Intensity Limitations in Particle Beams 2015

Electron cloud effects

Giovanni Rumolo

Many thanks to H. Bartosik, G. Iadarola, K. Li, L. Mether, A. Romano, M. Schenk

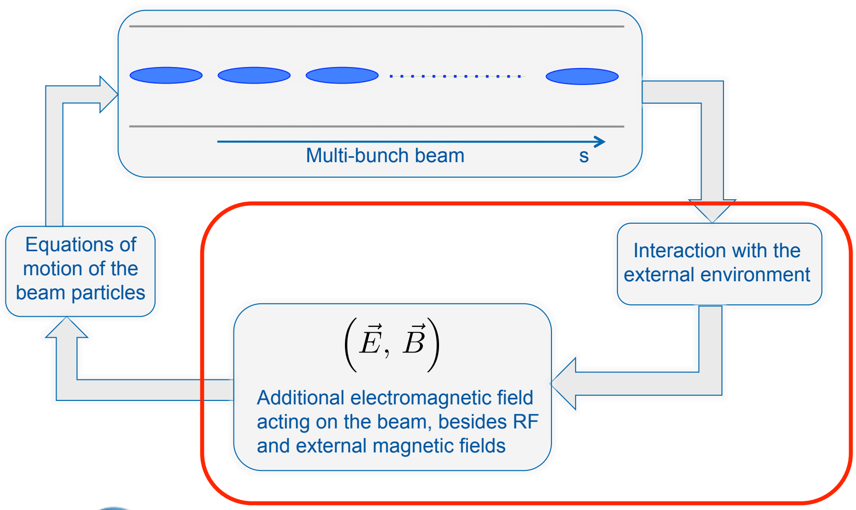
CAS on Intensity Limitations in Particle Beams 2015, 3-11 November, 2015
http://indico.cern.ch/event/362960/

Electron cloud effects in accelerators

- Primary sources of electrons in the vacuum chamber of accelerators: General concepts
- Formation of the electron clouds for bunched beams
  - Modeling of the impact of electrons against the chamber wall: Secondary electron emission & reflection
  - Build up process due to multipacting
  - Interaction with the beam: transverse beam instability and incoherent effects
  - Simulation techniques
- Machine/beam observables related to electron clouds
- Mitigation and cures

⇒ Important impact of electron cloud on the design/upgrade of high intensity machines

The instability loop



Reminder

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

Primary generation

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**

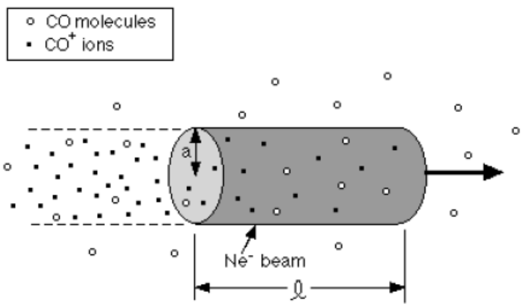
- Gas ionization and wall desorption produce both electrons and ions (the former one with the same rate, the second one with different rates depending on the desorption yields), photoemission is only a source of electrons
- The dominant mechanism depends upon the beam type and parameters, the vacuum level, the design (material, shape), roughness and cleanness of the inner surface of the beam pipe, etc.

Primary generation

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**

Residual gas ionization



The number of electron/ion pairs created via **scattering** per unit length ($\lambda = dN_{ion}/ds = dN_{el}/ds$) depends on the partial pressures of the components of the residual gas (P_n), the cross section of the ionization process for each of these species (σ_n), the number of particles per bunch (N_b). We can assume room temperature T=300 K

$$\lambda = \frac{N_b}{k_B T} \sum_{n=1}^{N} P_n \sigma_n = 3.22 \times 10^{-9} N_b \sum_{n=1}^{N} P_n \,[\mathrm{nTorr}]\, \sigma_n \,[\mathrm{MBarn}]$$

Residual gas ionization

- A list of features of charge production through **ionization** of the residual gas:
  1. Electron/ion pair production, all basically at rest in the volume swept by the passing beam
  2. The amount of produced pairs is mainly determined by the quality of the vacuum and the beam intensity.
  3. Weak dependency on the beam energy through the cross section of the ionization process (the ionization cross section does not vary significantly in the ranges of energy usually covered in accelerators).
  4. The composition of the rest gas is only important in machines operating with negatively charged particles → some ions can be trapped by the beam and accumulate, while some others can escape.
  5. In some regimes, ionization can be caused not only by scattering, but also by the electric field, becoming a severe source of primaries (e.g. CLIC Main Linac)

Residual gas ionization

- A list of features of charge production through **ionization** of the residual gas:
  1. Electron/ion pair production, all basically at rest in the volume swept by the passing beam
  2. The amount of produced pairs is mainly determined by the

qu…
3. We… …ross se… …section do… …ually co…
4. Th… …achines operating with negatively charged particles → some ions can be trapped by the beam and accumulate, while some others can escape.

Residual gas ionization is the primary mechanism responsible for both electron cloud formation in machines with positively charge particles (at least in certain regimes) and for ion production in machines with negatively charged particles!

  5. In some regimes, ionization can be caused not only by scattering, but also by the electric field, becoming a severe source of primaries (e.g. CLIC Main Linac)

Primary generation

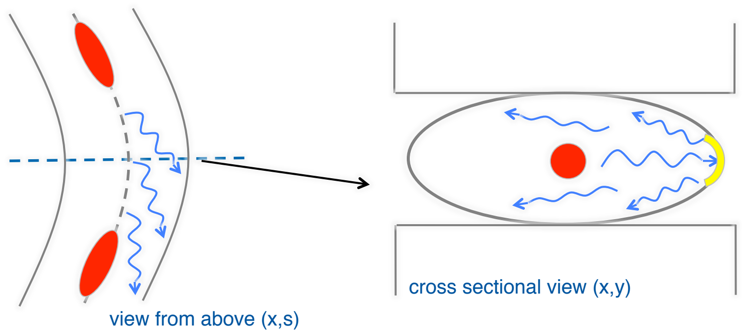
Generation of charged particles inside the vacuum chamber (primary, or seed, electrons)

Residual gas ionization

Photoelectrons from synchrotron radiation

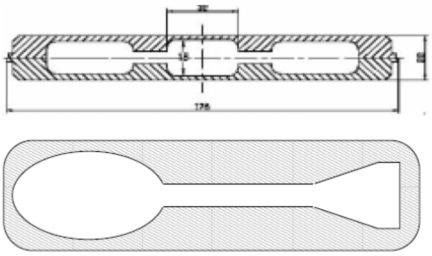
Desorption from the losses on the wall

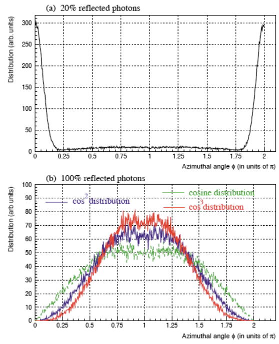
Photoemission



- When the beam is bent in a dipole magnet, it emits synchrotron radiation in the horizontal plane (bending plane)
- When the synchrotron radiation hits the beam pipe
  - partly it produces electron emission within a $1/\gamma$ angle from the point where it impinges
  - partly it is reflected inside the pipe and hits at different locations, too, producing electrons with a more complex azimuthal distribution.

Photoemission





- The vacuum chamber in dipoles can be designed in such a way as to absorb the direct synchrotron radiation into an antechamber (one sided in arcs, two-sided in wigglers). This solution is adopted in many synchrotron light sources (especially for heat load) and foreseen for wigglers in positron damping rings of linear colliders
- The surface directly hit by synchrotron radiation can be also machined in a way as to change the azimuthal distribution of the reflected radiation.
  - With smooth chamber it is assumed to be uniform on the beam pipe
  - E.g. with saw-tooth shape, distributions can be more like $\cos^2$ or $\cos^3$
- Percents of directly absorbed and reflected radiation come from lab measurements.

Photoemission

- The rate of electron production ($\lambda=dN_{el}/ds$) is given by the number of photons per beam particle per meter multiplied by the number of beam particles and by the photoemission yield of the surface, which depends on the energy of the photons (Y)
- An effective photoemission yield (Y^*) is used, which usually takes into account also of the antechamber or absorbers (e.g. $Y^*=0.1$ Y if we know that 90% of the radiation goes into the antechamber)
- When bent in a dipole on a path length L, a beam produces electrons at a rate given by the following formula.

$$\lambda = Y^* N_b \frac{dN_\gamma}{ds} = Y^* N_b \frac{5\pi\alpha\gamma}{\sqrt{3}L}$$

α is the fine structure constant, γ the relativistic factor of the beam, L the total length over which there is emitted radiation.
Y^* depends on the energy of the photons (it becomes negligible if the critical photon energy is below the work function of the metal, then grows proportionally with this energy, i.e. with the third power of γ)

Primary generation

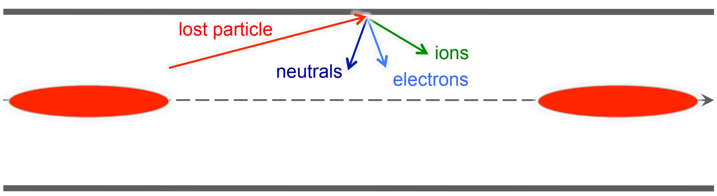
Generation of charged particles inside the vacuum chamber (primary, or seed, electrons)

Residual gas ionization

Photoelectrons from synchrotron radiation

Desorption from the losses on the wall

Beam particle loss



- Electrons, neutrals and ions can be also produced as a result of **slow beam particle losses** on the walls of the beam pipe..
- The different species are produced with rates dependent on their specific desorption yields. The types of ions desorbed depend on the material and surface of the pipe wall
- Desorption rates are functions of the beam energy and of the angle of incidence. The incidence is mainly considered to be grazing (shallow angles)
- Neutrals degrade the vacuum and contribute to the value of the *dynamic pressure*, i.e. the pressure in the beam pipe in presence of circulating beam. When the increased pressure causes in turn an increase of beam losses, this process may diverge, triggering a so-called pressure runaway (i.e. a vacuum instability)

Beam particle loss

- Beam particle loss takes place because of
  - Diffusion, emittance growth (IBS, scattering, bremsstrahlung, Touschek, beam-beam, noise excitation, resonance crossing, …), which cause the particles to exit the dynamic aperture and eventually hit the physical aperture.
  - Uncaptured beam lost at the beginning of the accelerating ramp.
- Diffusion losses are concentrated at the significant aperture restriction points. Capture losses, but also e.g. losses of ions having undergone charge exchange processes (stripping/capture), usually happen downstream from the bending magnets. Both can be intercepted with purposely designed collimators.
- An estimate of the average beam losses is based on the percent of beam lost over a certain number of turns, which can be roughly translated in number of beam particles lost per meter (n') though the desorption yield η_{el}

$$\lambda_{el} = \eta_{el} n'$$

November 2015 CAS – Electron Cloud 17

Electron cloud formation

- **Electrons can strongly affect the performance of machines operating with positively charged particles** (positrons, protons, heavy ions). There are observations of electron accumulation also for electron machines.
- Coasting (continuous) beams
  - Electrons emitted at the pipe surface are accelerated and decelerated in the beam field, and come to the other side of the pipe with a zero net energy gain → no contribution to accumulation
  - Ionization electrons are trapped and move with high frequency. Their accumulation around the beam to the neutralization level may endanger stability.
- Bunched beams
  - Trains of short bunches: under certain conditions, a process of multi-bunch multiplication is possible through the **secondary electron emission**, i.e. the electrons generated with the mechanisms so far considered (called primary) seed an avalanche process that leads to very high electron densities inside the beam pipe
  - Trains of long bunches: they can behave partly like coasting beams, with the advantage of having clearing gaps. However, again due to **secondary electron emission**, they may suffer from the so called trailing edge multipacting, which can cause intolerable electron accumulation especially at the tail of this type of bunches

November 2015 CAS – Electron Cloud 18

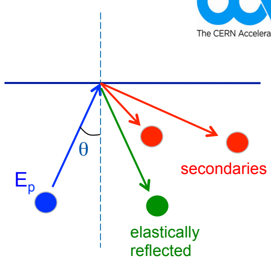
Electron cloud formation

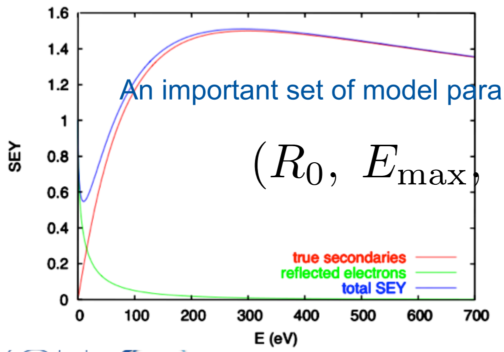
Generation of charged particles inside the vacuum chamber (primary, or seed, electrons)

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

Electron cloud formation

- When electrons hit the pipe wall, they do not just disappear…..
  - High energy electrons easily survive and actually multiply through **secondary electron emission**
  - Low energy electrons tend to survive long because they are likely to be elastically reflected.
- **Secondary electron emission is governed by the curve below**





An important set of model parameters

$$(R_0,\ E_{\max},\ \delta_{\max})$$

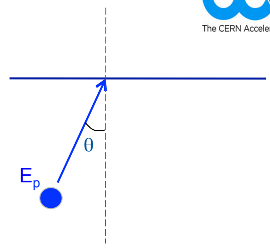
$$\delta_{\rm true} = \delta_{\max}\frac{sx}{s-1+x^s} \qquad x = \frac{E}{E_{\max}}$$

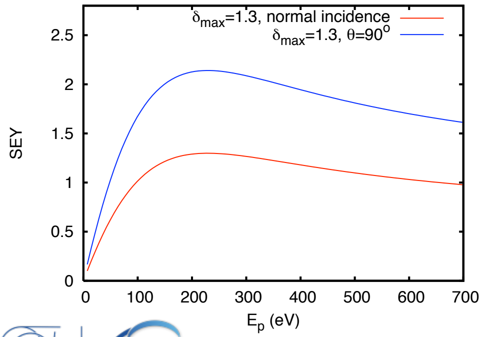
$$\delta_{\rm elas} = \frac{\left(\sqrt{E}-\sqrt{E+E_0}\right)^2}{\left(\sqrt{E}+\sqrt{E+E_0}\right)^2}$$

$$\delta_{\rm tot}(E) = \delta_{\rm true}(E) + R_0\cdot\delta_{\rm elas}(E)$$

Electron cloud formation

- When electrons hit the pipe wall, they do not just disappear…..
  - High energy electrons easily survive and actually multiply through **secondary electron emission**
  - Low energy electrons tend to survive long because they are likely to be elastically reflected.
- **Secondary electron emission is governed by the curve below**



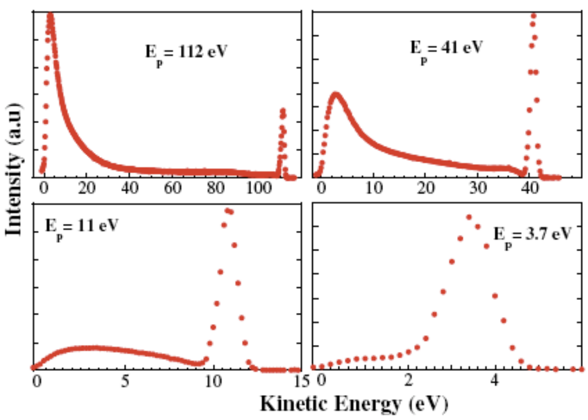


$$\delta^*_{\max}(\theta) = \delta_{\max} \exp\left[\frac{1}{2}(1-\cos\theta)\right]$$

$$E^*_{\max}(\theta) = E_{\max} \cdot [1 + 0.7\,(1-\cos\theta)]$$

Electron cloud formation

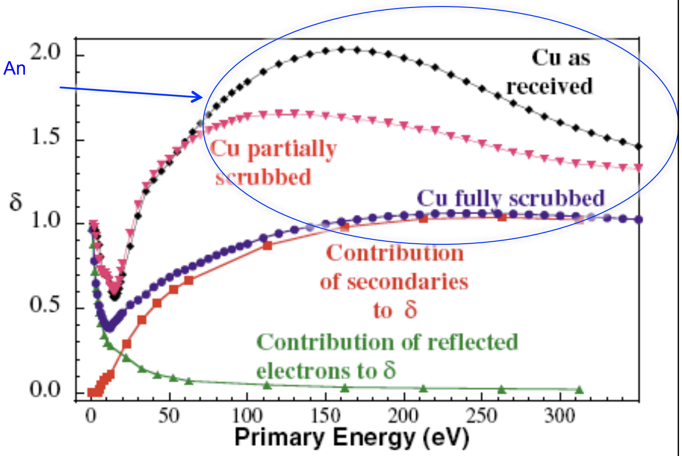
- Elastically reflected electrons, and their relevance at very low energies, have been measured (Cimino & Collins, 2004)
- From these measurements both secondary emission and elastic reflection have been fully characterized, although some doubts still persist on the best modeling at low energies



Electron cloud formation

- Elastically reflected electrons, and their relevance at very low energies, have been measured (Cimino & Collins, 2004)
- From these measurements both secondary emission and elastic reflection have been fully characterized → high probability of elastic reflection of electrons at low energy for technical surfaces

The SEY decreases in time… An effect of what we call "surface scrubbing"

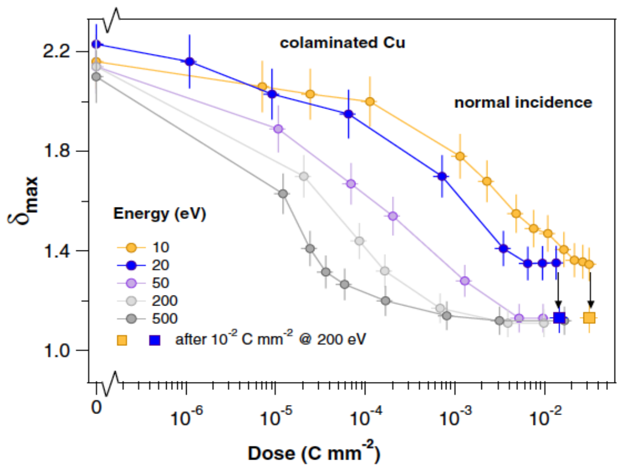


Electron cloud formation

- The SEY can be lowered by electron bombardment (**scrubbing effect**, efficiency depends on the deposited dose) or by radiation bombardment (conditioning effect). Also the PEY decreases by radiation.

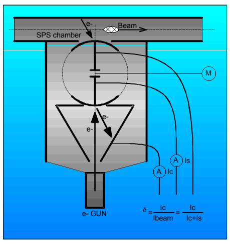
Measured in the lab by bombarding a surface with electrons with different energies

Scrubbing efficiency depends on the electron energy!

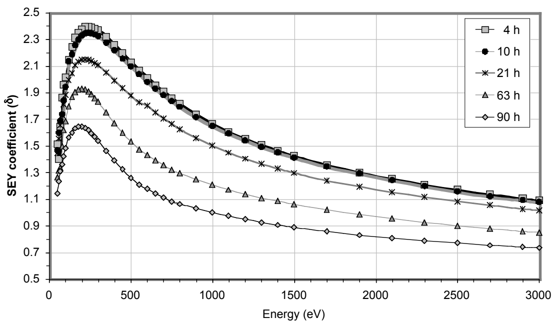


Electron cloud formation

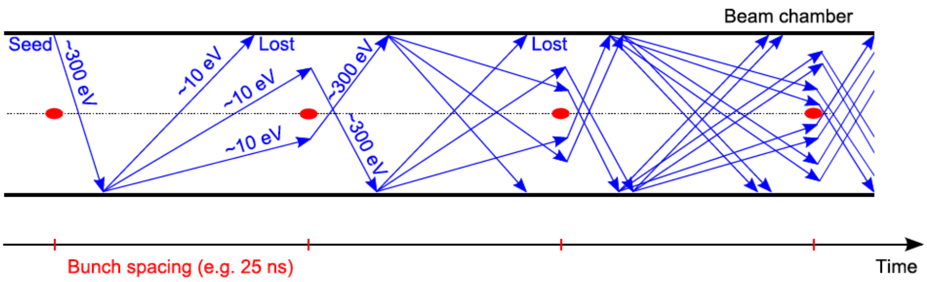
- The SEY can be lowered by electron bombardment (**scrubbing effect**, efficiency depends on the deposited dose) or by radiation bombardment (conditioning effect). Also the PEY decreases by radiation.
- Directly observed also in accelerator: Stainless Steel SEY decreases from above 2 to ~1.6 in the SPS after relatively high electron bombardment. Other materials, like the TiN, rely on conditioning to rapidly get very low maximum SEY (even below 1)



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



Electron cloud formation: Principle of multipacting

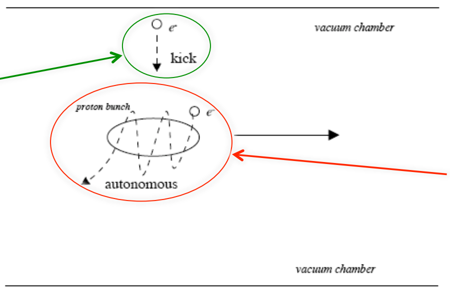


- The circulating beam particles produce "primary or seed electrons", which are attracted by the passing particle bunch and can be accelerated to energies up to several hundreds of eV.
- When an electron with this energy impacts the wall, "secondary electrons" are likely to be emitted.
- Secondaries have energies up to few tens of eV
  - Some impact the wall with these energies and are either absorbed or elastically reflected
  - Some are again accelerated in the next bunch's field and will produce more secondaries

Electron cloud formation: Principle of multipacting

- The picture proposed on the previous slide, though instructive, is simplified, because electrons actually fill the pipe and evolve differently according to their positions when the bunch arrives
- Critical parameters are bunch charge, spacing, chamber radius. While in general higher bunch charges and shorter spacings tend to facilitate multipacting, it is finally the combination of these three numbers to determine how low is the SEY threshold above which multipacting occurs

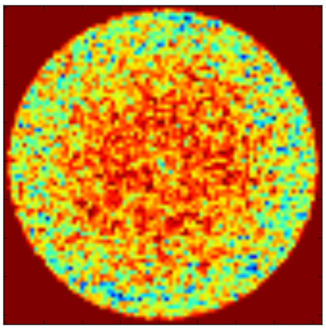
Electrons far enough from the beam are in kick regime, i.e. they just feel a strong electric kick when a bunch passes

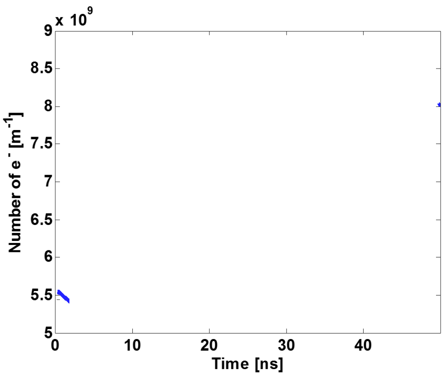


Electrons close to the beam and with low velocities are in autonomous regime, i.e. they oscillate around the bunch. The frequency of this oscillation, as well as the number of oscillations per bunch passage, are two important parameters!

Electron cloud formation: Illustration of multipacting

Beam pipe transverse cut

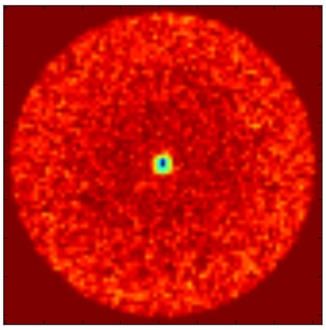


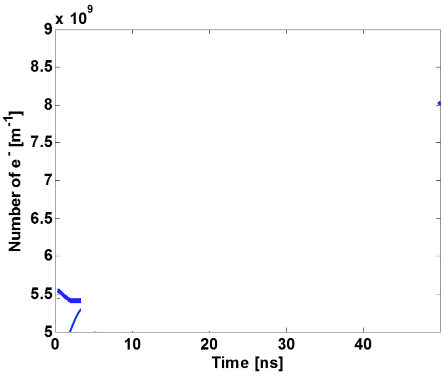


Electron cloud formation: Illustration of multipacting

The CERN Accelerator School

Beam pipe transverse cut



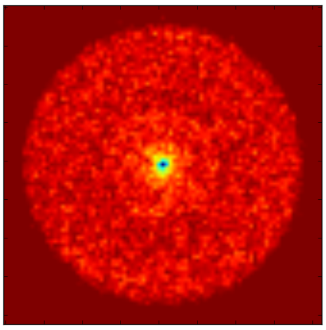


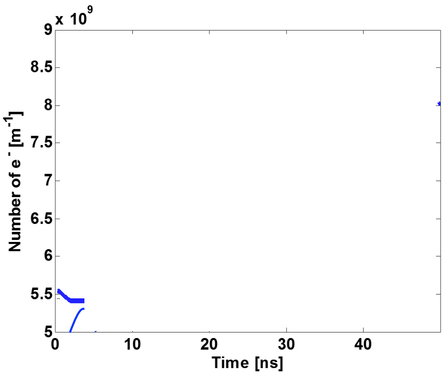
- **During the bunch passage** the electrons are accelerated by the beam **"pinched" at the center of the beam pipe**

Electron cloud formation: Illustration of multipacting

The CERN Accelerator School

Beam pipe transverse cut

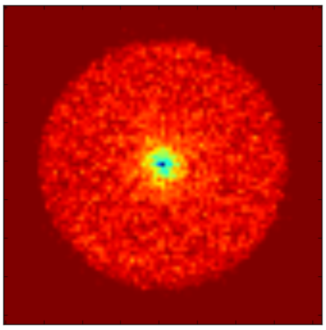


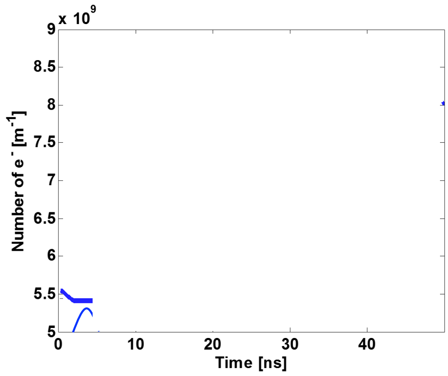


- **During the bunch passage** the electrons are accelerated by the beam **"pinched" at the center of the beam pipe**

Electron cloud formation: Illustration of multipacting

Beam pipe transverse cut

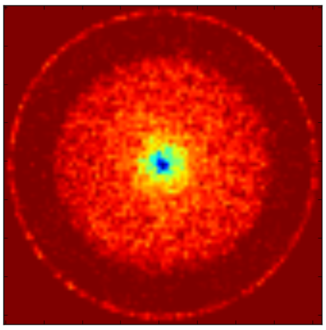


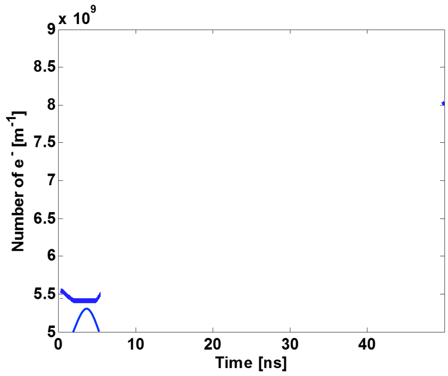


- **During the bunch passage** the electrons are accelerated by the beam **"pinched" at the center of the beam pipe**

Electron cloud formation: Illustration of multipacting

Beam pipe transverse cut

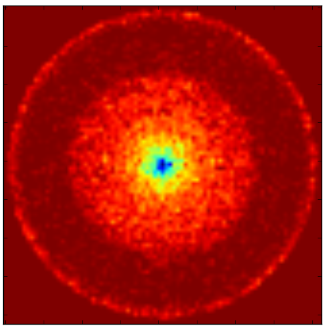


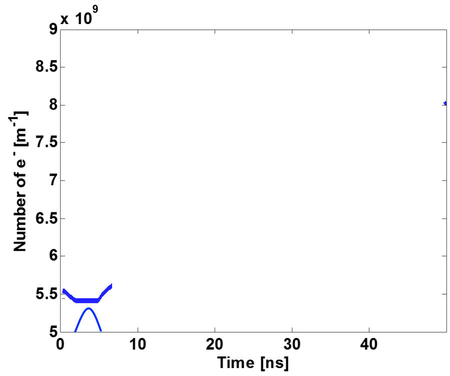


- **During the bunch passage** the electrons are accelerated by the beam **"pinched" at the center of the beam pipe**

Electron cloud formation: Illustration of multipacting

Beam pipe transverse cut

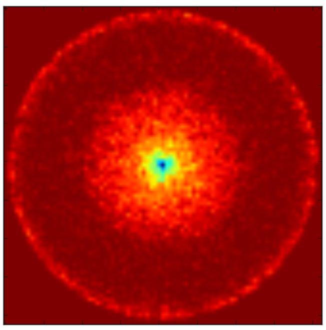


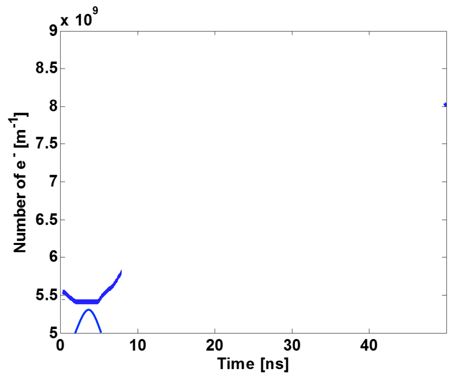


- **After the bunch passage** electrons **hit the wall (with E~100eV)**
- **If Secondary Electron Yield (SEY) of the surface is large enough,** secondary electrons can be generated

Electron cloud formation: Illustration of multipacting

Beam pipe transverse cut

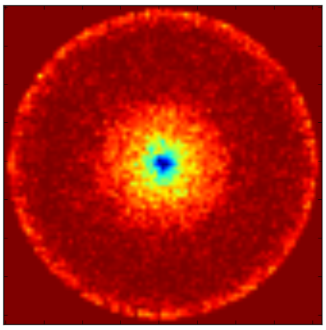


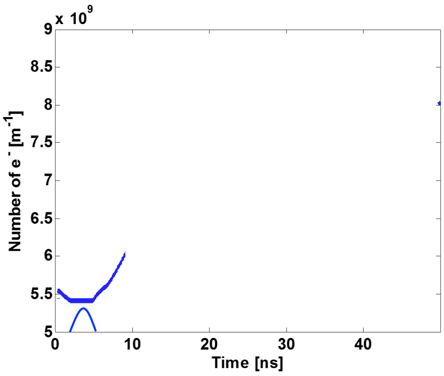


- **After the bunch passage** electrons **hit the wall (with E~100eV)**
- **If Secondary Electron Yield (SEY) of the surface is large enough,** secondary electrons can be generated

Electron cloud formation: Illustration of multipacting

Beam pipe transverse cut

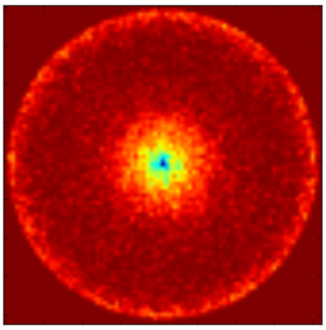


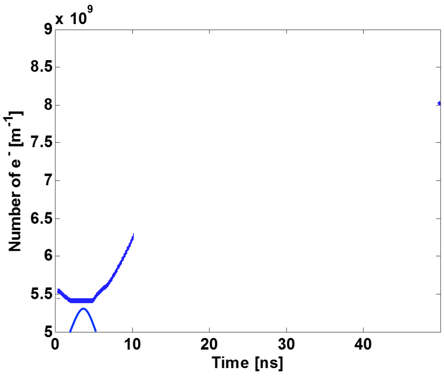


- **After the bunch passage** electrons **hit the wall (with E~100eV)**
- **If Secondary Electron Yield (SEY) of the surface is large enough,** secondary electrons can be generated

Electron cloud formation: Illustration of multipacting

Beam pipe transverse cut

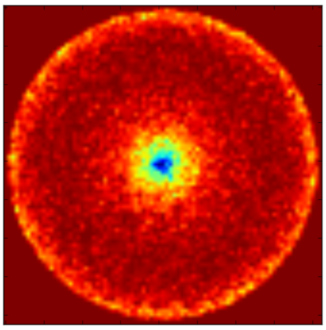


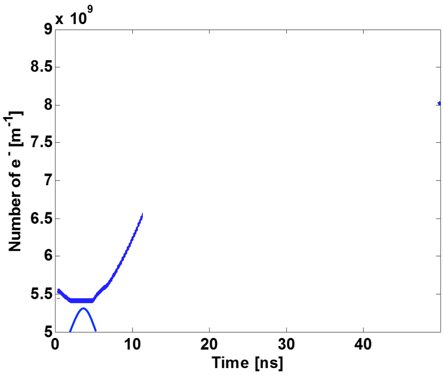


- **After the bunch passage** electrons **hit the wall (with E~100eV)**
- **If Secondary Electron Yield (SEY) of the surface is large enough,** secondary electrons can be generated

Electron cloud formation: Illustration of multipacting

Beam pipe transverse cut

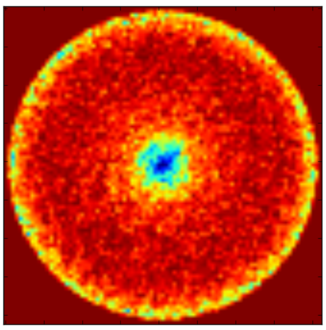


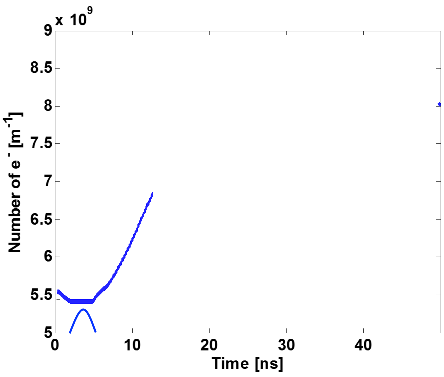


- **After the bunch passage** electrons **hit the wall (with E~100eV)**
- **If Secondary Electron Yield (SEY) of the surface is large enough,** secondary electrons can be generated

Electron cloud formation: Illustration of multipacting

Beam pipe transverse cut



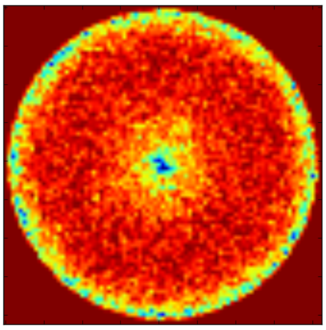


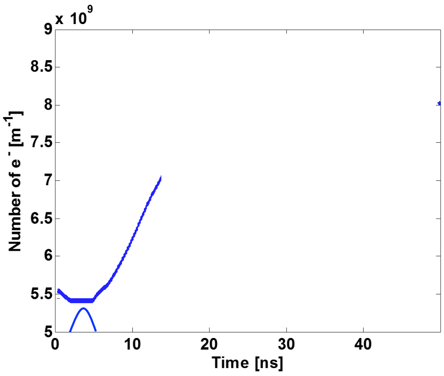
- **After the bunch passage** electrons **hit the wall (with E~100eV)**
- **If Secondary Electron Yield (SEY) of the surface is large enough,** secondary electrons can be generated

Electron cloud formation: Illustration of multipacting

The CERN Accelerator School

Beam pipe transverse cut



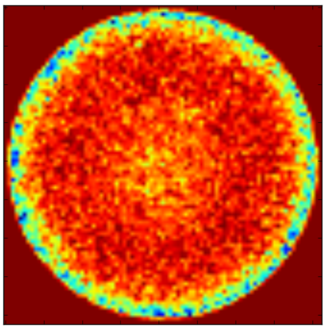


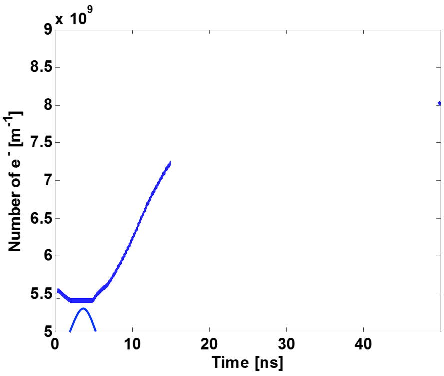
- **After the bunch passage** electrons **hit the wall (with E~100eV)**
- **If Secondary Electron Yield (SEY) of the surface is large enough,** secondary electrons can be generated

Electron cloud formation: Illustration of multipacting

The CERN Accelerator School

Beam pipe transverse cut

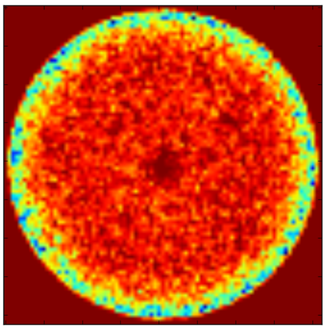


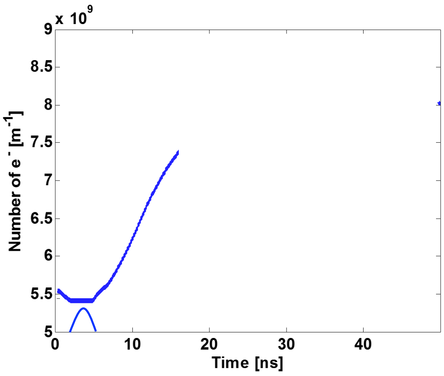


- **After the bunch passage** electrons **hit the wall (with E~100eV)**
- **If Secondary Electron Yield (SEY) of the surface is large enough,** secondary electrons can be generated

Electron cloud formation: Illustration of multipacting

Beam pipe transverse cut

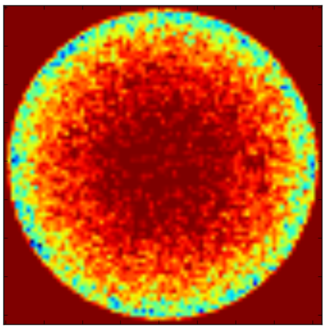


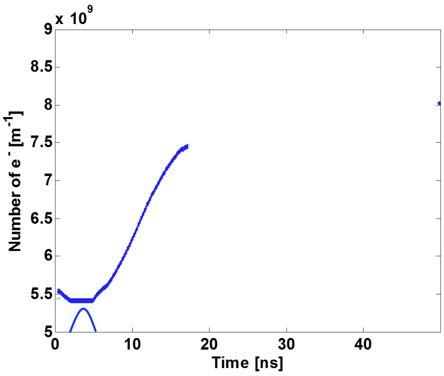


- **After the bunch passage** electrons **hit the wall (with E~100eV)**
- **If Secondary Electron Yield (SEY) of the surface is large enough,** secondary electrons can be generated

Electron cloud formation: Illustration of multipacting

Beam pipe transverse cut



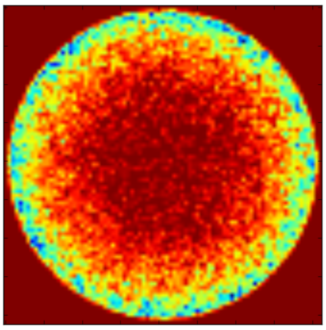


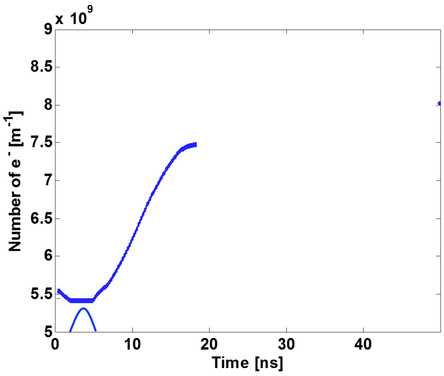
- **After the bunch passage** electrons **hit the wall (with E~100eV)**
- **If Secondary Electron Yield (SEY) of the surface is large enough,** secondary electrons can be generated

Electron cloud formation: Illustration of multipacting

The CERN Accelerator School

Beam pipe transverse cut



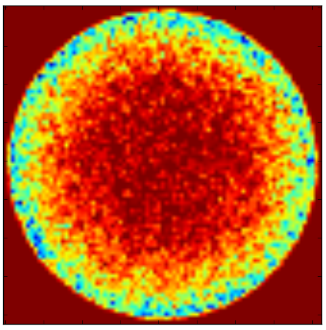


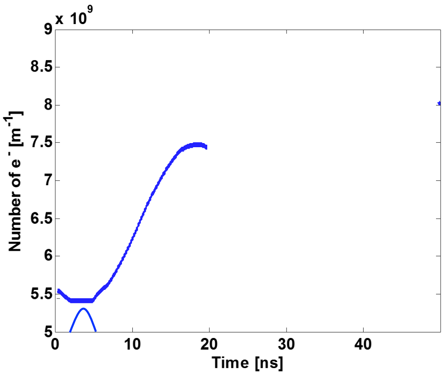
- **After the bunch passage** electrons **hit the wall (with E~100eV)**
- **If Secondary Electron Yield (SEY) of the surface is large enough,** secondary electrons can be generated

Electron cloud formation: Illustration of multipacting

The CERN Accelerator School

Beam pipe transverse cut

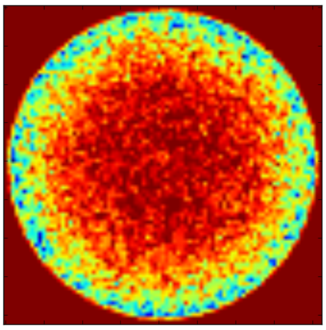


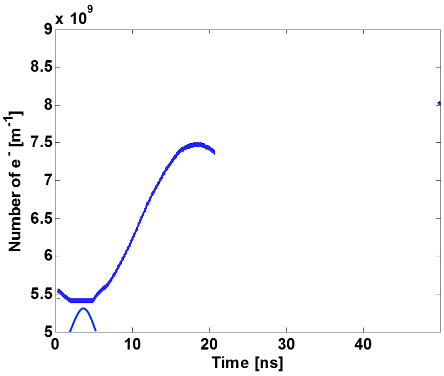


- Secondary electrons, emitted with **low energies (E~1eV)**, **are absorbed** without generation of further secondaries
- **Total number of electrons** begins decaying at this stage

Electron cloud formation: Illustration of multipacting

The CERN Accelerator School

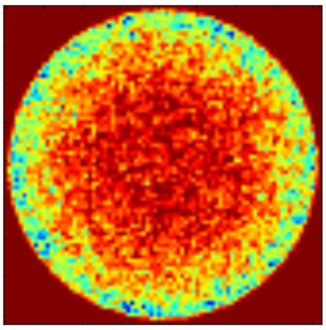


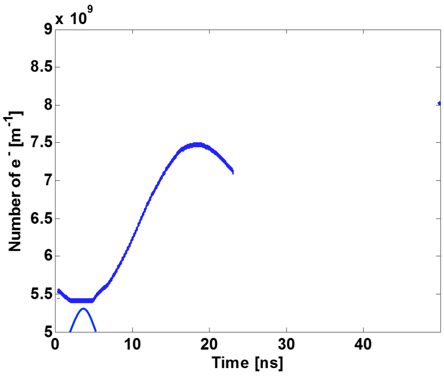


- Secondary electrons, emitted with **low energies (E~1eV)**, **are absorbed** without generation of further secondaries
- **Total number of electrons** begins decaying at this stage

Electron cloud formation: Illustration of multipacting

The CERN Accelerator School

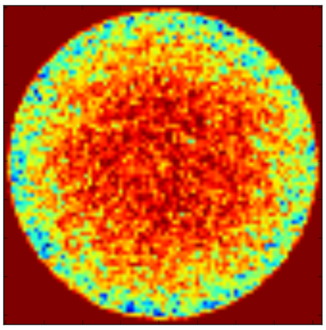


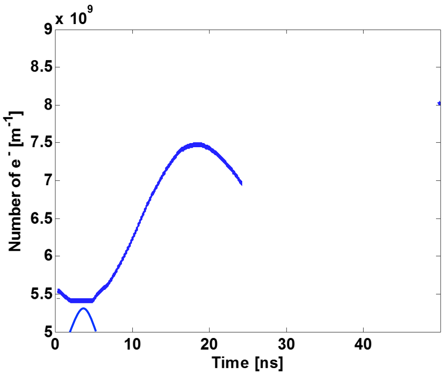


- Secondary electrons, emitted with **low energies (E~1eV)**, **are absorbed** without generation of further secondaries
- **Total number of electrons** begins decaying at this stage

Electron cloud formation: Illustration of multipacting

Beam pipe transverse cut

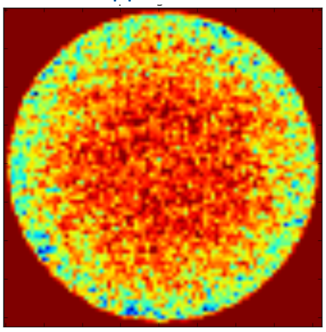


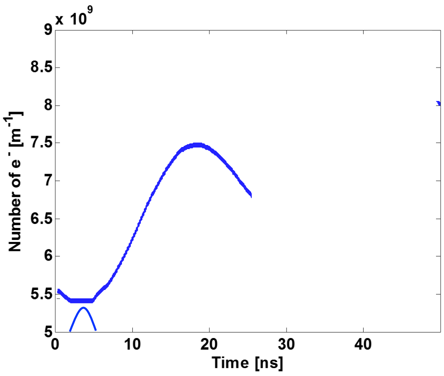


- Secondary electrons, emitted with **low energies (E~1eV)**, **are absorbed** without generation of further secondaries
- **Total number of electrons** begins decaying at this stage

Electron cloud formation: Illustration of multipacting

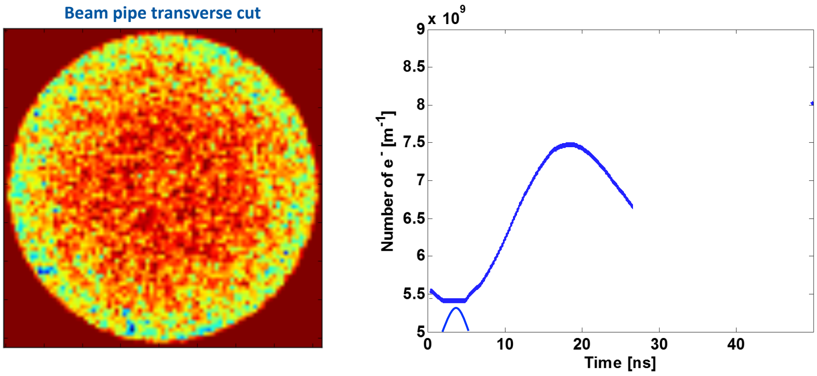
Beam pipe transverse cut





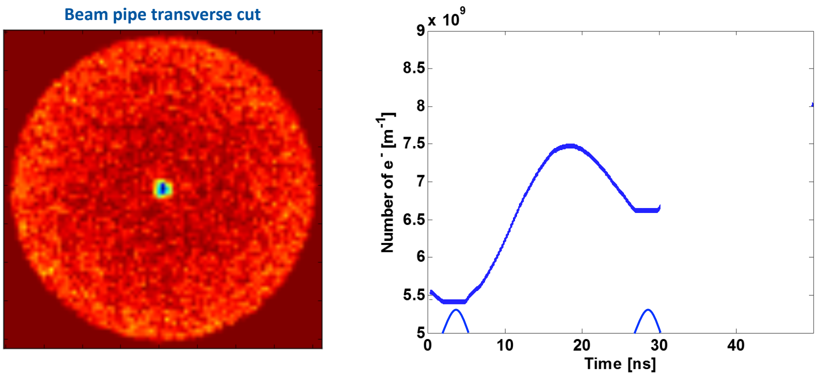
- Secondary electrons, emitted with **low energies (E~1eV)**, **are absorbed** without generation of further secondaries
- **Total number of electrons** begins decaying at this stage

Electron cloud formation: Illustration of multipacting



- Secondary electrons, emitted with **low energies (E~1eV)**, **are absorbed** without generation of further secondaries
- **Total number of electrons** begins decaying at this stage

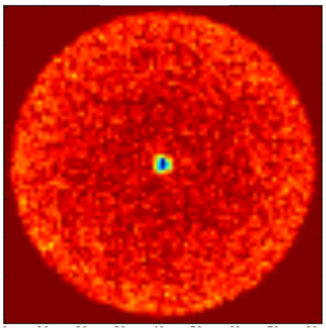
Electron cloud formation: Illustration of multipacting

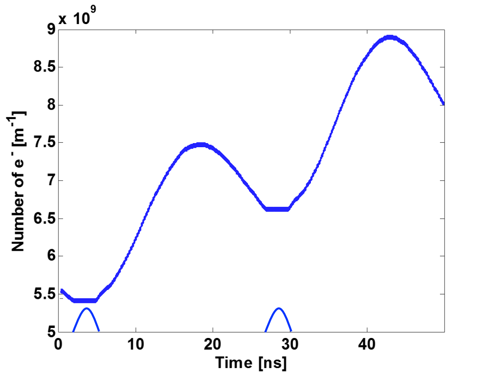


- **Another bunch passage can interrupt the decay** before reaching the initial value
- This could lead to **exponential growth** of the number of electrons

Electron cloud formation: Illustration of multipacting

Beam pipe transverse cut

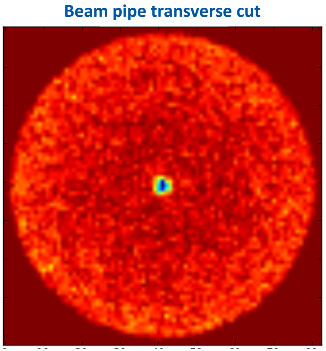


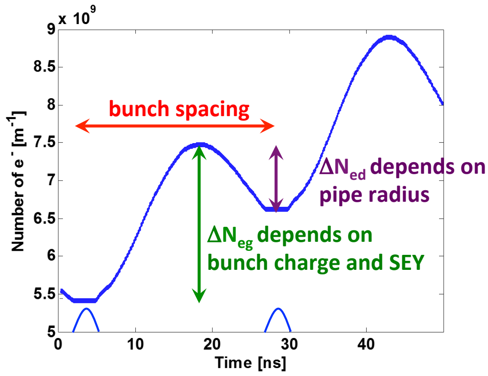


- **Another bunch passage can interrupt the decay** before reaching the initial value
- This could lead to **exponential growth** of the number of electrons

Electron cloud formation: Illustration of multipacting

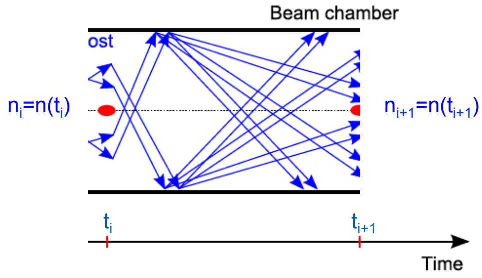
Beam pipe transverse cut





Electron cloud effect is strongly dependent on bunch spacing, bunch charge and pipe radius!

Electron cloud formation: A model for the multipacting process



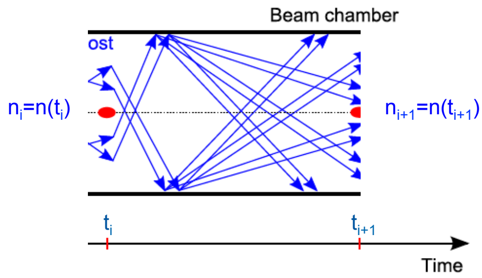
$$n_{i+1} = n_i + \int_0^{\infty} \int_{t_i}^{t_{i+1}} \Phi(E,t)\,(\delta(E)-1)\,dt\,dE + n_0$$

Energy spectrum of the electrons impacting the wall at time t

SEY of the chamber inner surface

Number of primary electrons generated by the bunch passage

Electron cloud formation: A model for the multipacting process



Defining a normalized integrated spectrum over the bunch spacing

$$\phi_i(E) = \frac{1}{n_i} \int_{t_i}^{t_{i+1}} \Phi(E,t)dt$$

$$n_{i+1} = n_i \underbrace{\left(1 + \int_0^{\infty} \phi_i(E)\,(\delta(E)-1)\,dE\right)}_{\delta_{\mathrm{eff},\,i}} + n_0$$

Electron cloud formation: A model for the multipacting process

As long as the interaction between electrons stays negligible, the normalized integrated spectrum does not depend on the bunch index

$$\phi_i(E) = \phi(E) \quad \Rightarrow \quad \delta_{\mathrm{eff},i} = \delta_{\mathrm{eff}}$$

$$n_i = n_0 \sum_{k=0}^{i} \delta_{\mathrm{eff}}^k$$

$$n_i = n_0 \frac{1-\delta_{\mathrm{eff}}^{i+1}}{1-\delta_{\mathrm{eff}}}$$

$\delta_{\mathrm{eff}} < 1$:

$$n_i \approx \frac{1}{1-\delta_{\mathrm{eff}}}$$

No exponential growth, only equilibrium between seed generation and loss to the walls

$\delta_{\mathrm{eff}} > 1$:

$$n_i \approx \frac{\delta_{\mathrm{eff}}^{i+1}}{\delta_{\mathrm{eff}}-1}$$

Exponential growth!

Electron cloud formation: A model for the multipacting process

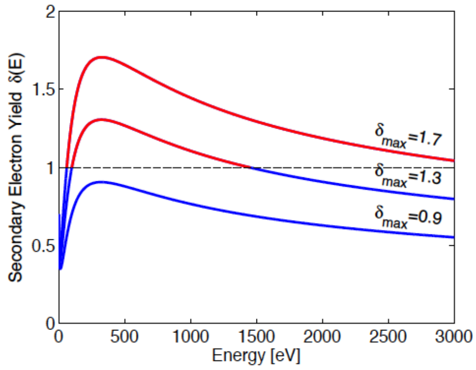
Let's have a closer look to δ_{eff}

$$\delta_{\mathrm{eff}} = 1 + \int_0^{\infty} \phi(E)\,[\delta(E)-1]\,dE$$

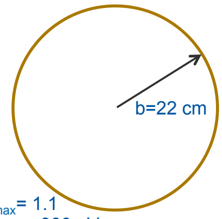
Whether δ_{eff} is below or above unity depends on whether the energy spectrum ϕ(E) overlaps more with the **absorber region** of the SEY curve (δ(E)<1) or the **emitter region** (δ(E)>1)

Absorber region is for low energies and possibly above a certain energy value, depending on E_{max} and δ_{max}

If δ_{max}<1, there is obviously no emitter region

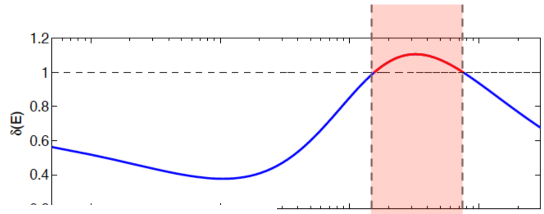


Electron cloud formation: Application of the model (1)

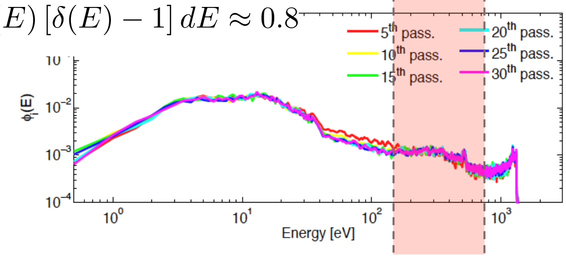


δ_{max}= 1.1
E_{max} = 300 eV
R_0 = 0.6

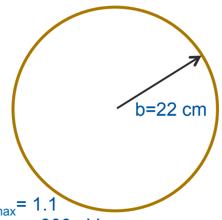
25 ns beam with 10^{11} p/b generates electrons due to gas ionization
The energy spectrum $\phi(E)$ is computed bunch by bunch through a simulation and is shown here below together with $\delta(E)$



$$\delta_{\rm eff} = 1 + \int_0^\infty \phi(E)\,[\delta(E) - 1]\,dE \approx 0.8$$

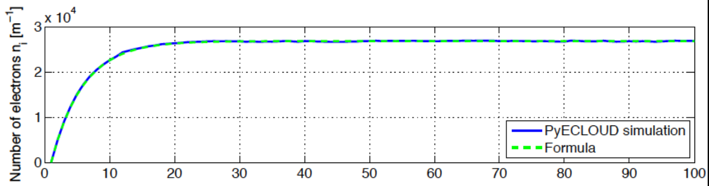


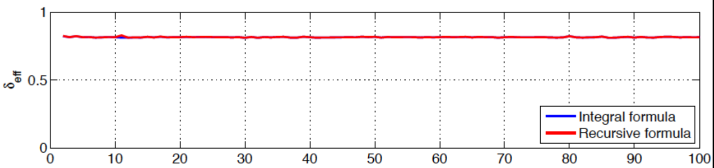
Electron cloud formation: Application of the model (1)



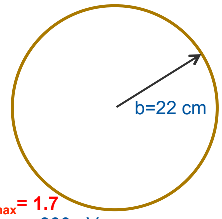
δ_{max}= 1.1
E_{max} = 300 eV
R_0 = 0.6

$$n_i = n_0 \frac{1 - \delta_{\rm eff}^{i+1}}{1 - \delta_{\rm eff}} \rightarrow 5 \cdot n_0 \ \ \text{when} \ \ i \geq 20$$



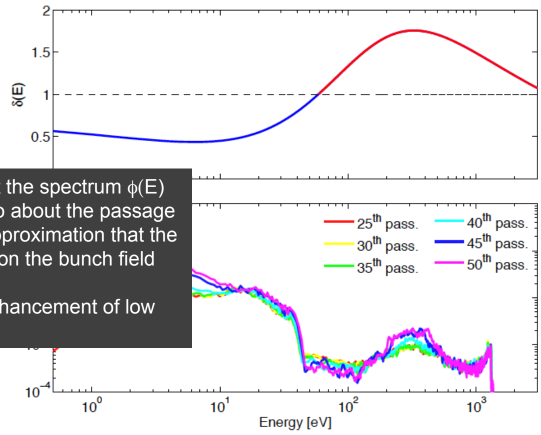


Electron cloud formation: Application of the model (2)



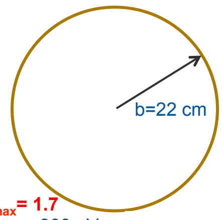
δ_{max}= 1.7
E_{max} = 300 eV
R_0 = 0.6

25 ns beam with 10^{11} p/b generates electrons due to gas ionization
The energy spectrum $\phi(E)$ is computed bunch by bunch through a simulation and is shown here below together with $\delta(E)$



First of all, it is clear that the spectrum $\phi(E)$ stays constant only up to about the passage of the 35th bunch (the approximation that the spectrum only depends on the bunch field does not hold anymore)
After that, there is an enhancement of low energy electrons.

Electron cloud formation: Application of the model (2)

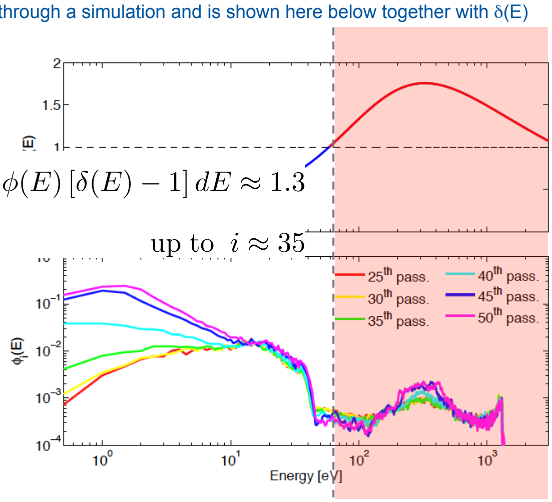


δ_{max}= 1.7
E_{max} = 300 eV
R_0 = 0.6

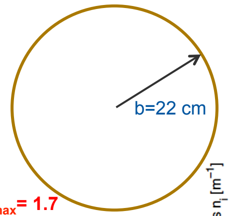
25 ns beam with 10^{11} p/b generates electrons due to gas ionization
The normalized integrated energy spectrum $\phi(E)$ is computed through a simulation and is shown here below together with $\delta(E)$

$$\delta_{\rm eff} = 1 + \int_0^\infty \phi(E)\,[\delta(E) - 1]\,dE \approx 1.3$$

up to $i \approx 35$

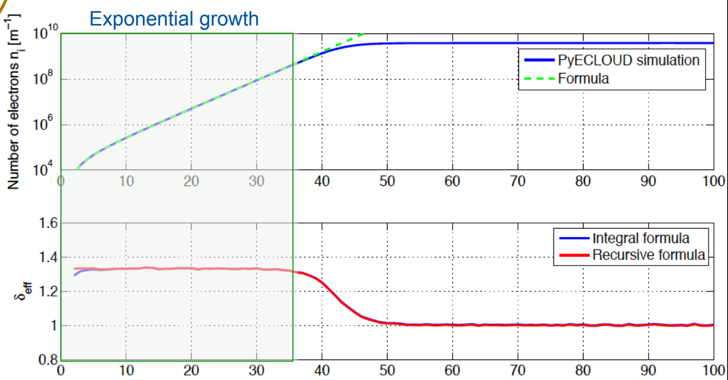


Electron cloud formation: Application of the model (1)

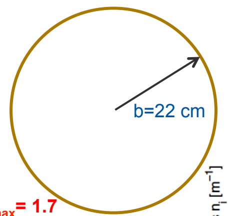


δ_{max}= 1.7
E_{max} = 300 eV
R_0 = 0.6

$$n_i \approx \frac{\delta_{\text{eff}}^{i+1}}{\delta_{\text{eff}} - 1} \quad \text{when} \quad i < 35$$

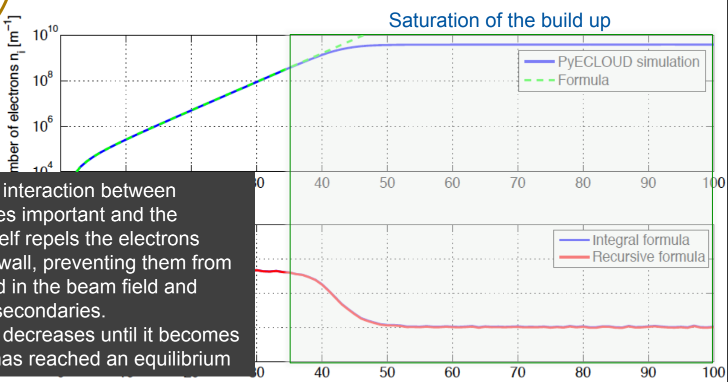


Electron cloud formation: Application of the model (2)



δ_{max}= 1.7
E_{max} = 300 eV
R_0 = 0.6

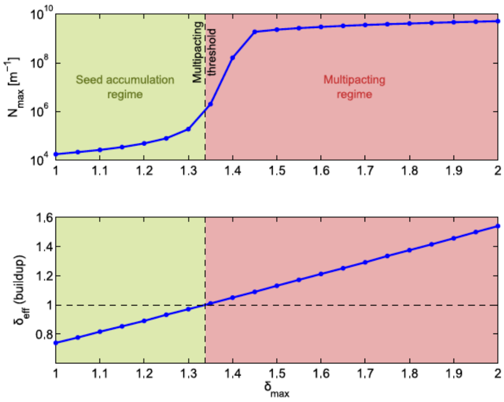
$$n_i \approx \frac{\delta_{\text{eff}}^{i+1}}{\delta_{\text{eff}} - 1} \quad \text{when} \quad i < 35$$



In saturation, the interaction between electrons becomes important and the electron cloud itself repels the electrons coming from the wall, preventing them from being accelerated in the beam field and producing more secondaries.
In this phase, δ_{eff} decreases until it becomes 1 and the cloud has reached an equilibrium

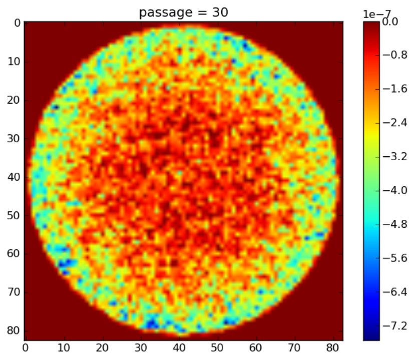
The multipacting threshold

- The equilibrium electron densities found in the two cases differ by many orders of magnitude (10^4 e/m without multipacting and 10^9 e/m with multipacting)
- Between these two cases we do not expect a smooth variation
  - Abrupt transition between the two regimes (determined by δ_{eff}=1): **multipacting threshold**
  - The electron density depends on the number of seeds and on δ_{max} when there is no multipacting, while it will hardly depend on either with strong multipacting



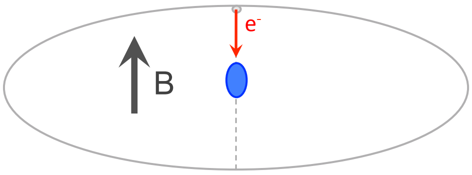
The electron distribution

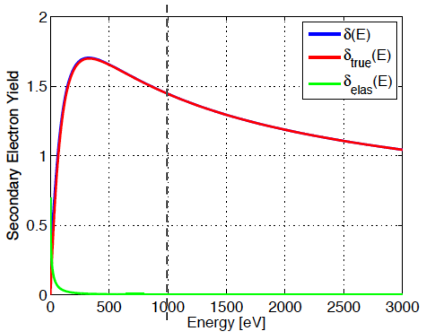
→ The electrons exhibit different transverse (x,y) distributions, according to the type of region in which the electron cloud is formed
  → In field free regions, the electrons tend to spread uniformly across the pipe section (rigorously true only in circular chambers)



The electron distribution

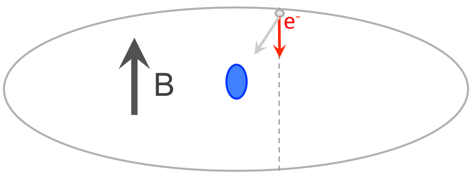
- The electrons exhibit different transverse (x,y) distributions, according to the type of region in which the electron cloud is formed
  - In dipole regions, the electron motion is confined along the lines of the magnetic field, and the cloud develops along one central or two side stripes, depending on the beam current and the position of E_{max} in the curve of the SEY.

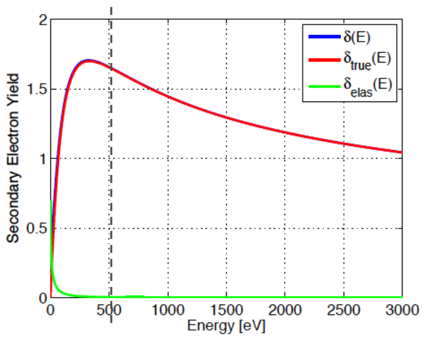




The electron distribution

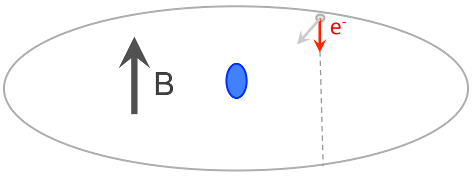
- The electrons exhibit different transverse (x,y) distributions, according to the type of region in which the electron cloud is formed
  - In dipole regions, the electron motion is confined along the lines of the magnetic field, and the cloud develops along one central or two side stripes, depending on the beam current and the position of E_{max} in the curve of the SEY.

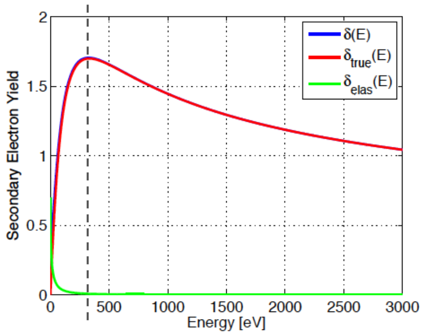




The electron distribution

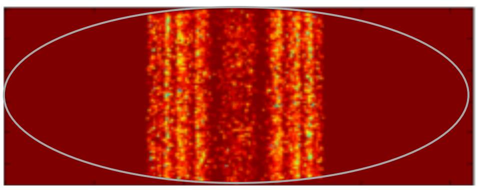
- The electrons exhibit different transverse (x,y) distributions, according to the type of region in which the electron cloud is formed
  - In dipole regions, the electron motion is confined along the lines of the magnetic field, and the cloud develops along one central or two side stripes, depending on the beam current and the position of E_{max} in the curve of the SEY.

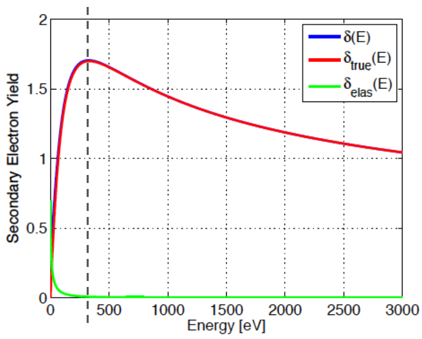




The electron distribution

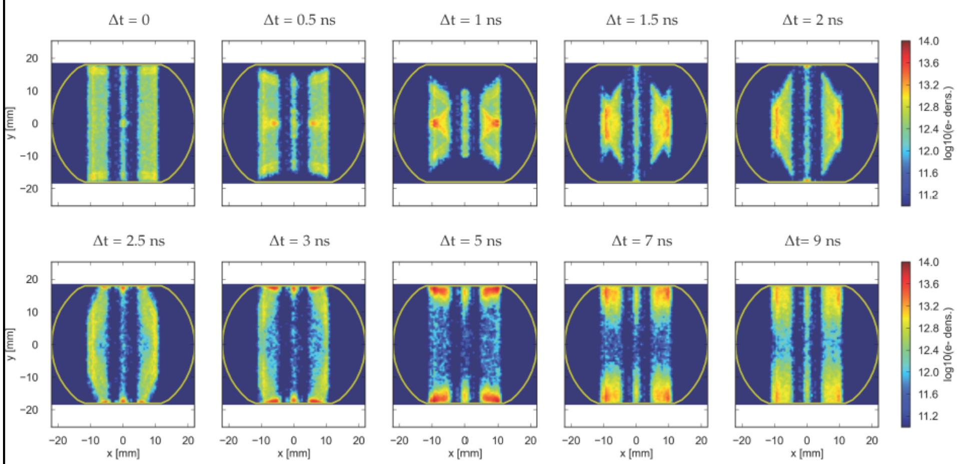
- The electrons exhibit different transverse (x,y) distributions, according to the type of region in which the electron cloud is formed
  - In dipole regions, the electron motion is confined along the lines of the magnetic field, and the cloud develops along one central or two side stripes, depending on the beam current and the position of E_{max} in the curve of the SEY.



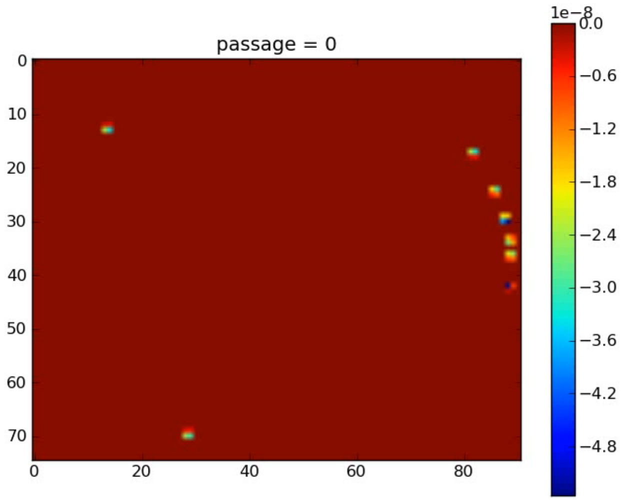


The electron distribution

- The electrons exhibit different transverse (x,y) distributions, according to the type of region in which the electron cloud is formed
  - In dipole regions, the electron motion is confined along the lines of the magnetic field. Example: snaposhots of multipacting in the dipole of an LHC arc cell during bunch passage and including secondary production.



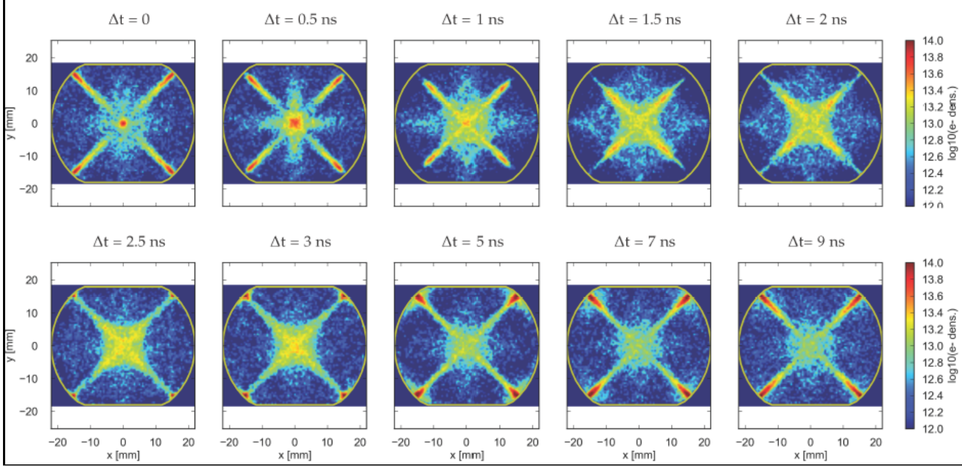
The electron distribution



The electron distribution

The CERN Accelerator School

- The electrons exhibit different transverse (x,y) distributions, according to the type of region in which the electron cloud is formed
  - In quadrupole regions, the electrons tend to multipact along the pole-to-pole lines of the cross section (example: snapshots of multipacting in an LHC arc quadrupole). Multipacting thresholds are usually lower in quadrupoles because electrons survive long thanks to trapping due to the magnetic gradient.



Effects of the electron cloud

The CERN Accelerator School

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

↓

After the passage of several bunches, the electron distribution inside the chamber reaches a stationary state (electron cloud) → Several effects associated

Effects of the electron cloud

The presence of an electron 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

} Machine observables

- ❑ Tune shift
  - Coherent along the train
  - Incoherent within the bunch
- ❑ Coherent instability
  - Single bunch effect affecting the last bunches of a train
  - Coupled bunch effect
- ❑ Beam size blow-up and emittance growth
- ❑ Luminosity loss in colliders
- ❑ Energy loss measured through the synchronous phase shift

} Beam observables

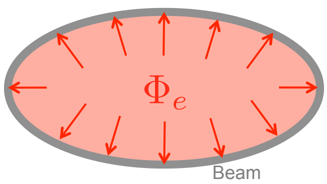
- ❑ Active monitoring: signal on dedicated electron detectors (e.g. strip monitors) and retarding field analysers

Machine observables

→ **Electrons hitting the chamber wall with 'stationary' energy spectrum Φ** (defined by δ_{eff}=1) are revealed through

1) **Dynamic pressure rise**

$$\frac{dn_{\mathrm{mol}}}{dt} = \frac{n}{T_{\mathrm{spac}}} \int_0^{\infty} \eta_e(E)\phi(E)dE$$



Beam chamber

Outgassing rate: produced gas molecules per unit time and unit length

Bunch spacing

Desorption yield for electrons of the inner wall surface (should be different for different gas species)

n represents the number of electrons present in the chamber at the arrival of bunch i at saturation
The term dn_{mol}/dt is a term of production in the vacuum equations and determines the pressure rise

Machine observables

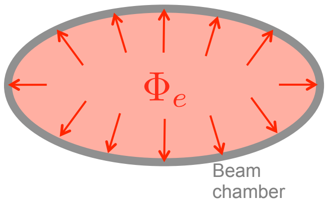
→ **Electrons hitting the chamber wall with 'stationary' energy spectrum Φ** (defined by $\delta_{eff}=1$) are revealed through

2) **Heat load**

$$\Delta W = \frac{n}{T_{\mathrm{spac}}} \int_0^{\infty} \phi(E) E dE$$

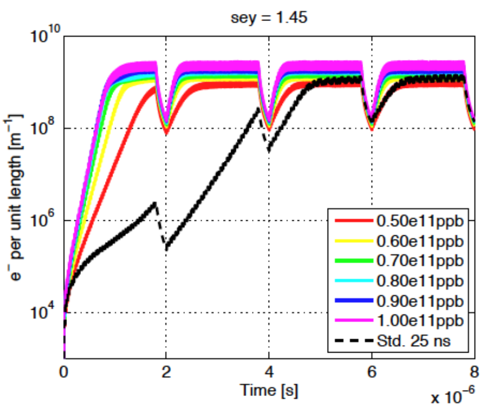
Power deposited on the inner wall per unit length

Bunch spacing



The power deposited on the wall can be quantified
- Locally, through temperature rise or reaction from cooling system (significant for cryogenic devices)
- Globally, through the stable phase shift, as the power lost by the beam has to be compensated by the RF system

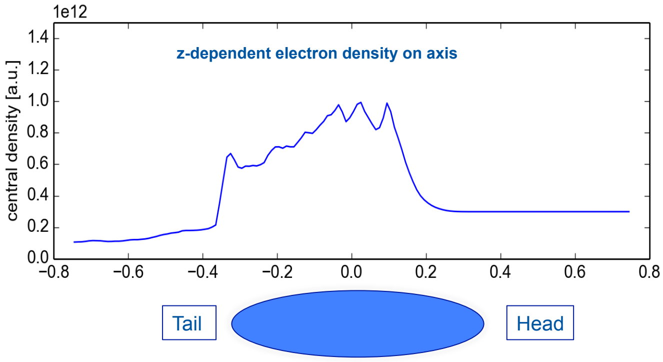
Beam effects along the train



→ Since the build up happens along the bunch train, the electron cloud becomes visible only from a certain bunch number, i.e. it affects bunches at the tail of the train

→ Examples
- Coherent tune shift due to the extra-focusing effect of the electron cloud (positive detuning)
- Stable phase shift along the train, as the energy lost by a bunch depends on the density of the electron cloud it interacts with.

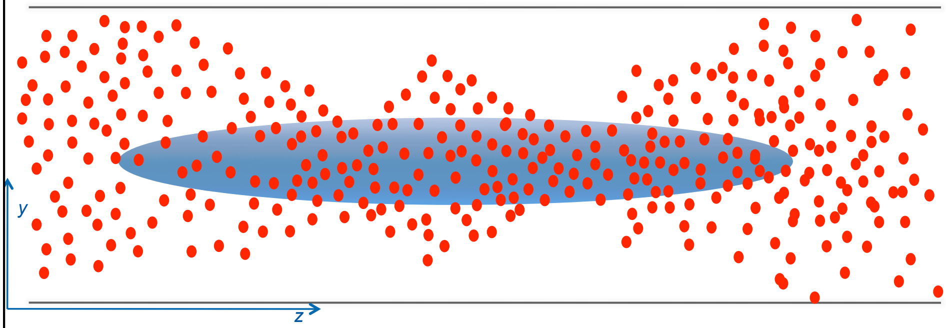
The electron pinch: intra-bunch effects



→ When the bunch arrives the electrons are drawn in and perform a fraction, one or more nonlinear oscillations according to their initial amplitudes (electron pinch)

→ This process results into an increasing electron density seen by particles along the passing bunch (mainly due to the electrons close to the beam → central density is important)
  - Can create head-tail coupling
  - Can create a z-dependent tune spread along the bunch (tune footprint of the electron cloud).

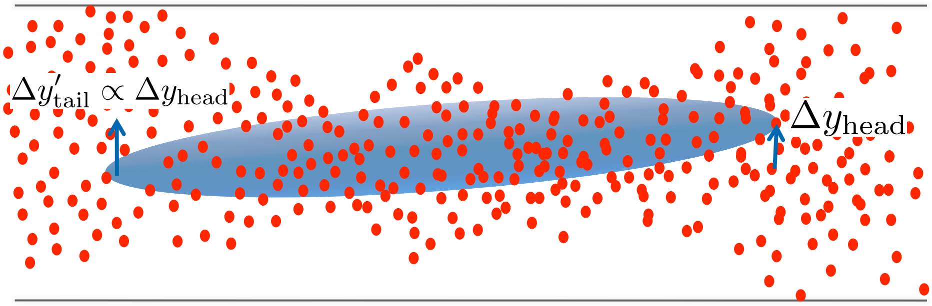
Single bunch electron cloud instability



- A beam going through an electron cloud focuses the electrons (pinch), so that the central density of electrons changes along the bunch
- Since electrons are drawn toward the bunch local centroid, this is the mechanism that can couple head and tail of a bunch

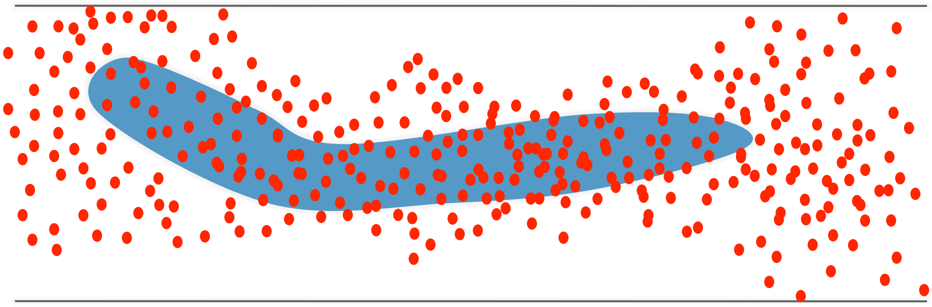
→ **While the bunch is perfectly centered on the pipe axis, the pinch also happens symmetrically and no coherent kick is generated along the bunch**

Single bunch electron cloud instability



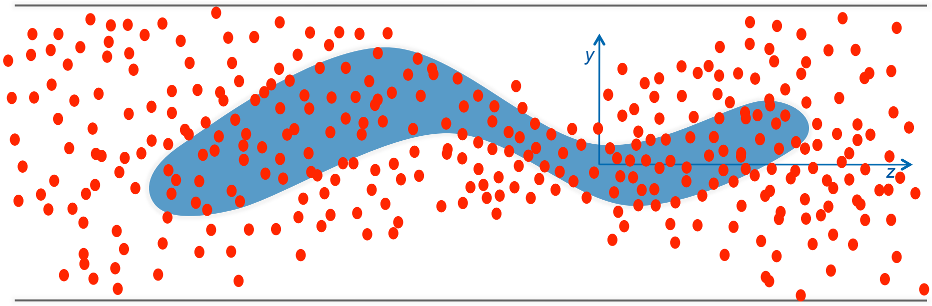
→ **If the head of the bunch is slightly displaced by an amount Δy_{head} , an asymmetric pinch will take place, resulting into a net kick felt by the bunch tail $\Delta y'_{tail}$**

Single bunch electron cloud instability



→ **After several turns (passages through the electron cloud), the "perturbation" in the head motion transfers to the bunch tail, and its amplitude may grow under some conditions**

Single bunch electron cloud instability



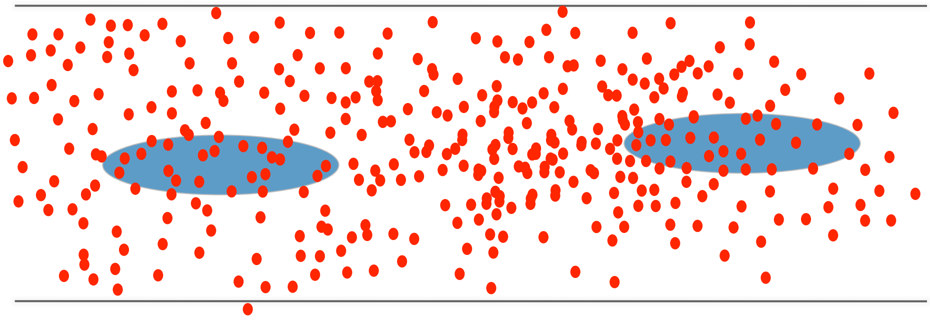
→ **After a number of turns much larger than the synchrotron period, the unstable coherent motion has propagated to the whole bunch**

Intra-bunch motion

Emittance blow up

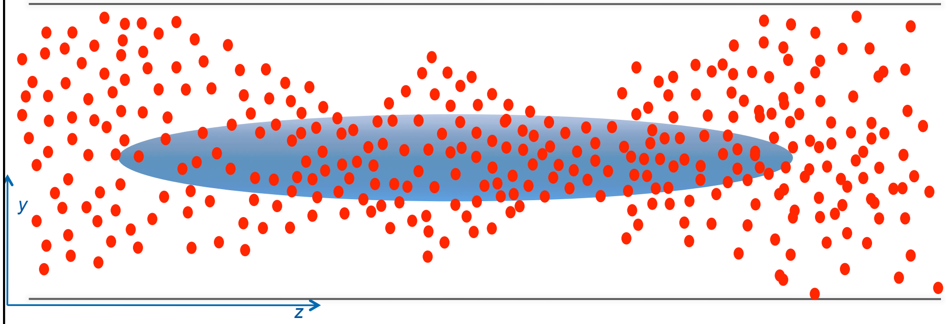
Examples will be shown in K. Li's lecture

Coupled bunch electron cloud instability



- → **A similar mechanism can also be responsible for bunch-to-bunch coupling, but it is more complicated because it involves electron motion between bunches (with secondary emission)**
- → **Dipoles, through the presence of the stripes, may facilitate this mechanism in the horizontal plane**

Electron cloud incoherent effects



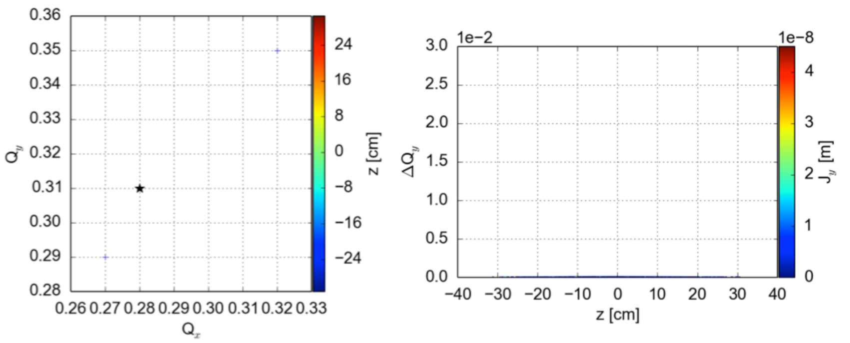
- Even when the electron density is not sufficient to drive a head-tail or bunch-to-bunch instability, the electron pinch is the origin of a z-dependent tune spread along the bunch
- Particles at the bunch head see the tune shift associated to the unpinched electron cloud, particles at the z locations where the electrons are pinched see the largest tune deviation (at least for a short enough bunch …)

→ **Gives rise potentially to incoherent effects (slow loss, emittance growth)**

Tune footprint from electron cloud in dipoles Example: LHC @450 GeV

- LHC nominal intensity 1.15e11 ppb
- Uniform initial distribution of the e-cloud
- The EC density is scanned between 0 and 10e11 e-/m^3

No ecloud, Q'= 0/0, octupole current @ 0 A

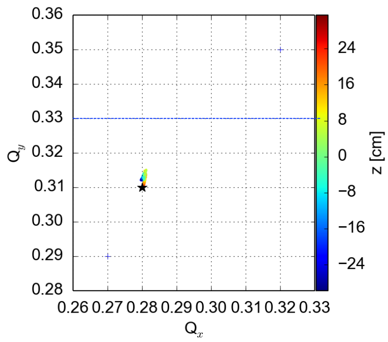


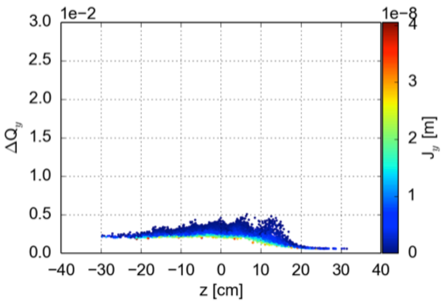
Tune footprint from electron cloud in dipoles
Example: LHC @450 GeV

The CERN Accelerator School

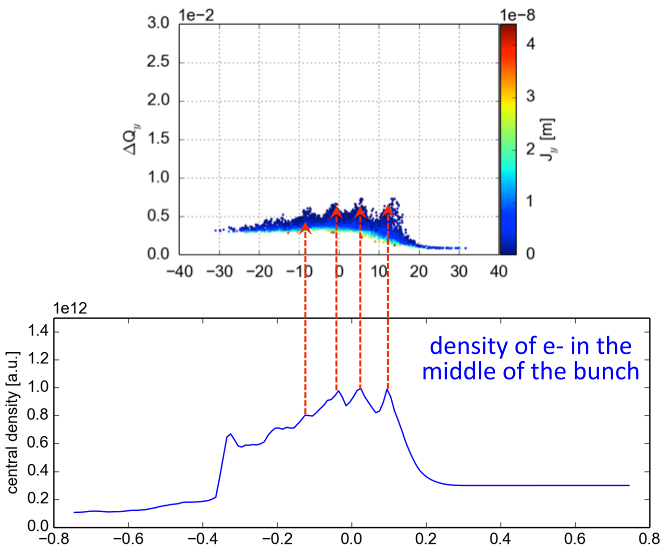
- LHC nominal intensity 1.15e11 ppb
- Uniform initial distribution of the e-cloud
- The EC density is scanned between 0 and 10e11 e-/m^3

2e11 e-/m^3, Q'= 0/0, octupole current @ 0 A





The CERN Accelerator School

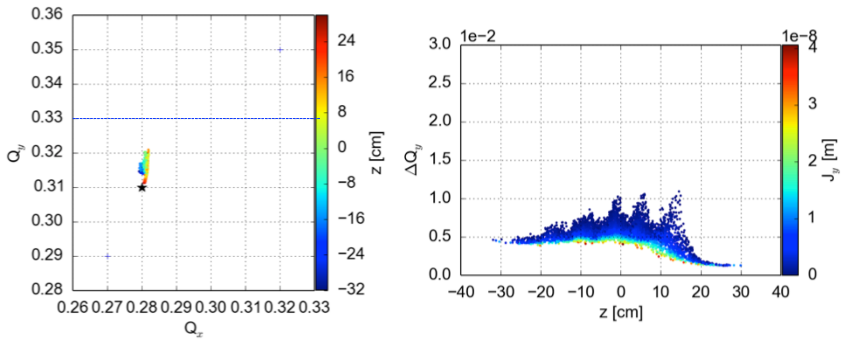


Every peak of e- density has an higher detuning of particles with smaller Jy

Tune footprint from electron cloud in dipoles Example: LHC @450 GeV

- LHC nominal intensity 1.15e11 ppb
- Uniform initial distribution of the e-cloud
- The EC density is scanned between 0 and 10e11 e-/m^3

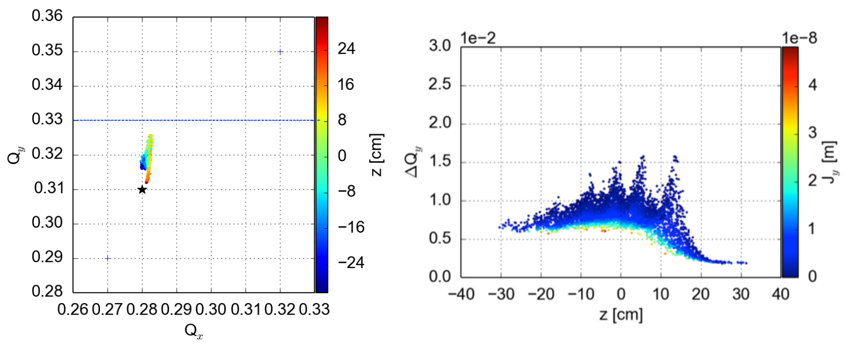
4e11 e-/m^3, Q'= 0/0, octupole current @ 0 A



Tune footprint from electron cloud in dipoles Example: LHC @450 GeV

- LHC nominal intensity 1.15e11 ppb
- Uniform initial distribution of the e-cloud
- The EC density is scanned between 0 and 10e11 e-/m^3

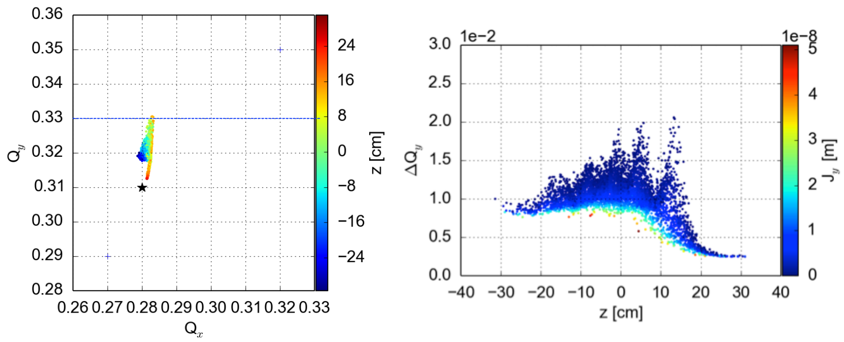
6e11 e-/m^3, Q'= 0/0, octupole current @ 0 A



Tune footprint from electron cloud in dipoles Example: LHC @450 GeV

- LHC nominal intensity 1.15e11 ppb
- Uniform initial distribution of the e-cloud
- The EC density is scanned between 0 and 10e11 e-/m^3

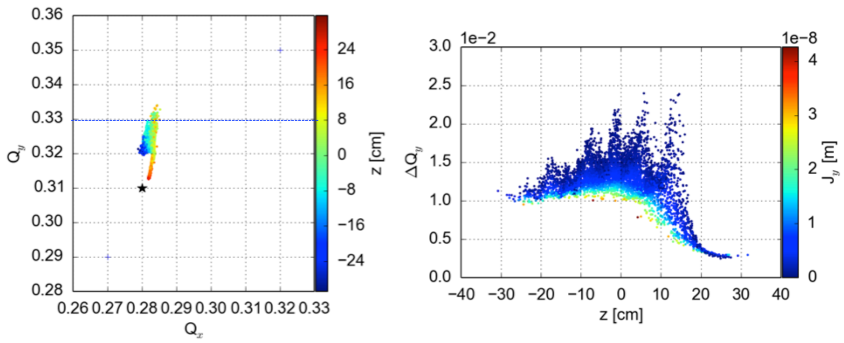
8e11 e-/m^3, Q'= 0/0, octupole current @ 0 A



Tune footprint from electron cloud in dipoles Example: LHC @450 GeV

- LHC nominal intensity 1.15e11 ppb
- Uniform initial distribution of the e-cloud
- The EC density is scanned between 0 and 10e11 e-/m^3

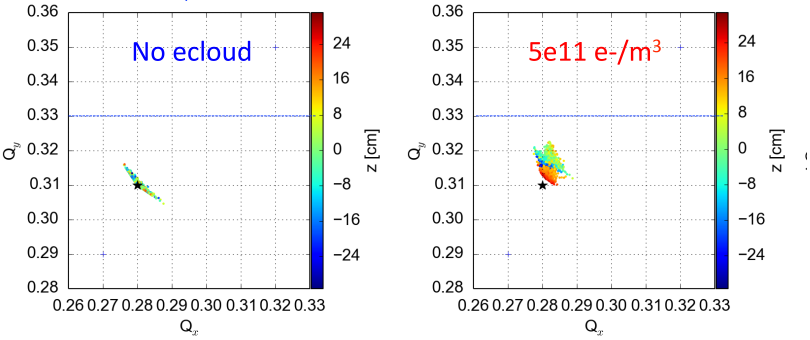
10e11 e-/m^3, Q'= 0/0, octupole current @ 0 A



Tune footprint from electron cloud in dipoles
Example: LHC @450 GeV

- LHC nominal intensity 1.15e11 ppb
- Uniform initial distribution of the e-cloud
- The octupole is turned on

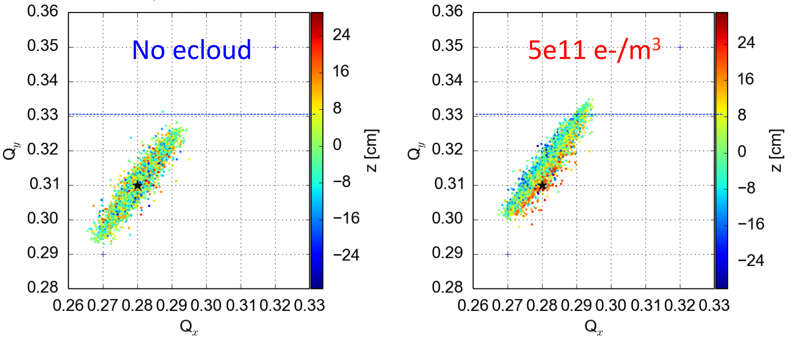
$Q_{H,V}'$= 0/0, octupole current @ 20 A



Tune footprint from electron cloud in dipoles
Example: LHC @450 GeV

- LHC nominal intensity 1.15e11 ppb
- Uniform initial distribution of the e-cloud
- The chromaticity is set to 15/20

$Q_{H,V}'$= 15/20, octupole current @ 20 A



Machine observations (historical)

- Novosibirsk proton storage ring (1967)
  Unusual transverse instabilities occurred for bunched and unbunched beams. Model of coupled electron/beam centroid oscillation.
- CERN ISR (1970s)
  Coasting beam instability and fast pressure rise for bunched proton beam.
- Los Alamos PSR (1988)
  Fast instability with beam loss above a threshold current (for bunched and unbunched beams)
- KEK PF (1989)
  Multibunch instability for positron bunch trains.

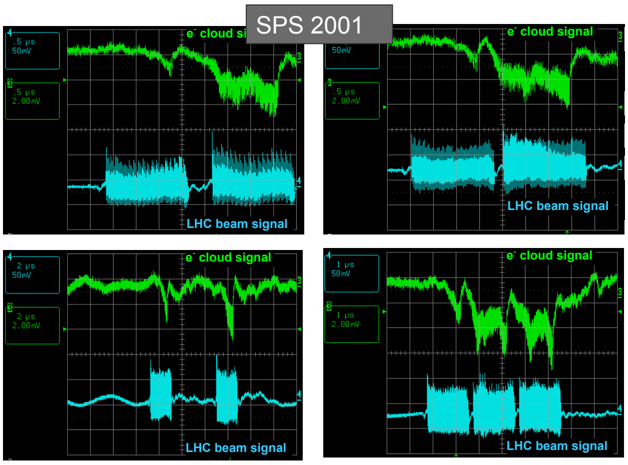
Machine observations (historical)

- CERN 1997
  Crash program is launched to study electron clouds because it is suspected that they may endanger LHC operation
- SPS and PS (since 1999)
  Evidence for electron cloud with LHC type beams (pressure rise, signals at the PUs, instability)
- KEKB and PEP-II (1999)
  E-cloud induced tune shifts along bunch train and instabilities.
- RHIC (2002)
  Pressure rise, tune shift, still unexplained instabilities (at transition). Electron detectors installed.

Machine observations (historical)

- **Tevatron, SNS, DaΦne (2003-2008)**
  Several signatures of electron cloud, like pressure rise or beam instabilities, are noticed in high intensity operation. Even ANKA suspects electron cloud to justify vacuum degradation and heating in the superconducting wiggler.
- **Cesr-TA (2008 → 2014)**
  A program to study specifically electron cloud issues is launched. Thanks to its tunability, the ring is used with positrons to study e-cloud and benchmark simulation codes.
- **LHC (2010-2015 → …)**
  Electron cloud appeared first as pressure rise in some common chambers with 150 ns beams. Then also as heat load in cold sectors and beam degradation with 75 and 50 ns (improved by scrubbing). It still dominates beam dynamics with 25 ns beams!

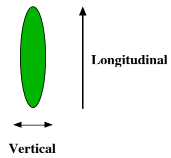
Examples of machine observations: SPS



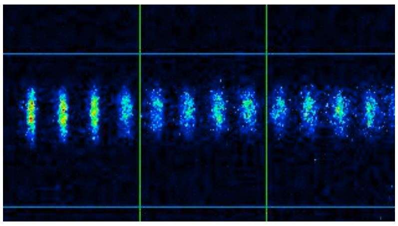
- The electron cloud signal first appeared in the SPS on the signal from a pick up as a shift of the baseline (depending on the charge collected by the electrodes)
- Correlation with train structure, length, gap were immediately apparent.

Examples of machine observations: KEK-LER

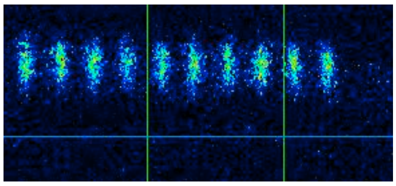
Vertical beam size blow up observed with a streak camera



Train head



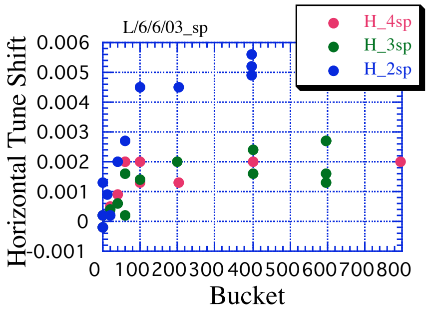
Train tail

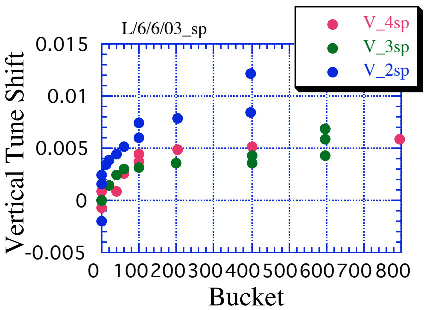


- The electron cloud causes beam size blow up (through instability and incoherent effects) that manifests itself at the tail of the bunch train
- Above an example of yz beam scan done in the KEK-LER

Examples of machine observations: KEK-LER

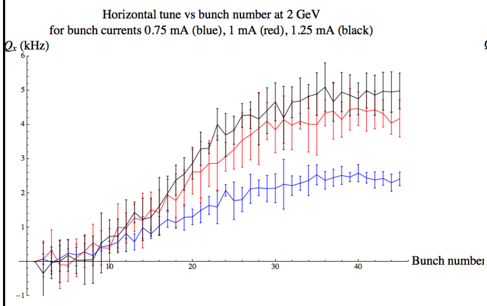
Bunch-by-bunch tune shift from the e-cloud:

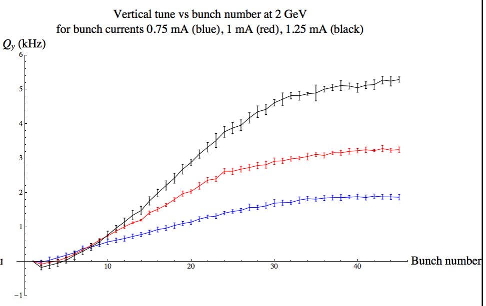




- The electron cloud causes a positive tune shift along the bunch train (if we could measure along the bunch, the tune shift would be also modulated along the bunch)
- Above an example tune shift along the train in the KEK-LER, for three different bunch spacings

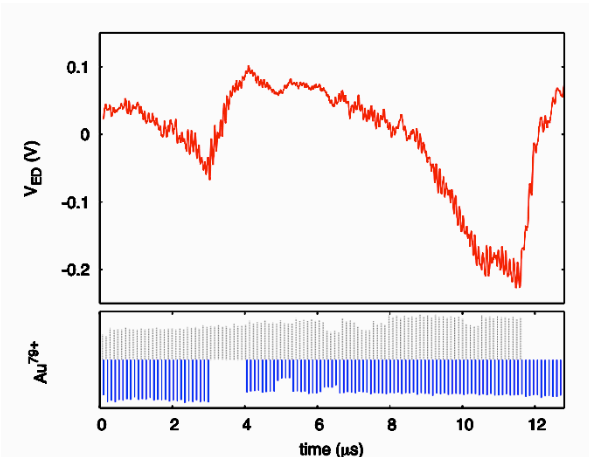
Examples of machine observations: Cesr-TA





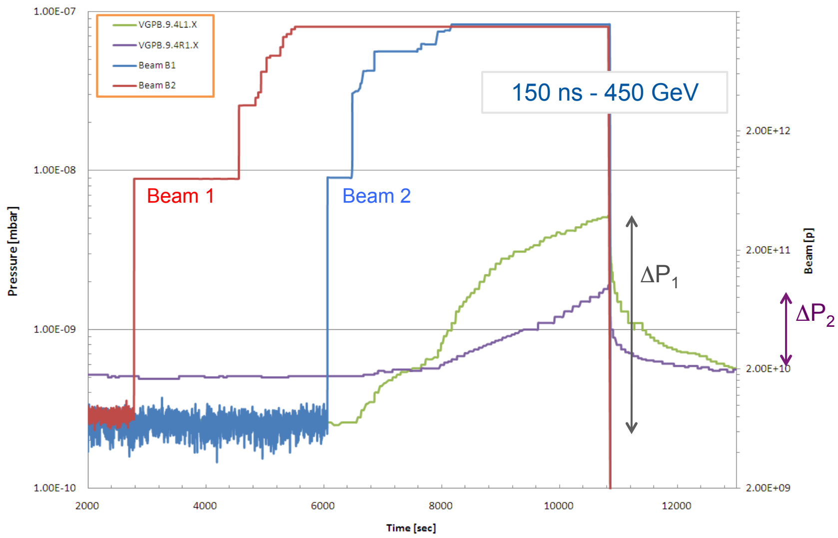
- Horizontal and vertical tune shifts along a 46 bunch train in Cesr-TA (Cornell facility presently used for electron cloud studies) taken during a positron run
- Dependence on the beam current is shown, clearly pointing to stronger electron cloud for higher currents.

Examples of machine observations: RHIC

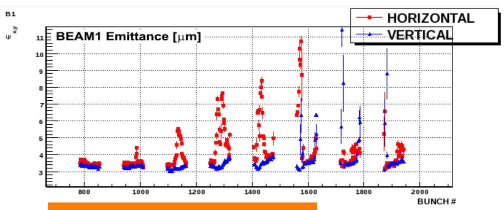


- The electron cloud measured the Interaction Region (IR) of the BNL-RHIC.
- The electron cloud only builds up when both beams come to the IR (requires therefore a shorter bunch spacing than the one in single ring)

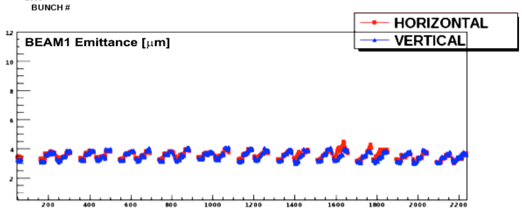
Examples of machine observations: LHC



Examples of machine observations: LHC



Day 1 – 300 bunches

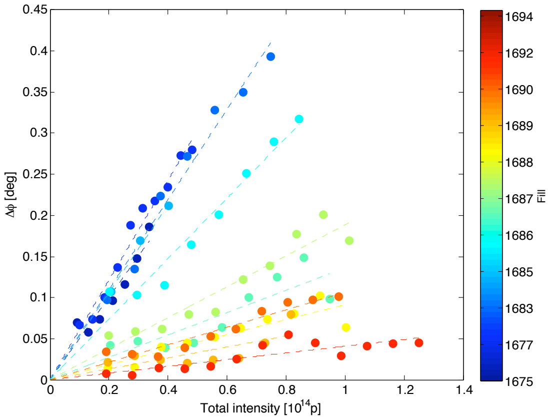


Day 3 – 800 bunches

⇒ Instabilities and emittance growth observed during the first part of the scrubbing run with 50 ns beams

⇒ No significant sign left at the end of the scrubbing

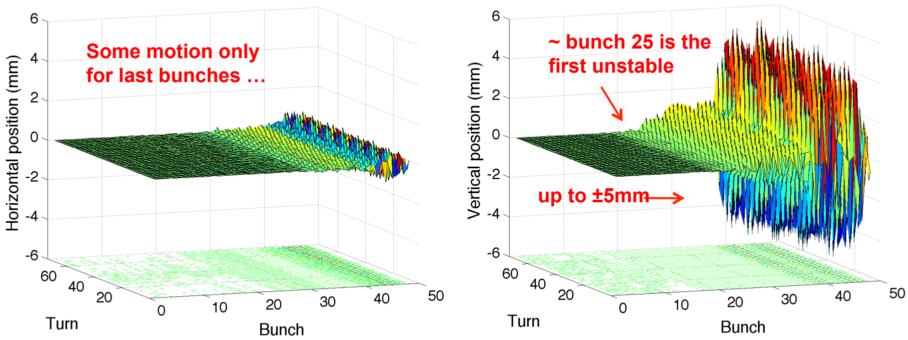
Examples of machine observations: LHC



⇒ The slope of the beam average phase shift with intensity has gradually decreased over the period of the scrubbing run with 50 ns beams

⇒ The slope $\Delta\phi_s/\Delta N$ has lost one order of magnitude thanks to scrubbing!

Examples of machine observations: LHC

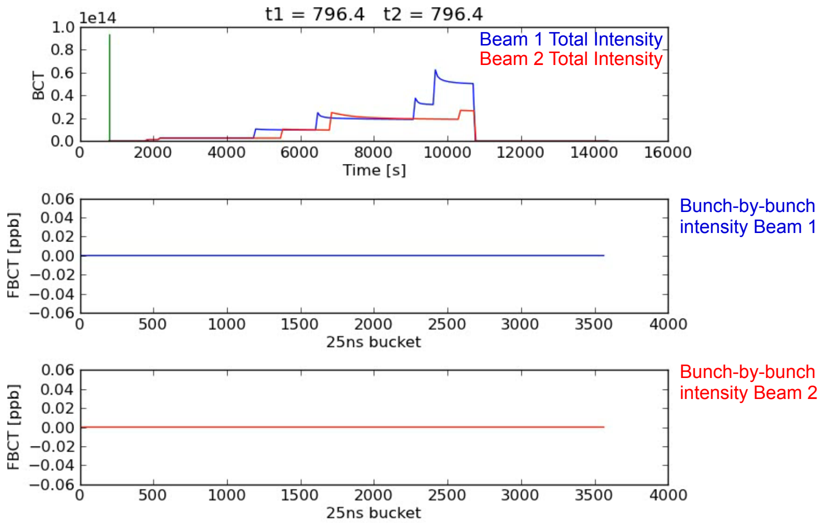


⇒ First injection of 48 bunches of 25 ns beam into the LHC in 2011

⇒ Beam was dumped twice due to a violent instability in the vertical plane, causing losses above the interlock threshold

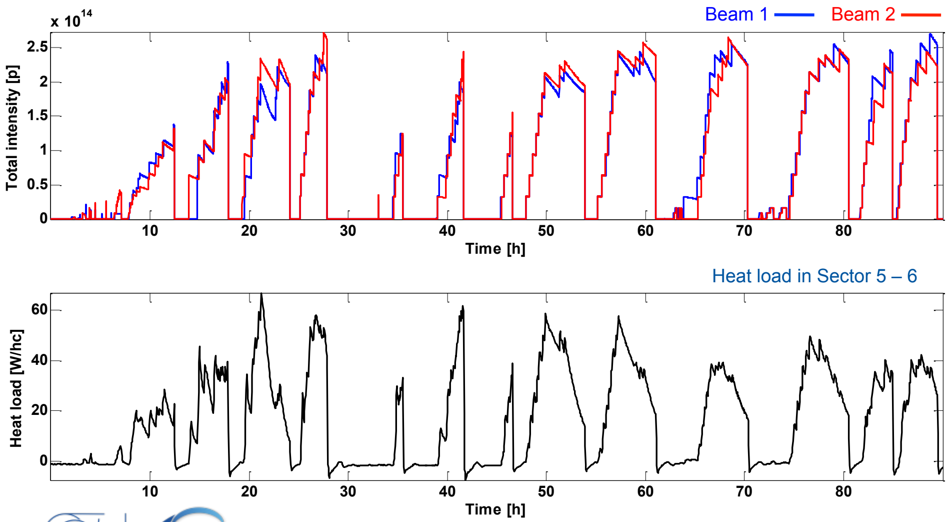
Examples of machine observations: LHC

⇒ First injection of 25 ns beams in 2012!



Examples of machine observations: LHC

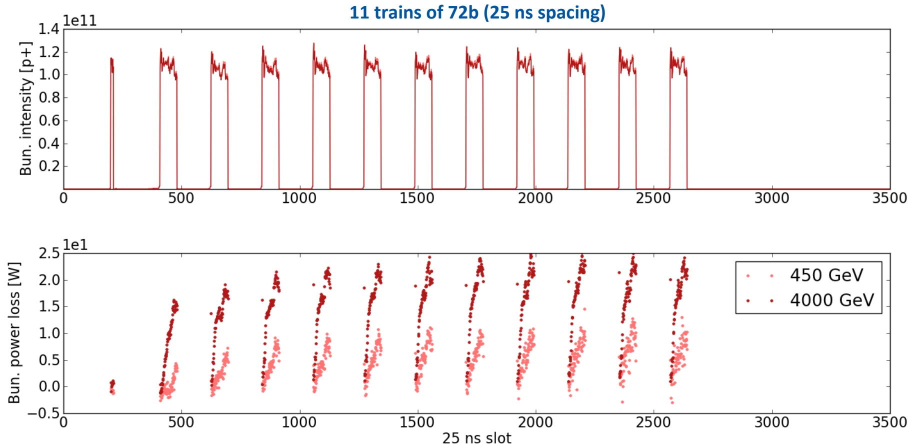
⇒ Heat load on the beam screen of the cold dipoles



Examples of machine observations: LHC

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

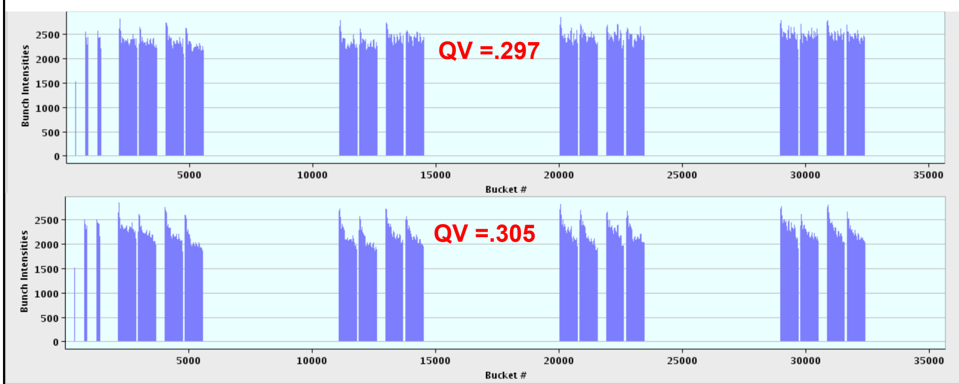
⇒ Larger electron cloud at 4 TeV is due to photoelectrons

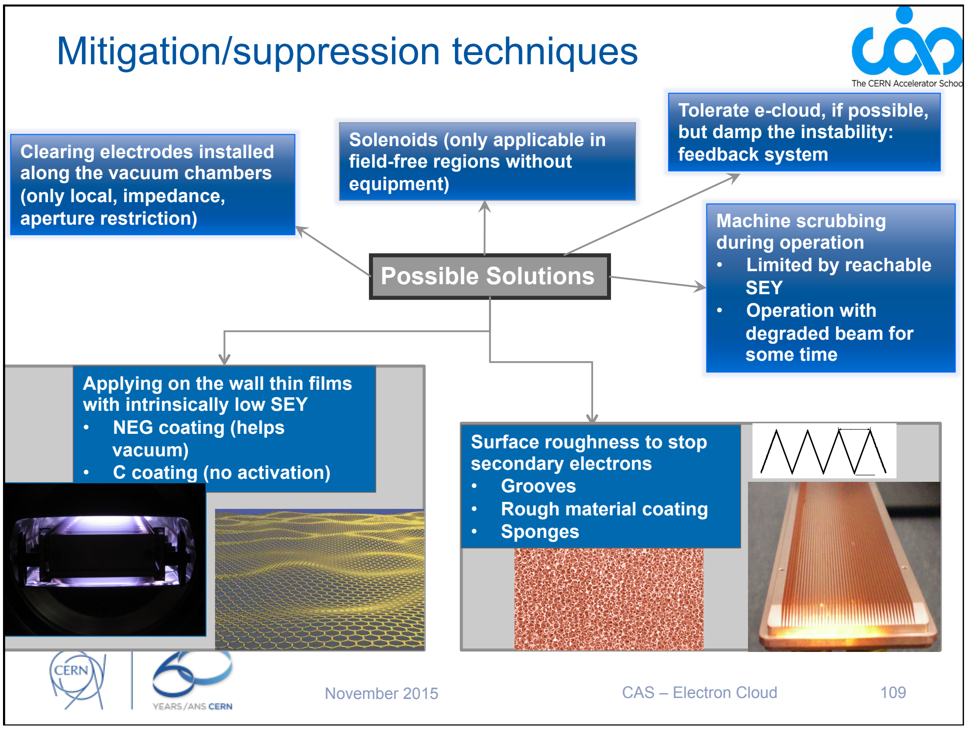


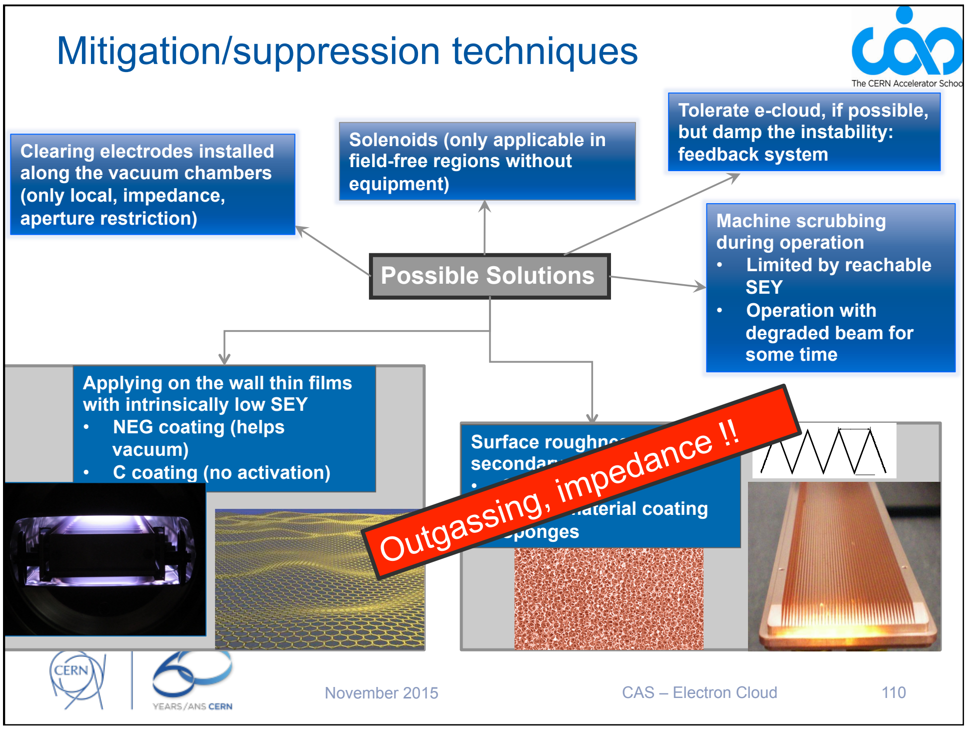
Examples of machine observations: LHC

⇒ Incoherent losses on trailing bunches due to working point close to third order integer and large tune spread from chormaticity and electron cloud

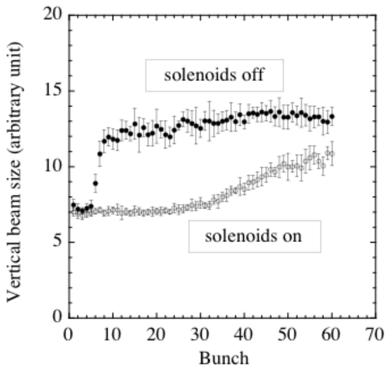
⇒ Cured by moving down the vertical tune

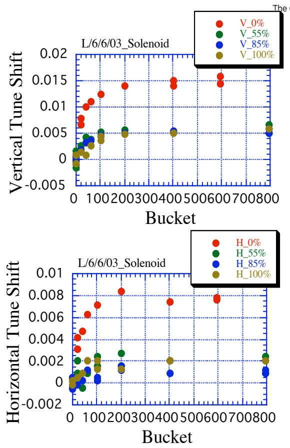



Mitigation/suppression techniques
The CERN Accelerator School
Clearing electrodes installed along the vacuum chambers (only local, impedance, aperture restriction)
Solenoids (only applicable in field-free regions without equipment)
Tolerate e-cloud, if possible, but damp the instability: feedback system
Possible Solutions
Machine scrubbing during operation
• Limited by reachable SEY
• Operation with degraded beam for some time
Applying on the wall thin films with intrinsically low SEY
• NEG coating (helps vacuum)
• C coating (no activation)
Surface roughness to stop secondary electrons
• Grooves
• Rough material coating
• Sponges
November 2015
CAS – Electron Cloud
109


Mitigation/suppression techniques
The CERN Accelerator School
Clearing electrodes installed along the vacuum chambers (only local, impedance, aperture restriction)
Solenoids (only applicable in field-free regions without equipment)
Tolerate e-cloud, if possible, but damp the instability: feedback system
Possible Solutions
Machine scrubbing during operation
• Limited by reachable SEY
• Operation with degraded beam for some time
Applying on the wall thin films with intrinsically low SEY
• NEG coating (helps vacuum)
• C coating (no activation)
Outgassing, impedance !!
November 2015
CAS – Electron Cloud
110

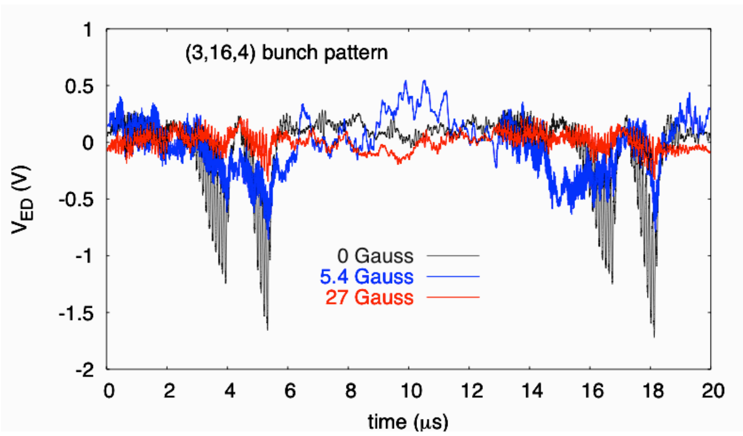
Mitigation/suppression: Solenoids





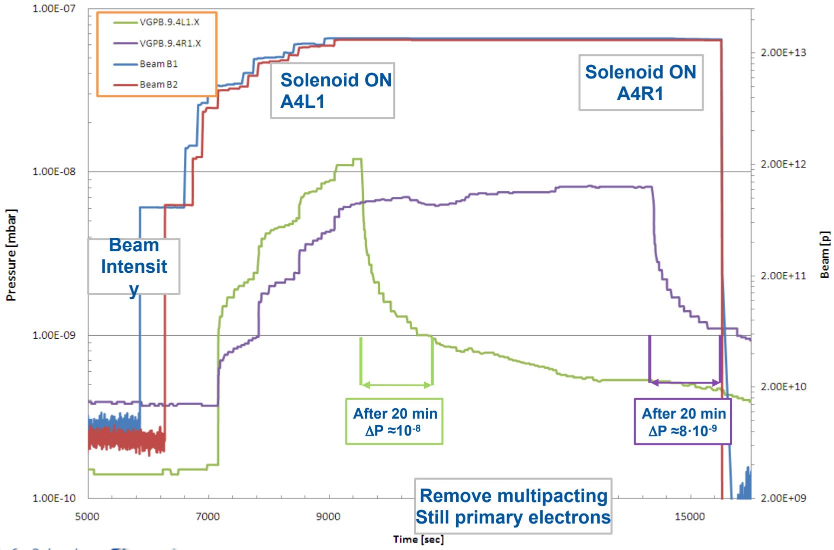
- Solenoids have been successfully used at the LER of KEKB
- Switching them on drastically reduces the beam size blow up as well as the tune shift along the batch

Mitigation/suppression: Solenoids

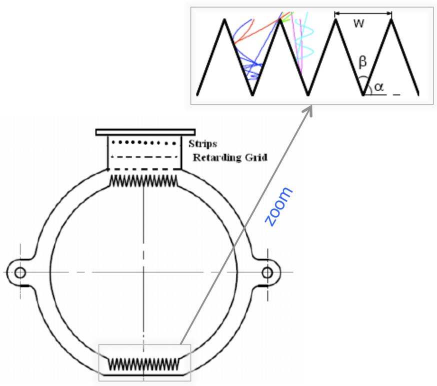


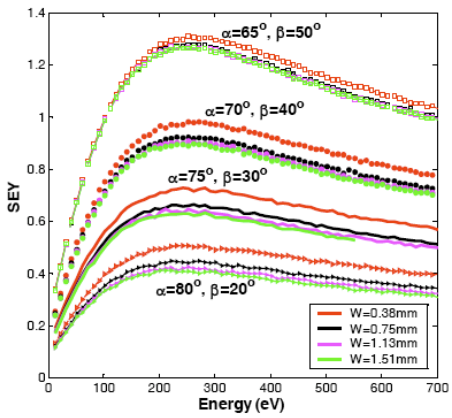
- Also at RHIC the beneficial effect of the solenoids has been observed
- By changing the intensity of the magnetic field, the electron cloud could be efficiently suppressed in a region with an electron detector.

Mitigation/suppression: Solenoids



Mitigation/suppression: Grooves



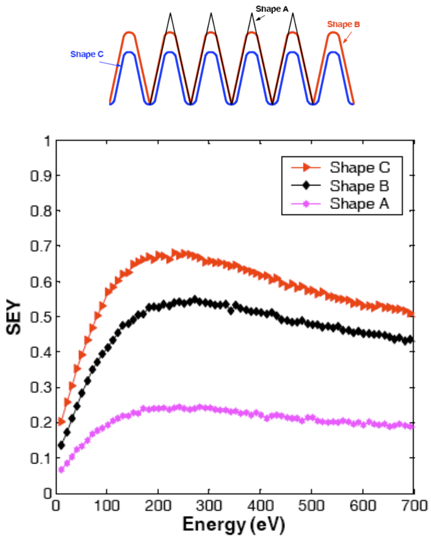


- To reduce the effective SEY, the inner surface of the beam pipe can be grooved, so that emitted electrons remain trapped
- Figure shows the effective SEY as a function of the groove angle and period, for a sample having δ_{max}=1.74 at E_{max}=330 eV

Mitigation/suppression: Grooves

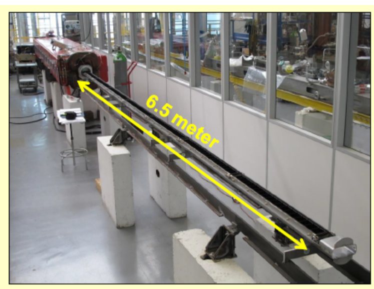
The CERN Accelerator School

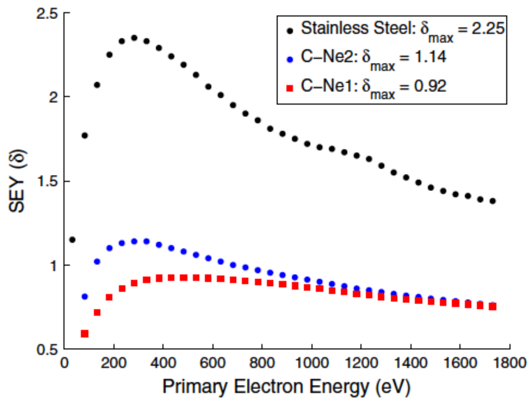
- Once angle and period are fixed, the efficiency of the grooving to reduce the SEY is found to depend on the shape of the tips.
- This solution raises the following concerns:
  - Impedance enhancement (beam stability)
  - Increased surface, which would make pumping more difficult (good vacuum)



Mitigation/suppression: a-C coating

The CERN Accelerator School

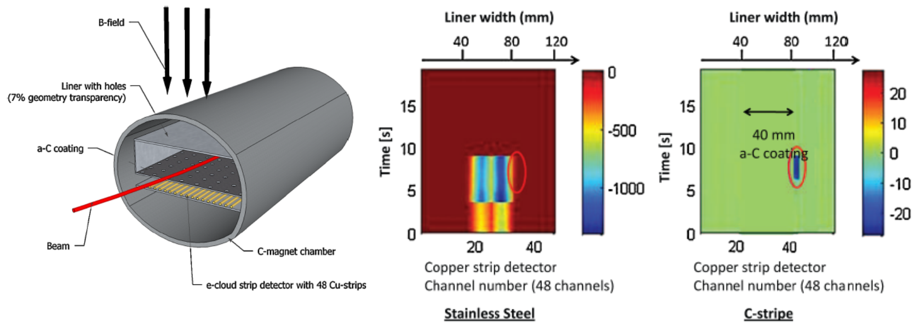




- To reduce the effective SEY, the inner surface of the beam pipe can be coated with a-C
- It is possible to reach values of δ_{max} below 1, measured in the laboratory …

Mitigation/suppression: a-C coating

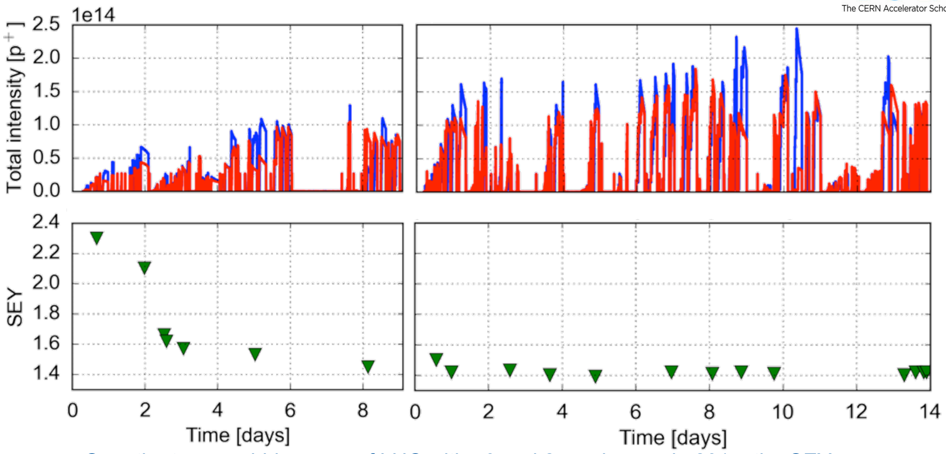
The CERN Accelerator School



- To reduce the effective SEY, the inner surface of the beam pipe can be coated with 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

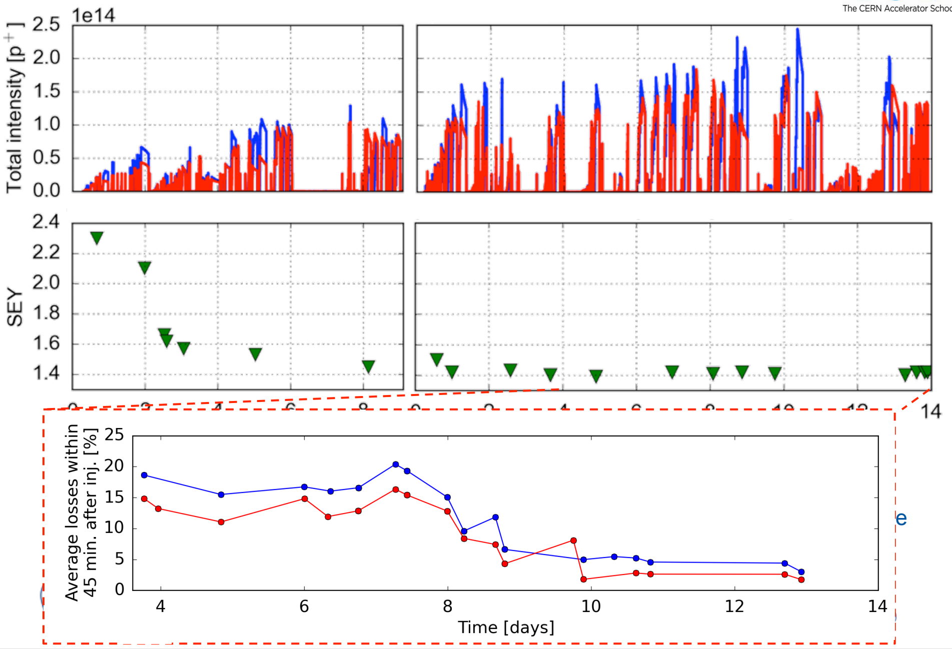
Mitigation/suppression: Scrubbing

The CERN Accelerator School

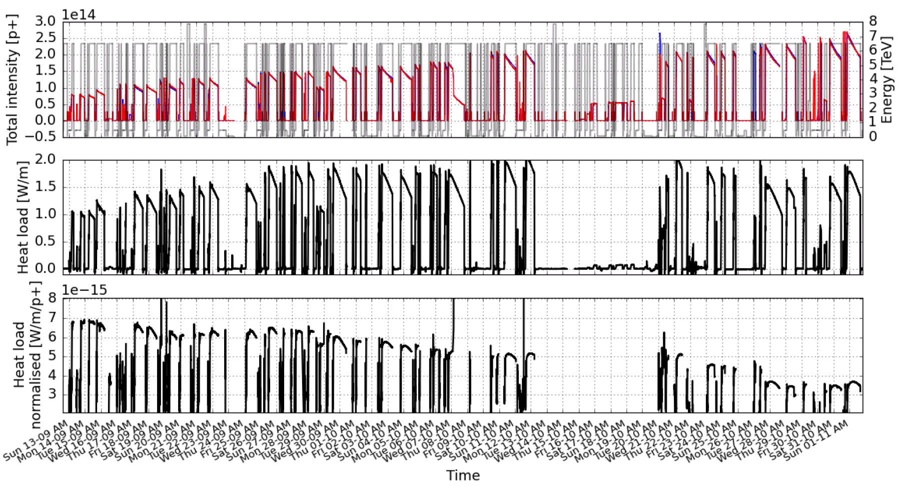


- Over the two scrubbing runs of LHC with 50 and 25 ns beams in 2015, the SEY was estimated to decrease from 2.3 to ~1.4, and the intensity was ramped up
- Scrubbing is fast in the early phase, but it then becomes much slower due to the nature of the process (more scrubbing → less electron cloud → less electron dose)

Mitigation/suppression: Scrubbing

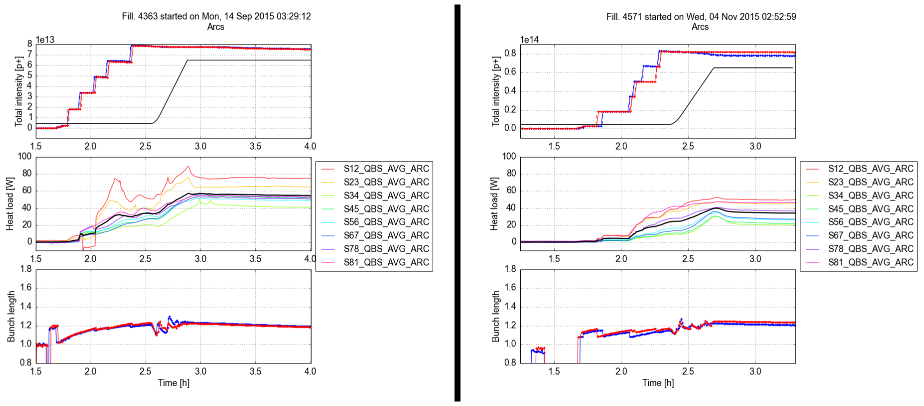


Mitigation/suppression: Scrubbing



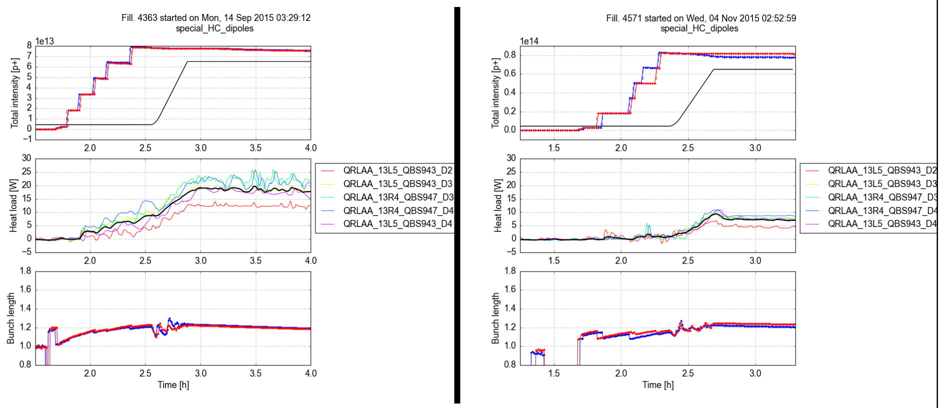
- Fortunately, in LHC we keep scrubbing also while producing physics …
- The normalised heat load in the beam screen of the arcs goes steadily down!

Mitigation/suppression: Scrubbing

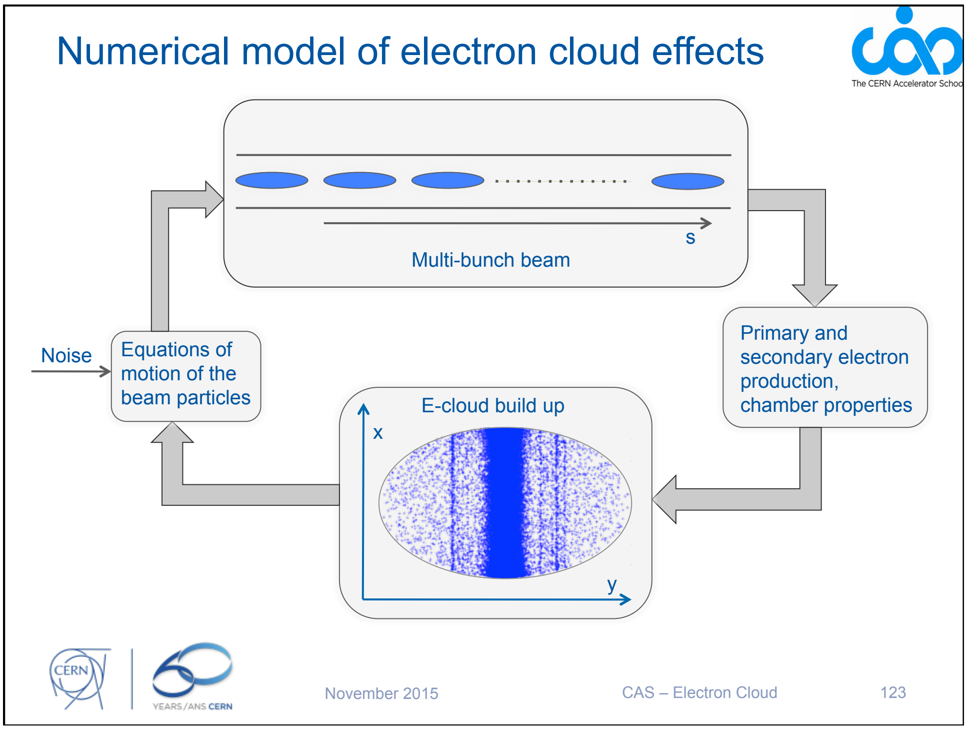


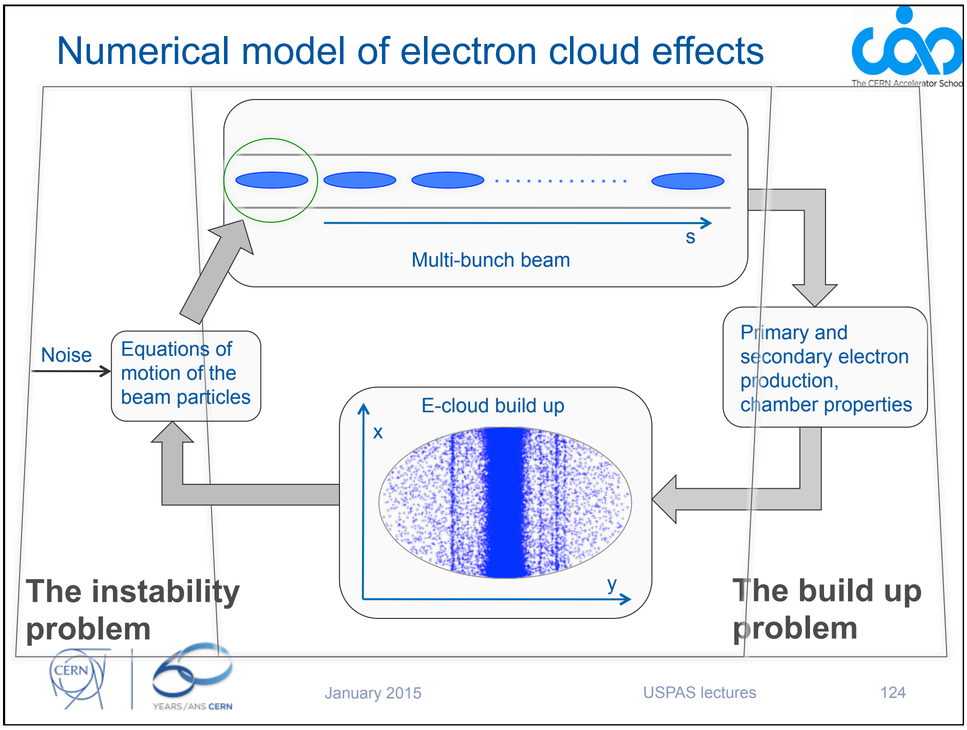
- A direct comparison between a fill at the beginning of the intensity ramp up and just before the end of the proton run (~2 months) reveals clear scrubbing
- Heat load in the arcs reduced by 30 to 60% according to the sector!

Mitigation/suppression: Scrubbing



- A direct comparison between a fill at the beginning of the intensity ramp up and just before the end of the proton run (~2 months) reveals clear scrubbing
- Even more visible in the arc dipoles, where the electron cloud has died out at 450 GeV!


Numerical model of electron cloud effects
The CERN Accelerator School
s
Multi-bunch beam
Primary and secondary electron production, chamber properties
Noise
Equations of motion of the beam particles
E-cloud build up
x
y
November 2015
CAS – Electron Cloud
123


Numerical model of electron cloud effects
s
Multi-bunch beam
Primary and secondary electron production, chamber properties
Noise
Equations of motion of the beam particles
E-cloud build up
x
y
The instability problem
The build up problem
January 2015
USPAS lectures
124

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, cutting edge research
- 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 → K. Li's lecture**
    - ✓ Single bunch
    - ✓ Multi-turn, or even multi-kick multi-turn

Build up simulation → **Instability simulation**

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

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, cutting edge research
- 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 → K. Li's lecture**
    - ✓ Single bunch
    - ✓ Multi-turn, or even multi-kick multi-turn

Build up simulation → **Instability simulation**

ECLOUD, PyECLOUD, POSINST, CSEC, …

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

HEADTAIL, PyHEADTAIL, CMAD, PEHTS, …

Numerical modeling: electron cloud build up

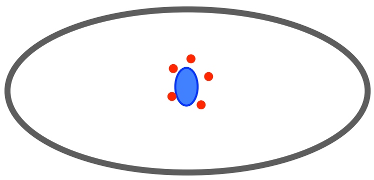
t=t+Δt

- Generate **seed e⁻**
- Evaluate the **electric field of beam** at macroparticles' location
- Evaluate the **e⁻ space charge electric field**
- **Move macroparticles** (t → t+Δt)
- Detect **impacts** and generate **secondaries**

Numerical modeling: electron cloud build up

t=t+Δt

- **Generate seed e⁻**
- Evaluate the electric field of beam at macroparticles' location
- Evaluate the e⁻ space charge electric field
- Move macroparticles (t → t+Δt)
- Detect impacts and generate secondaries



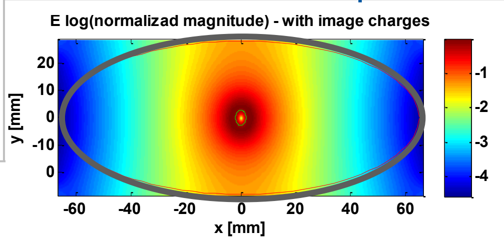
Evaluate the number of **seed e⁻** to be generated during the current time step and **generate macroparticles**:

- **Residual gas ionization** and **photoemission** are implemented
- Theoretical/empirical models are used to determine **macroparticle space and energy distributions**

Numerical modeling: electron cloud build up

t=t+Δt

- Generate seed e⁻
- **Evaluate the electric field of beam at macroparticles' location**
- Evaluate the e⁻ space charge electric field
- Move macroparticles (t → t+Δt)
- Detect impacts and generate secondaries

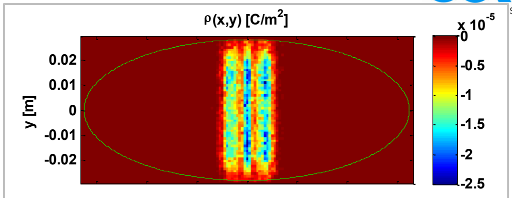


- The **field map** for the relevant chamber geometry and beam shape is **pre-computed on a suitable rectangular grid and loaded from file** in the initialization stage
- When the field at a certain location is needed a **linear (4 points) interpolation algorithm** is employed

Numerical modeling: electron cloud build up

t=t+Δt

- Generate seed e⁻
- Evaluate the electric field of beam at macroparticles' location
- **Evaluate the e⁻ space charge electric field**
- Move macroparticles (t → t+Δt)
- Detect impacts and generate secondaries



Use of PIC algorithm for e⁻ space charge field

Poisson equation:

$$\nabla^2 \phi(x,y) = -\frac{\rho(x,y)}{\epsilon_0}$$

with $\phi(x,y) = 0$ on the boundary

The **electric field**, given by:

$$\vec{E}(x,y) = -\nabla \phi(x,y)$$

is calculated on the grid points and interpolated at the macroparticles' positions

Numerical modeling: electron cloud build up

t=t+Δt

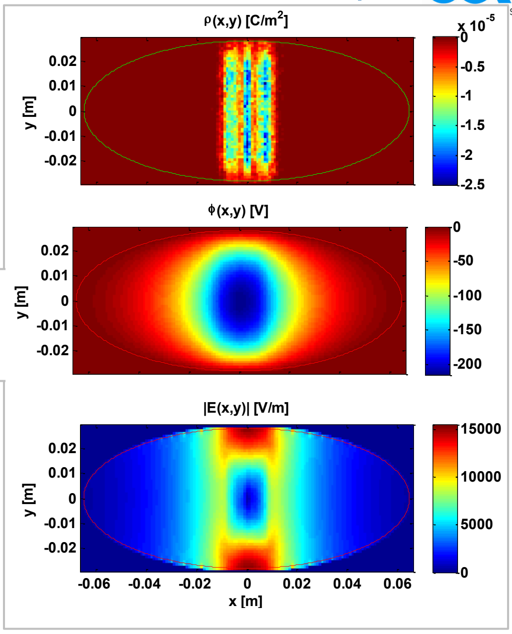
Generate seed e⁻

Evaluate the electric field of beam at macroparticles' location

Evaluate the e⁻ space charge electric field

Move macroparticles (t → t+Δt)

Detect impacts and generate secondaries



Numerical modeling: electron cloud build up

t=t+Δt

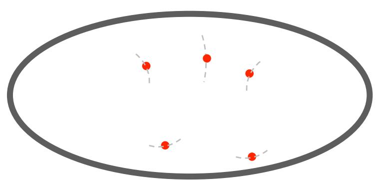
Generate seed e⁻

Evaluate the electric field of beam at macroparticles' location

Evaluate the e⁻ space charge electric field

Move macroparticles (t → t+Δt)

Detect impacts and generate secondaries



The equation of motion is integrated to **update macroparticles' position and momentum**:

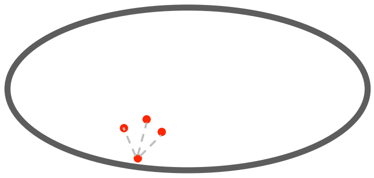
$$\frac{d\vec{p}}{dt} = -e\left[\vec{E}(\vec{r}(t),t) + \vec{v}(t) \times \vec{B}(\vec{r}(t))\right]$$

Boris tracker is used for efficiently and accurately dealing with fast cyclotron motion and slow drift in presence of magnetic gradients

Numerical modeling: electron cloud build up

t=t+Δt

- Generate seed e⁻
- Evaluate the electric field of beam at macroparticles' location
- Evaluate the e⁻ space charge electric field
- Move macroparticles (t → t+Δt)
- **Detect impacts and generate secondaries**



- When a MP hits the wall the SEY model is employed to generate **charge of emitted charge.** Energy and angle also come from theoretical/experimental models.
- According to the number of emitted electrons, macroparticles can be **simply rescaled** or **new are generated**.

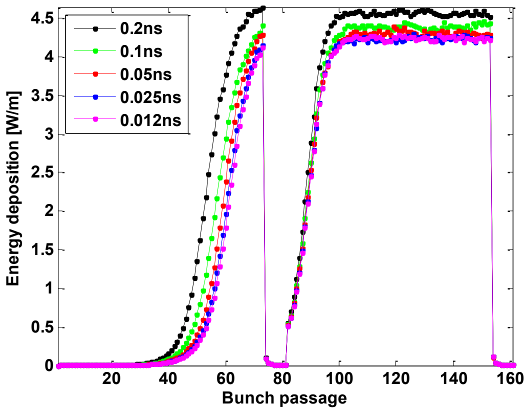
Numerical modeling: electron cloud build up

Electron cloud build up simulations pose several challenges:

- Management of the macroparticle size
  - The number of electrons in an electron cloud simulation varies by several orders of magnitude
  - The size of macroparticles needs to be adapted during the simulation to keep the number of macroparticles reasonable, but conserving the phase space of the ensemble
- Tracking in arbitrary magnetic field configurations and time varying electric fields
- Accurate beam field and electron space charge computation
  - Due to all the surface effects, the e⁻ dynamics in proximity of the wall is crucial, therefore the electric field calculation must be accurate also close to the EM boundary

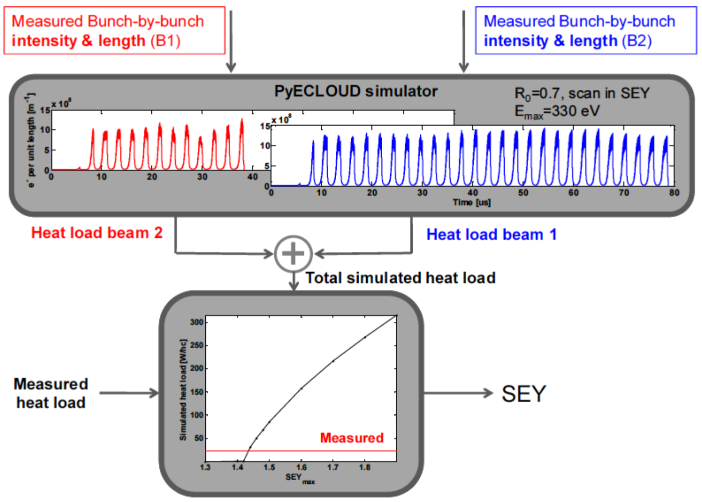
November 2015 CAS – Electron Cloud 134

Numerical modeling: electron cloud build up



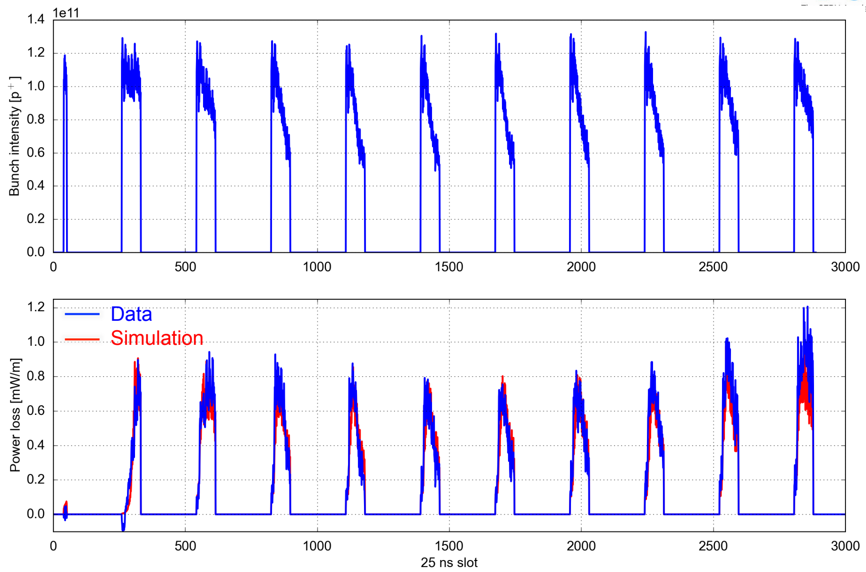
- A sample result of simulated build up, plotted as energy deposition on the chamber due to the electrons as a function of the bunch passage

Numerical modeling: electron cloud build up



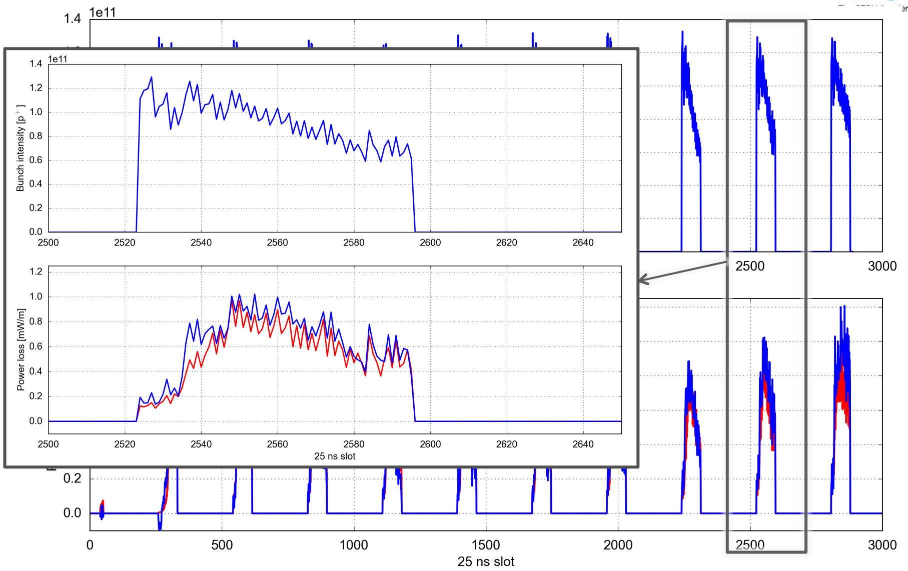
- Simulations can be used to infer the SEY of a surface from heat load measurements in known beam conditions ..

Numerical modeling: electron cloud build up



- .. or to determine the bunch-by-bunch phase shift

Numerical modeling: electron cloud build up



- .. or to determine the bunch-by-bunch phase shift

Summary of electron cloud effects

- **Electron clouds** can build up in accelerators operating with beams of positively charged particles in some parameter ranges.
  - Several detrimental effects:
    - Pressure rise & heat load
    - Energy loss, beam instability, poor beam lifetime, emittance blow up
  - Mitigation/suppression strategies exist and can be applied to both running and new machines
    - Machine scrubbing
    - Surface coating with low SEY materials or surface machining
    - Solenoids, clearing electrodes
  - Well-established numerical models exist to model separately electron cloud build up and beam instability (single bunch)

Thank you for your attention