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

Kevin Li and Giovanni Rumolo

Outline

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

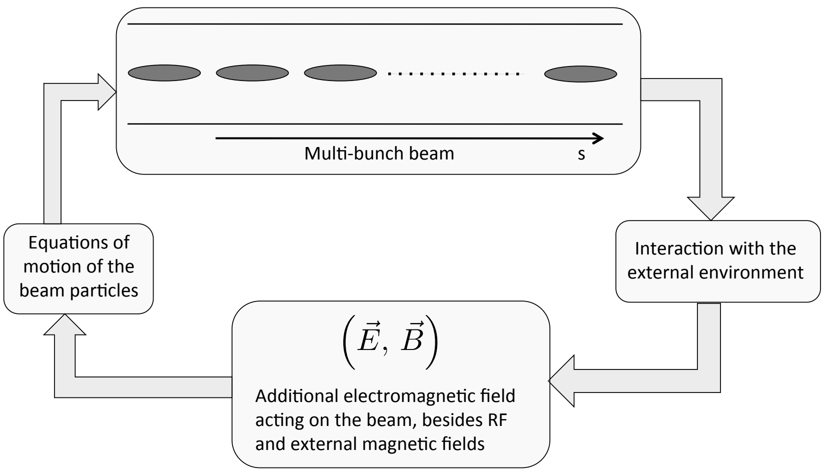
Signpost

- 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
- 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

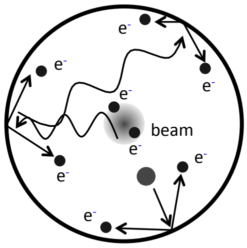
Electron production

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

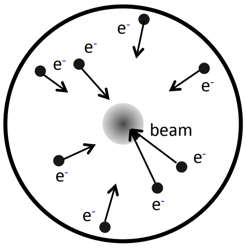
Desorption from the losses on the wall

- 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)

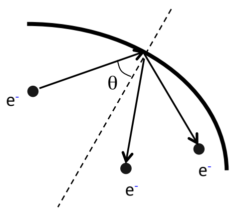
• Acceleration of primary electrons in the beam field

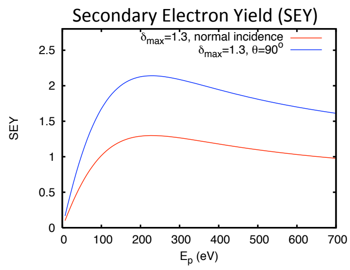


Electron production

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

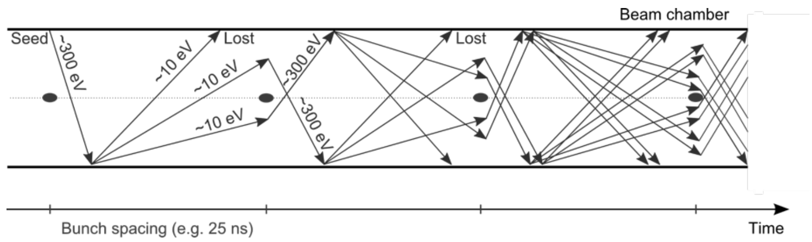




Electron production

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



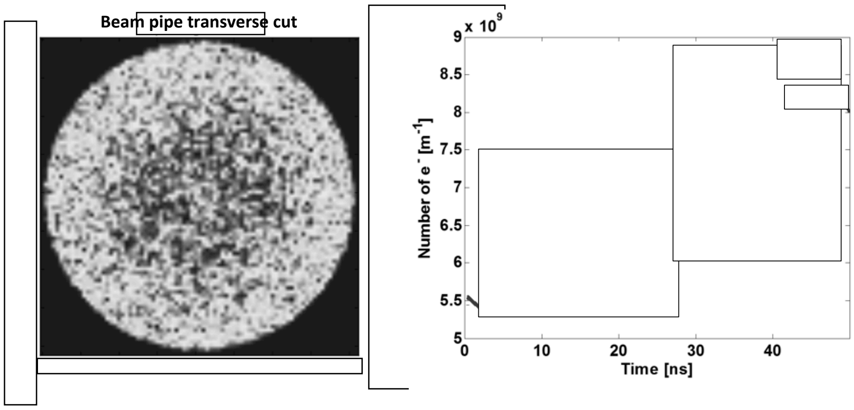
Electron production

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

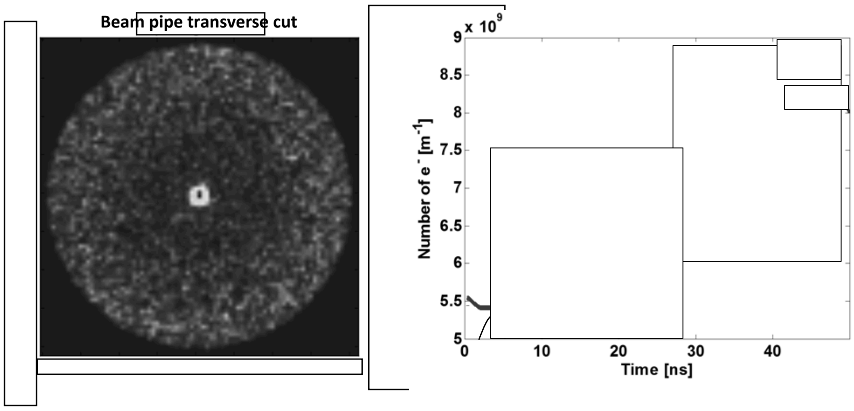
After the passage of several bunches, the electron distribution inside the chamber reaches a dynamic steady state (electron cloud)

Electron cloud formation cartoon



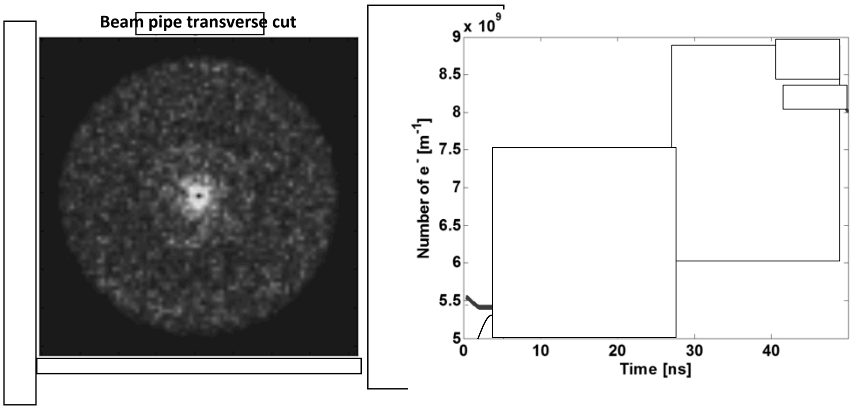
Assume an initial distribution of electrons
(from any of the mechanisms discussed before)

Electron cloud formation cartoon



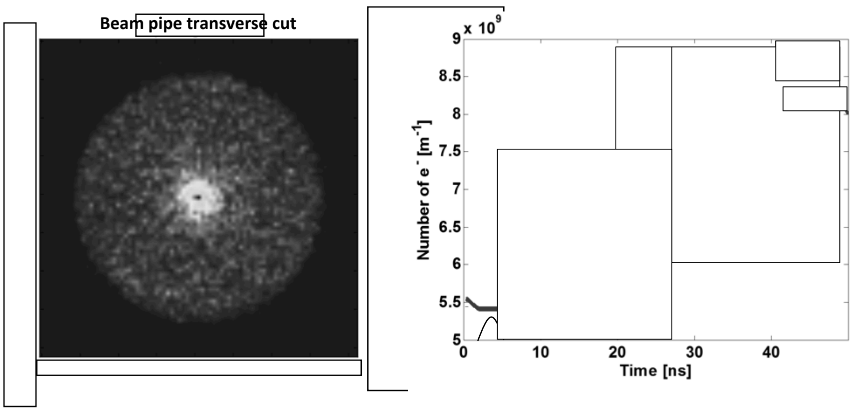
“Pinch” of electrons when bunch is passing

Electron cloud formation cartoon



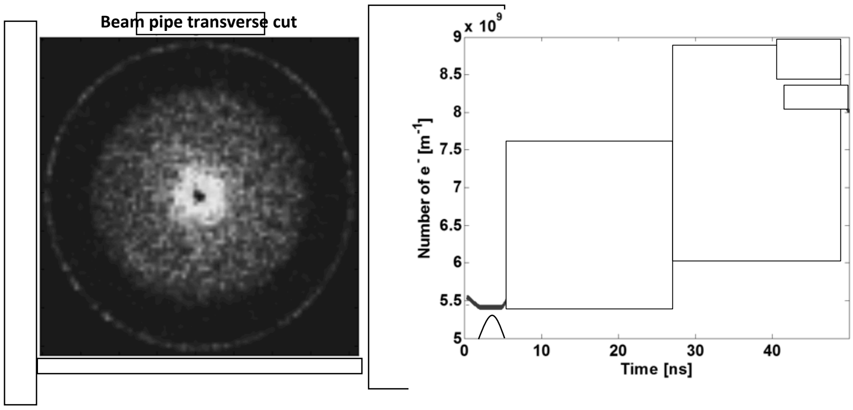
"Pinch" of electrons when bunch is passing

Electron cloud formation cartoon



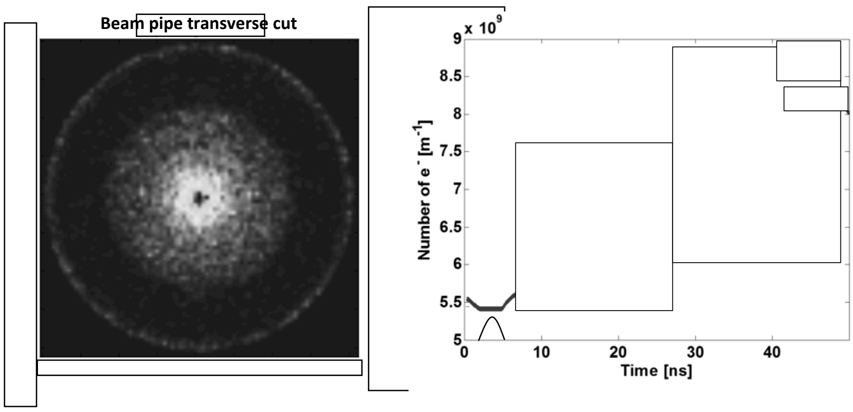
"Pinch" of electrons when bunch is passing

Electron cloud formation cartoon



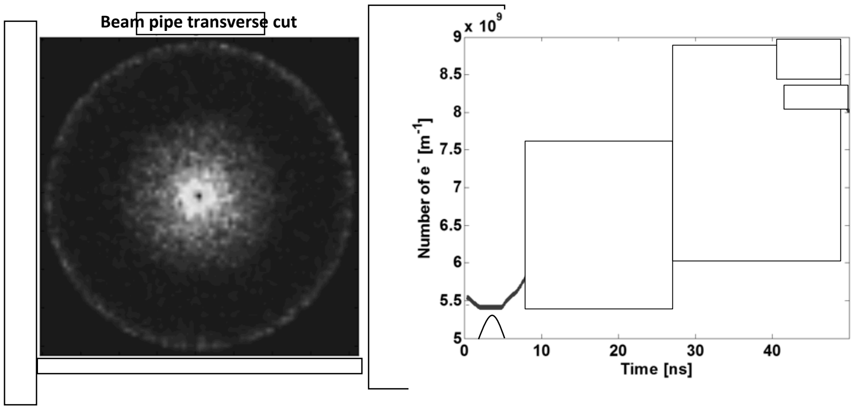
Few high energy (>100 eV) electrons reach the chamber wall already on the falling edge of the bunch and start producing secondaries

Electron cloud formation cartoon



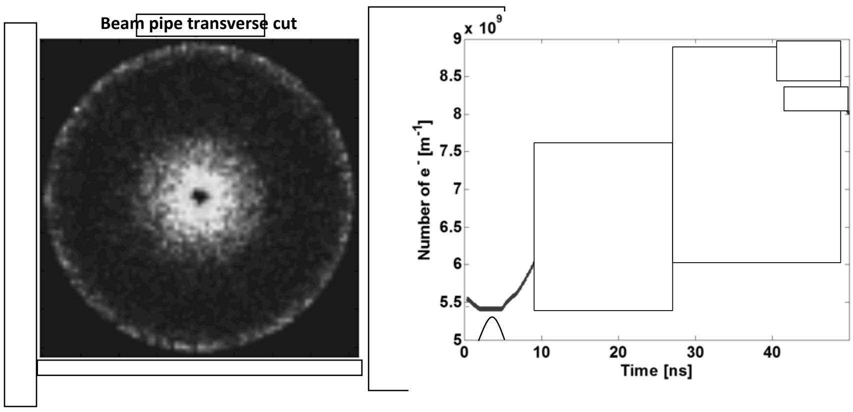
High energy electrons (>100 eV) reaching the chamber wall produce more secondaries

Electron cloud formation cartoon



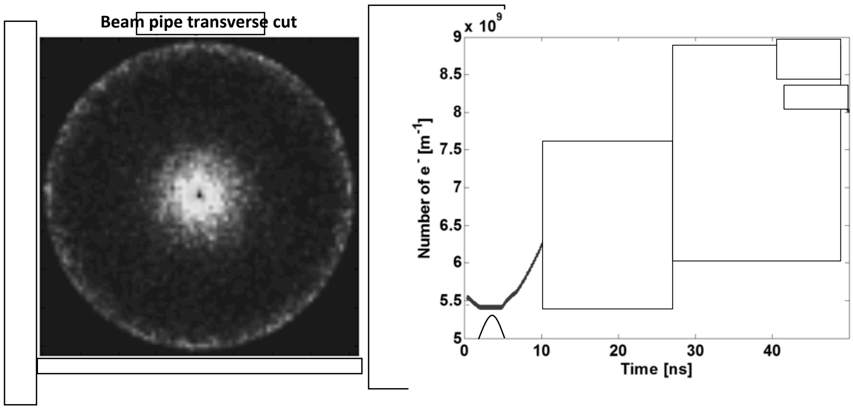
High energy electrons (>100 eV) reaching the chamber wall produce more secondaries

Electron cloud formation cartoon



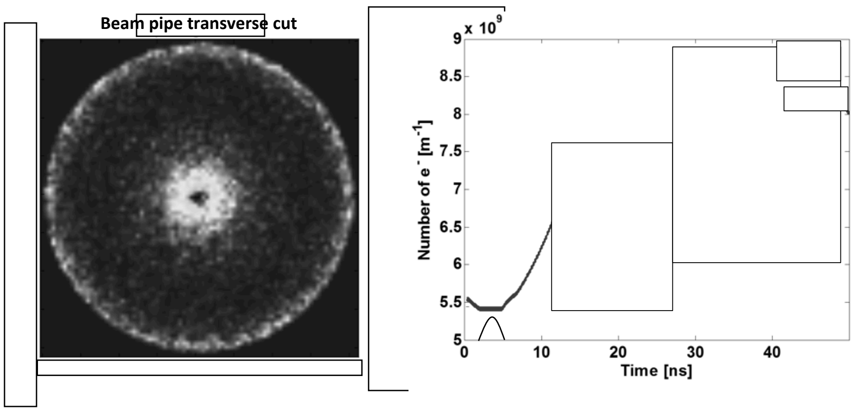
High energy electrons (>100 eV) reaching the chamber wall produce more secondaries

Electron cloud formation cartoon



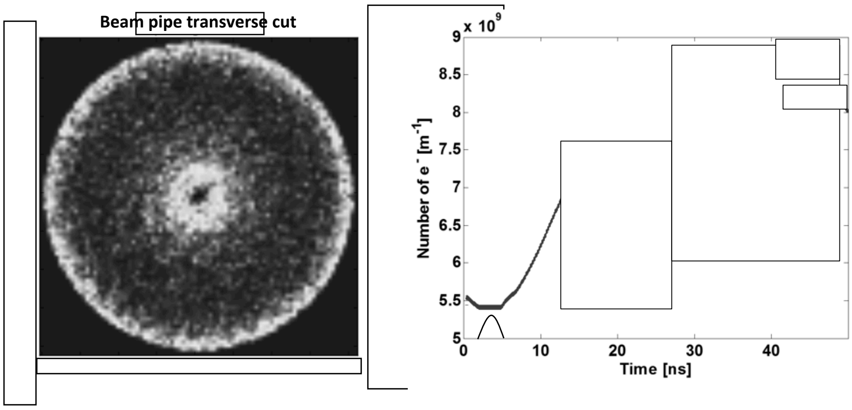
High energy electrons (>100 eV) reaching the chamber wall produce more secondaries

Electron cloud formation cartoon



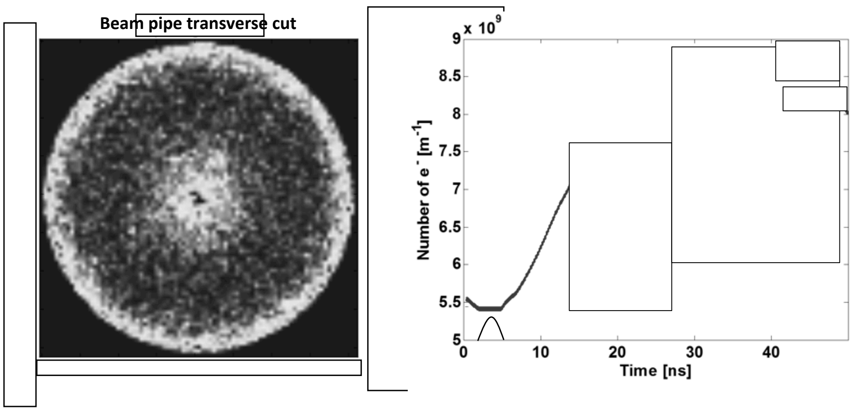
As they are produced, the emitted secondaries form a halo near the chamber wall because they have low energy (up to 10 eV)

Electron cloud formation cartoon



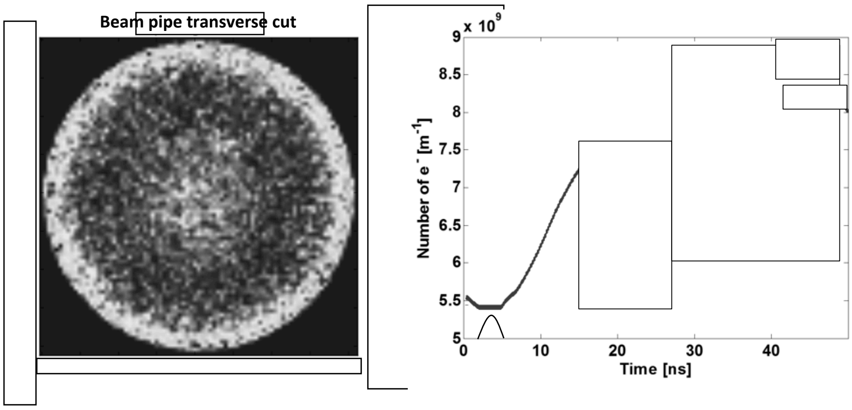
As they are produced, the emitted secondaries form a halo near the chamber wall because they have low energy (up to 10 eV)

Electron cloud formation cartoon



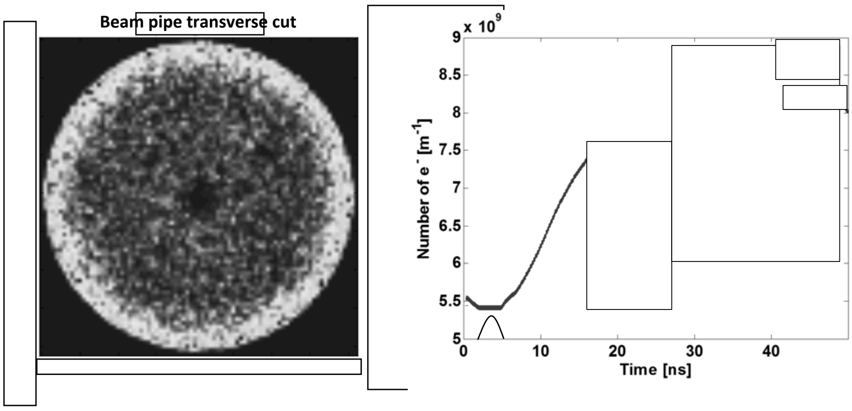
As they are produced, the emitted secondaries form a halo near the chamber wall because they have low energy (up to 10 eV)

Electron cloud formation cartoon



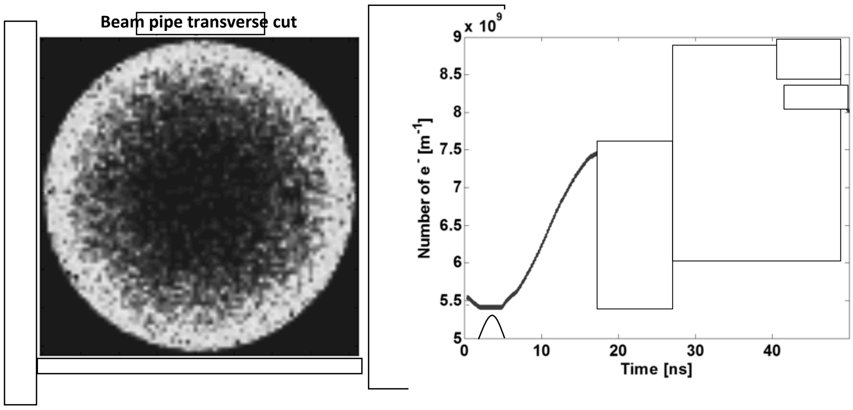
While the halo gets more and more populated,
the center is gradually depleted

Electron cloud formation cartoon



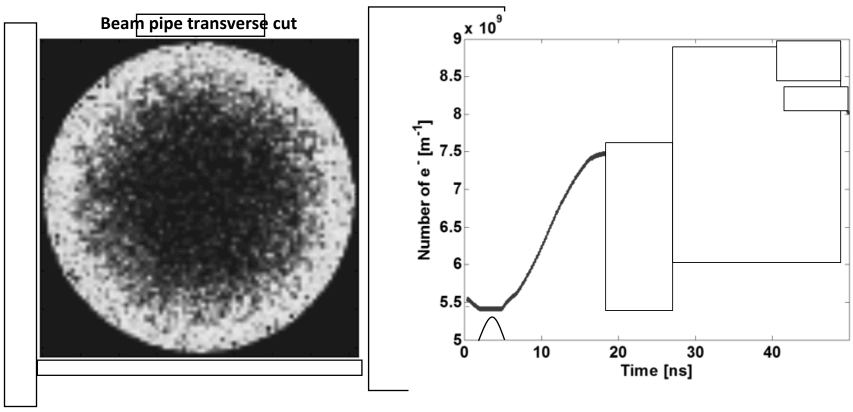
While the halo gets more and more populated,
the center is gradually depleted

Electron cloud formation cartoon



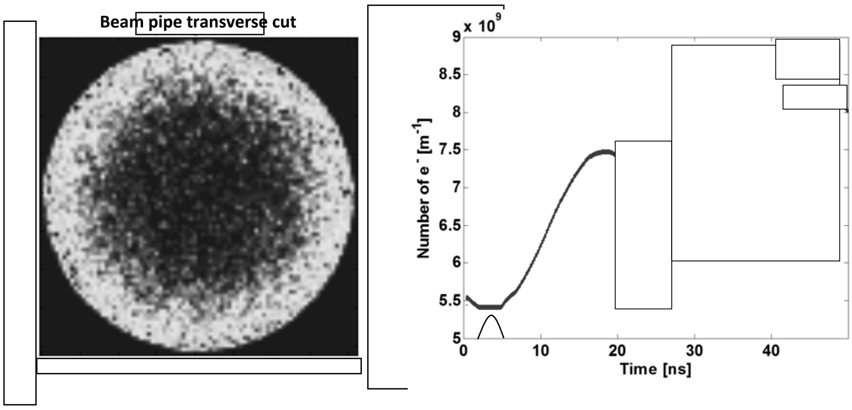
While the halo gets more and more populated,
the center is gradually depleted

Electron cloud formation cartoon



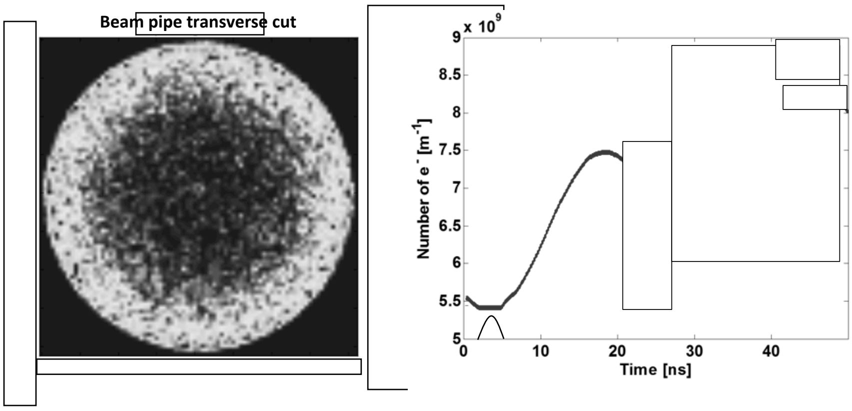
The center is strongly depleted
No more secondaries are produced because there are
no longer high energy electrons reaching the walls

Electron cloud formation cartoon



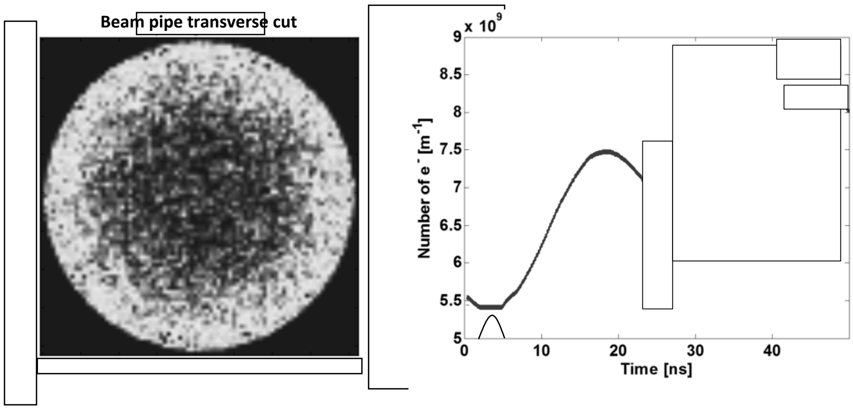
No more secondaries are produced because there are no longer high energy electrons reaching the walls
Some low energy electrons are absorbed at the walls

Electron cloud formation cartoon



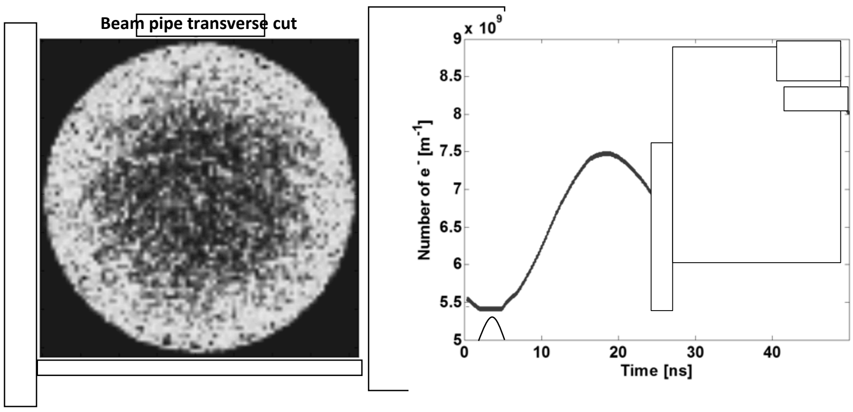
No more secondaries are produced because there are no longer high energy electrons reaching the walls
Some low energy electrons are absorbed at the walls

Electron cloud formation cartoon



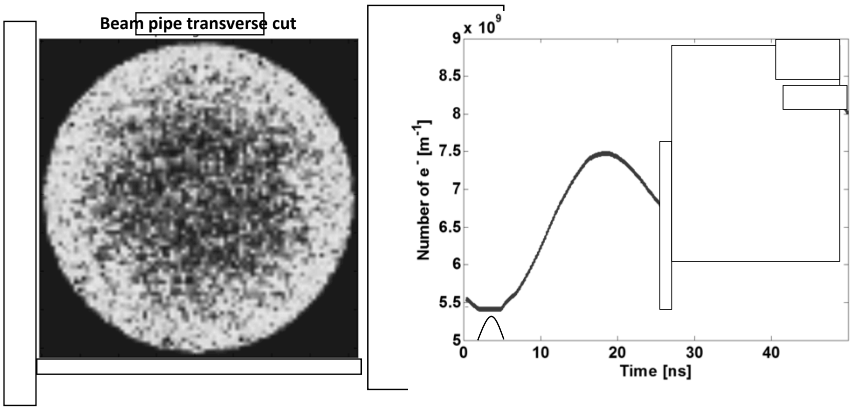
No more secondaries are produced because there are
no longer high energy electrons reaching the walls
Some low energy electrons are absorbed at the walls

Electron cloud formation cartoon



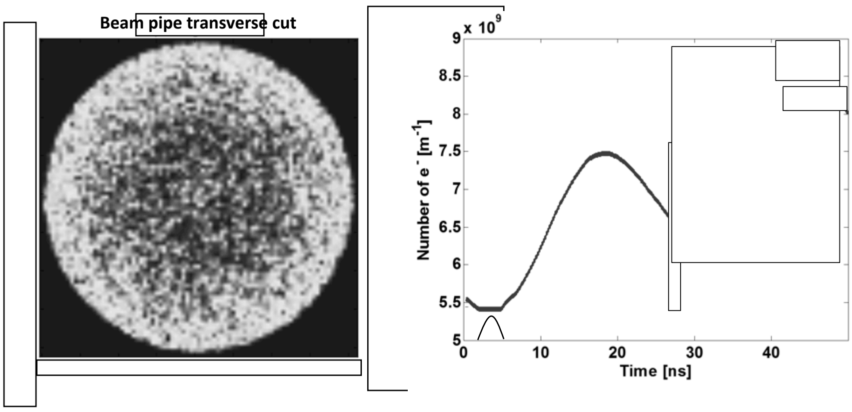
No more secondaries are produced because there are
no longer high energy electrons reaching the walls
Some low energy electrons are absorbed at the walls

Electron cloud formation cartoon



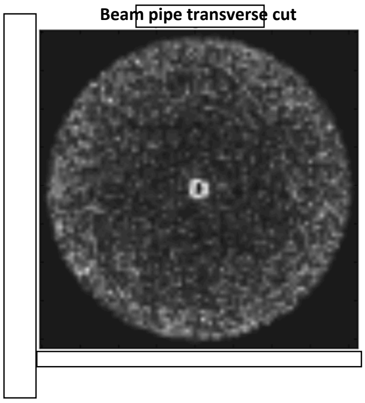
No more secondaries are produced because there are no longer high energy electrons reaching the walls
Some low energy electrons are absorbed at the walls

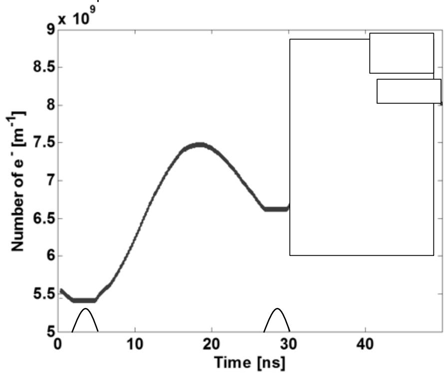
Electron cloud formation cartoon



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 while the center gets repopulated

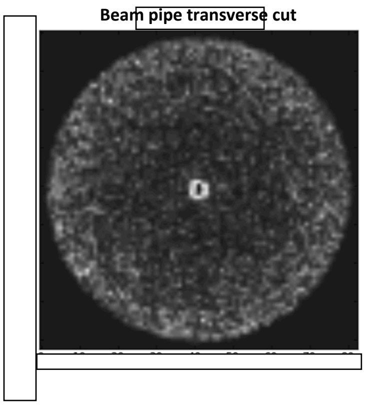
Electron cloud formation cartoon

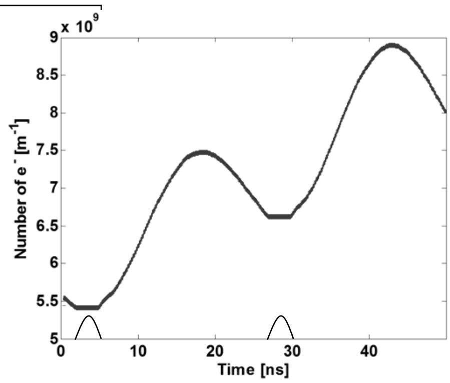




But then the next bunch comes, there is a new pinch and the whole process starts all over

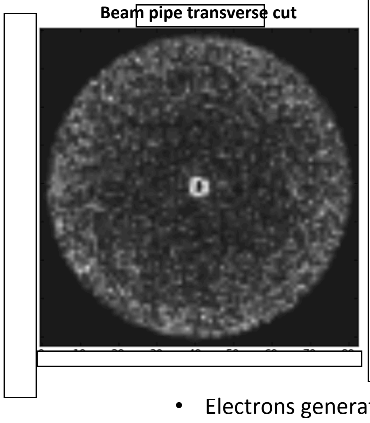
Electron cloud formation cartoon

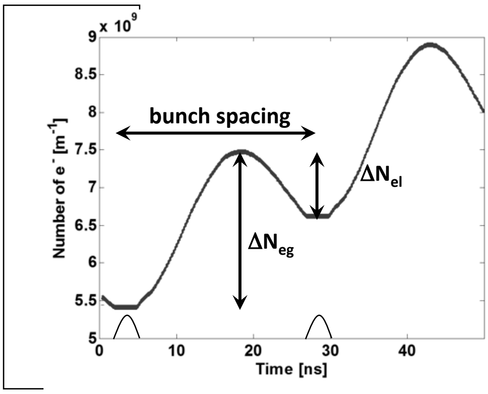




And it all repeats until the next bunch comes

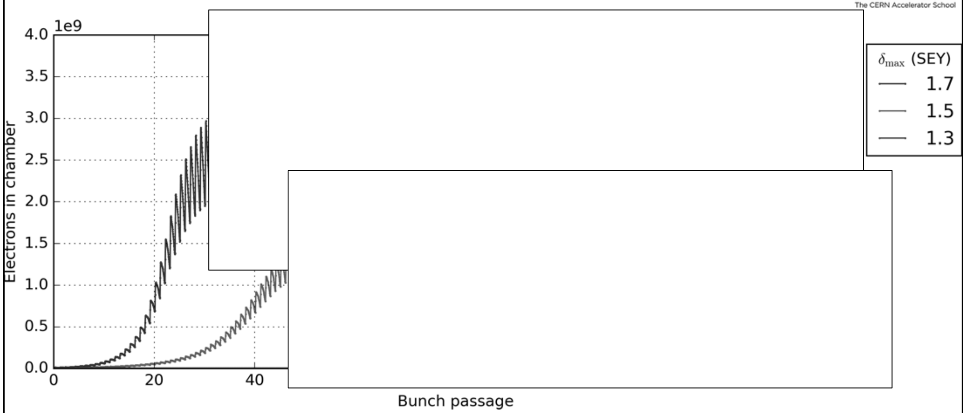
Electron cloud formation cartoon





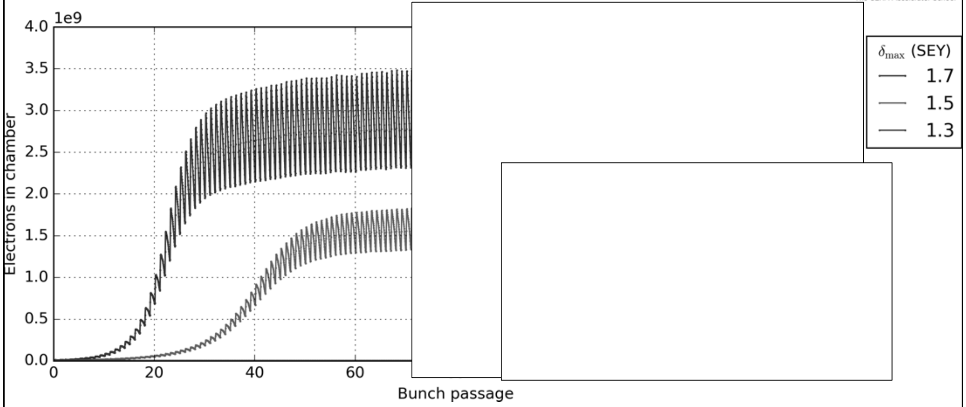
- Electrons generated (ΔN_{eg}) depend on bunch charge, chamber radius and surface SEY
- Electrons lost (ΔN_{el}) depend on chamber radius and probability of reflection at low energy
- Balance between the two depends on bunch spacing

Electron cloud formation cartoon



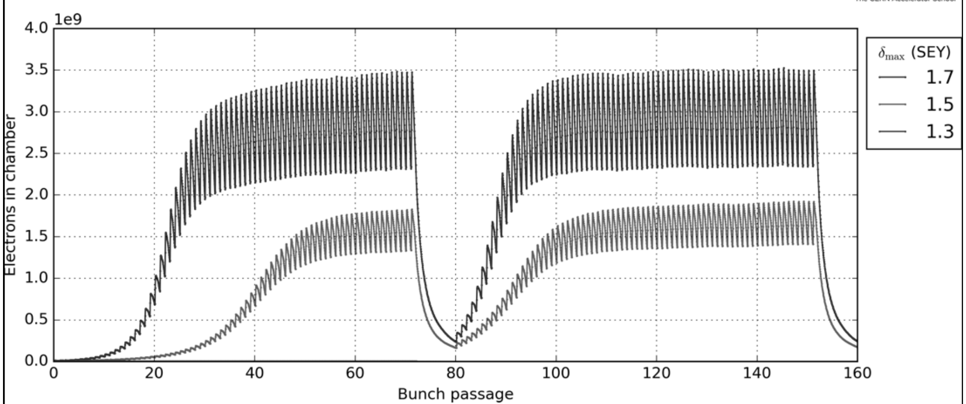
- Bunch after bunch, the e-cloud grows exponentially (if SEY above a certain threshold value)

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

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?

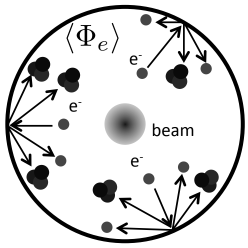
Part 4: Electron cloud – Build up and effects on beam dynamics

- 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



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

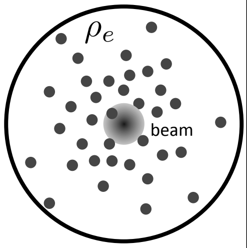
$$\Delta W = \int \langle\Phi_e(E)\rangle E dE$$

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

Machine observables



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

Machine observables

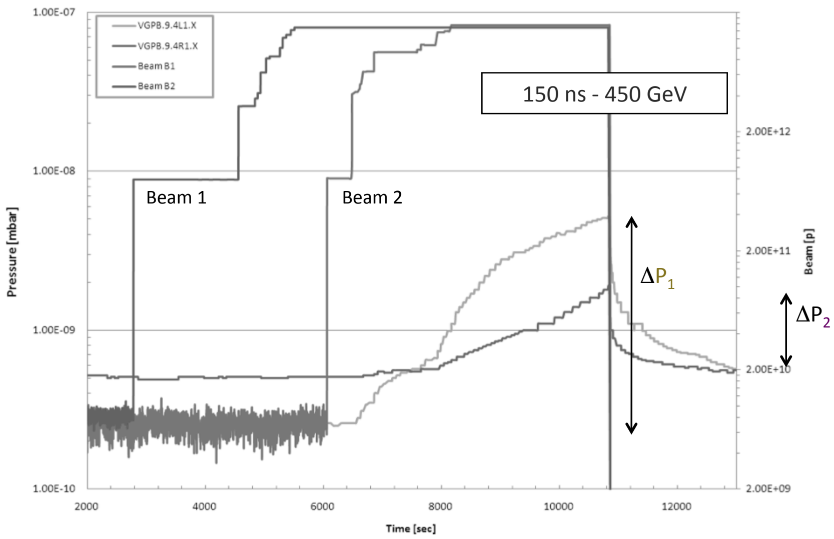
Beam observables

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

Electron cloud effects: pressure rise

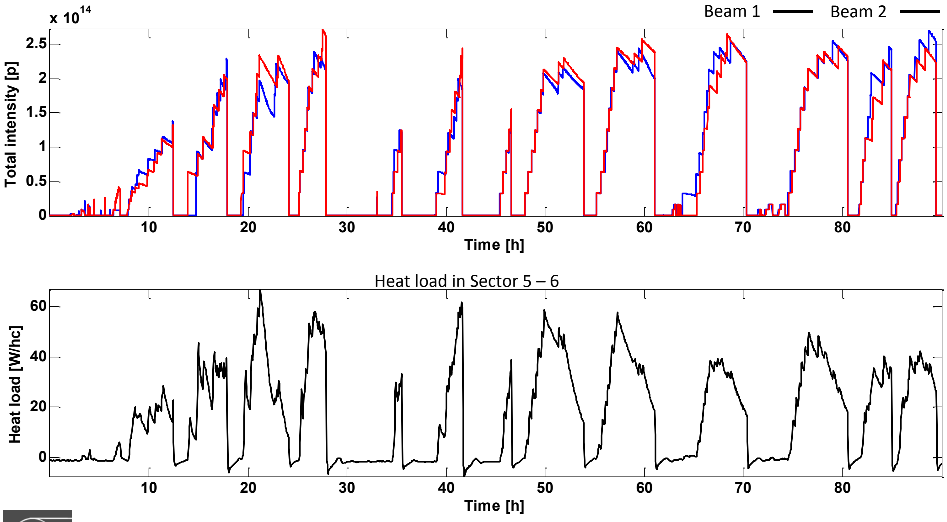
- **Early LHC operation**
  - Routine operation with 150 ns beams started in Summer 2010
  - Electron cloud made its first appearance as a **pressure rise** in the common chamber in presence of both beams, i.e. for effectively lower bunch spacings

Electron cloud effects: pressure rise

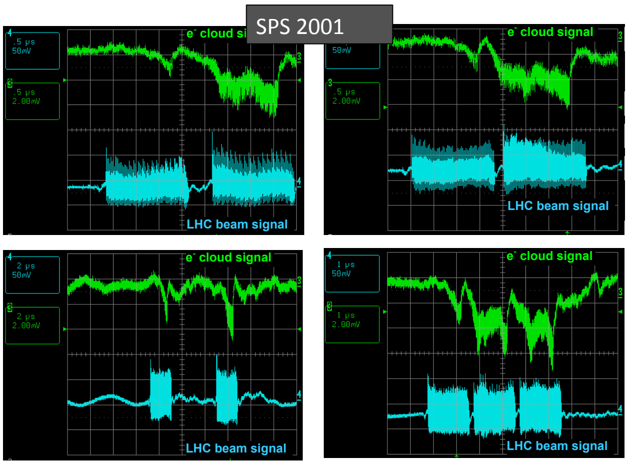


Electron cloud effects: heat load

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



Electron cloud effects: pick up signal

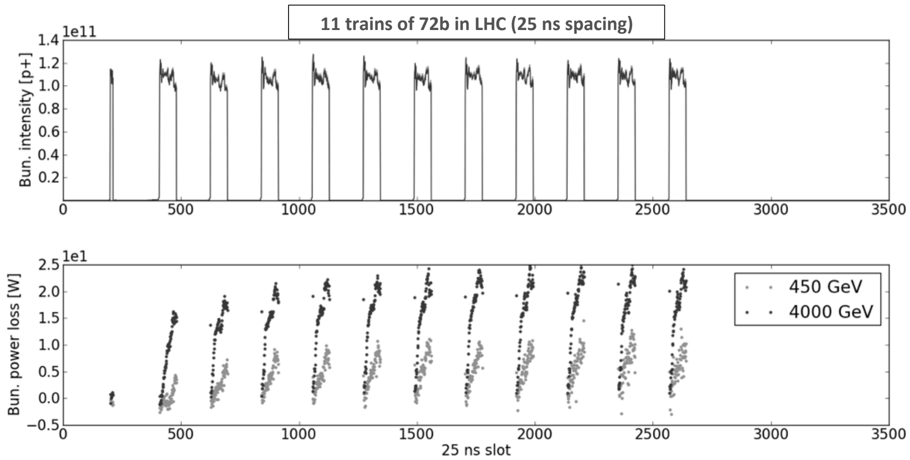


- The electron cloud signal first appeared in the SPS on the signal from a pick up as a shift of the baseline (depending on the charge collected by the electrodes)
- Correlation with train structure, length, gap were immediately apparent.

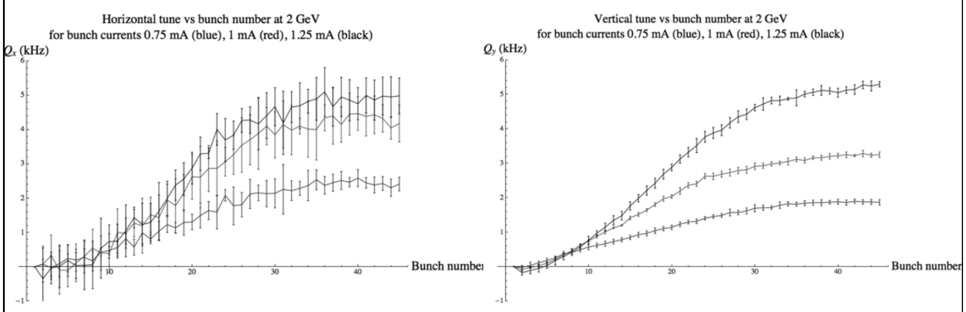
Electron cloud effects: stable phase shift

⇒ 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



- 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

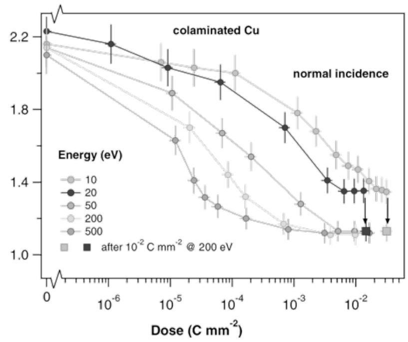
- We have learned that **electron clouds** can build up in the vacuum chamber of an accelerator operating in a certain range of beam parameters.
- Electron clouds are associated to **many detrimental effects**, like pressure rise, additional heat load, tune and stable phase shift, beam degradation through 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

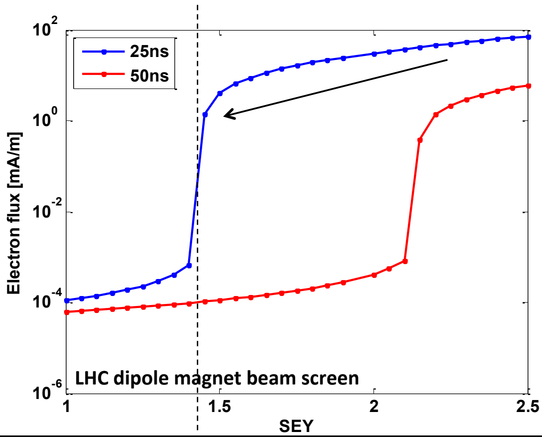
- Fortunately, the SEY of a surface is not a fixed property but it becomes lower under electron bombardment (scrubbing)
- Laboratory measurements show that
  - o SEY decreases quickly at the beginning of the process, then slows down
  - o Electrons with different energies have different 'scrubbing efficiency'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



Surface scrubbing

The CERN Accelerator School

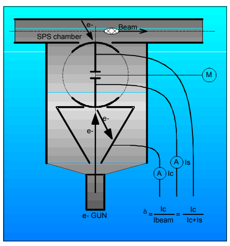
- If an accelerator can be run in **e-cloud regime**, scrubbing is expected to naturally occur (beam induced scrubbing)
  - Fortunately **beam dynamics knobs** exist to preserve beam stability, although lifetime might be poor in presence of significant e-cloud
  - Dedicated **scrubbing runs** can be used to lower the SEY



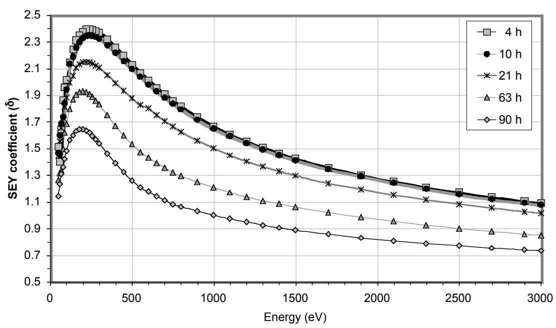
Surface scrubbing

The CERN Accelerator School

- **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)

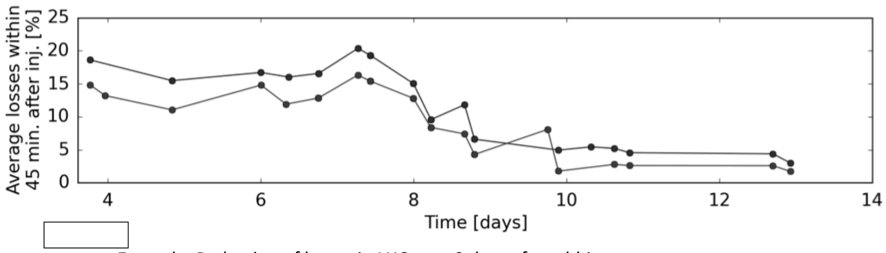


Schematic view of the in-situ SEY detector installed in the SPS



Surface scrubbing

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

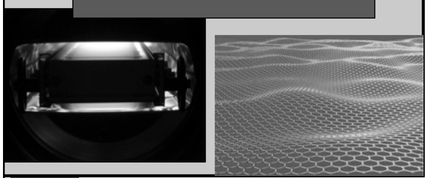
- **Beam-induced scrubbing**
  - Has been measured directly at the SPS with a Stainless Steel rotatable sample exposed to the beam or to SEY measurement device (2004)
  - Is revealed by improving accelerator conditions over time, e.g. decrease of pressure rise, heat load, stable phase shift, general improvement of beam quality (lower losses, less emittance growth)

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

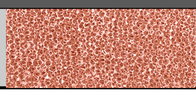
Mitigation/suppression techniques

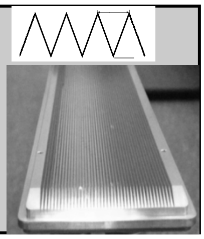
Possible Solutions

- Clearing electrodes installed along the vacuum chambers (only local, may cause impedance, aperture restriction)
- Solenoids (only applicable in field-free regions without equipment)
- Tolerate e-cloud, if possible, but damp the instability: feedback system
- Machine scrubbing during operation
  - Operation with degraded beam for some time
  - Limited by reachable SEY, may be insufficient
- Applying on the wall thin films with intrinsically low SEY
  - NEG coating (helps vacuum)
  - C coating (no activation)

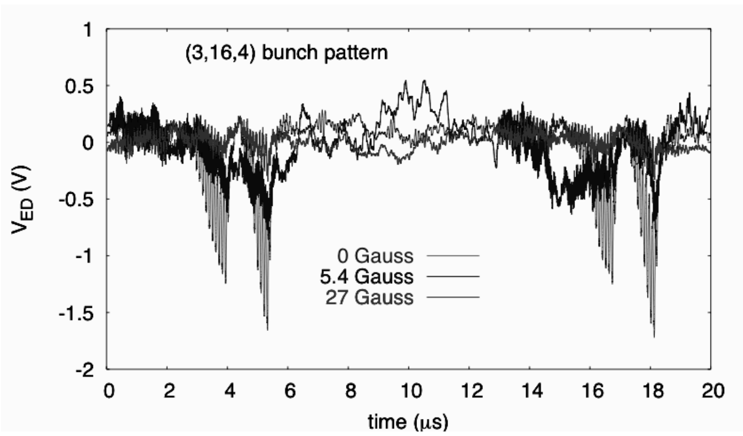


- Surface treatment to inhibit secondary electrons
  - Grooves
  - Roughness
  - Sponges
  - Laser ablation



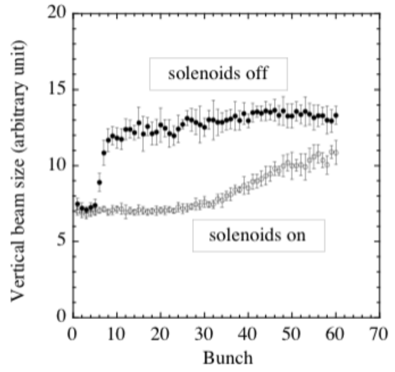


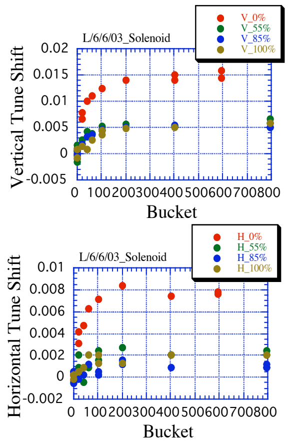
Examples: solenoids (I)



- Beneficial effect of the solenoids measured at the heavy ion collider RHIC (BNL)
- By changing the intensity of the magnetic field, the electron cloud was seen to be efficiently suppressed in a region equipped with an electron detector.

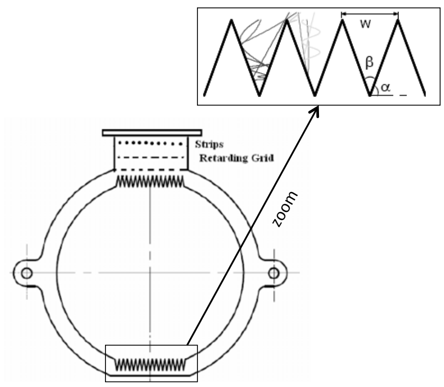
Examples: solenoids (II)

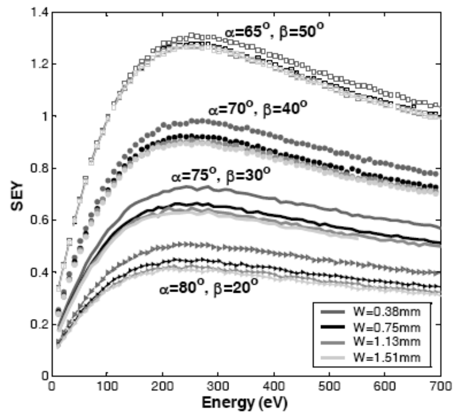




- Beneficial effect of solenoids measured at the LER of KEKB
- Drastic reduction of the beam size blow up as well as the tune shift along the batch

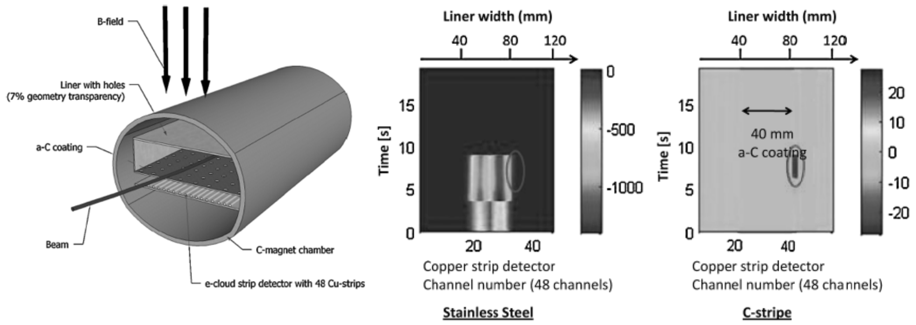
Examples: grooves





- To reduce the effective SEY, the inner surface of the beam pipe can be grooved, so that emitted electrons remain trapped
- Figure shows the effective SEY as a function of the groove angle and period, for a sample having δ_{max}=1.74 at E_{max}=330 eV

Examples: carbon coating



- To reduce the effective SEY, the inner surface of the beam pipe can be coated with amorphous carbon (a-C)
- It is possible to reach values of δ_{max} below 1, measured in the laboratory and also verified by measurements at an electron cloud detector in the SPS

Signpost

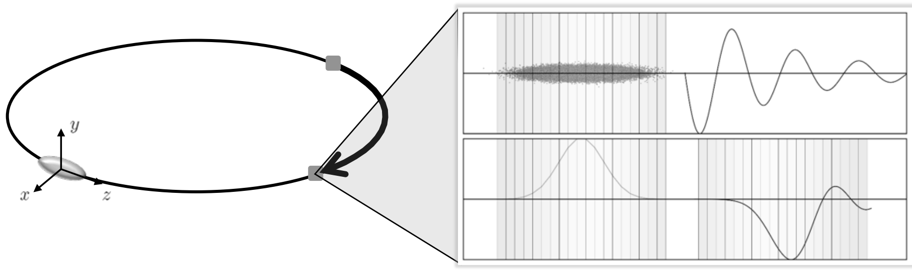
- We have learned that **electron clouds** can build up in the vacuum chamber of an accelerator operating in a certain range of beam parameters.
- They are the origin of **many detrimental effects**, like pressure rise, additional heat load, beam degradation through instability and emittance growth
- 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

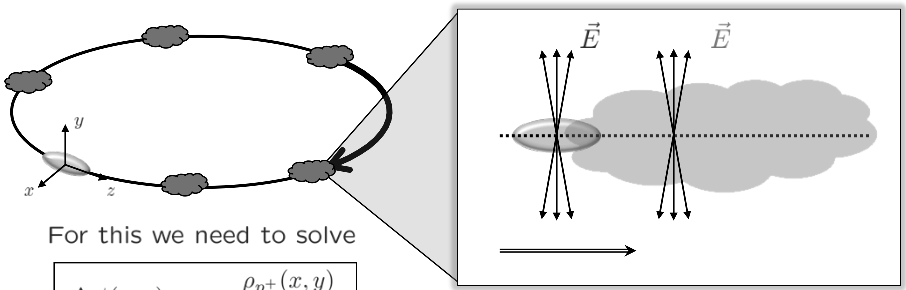
Accelerator beam system - wakefields

- 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

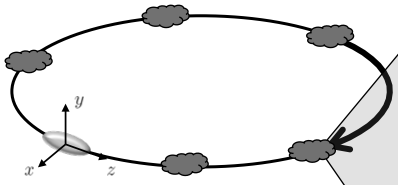
$$\Delta\,\phi(x,y)_{p^+} = -\frac{\rho_{p^+}(x,y)}{\varepsilon_0}$$

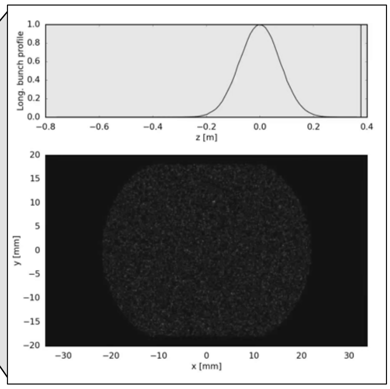
$$\Delta\,\phi(x,y)_{e^-} = -\frac{\rho_{e^-}(x,y)}{\varepsilon_0}$$

and apply the corresponding kicks to the cloud and the beam

Electron clouds in a drift section

• Two stream collective interaction – much more complicated





For this we need to solve

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

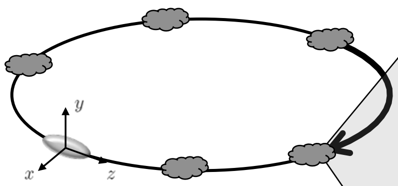
$$\Delta\,\phi(x,y)_{e^-} = -\frac{\rho_{e^-}(x,y)}{\varepsilon_0}$$

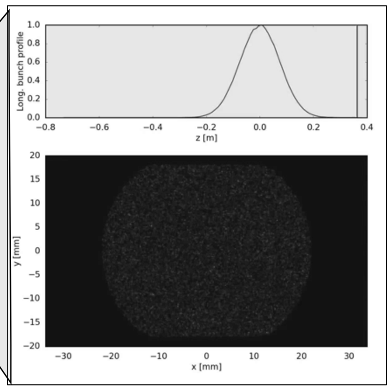
and apply the corresponding kicks to the cloud and the beam

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

Electron clouds in a bending magnet

• Two stream collective interaction – much more complicated





For this we need to solve

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

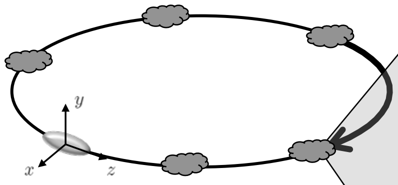
$$\Delta\,\phi(x,y)_{e^-} = -\frac{\rho_{e^-}(x,y)}{\varepsilon_0}$$

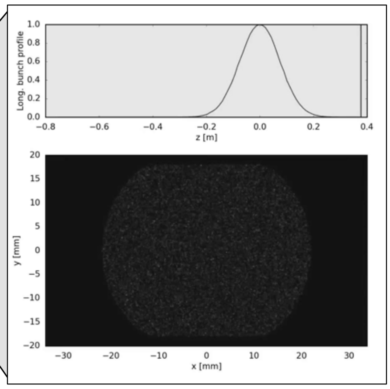
and apply the corresponding kicks to the cloud and the beam

• 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

- Two stream collective interaction – much more complicated





For this we need to solve

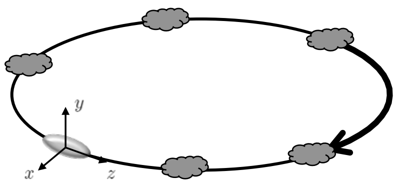
$$\Delta\,\phi(x,y)_{p^+} = -\frac{\rho_{p^+}(x,y)}{\varepsilon_0}$$

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

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

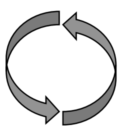
Electron clouds in a quadrupole magnet



For this we need to solve

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

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

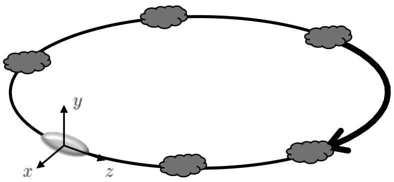


and apply the corresponding kicks to the cloud and the beam

- Again, we close a loop as the beam **can feed back onto itself** via the e-cloud.
- The coupled system can enter into a state where the charged particle beam motion **is excited and can become unstable**.

Accelerator beam system – e-cloud

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



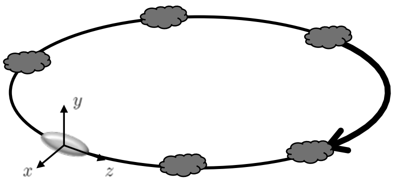
- Basic loop of tracking with electron clouds:
  - Transport beam along segment to interaction point

Accelerator beam system – e-cloud

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

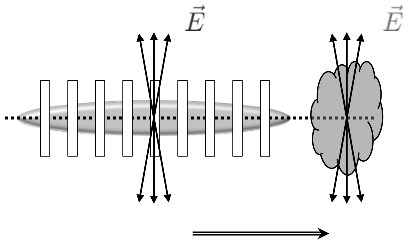
$$\Delta\vec{x}'[i] = -\frac{e^2}{m\gamma\beta^2c^2}\vec{E}_{e^-}\, C \qquad \Delta\dot{\vec{x}} = -\frac{e}{m}\left(\vec{E}_{p^+}[i] + \frac{\dot{\vec{x}}\times\vec{B}}{c}\right)\Delta t$$

Particles in/fields from slice i



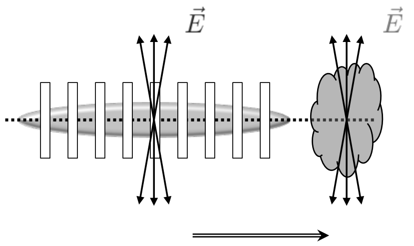
- Basic loop of tracking with electron clouds:
  - Transport beam along segment to interaction point
  - Apply e-cloud kick
    → get fields from PIC step

E-cloud beam system



- 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 one 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



For this we need to solve

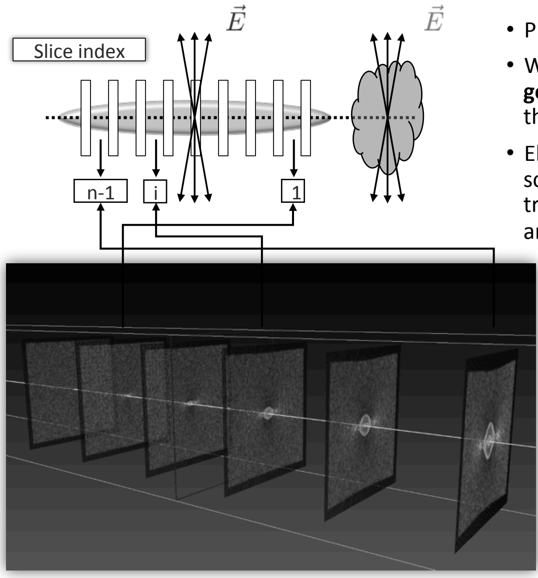
$$\vec{\nabla} \cdot \vec{E}_{p^+} = \frac{\rho_{p^+}}{\varepsilon_0}$$

$$\vec{\nabla} \cdot \vec{E}_{e^-} = \frac{\rho_{e^-}}{\varepsilon_0}$$

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 one 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

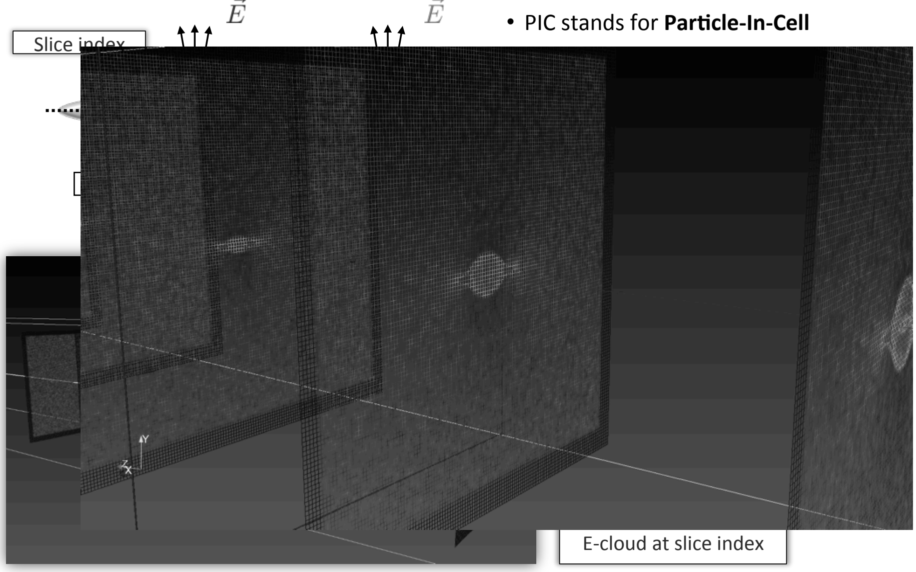


- PIC stands for **Particle-In-Cell**
- We use this method to compute **fields generated by particles** to solve e.g. the Poisson equation
- Electron motion occurs at the time scale of a slice of a bunch length → track single slices through the e-cloud and **apply integrated kicks**
  - **Compute electric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

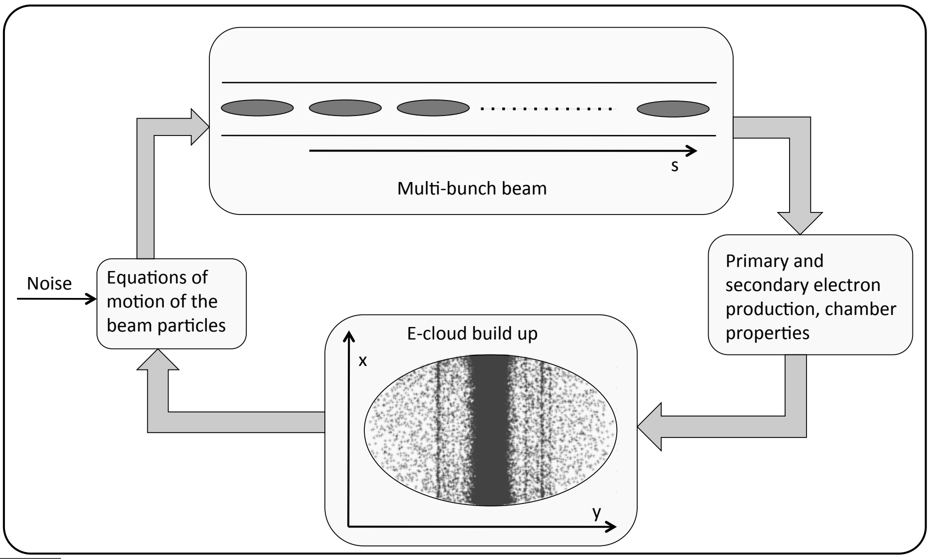
E-cloud beam system

- PIC stands for **Particle-In-Cell**

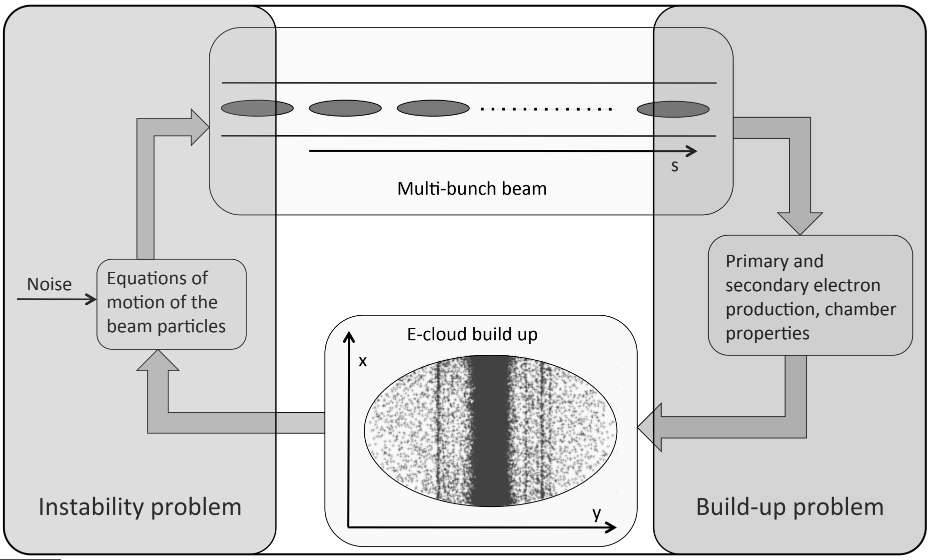


E-cloud at slice index

Numerical model of electron cloud effects

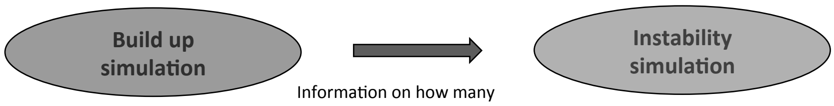


Numerical model of electron cloud effects



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

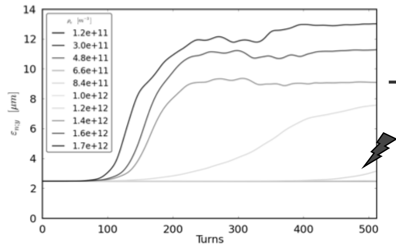
HEADTAIL, PyHEADTAIL, CMAD, PEHTS, …

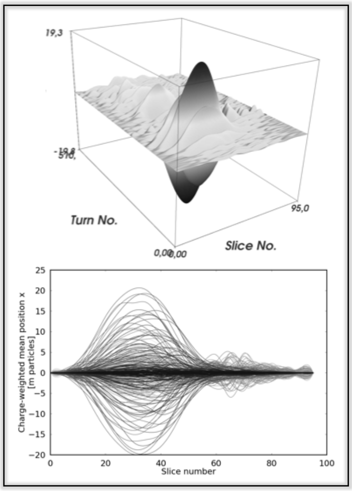
Numerical model of electron cloud effects

- 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

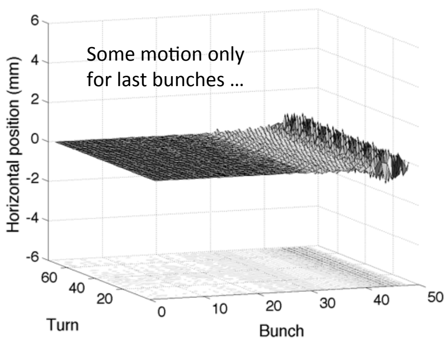


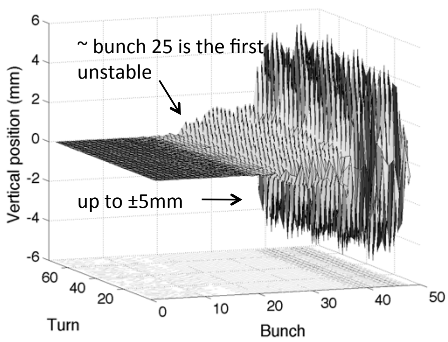


- Coherent instabilities occur when a certain **central cloud density threshold** is breached
- This leads to **coherent intra bunch motion** which grows **exponentially**
- A consequence is **emittance blow-up** and **losses**

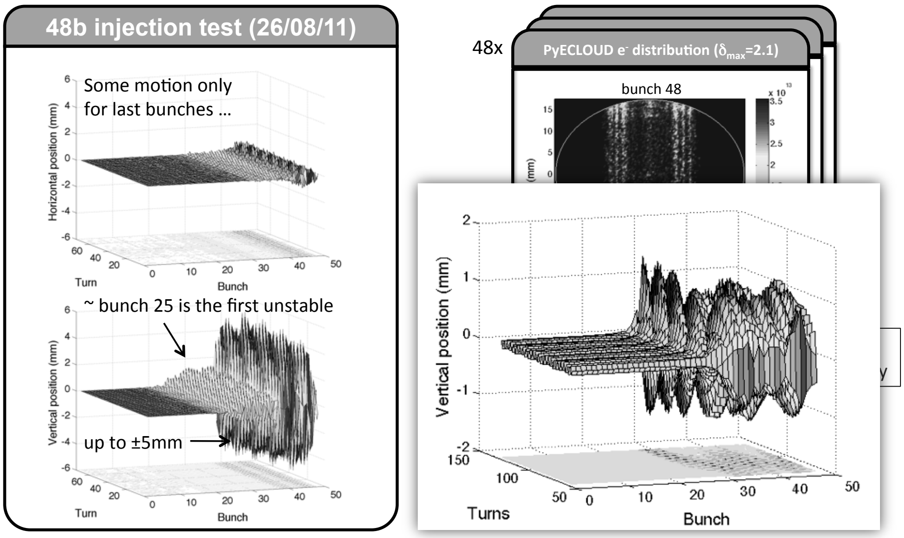
Ex. of coherent e-cloud effects in the LHC

- 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



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

The End