CERN

CAS Advanced Accelerator Physics

Collective effects

Part 4: Electron cloud – build up and effects on beam dynamics

Kevin Li and Giovanni Rumolo

Outline

We have learned about the concept of **particles**, **macroparticles** and **particle distributions** as well as some **peculiarities of multiparticle dynamics** in accelerators.

We have learned about the basic **concept of wake fields** and how these can be characterized as a **collective effect** in that they depend on the particle distribution.

We have learned the **impact of these** in the longitudinal and transverse planes.

We are ready to look into a new, but popular ☺, source of collective effects, i.e. the **electron cloud.**

Part 4: Electron cloud – Build up and effects on beam dynamics

- Electron cloud build up
  - Electron production and multiplication
  - Observation in accelerator rings
- Scrubbing and other techniques of mitigation/suppression
- E-cloud induced instabilities and incoherent effects

Outline

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We will look into the description and the impact of **electron cloud**.

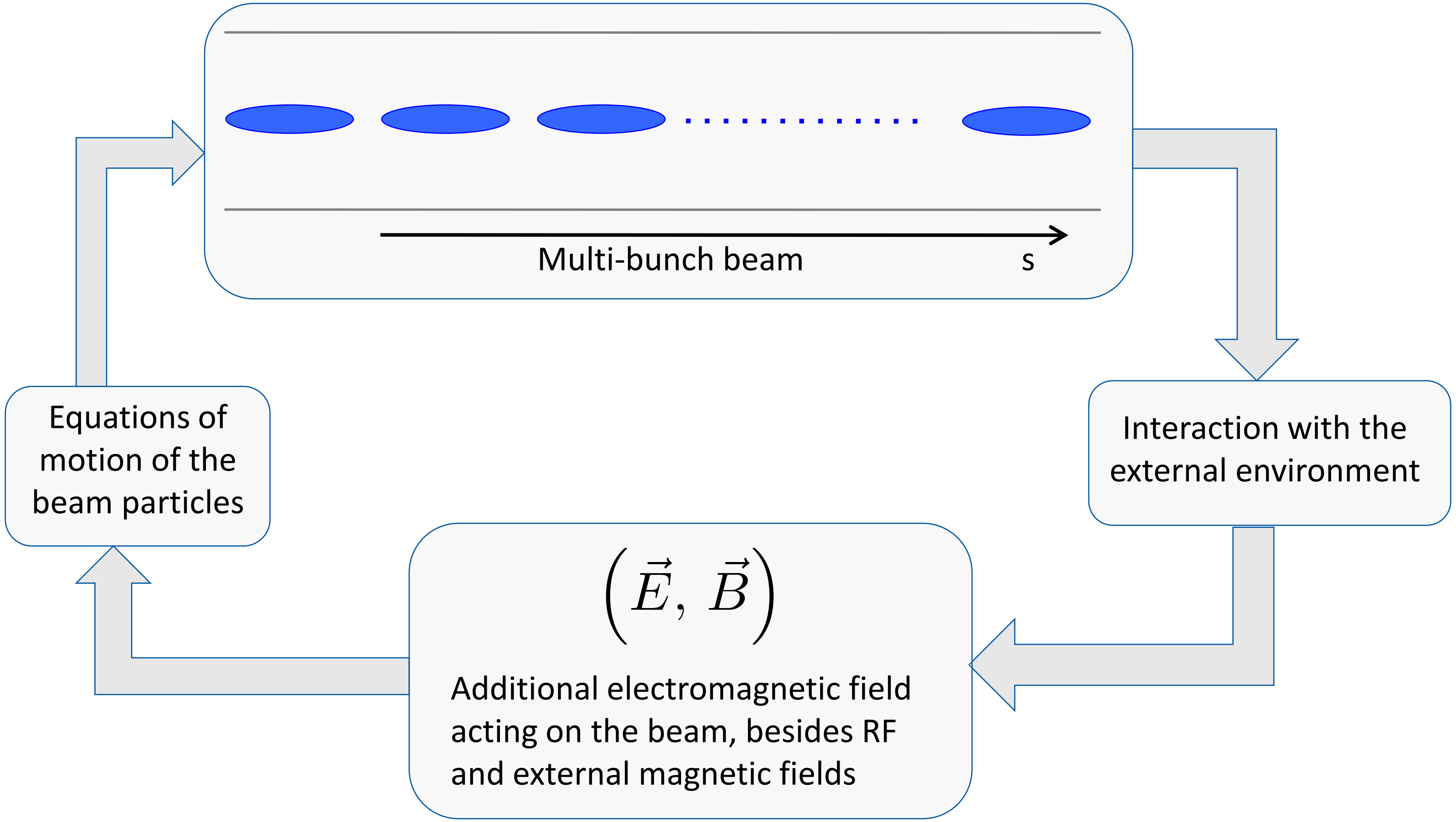
We will discuss the conditions for an electron cloud to build in the vacuum chamber of an accelerator and mitigation/suppression techniques.

We will also show some examples linked to **electron cloud effects** such as beam induced instability and incoherent effects.

Part 4: Electron cloud – Build up and effects on beam dynamics

- Electron cloud build up
  - Electron production and multiplication
  - Observation in accelerator rings
- Scrubbing and other techniques of mitigation/suppression
- E-cloud induced instabilities and incoherent effects

Reminder: The instability loop



Reminder

Interaction of the beam with the external environment

Pure EM interaction

- Maxwell's equations
  - The beam as the source term
  - Boundary conditions given by the chamber in which the beam is propagating
- Generation of wake functions/impedances

$$\left(\vec{E},\ \vec{B}\right)$$

Additional electromagnetic field acting on the beam, besides RF and external magnetic fields

Different type of interaction possible

Interaction of the beam with the external environment

The electron cloud
- Electron production and accumulation
- Poisson's equation with
  - The electron cloud as the source term
  - Boundary conditions given by the chamber in which the electron cloud builds up

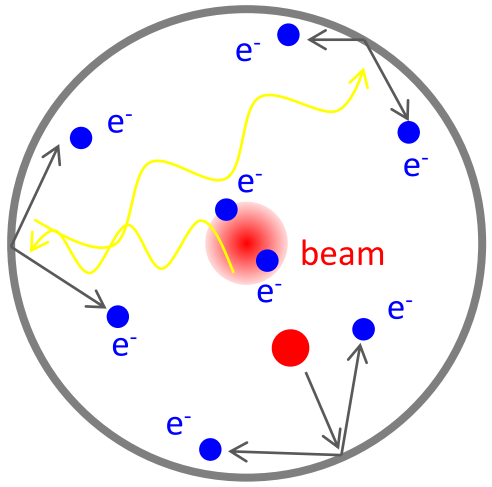
$$\left(\vec{E},\ \vec{B}\right)$$

Additional electromagnetic field acting on the beam, besides RF and external magnetic fields

Electron production

Generation of charged particles inside the vacuum chamber (primary, or seed, electrons)

- **Residual gas ionization**
- **Photoelectrons from synchrotron radiation**
- **Desorption from the losses on the wall**



Electron production

Generation of charged particles inside the vacuum chamber (primary, or seed, electrons)

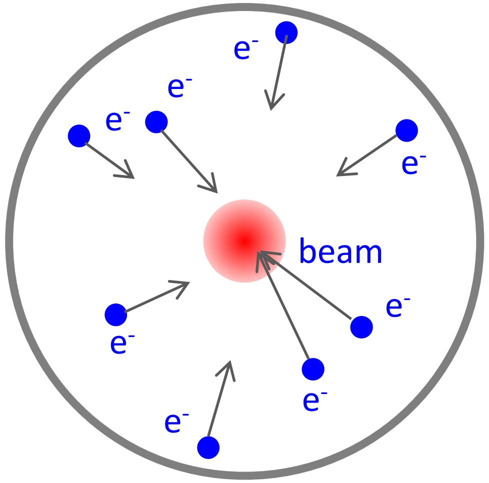
- **Residual gas ionization**
- **Photoelectrons from synchrotron radiation**
- **Desorption from the losses on the wall**

- Gas ionization and wall desorption produce both electrons and ions (the former one with the same rate, the second one with different rates depending on the desorption yields), photoemission is only a source of electrons
- The dominant mechanism depends upon e.g.
  - Beam type and parameters (e.g. lepton vs hadrons, beam energy)
  - Vacuum level
  - Design (material, shape), roughness, cleanness of the inner surface of chamber

Electron production

Generation of charged particles inside the vacuum chamber (primary, or seed, electrons)

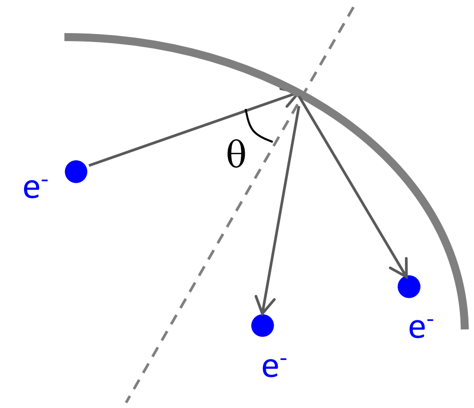
- **Acceleration of primary electrons in the beam field**

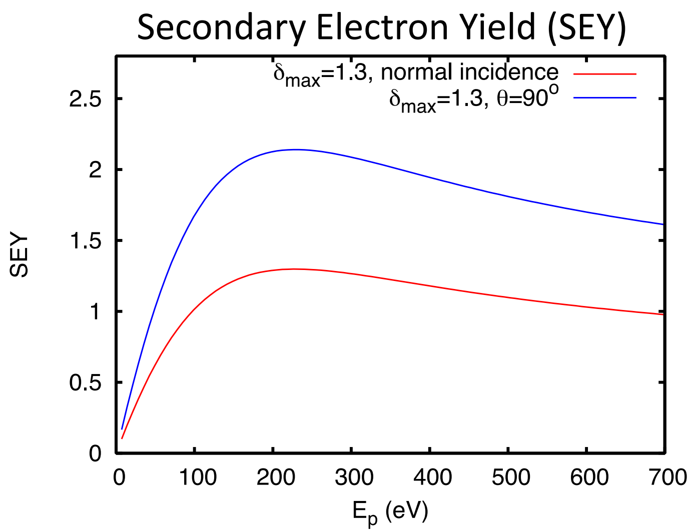


Electron production

Generation of charged particles inside the vacuum chamber (primary, or seed, electrons)

- **Acceleration of primary electrons in the beam field**
- **Secondary electron production when hitting the wall**

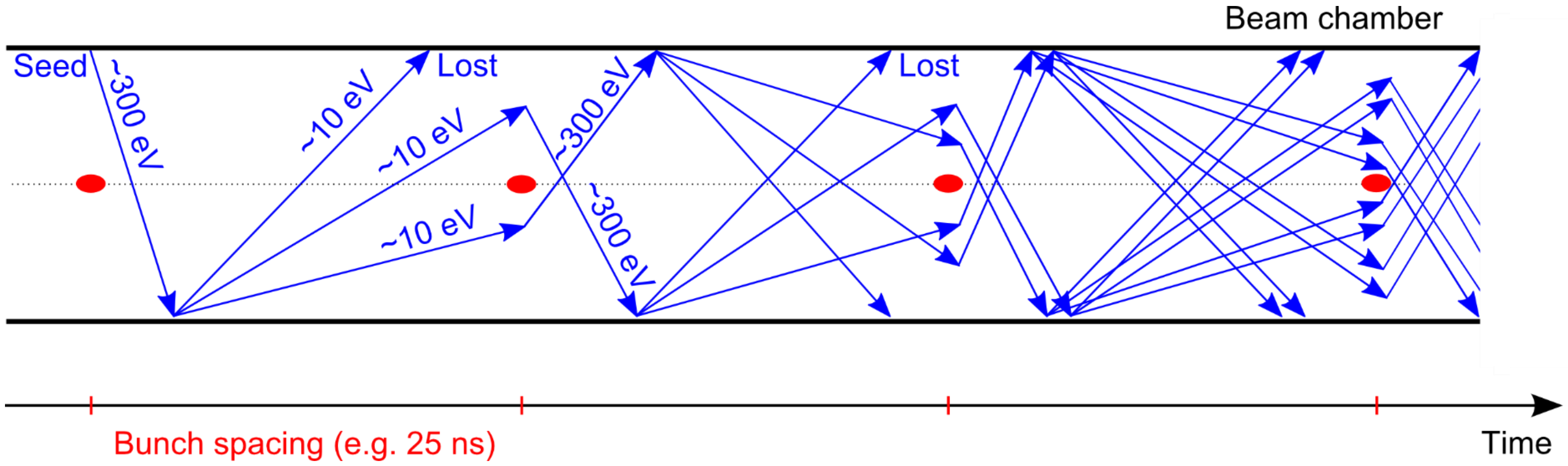




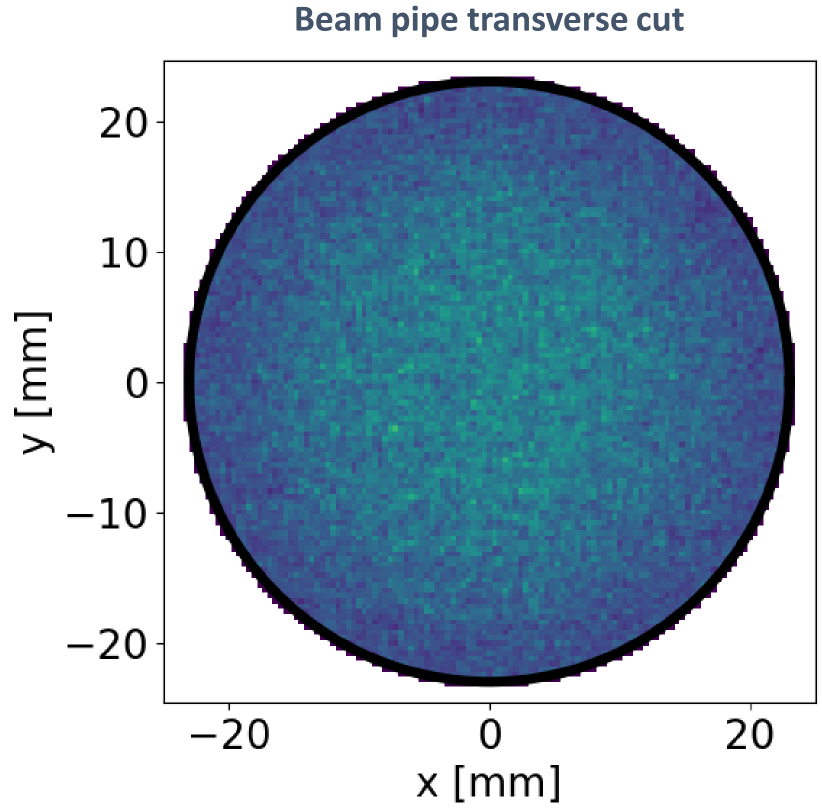
Electron production

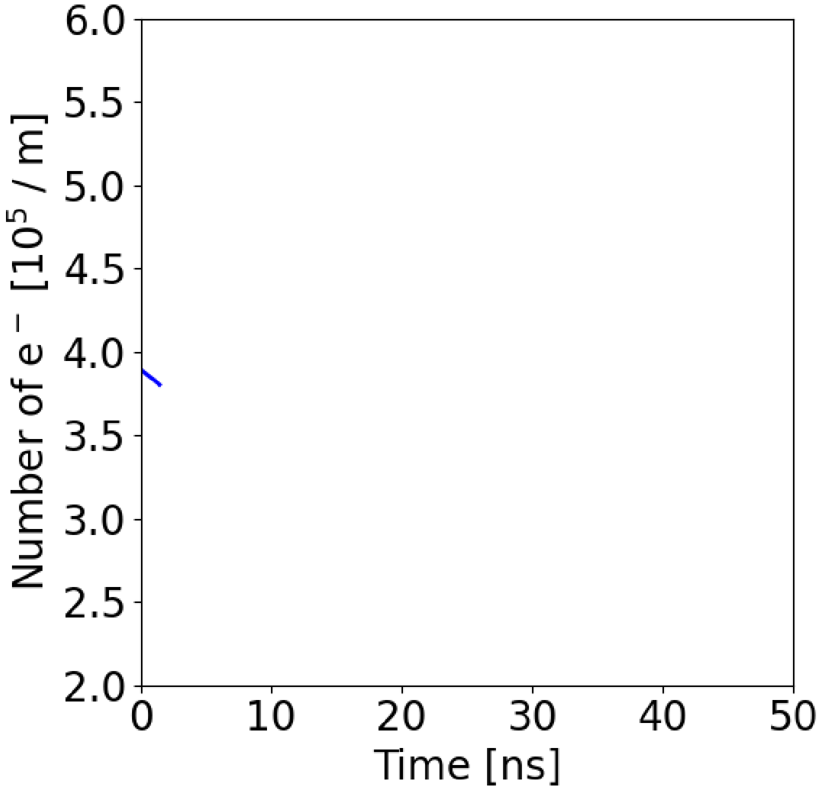
Generation of charged particles inside the vacuum chamber
(primary, or seed, electrons)

- Acceleration of primary electrons in the beam field
- Secondary electron production when hitting the wall
- Avalanche electron multiplication if SEY > 1



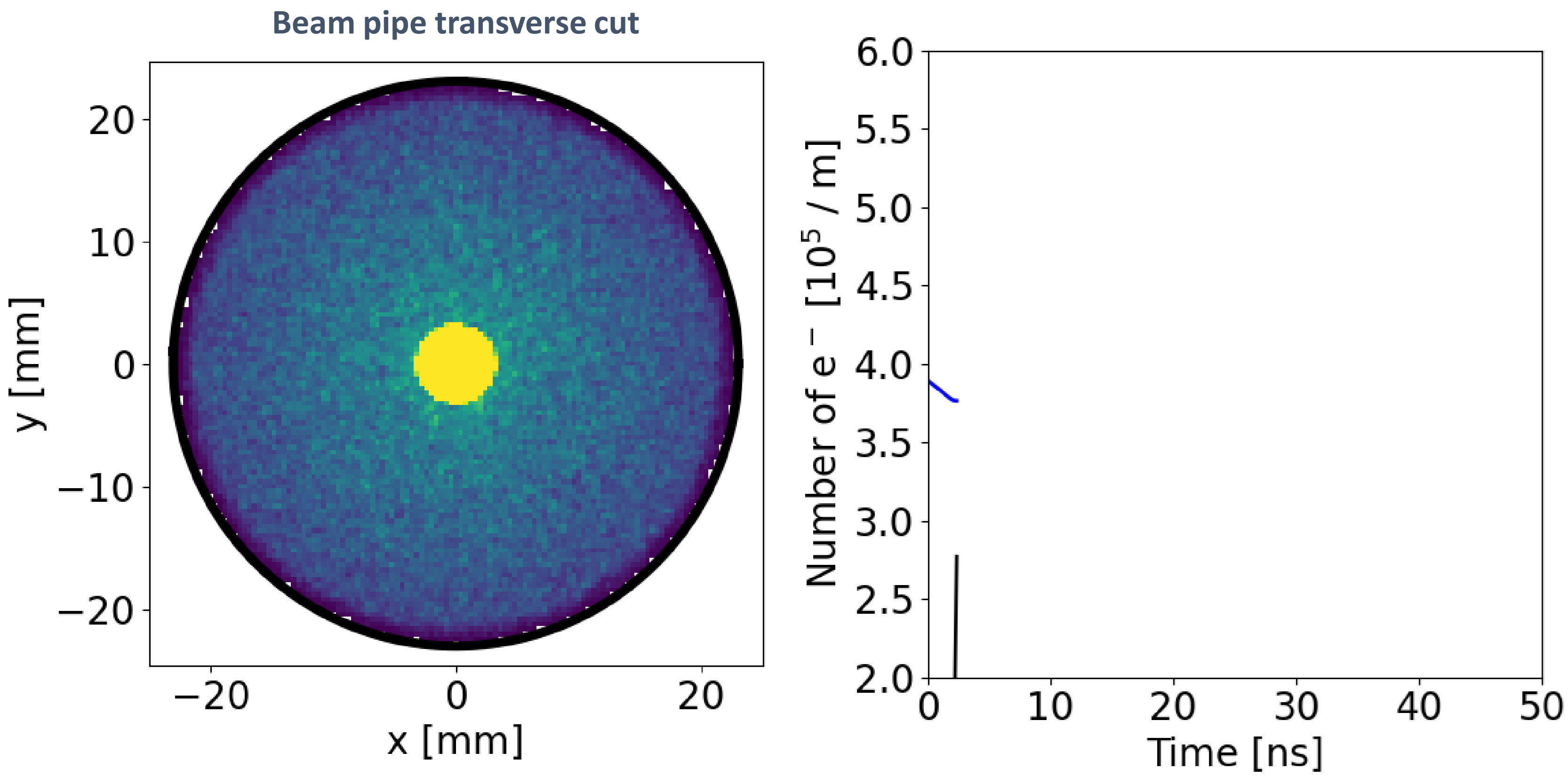
Electron cloud formation cartoon





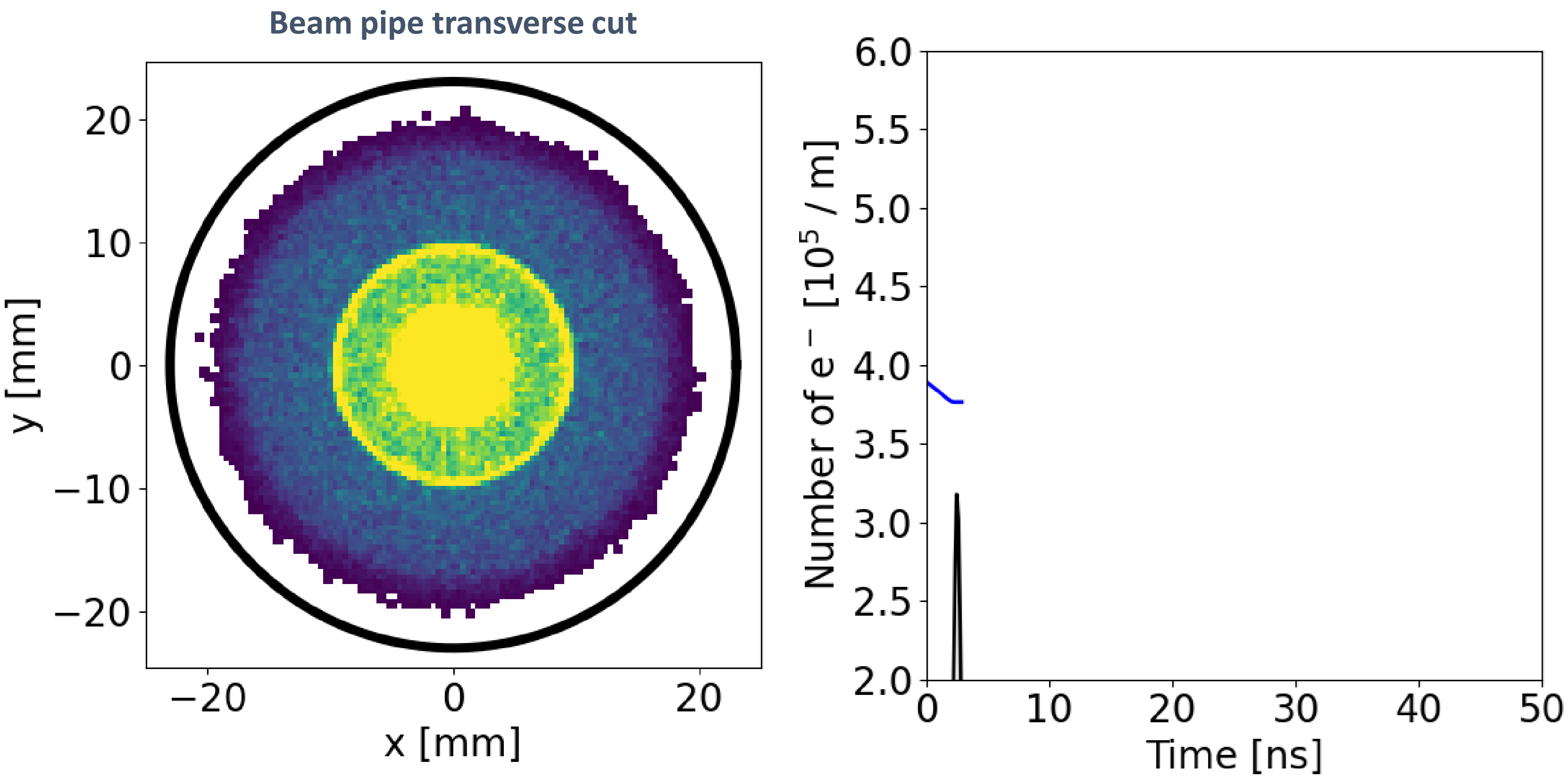
Assume an initial distribution of electrons
(from any of the mechanisms discussed before)

Electron cloud formation cartoon



"Pinch" of electrons when bunch is passing

Electron cloud formation cartoon



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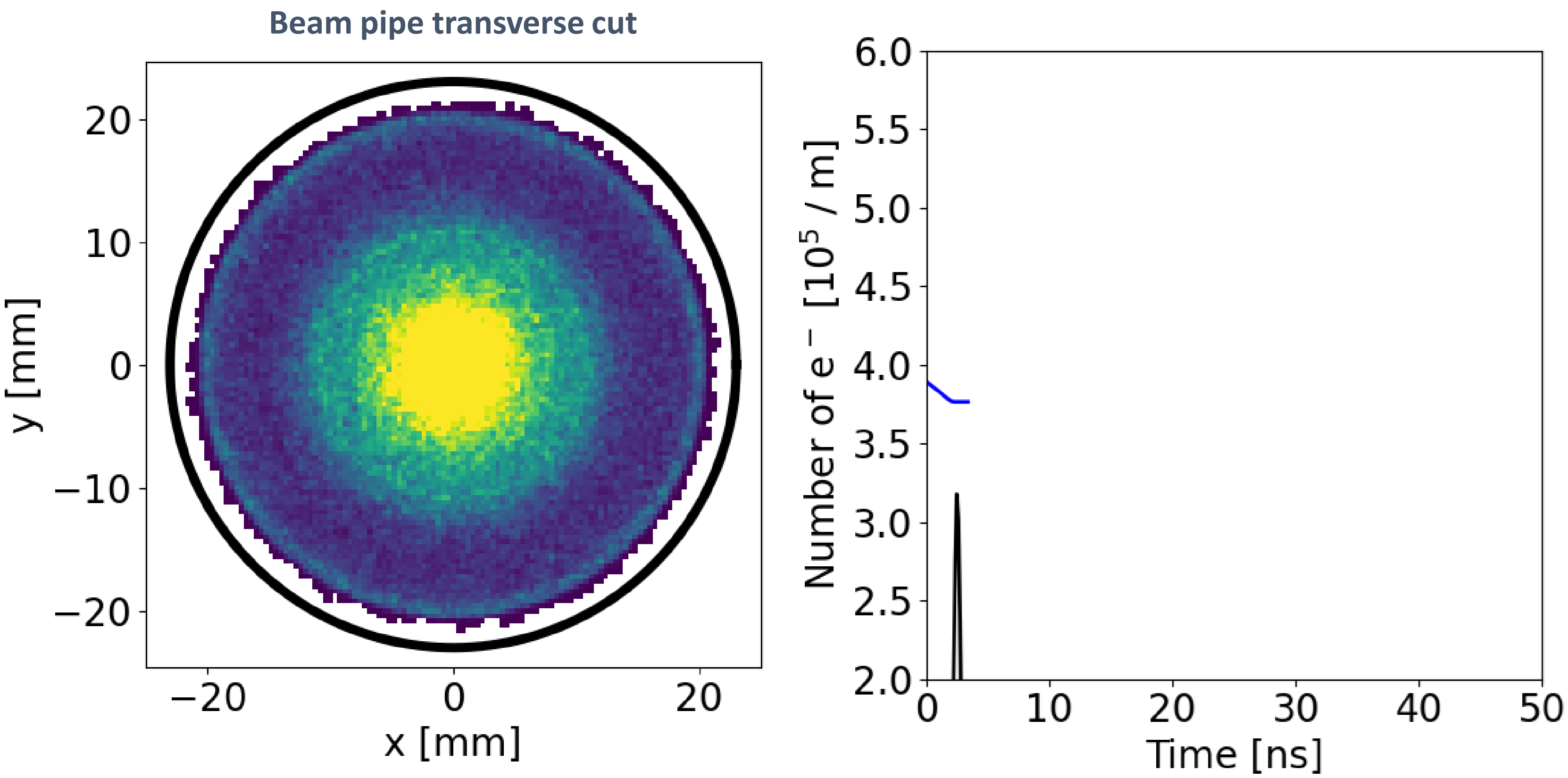

"Pinch" of electrons when bunch is passing

Electron cloud formation cartoon

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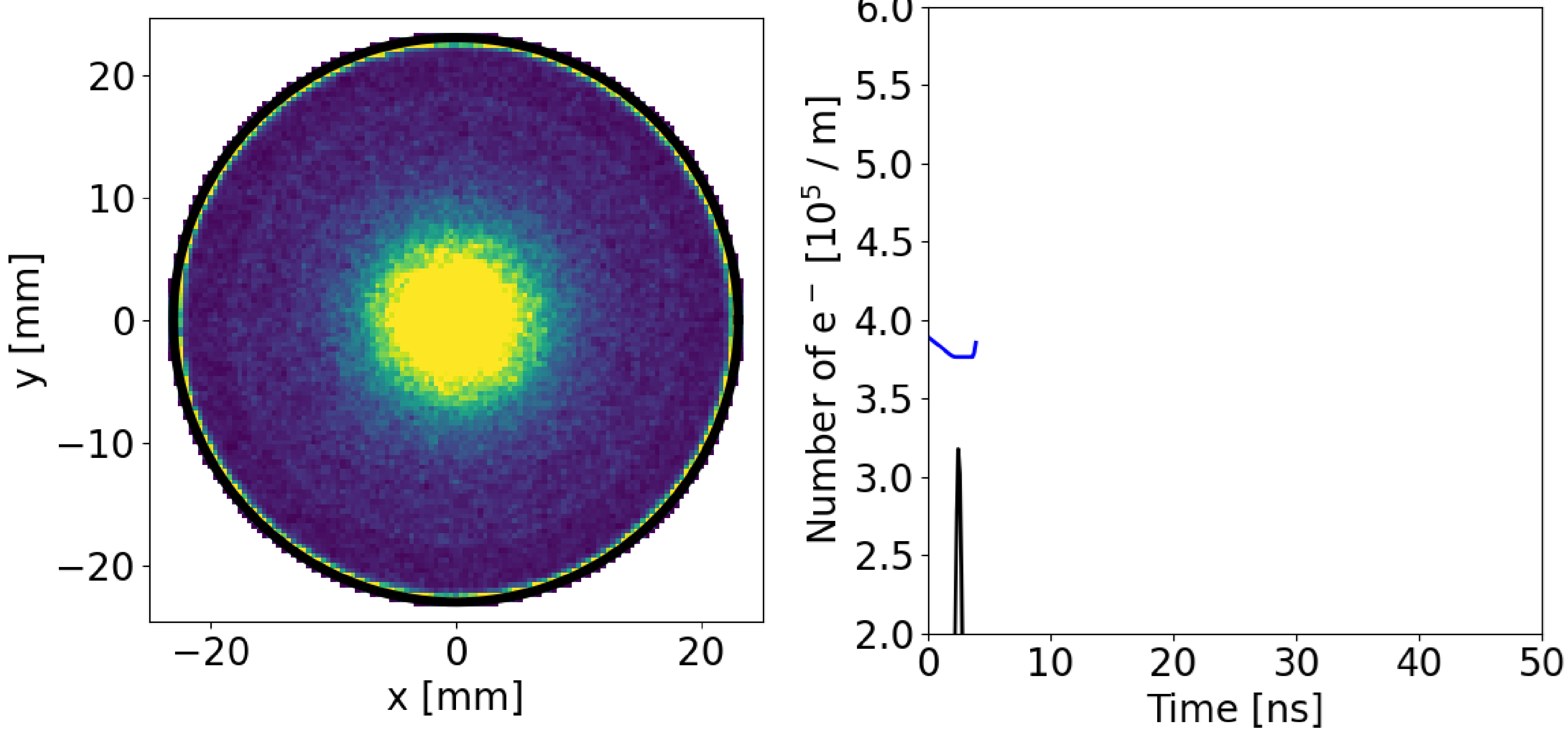
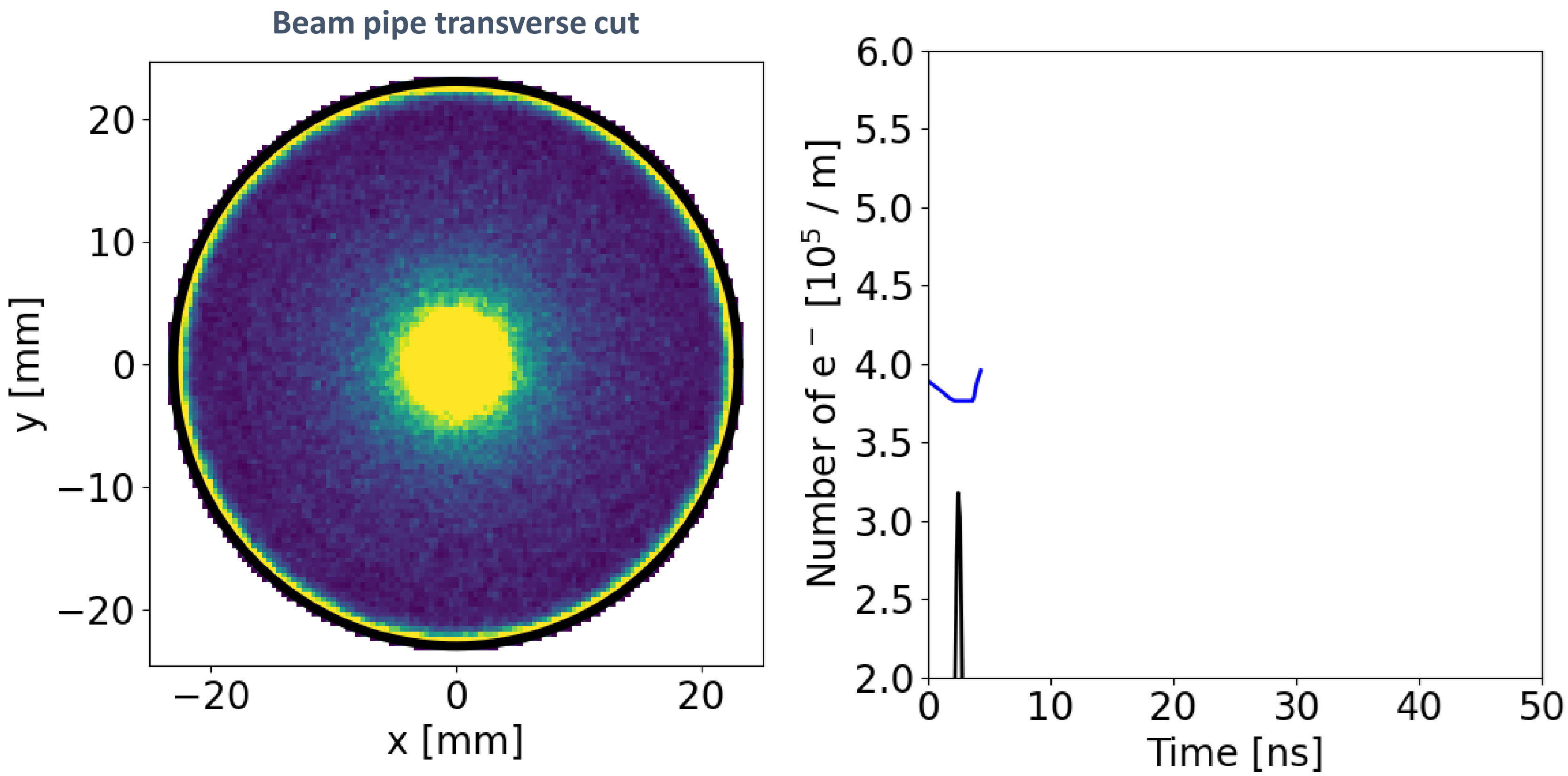
Beam pipe transverse cut



Few high energy (>100 eV) electrons reach the chamber wall already on the falling edge of the bunch and start producing secondaries

Electron cloud formation cartoon



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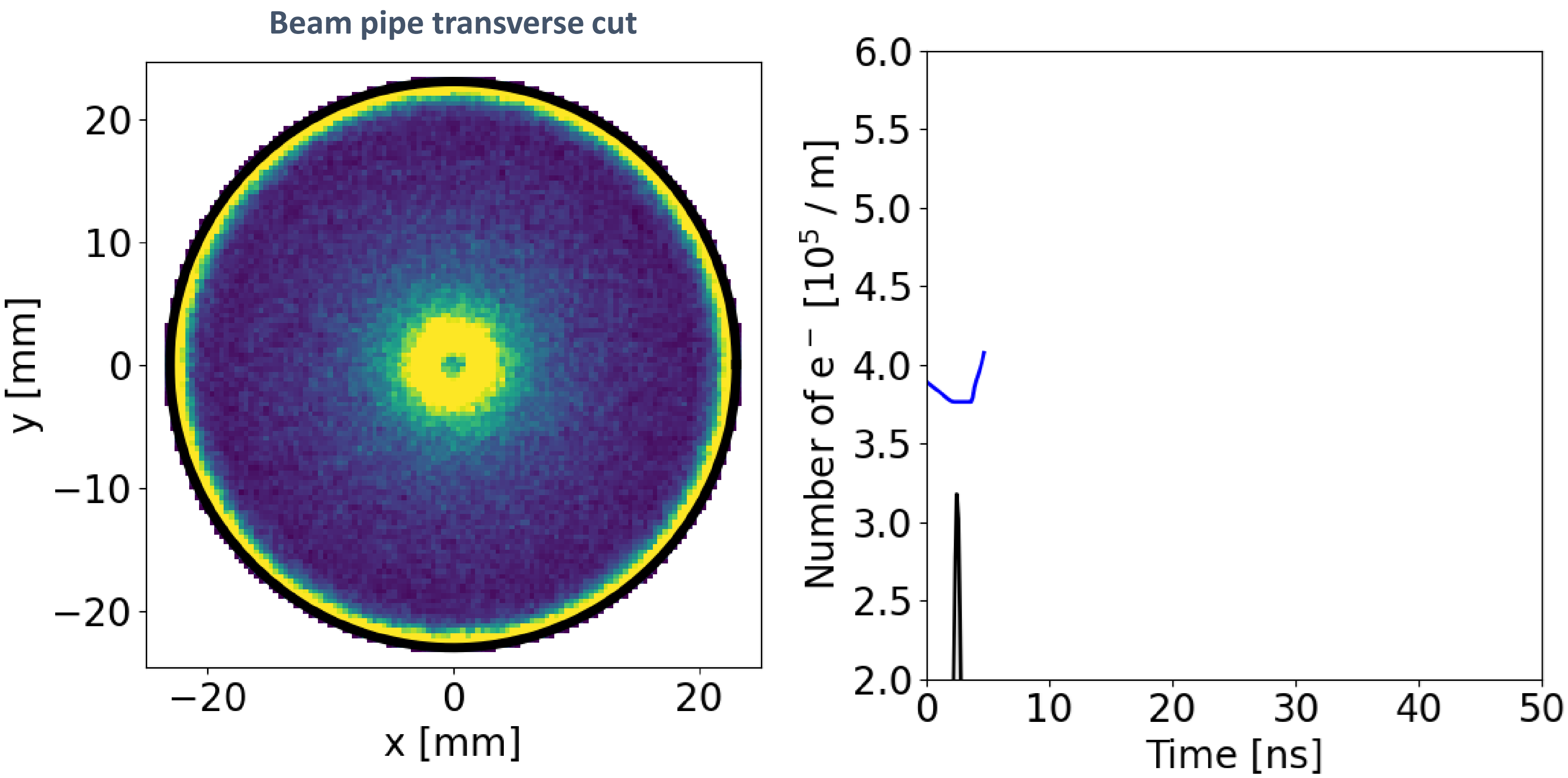
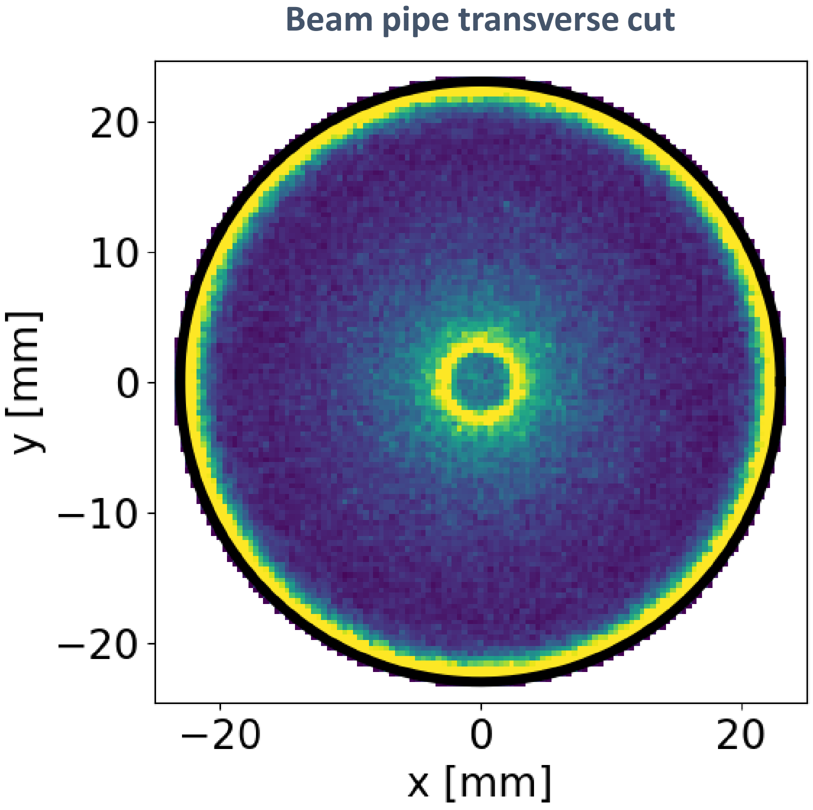
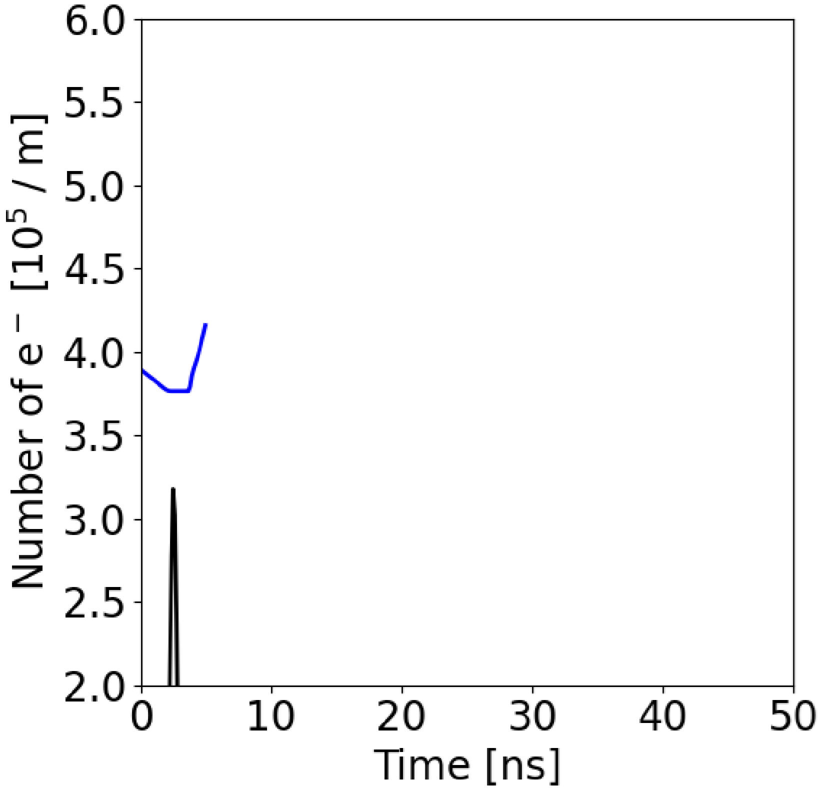


More high energy electrons (>100 eV) reaching the chamber wall keep producing secondaries

Electron cloud formation cartoon





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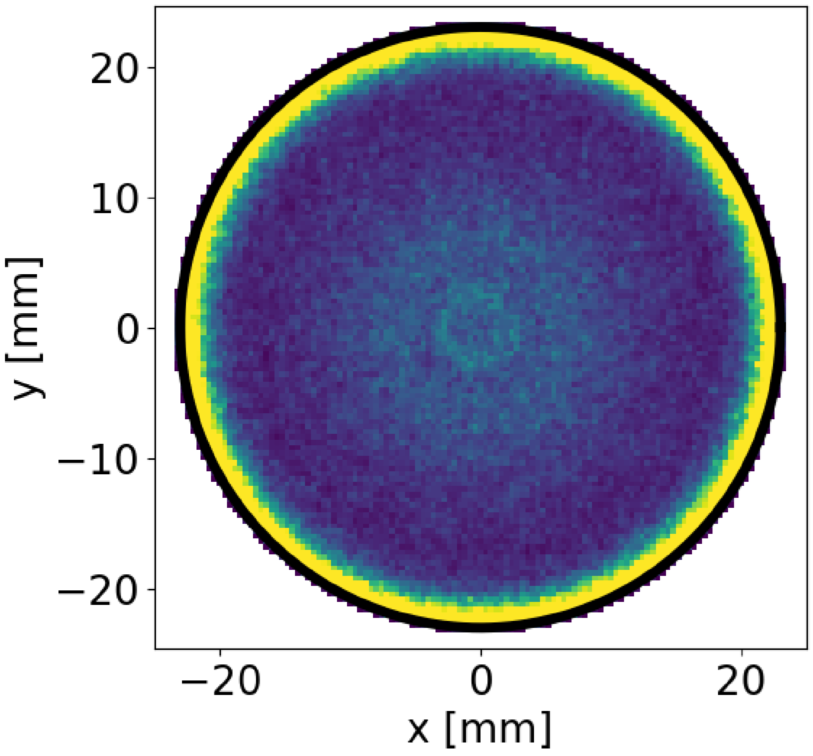
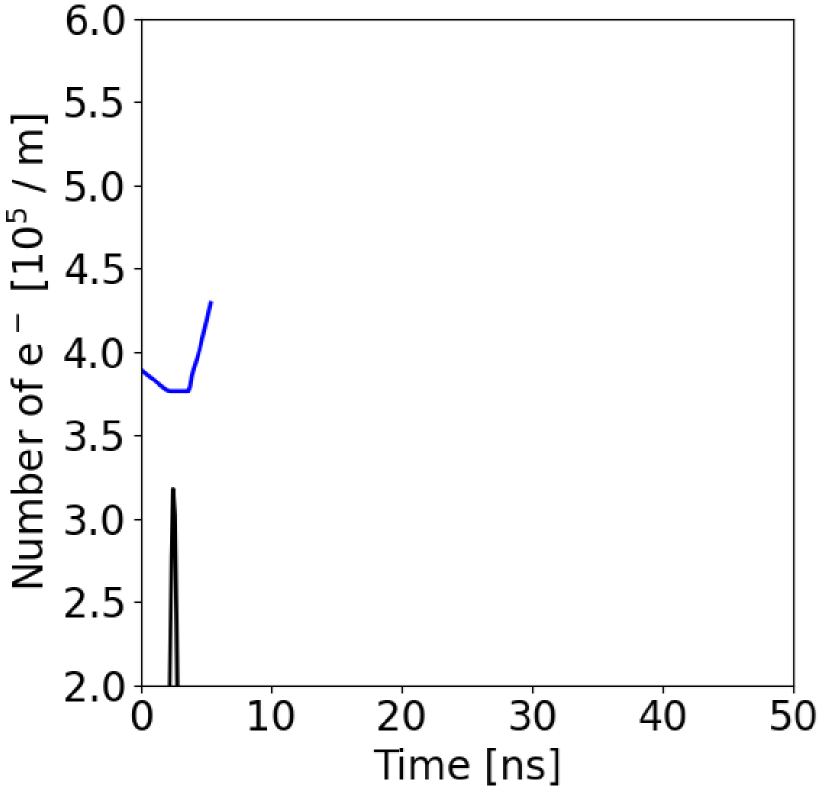
Electron cloud formation cartoon

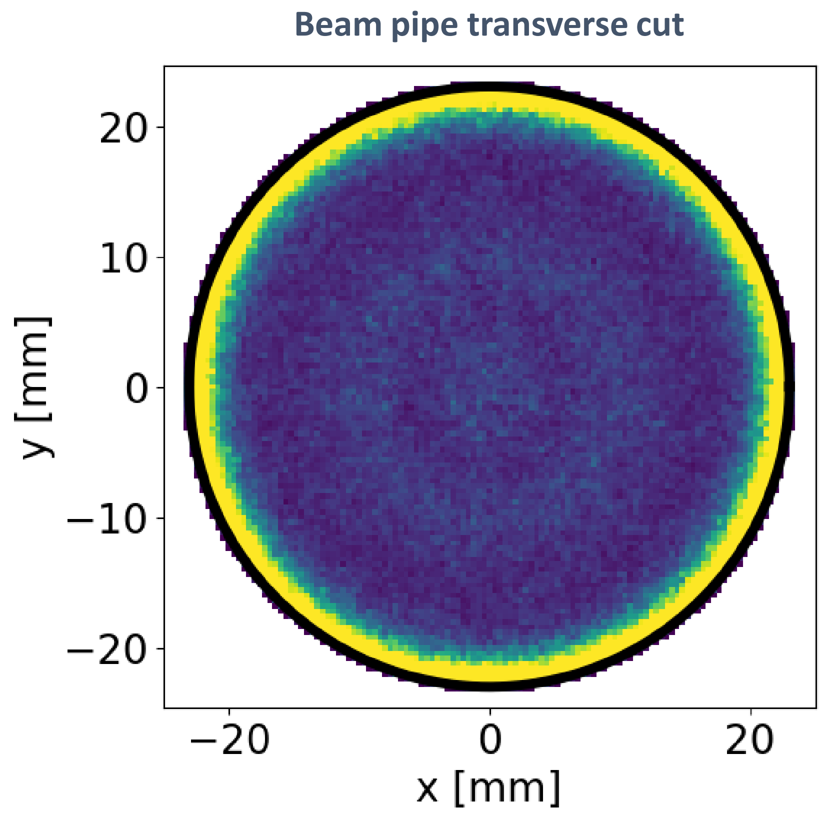
Beam pipe transverse cut

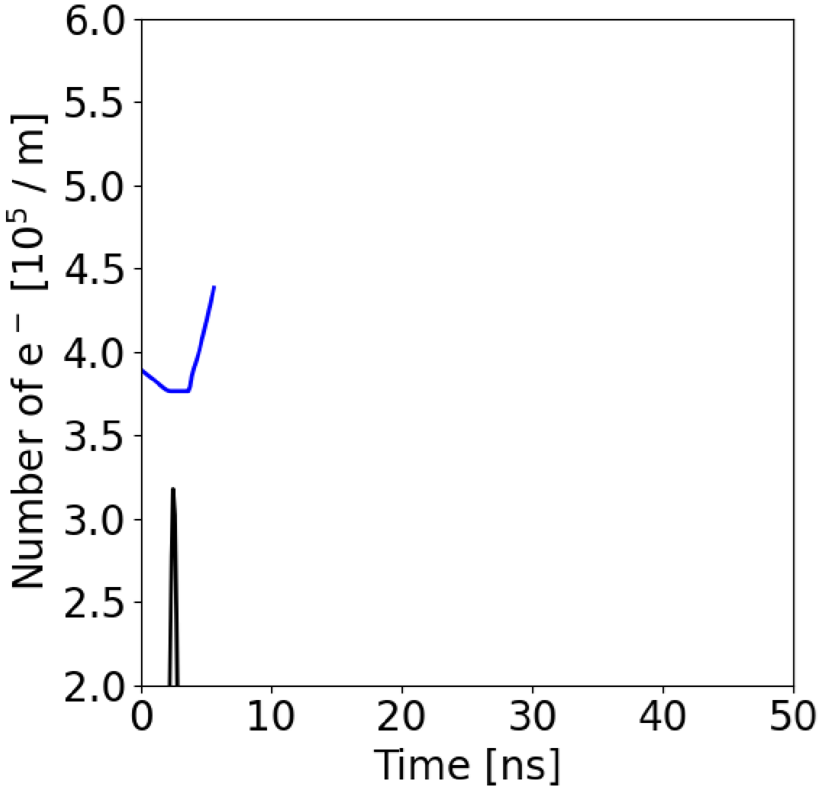




As they are produced, the emitted secondaries form a halo near the chamber wall because they have low energy (up to 10 eV)

Electron cloud formation cartoon





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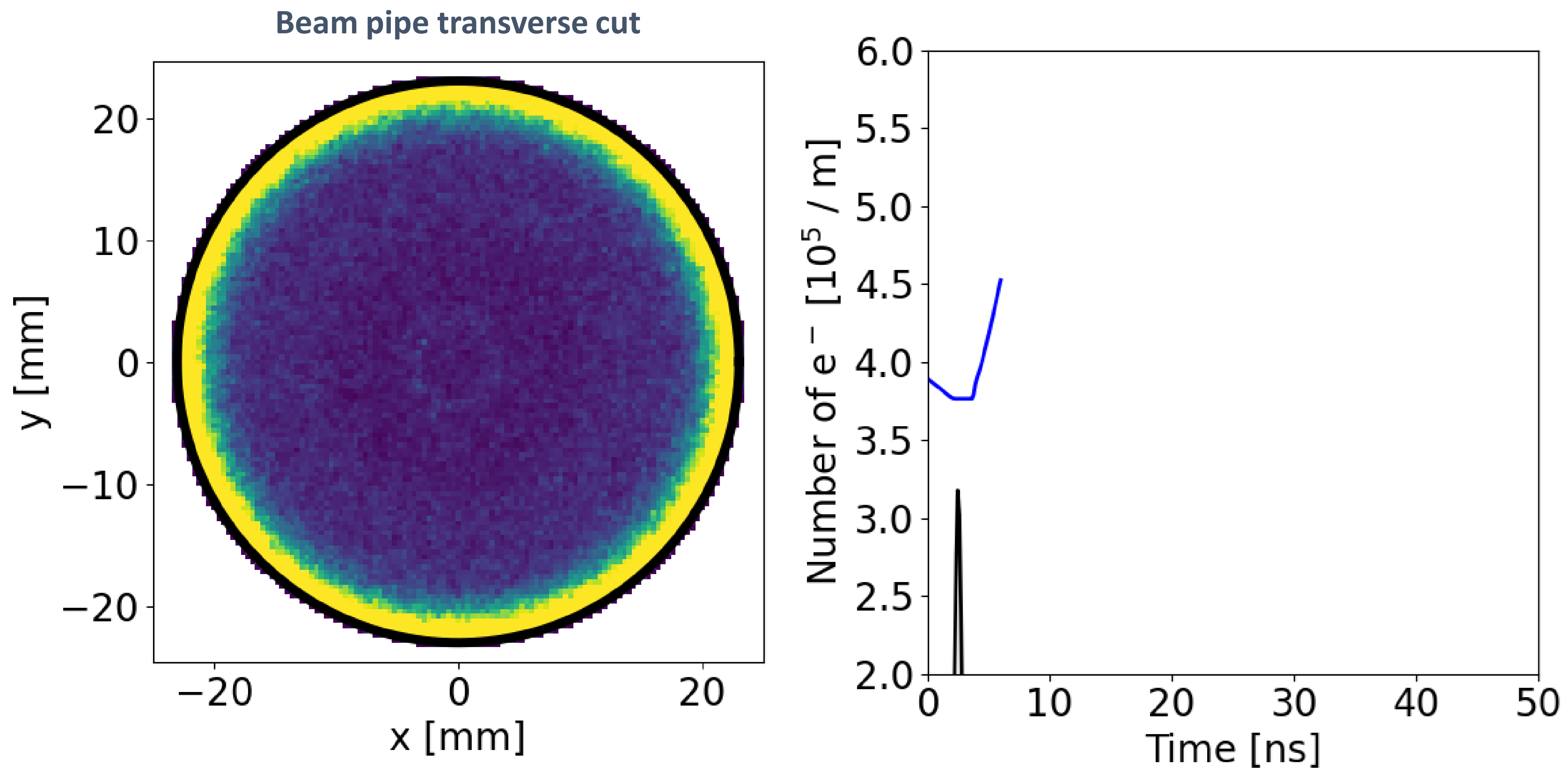
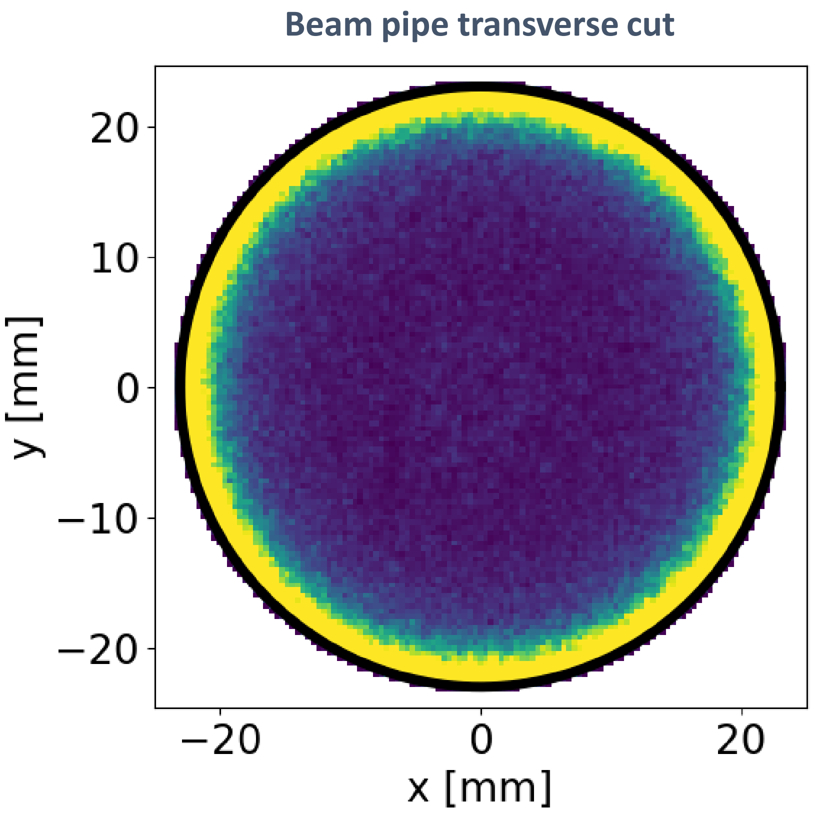
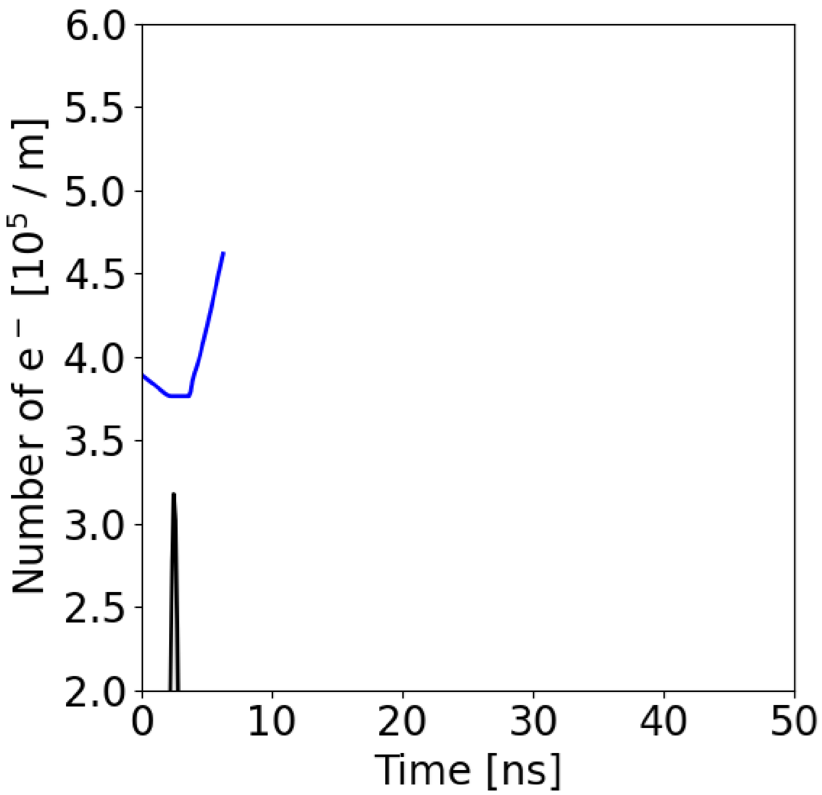


While the halo gets more and more populated,
the center is gradually depleted

Electron cloud formation cartoon





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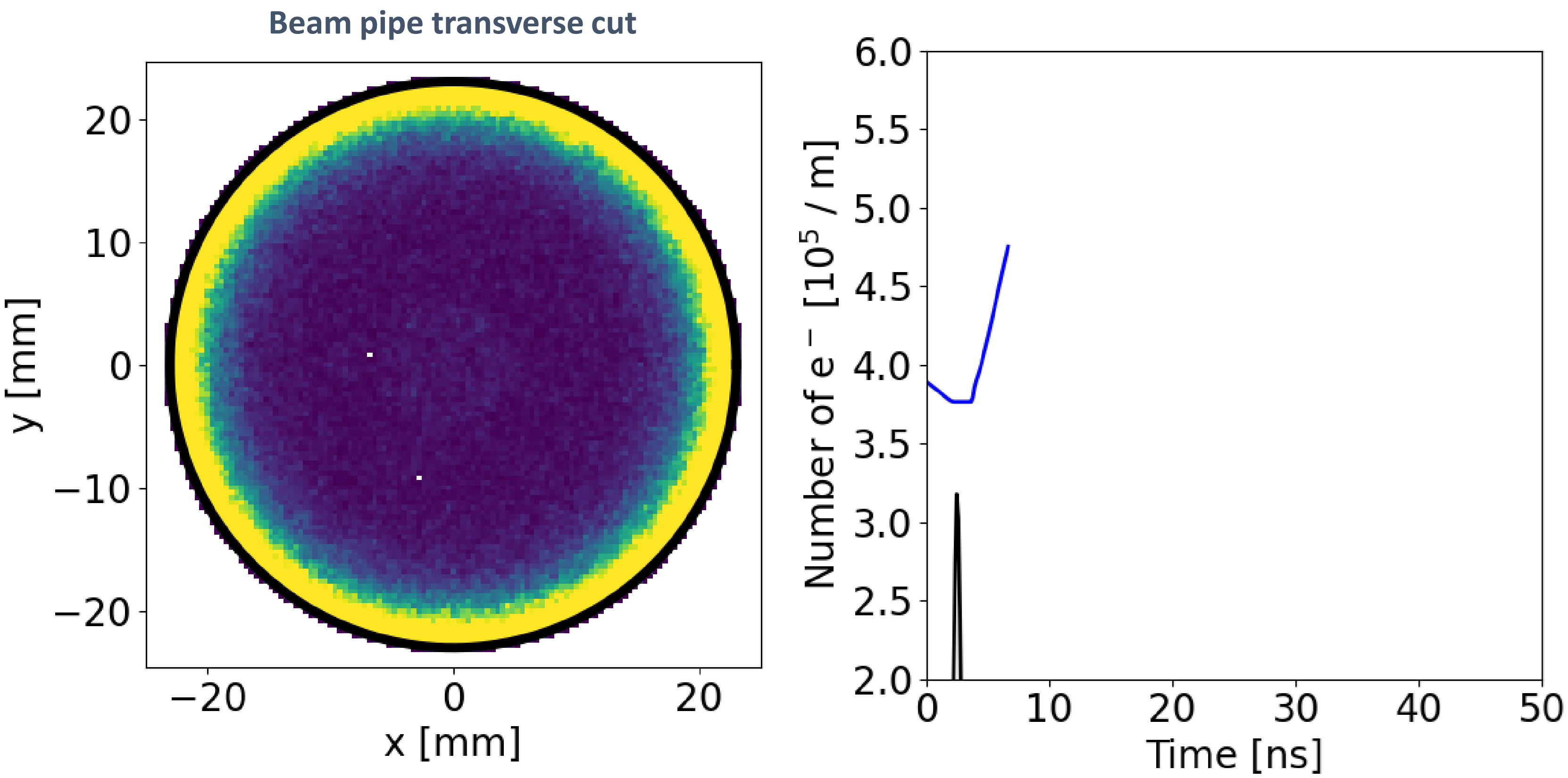

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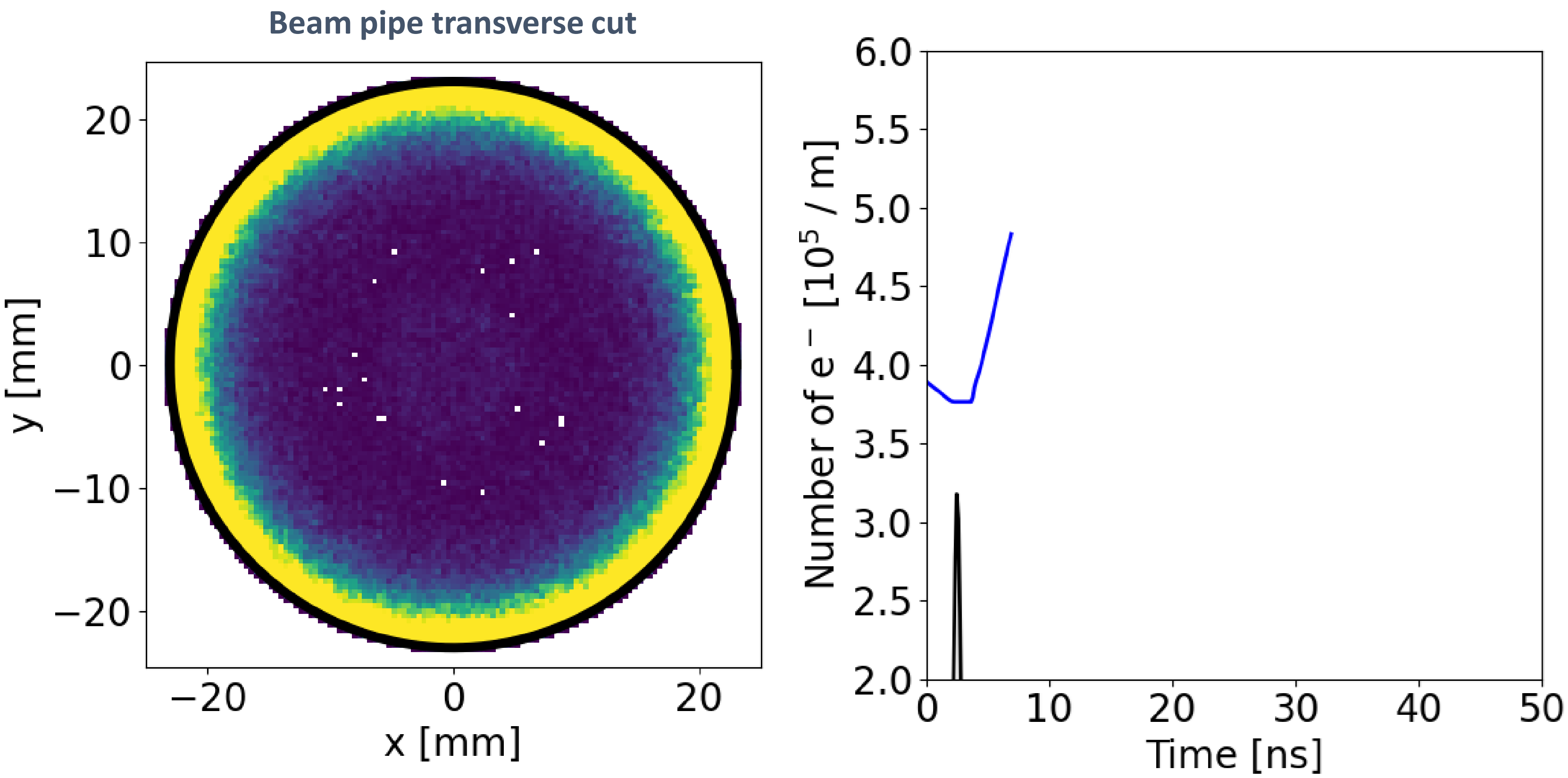

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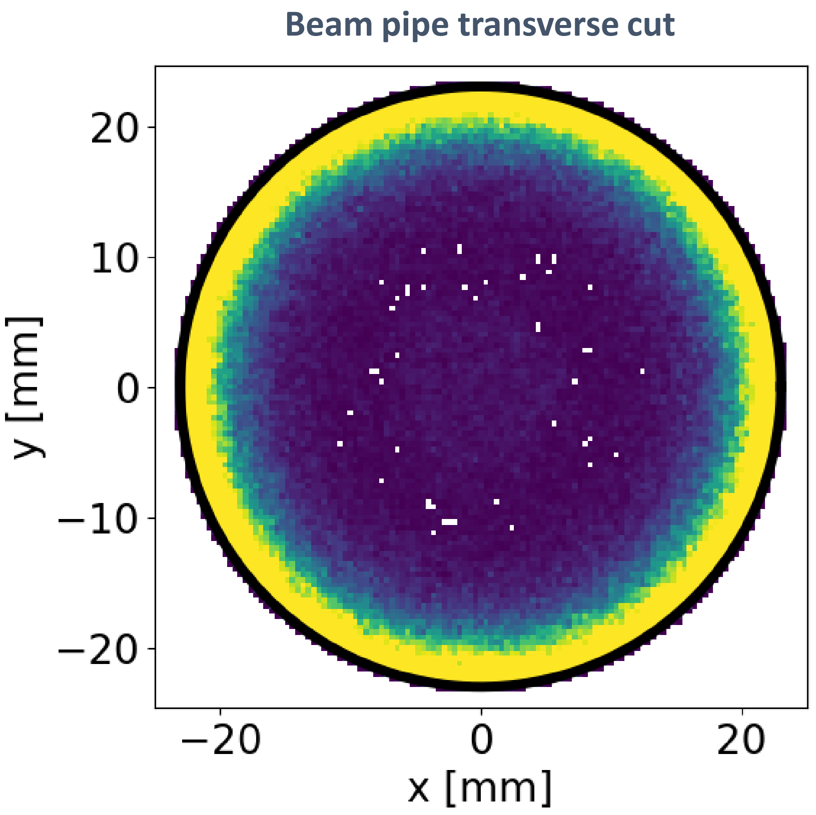

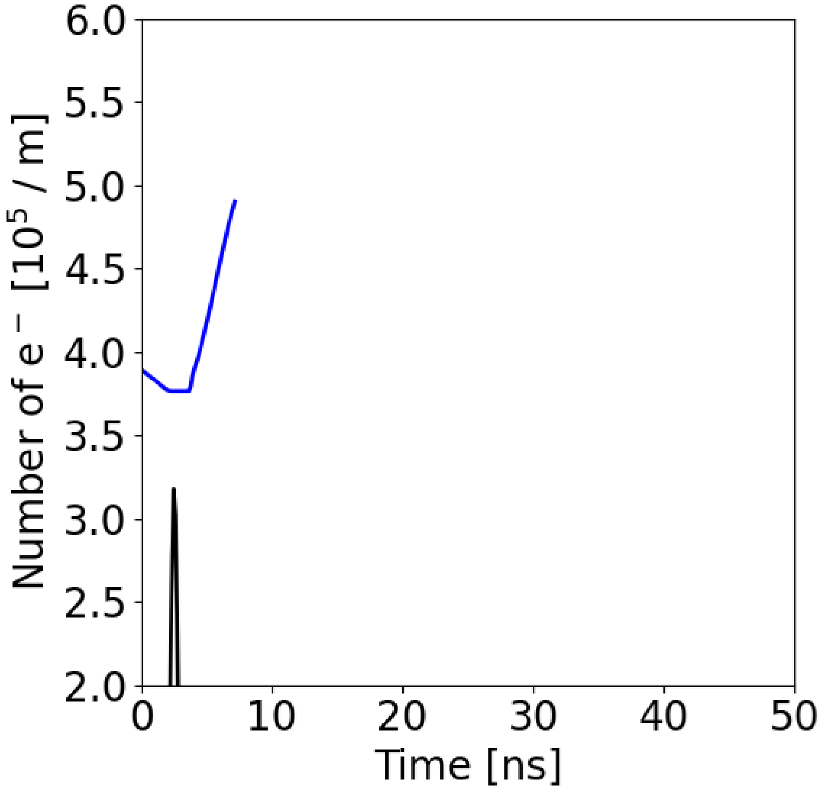

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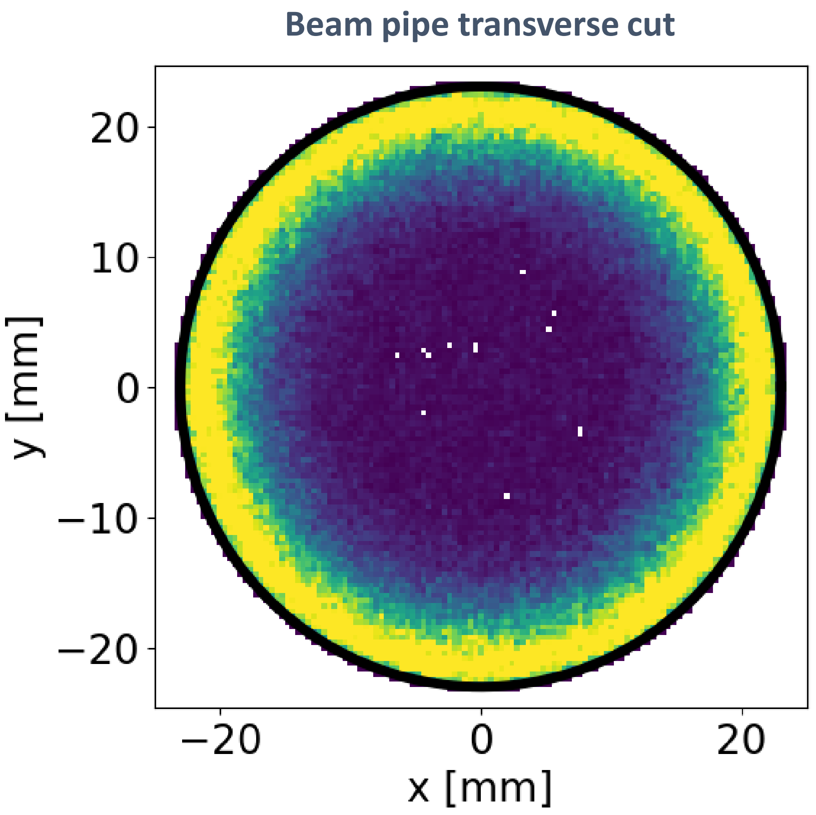
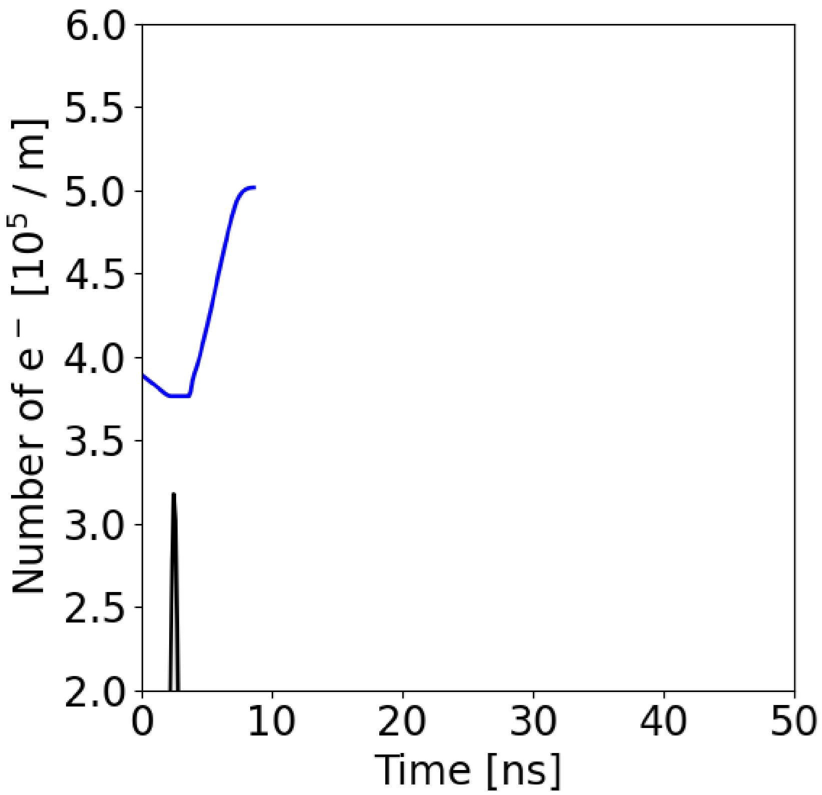
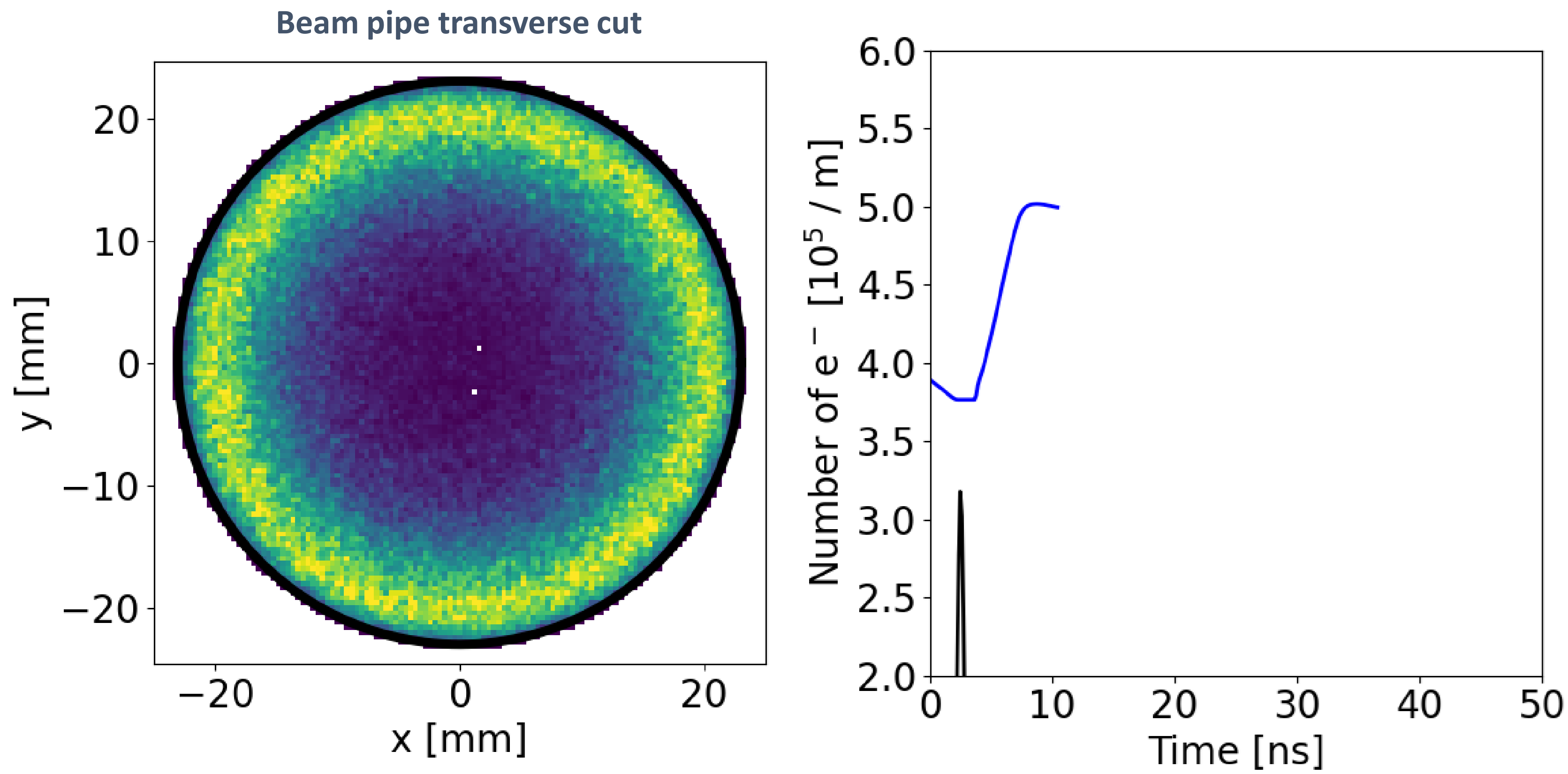




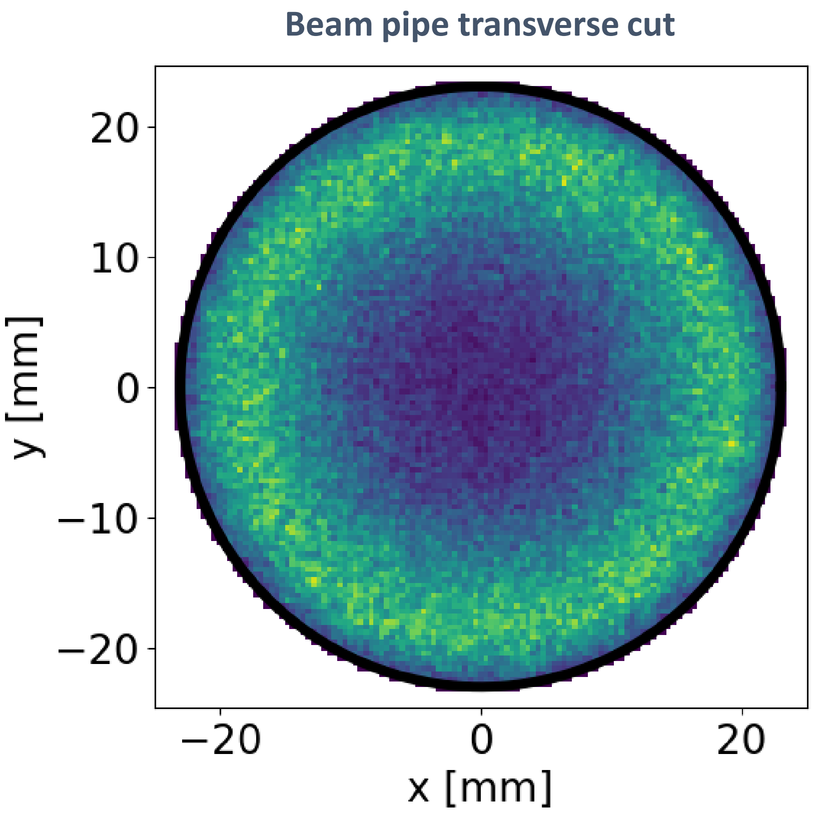
The center is strongly depleted
No more secondaries are produced because there are no longer high energy electrons reaching the walls

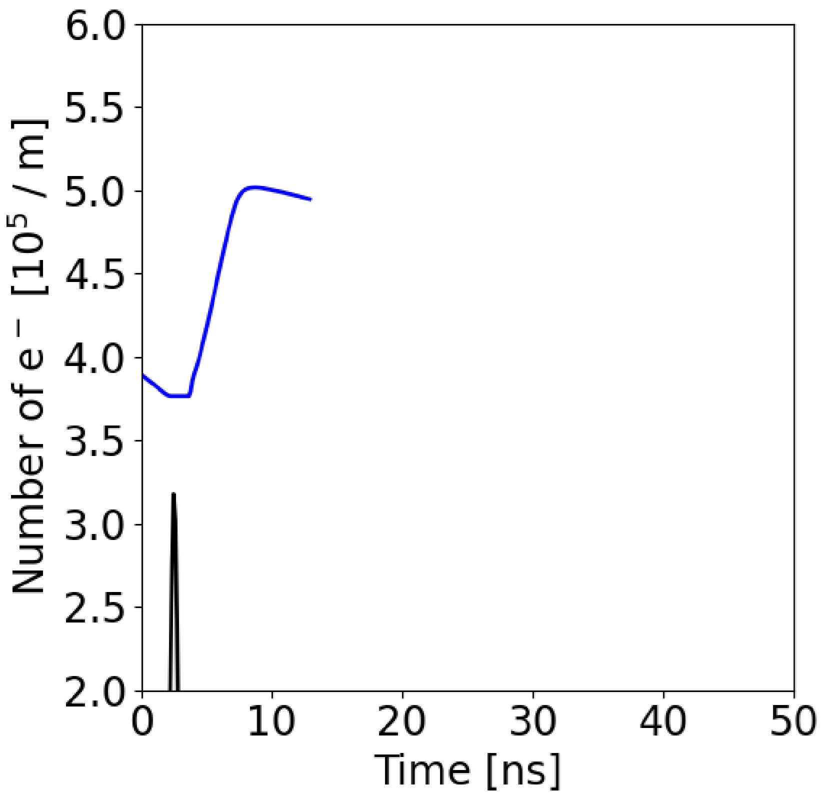
Electron cloud formation cartoon



No more secondaries are produced because there are no longer high energy electrons reaching the walls
Some low energy electrons are absorbed at the walls

Electron cloud formation cartoon





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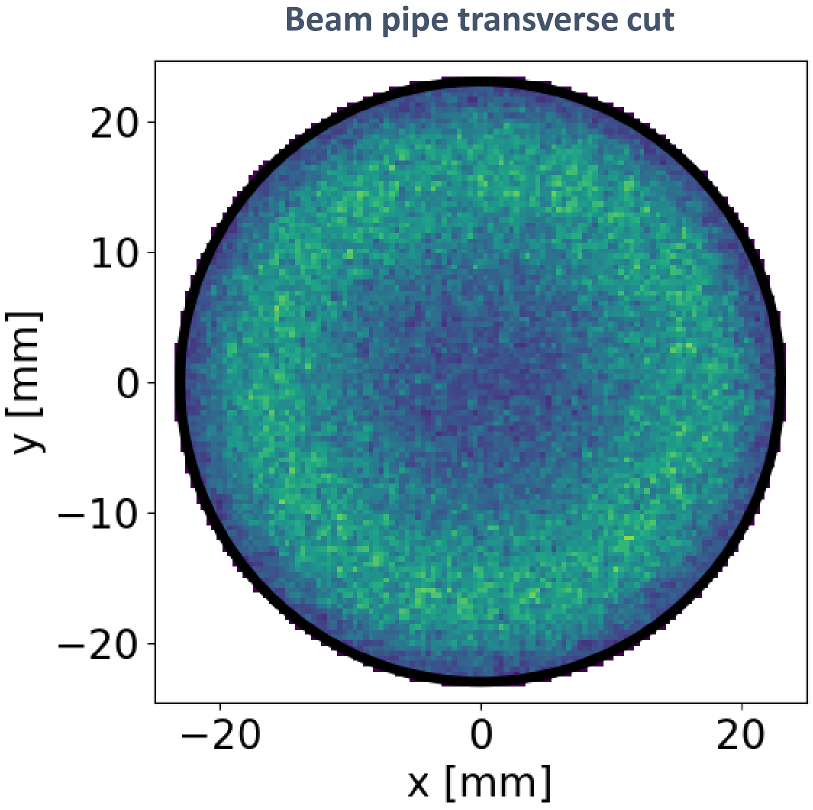

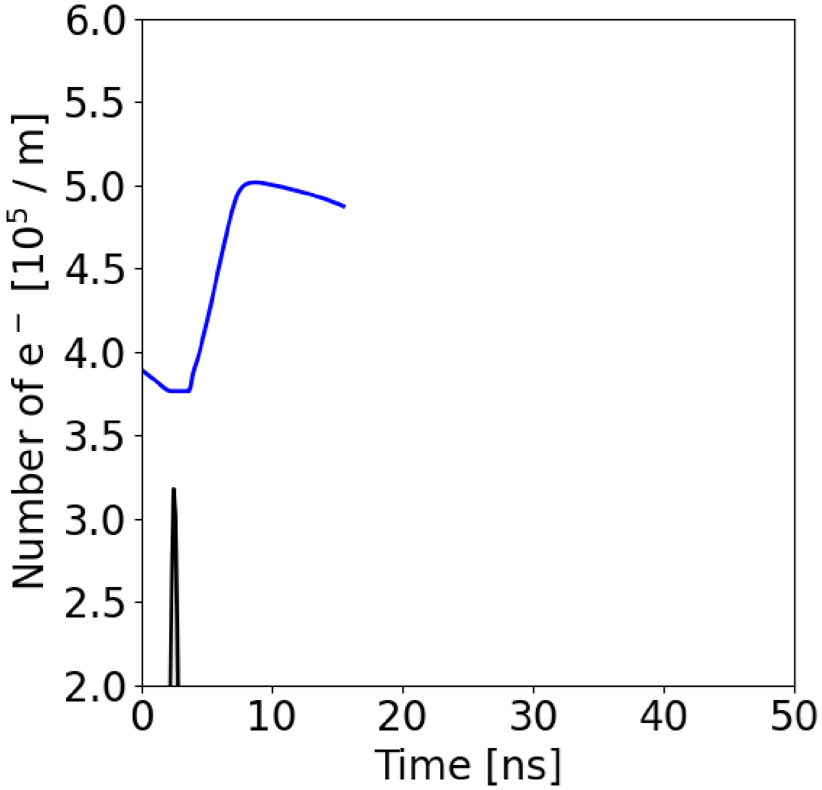

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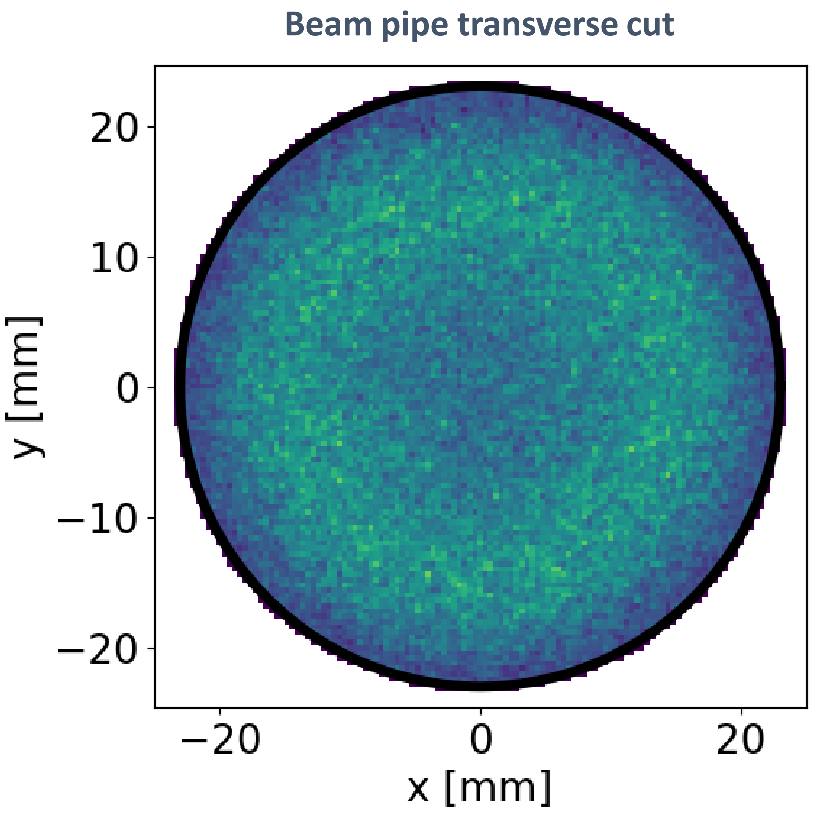
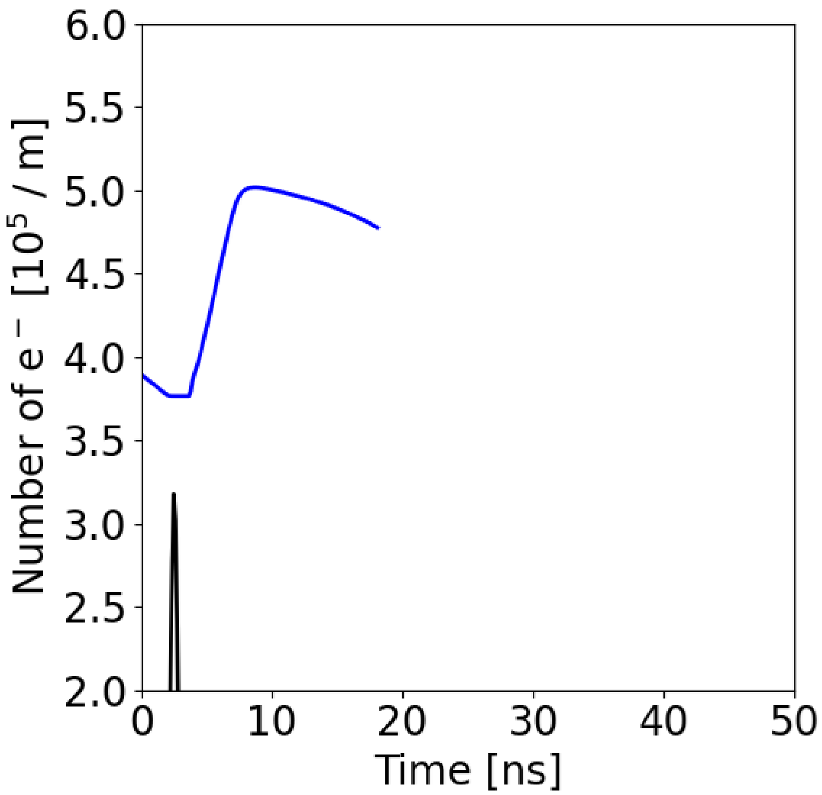
Electron cloud formation cartoon





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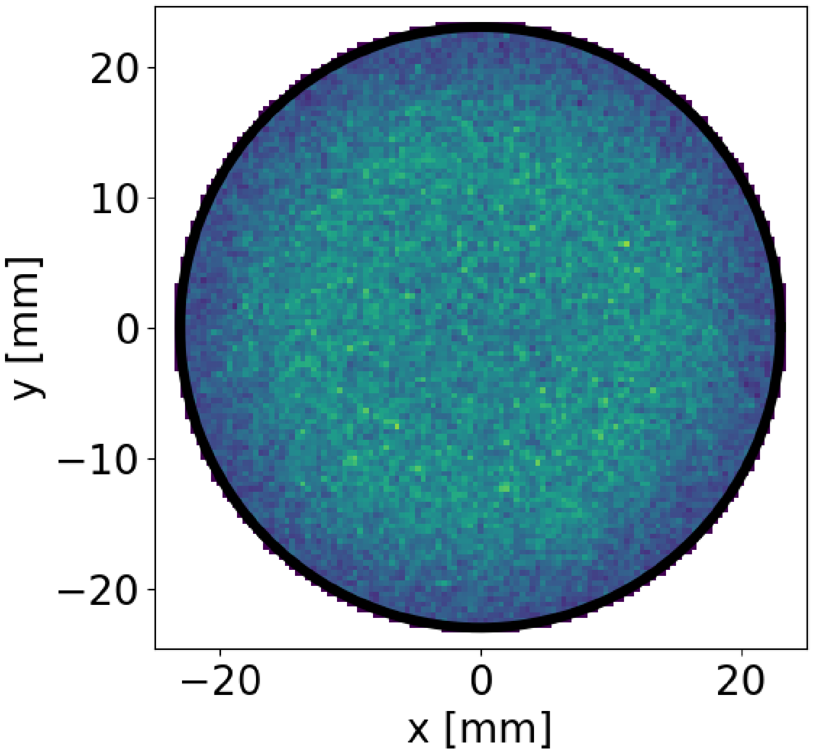
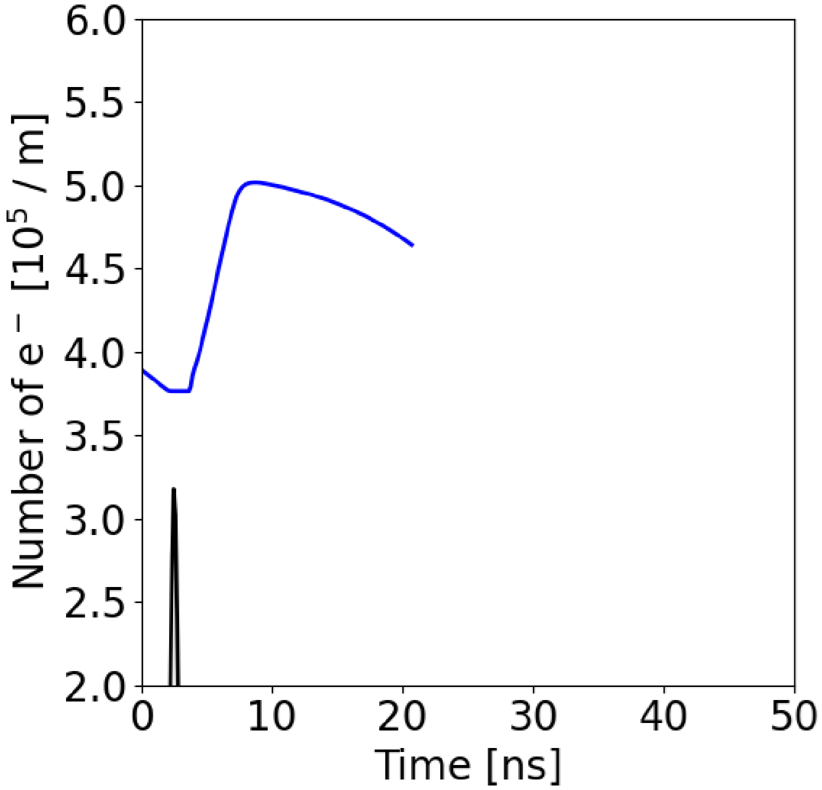
Some low energy electrons are absorbed at the walls

Electron cloud formation cartoon

Beam pipe transverse cut



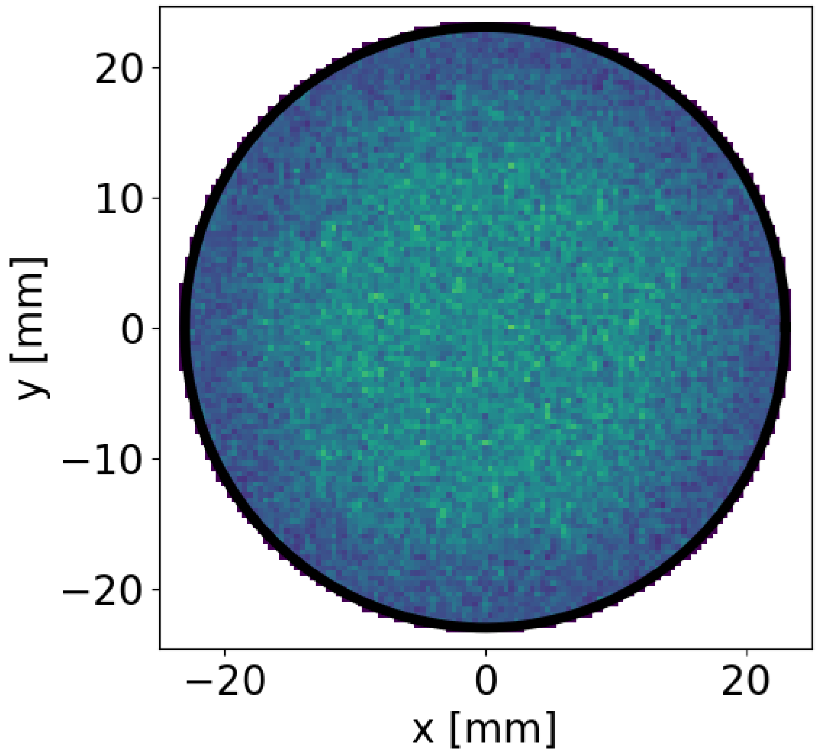


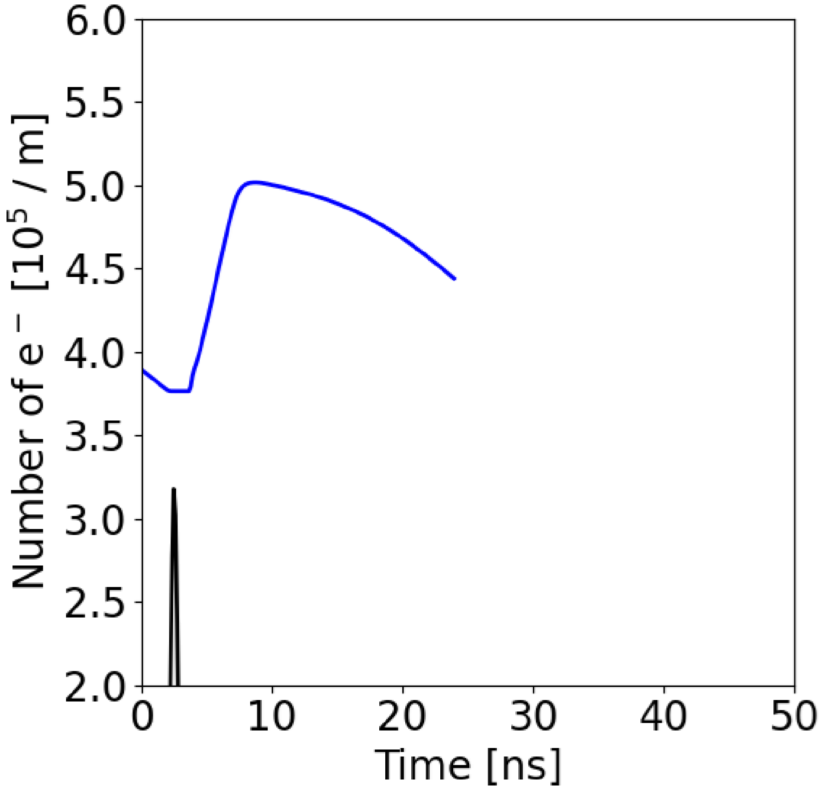
No more secondaries are produced because there are no longer high energy electrons reaching the walls

Now the center gets repopulated

Electron cloud formation cartoon

Beam pipe transverse cut





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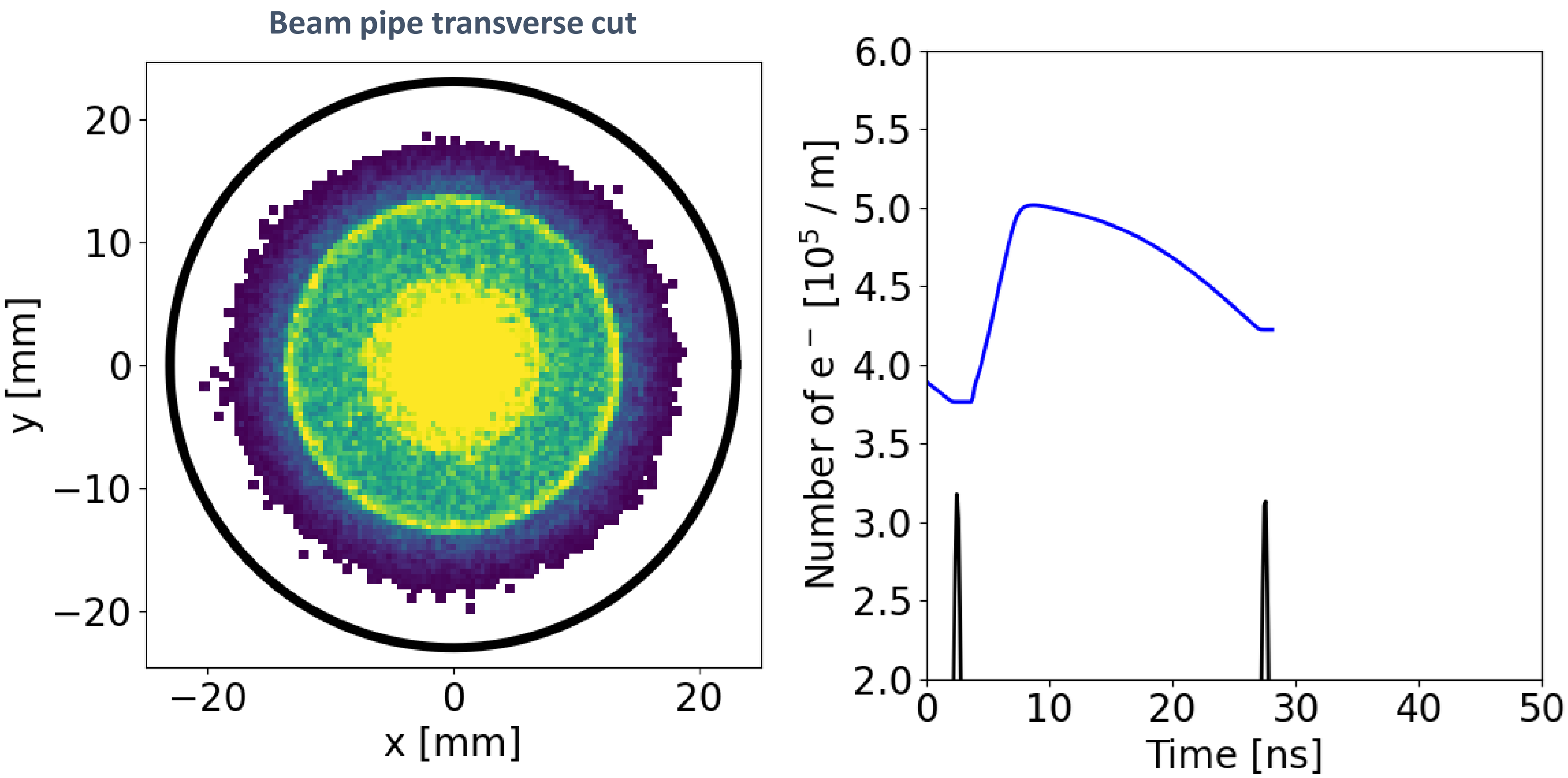
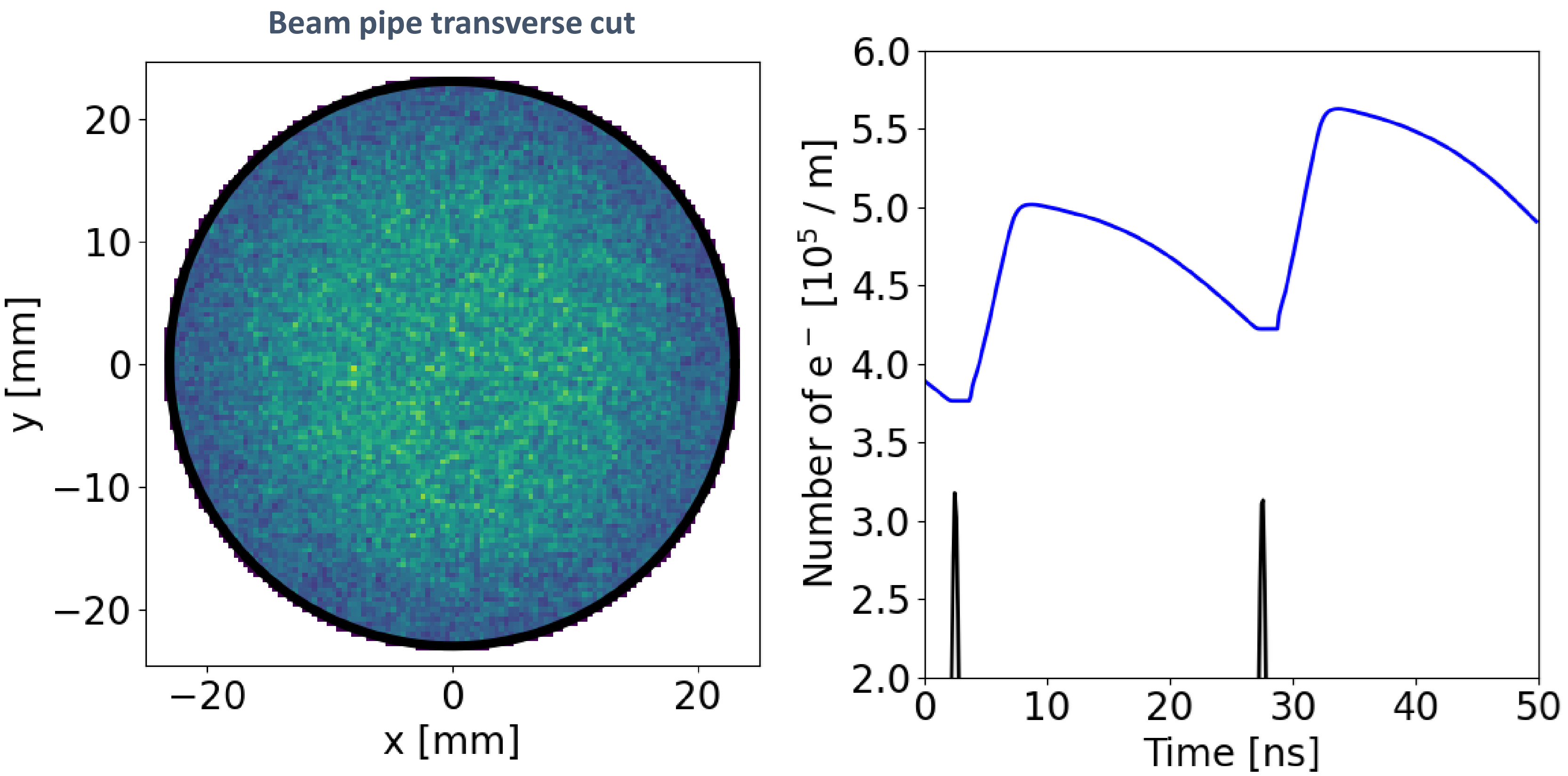
Electron cloud formation cartoon



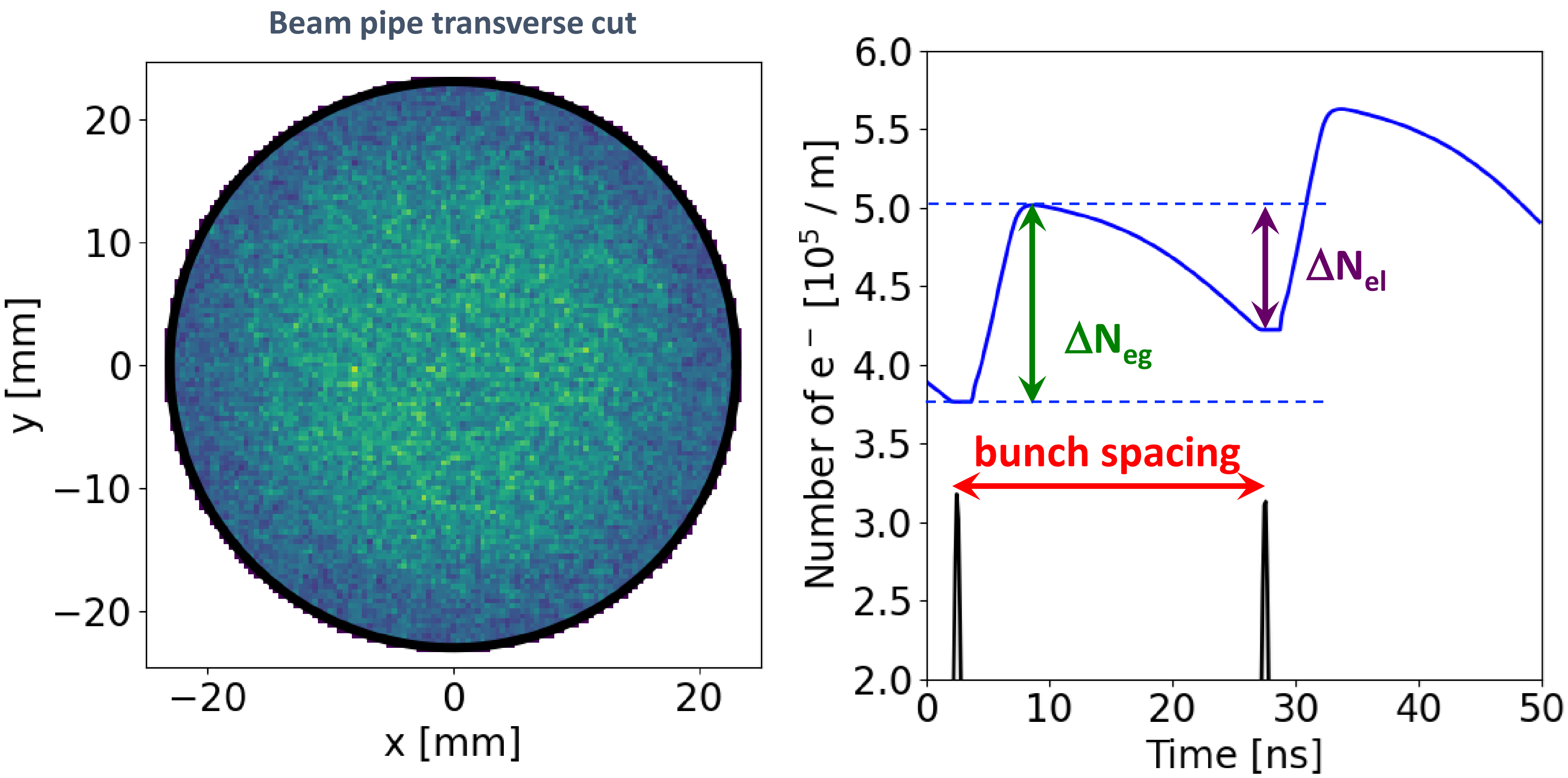
But then the next bunch comes, there is a new pinch and the whole process starts all over

Electron cloud formation cartoon



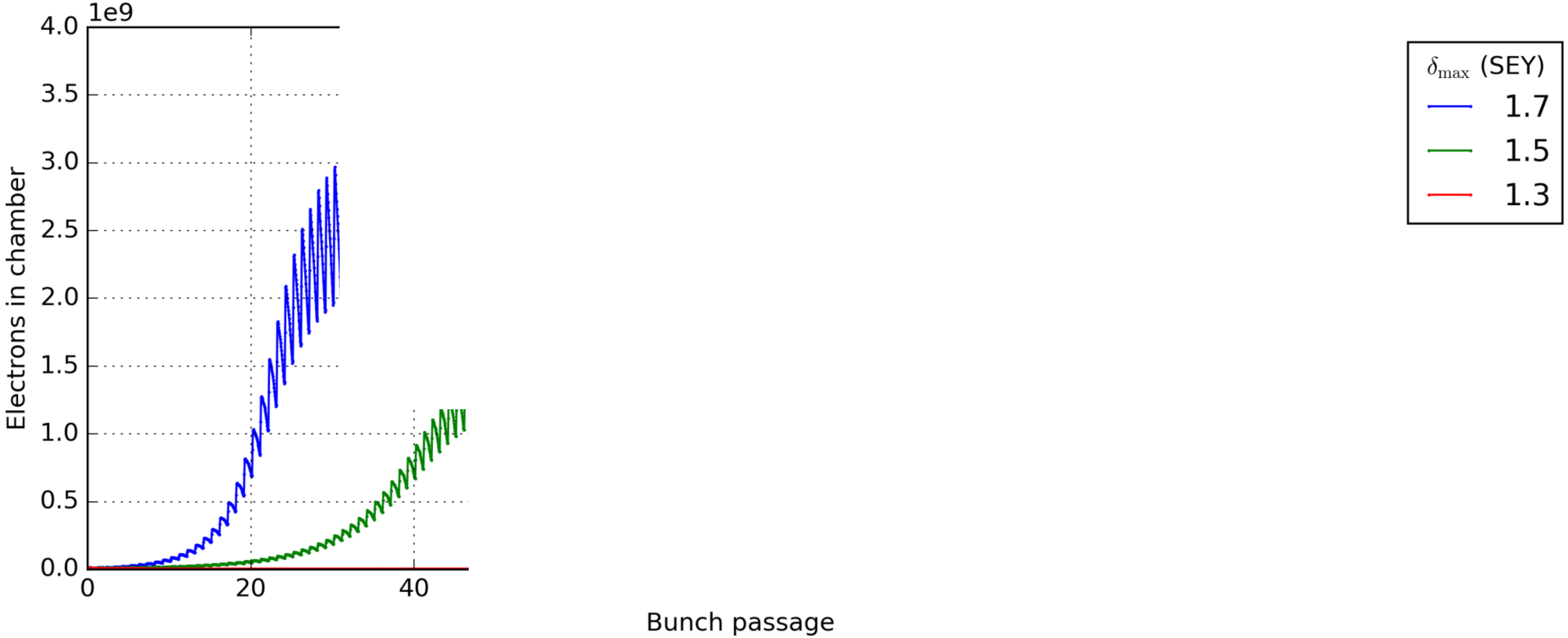
And it all repeats until the next bunch comes

Electron cloud formation cartoon



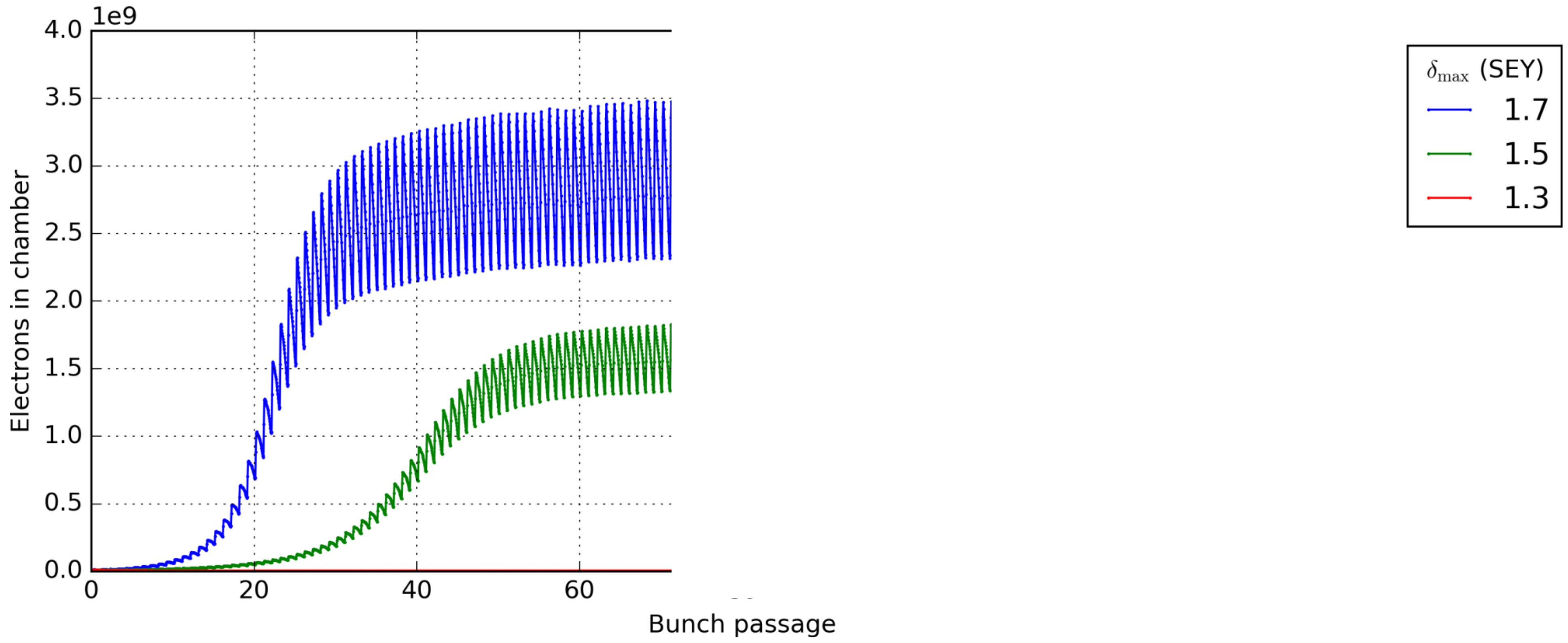
- Electrons generated (ΔN_{eg}) depend on bunch charge, chamber radius and surface SEY
- Electrons lost (ΔN_{el}) depend on chamber radius and probability of reflection at low energy
- Balance between the two depends on **bunch spacing**

Electron cloud formation cartoon



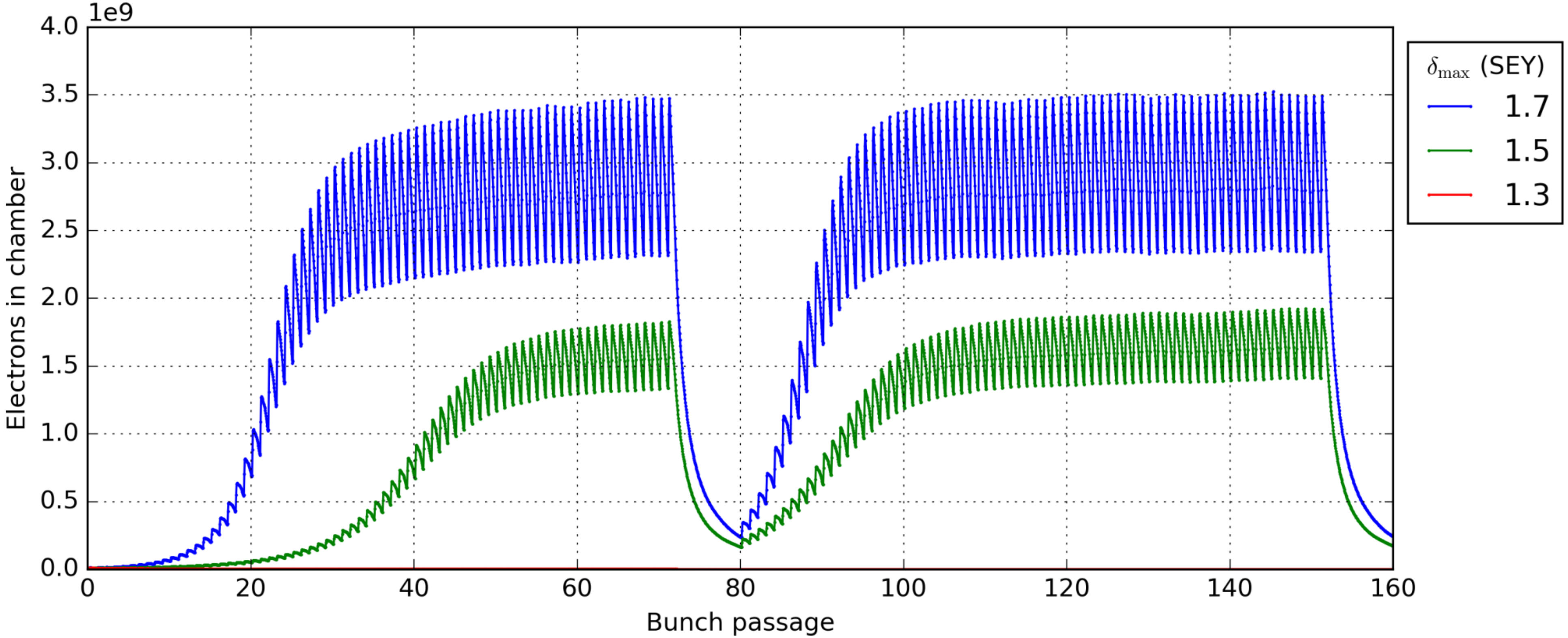
- Bunch after bunch, the e-cloud grows exponentially (if SEY above a certain threshold value)

Electron cloud formation cartoon



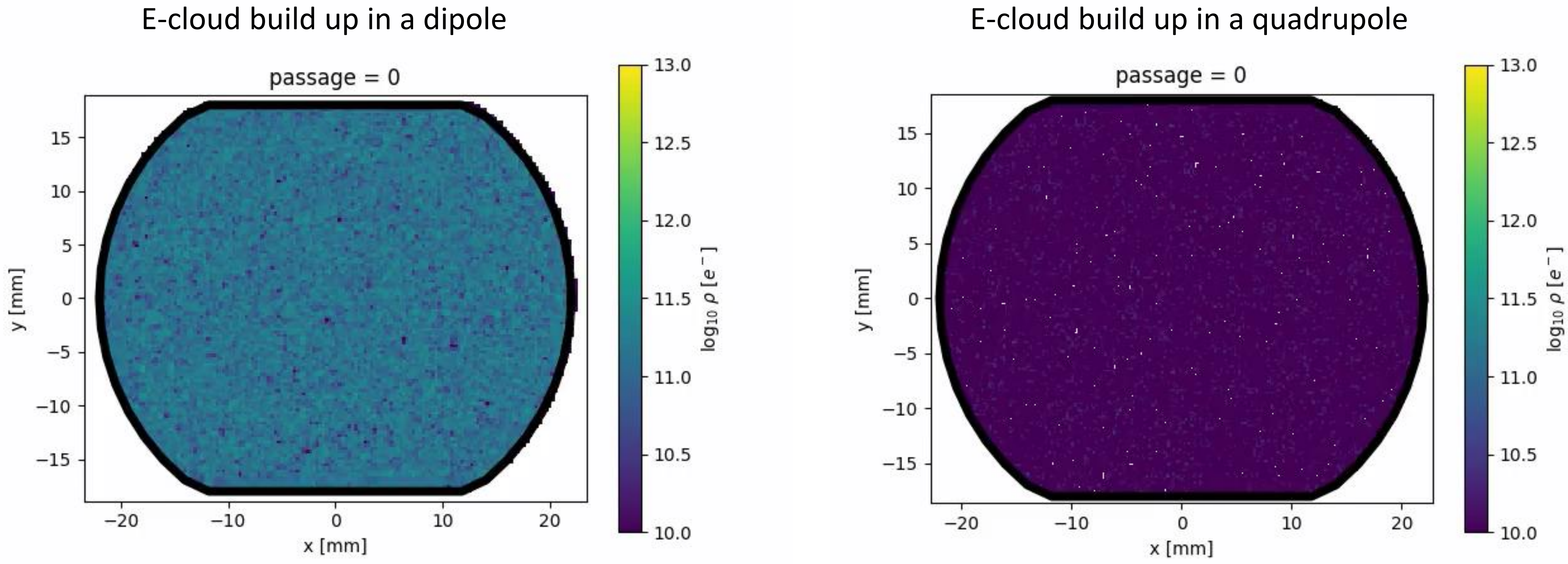
- Bunch after bunch, the e-cloud grows exponentially (if SEY above a certain threshold value)
- The exponential rise stops when the space charge of the electrons becomes significant → At this point electron generation and loss compensate each other

Electron cloud formation cartoon



- Bunch after bunch, the e-cloud grows exponentially (if SEY above a certain threshold value)
- The exponential rise stops when the space charge of the electrons becomes significant → At this point electron generation and loss compensate each other
- The electron cloud decays in the gaps between trains

Electron cloud formation movies



Signpost

We have learned that **electrons are generated** in the vacuum chamber of an accelerator when the beam passes.

We have learned that:

- The number of electrons can grow because of secondary electron emission at the chamber walls
- The process at some point saturates because of the electron cloud space charge
- A significant electron density builds up in the machine while bunches are passing → electron cloud

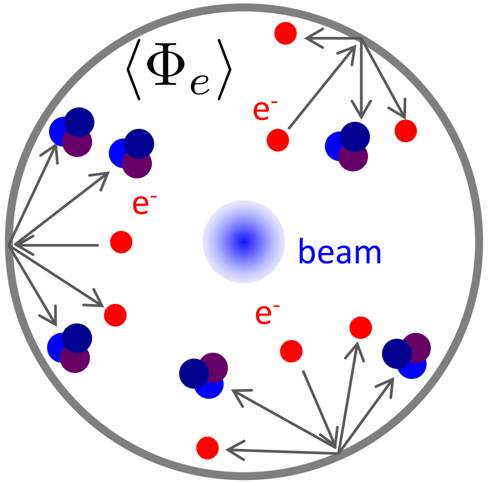
Once the machine operates with **electron cloud**, what do we observe?

Part 4: Electron cloud – Build up and effects on beam dynamics

- Electron cloud build up
  - Electron production and multiplication
  - Observation in accelerator rings
- Scrubbing and other techniques of mitigation/suppression
- E-cloud induced instabilities and incoherent effects

Electron cloud effects

- The presence of an e-cloud inside an accelerator ring is revealed by several **typical signatures**
  - ✓ Fast pressure rise, outgassing
  - ✓ Additional heat load
  - ✓ Baseline shift of the pick-up electrode signal
  - ✓ Synchronous phase shift along the bunch train due to energy loss



$$\Delta P \propto \int \eta_e(E) \langle \Phi_e(E) \rangle dE$$

$$\Delta W = \int \langle \Phi_e(E) \rangle E dE$$

Electron cloud effects

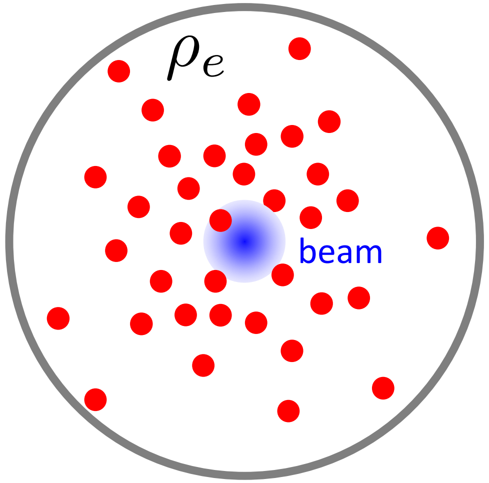
- The presence of an e-cloud inside an accelerator ring is revealed by several **typical signatures**
  - ✓ Fast pressure rise, outgassing
  - ✓ Additional heat load
  - ✓ Baseline shift of the pick-up electrode signal
  - ✓ Synchronous phase shift along the bunch train due to energy loss

  } Machine observables

  - ✓ Tune shift along the bunch train
  - ✓ Coherent instability
  - ✓ Single bunch effect affecting the last bunches of a train
  - ✓ Coupled bunch effect
  - ✓ Poor beam lifetime and emittance growth

  } Beam observables

  - ✓ Active monitoring: signal on dedicated electron detectors (e.g. strip monitors) and retarding field analysers

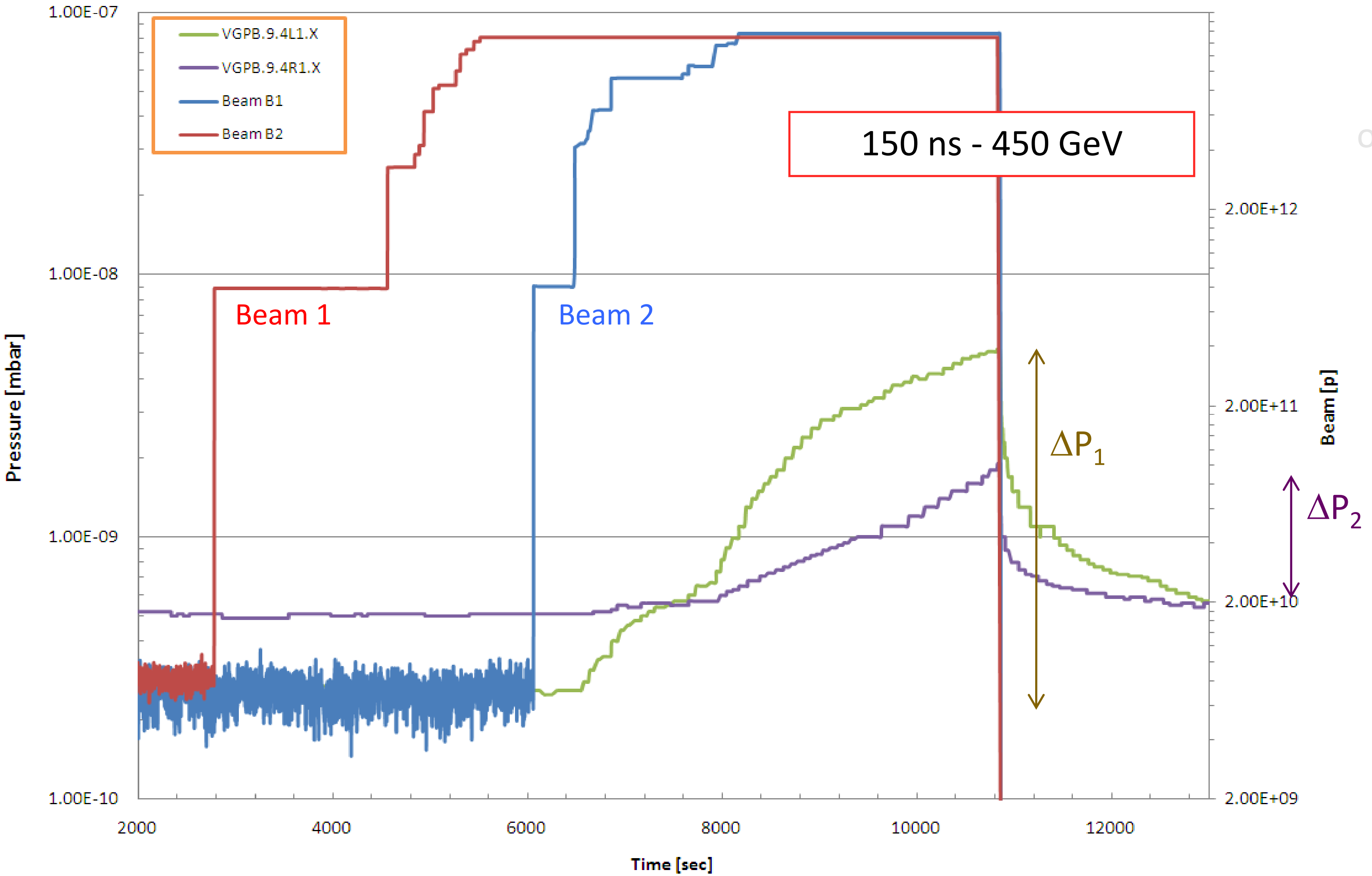


Electron cloud effects: pressure rise

- **Early LHC operation**
  - Routine operation with 150 ns beams started in Summer 2010
  - Electron cloud made its first appearance as a **pressure rise** in the common chamber in presence of both beams, i.e. for effectively lower bunch spacings

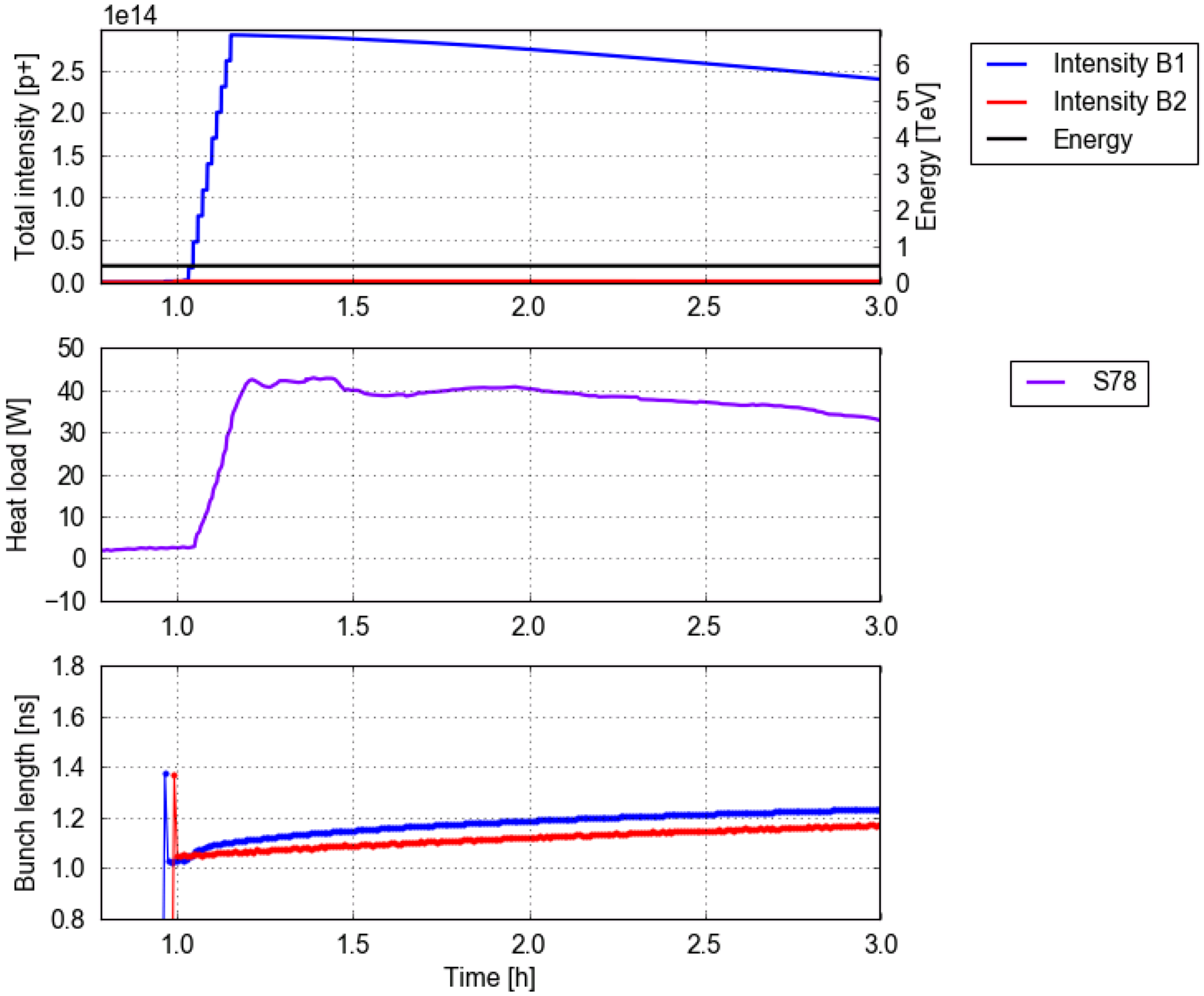
Electron cloud effects: pressure rise

- Early LHC c
  - Routine
  - Electro … of both beams, i.e. for



Electron cloud effects: heat load

⇒ Heat load on the LHC beam screen of the cold arcs

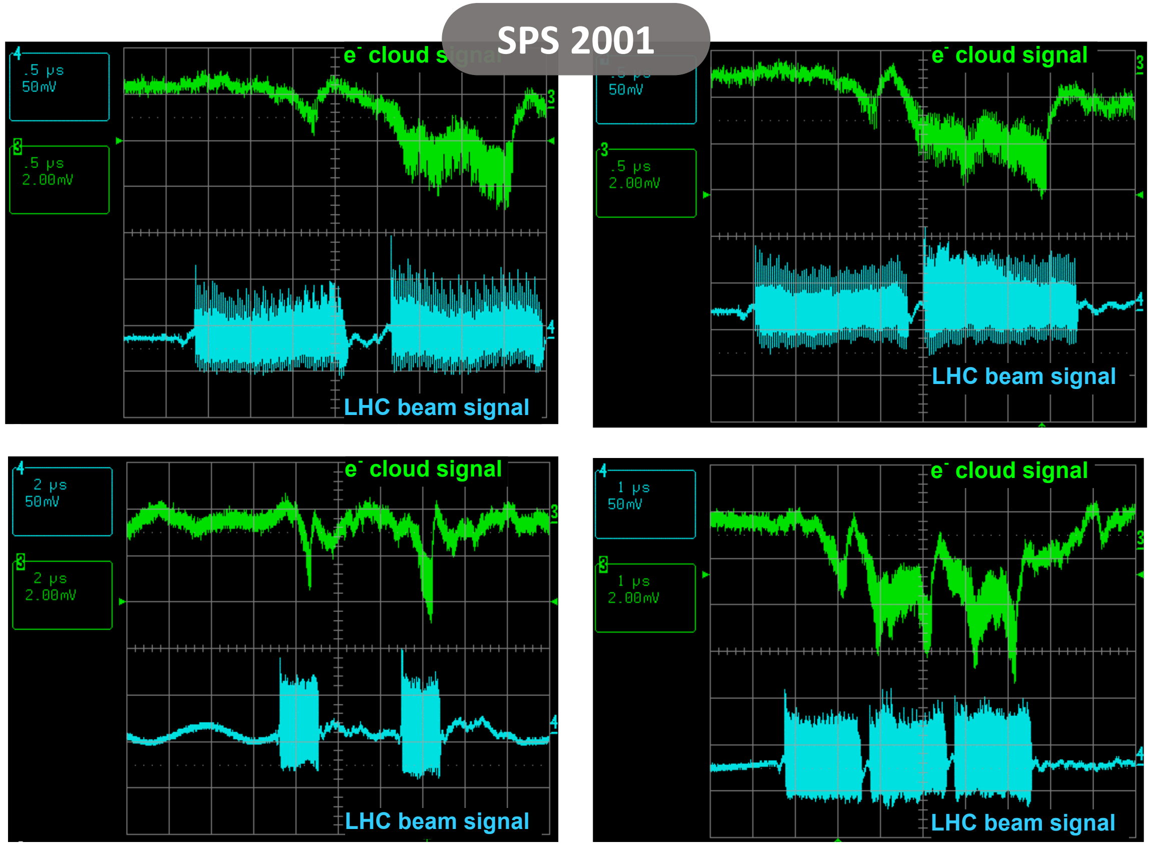


Electron cloud effects: pickup signals

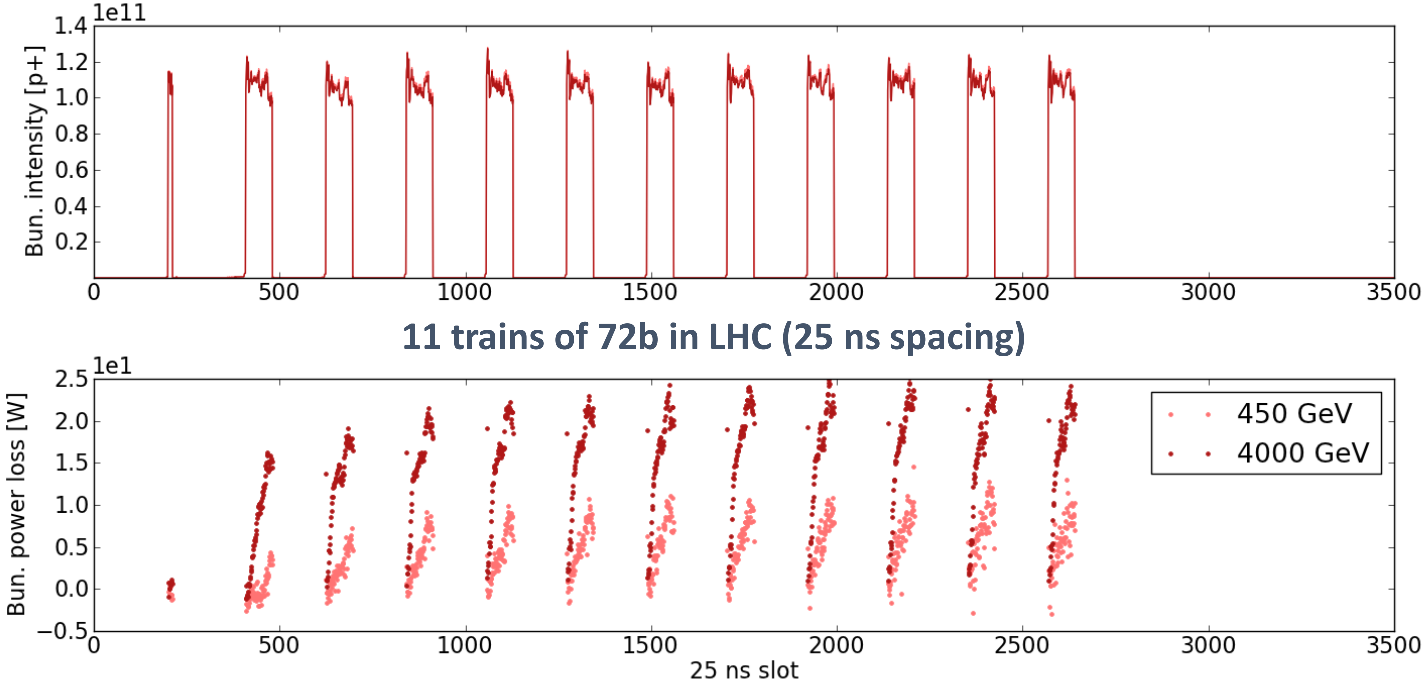
⇒ Heat load on the LHC beam screen of the cold arcs

⇒ The electron cloud signal first appeared in the SPS on the signal from a pick up as a shift of the baseline (depending on the charge collected by the electrodes)

⇒ Correlation with train structure, length, gap were immediately apparent.



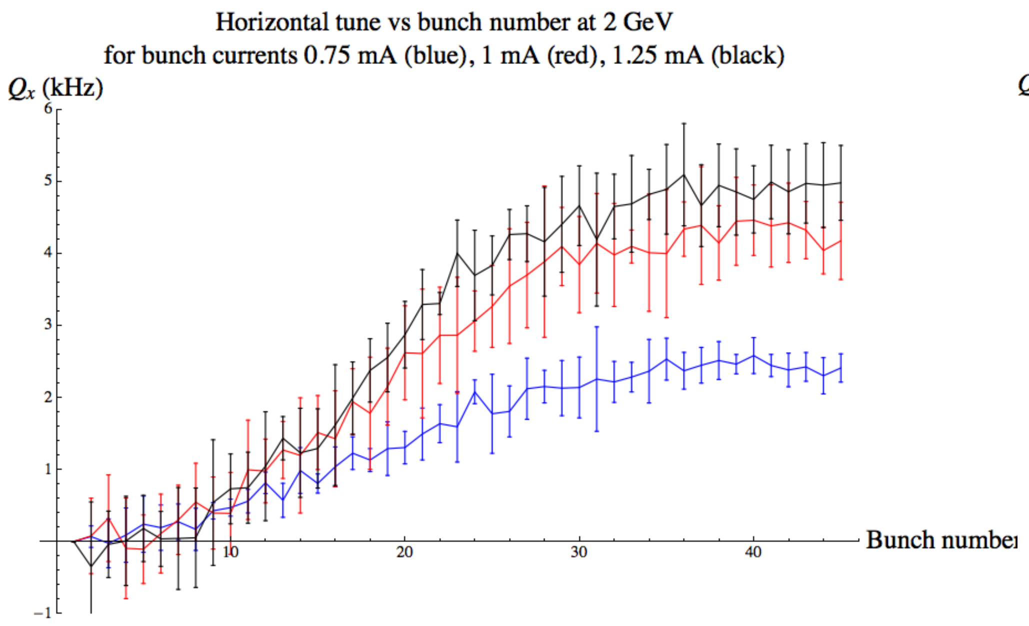
Electron cloud effects: stable phase shift

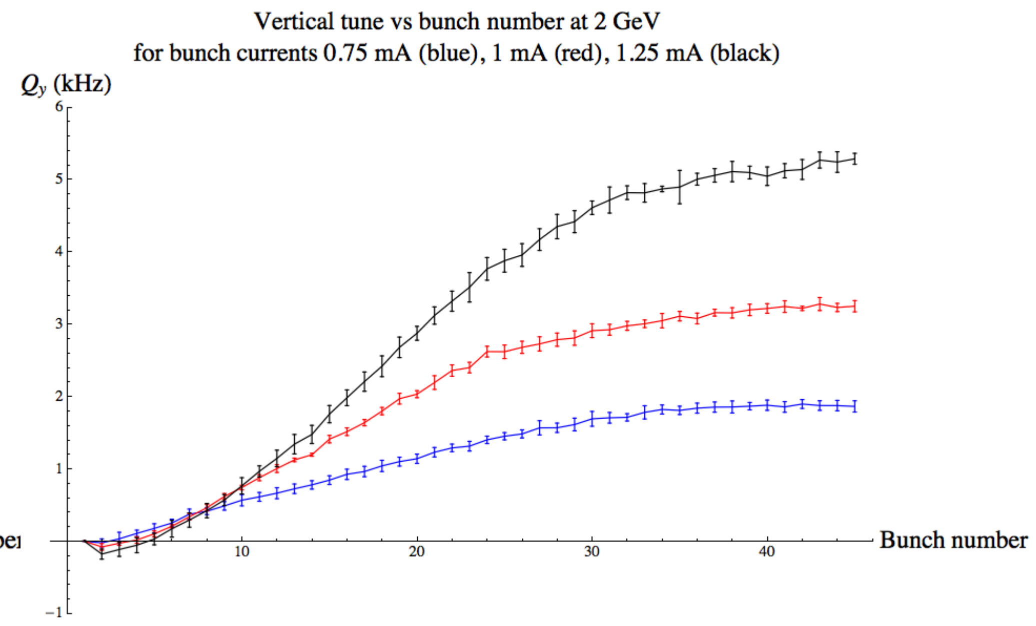


⇒ Bunch-by-bunch phase shift reveals the shape of the e-cloud build up

⇒ Larger electron cloud at 4 TeV is due to photoelectrons

Electron cloud effects: tune shift





⇒ Bunch-by-bunch phase shift reveals the shape of the e-cloud build up

⇒ Larger electron cloud at 4 TeV is due to photoelectrons

⇒ Horizontal and vertical tune shifts along a 46 bunch train in Cesr-TA (Cornell facility used for electron cloud studies) taken during a positron run

⇒ Higher currents lead to stronger electron cloud.

Signpost

We have learned that **electron clouds** can build up in the vacuum chamber of an accelerator operating in a certain range of beam parameters.

Electron clouds are associated to **many detrimental effects**, like pressure rise, additional heat load, tune and stable phase shift, beam degradation through instability and emittance growth

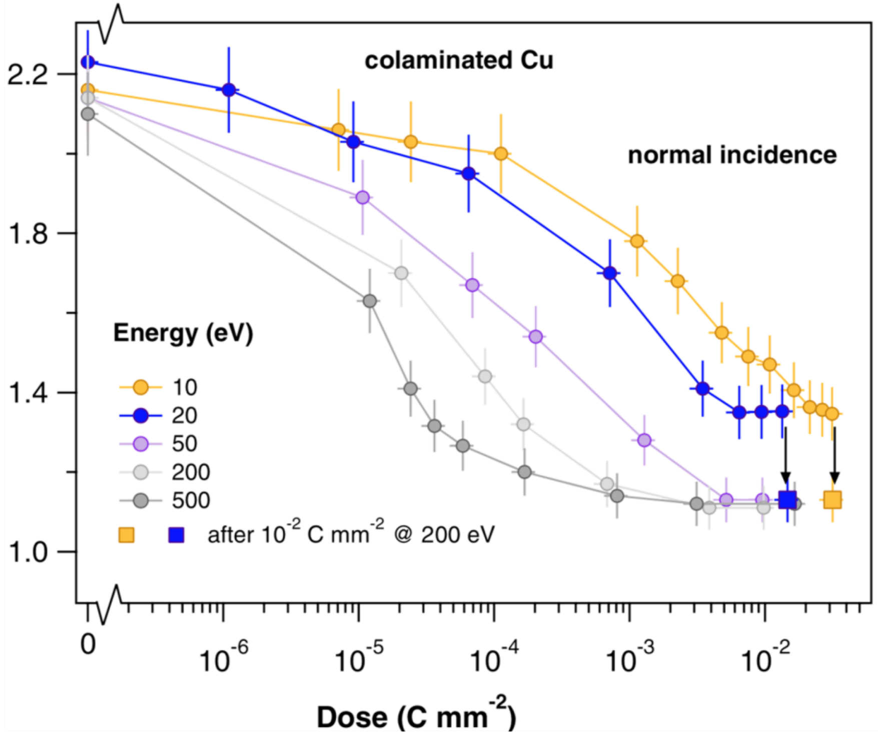
How can we avoid or cure it?

Part 4: Electron cloud – Build up and effects on beam dynamics

- Electron cloud build up
  - Electron production and multiplication
  - Observation in accelerator rings
- Scrubbing and other techniques of mitigation/suppression
- E-cloud induced instabilities and incoherent effects

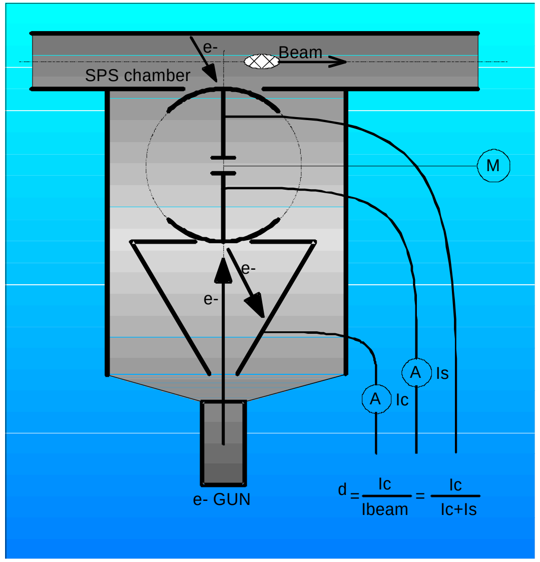
Surface scrubbing

- Fortunately, the SEY of a surface is not a fixed property but it becomes lower under electron bombardment (scrubbing)
- Laboratory measurements show that
  - SEY decreases quickly at the beginning of the process, then slows down
  - Electrons with different energies have different 'scrubbing efficiency'
  - The 'final' value of SEY depends on material, e- energy, temperature, vacuum composition, more?

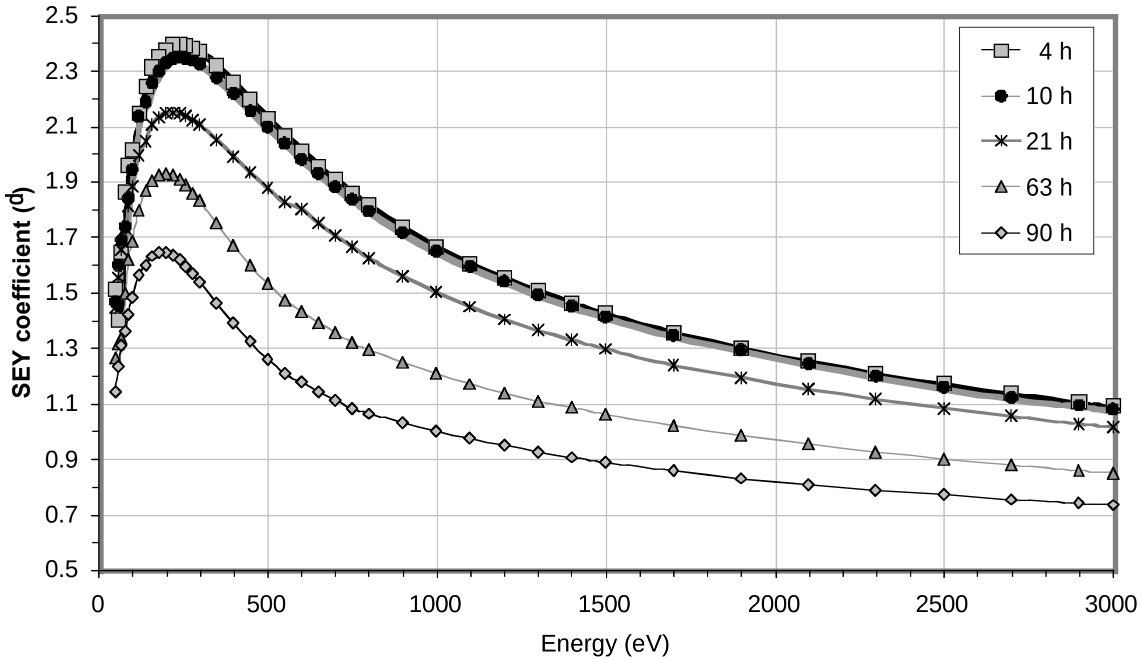


Surface scrubbing

- Beam-induced scrubbing
  - Has been measured directly at the SPS with a Stainless Steel rotatable sample exposed to the beam or to SEY measurement device (2004)

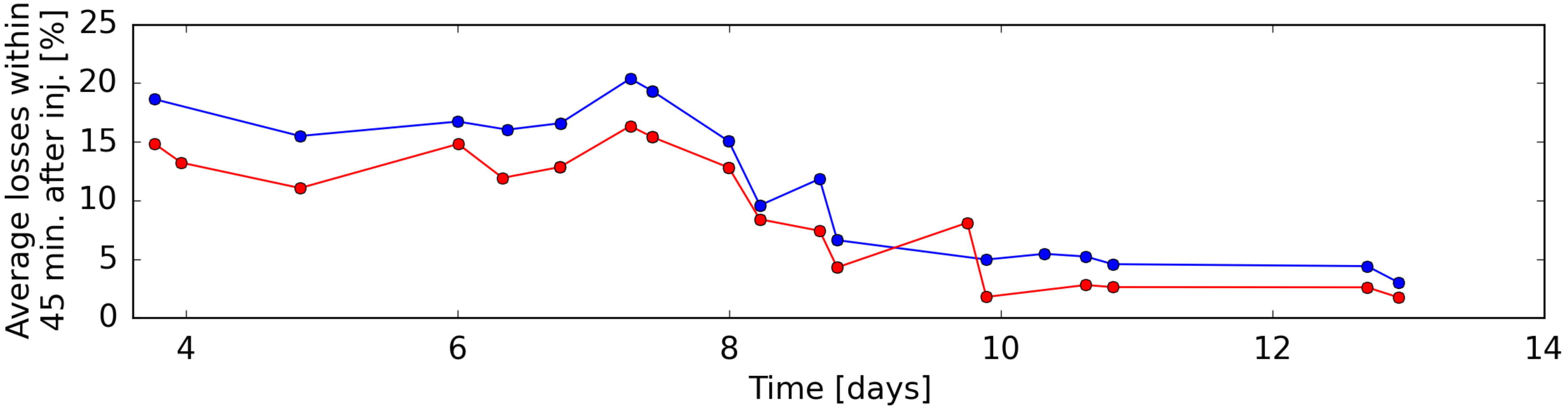


Schematic view of the in-situ SEY detector installed in the SPS



Surface scrubbing

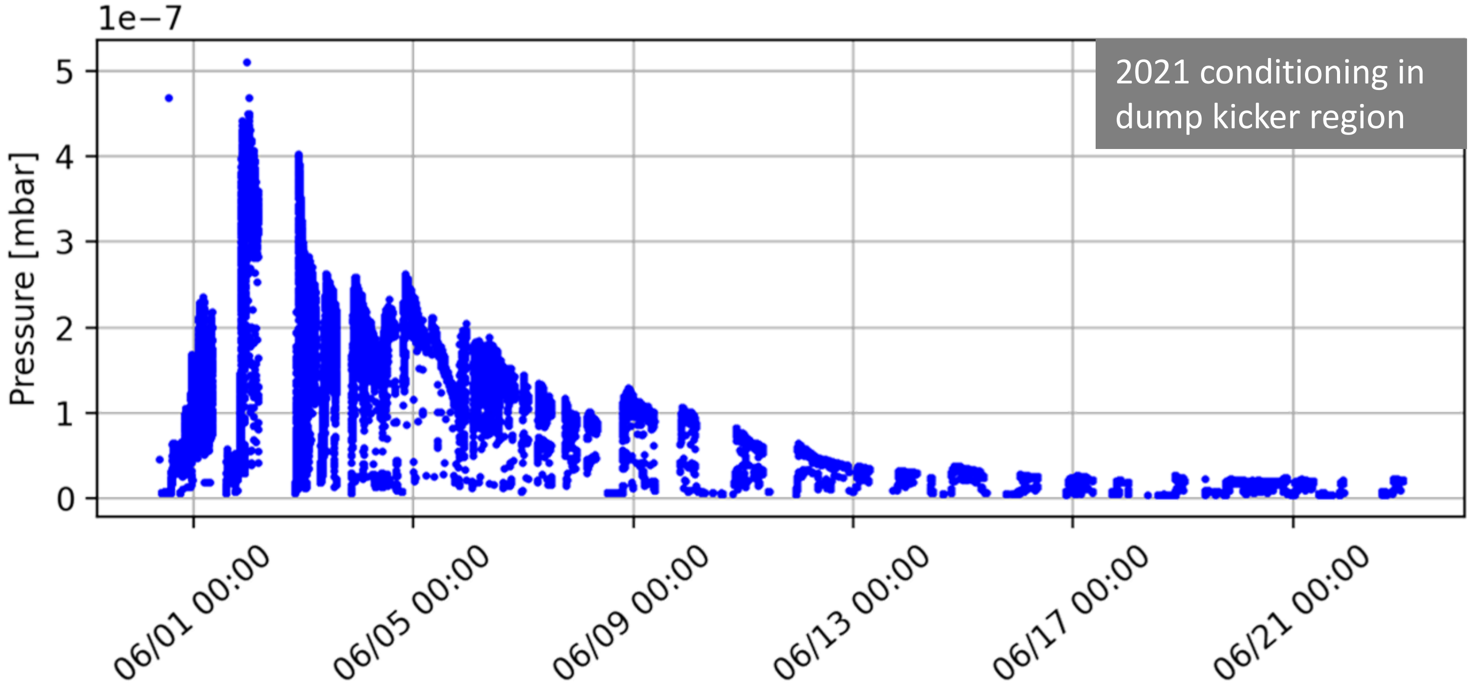
- Beam-induced scrubbing
  - Is revealed by improving accelerator conditions over time, e.g. decrease of pressure rise, heat load, stable phase shift, **general improvement of beam quality (lower losses, less emittance growth)**



Example 1: Reduction of losses in LHC over 9 days of scrubbing
(no clear reduction visible in first phase due to increasing length of the injected trains)

Surface scrubbing

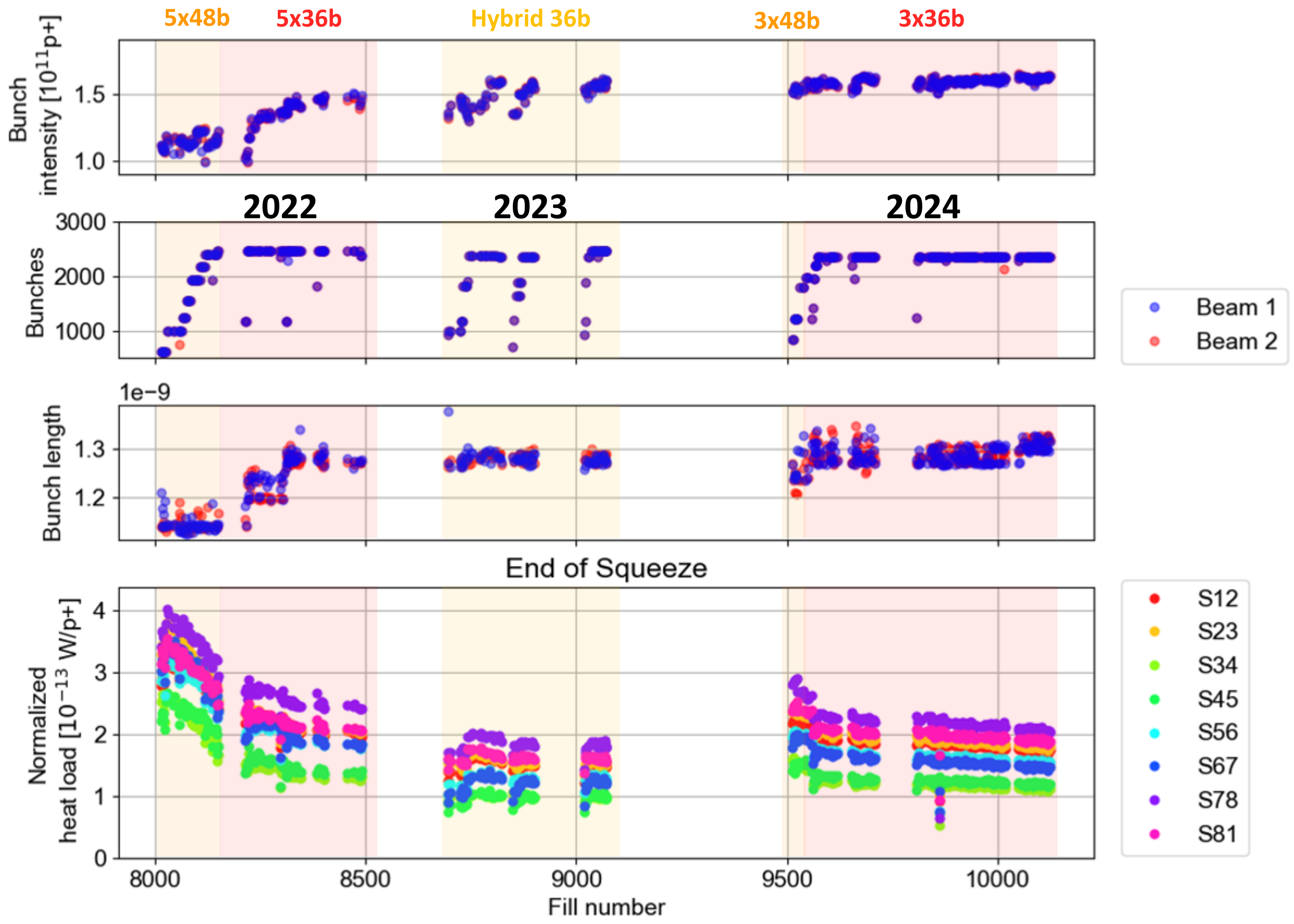
- Beam-induced scrubbing
  - Is revealed by improving accelerator conditions over time, e.g. decrease of pressure rise, **heat load**, stable phase shift, general improvement of beam quality (lower losses, less emittance growth)



Example 2: Reduction of pressure rise in the dump kicker region of the SPS over 1 month of scrubbing

Surface scrubbing

- Beam-induced scrubbing
  - Is revealed by improving accelerator conditions over time, e.g. decrease of **pressure rise**, heat load, stable phase shift, general improvement of beam quality (lower losses, less emittance growth)



Example 3: Reduction of heat load in LHC sectors over 3 years of running

Many accelerators rely nowadays on beam induced scrubbing to reach their desired performance!

Mitigation/suppression techniques

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Solenoids (only applicable in field-free regions without equipment)

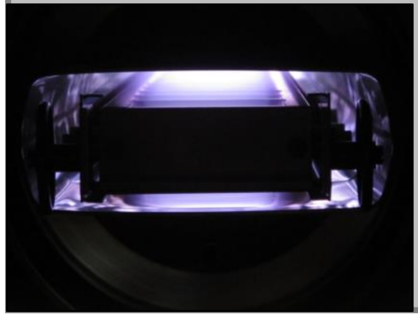
Tolerate e-cloud, if possible, but damp the instability: feedback system

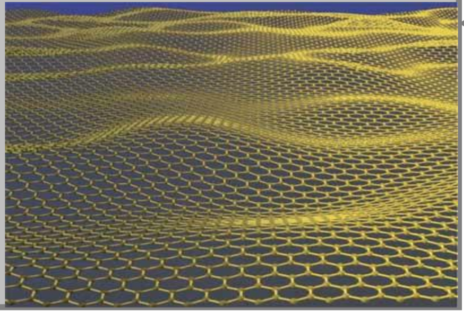
Clearing electrodes installed along the vacuum chambers (only local, may cause impedance, aperture restriction)

Machine scrubbing during operation
- Operation with degraded beam for some time
- Limited by reachable SEY, may be insufficient

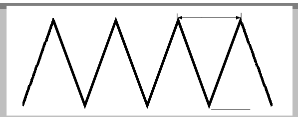
Possible Solutions

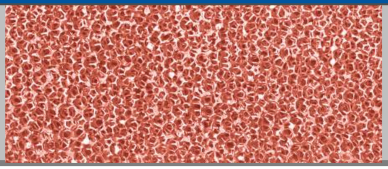
Applying on the wall thin films with intrinsically low SEY
- NEG coating (helps vacuum)
- C coating (no activation)

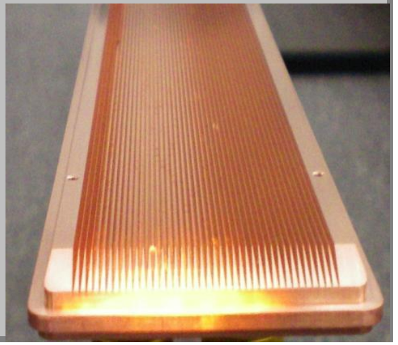




Surface treatment to inhibit secondary electrons
- Grooves
- Roughness
- Sponges
- Laser ablation







Signpost

We have learned that **electron clouds** can build up in the vacuum chamber of an accelerator operating in a certain range of beam parameters.

They are the origin of **many detrimental effects**, like pressure rise, additional heat load, beam degradation through instability and emittance growth.

They can be self-healing through beam induced scrubbing or they can be avoided by design (surface coating/treatment, solenoids, clearing electrodes).

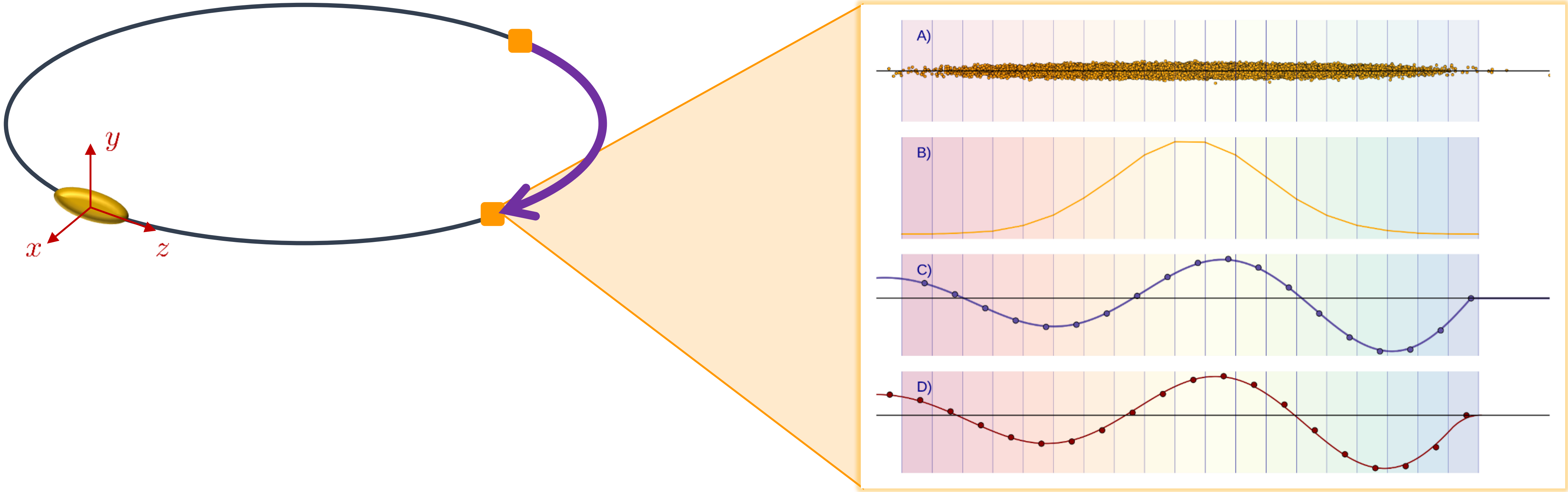
What is the mechanism through which an **electron cloud degrades the beam**?

Part 4: Electron cloud – Build up and effects on beam dynamics

- Electron cloud build up
  - Electron production and multiplication
  - Observation in accelerator rings
- Scrubbing and other techniques of mitigation/suppression
- E-cloud induced instabilities and incoherent effects

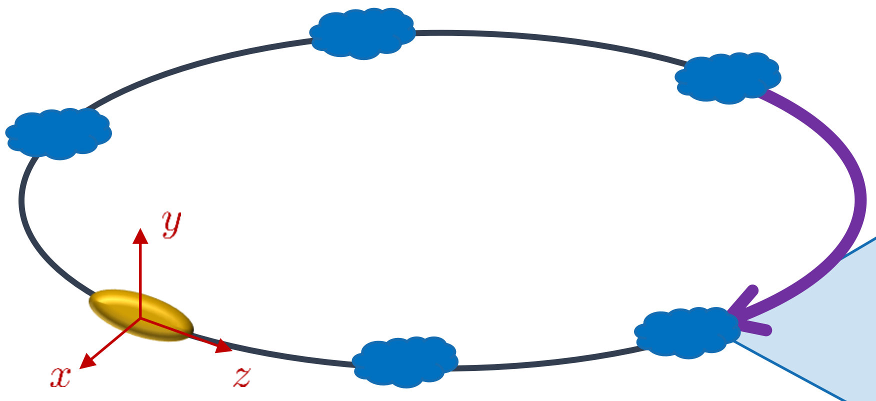
Accelerator beam system - wakefields

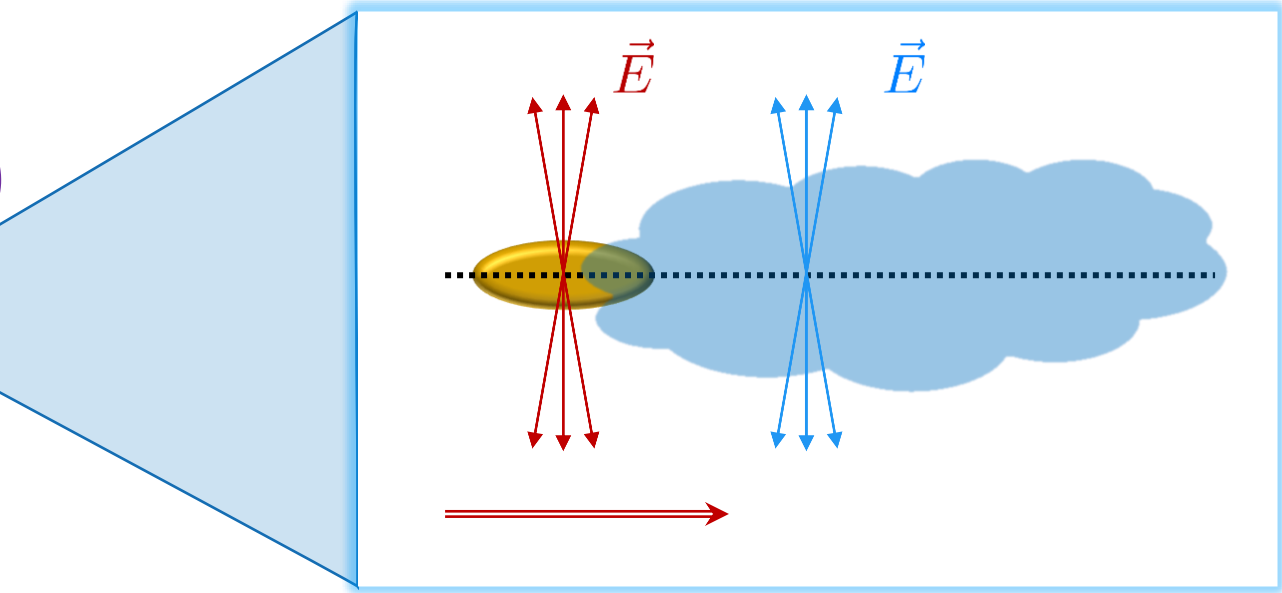
- Our first ‘real’ collective interaction from impedances



Accelerator beam system – electron clouds

- Two stream collective interaction – much more complicated





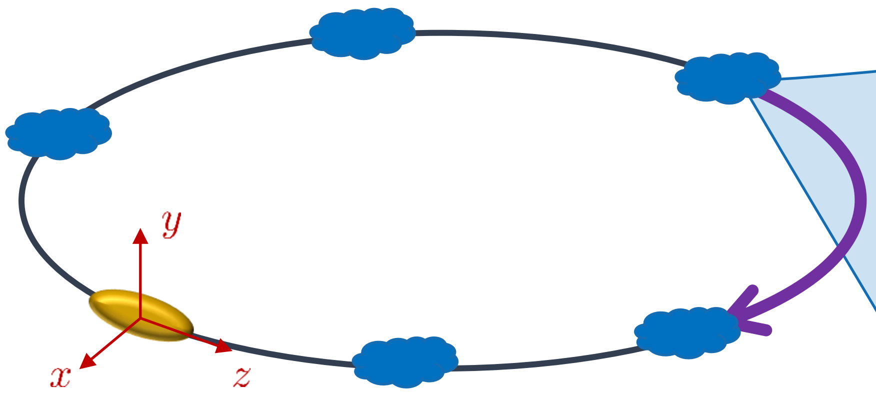
For this we need to solve

$$\Delta\,\phi(x,y)_{p^+} = -\frac{\rho_{p^+}(x,y)}{\varepsilon_0}$$

$$\Delta\,\phi(x,y)_{e^-} = -\frac{\rho_{e^-}(x,y)}{\varepsilon_0}$$

and apply the corresponding kicks to the cloud and the beam

Electron clouds in a drift space



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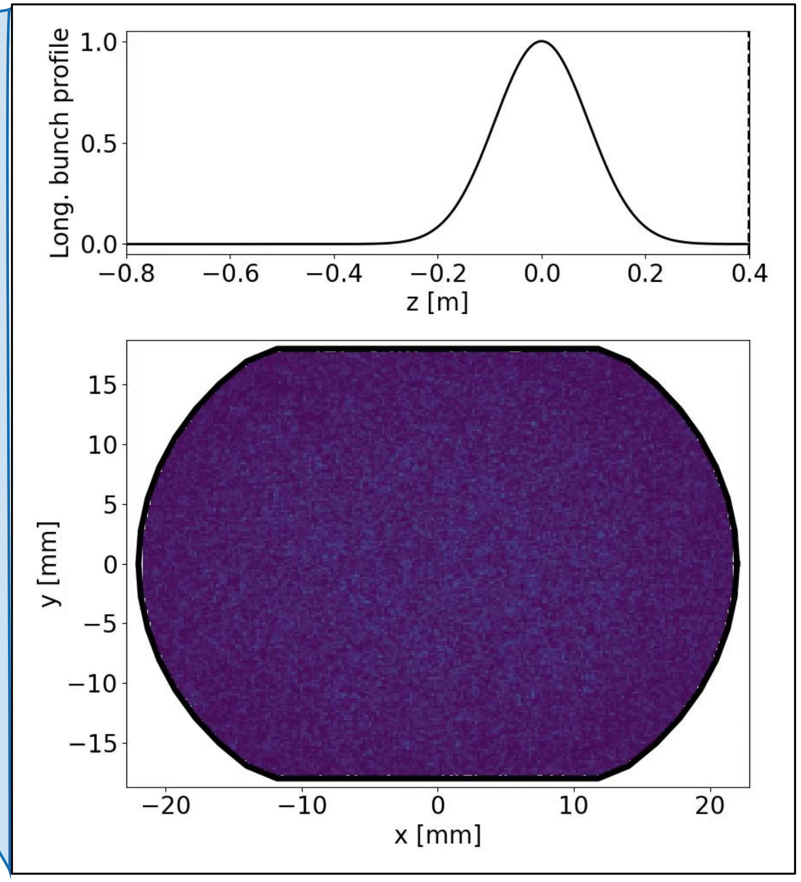
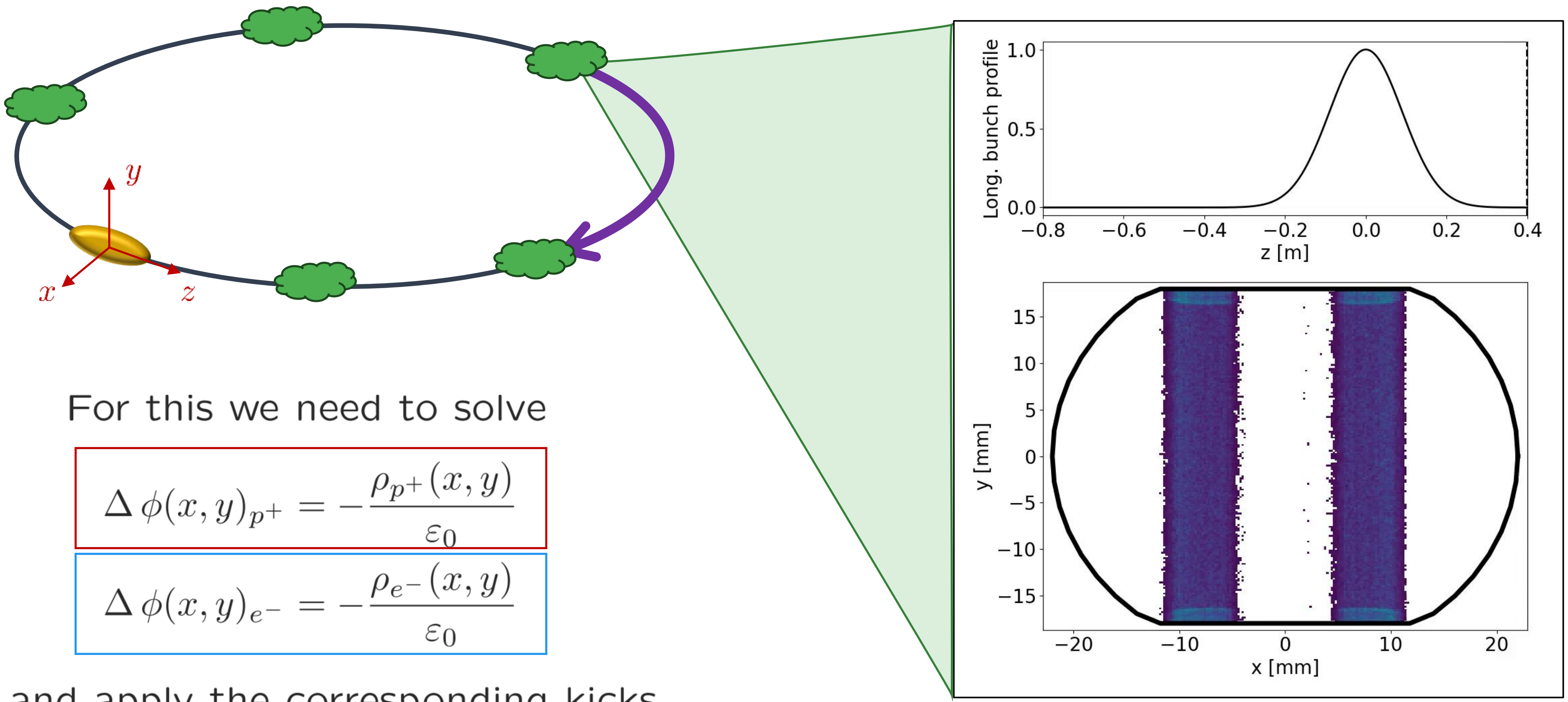


- Beam passage leads to a pinch of the cloud which in turn acts back on the beam – differently each turn

Electron clouds in a bending magnet

- Two stream collective interaction – much more complicated



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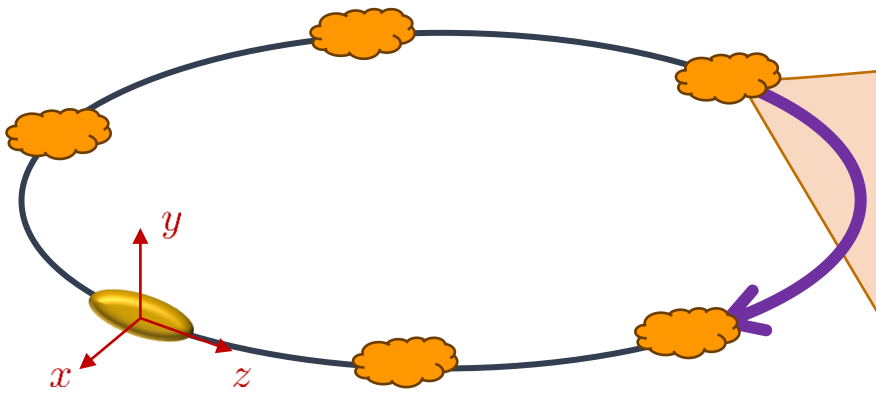
and apply the corresponding kicks to the cloud and the beam

- Beam passage leads to a pinch of the cloud which in turn acts back on the beam – differently each turn

Electron clouds in a quadrupole magnet



For this we need to solve

$$\Delta\,\phi(x,y)_{p^+} = -\frac{\rho_{p^+}(x,y)}{\varepsilon_0}$$

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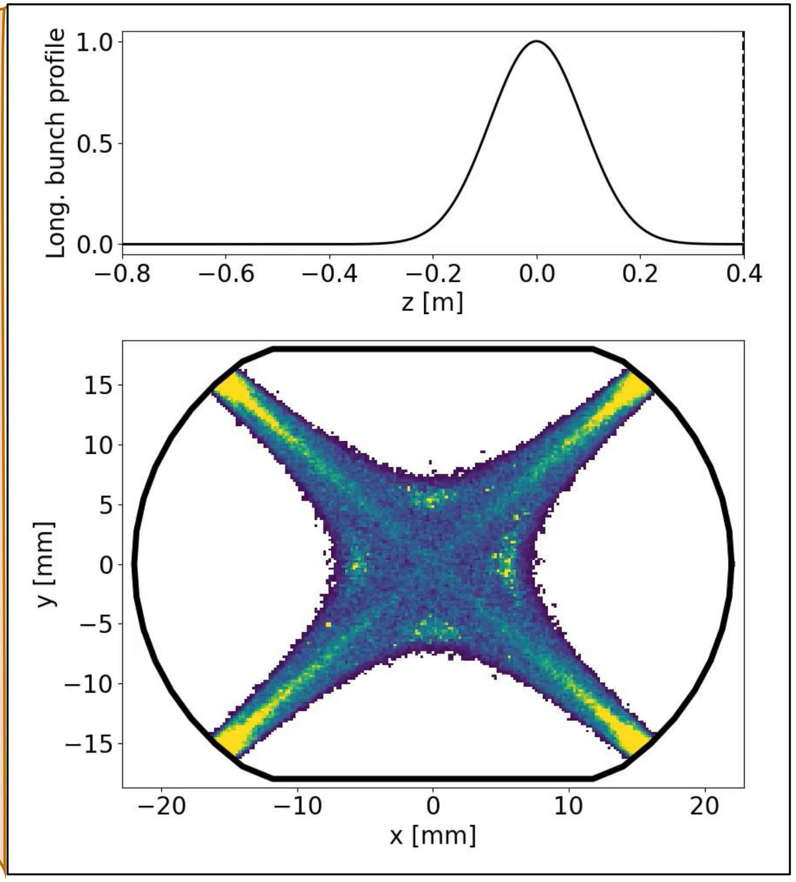
and apply the corresponding kicks to the cloud and the beam

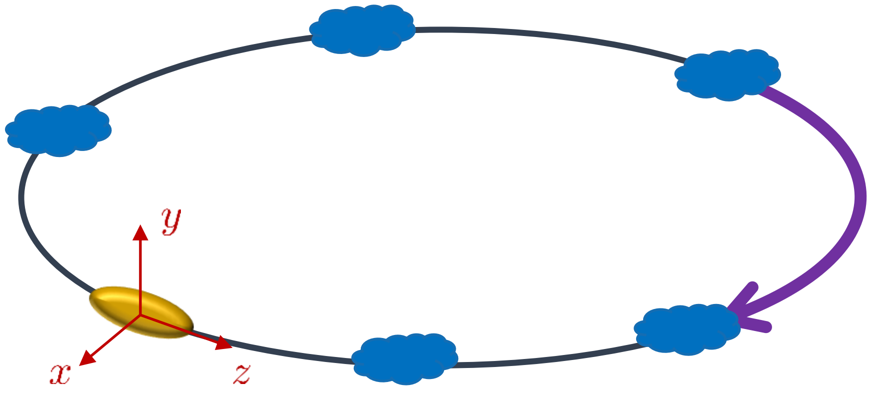
- Two stream collective interaction – much more complicated



- Beam passage leads to a pinch of the cloud which in turn acts back on the beam – differently each turn

Accelerator beam system – e-cloud

$$\mathcal{M} = \begin{pmatrix} \sqrt{\beta_1} & 0 \\ -\frac{\alpha_1}{\sqrt{\beta_1}} & \frac{1}{\sqrt{\beta_1}} \end{pmatrix} \begin{pmatrix} \cos(\Delta\mu_i) & \sin(\Delta\mu_i) \\ -\sin(\Delta\mu_i) & \cos(\Delta\mu_i) \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{\beta_0}} & 0 \\ \frac{\alpha_0}{\sqrt{\beta_0}} & \sqrt{\beta_0} \end{pmatrix}$$



- Basic loop of tracking with electron clouds:
  - Transport beam along segment to interaction point

Accelerator beam system – e-cloud

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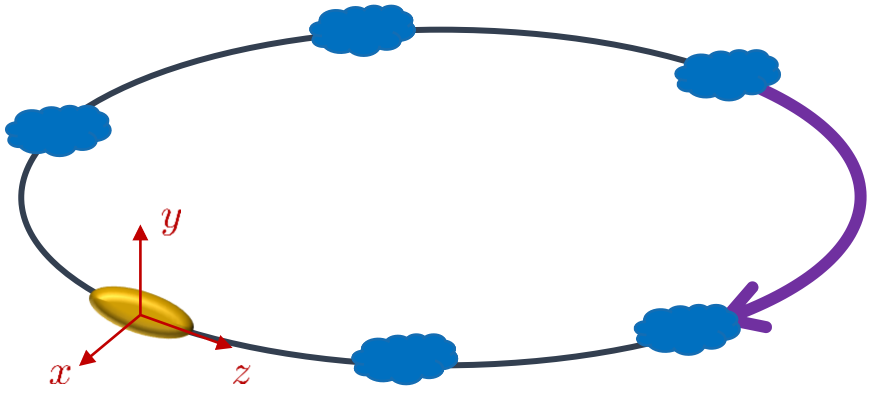
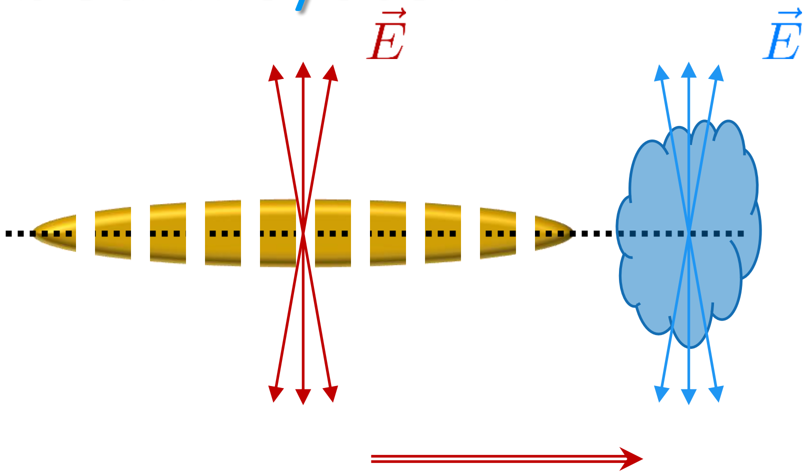
$$\Delta\vec{x}'[i] = -\frac{e^2}{m\gamma\beta^2c^2}\vec{E}_{e-}\,C \qquad \Delta\dot{\vec{x}} = -\frac{e}{m}\left(\vec{E}_{p+}[i] + \frac{\dot{\vec{x}} \times \vec{B}}{c}\right)\Delta t$$

Particles in/fields from slice i



- Basic loop of tracking with electron clouds:
  - Transport beam along segment to interaction point
  - Apply e-cloud kick
    → get fields from PIC step

E-cloud beam system



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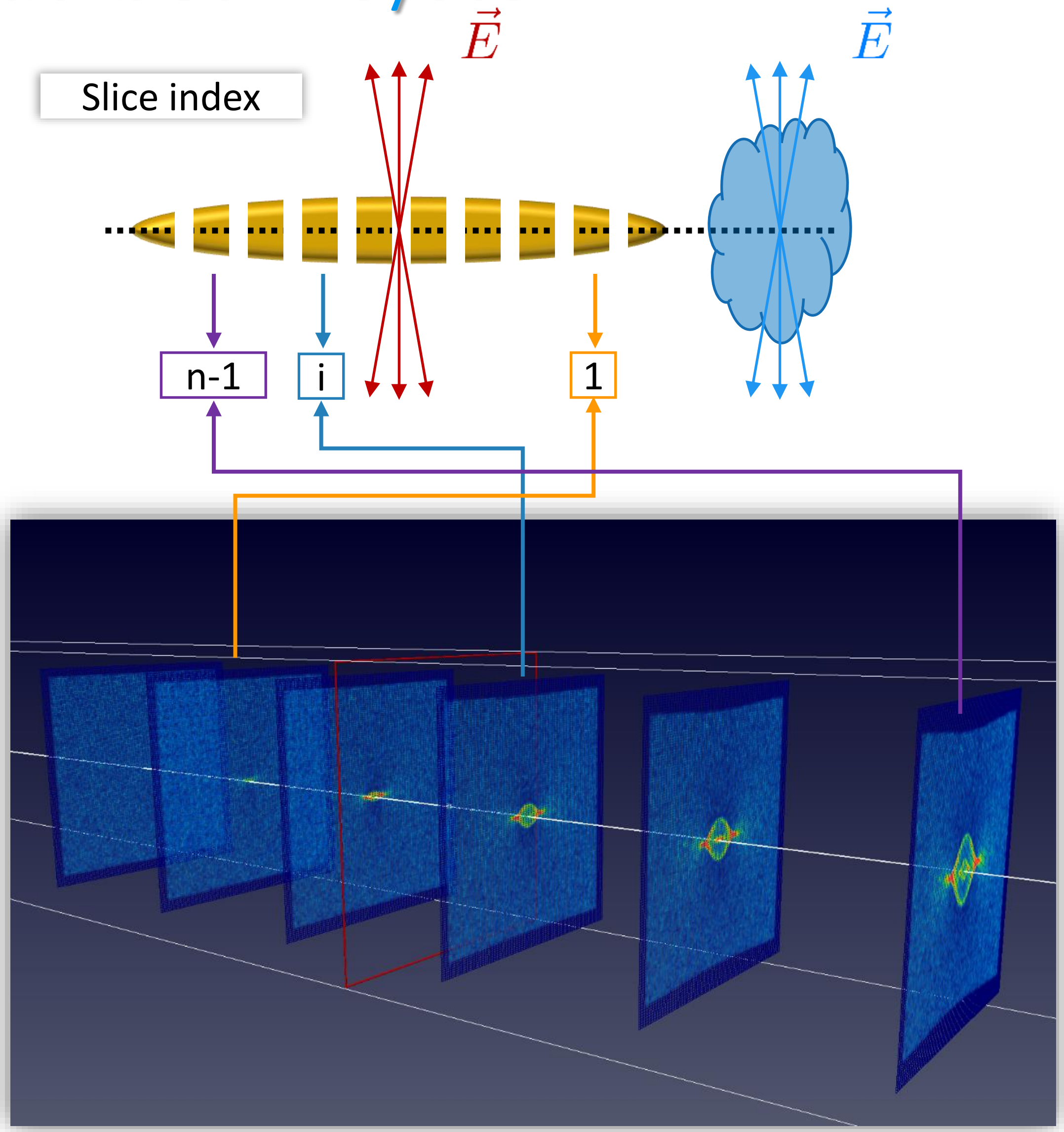
and apply the corresponding kicks to the cloud and the beam

- PIC stands for **Particle-In-Cell**
- We use this method to compute **fields generated by particles** to solve e.g. the Poisson equation
- Electron motion occurs at the time scale of a slice of a bunch length → track single slices through the e-cloud and **apply integrated kicks**
  - **Compute electric fields** from bunch slice and from e-cloud
  - **Apply kicks** to protons and electrons
  - **Push electrons** by one slice length
  - Track **next slice** through e-cloud

E-cloud beam system



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  - **Compute electric fields** from one slice and from e-cloud
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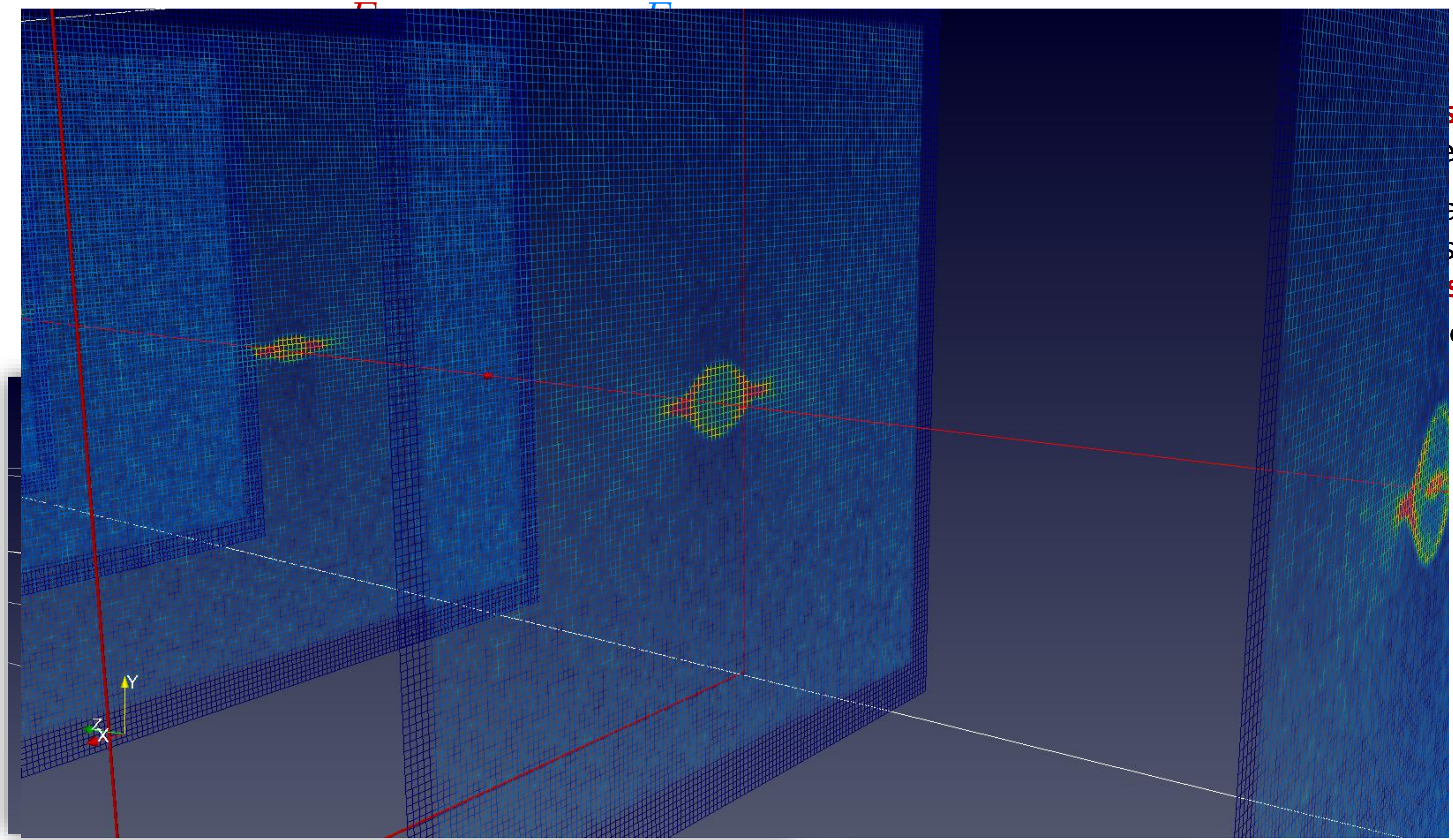
  - Track **next slice** through e-cloud

E-cloud at slice index

E-cloud beam system



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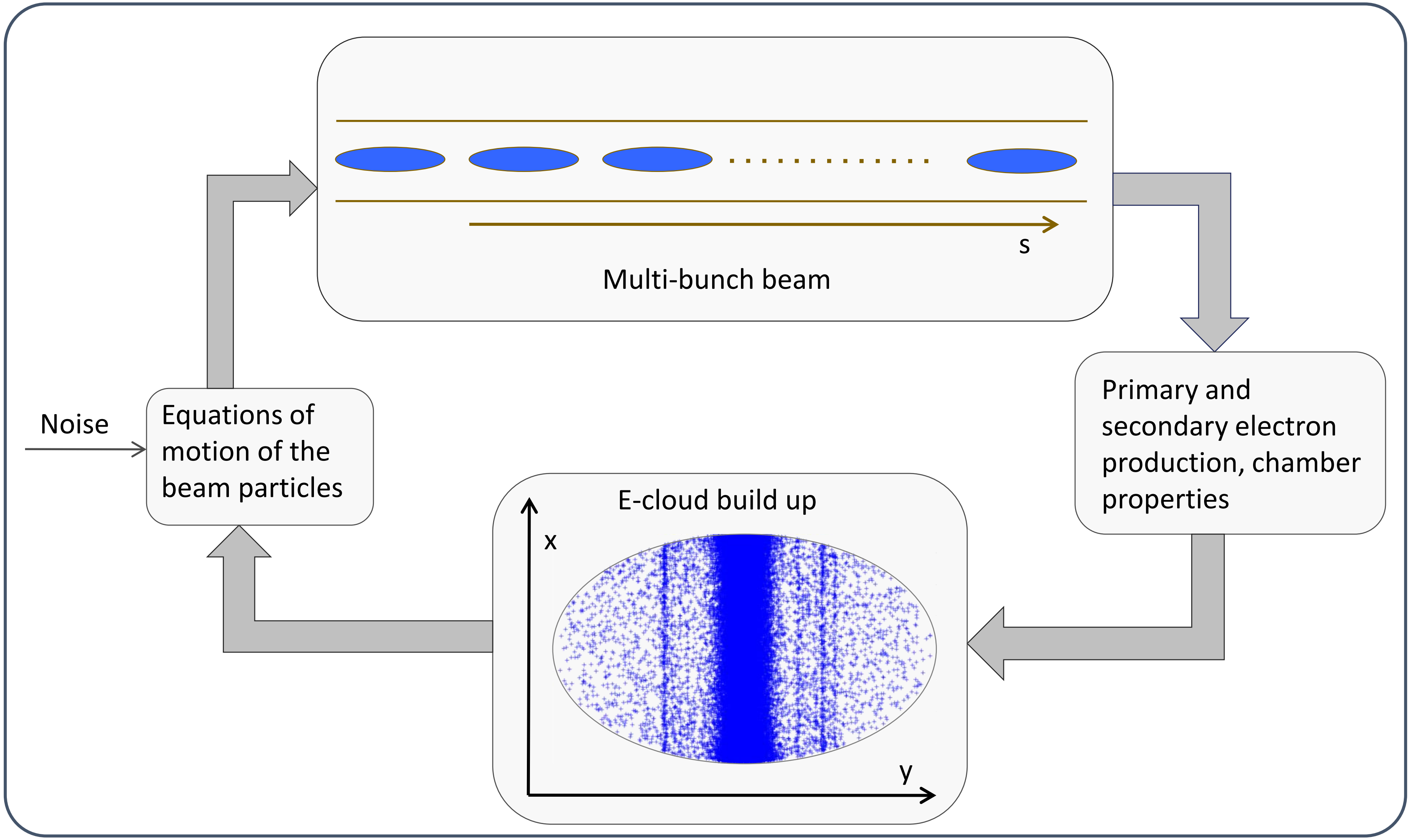
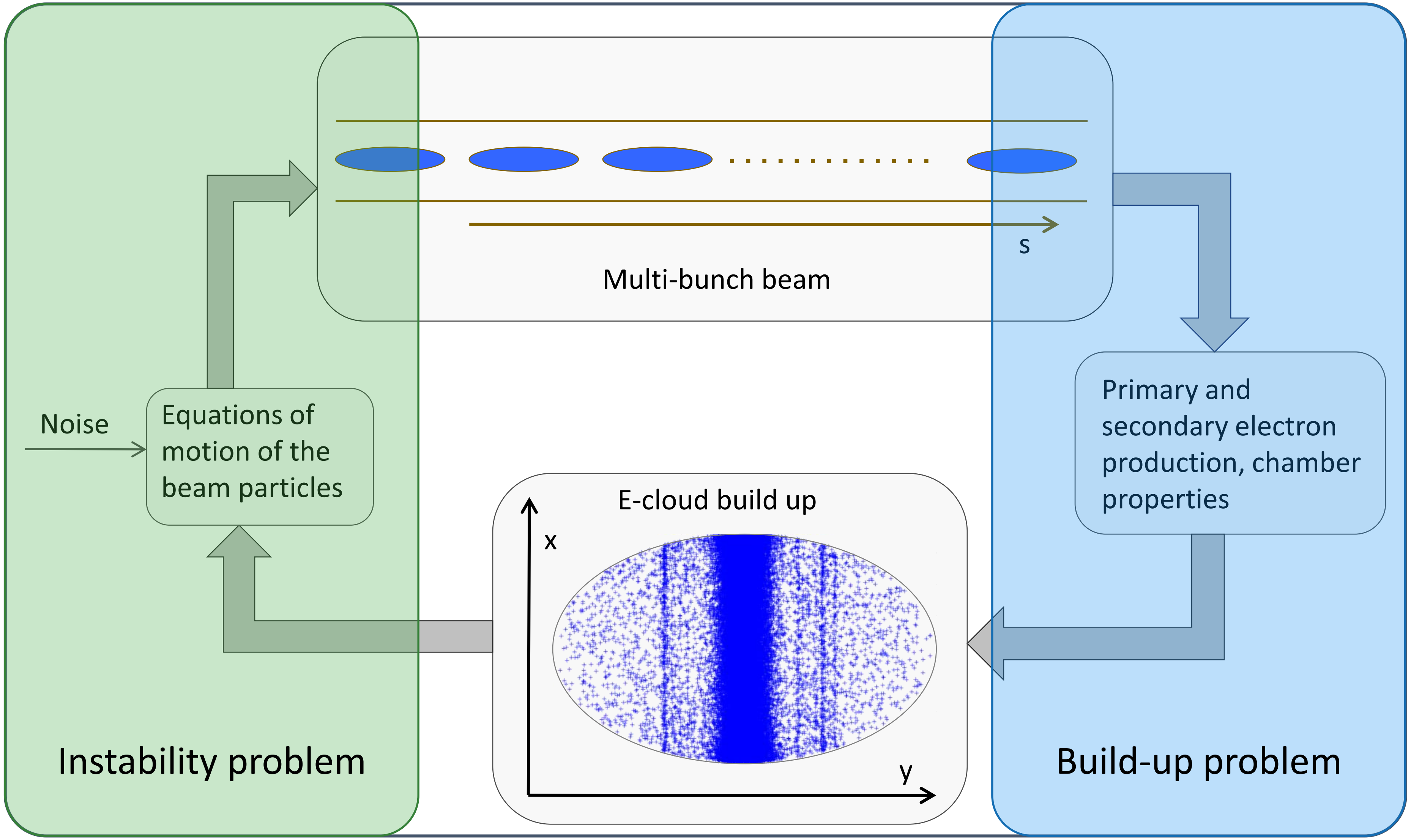
Numerical model of electron cloud effects



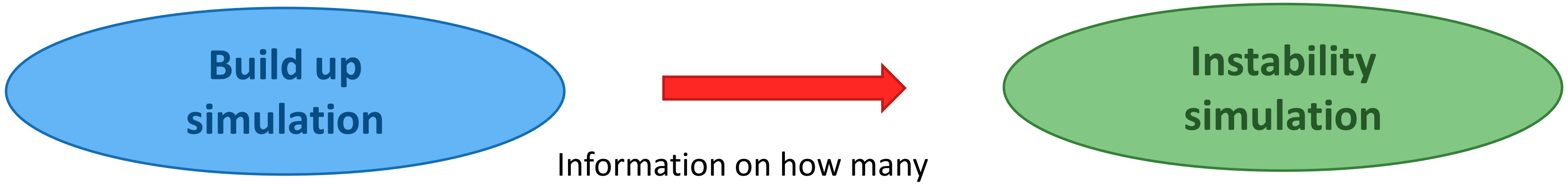
Numerical model of electron cloud effects



Numerical model of electron cloud effects

- Coupled bunch electron cloud instability naturally needs a self-consistent solution of the electron cloud problem
  - A broad time scale to cover, currently working on the problem

- For the moment we simulate the two branches separately (similar to what is done for impedances):
  - **Electron cloud build up**
    - ✓ Multi-bunch
    - ✓ Usually single passage, single turn or just few turns
  - **Electron cloud instability**
    - ✓ Single bunch
    - ✓ Multi-turn, or even multi-kick multi-turn



ECLOUD, PyECLOUD, POSINST, CSEC, …

Information on how many electrons interact with a bunch:
- central density
- detailed distribution

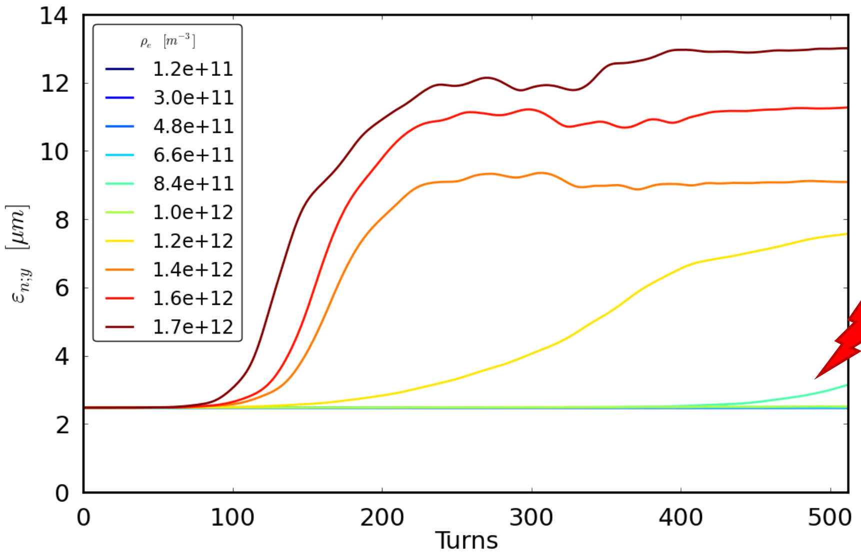
HEADTAIL, PyHEADTAIL, CMAD, PEHTS, …

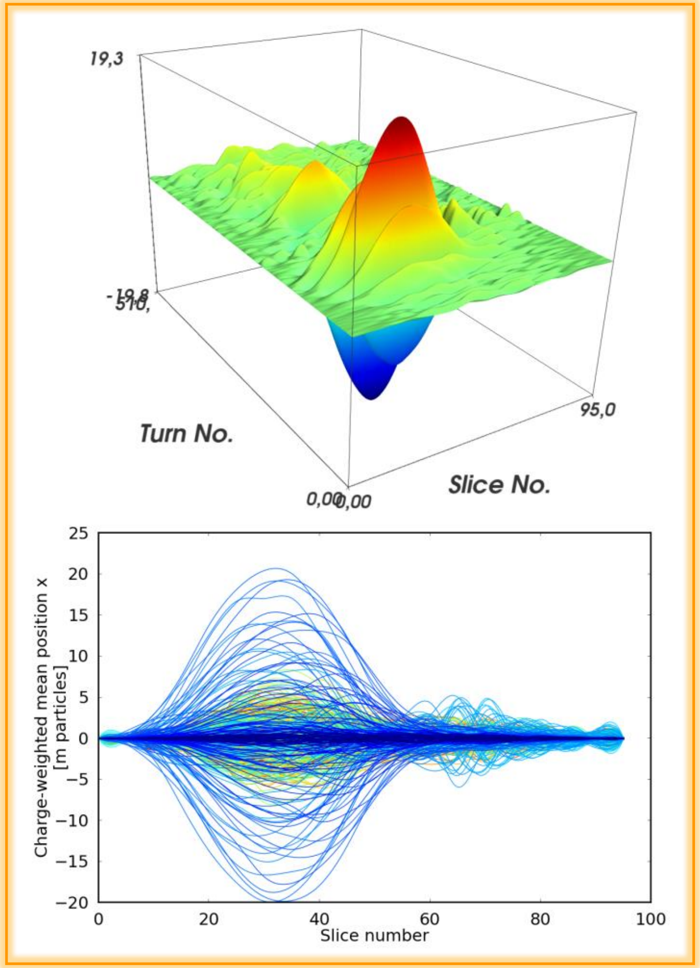
Numerical model of electron cloud effects

- In principle both **coherent instability** and **incoherent emittance growth** could be predicted by these simulations
- Evolution of a beam interacting with an electron cloud depends on a **significant number of parameters** in a non-trivial way
  - Bunch length (longitudinal emittance)
  - Beam transverse sizes (emittances and beta functions at the electron cloud location)
  - Beam energy
  - Beam current (number of particles per bunch)
  - Chromaticity
  - Magnetic field (field-free, dipole, quadrupole)
  - Electron cloud density and distribution (in reality determined by many of the above parameters, but can be set independently in simulations)

Electron cloud induced instabilities

- Typical e-cloud simulation try to identify the e-cloud **central density threshold** for an **instability**
- Scans in the central density are performed until an **exponential growth** can be observed in the emittance

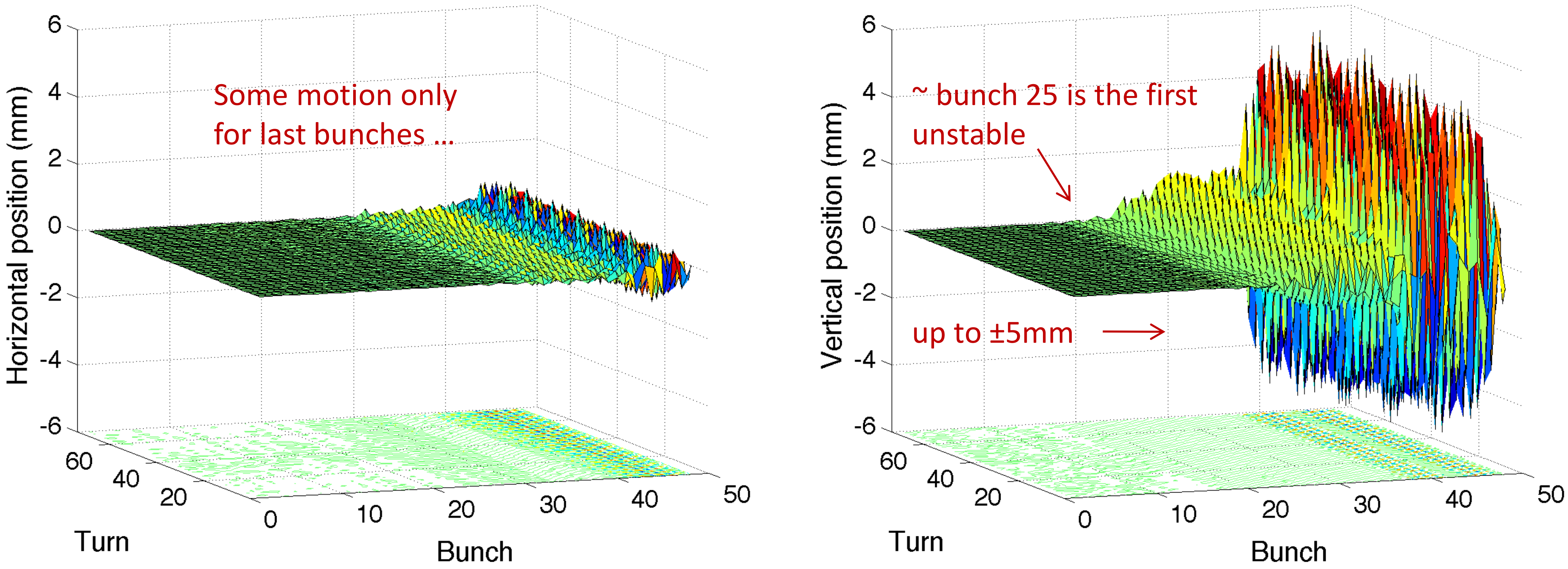




- Coherent instabilities occur when a certain **central cloud density threshold** is breached
- This leads to **coherent intra bunch motion** which grows **exponentially**
- A consequence is **emittance blow-up** and **losses**

Ex. of coherent e-cloud effects in the LHC

- First injection of 48 bunches of 25 ns beam into the LHC in 2011
- Beam was dumped twice due to a violent instability in the vertical plane, causing losses above the interlock threshold



Ex. of coherent e-cloud effects in the LHC

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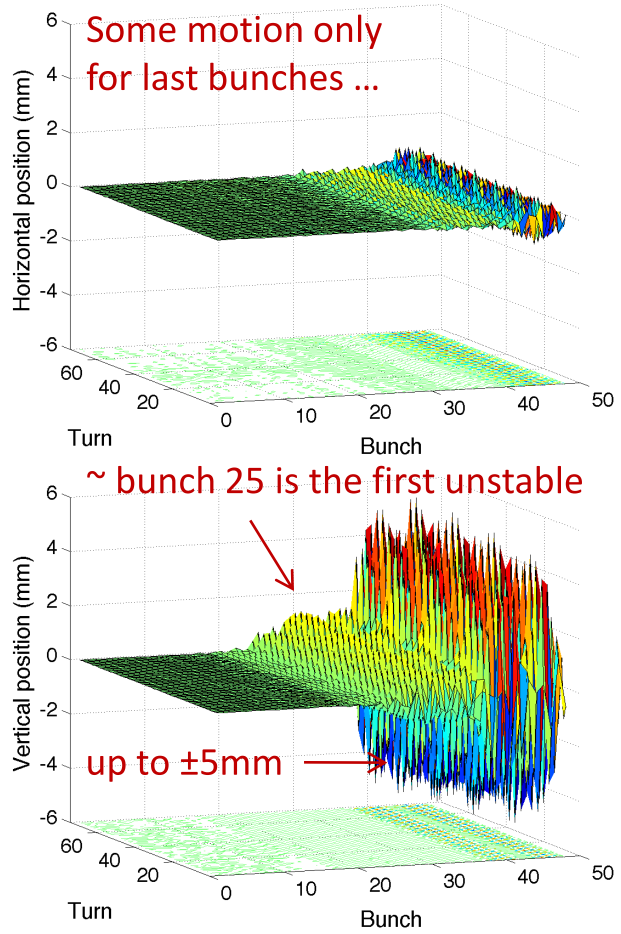
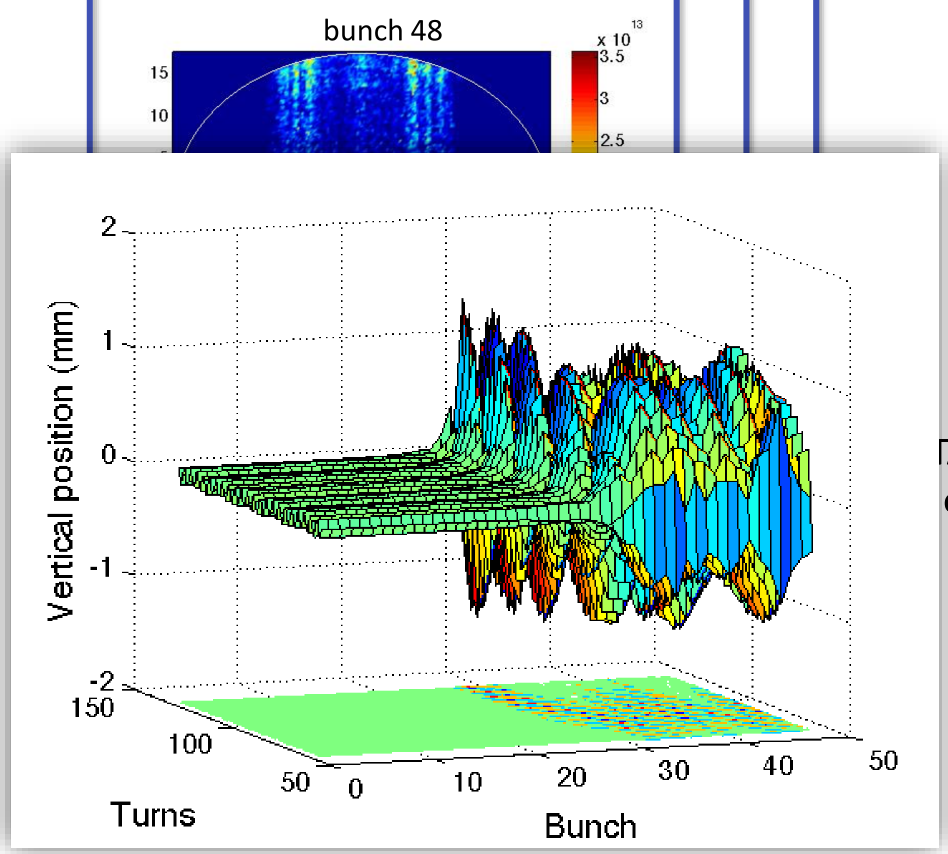
48b injection test (26/08/11)



48x

PyECLOUD e⁻ distribution (δ_{max}=2.1)



TAIL simulations
onset of instability

Signpost

We have learned that **electron clouds** can build up in the vacuum chamber of an accelerator operating in a certain range of beam parameters.

We have seen some of the **detrimental effects** of electron clouds on the machine.

We have seen methods on how to **suppress or mitigate the build up** of electron clouds.

We have seen how we can **conceptually model** the beam-electron cloud interaction and some **examples of electron cloud induced instabilities**.

Part 4: Electron cloud – Build up and effects on beam dynamics

- Electron cloud build up
  - Electron production and multiplication
  - Observation in accelerator rings
- Scrubbing and other techniques of mitigation/suppression
- E-cloud induced instabilities and incoherent effects

The End

PIC solvers in brief

- In many of our codes, Particle in Cell (PIC) algorithms are used to compute the electric field generated by a set of charged particles in a set of discrete points (can be the locations of the particles themselves, or of another set of particles)
- The solution typically consists of 4 stages:
  1. Charge scatter from macroparticles (MPs) to grid (reduction of macroparticles)
  2. Calculation of the electrostatic potential at the nodes
  3. Calculation of the electric field at the nodes (gradient evaluation)
  4. Field gather from grid to MPs

PIC solvers in brief

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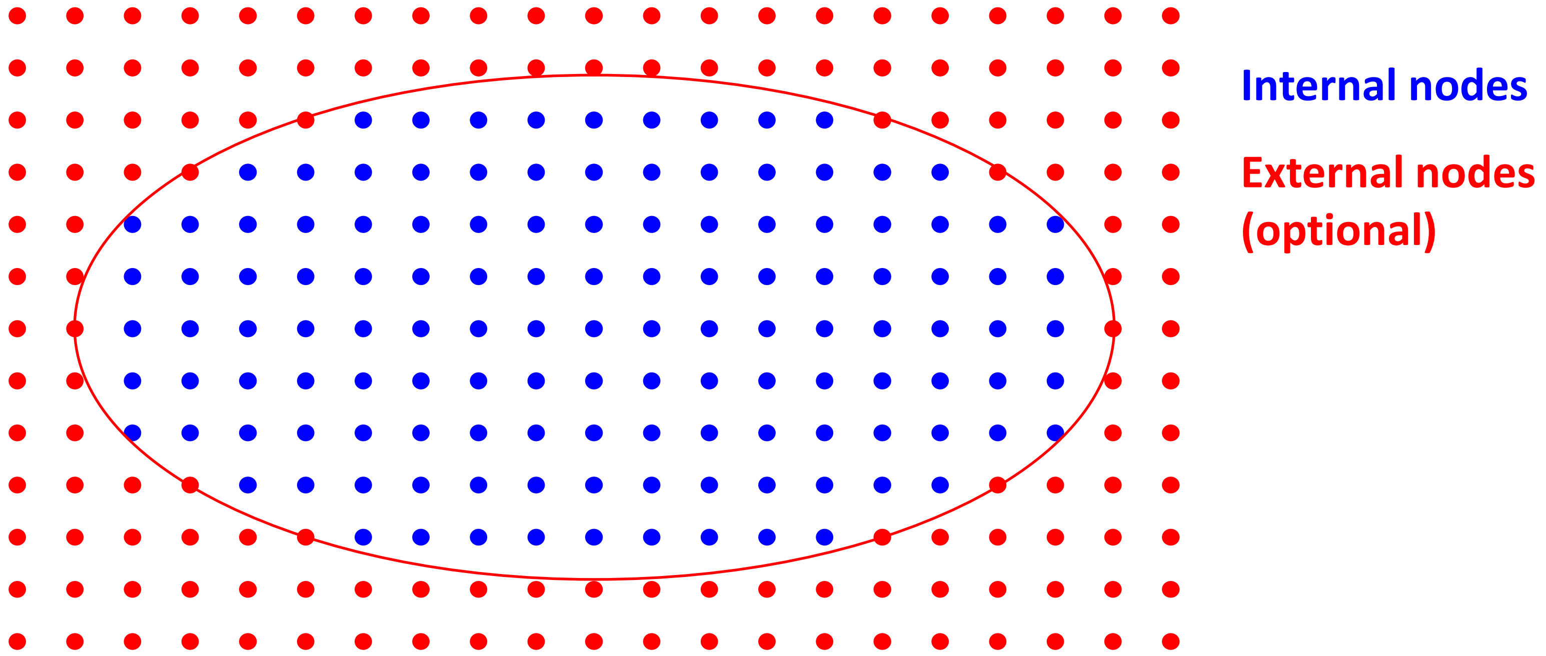

Uniform square grid

PIC solvers – basic steps

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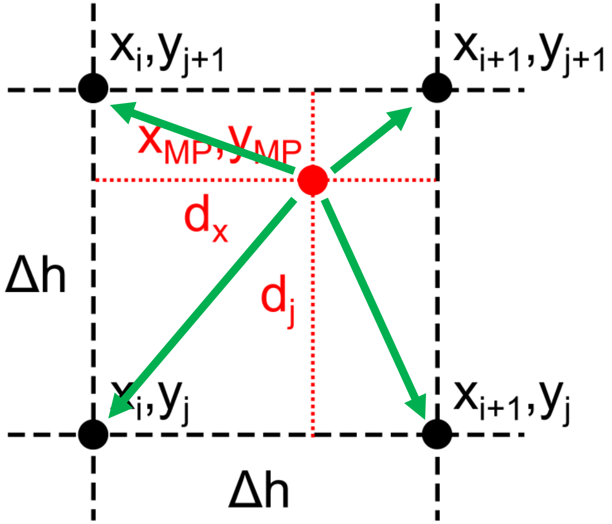

$$\rho_{i,j} = \rho_{i,j} + \frac{q\, n_{\mathrm{MP}}}{\Delta h}\left(1 - \frac{d_x}{\Delta h}\right)\left(1 - \frac{d_y}{\Delta h}\right)$$

$$\rho_{i+1,j} = \rho_{i+1,j} + \frac{q\, n_{\mathrm{MP}}}{\Delta h}\left(\frac{d_x}{\Delta h}\right)\left(1 - \frac{d_y}{\Delta h}\right)$$

$$\rho_{i,j+1} = \rho_{i,j+1} + \frac{q\, n_{\mathrm{MP}}}{\Delta h}\left(1 - \frac{d_x}{\Delta h}\right)\left(\frac{d_y}{\Delta h}\right)$$

$$\rho_{i+1,j+1} = \rho_{i+1,j+1} + \frac{q\, n_{\mathrm{MP}}}{\Delta h}\left(\frac{d_x}{\Delta h}\right)\left(\frac{d_y}{\Delta h}\right)$$

PIC solvers – basic steps

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$$\begin{cases} \nabla^2 \phi(x,y) = -\dfrac{\rho(x,y)}{\varepsilon_0} \\ \text{Boundary conditions (e.g., perfectly conducting, open, periodic)} \end{cases}$$

- Different numerical approaches exist to solve these types of equations each with its own advantages and drawbacks:
  - Open space FFT solver (explicit, very fast but open boundaries)
  - Rectangular boundary FFT solver (explicit, very fast but only rectangular boundaries)
  - Finite Difference implicit Poisson solver (arbitrary chamber shape, sparse matrix, possibility to use Shortley Weller boundary refinement, KLU fast routines, computationally more demanding)
  - Dual or multi-grid in combination with direct or iterative solvers

PIC solvers – basic steps

- The solution typically consists of 4 stages:
  1. Charge scatter from macroparticles (MPs) to grid (reduction of macroparticles)
  2. Calculation of the electrostatic potential at the nodes
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  4. Field gather from grid to MPs

$$\mathbf{E} = -\nabla\phi$$

$$(E_x)_{i,j} = -\frac{\phi_{i+1,j} - \phi_{i-1,j}}{2\Delta h}$$

$$(E_y)_{i,j} = -\frac{\phi_{i,j+1} - \phi_{i,j-1}}{2\Delta h}$$

PIC solvers – basic steps

- The solution typically consists of 4 stages:
  1. Charge scatter from macroparticles (MPs) to grid (reduction of macroparticles)
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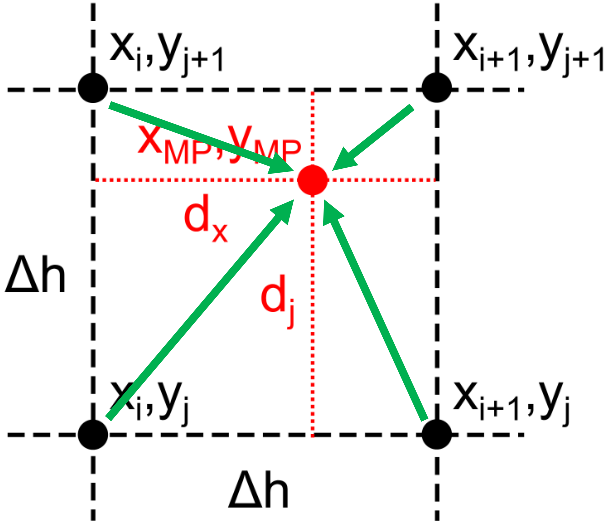
  3. Calculation of the electric field at the nodes (gradient evaluation)
  4. Field gather from grid to MPs

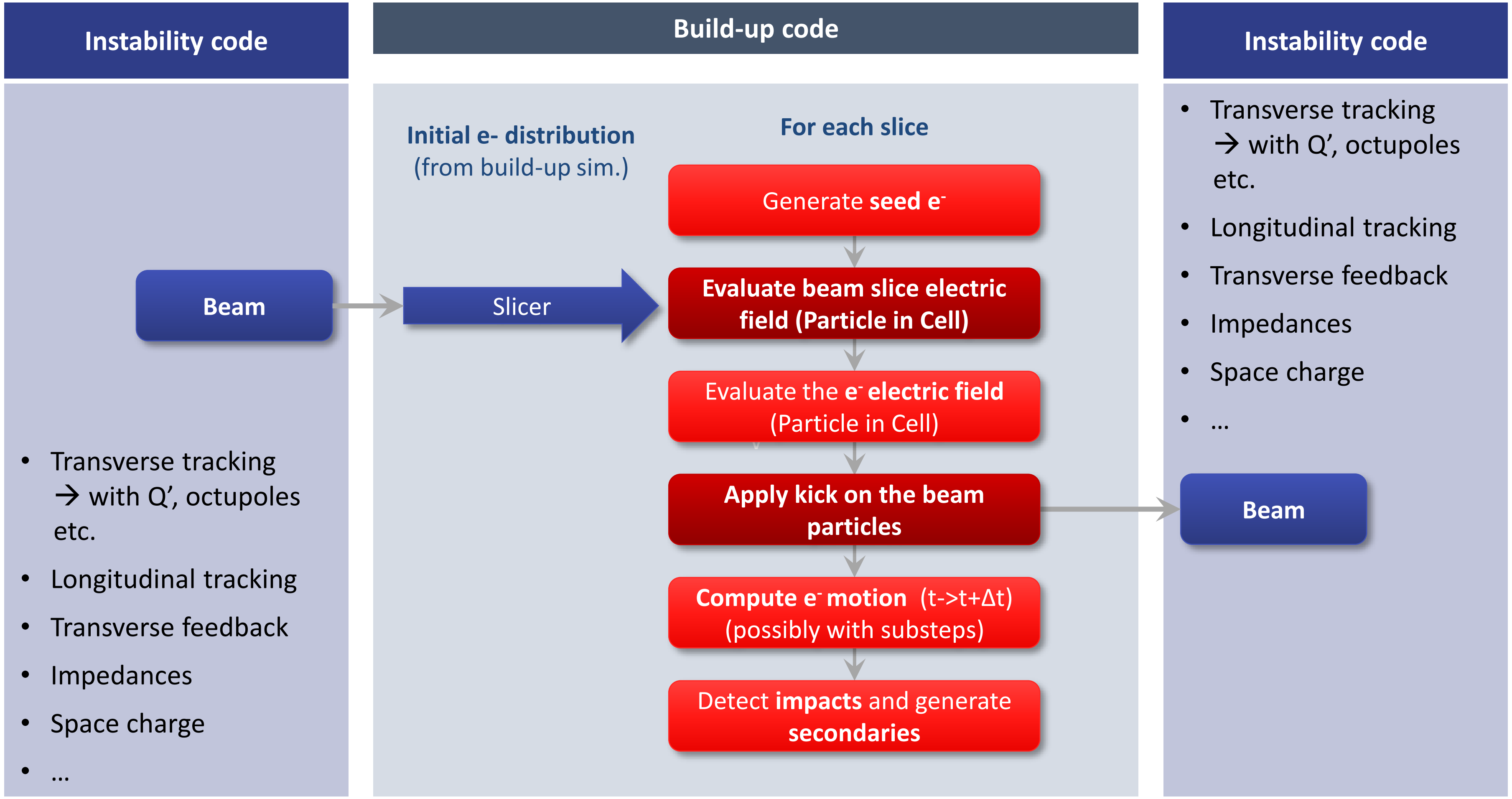


$$\mathbf{E}\left(x_{\mathrm{MP}}, y_{\mathrm{MP}}\right) =$$

$$\mathbf{E}_{i,j}\left(1-\frac{d_x}{\Delta h}\right)\left(1-\frac{d_y}{\Delta h}\right)+\mathbf{E}_{i+1,j}\left(\frac{d_x}{\Delta h}\right)\left(1-\frac{d_y}{\Delta h}\right)$$
$$+\mathbf{E}_{i,j+1}\left(1-\frac{d_x}{\Delta h}\right)\left(\frac{d_y}{\Delta h}\right)+\mathbf{E}_{i+1,j+1}\left(\frac{d_x}{\Delta h}\right)\left(\frac{d_y}{\Delta h}\right)$$

Numerical model of electron cloud effects

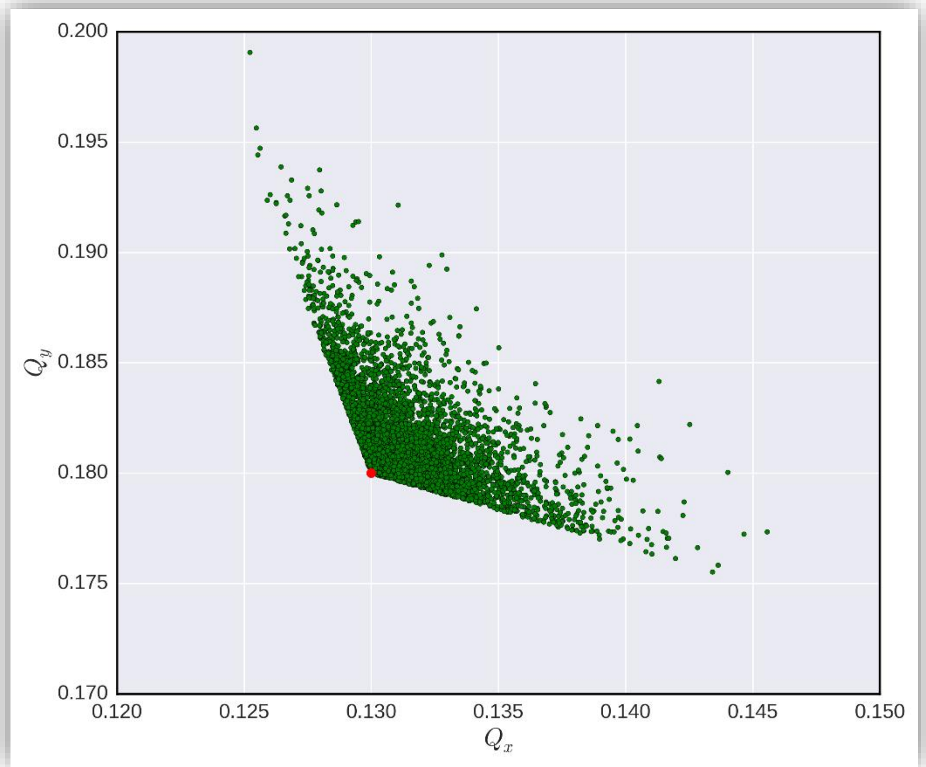
- A self-consistent treatment requires the combination of an instability and a build-up code
- Becomes easily possible with modular structure and good design of codes (e.g. object orientation)



Legend: From instability code – From build-up code – Interaction between the two codes

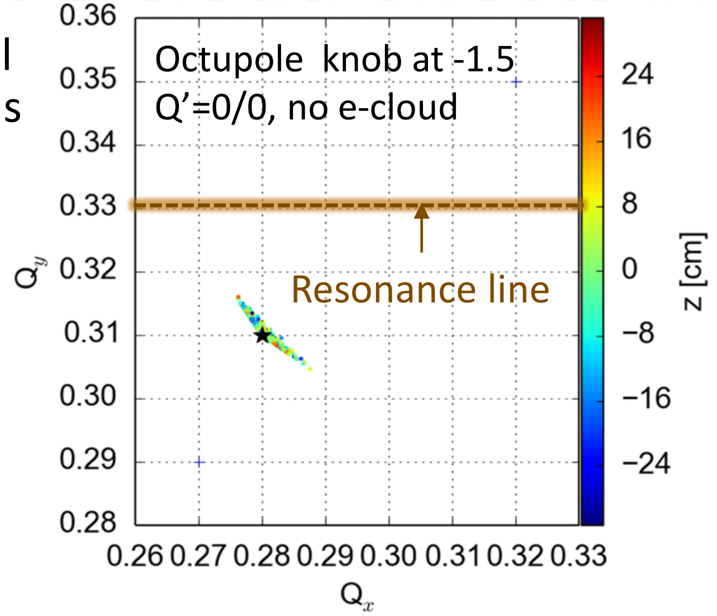
Ex. of incoherent e-cloud effects in the LHC

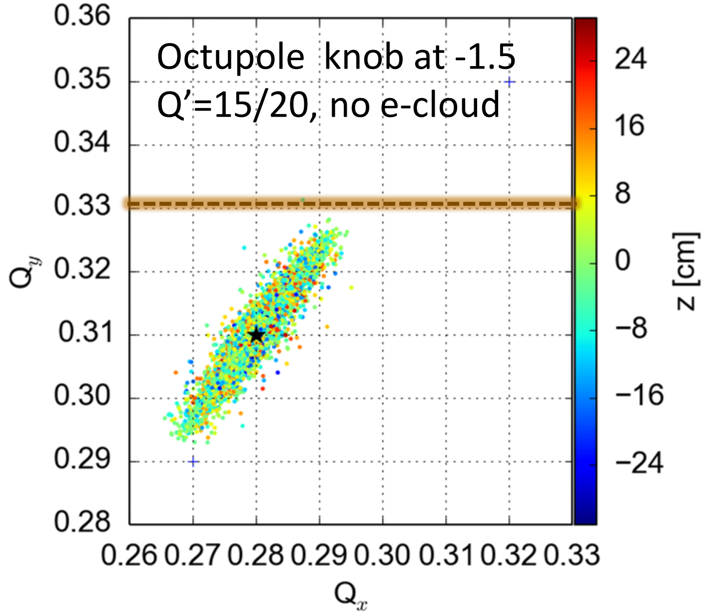
- Remember tune footprint from octupoles in Part I

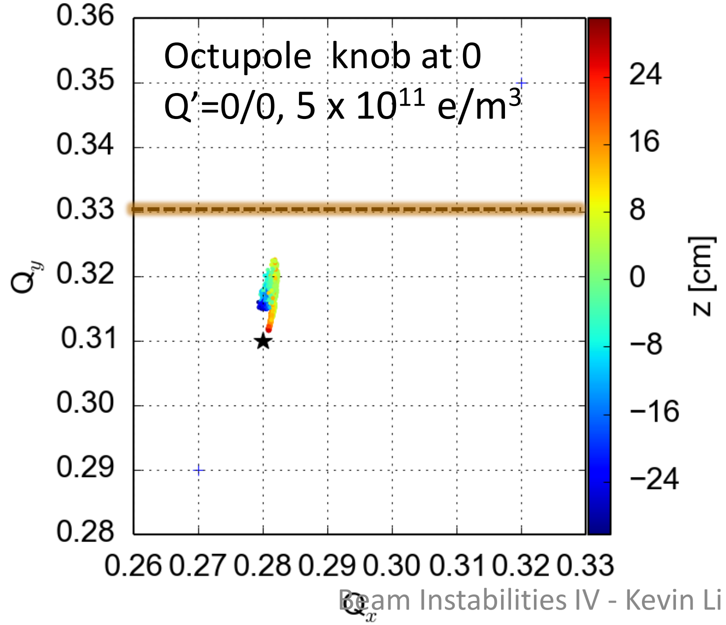


Ex. of incoherent e-cloud effects in the LHC

- Macroparticle simulations allow to obtain tune footprints from all effects separated

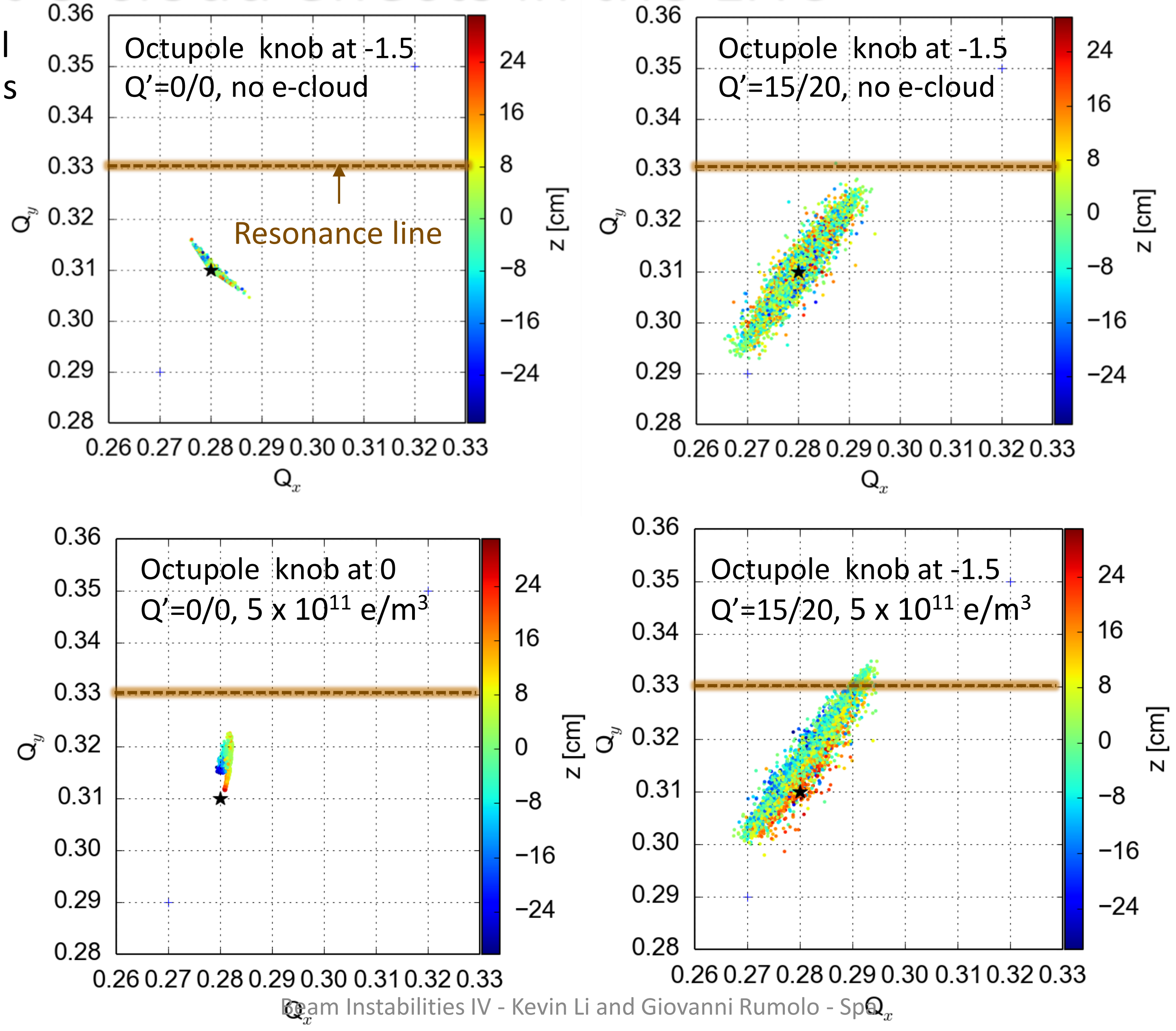






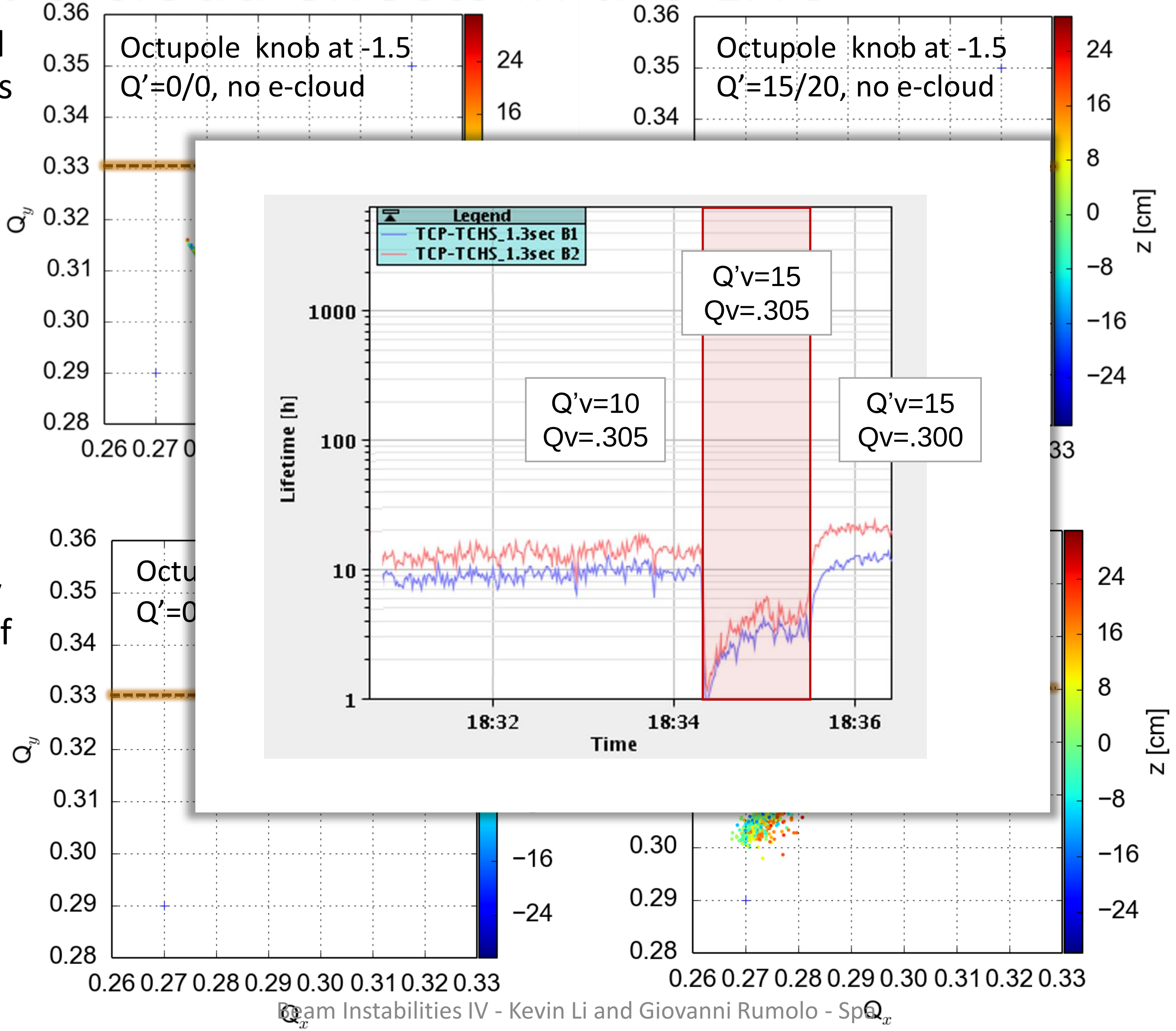
Ex. of incoherent e-cloud effects in the LHC

- Macroparticle simulations allow to obtain tune footprint from all effects separated
- … as well as from all effects combined



Ex. of incoherent e-cloud effects in the LHC

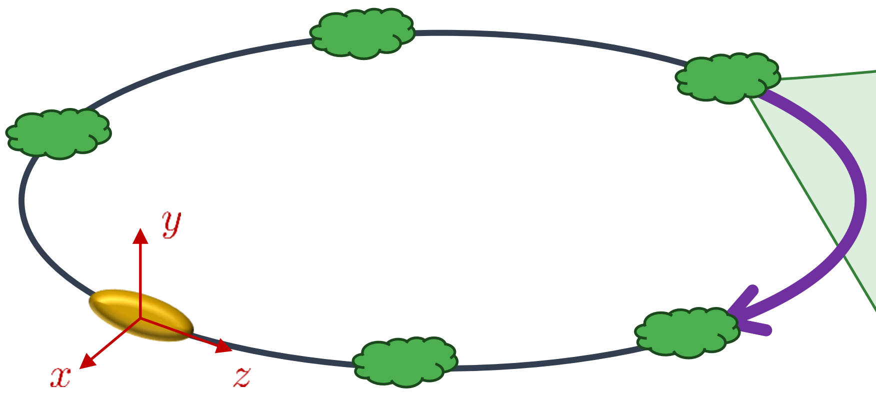
- Macroparticle simulations allow to obtain tune footprint from all effects separated
- … as well as from all effects combined
- … to identify the source of incoherent losses in the LHC

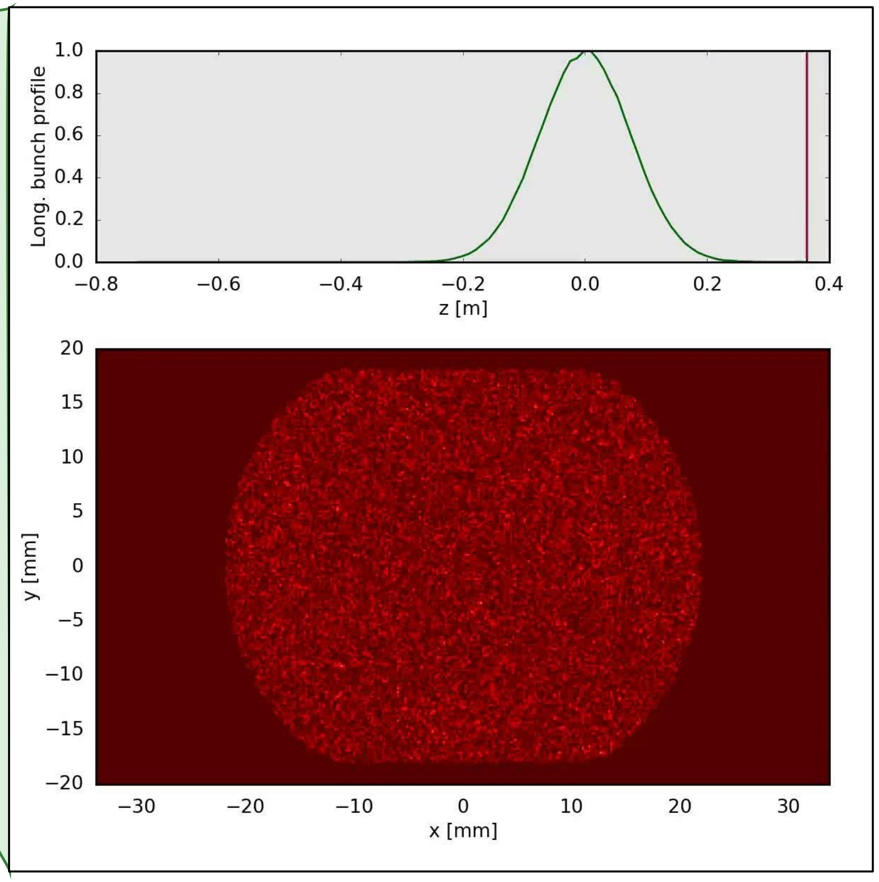


Backup - wakefields

Electron clouds in a bending magnet

- Two stream collective interaction – much more complicated





For this we need to solve

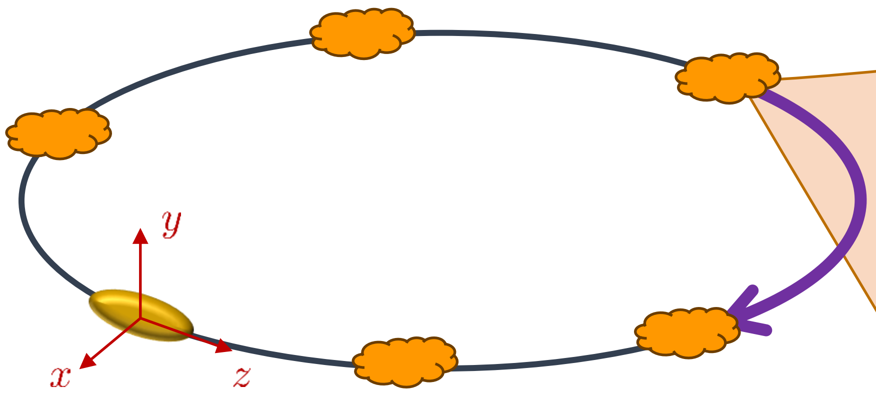
$$\Delta\,\phi(x,y)_{p^+} = -\frac{\rho_{p^+}(x,y)}{\varepsilon_0}$$

$$\Delta\,\phi(x,y)_{e^-} = -\frac{\rho_{e^-}(x,y)}{\varepsilon_0}$$

and apply the corresponding kicks to the cloud and the beam

- Beam passage leads to a pinch of the cloud which in turn acts back on the beam – differently each turn

Electron clouds in a quadrupole magnet



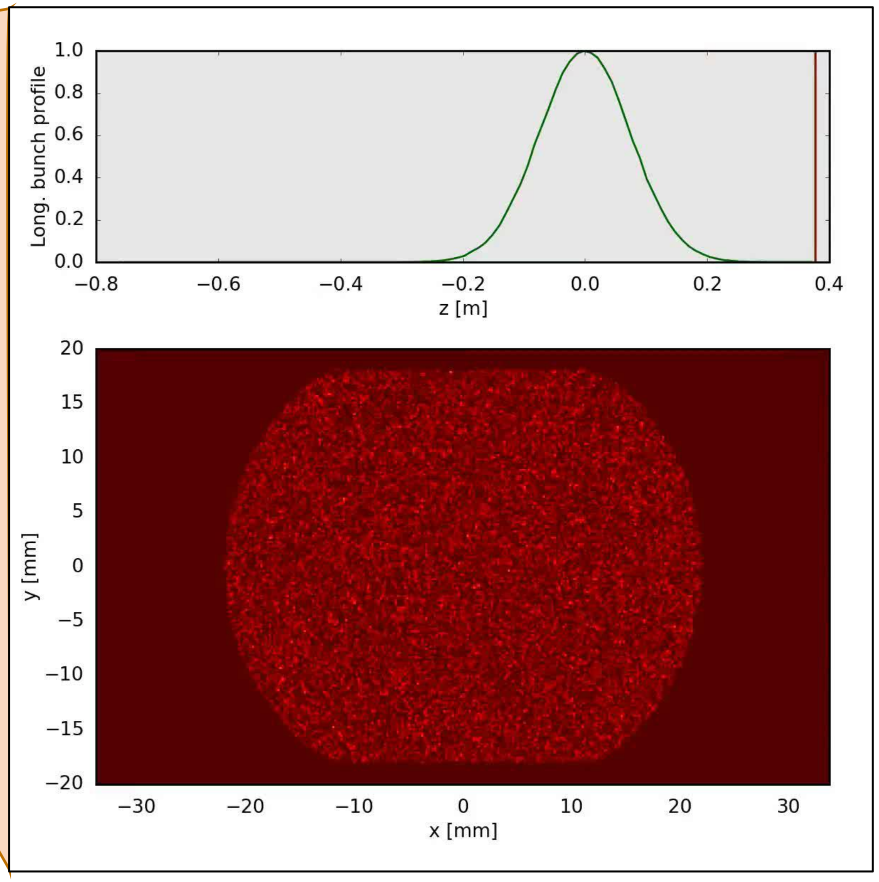
For this we need to solve

$$\Delta\,\phi(x,y)_{p^+} = -\frac{\rho_{p^+}(x,y)}{\varepsilon_0}$$

$$\Delta\,\phi(x,y)_{e^-} = -\frac{\rho_{e^-}(x,y)}{\varepsilon_0}$$

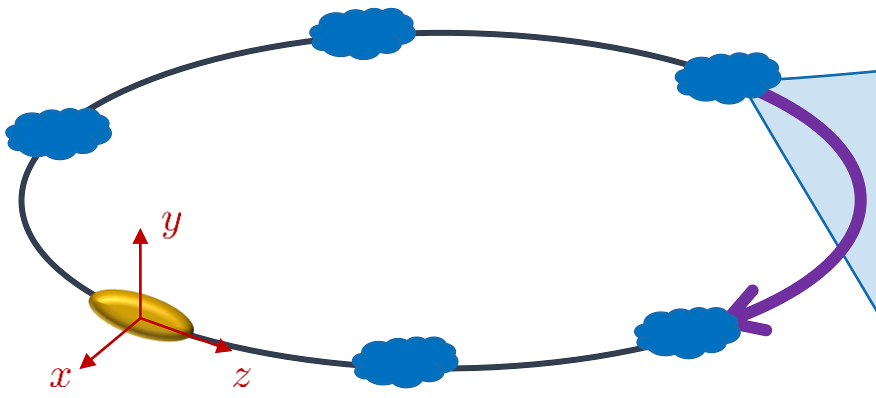
and apply the corresponding kicks to the cloud and the beam

- Two stream collective interaction – much more complicated



- Beam passage leads to a pinch of the cloud which in turn acts back on the beam – differently each turn

Electron clouds in a drift space



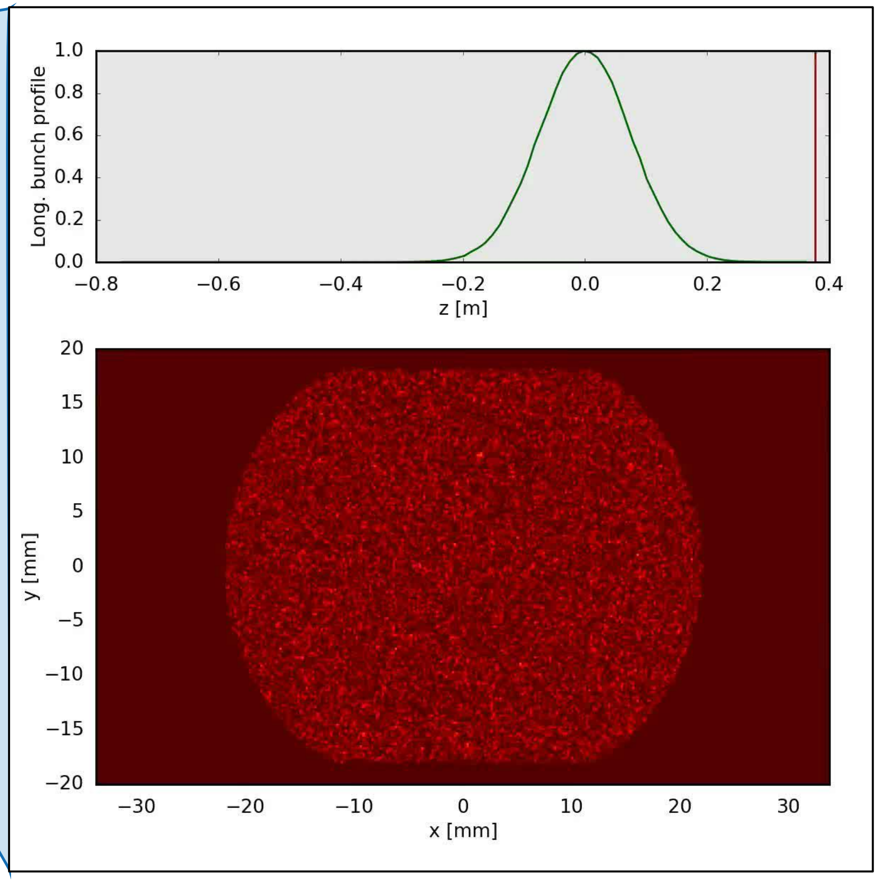
For this we need to solve

$$\Delta\,\phi(x,y)_{p^+} = -\frac{\rho_{p^+}(x,y)}{\varepsilon_0}$$

$$\Delta\,\phi(x,y)_{e^-} = -\frac{\rho_{e^-}(x,y)}{\varepsilon_0}$$

and apply the corresponding kicks to the cloud and the beam

- Two stream collective interaction – much more complicated



- Beam passage leads to a pinch of the cloud which in turn acts back on the beam – differently each turn