Electron cloud at the LHC and LHC injectors

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Outline

- Basics of electron cloud in particle accelerators
  - Electron cloud build up and effects on the beam
  - Scrubbing

- Electron cloud studies in the CERN accelerators

- Closing remarks
Basics of electron cloud

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

Residual gas ionization

Desorption from the losses on the wall

Photoelectrons from synchrotron radiation
Basics of electron cloud

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

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

Dangerous if $SEY > 1$
Basics of electron cloud

Generation of electrons 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

Diagram:
- Seed electrons (~300 eV)
- Lost electrons (~10 eV)
- Beam chamber

Bunch spacing (e.g. 25 ns)

Time
Basics of electron cloud

Generation of electrons 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 dynamic steady state (electron cloud)
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Basics of electron cloud

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

- Acceleration of primary electrons in the beam field
- Secondary electron production when hitting the wall
- Avalanche electron multiplication
Effects of the electron cloud

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 due to the 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 due to the 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
Effects of the electron cloud

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- Active monitoring: signal on dedicated electron detectors (e.g. strip monitors) and retarding field analysers
CERN's accelerator complex

- **LHC** (Large Hadron Collider)
- **SPS** (Super Proton Synchrotron)
- **PS** (Proton Synchrotron)

Key: 
- p (proton)  
- ion  
- neutrons  
- $\bar{p}$ (antiproton)  
- proton/antiproton conversion  
- neutrinos  
- electron

Institutions:
- ALICE
- ATLAS
- CMS
- LHCb
- CNGS (Gran Sasso)

Facilities:
- AD (1999, 182 m)
- BOOSTER (1972, 157 m)
- ISOLDE (1989)
- PS (1959, 628 m)
- LEIR (2005, 78 m)
- LINAC 2
- LINAC 3
- n-ToF (2001)
- CTF3 (e-)
- TT10
- TT12
- TT2
- TT60
- TT40
- TT41
- TI8
- North Area
- East Area

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Conditions for e-cloud formation (beam structure, chamber geometry and properties) are potentially met in PS, SPS and LHC.
Surface scrubbing

- Fortunately, the SEY of a surface 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?

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R. Cimino et al.,
ECLOUD12, Elba Island
Surface scrubbing

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

- **Beam-induced scrubbing** is different from lab scrubbing
  - It becomes even slower while it progresses, due to the decrease of the electron flux as the SEY decreases
Surface scrubbing

- **Beam-induced scrubbing** is different from lab scrubbing
  - It becomes even slower while it progresses, due to the decrease of the electron flux as the SEY decreases
  - It comes from pulsed electron bombardment (MHz) with a broad spectrum of energies
  - It happens in the vacuum chamber of an accelerator
    - It is localized according to e-cloud distribution pattern and may be affected when beam properties or magnetic field change
    - It is affected by other mechanisms (ion or photon bombardment)
    - Its evolution is related to vacuum dynamics in the chamber

![Quadrupole](image1.png)
![Dipole](image2.png)
Beam-induced scrubbing

- Has been measured directly at the SPS with StSt rotatable sample exposed to the beam or to SEY measurement device (2004)

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

<table>
<thead>
<tr>
<th>Energy (eV)</th>
<th>SEY coefficient (δ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>500</td>
<td>0.7</td>
</tr>
<tr>
<td>1000</td>
<td>0.9</td>
</tr>
<tr>
<td>1500</td>
<td>1.1</td>
</tr>
<tr>
<td>2000</td>
<td>1.3</td>
</tr>
<tr>
<td>2500</td>
<td>1.5</td>
</tr>
<tr>
<td>3000</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Legend:
- 4 h
- 10 h
- 21 h
- 63 h
- 90 h
Surface scrubbing

- Beam-induced scrubbing
  - Is revealed by improving accelerator conditions over time, e.g. decrease of pressure rise, heat load, stable phase shift, improvement of beam quality → not obvious sometimes, as timescales can be long and effects are entangled
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![Graph showing total intensity and heat load over time](image)

Average heat load normalised to beam current
The e-cloud has been observed/studied at the

- Proton Synchrotron (PS)
- Super Proton Synchrotron (SPS)
- Large Hadron Collider (LHC)

G. Iadarola et al.
THPAB043
Electron cloud in the CERN accelerators

- The e-cloud has been observed/studied at the
  - Proton Synchrotron (PS)
  - Super Proton Synchrotron (SPS)
  - Large Hadron Collider (LHC)

... some highlights for SPS and LHC ...
Electron cloud in the SPS

- Strong limitation due to e-cloud with 25 ns beams until ~2011
  - Instabilities at injection to be cured with high chromaticity (V) and transverse feedback system (H)
  - Severe pressure rise around the machine
  - Strong emittance growth along bunch trains

![Graph showing electron cloud in the SPS]
Electron cloud in the SPS

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- **Scrubbing runs** since 2002 with long cycles at 26 GeV (each lasting from 2 days to 2 weeks)

- No significant degradation seen for **four trains of 72 bunches of nominal 25 ns beam (1.2e11 p/b)** after 2010

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2002 (14d) 2003 (8d) 2004 (10d) 2006 (5d) 2007 (7d) 2008 (2.5d) 2009 (1.5d) 2010-11 (-) 2012 (5d)
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- ~1 **month** before 2005 long shutdown
  - **16 days** in 2006 – 2009
Electron cloud in the SPS

- **Strip detectors** installed to measure the integrated signal of electron current through holes in the vacuum chamber
  - Four monitors installed to measure e-cloud in different geometries, with different materials or surface treatment (with possible B field)
  - Reconstruction of **horizontal profile** but no time resolved signal
Electron cloud in the SPS

- **Strip detectors** installed to measure the integrated signal of electron current through holes in the vacuum chamber
  - Comparing experimental data against simulations for different magnetic fields applied

\[ B = 42 \text{ G} \]
Electron cloud in the SPS

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B = 83 G
Electron cloud in the SPS

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![Graphs showing measurement and simulation of electron flux](image)

*B = 125 G*
Electron cloud in the SPS

- **Strip detectors** installed to measure the integrated signal of electron current through holes in the vacuum chamber
  - Comparing experimental data against simulations for different magnetic fields applied

\[ B = 175 \text{G} \]
Electron cloud in the SPS

- **Strip detectors** installed to measure the integrated signal of electron current through holes in the vacuum chamber
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\[ B = 250 \, \text{G} \]
Electron cloud in the SPS

- **Strip detectors** installed to measure the integrated signal of electron current through holes in the vacuum chamber
  - Comparing experimental data against simulations for different magnetic fields applied

\[ B = 833 \, \text{G} \]

![Measurement vs Simulation](image)
Electron cloud in the SPS

- **Strip detectors** installed to measure the integrated signal of electron current through holes in the vacuum chamber
  - Comparing experimental data against simulations for different magnetic fields applied

\[ B = 1000 \text{ G} \]
Electron cloud in the SPS: the future

- **SPS** is presently producing the beams for LHC within specifications.

- In the future, **intensity and brightness out of the SPS will double** and the path against e-cloud is so defined:
  - Continue relying on scrubbing on the long term.
  - a-C coat selected chambers with low SEY threshold (amounting to about 20% of the total).
  - Continue a-C coating during next Long Shutdown, if necessary.

Dipole chamber cathode

M. Van Gompel & CERN coating team, MOOCA3

Straight Section Chamber cathode
Electron cloud in the SPS: the future

⇒ Logistics for **a-C coating** of different types of chambers successfully proven during the last Technical Stop.

M. Van Gompel & CERN coating team, MOOCA3
Electron cloud in the LHC

- **LHC** showed first signs of e-cloud with 150 ns beams (2010), but only in the form of **pressure rise** in the interaction regions
  - **Solenoids** were applied at some locations and worked effectively to suppress locally the e-cloud
Electron cloud in the LHC

- It was with **50 ns beams** (2011) that clear signs of beam degradation from e-cloud appeared
  - Scrubbing run (10 days) necessary (beginning 2011) to go in physics production with 50 ns beams

Day 1 of scrubbing – 300 bunches
Electron cloud in the LHC

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  - Scrubbing run (10 days) necessary (beginning 2011) to go in physics production with 50 ns beams
  - However, injection of the first 25 beams led to strong e-cloud driven instabilities → High chromaticity needed at injection

**First injection of 48 bunches with 25 ns spacing**

![Measurement and Simulation](chart.png)
Electron cloud in the LHC

- It was with **50 ns beams** (2011) that clear signs of beam degradation from e-cloud appeared
  - Scrubbing run (10 days) necessary (beginning 2011) to go in physics production with 50 ns beams
  - However, injection of the first 25 beams led to strong e-cloud driven instabilities → High chromaticity needed at injection
  - Tests with 25 ns beams in the course of 2011 already provided enough ‘**conditioning margin**’ in the arcs to run stably 50 ns beams for physics throughout 2011 and 2012, without requiring additional dedicated scrubbing runs
The evolution of the SEY in the beam screen of the arcs in 2011 could be reconstructed using the **measured heat load data** in combination with **PyECLoud simulations** done with the measured beam profiles.
Electron cloud in the LHC

- The scrubbing achieved until end 2012 was undone when LHC was vented during Long Shutdown 1 (LS1)
- In 2015 it took **24 days** of patient and gradual scrubbing to enable LHC to start physics production with 25 ns beams
Electron cloud in the LHC

- To fill LHC with 25 ns beams in presence of electron cloud it has been necessary to run with high chromaticity and octupole currents throughout the cycle (A. Romano’s poster, TUPVA018)
- More scrubbing has been accumulated while running for physics with 25 ns beams during 2015 and 2016 (poster TUPVA019)
Electron cloud in the LHC

- To fill LHC with 25 ns beams in presence of electron cloud it has been necessary to run with high chromaticity and octupole currents throughout the cycle (A. Romano’s poster, TUPVA018).
- More scrubbing has been accumulated while running for physics with 25 ns beams during 2015 and 2016 (poster TUPVA019).

Open questions:
Why do different sectors behave differently?
Has scrubbing saturated or can we still gain something?
Electron cloud in the LHC: the future

• In the High Luminosity (HL) era, LHC will also run with double intensity and brightness
• Dependence on bunch intensity seems to be favorable in both dipoles and quadrupoles for low enough SEY values (pending experimental verification)
Electron cloud in the LHC: the future

• In the **High Luminosity** (HL) era, LHC will also run with **double intensity and brightness**
• Dependence on bunch intensity seems to be favorable in both dipoles and quadrupoles for low enough SEY values (pending experimental verification)
• **Back up solution**: Use low electron cloud filling patterns with gaps to suppress the build up of the electron cloud (proved to work!)
  ○ At the expense of the number of bunches in the machine
Electron cloud in the LHC: the future

25 ns beam in full trains of 72 bunches

25 ns beam in trains of 56 bunches with gaps
Closing remarks

- Thanks to intensive measurements and highly empowered simulation tools, we have reached a deep knowledge of the electron cloud in the different CERN accelerators.

- Some lessons learnt on the way
  - **Scrubbing** is a formidable weapon to run machines with no surface treatment of the vacuum chamber surface, provided that
    - The SEY threshold for the desired beam parameters is not below the achievable range
    - Efficient ways of **stabilising the beam** (e.g. chromaticity, transverse feedback, Landau damping) can be employed operationally and scrubbing runs are performed
    - Point-like limitations from e-cloud are carefully avoided
  - **Surface treatments** to lower the SEY have been extensively developed and should become baseline for future machines operating with parameters in the e-cloud range (compatibly with impedance and other constraints)
Thank you for your attention