Weak-strong simulations of electron cloud effects from the Inner Triplets of the Large Hadron Collider

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Many thanks to: G. Rumolo, H. Bartosik, Y. Papaphilippou, F. Van der Veken

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Outline

1. Introduction and motivation

2. Description of simulation method

3. Simulation results:
   a) Validation
   b) Frequency map analysis
   c) Dynamic aperture

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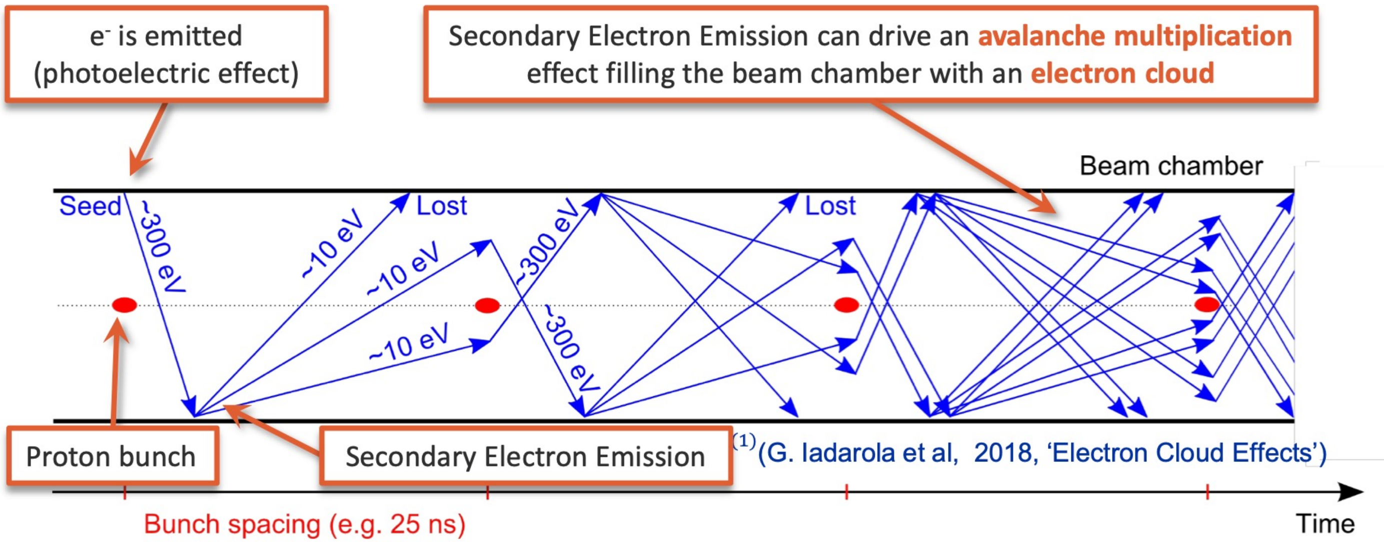
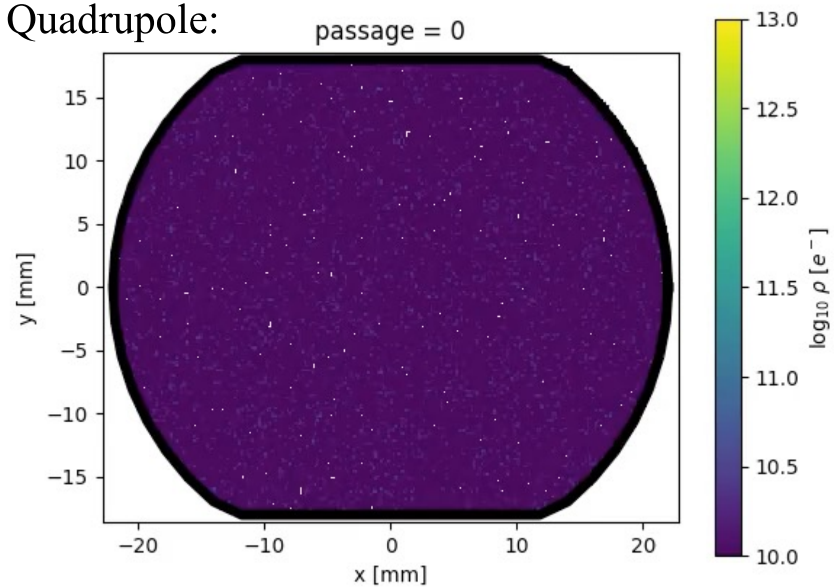
Electron clouds



1. Electrons are introduced into the chamber (residual gas ionization / synchr. rad. + photoelectric effect)
2. Electrons are accelerated by passing bunches and impact on beam chamber, emitting more electrons.

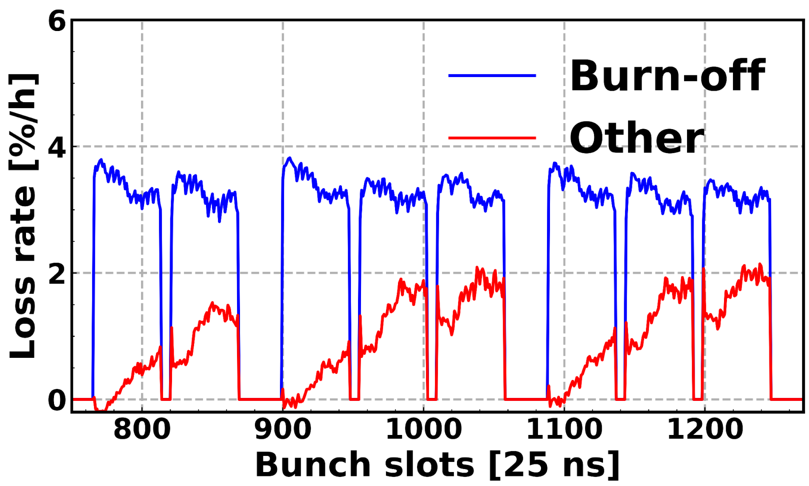
If conditions allow, **electrons multiply exponentially!**

Quadrupole:



[PyECLOUD simulation]

Motivation



Slow proton beam loss comes from:

- Luminosity **burn-off** (inelastic p-p collisions).
- Additional losses (Beam dynamics).

Luminosity (ATLAS + CMS)

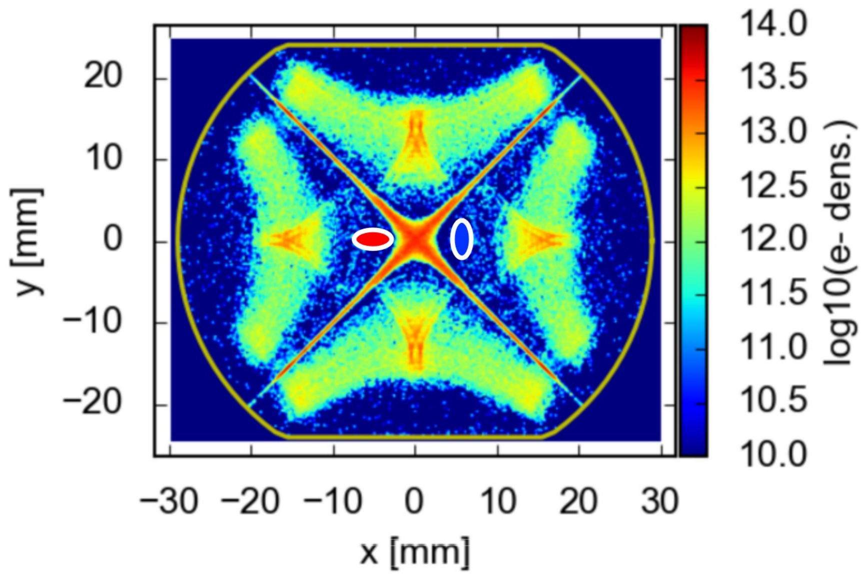
$$\left(-\frac{dI}{dt}\right)_{\text{other}} = \underbrace{\left(-\frac{dI}{dt}\right)_{\text{total}}} - \sigma_{\text{inel.}} \cdot \overbrace{\mathcal{L}}$$

Total loss rate (Fast Beam Current Transformer)

Several configurations were tested. All observations point to the **e-cloud forming in the Inner Triplet quadrupoles. (Final focusing quadrupoles)**

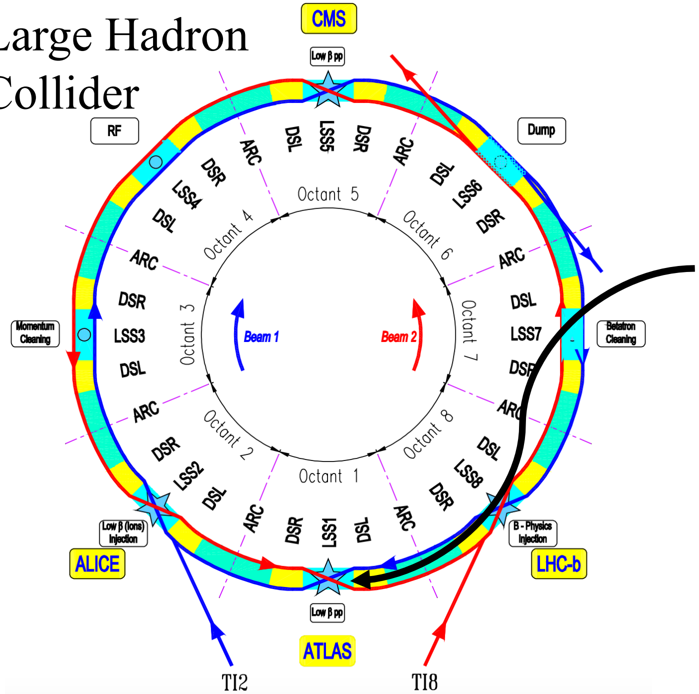
Good news: HL-LHC Inner Triplet will have a-C coating to suppress e-cloud formation.

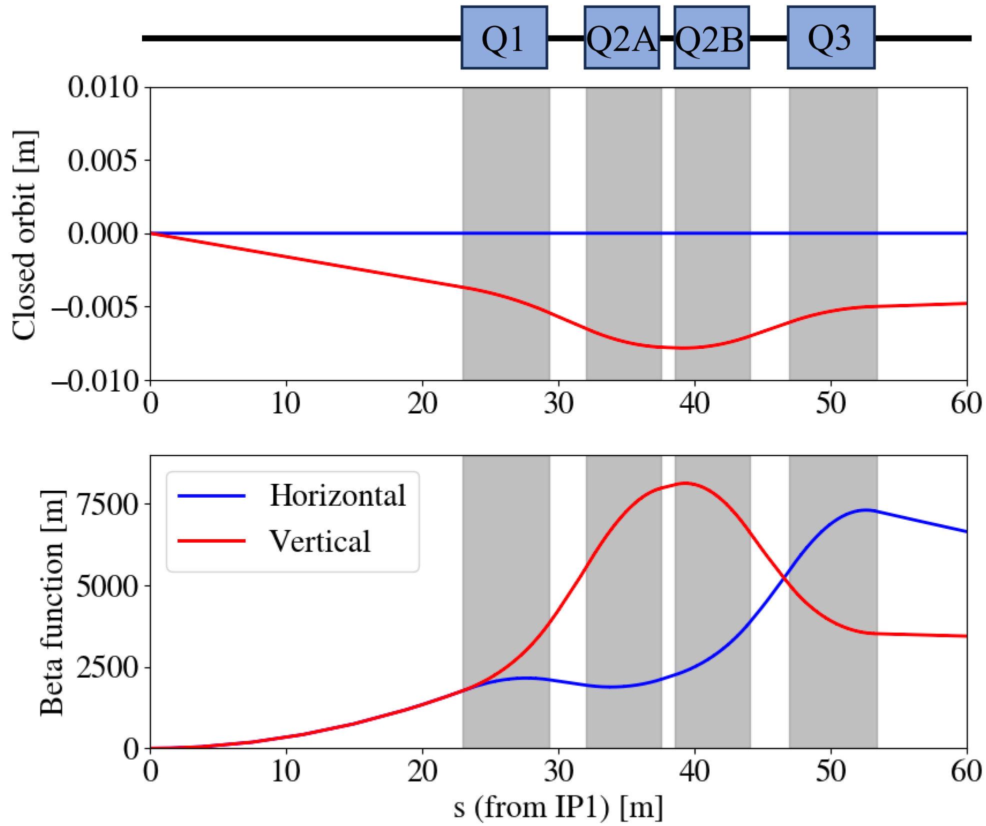
Can we simulate these losses?
(By looking for a reduction of dynamic aperture in particle tracking simulations)



The Inner Triplet

Large Hadron Collider

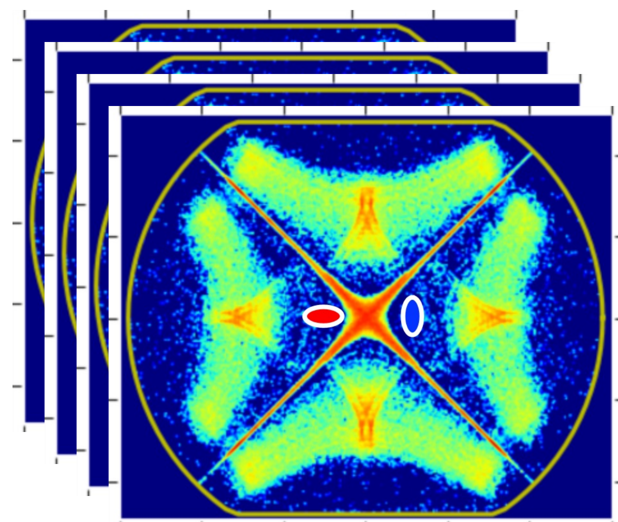




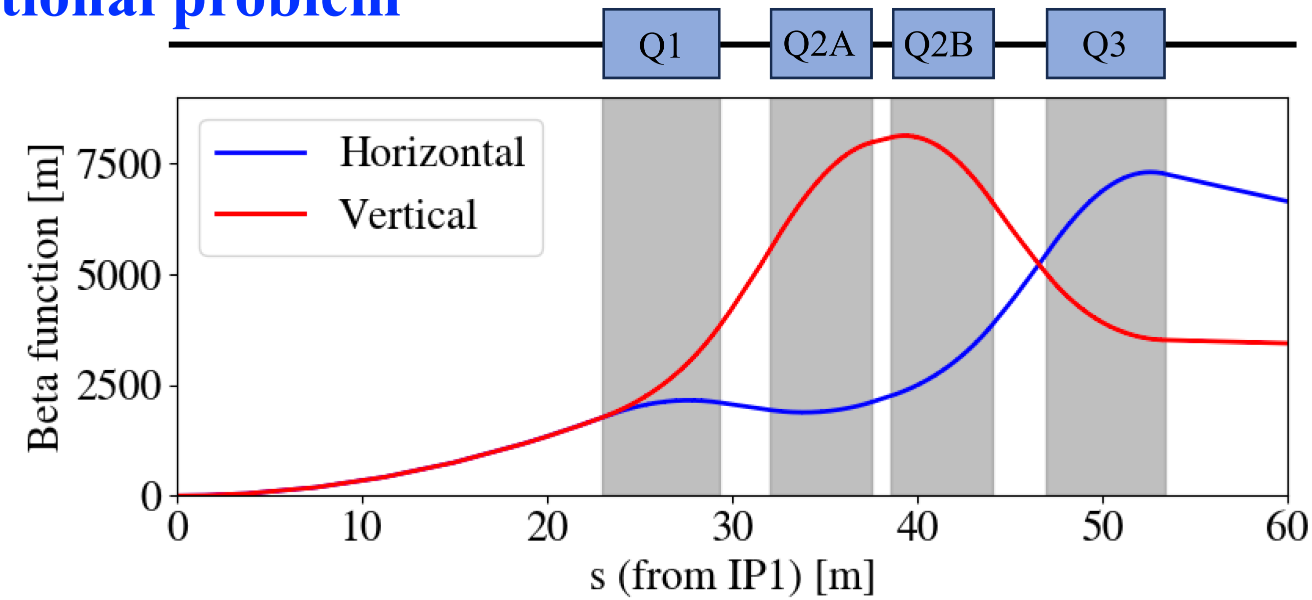
The Inner Triplets are complex and in ≈ 30 m :

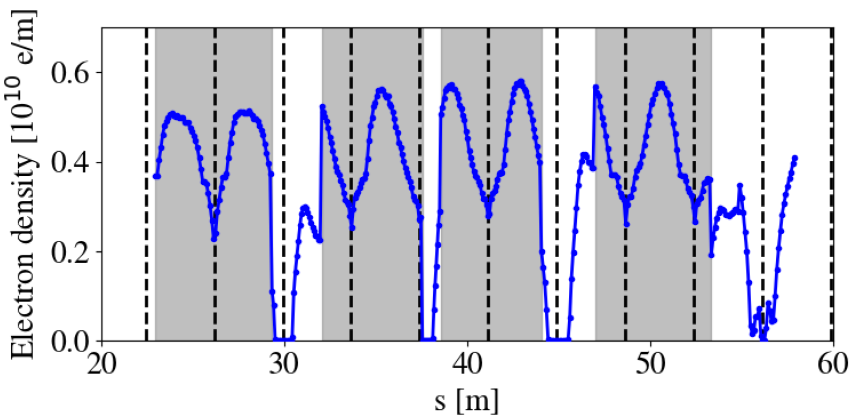
- Two beams present arriving at different times at each slice (w.r.t. to each other).
- Rapidly changing closed orbit.
- Rapidly changing betatron functions.

Many slices are necessary.



The computational problem





- E-cloud strongly depends on delay between two beams:
  - Less e-cloud at locations of beam-beam long-range interactions
  - Less e-cloud in drift spaces.

- 384 slices per triplet → 4 triplets, 1536 slices.
- ≈ 4GB per slice → **≈ 6 TB**

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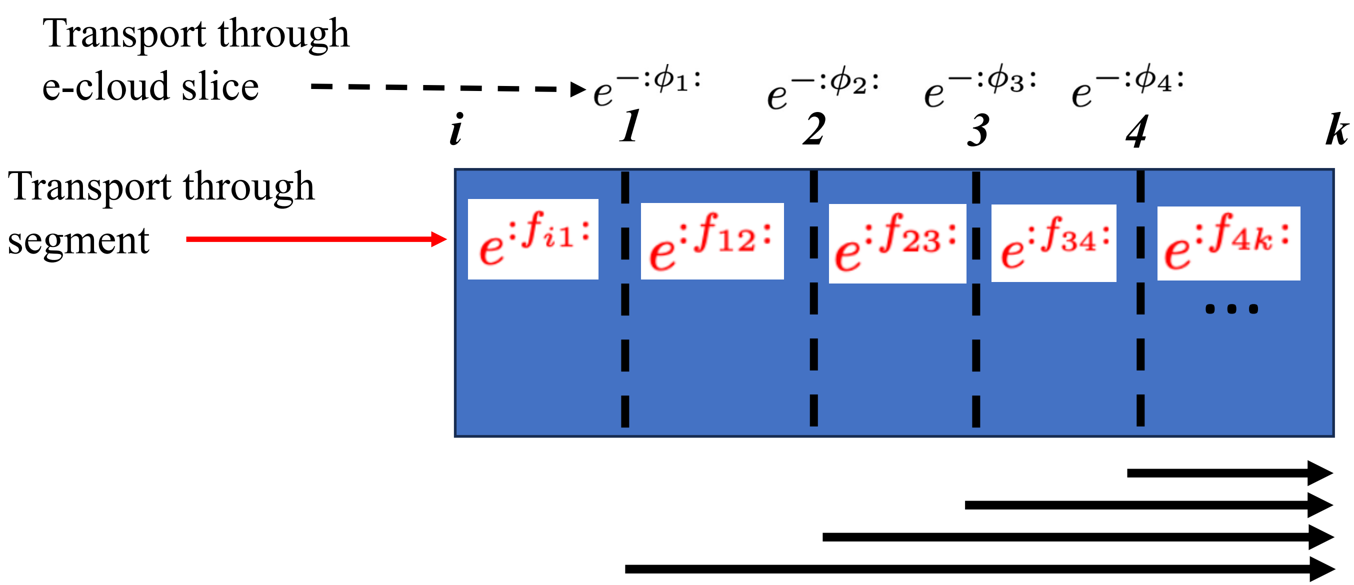
Strategy

[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.

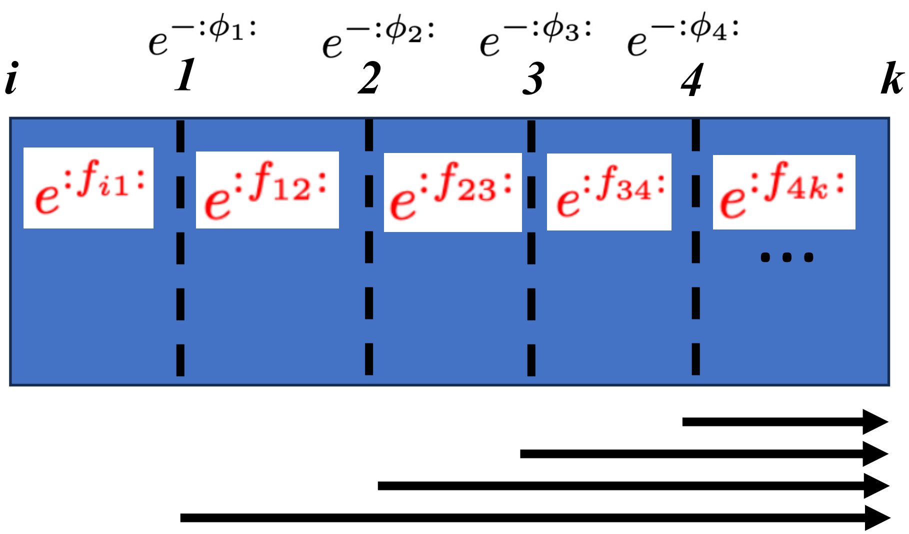
1. Transport slices to same location.
2. Slices commute (only depend on x, y, ζ). They can be summed.

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



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 $\mu_{ij} \approx 0$

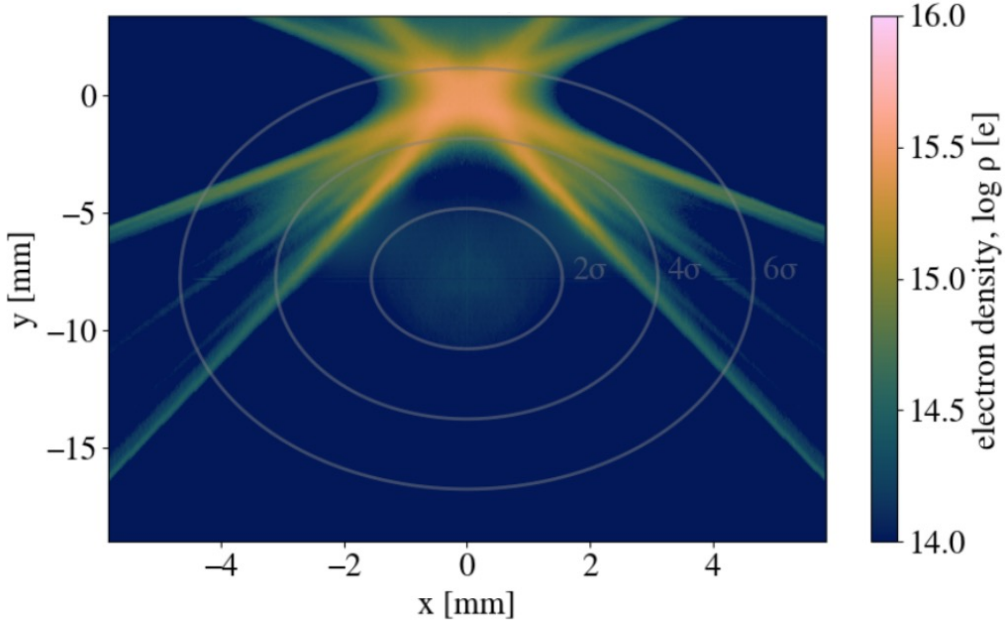
(3rd approximation):
No longitudinal motion $e^{:f_{ij}:}\zeta = \zeta$

Effective (lumped) e-cloud:

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

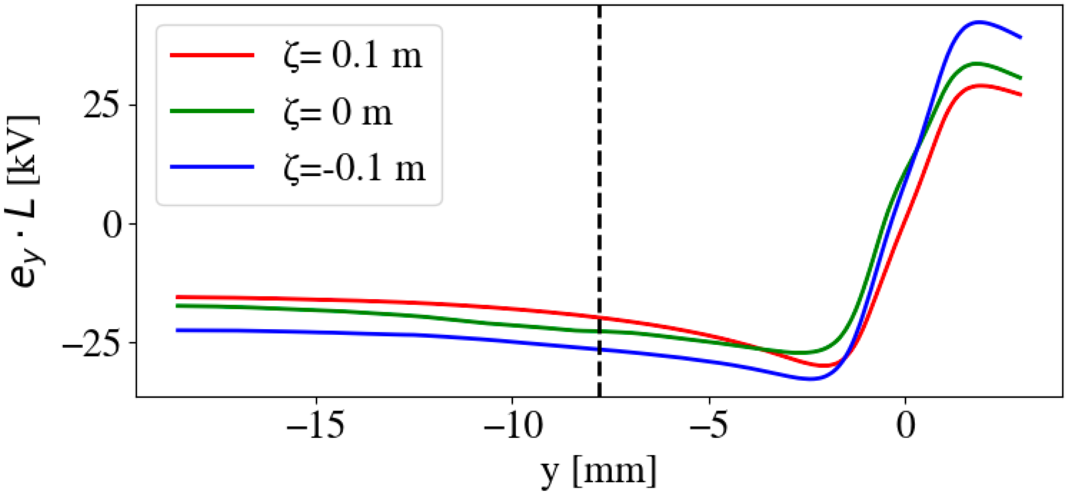
- Combines all slices into one scalar potential.
- Equation can be evaluated on a 3D grid, and treated as a single slice.

Effective e-cloud



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

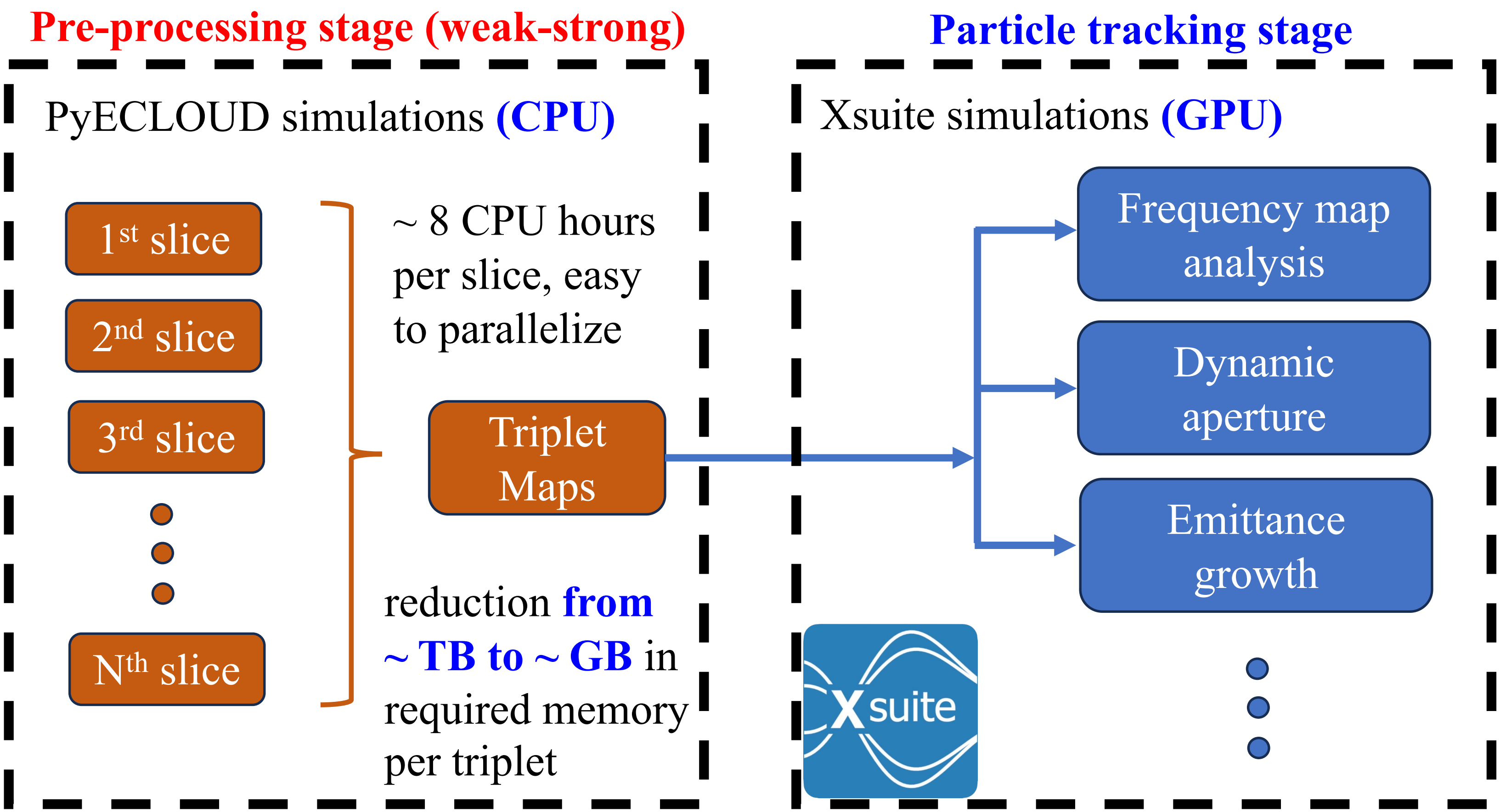
- Non-linear time-dependent forces.
- Forces become exceedingly non-linear at large amplitudes of oscillation.



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

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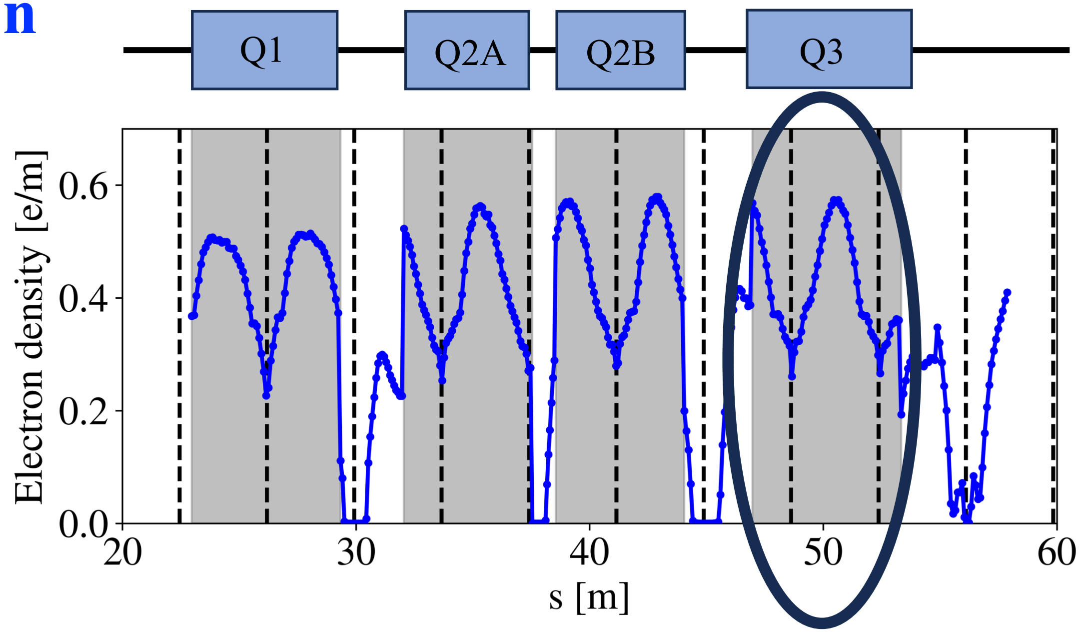
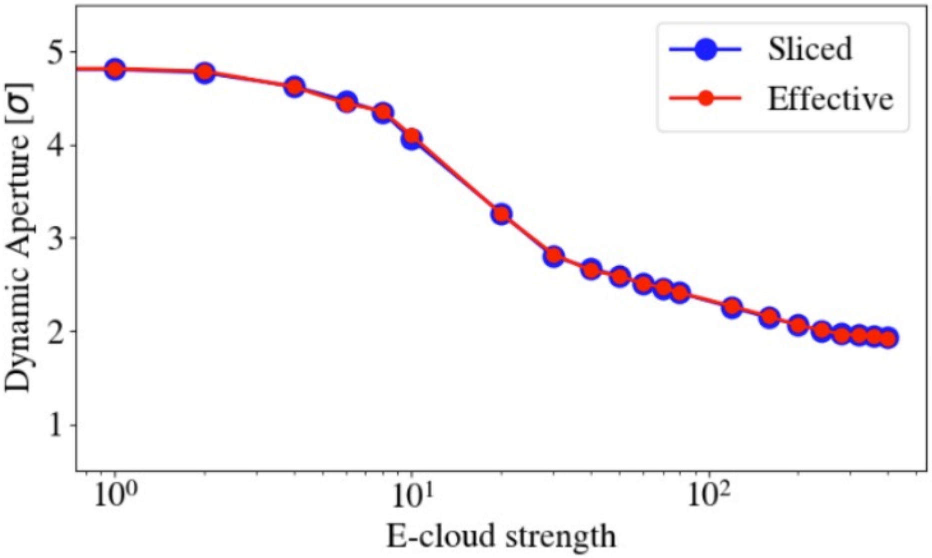
Validation



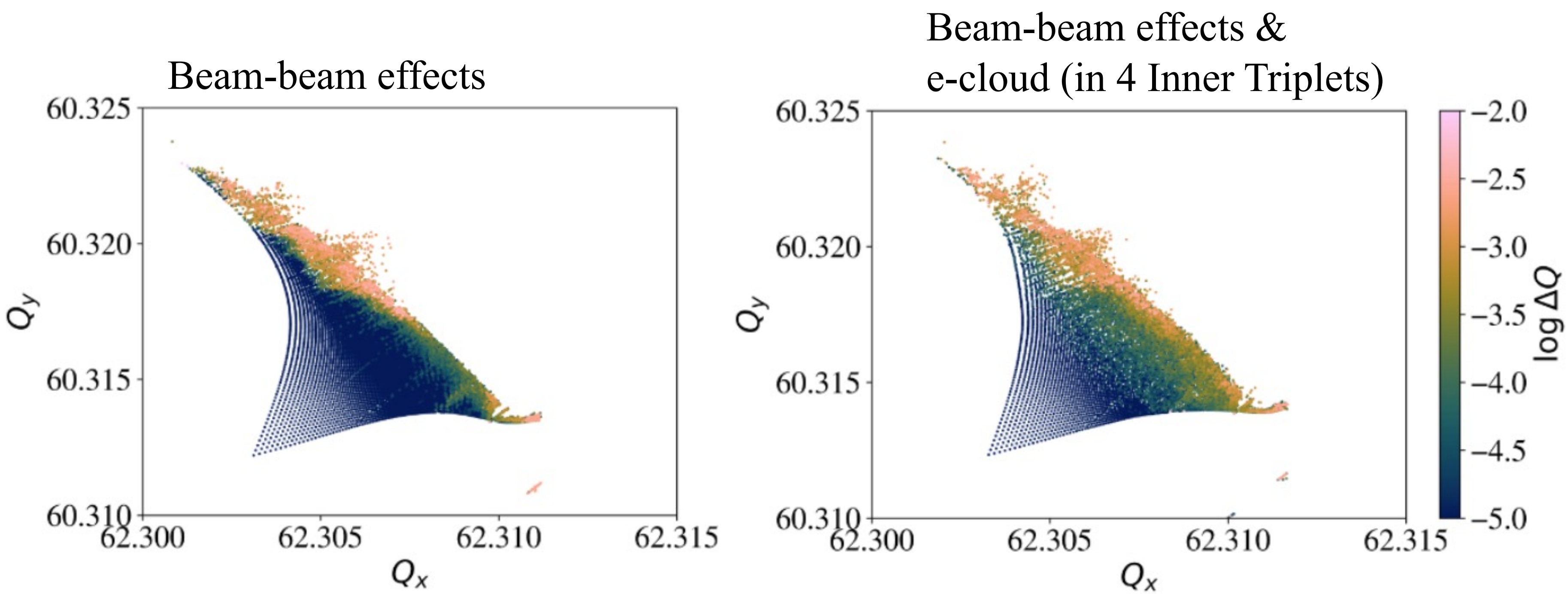
- Focus on Q3 quadrupole (right of interaction point 1): Q3R1.
- 64 slices, can fit in 1TB RAM computers.

- Dynamic aperture simulations to test previous equation.

- Good agreement.



Frequency Map Analysis



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

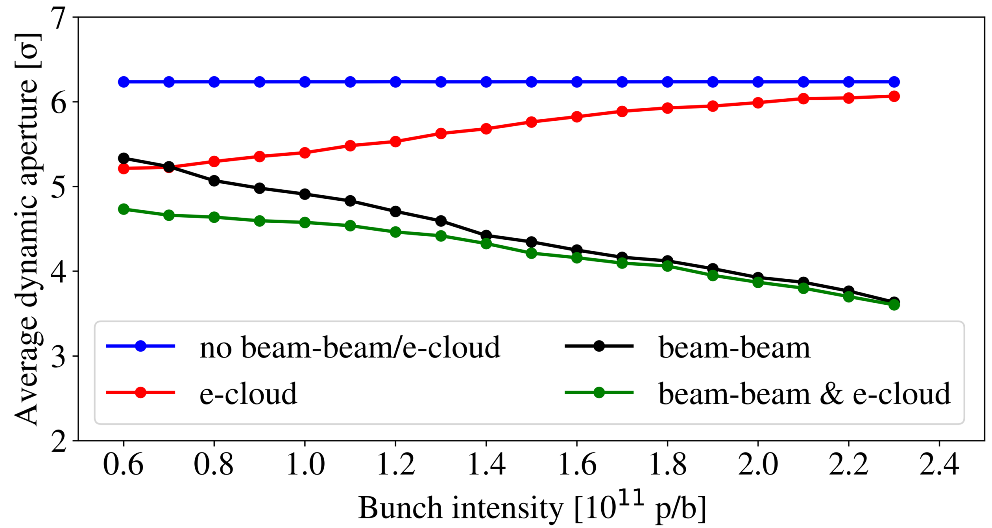
Difference in tune → tune is not constant and so trajectory is chaotic.

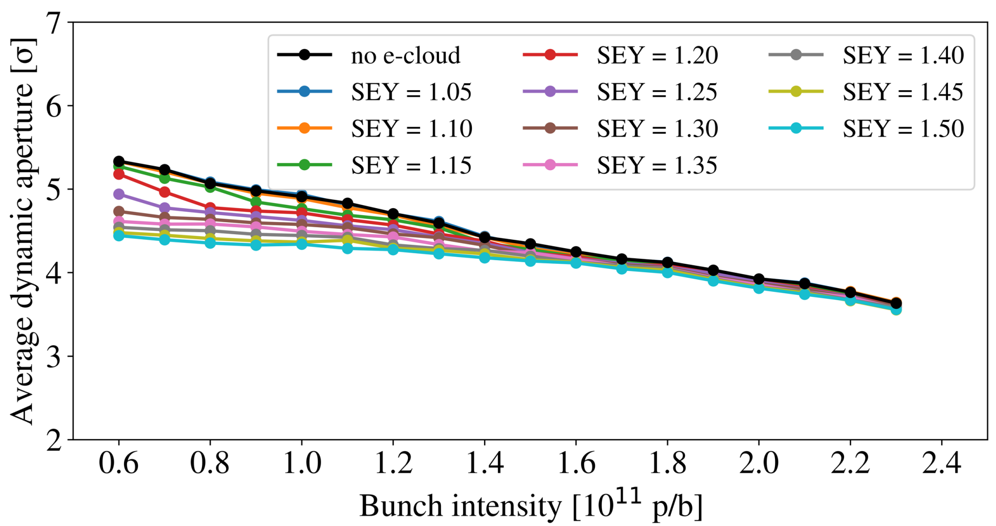
- E-cloud doesn't cause a significant tune-shift (compared to beam-beam effects)
- Visible effect of e-cloud → increase of non-linearities.

Dynamic aperture

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.





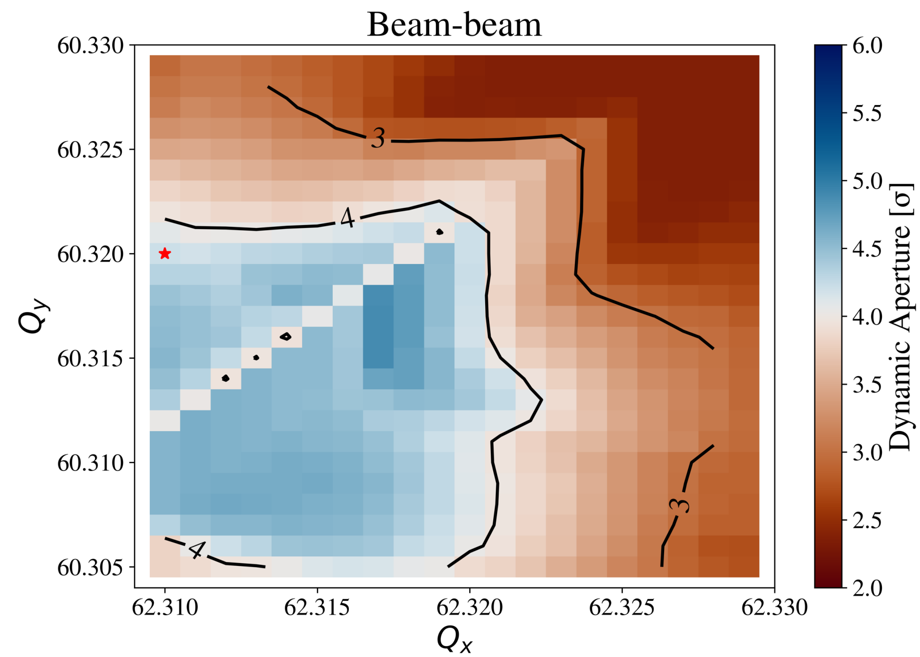
Dynamic aperture
Tune scan

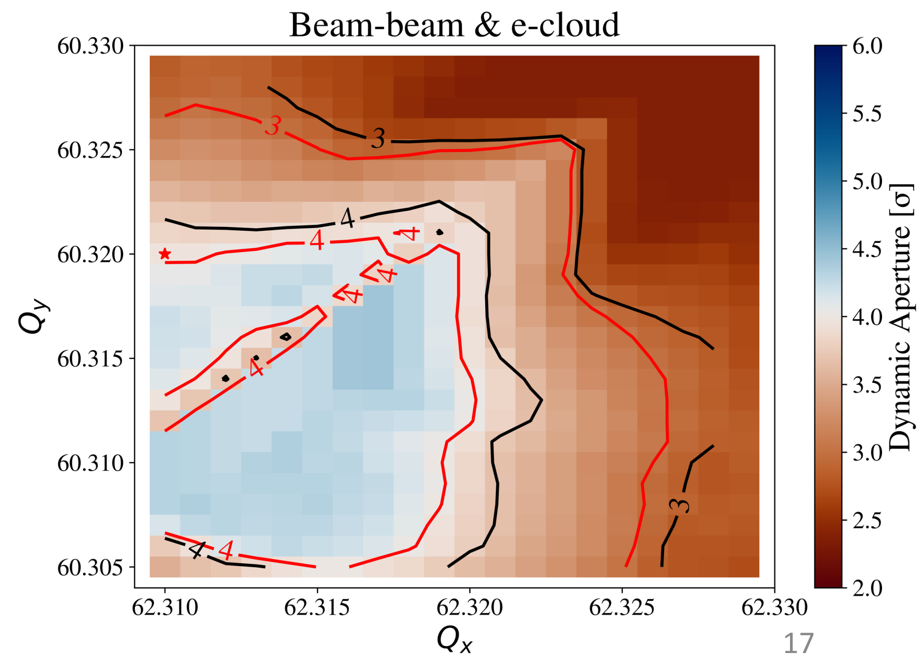
Dynamic aperture over 1 000 000 turns, including the e-clouds in the 4 inner triplets (left and right of i.p. 1 and 5). Simulations varying the working point.

- 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





Conclusions

- Region around Inner Triplets is complicated.
- Electron cloud effects from the inner triplets in the LHC can be simulated.
- **Method was developed and benchmarked** to be able to simulate effects **in a sustainable manner**, by reducing memory consumption.
- Frequency Map Analysis:
  1. Increased chaoticity that goes deeper into the distribution of particles.
  2. No significant tune-shift effects
- Dynamic aperture studies:
  1. Effect that can be at least as strong as beam-beam effects at low bunch intensities.
  2. Cannot be mitigated with a change in working point.
- Strategy of HL-LHC upgrade project to coat the new inner triplets with amorphous carbon remains a good solution.

Thank you for your attention!
Konstantinos Paraschou

Backup slides

Simulation parameters

Beam parameters:

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

norm. emittance = 2 μm

r.m.s. bunch length = 0.09 m

Energy = 6.8 TeV

Surface parameters:

SEY = 1.30

2023 Optics with β^* = 30 cm

Half-crossing angle : 160 μrad

Working point:

Qx = 62.31

Qy = 60.32

Non-linearities to mitigate coherent instabilities:

Q’ = 20

I_MO = 300 A

Residual uncorrected global linear coupling:

$Re[C^-]$ = 0.001

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:

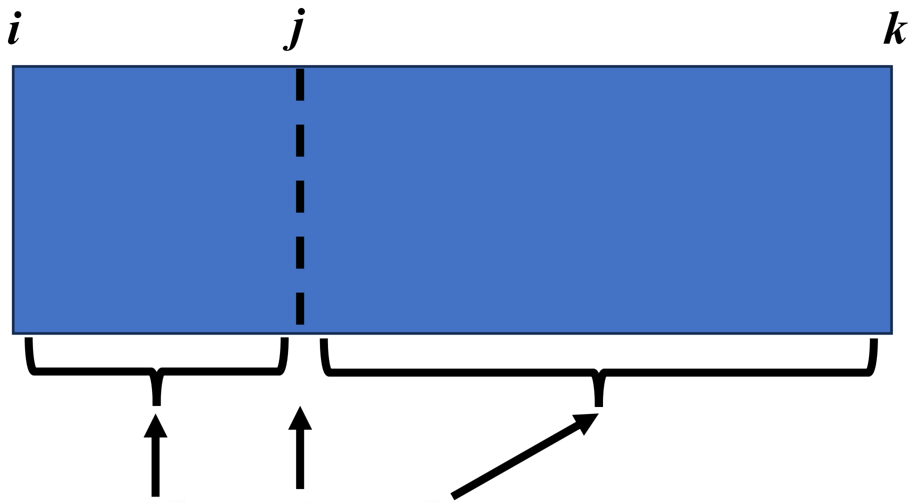
$$e^{:f_{ij}:} e^{:\phi_j:} e^{:f_{jk}:}$$

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***

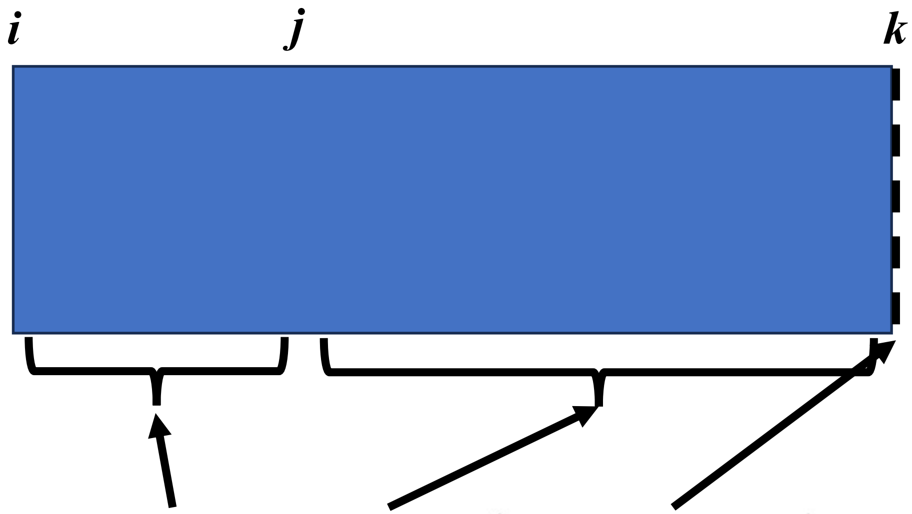
f_{jk} : Hamiltonian of transport between location ***j*** and ***k***

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 $e^{:f:}g(x) = g(e^{:f:}x)$

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

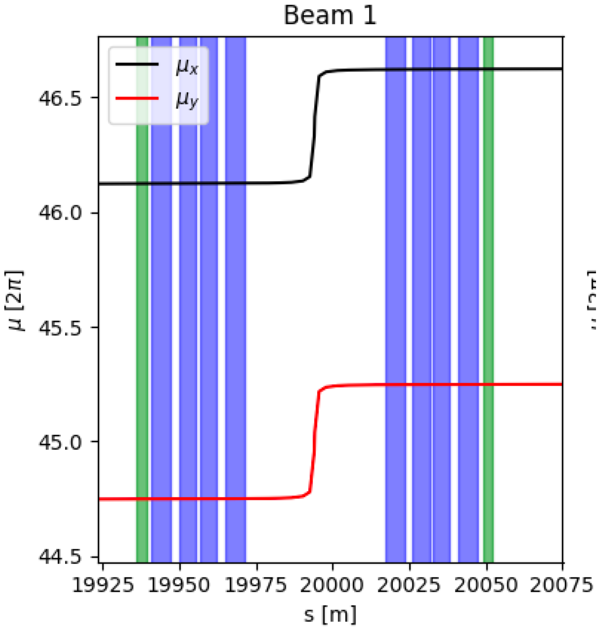
$$e^{:-f_{jk}:}\phi_j(x, y, \zeta) = \phi_j(e^{:-f_{jk}:}x, e^{:-f_{jk}:}y, e^{:-f_{jk}:}\zeta)$$

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

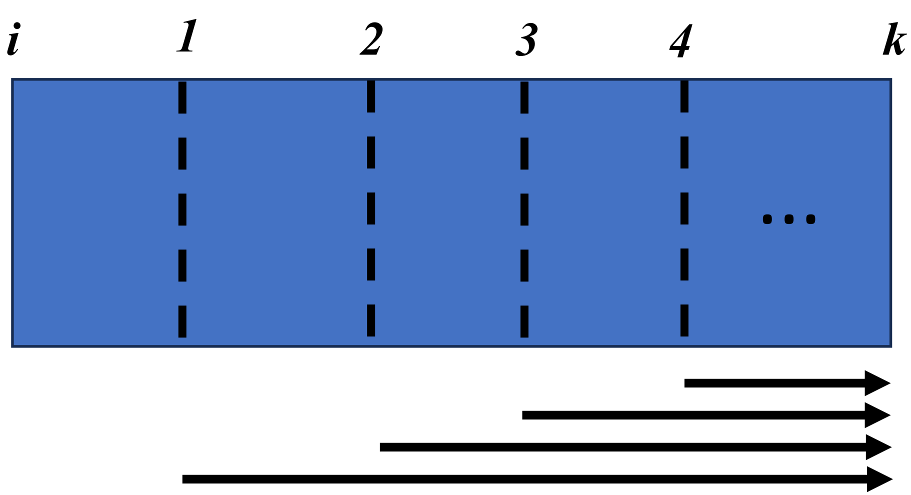
Third approximation: longitudinal coordinate doesn't change. $$e^{:f_{ij}:}\zeta = \zeta$$

Effective 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.