Modelling Slow Beam Degradation from Electron Clouds in the Large Hadron Collider

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CERN → DESY

Acknowledgements to my previous colleagues
in the BE-ABP group at CERN

Joint DESY and University of Hamburg
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Outline

1. Introduction to electron clouds and the LHC

2. Scenario 1: Emittance growth at injection energy (450 GeV)

3. Scenario 2: Extra beam losses during collision (6.8 TeV)

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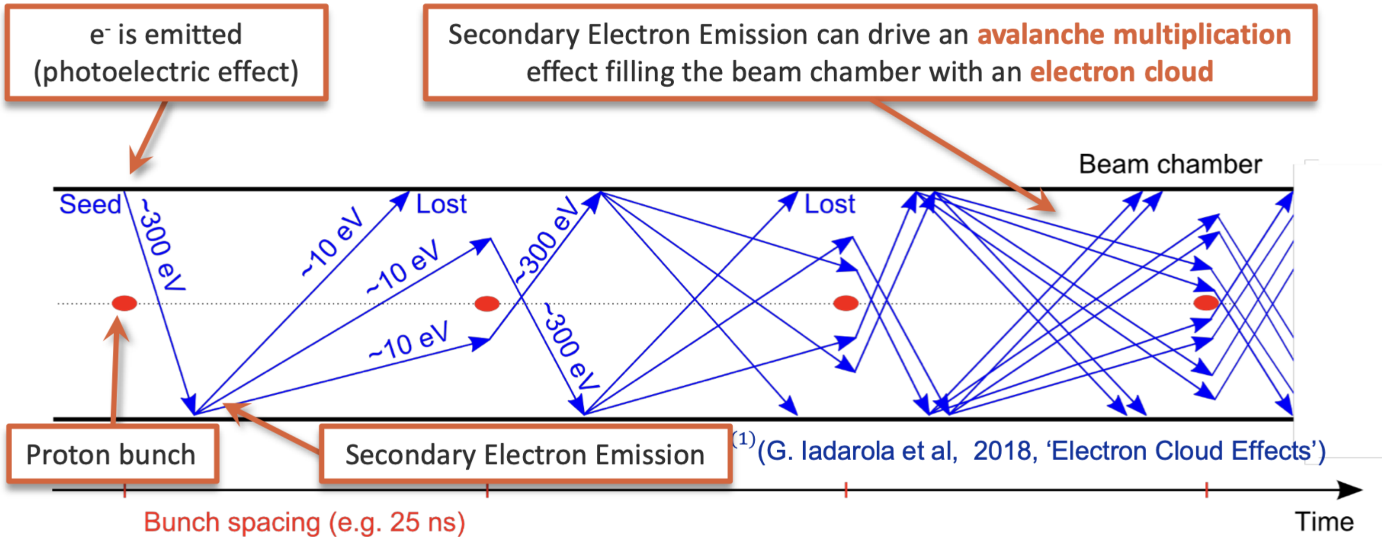
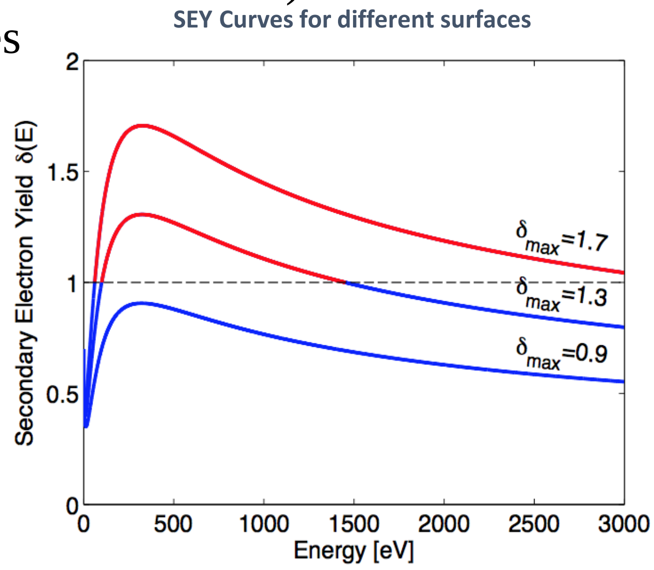
Electron clouds



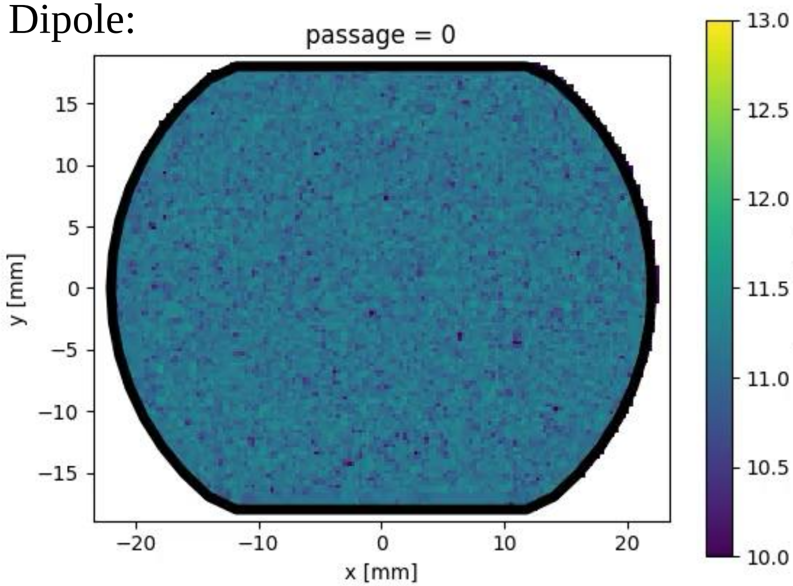
1. Electrons are introduced into the beam chamber (residual gas ionization / synchr. rad. + photoelectric effect)
2. Electrons are accelerated by passing bunches and impact on beam chamber.
   - Depending on energy of electron and **Secondary Emission Yield** of surface, electrons can be emitted.

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

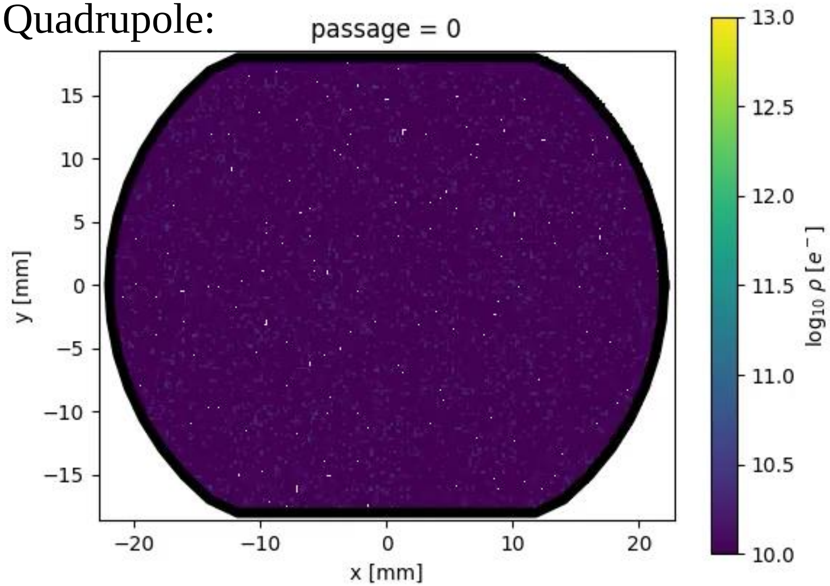


Electron clouds

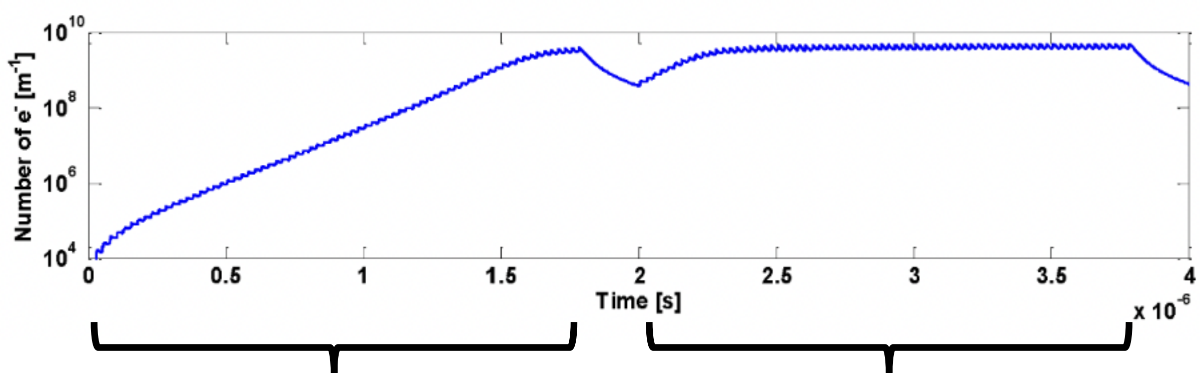
Dipole:



Quadrupole:



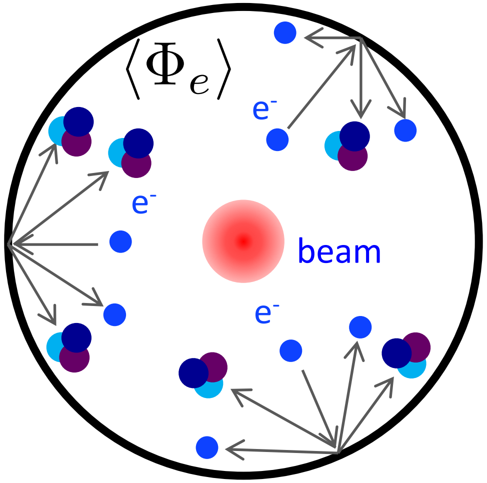
- Electrons multiply until a saturation is reached.
- Number of electrons quickly decays when bunches are not passing.
- Magnetic fields strongly affect the e-cloud.



72 bunch passages

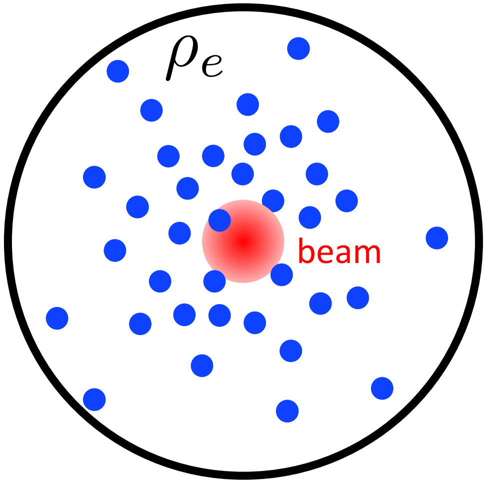
72 bunch passages

Electron cloud effects



The electron flux to the wall is responsible for

- Spurious signal for beam instrumentation
- Dynamic pressure rise
- Heat deposition **(One of the largest limitations in the LHC)**



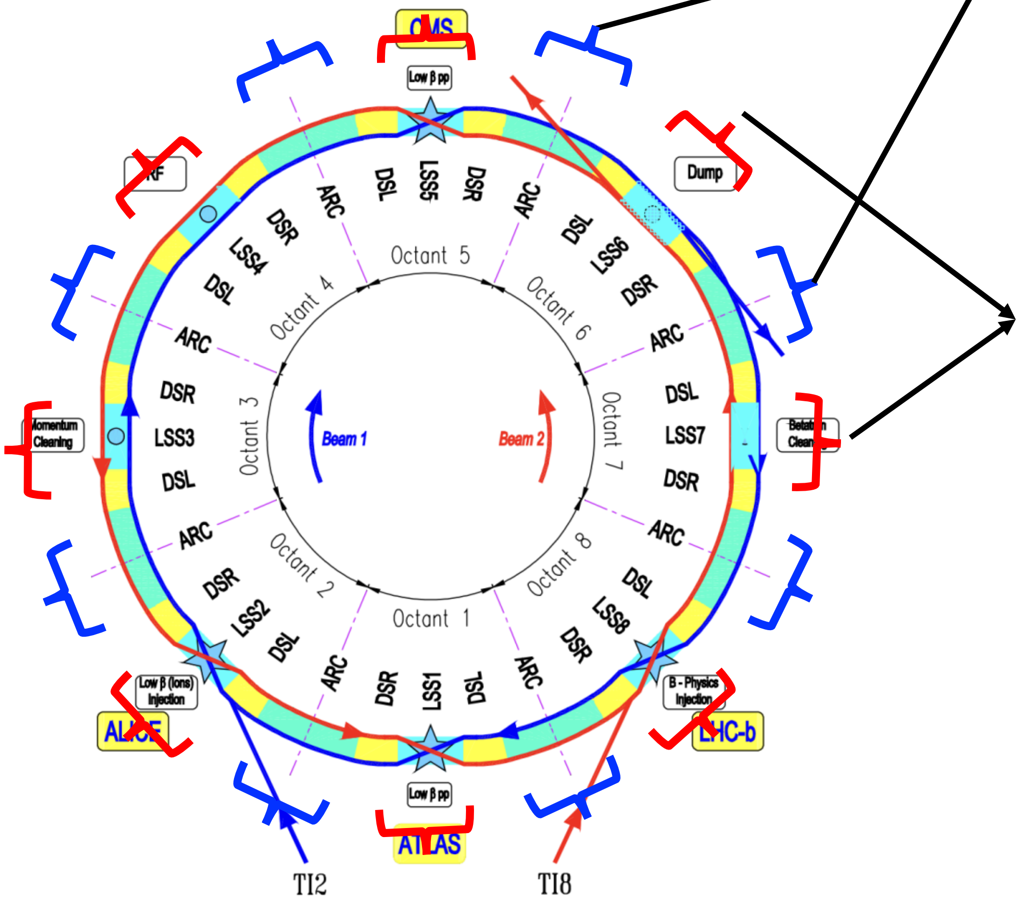
The electron density inside the chamber causes:

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

Focus of this talk

The Large Hadron Collider

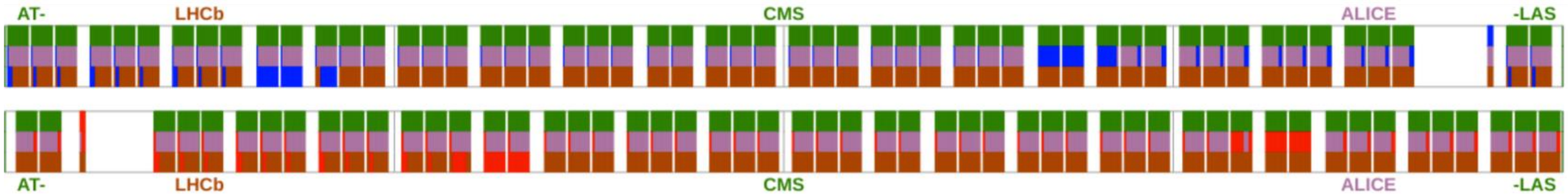
[LHC Design Report]



- 8 Arcs:
  23 "FODO" cells per arc:
  1. Focusing Quadrupole
  2. 3x Dipoles
  3. Defocusing Quadrupole
  4. 3x Dipoles
- 8 Insertion Regions:
  1. **ATLAS**
  2. **ALICE**
  3. Momentum cleaning
  4. RF - Beam Instrum.
  5. **CMS**
  6. LHC Dump
  7. Betratron cleaning
  8. **LHCb**

Primary purpose of the LHC is to provide high-energy proton-proton collisions to the experiments (ATLAS, CMS, ...) which study their byproducts.

Filling scheme



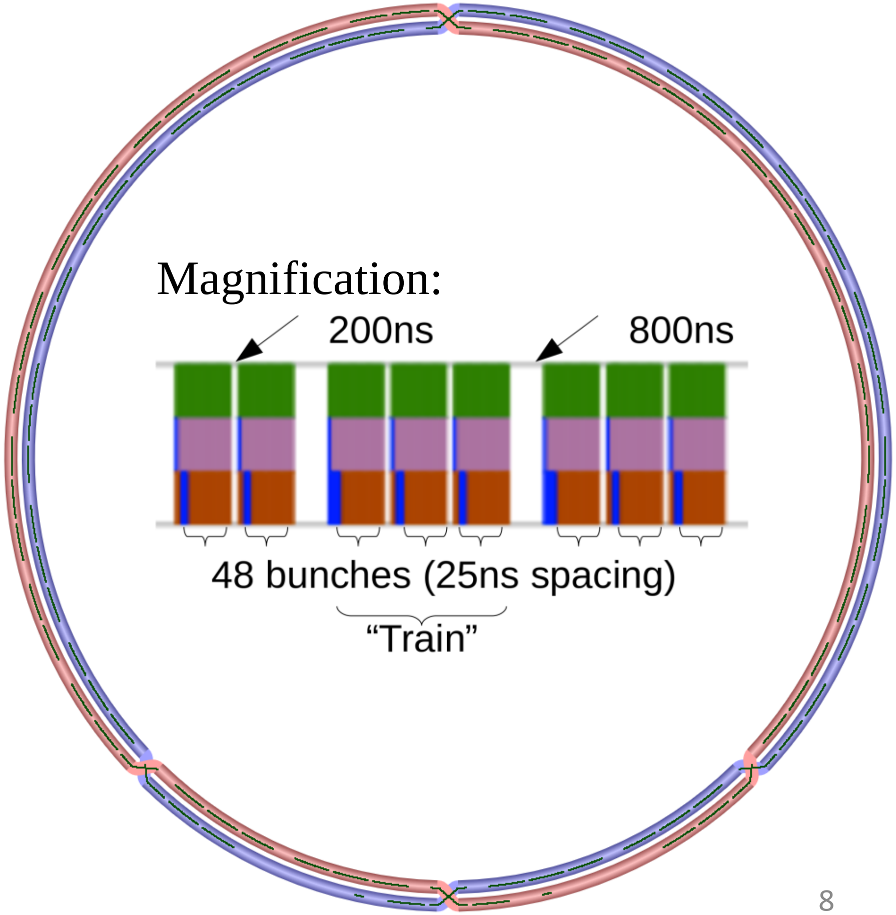
Standard 2018 Physics filling scheme (2556 bunches) [lpc.web.cern.ch]

Beam is composed of repeating patterns (trains):

- 2x48 bunches,
- 3x48 bunches.

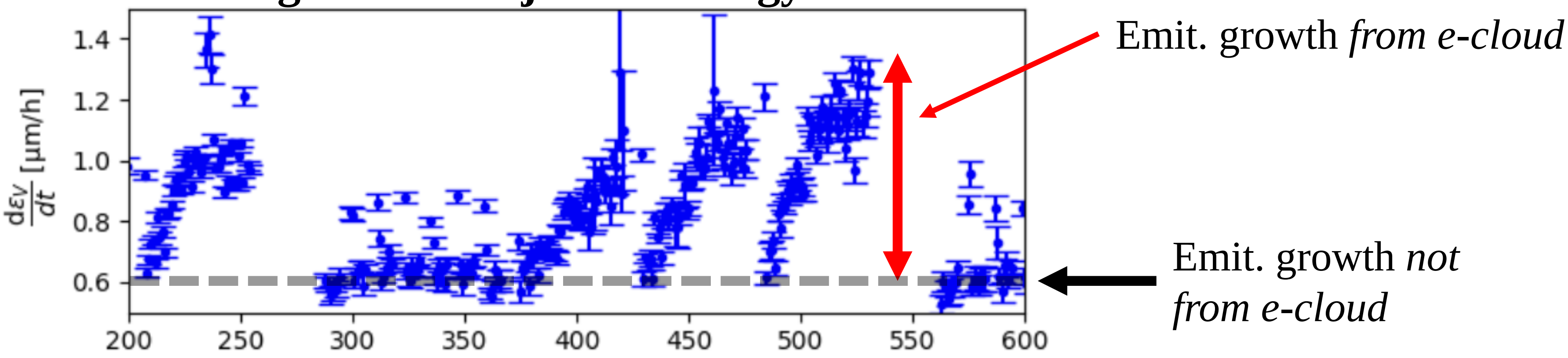
Bunches **spaced by 25ns**.

- 200ns: Small gap, e-cloud partially resets.
- 800ns: Big gap, e-cloud almost completely resets.



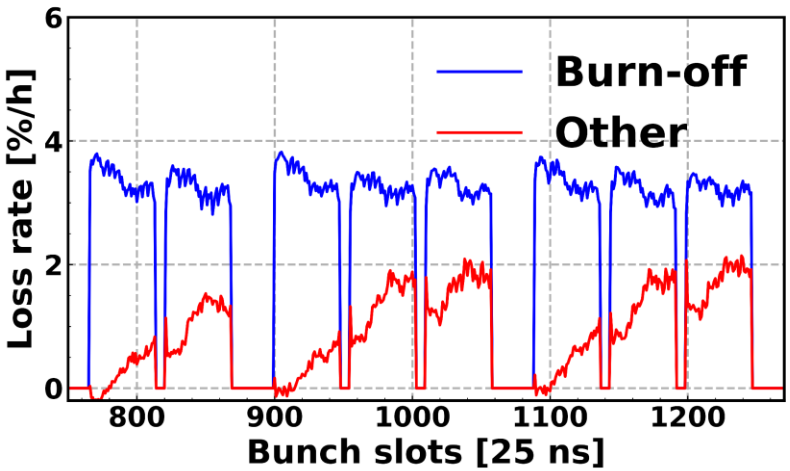
Recognizing electron cloud effects

Emittance growth at injection energy:



Extra beam losses during collisions (6.8 TeV):

- Most losses come from inelastic proton-proton collisions (“burn-off”).
- Additional losses with a pattern that grows within the “train” of bunches.



Universal characteristic of e-cloud to grow from the head to the tail of a beam.

Outline

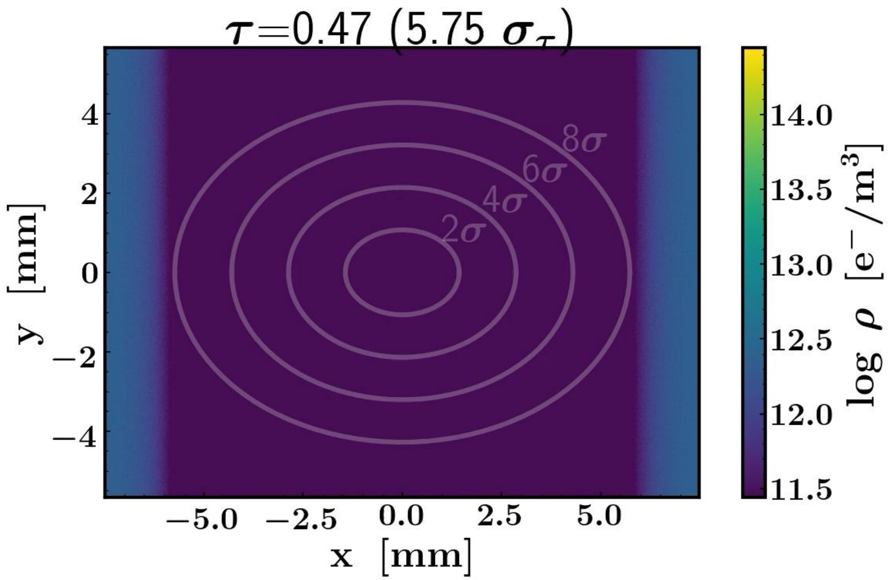
1. Introduction to electron clouds and the LHC

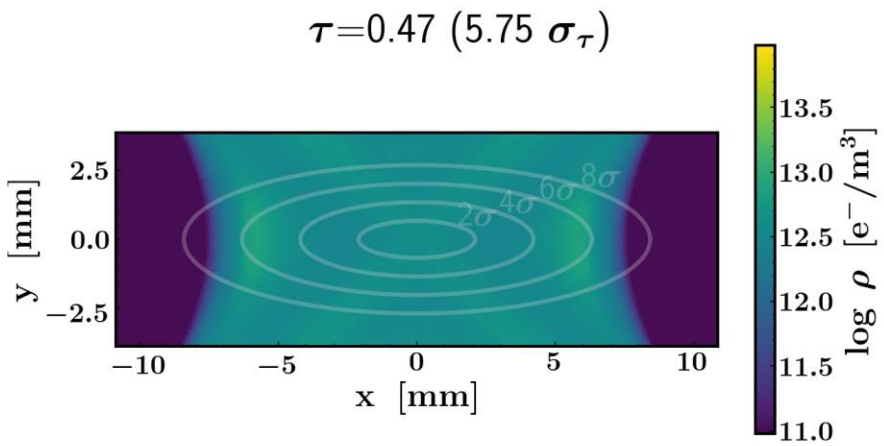
2. Scenario 1: Emittance growth at injection energy (450 GeV)

3. Scenario 2: Extra beam losses during collision (6.8 TeV)

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"

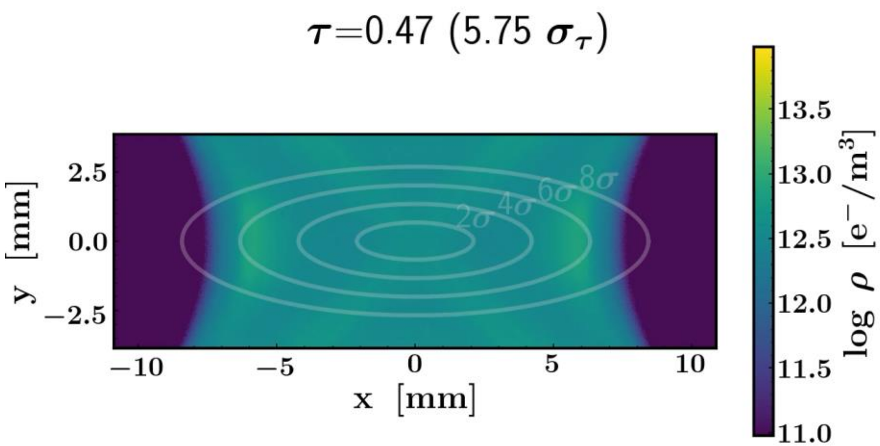
→ Increase of proton oscillation amplitude → losses + emittance growth.

Electron cloud pinch

- Collective effect
- Affects single-particle dynamics
- E-cloud dynamics: **~ ns**
- Single-particle dynamics: **~ minutes**
- Complex forces

Weak-strong approximation:

- Compute evolution of electron cloud once (PyECLOUD).
- Field-maps of several GB.
- Re-use in particle tracking code (Xsuite).
- Simulate non-linear lattice of LHC.



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

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

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

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

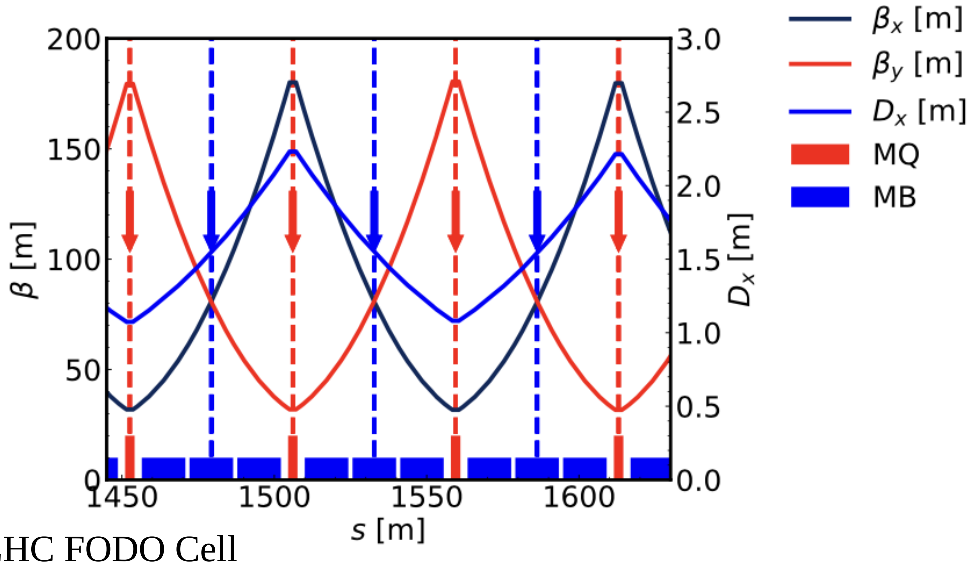
- 3D grid (~400^3 points) of scalar potential φ, interpolated to provide symplectic kick, with a thin-lens approximation.

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.

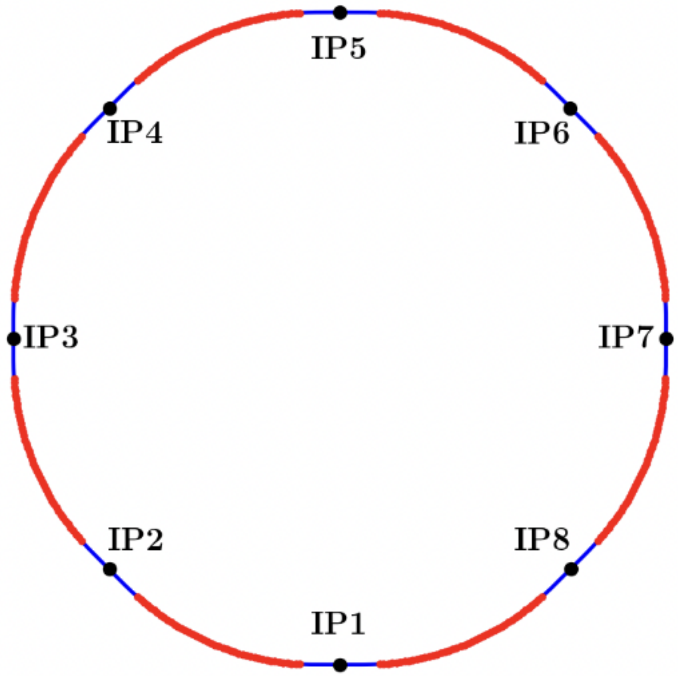


LHC FODO Cell

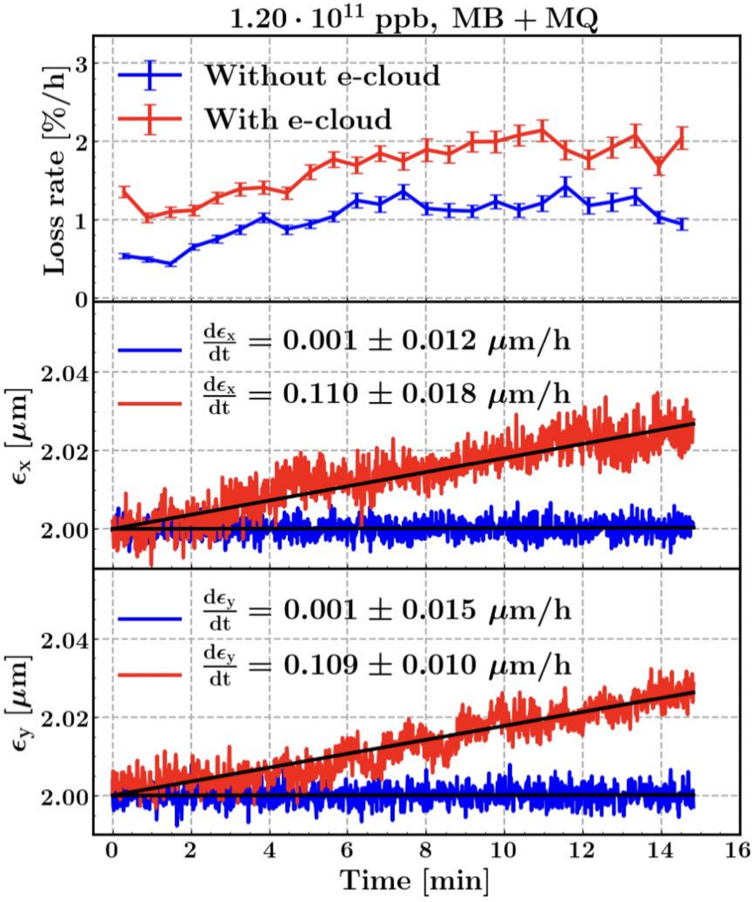
- Betatron and dispersion functions stay the same between each cell.
- Approximate SEY as uniform everywhere. Large fluctuations in reality.
- Effect from saturated e–cloud.

E-cloud setup

- One dipole-type e-cloud per half-cell
→ 46 interactions per arc
→ 368 interactions.
- One quadrupole-type e-cloud per half-cell
→ 45 interactions per arc
→ 360 interactions.



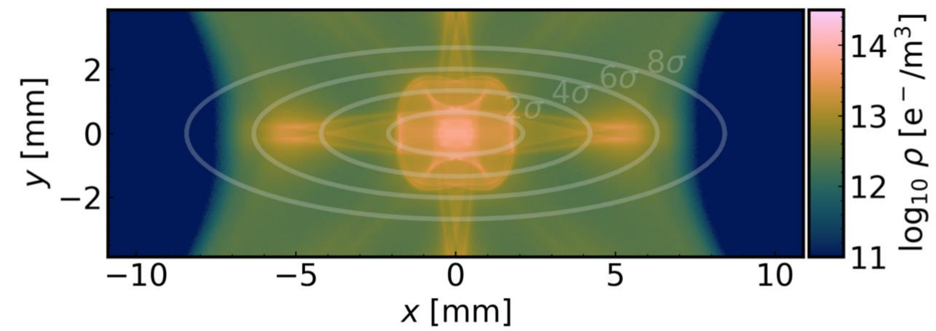
Tracking time per e-cloud type (~360 interactions) is about as much as rest of the lattice (11k tracking elements).

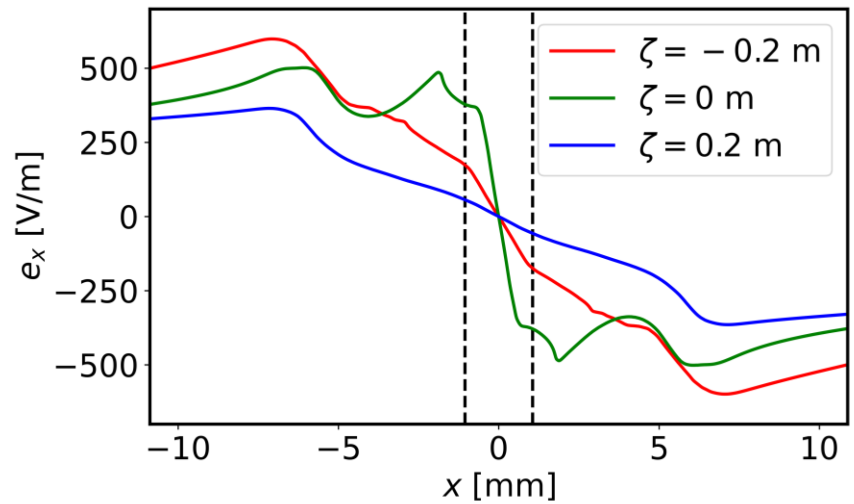


Total simulation time: ~ 7 days for 10M turns (15 minutes of beam time), 20 000 particles, per Nvidia V100 GPU

Electron cloud induced forces

- Emittance growth is driven by the e-cloud in the main quadrupoles.
- Electron clouds induce **time-dependent** forces.
- Forces are highly non-linear in the vicinity of large local densities.
- Clouds forming in quadrupoles exhibit strong density in the center.
- In the LHC, $\approx 90^{o}$ phase advance between main quadrupoles in the arcs.





Optics and incoherent e-cloud effects at injection

- Off-momentum Frequency Map Analysis

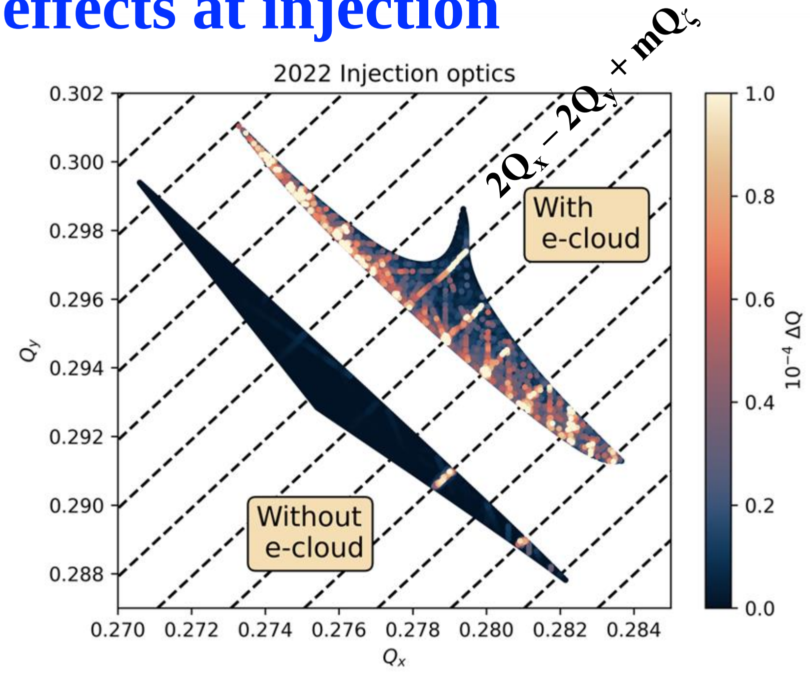
- Synchro-betatron resonances identified as cause of emittance growth ($2Q_x - 2Q_y + mQ_\zeta = 4$)

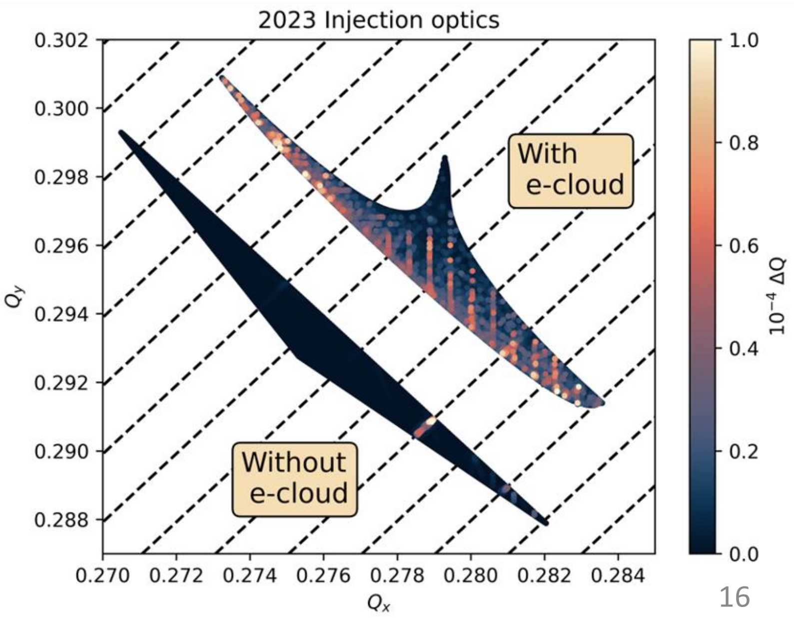
- Modifications to the LHC injection optics were proposed to: Change phase advance between different arcs to self-compensate **Resonance Driving Terms**.

  a) from main octupole magnets.

  b) from electron clouds in the main quadrupoles.

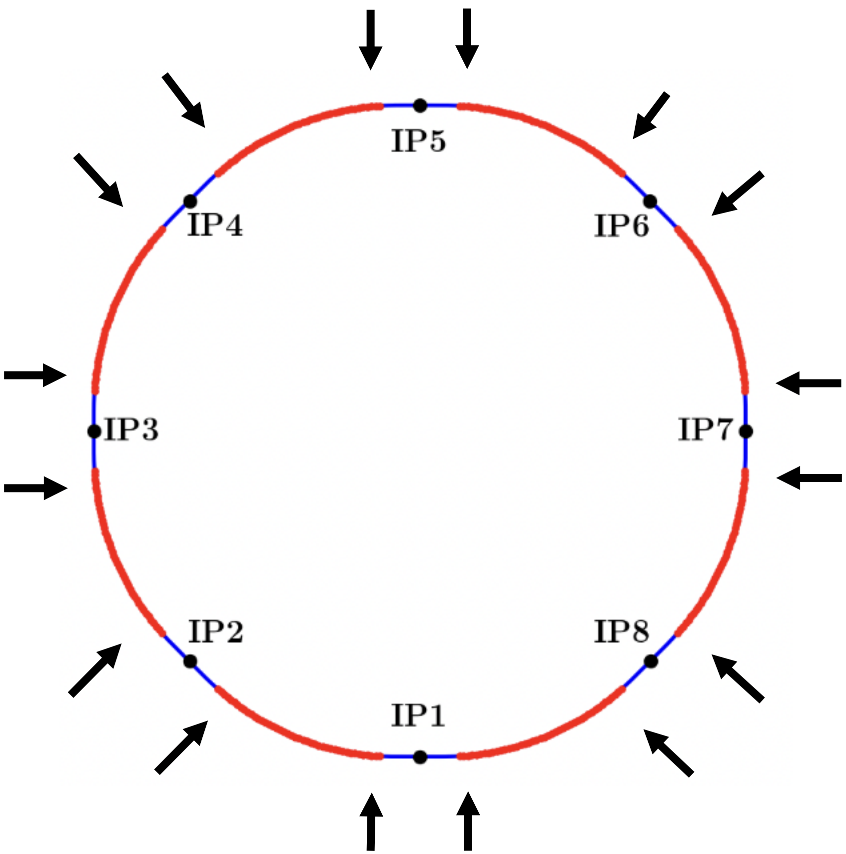
- New optics in operation since 2023.





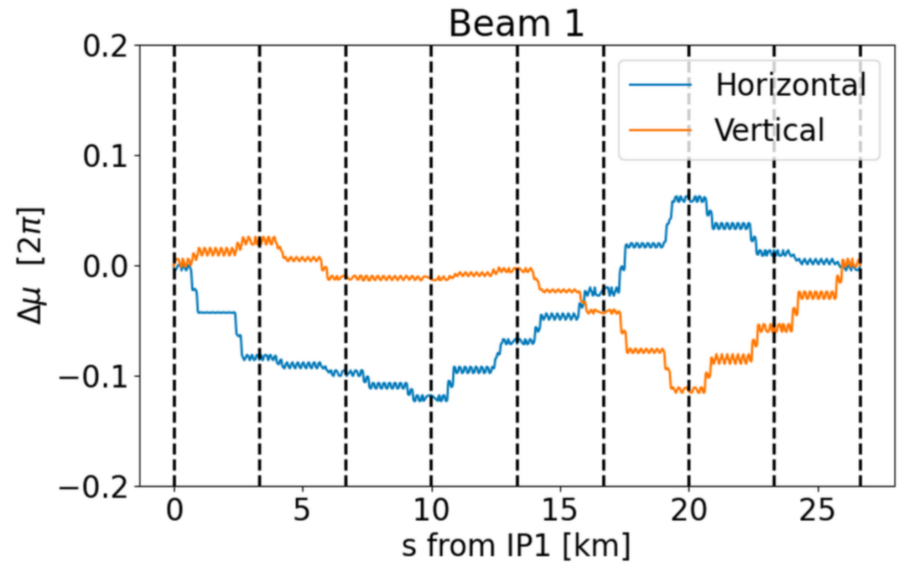
Optics change

"Trim" quadrupoles, used for tune change.

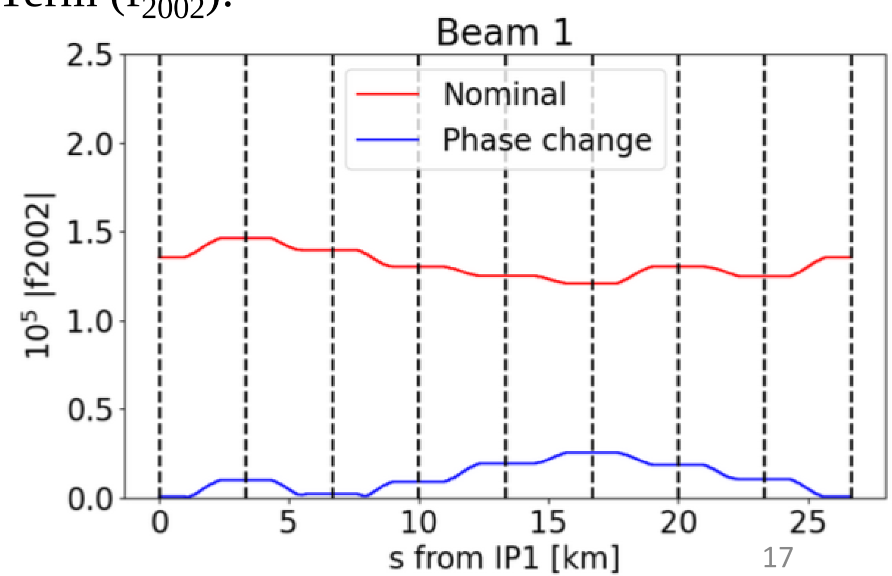


- Small change on beta functions (< 5%).

Induced phase advance change:



Effect on octupoles' Resonance Driving Term (f_{2002}):



Expectations from simulation

Old optics,
new optics

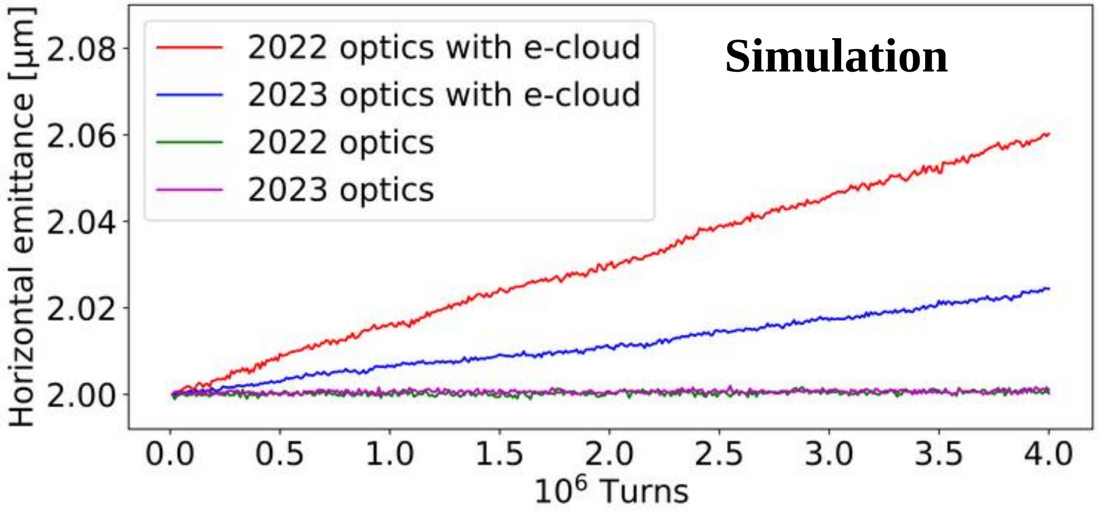
Repeating the emittance growth simulations:

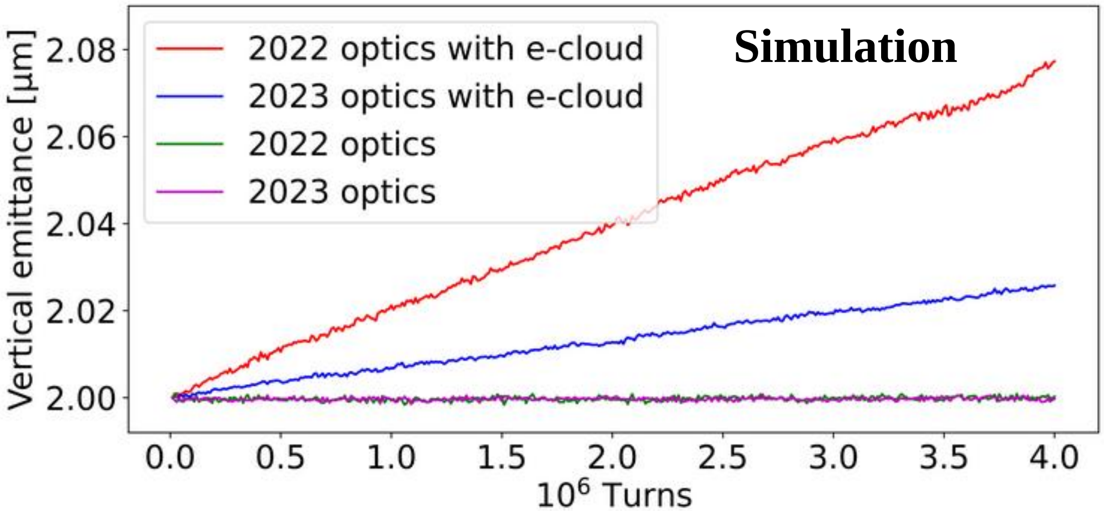
- Emittance growth rate is not expected to go to zero.

Additional effects not shown here:

- Reduction of beam loss rate,
- Reduction of "halo" formation (non-gaussian transverse beam profile)

Simulations (and optics modification) assume electron cloud is uniformly distributed along the different quadrupoles.
In reality it is not.





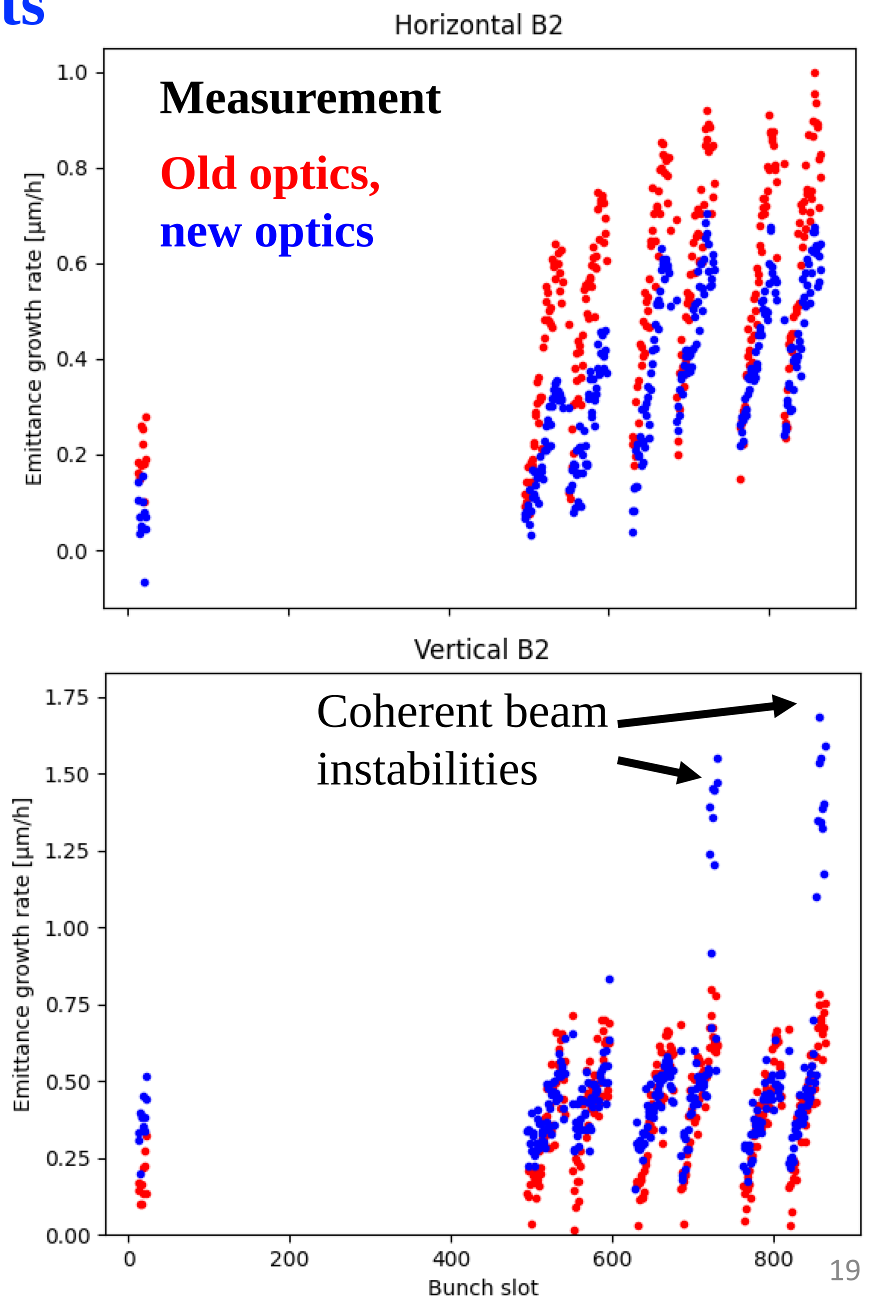
Experimental measurements

- Machine studies in 2024 confirm the positive impact on emittance.

- Positive impact also on beam lifetime, and beam halo formation.

Unexpected feature :

- Emittance growth of "first" bunch (not e-cloud) is sometimes increased.



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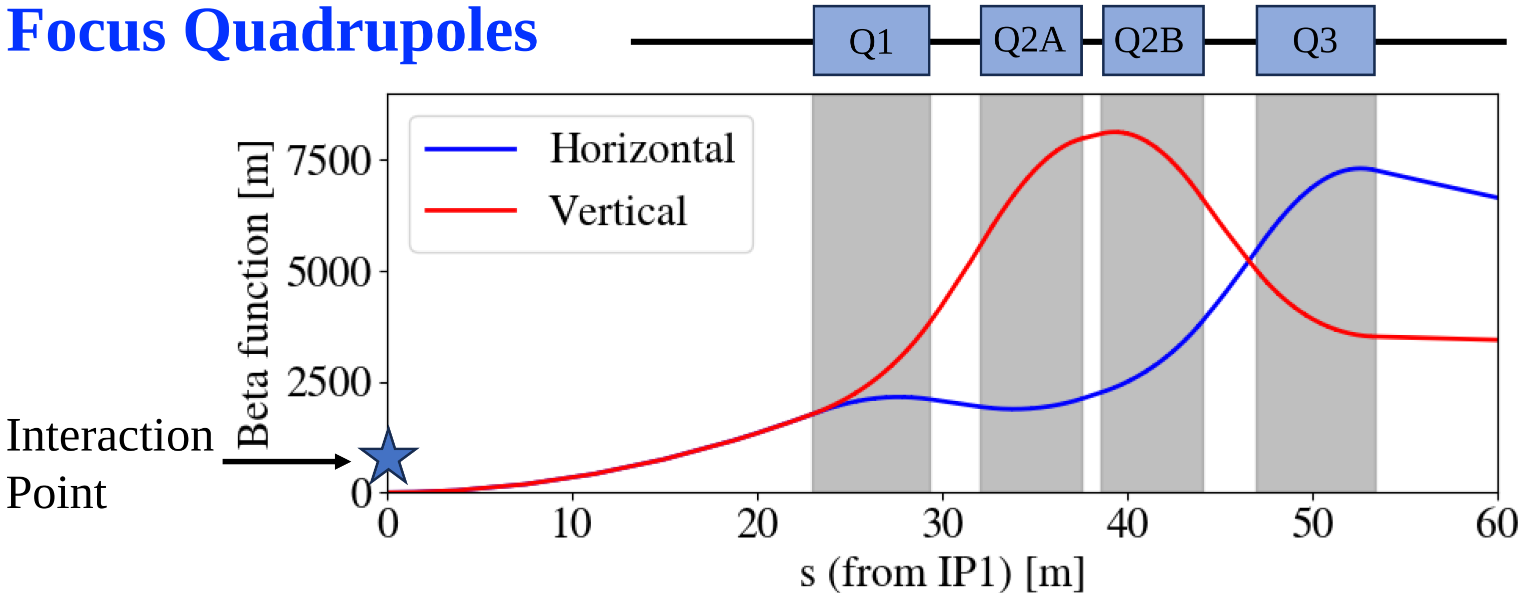
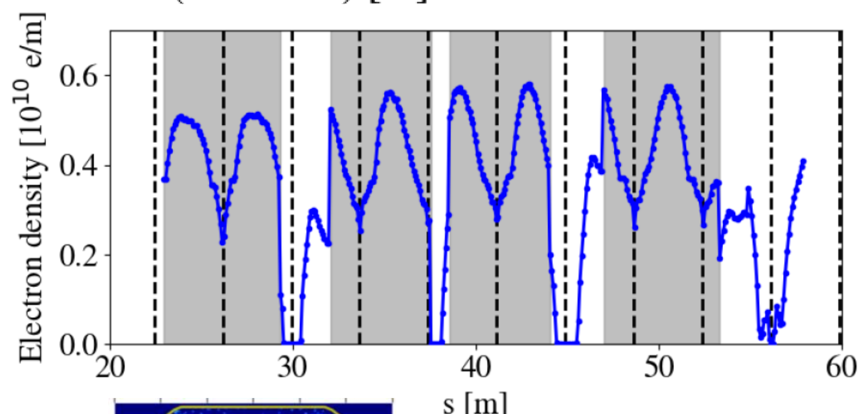
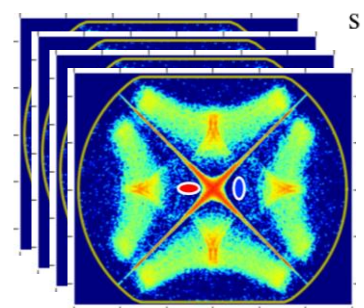
Simulating electron cloud in the Final Focus Quadrupoles



- E-cloud in final focus quadrupoles (Inner Triplets) known to cause slow beam loss when beams are in collission.
- E-cloud density strongly depends on location.



- 384 slices per triplet → 4 triplets, 1536 slices.
- ≈ 4GB per slice → **≈ 6 TB**
  not sustainable



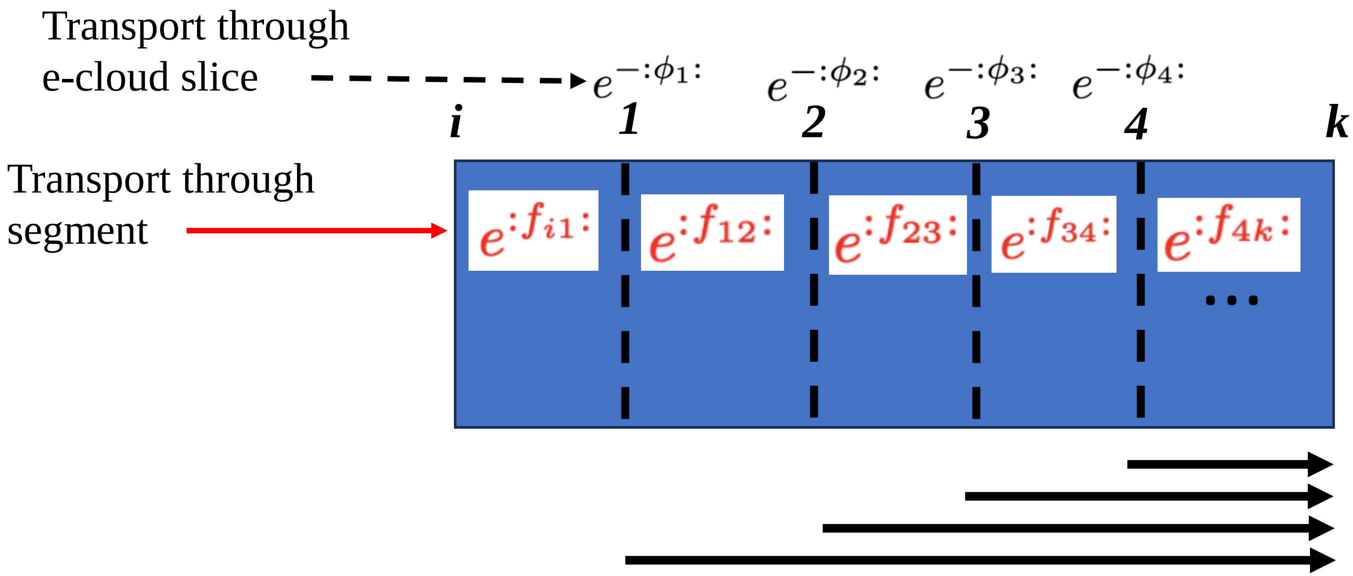
Strategy

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

An e-cloud slice can be described by a scalar potential $\phi(x, y, \zeta)$ in a thin-lens formalism.

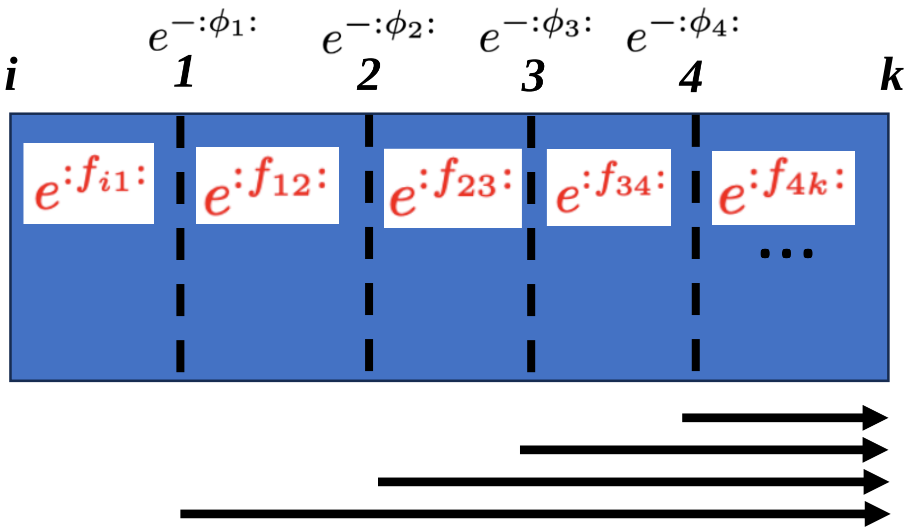
1. Transport slices to same location.
2. Slices commute (only depend on x, y, ζ). They can be summed.

$$
\left.
\begin{aligned}
x, y, \zeta &\mapsto x, y, \zeta \\
p_x &\mapsto p_x - \frac{qL}{\beta_0 P_0 c}\frac{\partial \phi}{\partial x}(x, y, \zeta) \\
p_y &\mapsto p_y - \frac{qL}{\beta_0 P_0 c}\frac{\partial \phi}{\partial y}(x, y, \zeta) \\
p_\zeta &\mapsto p_\zeta - \frac{qL}{\beta_0 P_0 c}\frac{\partial \phi}{\partial \zeta}(x, y, \zeta)
\end{aligned}
\right\} e^{-:\phi:}
$$



ζ refers to s – $\beta_0$ct, the longitudinal distance from the reference particle

Approximations



(1st approximation):
Courant-Snyder parameterization

$$e^{:f_{ij}:}x = \sqrt{\frac{\beta_j}{\beta_i}}\left(\cos\mu_{ij} + \alpha_i \sin\mu_{ij}\right)(x - x_i) + \sqrt{\beta_i\beta_j}\,\sin\mu_{ij}\left(p_x - p_{x,i}\right) + x_j$$

(2nd approximation):
Constant phase advance $\mu_{ij} \approx 0$

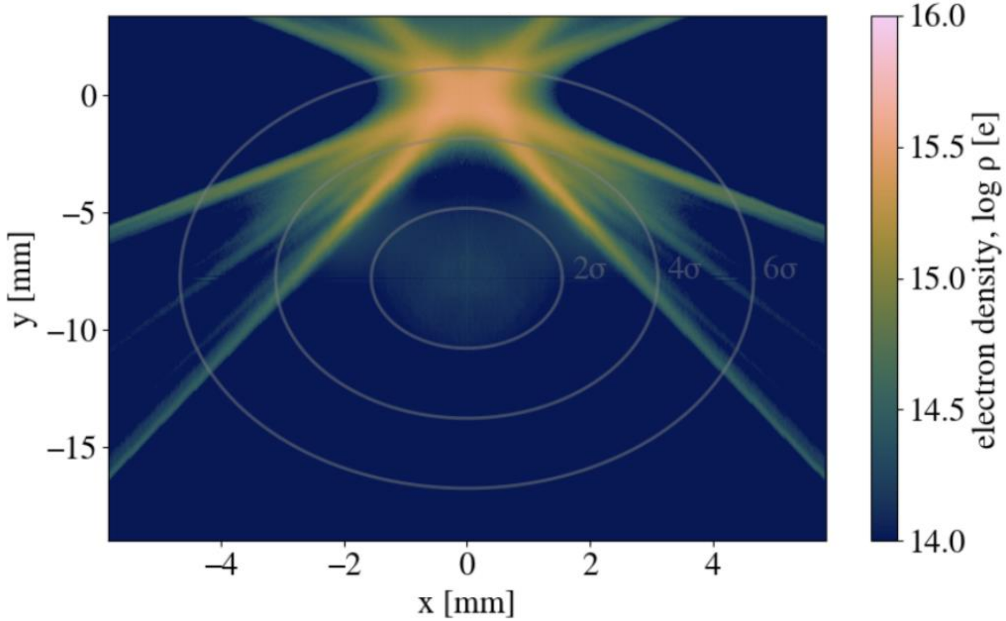
(3rd approximation):
No longitudinal motion $e^{:f_{ij}:}\zeta = \zeta$

Effective (lumped) e-cloud:

$$\Phi(x,y,\zeta) = \sum_i \phi_i\left(\sqrt{\frac{\beta_{x,i}}{\beta_{x,k}}}(x - x_k) + x_i,\ \sqrt{\frac{\beta_{y,i}}{\beta_{y,k}}}(y - y_k) + y_i,\ \zeta\right)$$

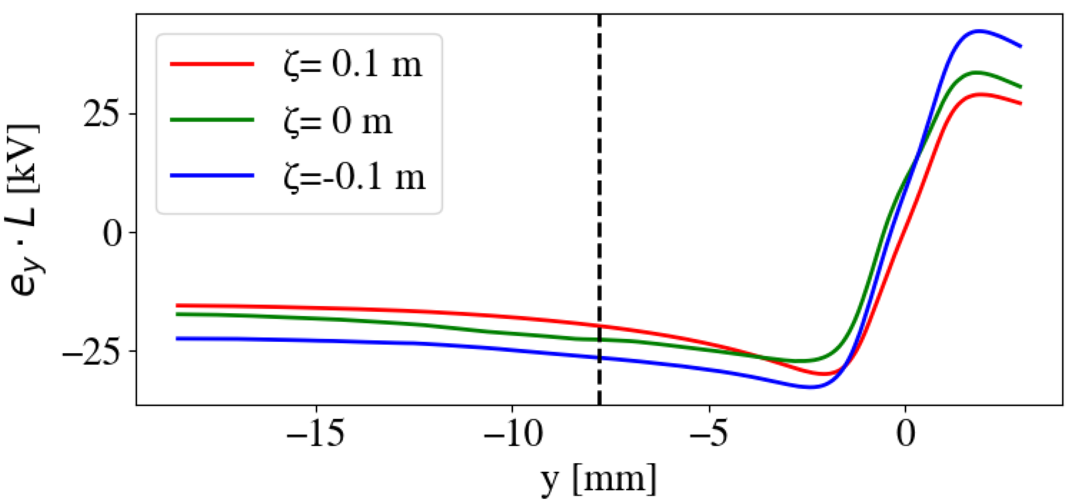
- Combines all slices into one scalar potential.
- Equation can be evaluated on a 3D grid, and treated as a single slice.

Effective e-cloud



$$\Phi(x, y, \zeta) = \sum_i \phi_i \left(\sqrt{\frac{\beta_{x,i}}{\beta_{x,k}}} (x - x_k) + x_i, \sqrt{\frac{\beta_{y,i}}{\beta_{y,k}}} (y - y_k) + y_i, \zeta \right)$$

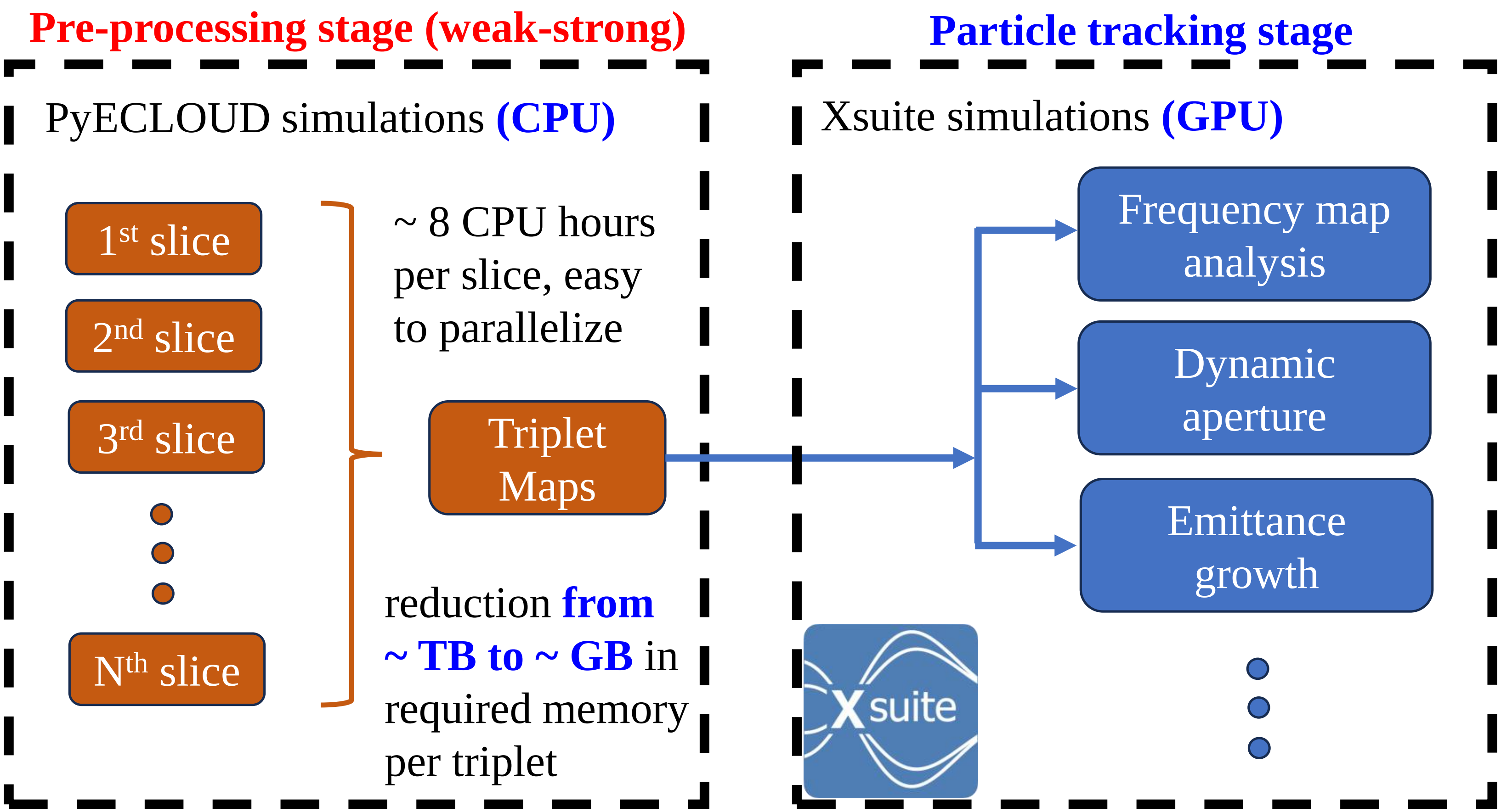
- Non-linear time-dependent forces.
- Forces become exceedingly non-linear at large amplitudes of oscillation.



Weak-strong simulations:

- Assume e-cloud is in a steady state.
- Map is constructed once in a “pre-processing stage”, and re-used during particle tracking.

Simulation flow



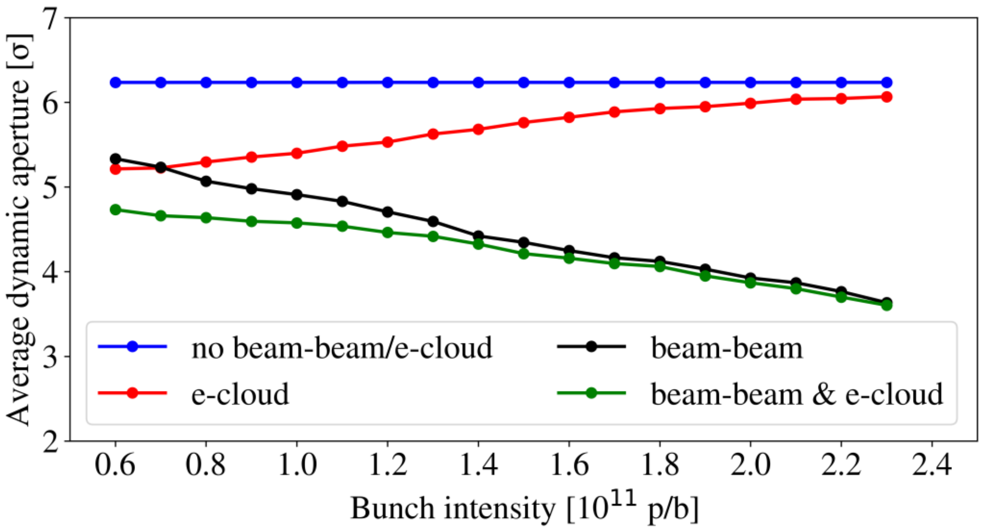
Tracking time for 1 000 000 turns, 20 000 particles in A100 GPU:

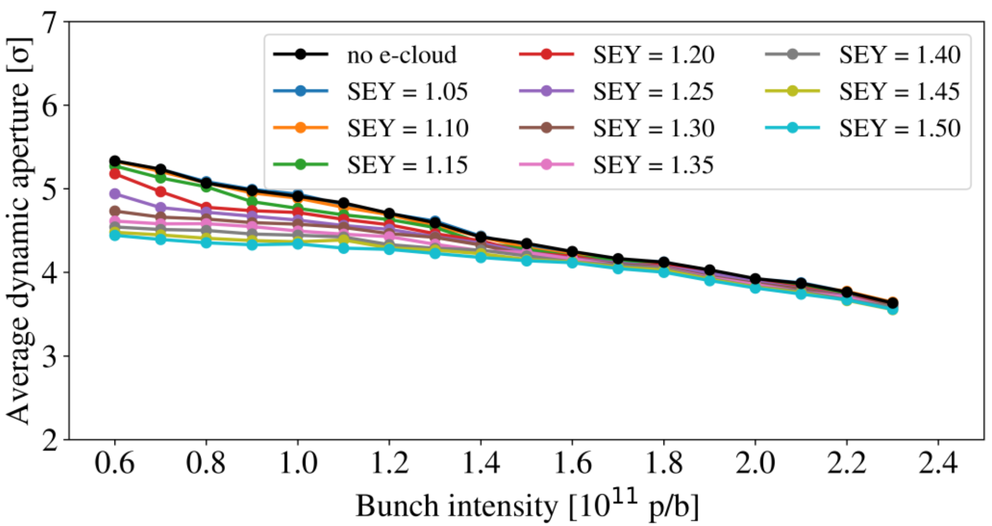
LHC lattice :	5.7 hours
LHC lattice + beam-beam :	6.1 hours
LHC lattice + beam-beam + e-cloud :	7.0 hours

Dynamic aperture

Dynamic aperture over 1 000 000 turns, including the e-clouds in the 4 inner triplets (left and right of i.p. 1 and 5).

- E-cloud in triplet scales favorably with higher intensity.
- E-cloud effects can become as strong as beam-beam effects at low bunch intensities.
- E-clouds are worse with larger Secondary Emission Yield (SEY).
- SEY < 1.10 will be enough to mitigate the effect of e-cloud in the triplets.





Summary

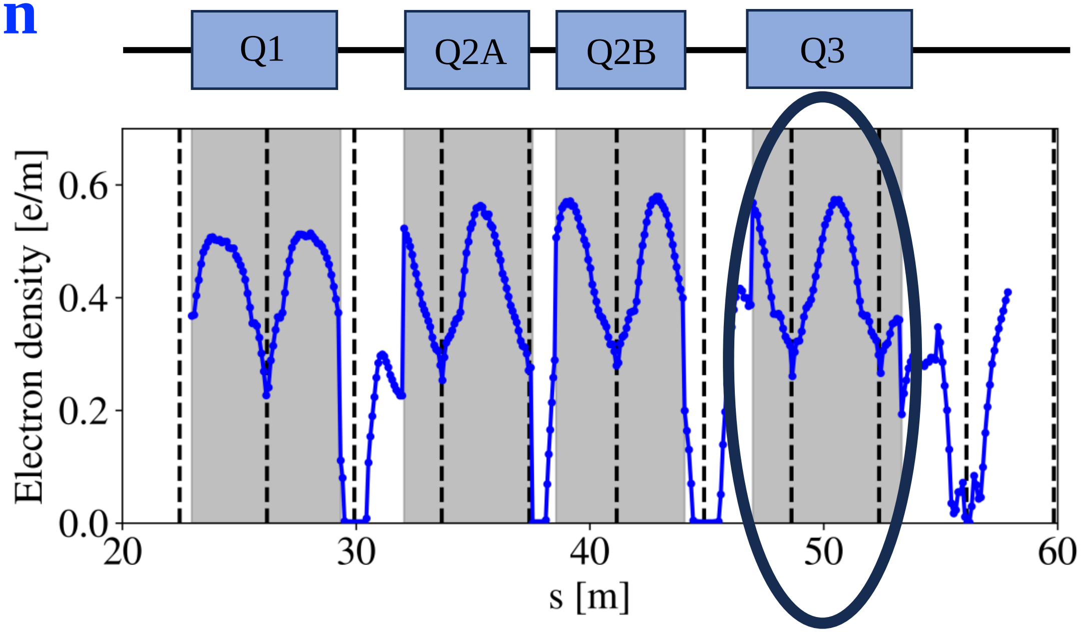
- Simulated **incoherent electron cloud effects**, massive simulation campaigns with GPUs.

- At injection energy:
  - Found in simulations the measured emittance growth.
  - Unexpectedly, realized that optics could partially alleviate some of the undesired effects.
  - Optics in operation since 2023, enjoying the benefits.

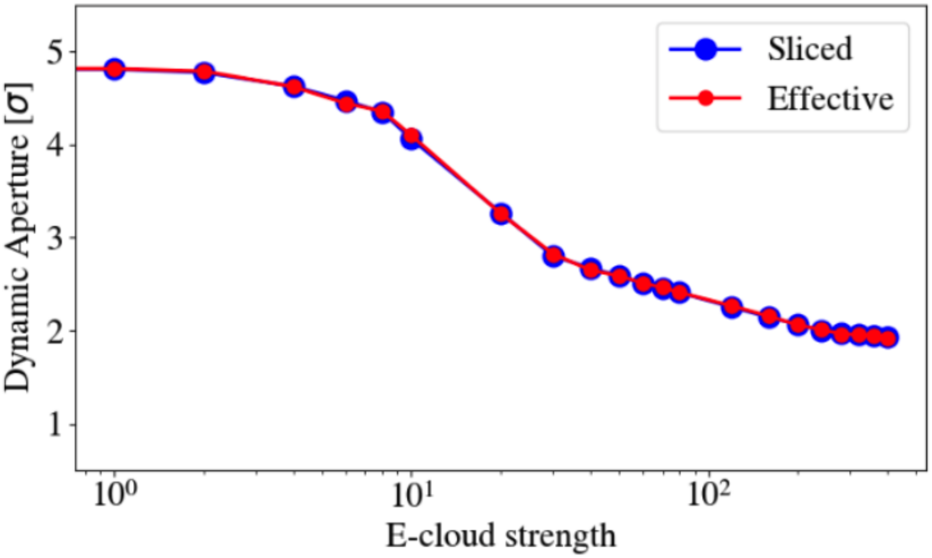
- During collisions:
  - Extremely complex electron cloud field-maps, requiring ~TBs of memory.
  - Developed method to simulate with sustainable memory requirements.
  - Reproduced qualitative behavior in simulations (dynamic aperture).
  - Reassured that measures taken for the High-Luminosity LHC Upgrade (amorphous carbon coating) are sufficient.

Thank you for your attention!
Konstantinos Paraschou

Validation

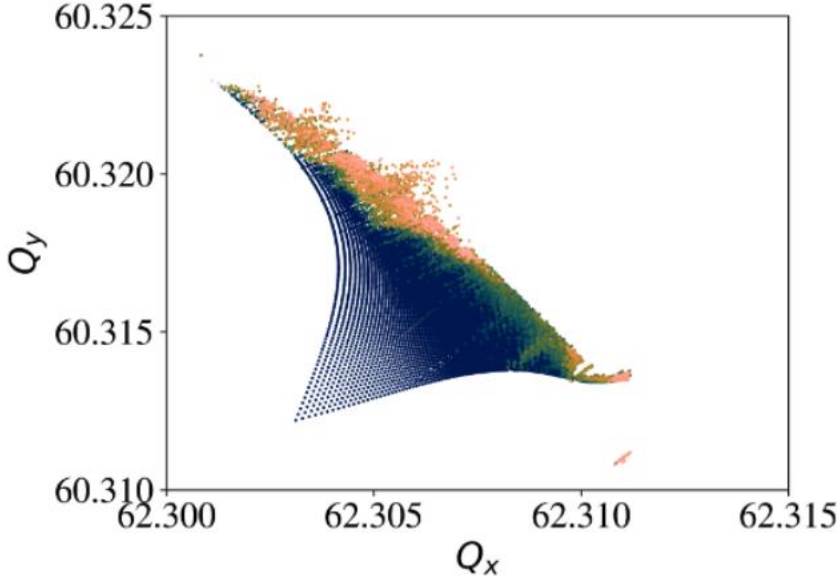


- Focus on Q3 quadrupole (right of interaction point 1): Q3R1.
- 64 slices, can fit in 1TB RAM computers.
- Dynamic aperture simulations to test previous equation.
- Good agreement.

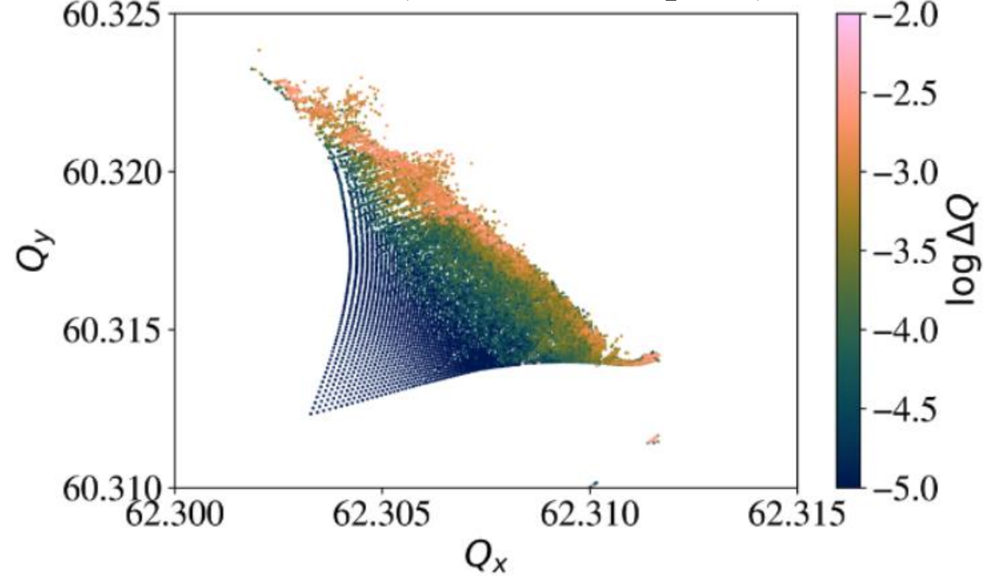


Frequency Map Analysis

Beam-beam effects



Beam-beam effects &
e-cloud (in 4 Inner Triplets)



- Tracking over 100 000 turns, tune evaluated over:
  - First 50 000 turns,
  - Last 50 000 turns.

Difference in tune → tune is not constant and so trajectory is chaotic.

- E-cloud doesn’t cause a significant tune-shift (compared to beam-beam effects)
- Visible effect of e-cloud → increase of non-linearities.

Dynamic aperture
Tune scan

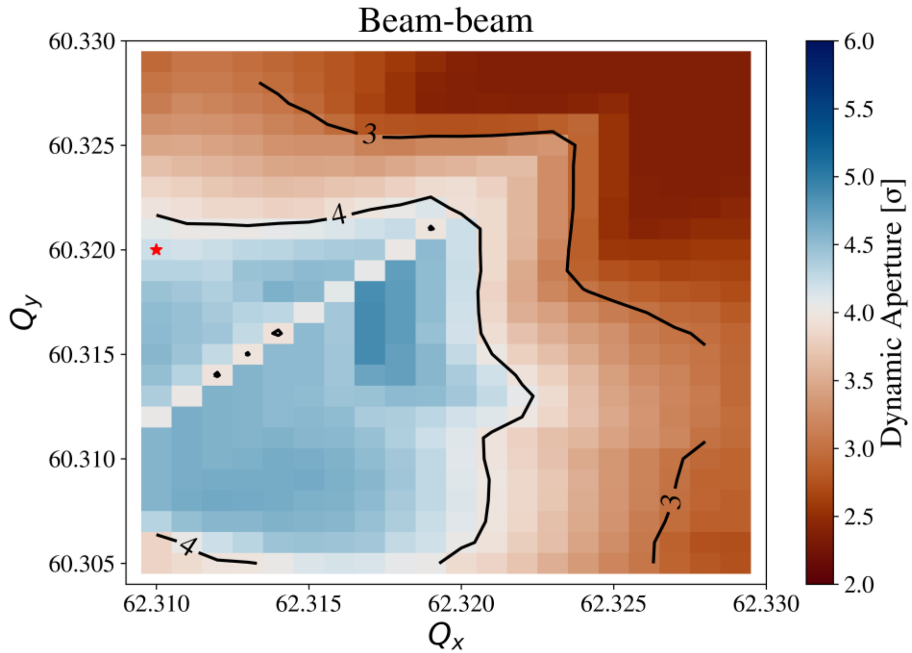
Dynamic aperture over 1 000 000 turns, including the e-clouds in the 4 inner triplets (left and right of i.p. 1 and 5). Simulations varying the working point.

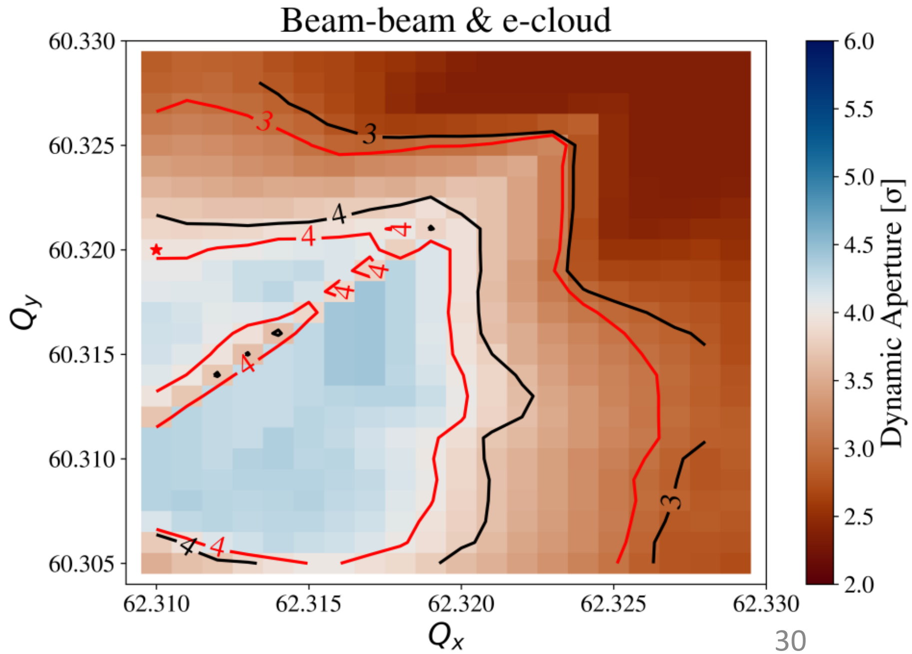
- E-cloud effects cause a reduction of dynamic aperture for all tunes.
- The optimal working point remains similar.

Simulation parameters:

Bunch intensity = 1.2 10^{11} p/b

SEY = 1.30





Synchro-betatron RDTs

Resonance: $(j-k)Q_x+(l-m)Q_y$

Octupole:

$$f^{(1)}_{jklm}(s) = \frac{\sum_w h_{w,jklm} e^{i[(j-k)\Delta\phi^{(s)}_{w,x}+(l-m)\Delta\phi^{(s)}_{w,y}]}}{1-e^{2\pi i[(j-k)Q_x+(l-m)Q_y]}}$$

$$H \propto (x^4 - 6x^2y^2 + y^4)$$

Electron cloud:

$$f^{(1)}_{jklmno}(s) = \frac{\sum_w h_{w,jklmno} e^{i\left[(j-k)\Delta\phi^{(s)}_{w,x}+(l-m)\Delta\phi^{(s)}_{w,y}+(n-o)\Delta\phi^{(s)}_{w,\zeta}\right]}}{1-e^{2\pi i[(j-k)Q_x+(l-m)Q_y+(n-o)Q_\zeta]}}$$

$$\tilde{H}_{ec}(x,y,\zeta) = \sum_k \varphi_{00k}\zeta^k + \quad \text{(acceleration)}$$

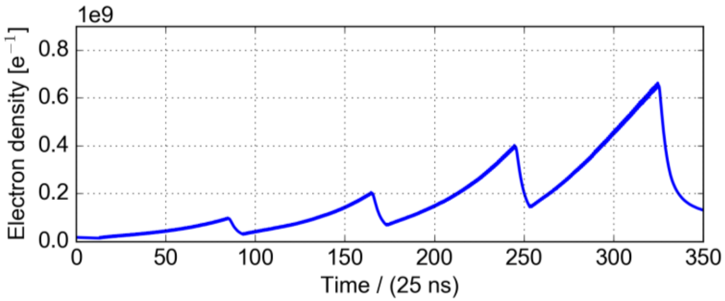
$$+ x^2\sum_k \varphi_{20k}\zeta^k + y^2\sum_k \varphi_{02k}\zeta^k + \quad \text{(tune shift, chromaticity-like effects)}$$

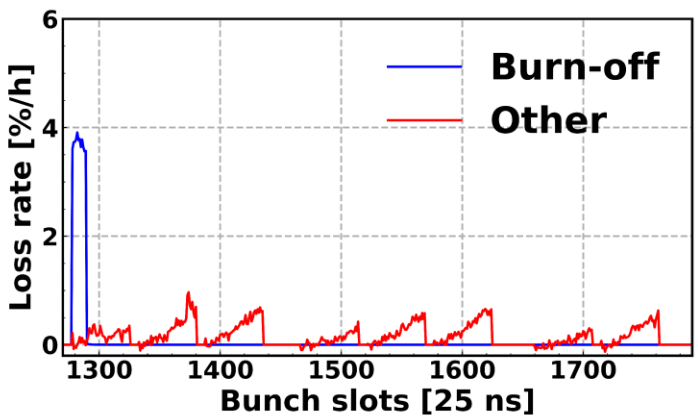
$$+ x^4\sum_k \varphi_{40k}\zeta^k + x^2y^2\sum_k \varphi_{22k}\zeta^k + y^4\sum_k \varphi_{04k}\zeta^k + \quad \text{(octupole-like)}$$

$$+ \dots$$

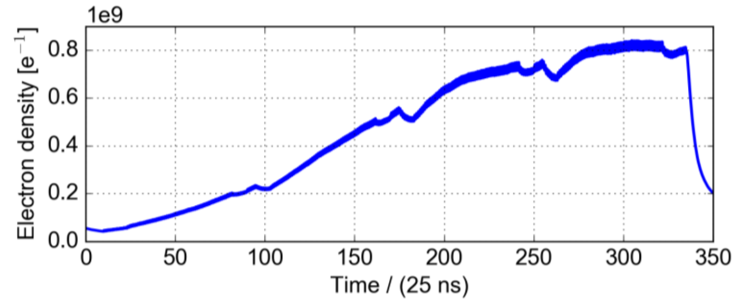
Buildup simulations in Inner Triplet quadrupoles

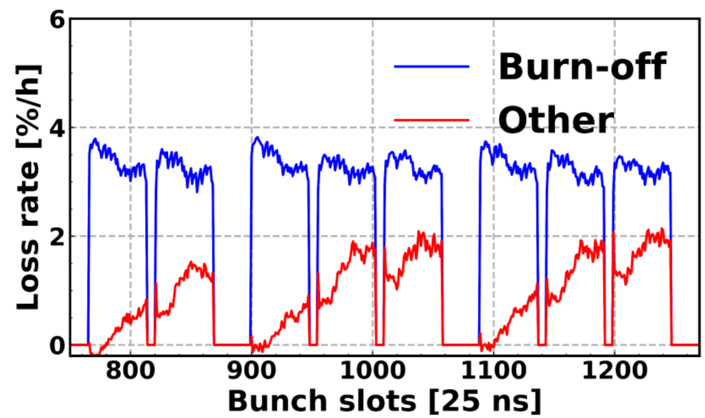
One beam:





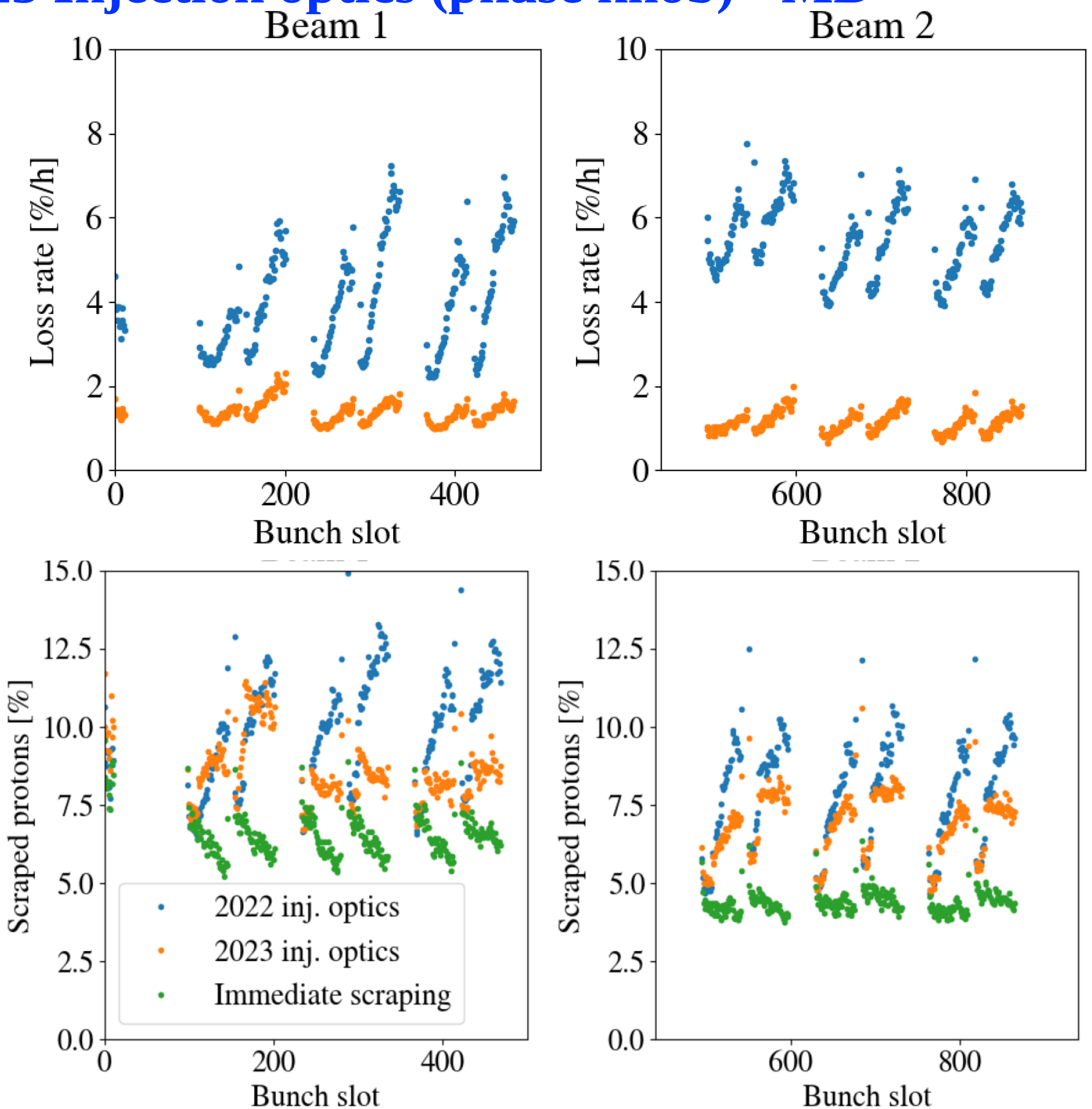
Two beams:



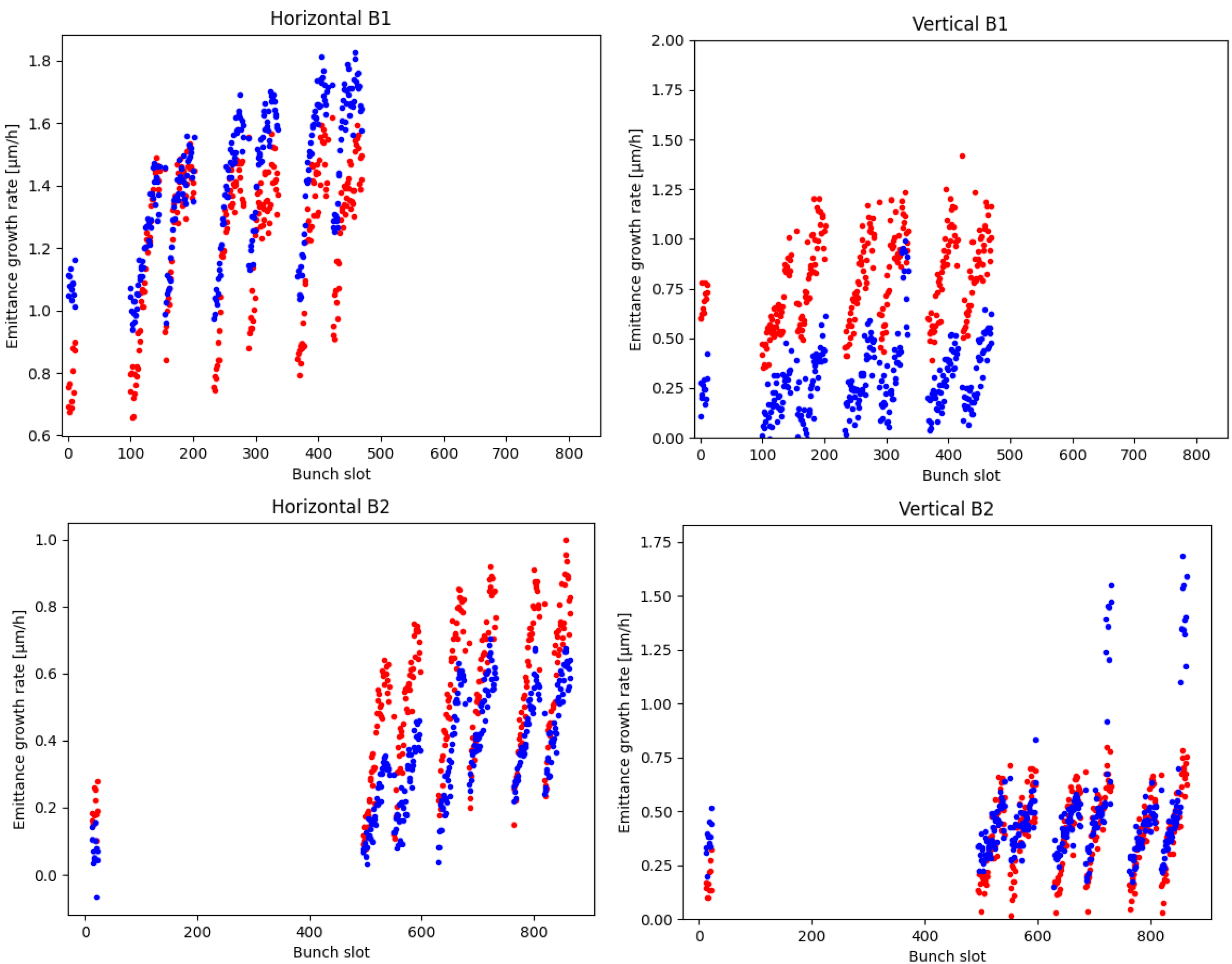


The bunch-by-bunch pattern of the losses resembles the e-cloud buildup simulations of the Inner Triplet quadrupoles.

2023 Injection optics (phase knob) - MD



2023 Injection optics (phase knob) - MD



Lie tranformations

Lie transformations are operators that describe the solution of Hamiltonian systems:

$$z(L) = e^{-:LH:} z(0)$$

where $:H: f = [H, f] = \sum_i \left(\frac{\partial H}{\partial q_i} \frac{\partial f}{\partial p_i} - \frac{\partial f}{\partial q_i} \frac{\partial H}{\partial p_i} \right)$ is the Poisson bracket.

Example:

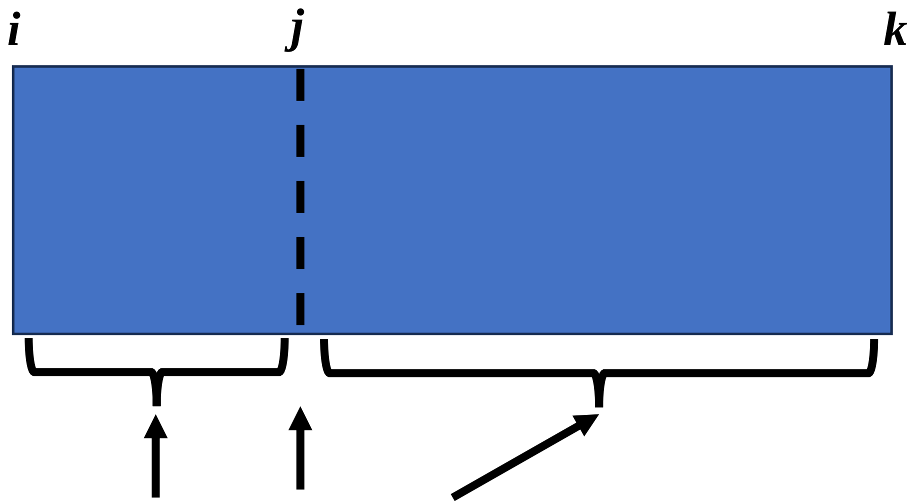
$$e^{:f_{ij}:} e^{:\phi_j:} e^{:f_{jk}:}$$

Transport through element with Hamiltonian f_{ij}

Transport through element with Hamiltonian ϕ_j

Transport through element with Hamiltonian f_{jk}

Lie transformations



$$e^{:f_{ij}:}e^{:\phi_j:}e^{:f_{jk}:}$$

ϕ_j : Hamiltonian of e-cloud interaction for one slice at location ***j***

f_{ij} : Hamiltonian of transport between location ***i*** and ***j***

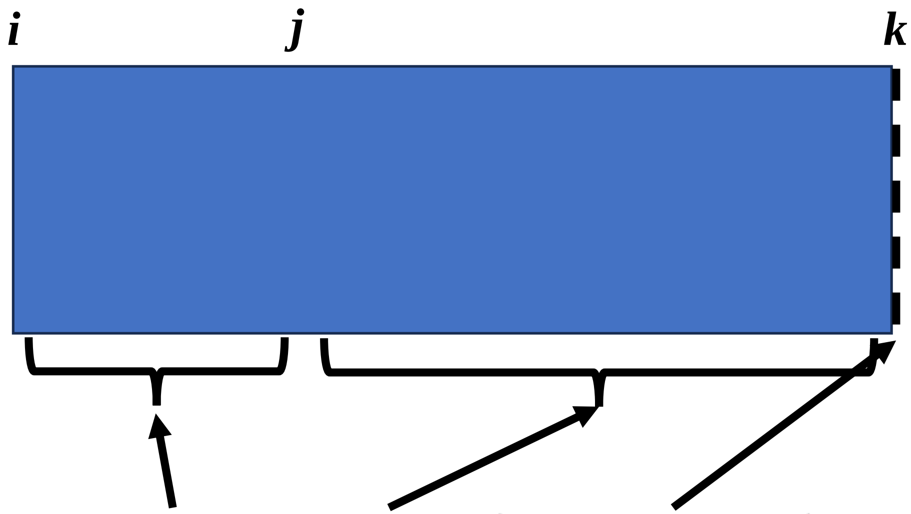
f_{jk} : Hamiltonian of transport between location ***j*** and ***k***

Step 1: use property $e^{:-f:}e^{:g:}e^{:f:} = \exp(:e^{:-f:}g:)$

$$e^{:f_{ij}:}e^{:\phi_j:}e^{:f_{jk}:} = e^{:f_{ij}:}e^{:f_{jk}:}e^{-:f_{jk}:}e^{:\phi_j:}e^{:f_{jk}:}$$

$$= e^{:f_{ij}:}e^{:f_{jk}:}exp\left(:e^{:-f_{jk}:}\phi_j:\right)$$

Lie transformations



$$e^{:f_{ij}:}e^{:f_{jk}:}exp\left(:e^{:-f_{jk}:}\phi_j:\right)$$

- We have transported the e-cloud slice (without approximation).
- We need to simplify

$$exp\left(:e^{:-f_{jk}:}\phi_j:\right)$$

Step 2: use property $e^{:f:}g(x) = g(e^{:f:}x)$

$$\phi_j = \phi_j(x, y, \zeta)$$

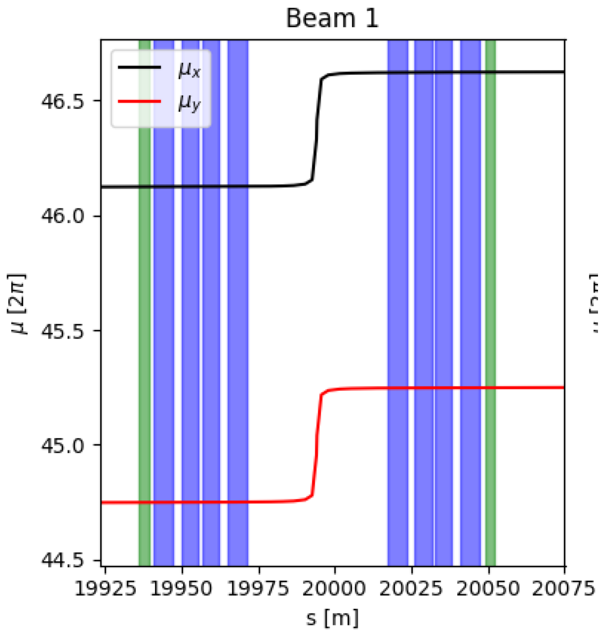
$$e^{:-f_{jk}:}\phi_j(x, y, \zeta) = \phi_j(e^{:-f_{jk}:}x, e^{:-f_{jk}:}y, e^{:-f_{jk}:}\zeta)$$

Lie transformations – Courant-Snyder parameterization

$$e^{:-f_{jk}:}\phi_j(x,y,\zeta) = \phi_j(e^{:-f_{jk}:}x, e^{:-f_{jk}:}y, e^{:-f_{jk}:}\zeta)$$

Courant-Snyder parameterization (first approximation):

$$e^{:f_{ij}:}x = \sqrt{\frac{\beta_j}{\beta_i}}\left(\cos\mu_{ij} + \alpha_i \sin\mu_{ij}\right)(x - x_i) + \sqrt{\beta_i\beta_j}\sin\mu_{ij}\left(p_x - p_{x,i}\right) + x_j$$



Constant phase advance (second approximation):

$$\mu_{ij} \approx 0$$

Transformation becomes: $e^{:f_{ij}:}x = \sqrt{\frac{\beta_j}{\beta_i}}(x - x_i) + x_j$

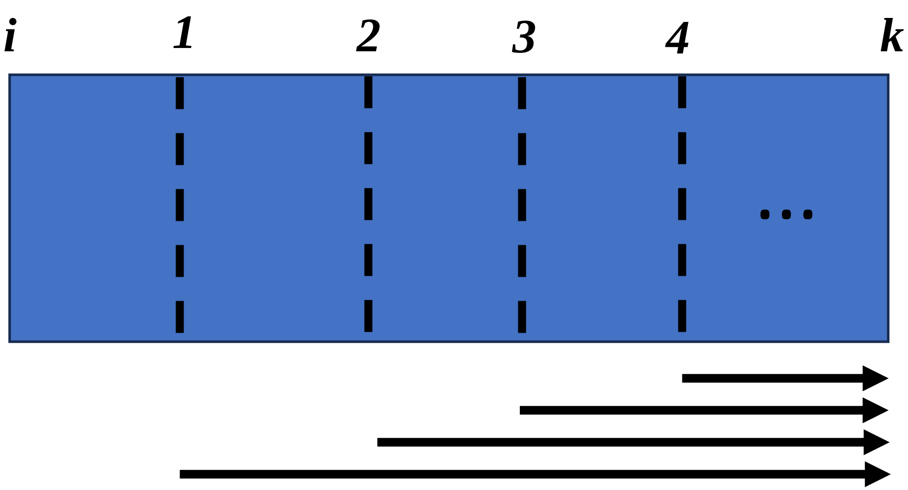
Third approximation: longitudinal coordinate doesn't change. $e^{:f_{ij}:}\zeta = \zeta$

Super-e-cloud

$$e^{:-f_{jk}:}\phi_j(x,y,\zeta) = \phi_j(e^{:-f_{jk}:}x, e^{:-f_{jk}:}y, e^{:-f_{jk}:}\zeta)$$

$$e^{:-f_{jk}:}\phi_j = \phi_j\left(\sqrt{\frac{\beta_{x,j}}{\beta_{x,k}}}(x-x_k)+x_j, \sqrt{\frac{\beta_{y,j}}{\beta_{y,k}}}(y-y_k)+y_j, \zeta\right)$$

Equation is manageable in this form.
ϕ_j is defined on a 3D grid, we just need to reinterpolate based on the above equation.



$$\Phi(x,y,\zeta) = \sum_i \phi_i\left(\sqrt{\frac{\beta_{x,i}}{\beta_{x,k}}}(x-x_k)+x_i, \sqrt{\frac{\beta_{y,i}}{\beta_{y,k}}}(y-y_k)+y_i, \zeta\right)$$

- 1536 simulations each to:
- Do electron cloud buildup,
- Detailed bunch passage "pinch".
- Combine on-the-fly to same 4 files.