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

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We will look into the description and the impact of **electron cloud**. We will discuss the conditions for an electron cloud to build in the vacuum chamber of an accelerator and mitigation/suppression techniques. We will also show some examples linked to **electron cloud effects** such as beam induced instability and incoherent effects.

**Part 4: Electron cloud –**

**Build up and effects on beam dynamics**

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

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• **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

Multi-bunch beam $s$

Equations of motion of the beam particles

Interaction with the external environment

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

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

\[(\vec{E}, \vec{B})\]

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

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

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

- 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, cleanliness of the inner surface of chamber

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

Residual gas ionization

Desorption from the losses on the wall

Photoelectrons from synchrotron radiation
Electron production

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• 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

Secondary Electron Yield (SEY)

\[ \delta_{\text{max}} = 1.3, \text{ normal incidence} \]
\[ \delta_{\text{max}} = 1.3, \theta = 90^\circ \]
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 $SEY > 1$
Assume an initial distribution of electrons (from any of the mechanisms discussed before)
“Pinch” of electrons when bunch is passing
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Few high energy (>100 eV) electrons reach the chamber wall already on the falling edge of the bunch and start producing secondaries.
High energy electrons (>100 eV) reaching the chamber wall produce more secondaries
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As they are produced, the emitted secondaries form a halo near the chamber wall because they have low energy (up to 10 eV)
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While the halo gets more and more populated, the center is gradually depleted.
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While the halo gets more and more populated, the center is gradually depleted
The center is strongly depleted
No more secondaries are produced because there are no longer high energy electrons reaching the walls
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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.
Beam pipe transverse cut

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.
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.
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
Electrons generated ($\Delta N_{eg}$) depend on bunch charge, chamber radius and surface SEY.

Electrons lost ($\Delta N_{el}$) 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)
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• The exponential rise stops when the space charge of the electrons becomes significant → At this point electron generation and loss compensate each other
• 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
• 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?

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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

\[
\Delta P \propto \int \eta_e(E) \langle \Phi_e(E) \rangle dE \\
\Delta W = \int \langle \Phi_e(E) \rangle E dE
\]
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**
  - Single bunch effect affecting the last bunches of a train
  - Coupled bunch effect
- **Poor beam lifetime** and **emittance growth**
Electron cloud effects

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- **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

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Beam 1

Beam 2

150 ns - 450 GeV
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.
• 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?

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• **Scrubbing and other techniques of mitigation/suppression**
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Surface scrubbing

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

![Graph showing the effect of dose on SEY for different energies and materials.](image-url)
Surface scrubbing

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

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

![Schematic view of the in-situ SEY detector installed in the SPS](image)
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)

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

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

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

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

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

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

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

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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

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

For this we need to solve

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

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and apply the corresponding kicks to the cloud and the beam
Electron clouds in a bending magnet

- Two stream collective interaction – much more complicated

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Electron clouds in a quadrupole magnet

- Two stream collective interaction – much more complicated

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and apply the corresponding kicks to the cloud and the beam
Accelerator beam system – e-cloud

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

- Basic loop of tracking with electron clouds:
  - Transport beam along segment to interaction point
Accelerator beam system – e-cloud

\[ M = \left( \begin{array}{cc} \sqrt{\beta_1} & 0 \\ -\frac{\alpha_1}{\sqrt{\beta_1}} & \frac{1}{\sqrt{\beta_1}} \end{array} \right) \left( \begin{array}{cc} \cos(\Delta \mu_i) & \sin(\Delta \mu_i) \\ -\sin(\Delta \mu_i) & \cos(\Delta \mu_i) \end{array} \right) \left( \begin{array}{cc} \frac{1}{\sqrt{\beta_0}} & 0 \\ \frac{\alpha_0}{\sqrt{\beta_0}} & \frac{1}{\sqrt{\beta_0}} \end{array} \right) \]

\[ \Delta \vec{x}'[i] = -\frac{e^2}{m\gamma\beta^2c^2} \vec{E}_e - C \]

\[ \Delta \vec{x} = -\frac{e}{m} \left( \vec{E}_{p+}[i] + \frac{\vec{x} \times \vec{B}}{c} \right) \Delta t \]

- Basic loop of tracking with electron clouds:
  - Transport beam along segment to interaction point
  - Apply e-cloud kick
    \[ \rightarrow \text{get fields from PIC step} \]
• 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
• 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

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**E-cloud beam system**

Slice index

- $E_{\text{cloud at slice index}}$
E-cloud beam system

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

Slice index

$E$-cloud at slice index
Numerical model of electron cloud effects

Multi-bunch beam

Equations of motion of the beam particles

Noise

Primary and secondary electron production, chamber properties

E-cloud build up

x

y
Numerical model of electron cloud effects

- Multi-bunch beam
- Primary and secondary electron production, chamber properties
- Equations of motion of the beam particles
- E-cloud build up
- Instability problem
- Build-up problem
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

Some motion only for last bunches ...

~ bunch 25 is the first unstable

up to ±5mm
Ex. of coherent e-cloud effects in the LHC

48b injection test (26/08/11)

Some motion only for last bunches ...

~ bunch 25 is the first unstable

up to ±5mm

48x PyECLOUD e− distribution (δ_{max}=2.1)
We have learned that electron clouds can build up in the vacuum chamber of an accelerator operating in a certain range of beam parameters.

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

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

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

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- Electron cloud build up
  - Electron production and multiplication
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- E-cloud induced instabilities and incoherent effects
The End
PIC solvers in brief

• In many of our codes, Particle in Cell (PIC) algorithms are used to compute the electric field generated by a set of charged particles in a set of discrete points (can be the locations of the particles themselves, or of another set of particles).

• The solution typically consists of 4 stages:
  1. Charge scatter from macroparticles (MPs) to grid (reduction of macroparticles)
  2. Calculation of the electrostatic potential at the nodes
  3. Calculation of the electric field at the nodes (gradient evaluation)
  4. Field gather from grid to MPs
PIC solvers in brief

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

![Uniform square grid](image)
PIC solvers – basic steps

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  1. Charge scatter from macroparticles (MPs) to grid (reduction of macroparticles)
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\[
\begin{align*}
\rho_{i,j} &= \rho_{i,j} + \frac{q n_{\text{MP}}}{\Delta h} \left( 1 - \frac{d_x}{\Delta h} \right) \left( 1 - \frac{d_y}{\Delta h} \right) \\
\rho_{i+1,j} &= \rho_{i+1,j} + \frac{q n_{\text{MP}}}{\Delta h} \left( \frac{d_x}{\Delta h} \right) \left( 1 - \frac{d_y}{\Delta h} \right) \\
\rho_{i,j+1} &= \rho_{i,j+1} + \frac{q n_{\text{MP}}}{\Delta h} \left( 1 - \frac{d_x}{\Delta h} \right) \left( \frac{d_y}{\Delta h} \right) \\
\rho_{i+1,j+1} &= \rho_{i+1,j+1} + \frac{q n_{\text{MP}}}{\Delta h} \left( \frac{d_x}{\Delta h} \right) \left( \frac{d_y}{\Delta h} \right)
\end{align*}
\]
PIC solvers – basic steps

• The solution typically consists of 4 stages:
  1. Charge scatter from macroparticles (MPs) to grid (reduction of macroparticles)
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\[ \nabla^2 \phi(x, y) = -\frac{\rho(x, y)}{\varepsilon_0} \]

Boundary conditions (e.g., perfectly conducting, open, periodic)

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

• The solution typically consists of 4 stages:

1. Charge scatter from macroparticles (MPs) to grid (reduction of macroparticles)
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\[ E = - \nabla \phi \]

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

\[ (E_y)_{i,j} = - \frac{\phi_{i,j+1} - \phi_{i,j-1}}{2\Delta h} \]
PIC solvers – basic steps

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

\[
E(x_{MP}, y_{MP}) = \\
E_{i,j} \left(1 - \frac{d_x}{\Delta h}\right) \left(1 - \frac{d_y}{\Delta h}\right) + E_{i+1,j} \left(\frac{d_x}{\Delta h}\right) \left(1 - \frac{d_y}{\Delta h}\right) + E_{i,j+1} \left(1 - \frac{d_x}{\Delta h}\right) \left(\frac{d_y}{\Delta h}\right) + E_{i+1,j+1} \left(\frac{d_x}{\Delta h}\right) \left(\frac{d_y}{\Delta h}\right)
\]
Numerical model of electron cloud effects

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

**Legend:** From instability code – From build-up code – Interaction between the two codes
Ex. of incoherent e-cloud effects in the LHC

• Remember tune footprint from octupoles in Part I
Ex. of incoherent e-cloud effects in the LHC

• Macroparticle simulations allow to obtain tune footprints from all effects separated.
Ex. of incoherent e-cloud effects in the LHC

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

### Octupole knob at -1.5
- $Q' = 0/0$, no e-cloud
- $Q' = 15/20$, no e-cloud

### Octupole knob at 0
- $Q' = 0/0$, $5 \times 10^{11} \text{ e/m}^3$
- $Q' = 15/20$, $5 \times 10^{11} \text{ e/m}^3$
Ex. of incoherent e-cloud effects in the LHC

- Macroparticle simulations allow to obtain tune footprint from all effects separated
- ... as well as from all effects combined
- ... to identify the source of incoherent losses in the LHC
Backup - wakefields
Electron 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)
Surface scrubbing

- 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

![Graph showing Electron flux vs SEY for 25ns and 50ns]
• 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.
• 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 $\delta_{\text{max}}=1.74$ at $E_{\text{max}}=330$ 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 $\delta_{\text{max}}$ below 1, measured in the laboratory and also verified by measurements at an electron cloud detector in the SPS
• 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**?

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