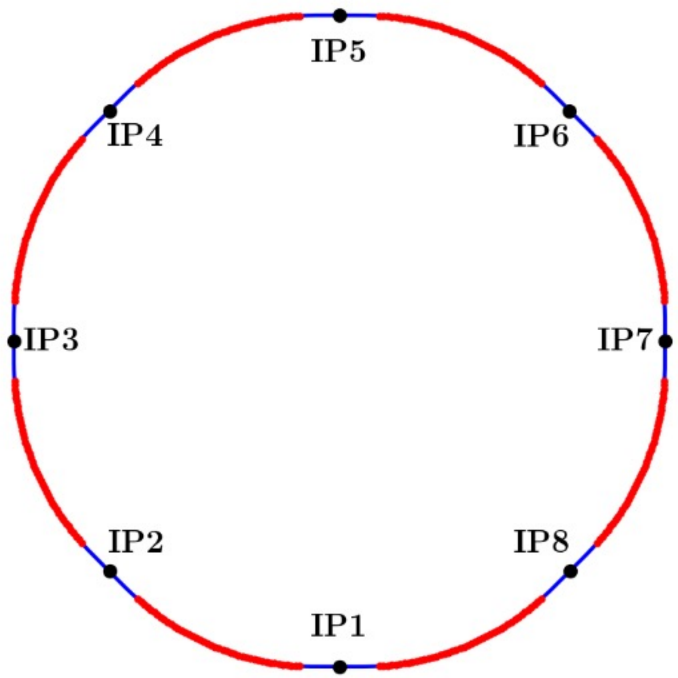
We place one interaction for each three dipoles and each quadrupole.



LHC FODO Cell

- Betatron and dispersion functions stay the same between each cell.
- Approximate SEY as uniform everywhere. Large fluctuations in reality.
- Effect from saturated e–cloud.

E-cloud setup

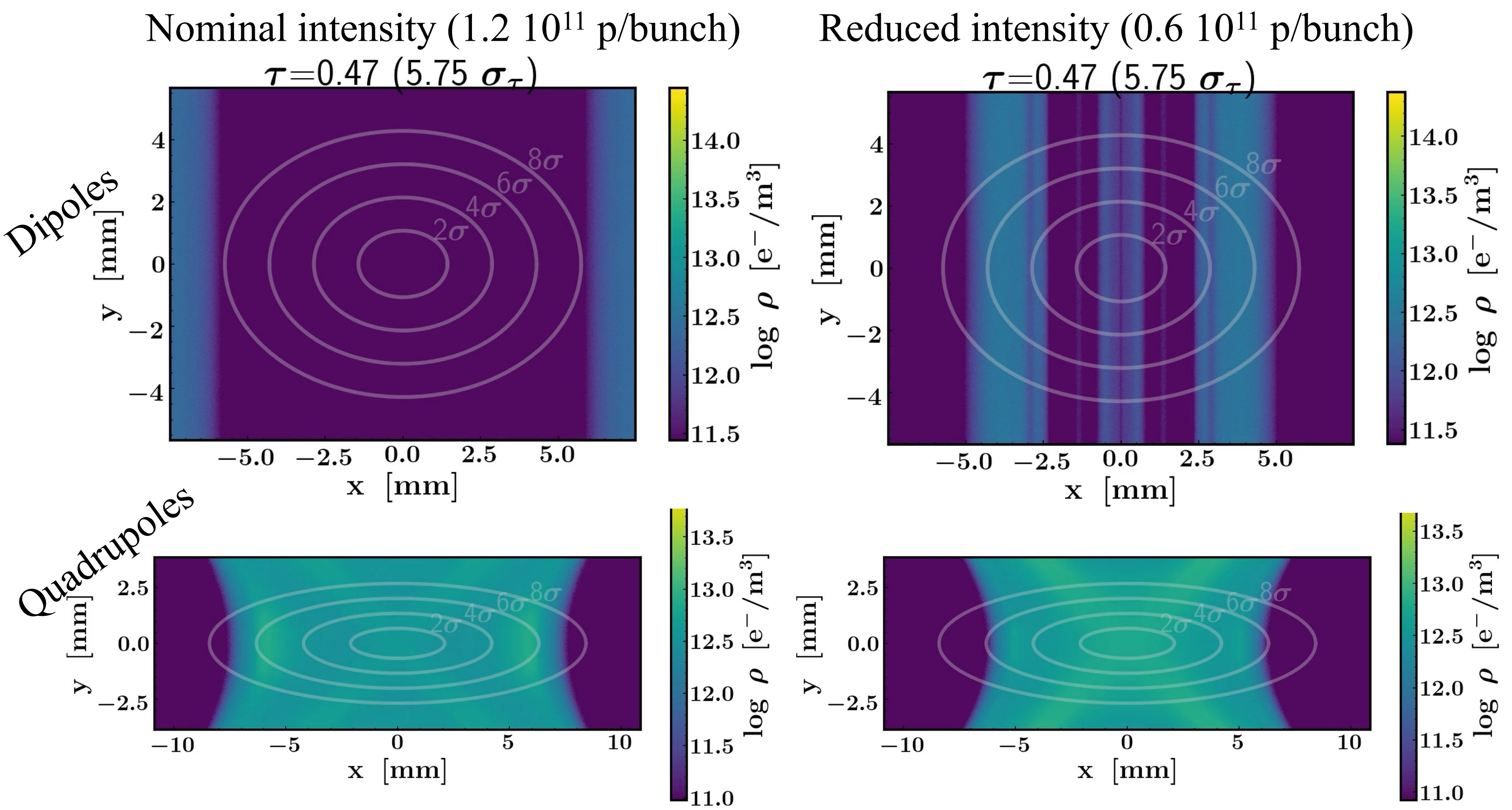


- One MB e-cloud per half-cell
→ 46 interactions per arc
→ 368 interactions.

- One MQ e-cloud per half-cell
→ 45 interactions per arc
→ 360 interactions.

Tracking time per e-cloud type (~360 interactions) is about as much as rest of the lattice (11k tracking elements).

E-cloud setup



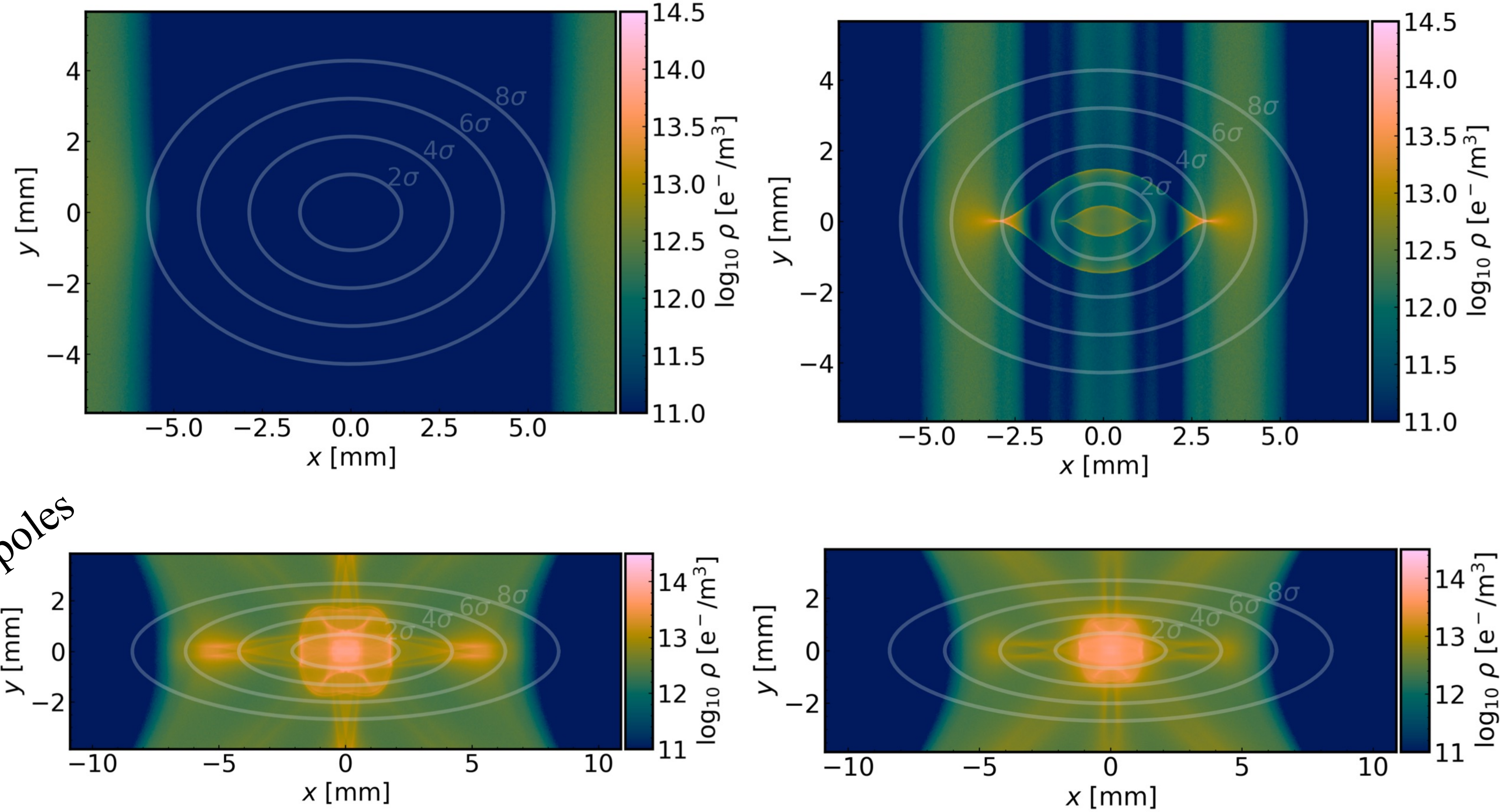
- Dipoles: Reduced bunch intensity leads to larger e$^-$ density close to the beam.
- Quadrupoles: Small dependence on bunch intensity, large e$^-$ densities close to beam.

E-cloud setup

Nominal intensity (1.2 10^{11} p/bunch) Reduced intensity (0.6 10^{11} p/bunch)

Dipoles

Quadrupoles



- Dipoles: Reduced bunch intensity leads to larger e^- density close to the beam.
- Quadrupoles: Small dependence on bunch intensity, large e^- densities close to beam.

Simulation Parameters

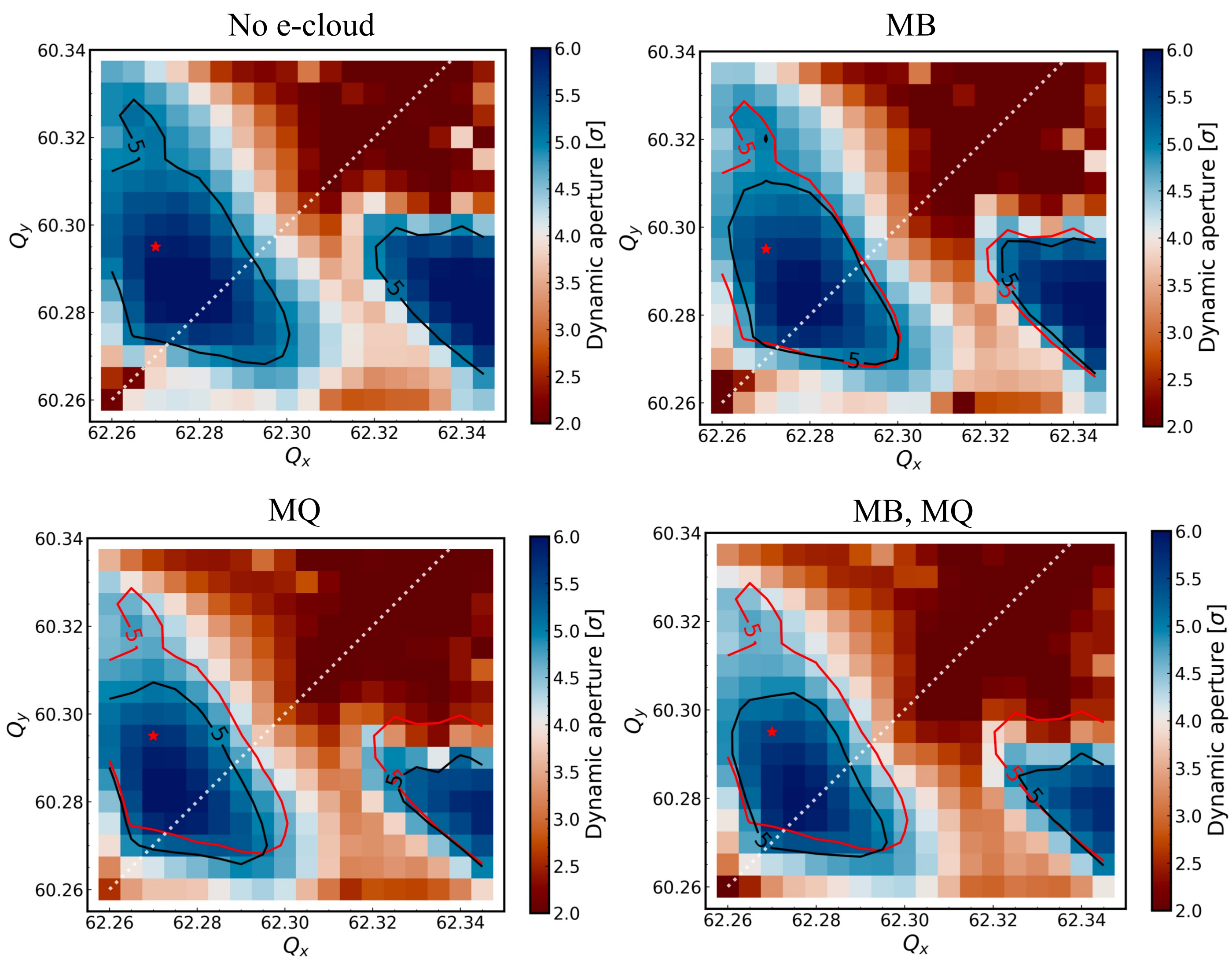
Typical LHC at injection, 2018

Bunch intensity : 1.20 10^{11} protons
Energy : 450 GeV
Chromaticity : 15/15
Octupole magnet's current : 40 A
Bunch spacing : 25 ns
Transverse norm emittances : 2 μm/ 2 μm
R.M.S. bunch length : 0.09 m
Betatron tunes : 62.270/60.295
RF voltage : 6 MV

The three primary collimators (TCP) in IR7 (as black absorbers) are included in the lattice at their typical configuration (5.7 "collimation" $\sigma \rightarrow$ 7.5 beam σ).

There is **no** uncorrected linear coupling, magnet field imperfections, magnet misalignments or beam-beam interactions in the lattice.

Tune scan



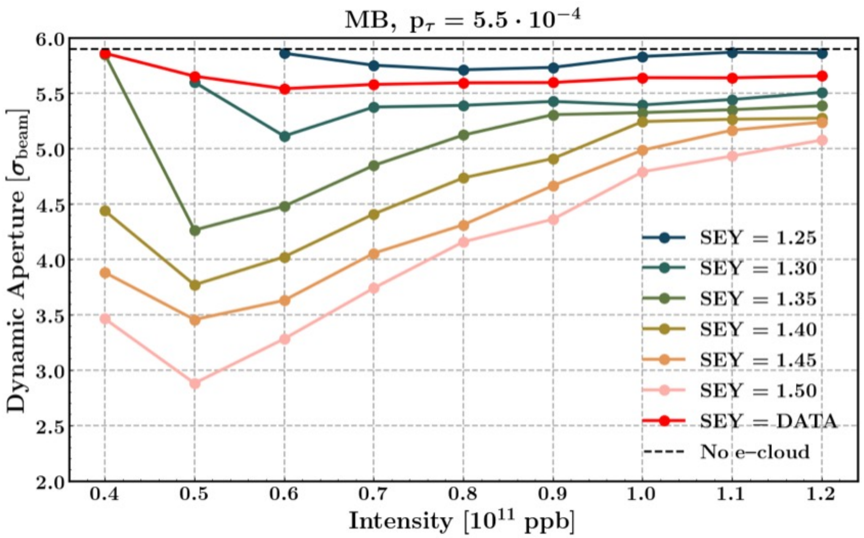
E-cloud reduces available tune space.

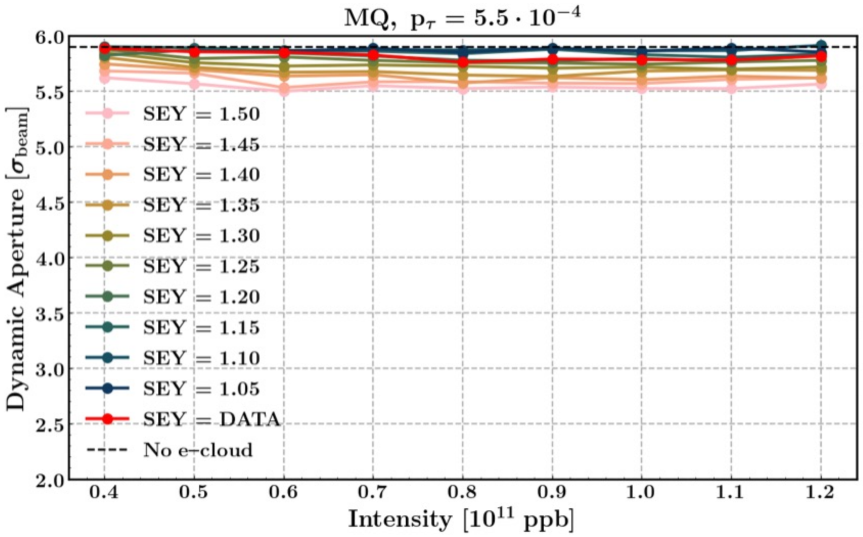
Still dominated by strong octupoles and chromaticity.

No better working point without approaching diagonal.

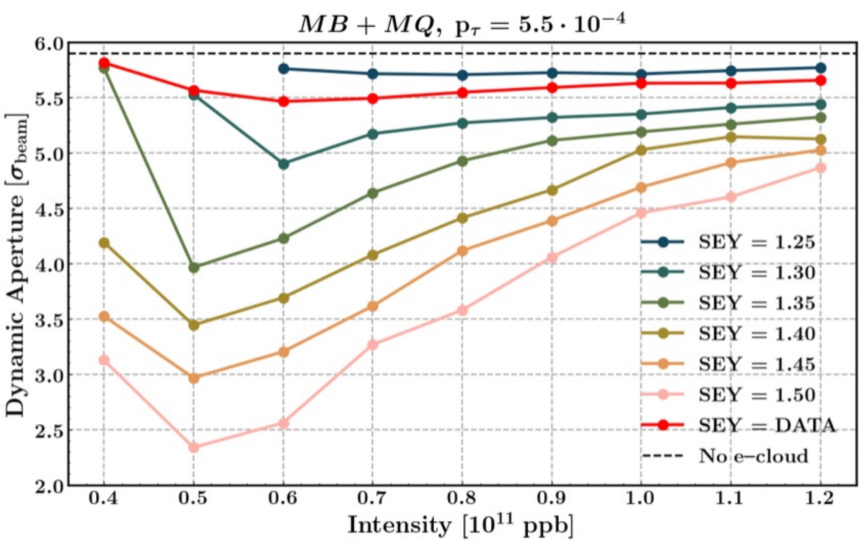
(SEY_{MB} : 1.3, SEY_{MQ} : 1.3)

Secondary Emission Yield (SEY) - Intensity scan

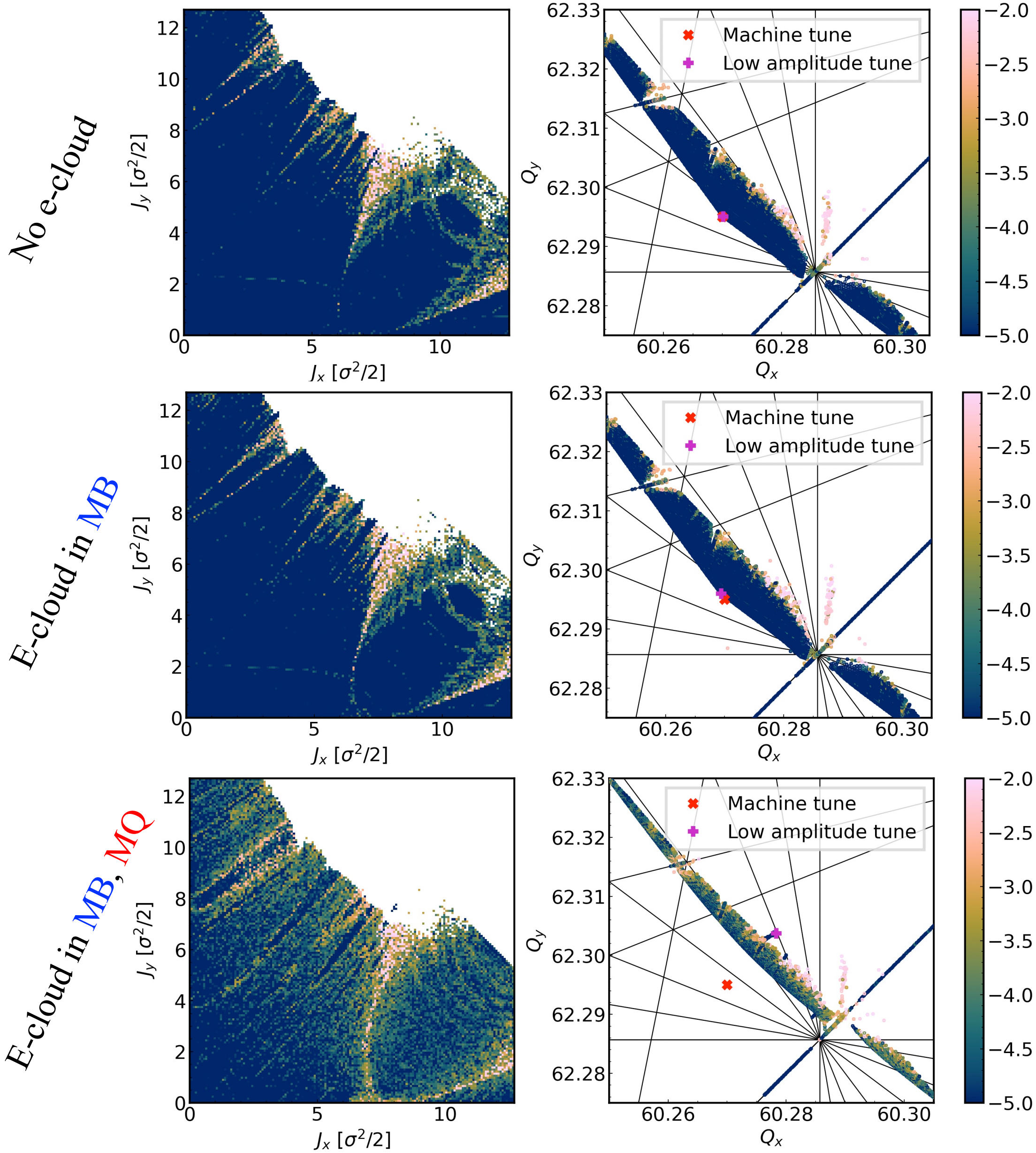




- Larger Secondary electron Emission Yield (of beam pipe) → → stronger e-cloud → less DA
- Dipoles (MB): strong dependence with bunch intensity, correlated to e⁻ density close to the beam.
- Quadrupoles (MQ): weak dependence with bunch intensity



Frequency Map Analysis – Nominal intensity (1.2 10^{11} p/b)



Nominal intensity

Dipoles (MB):

→ tiny tune-shift

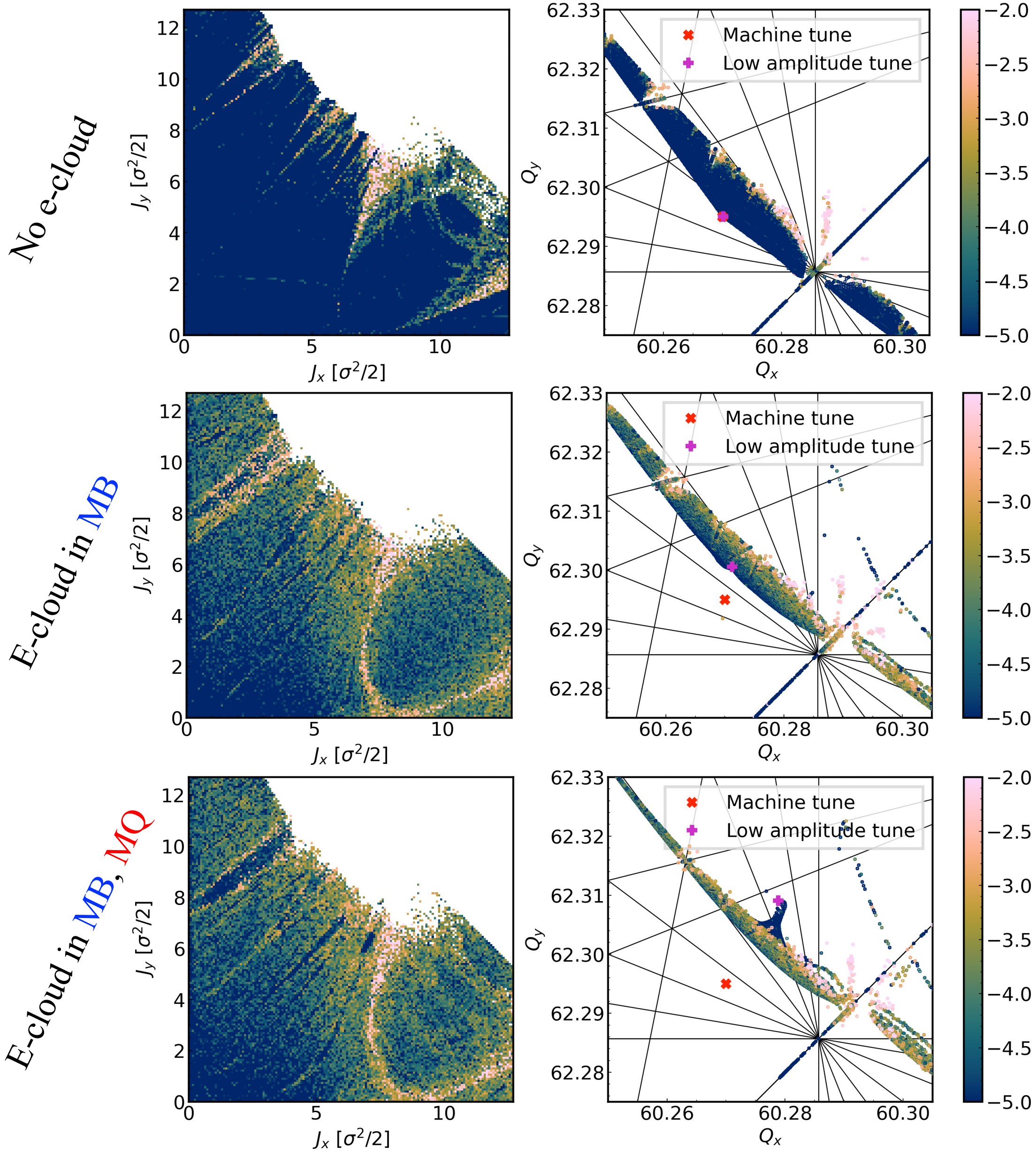
→ negligible effect

Quadrupoles (MQ):

→ large tune-shift

→ more resonances

Frequency Map Analysis – Reduced intensity (0.6 10^{11} p/b)



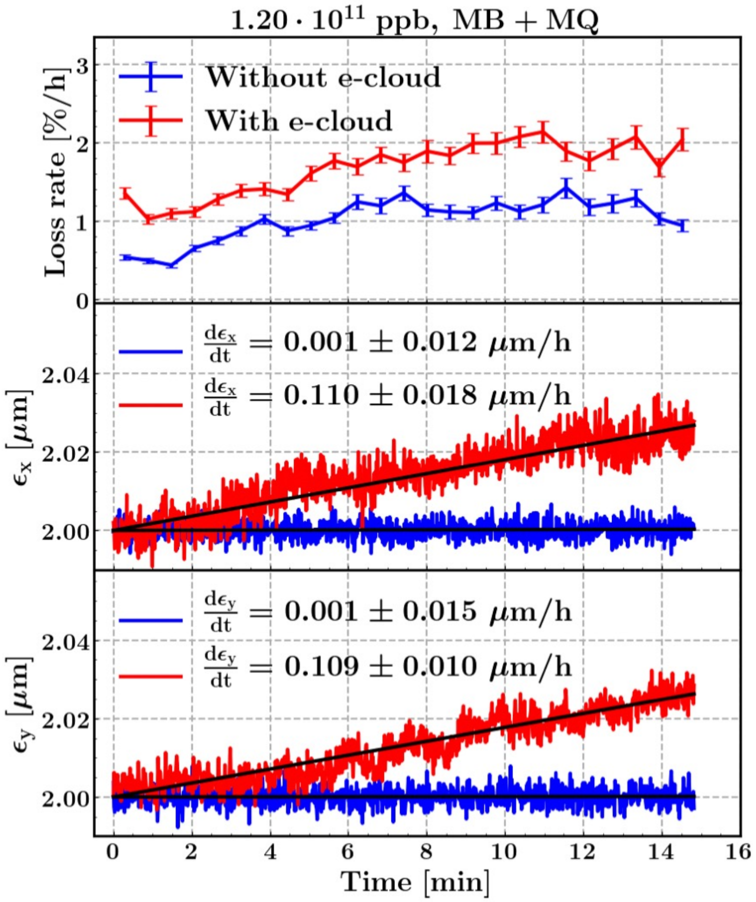
Reduced intensity
Dipoles (MB):
→ larger tune-shift
→ more resonances

Quadrupoles (MQ):
→ large tune-shift
→ more resonances

Reminder:
Significant e^- density appears on the beam location in dipole magnets for reduced intensity.

Particles are on-momentum.
Work in progress to try identify synchro-betatron resonances.

Long simulations (10M turns → 15min beam time)



Incoherent effects in the LHC are typically very slow processes. Need to simulate long timescales.
Recent advances (SixTrackLib/XSuite) allow the direct simulation of particle distributions with GPUs for such times.

In long term simulations we observe:
- small increase of losses
- horizontal emittance growth,
- vertical emittance growth,

when e-clouds are included.

Experimental observations show emittance growth in the same order of magnitude. For quantitative comparisons we have planned dedicated MDs in Run 3.

Conclusion and Remarks

Observations:

- Electron cloud in the insertion region quadrupoles is significant. Reduces integrated luminosity.

Simulations:

- We can do particle tracking simulations with **arbitrarily complex e-clouds in arbitrarily complex lattices for millions of turns.**
- Simulated simplified scenario at injection energy. Interplay with non-linear magnetic imperfections expected.
- Simulations have reproduced the expected qualitative behavior.
- Very long simulation timescales (several minutes) are in reach. (Using GPUs)

Outlook for the future:

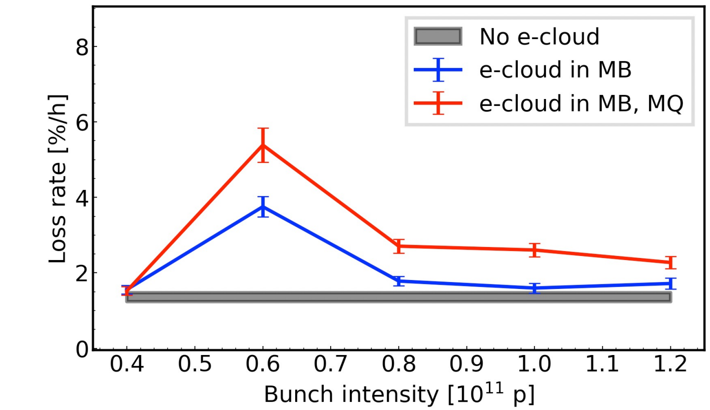
- Comparison with experimental measurements needs specialized tests.
  → Soon to be carried out in the LHC.
- Simulate more complex scenario of collisions in LHC: Strong electron clouds in the Insertion Region quadrupoles + beam-beam effects.

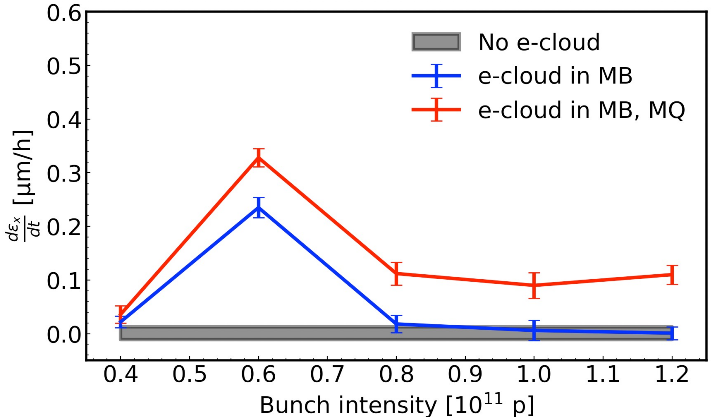
Thank you for your attention!

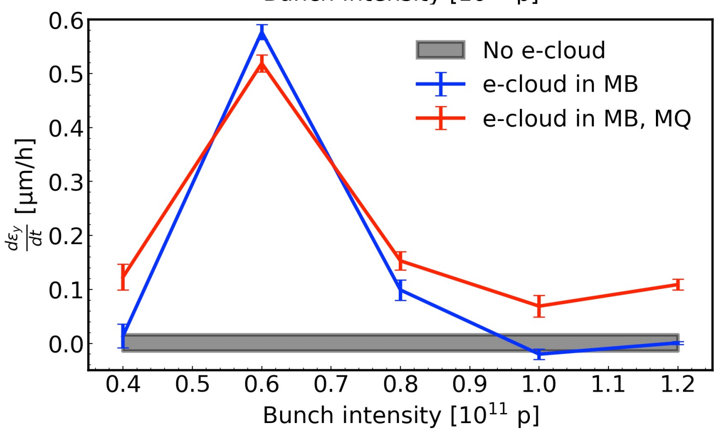
Konstantinos Paraschou

Backup slides

Long simulations (10M turns → 15min beam time)







MB (Dipoles):

- Losses stronger at reduced intensity.
- Emittance growth only at reduced intensity.
- Vertical growth larger than horizontal.

MQ (Quadrupoles):

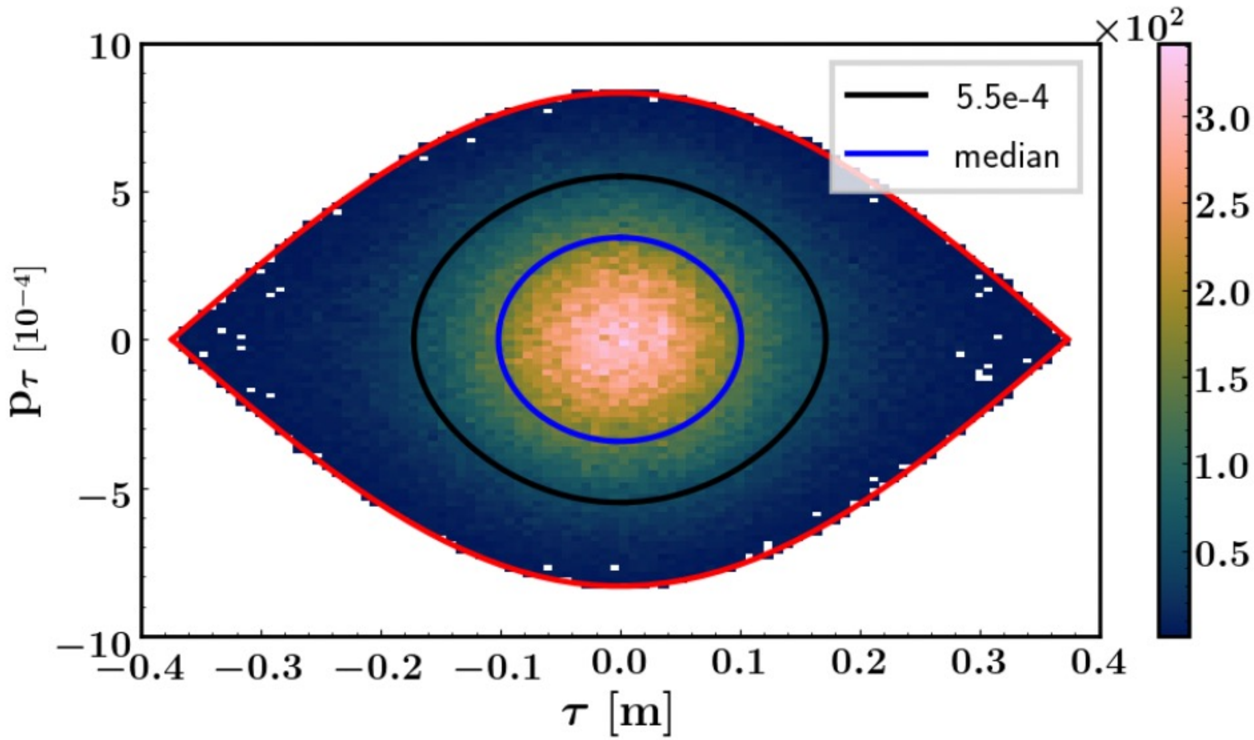
- Losses across all intensities.
- Emittance growth at all intensities.
- Similar growths in both horizontal and vertical.

Effects strongly correlated with the e^- density close to the beam.

Reminder:

- MB show large densities around the beam for reduced intensities,
- MQ for all intensities.

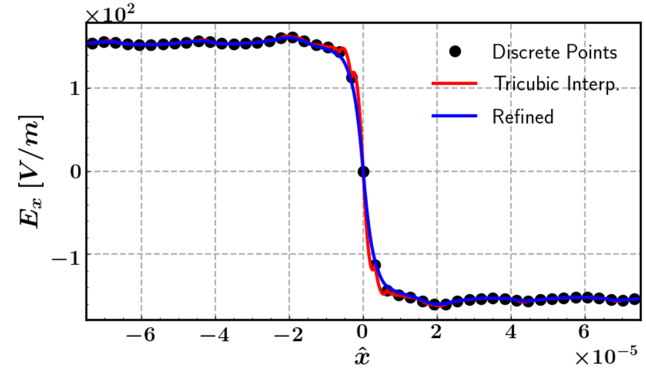
The RF bucket

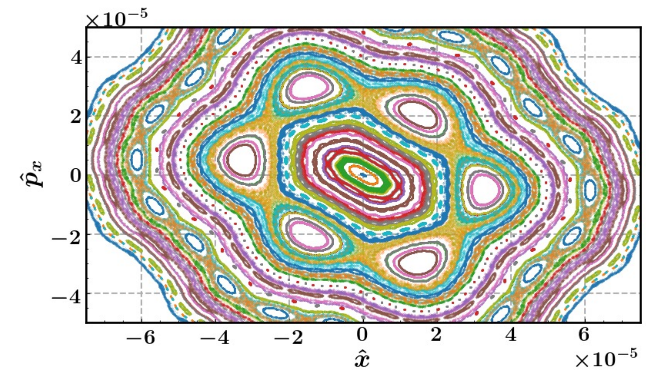


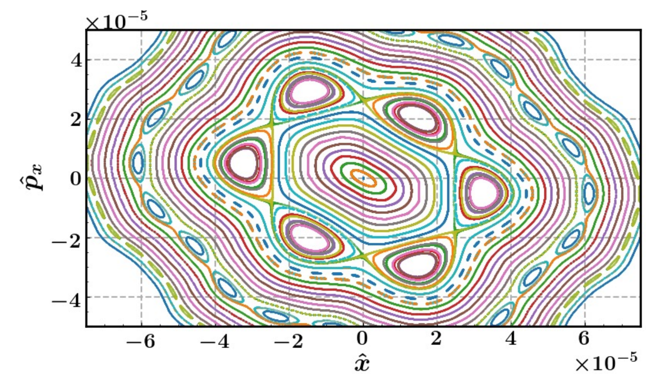
- DA simulations done for off-momentum particles ($p_\tau = 5.5\ 10^{-4}$).
- FMA simulations done for on-momentum particles ($p_\tau = 0$).
- Long-term tracking simulations with particles across the full bucket.
- Work in progress: FMA with off-momentum particles.

Impact of tricubic interpolation irregularities

- Simple tracking of linear 2D phase space rotation and an e-cloud symplectic kick.
- Very important to minimize irregularities.
- By reducing them, there is significant impact on the particle motion.

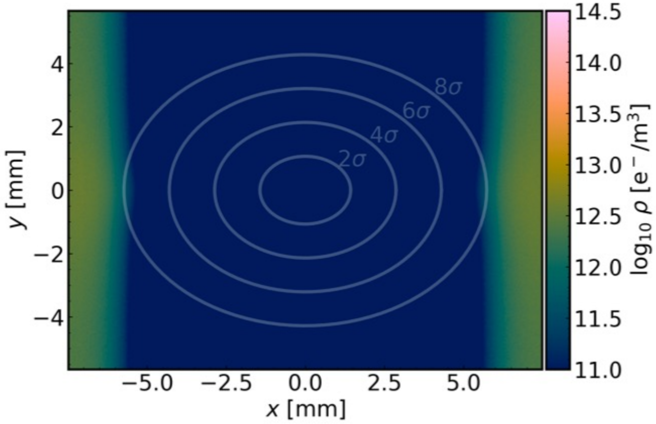


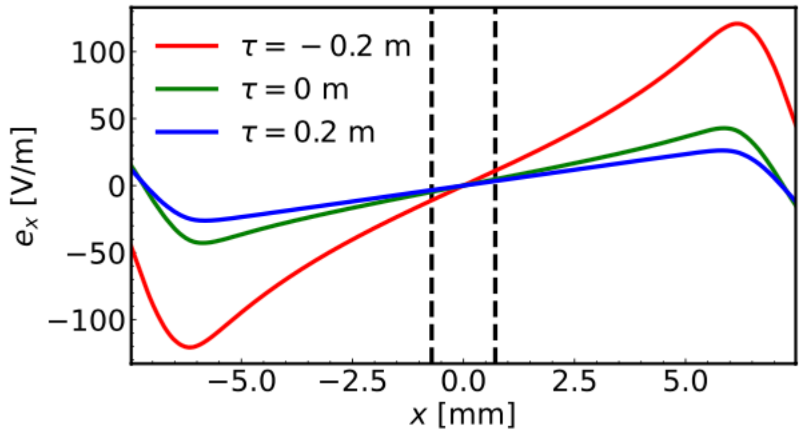




Induced forces

Dipole magnet:





Quadrupole magnet: