Dust-charging environment in accelerators: electron clouds

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Workshop on Dust Charging and Beam-Dust Interaction in Particle Accelerators
CERN, Geneva, Switzerland
13 June 2023

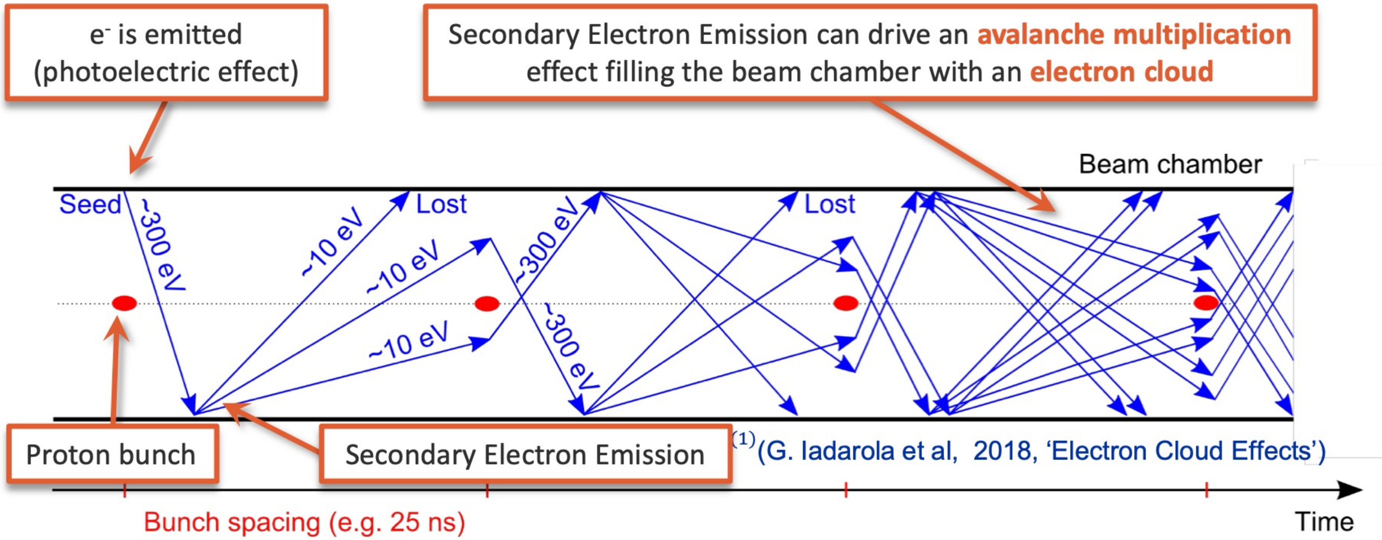
Outline

1. Basic mechanisms of electron cloud formation

2. Implications of electron clouds

3. Mitigation measures

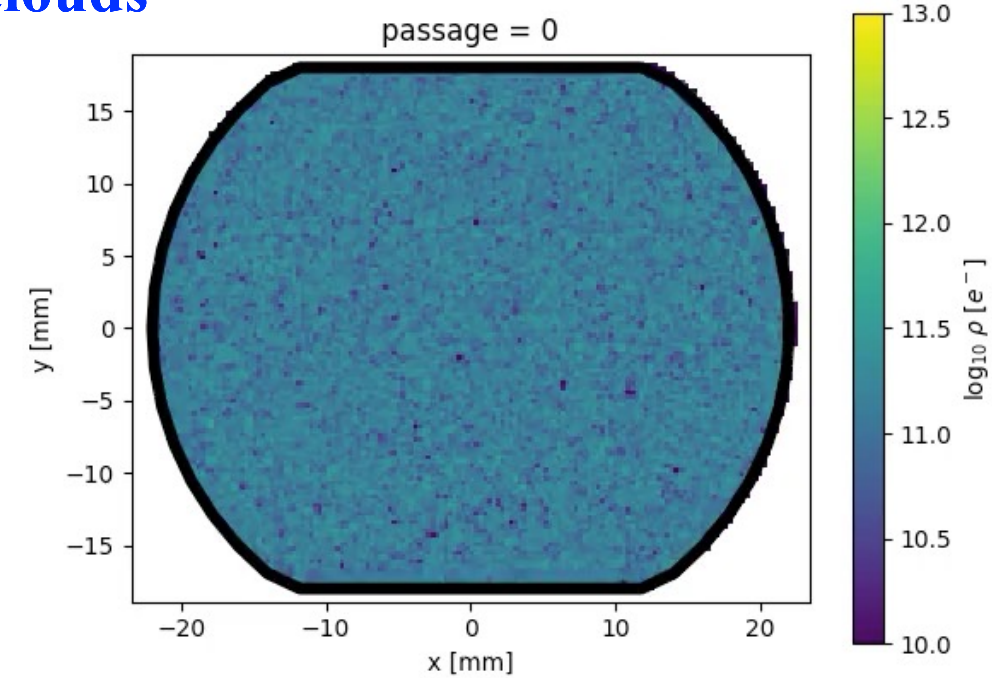
Electron clouds



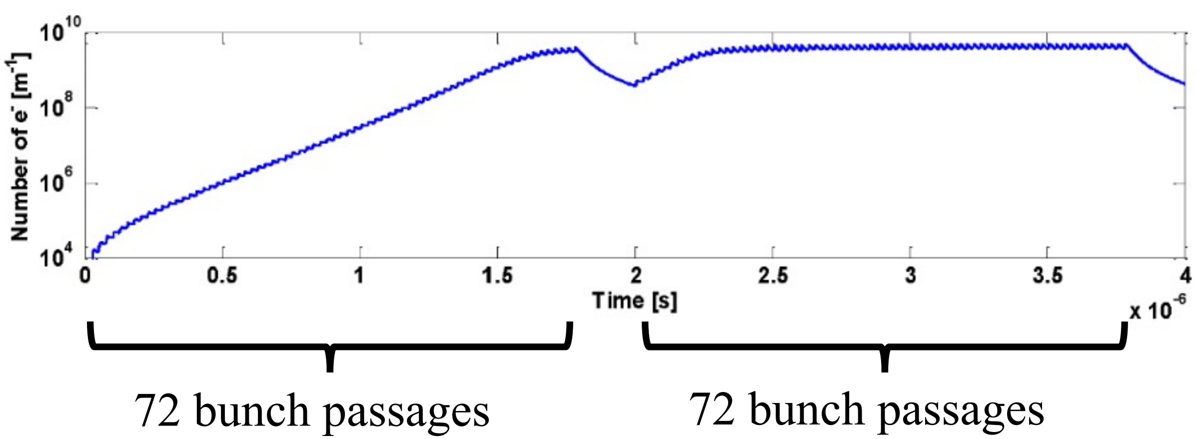
1. Electrons are introduced into the beam chamber (residual gas ionization / synchr. rad. + photoelectric effect)
2. Electrons are accelerated by passing bunches and impact on beam chamber.
   - Depending on energy of electron and **Secondary Emission Yield** of surface, electrons can be emitted.

If conditions allow, **electrons multiply exponentially (multipacting)!**

Electron clouds



- Electrons multiply until a dynamic equilibrium is reached.
- Number of electrons quickly decays when bunches are not passing.



Main ingredients of e-clouds

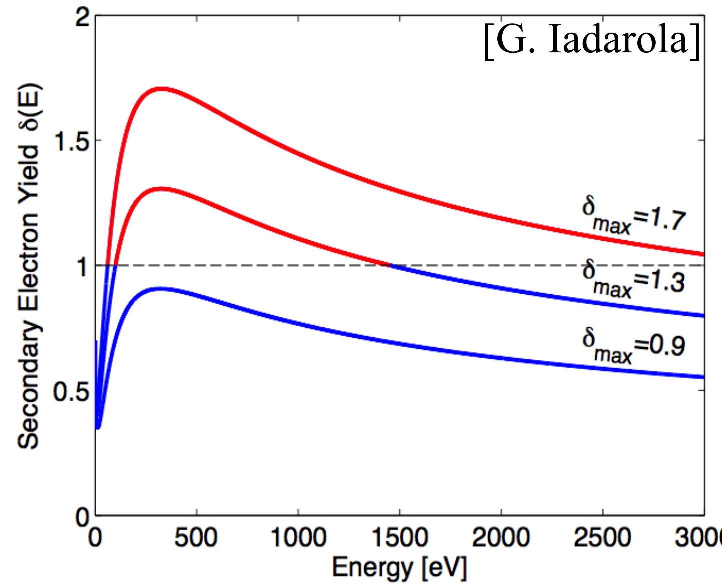
- **Particle beam:**
  1. Positively charged
  2. Bunch spacing *(25 ns)*
  3. Bunch intensity *(1.2 10^{11} p+/bunch)*
  4. Bunch length *(1.2 ns)*

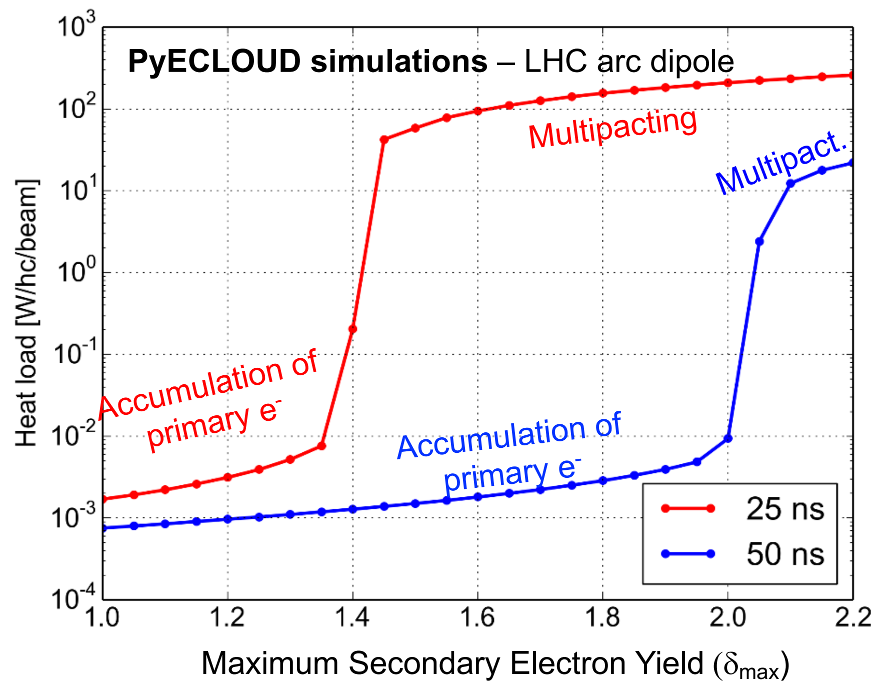
- **Beam chamber:**
  1. Geometry
     a. e^- time of flight
     b. e^- acceleration
  2. **Secondary Emission Yield**
     (Ratio between emitted and impacting electrons vs energy)

$$\delta(E) = \frac{I_{\text{emit}}}{I_{\text{imp}}(E)}$$

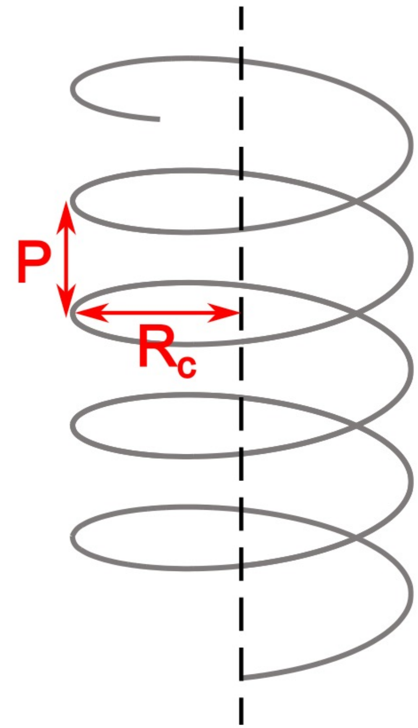
- **External magnetic field**

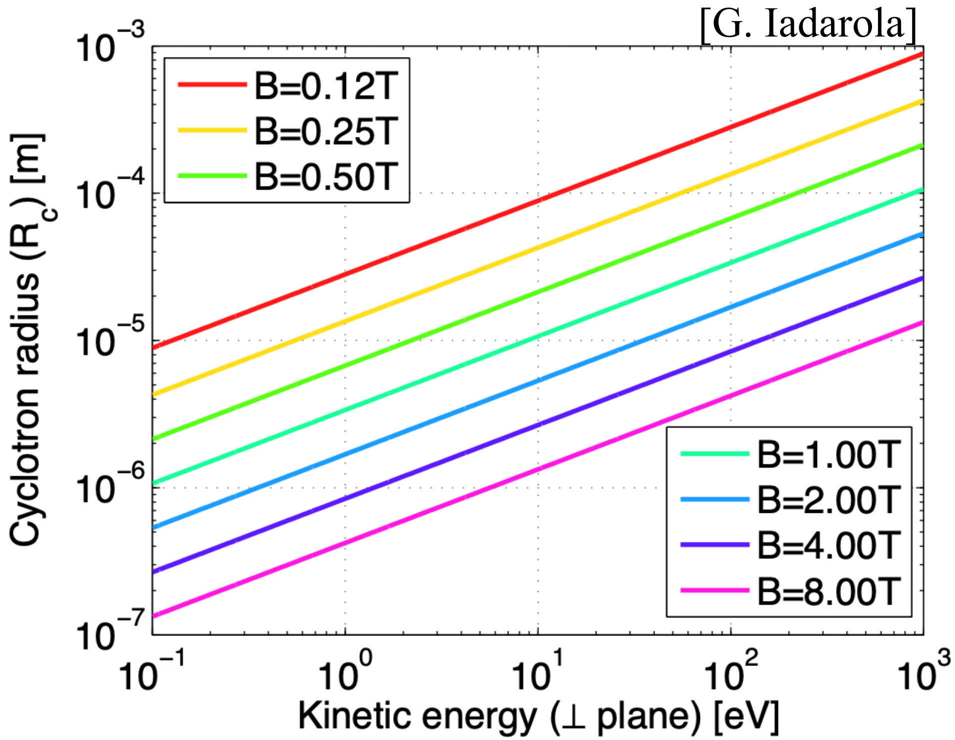
SEY Curves for different surfaces





Magnetic fields

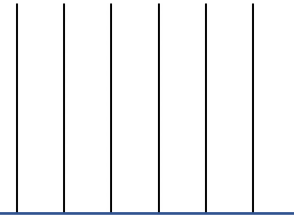


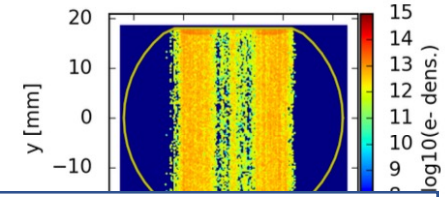


- In magnetic fields, electrons perform helicoidal trajectories along magnetic field lines.
- Even in "weak" fields, radius is rather small.
  → Electrons are practically moving along magnetic field lines.

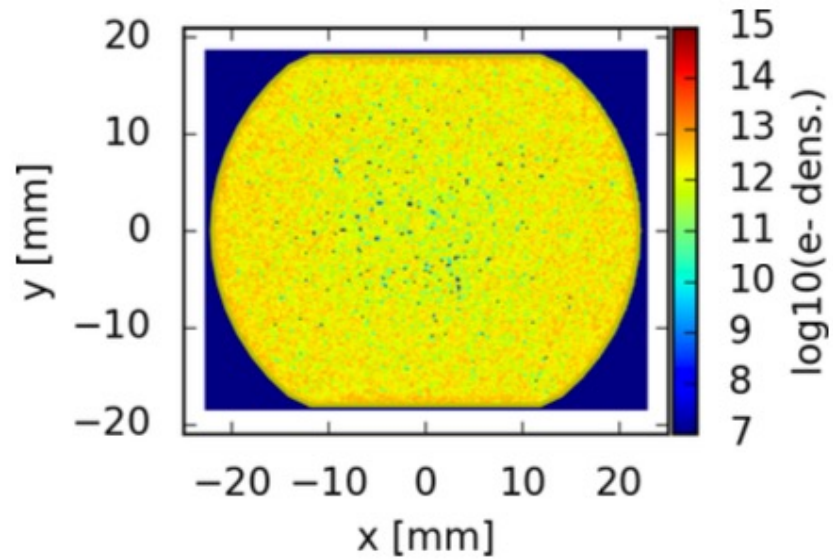
Typical magnets in synchrotrons

- Dipole magnets:
  → Bend reference trajectory

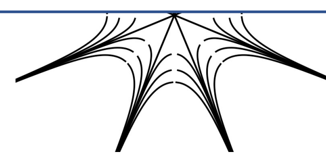


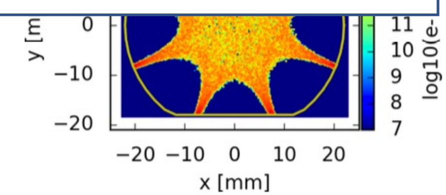


- Drift space / no magnetic field
  → electrons not constrained



→ Control dependence of focusing on oscillation amplitude





[*P. Dijkstal* and *G. Iadarola]*

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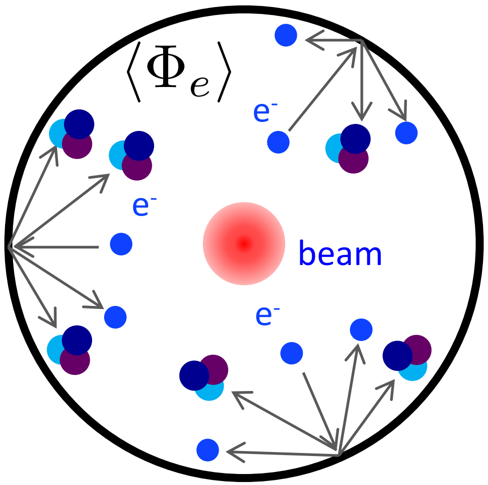
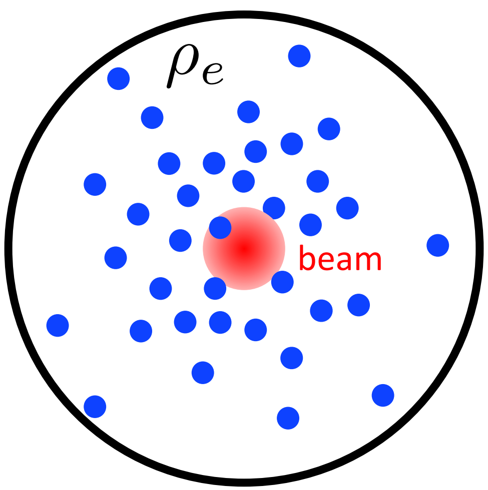
Electron cloud effects



The electron flux to the wall is responsible for

- Dynamic pressure rise
- Heat deposition
- Spurious signal for beam instrumentation
- **Dust-charging**

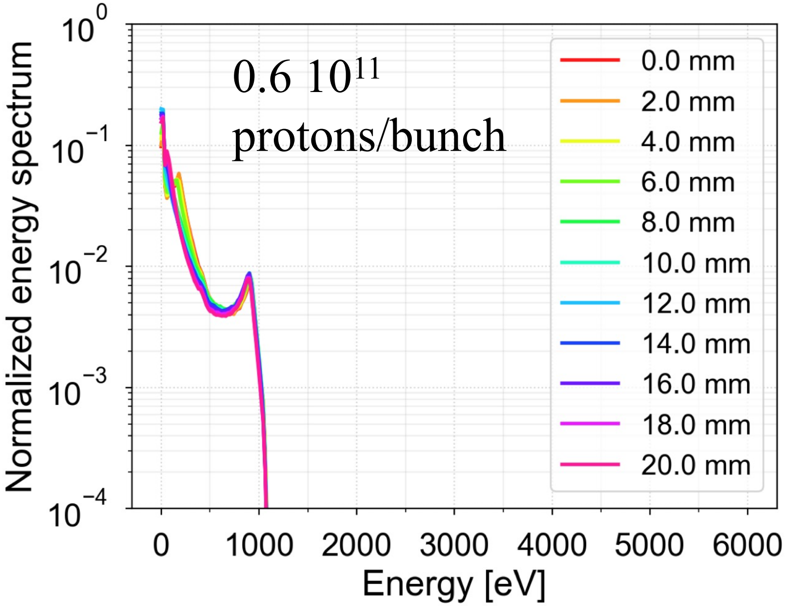


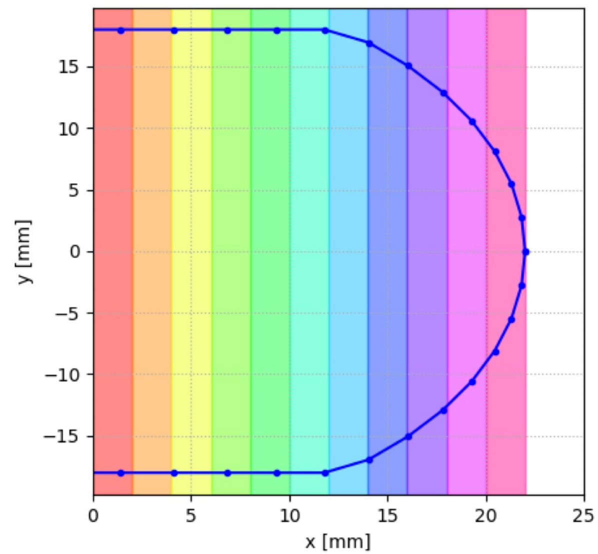
[G. Rumolo]

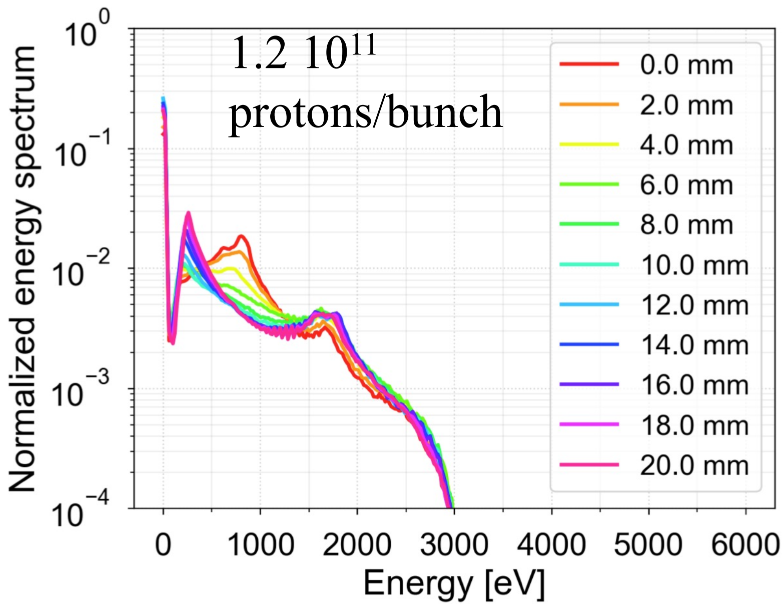
The electron density inside the chamber causes:

- Tune shift along the bunch train
- Synchronous phase shift along bunch train.
- Coherent beam instabilities (single and coupled bunch)
- Incoherent effects (beam lifetime degradation and slow emittance growth)
- Formation of ion clouds (See talk by L. Mether)

Impacting electron energy in a Drift space



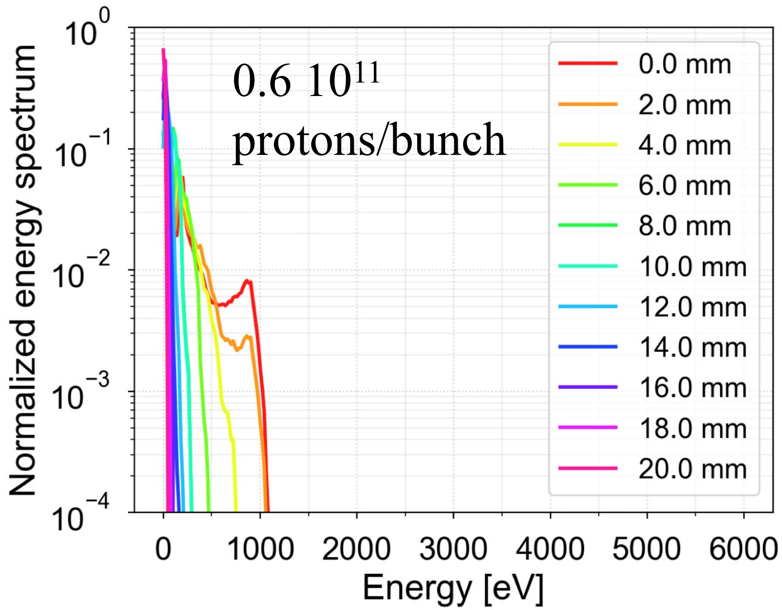


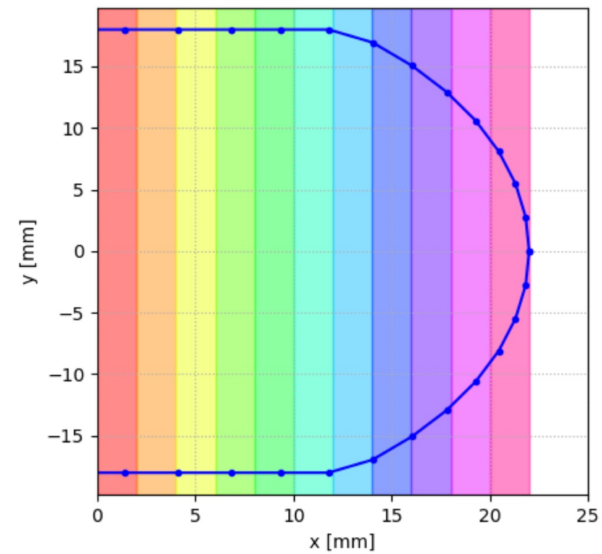


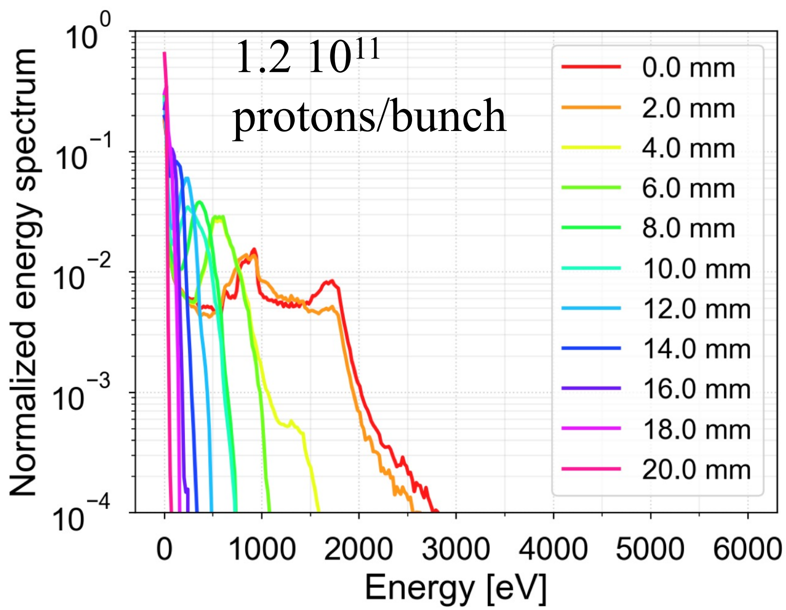
- Vast majority of electrons are low energy O(10 eV), decelerated by the electron space charge.
- Many high energy electrons O(1 keV), accelerated by the beam.
- Electron energy similar at different distances from beam (center). **(Drift)**

[G. Skripka, Electron Cloud Meeting #71]

Impacting electron energy in a Dipole magnet







- Vast majority of electrons are low energy O(10 eV), decelerated by the electron space charge.
- Many high energy electrons O(1 keV), accelerated by the beam.
- Electron energy heavily depends on distance from beam (center). **(Dipole)**

[G. Skripka, Electron Cloud Meeting #71]

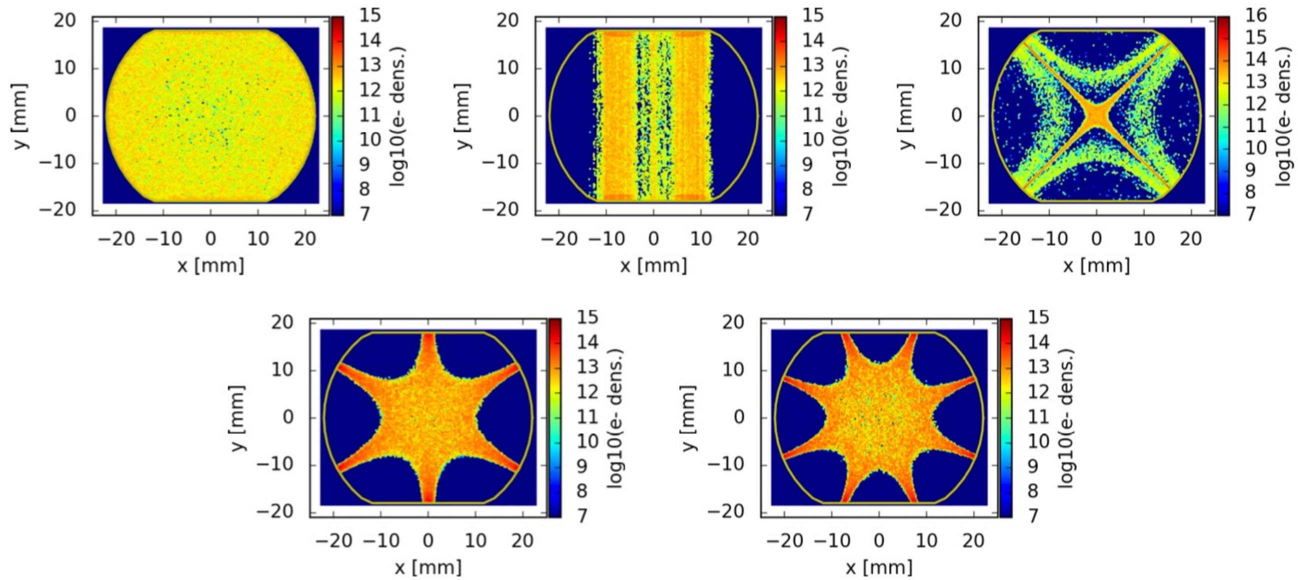
Impacting electron energy summary

- Vast majority of electrons are low energy O(10 eV), decelerated by the electron space charge.
- Higher bunch intensity leads to higher energy electrons O(1 keV).

1) Drift space: No strong azimuthal preference.

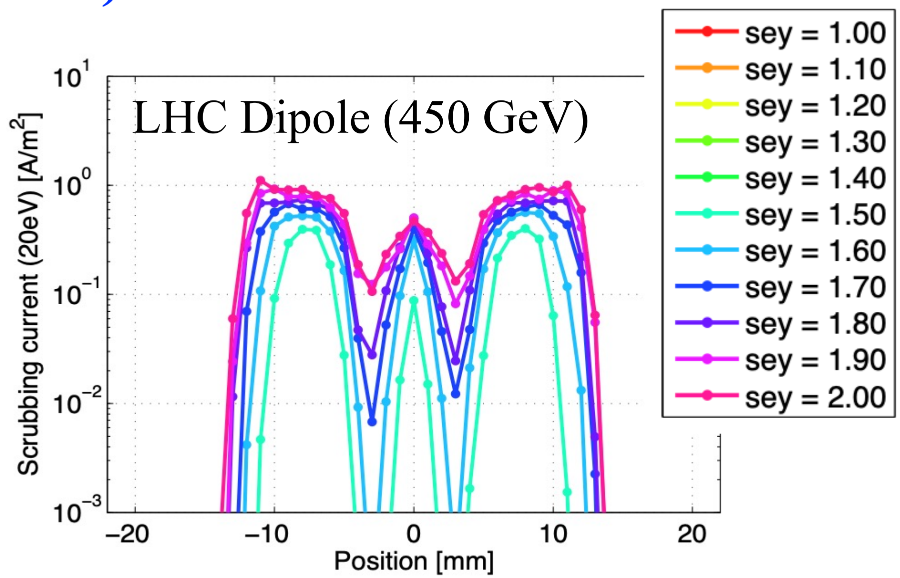
2) Dipole magnet: Electron energy depends on impact point.

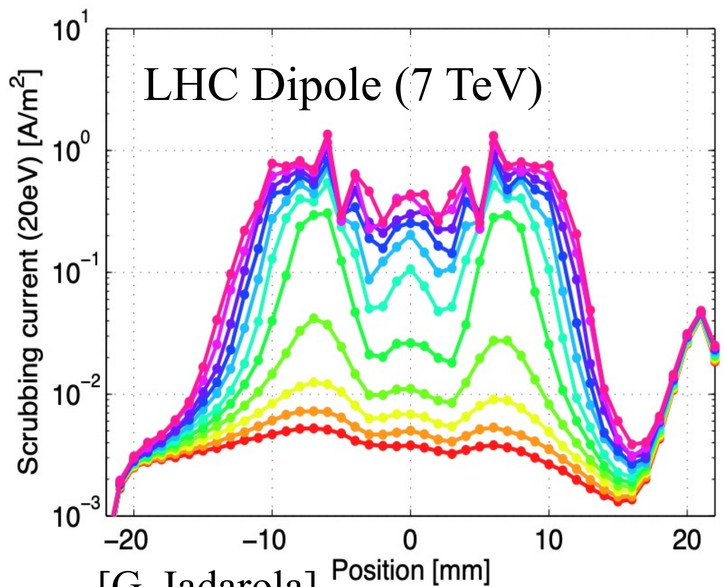
3) Quadrupole, sextupole, octupole, e.t.c. magnets: All electrons converge to the magnetic poles.



Current density (Dipole magnets)

- Current density depends on many parameters:
  1. Secondary Emission Yield
  2. Primary electrons (Synchr. rad.)
  3. Bunch intensity
  4. External magnetic field
  5. Position in vacuum chamber
  6. ...
- Current density can span over several orders of magnitudes.
- **Up to O(1 A/m^2) in dipole magnets.**
- Even higher in higher order magnets but current is localized.





[G. Iadarola]

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1. Basic mechanisms of electron cloud formation

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Mitigation measures

1. Coating of the vacuum chamber surface with a low-SEY material, e.g.:
    a. Amorphous carbon coating,
    b. Non-Evaporable Getter,
    c. ...

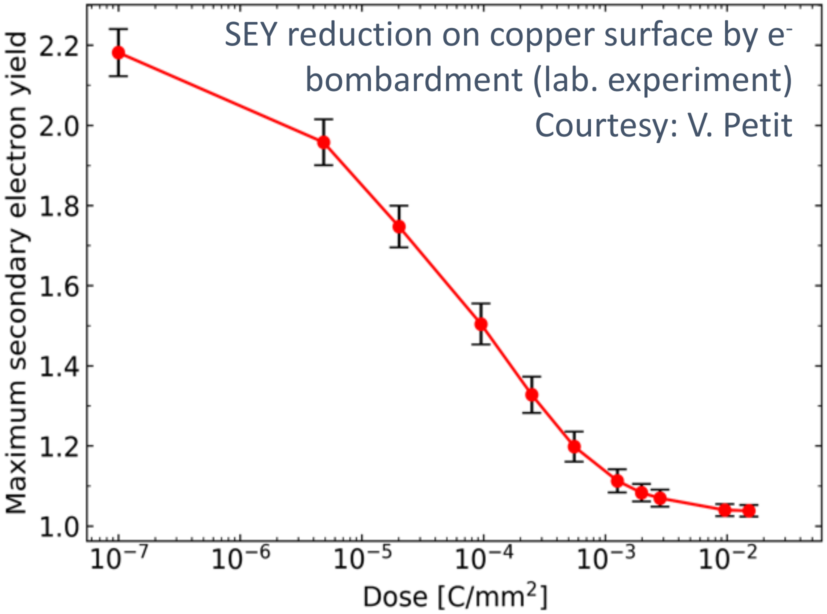
2. Change surface properties (see also talk by M. Himmerlich):
    a. Artificially induced roughness,
    b. Laser ablation,
    c. Macroscopic grooves,
    d. ...

3. Perturb electron dynamics to inhibit multipacting:
    a. Clearing electrodes (electric fields),
    b. Weak solenoid magnets (magnetic fields).

4. **Beam-induced scrubbing**

Beam-induced scrubbing

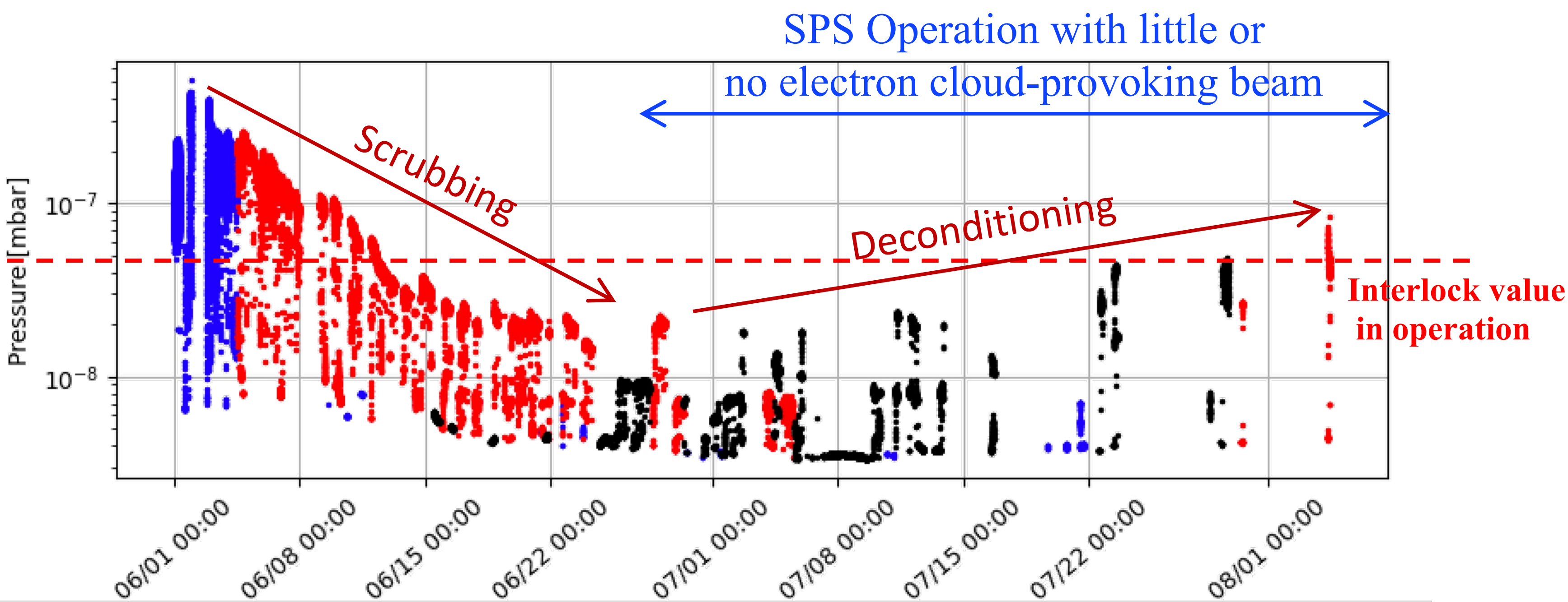
- The SEY of a surface is known to decrease under electron bombardment (scrubbing)
- Running an accelerator with electron cloud will gradually reduce the electron cloud itself
- E-cloud is self-curing if SEY can reduce below the threshold value
- In most cases, scrubbing will not completely stop electron cloud formation.



Unfortunately, surfaces may (partially) lose scrubbing.

Limitations of beam-induced scrubbing: Deconditioning

- In 2021, a newly installed kicker magnet in the SPS had a high Secondary Emission Yield → High pressure above operational limits.
- SPS was operated for weeks with high-intensity beams for the sole purpose of "beam-induced scrubbing" on this (and other) magnet(s).

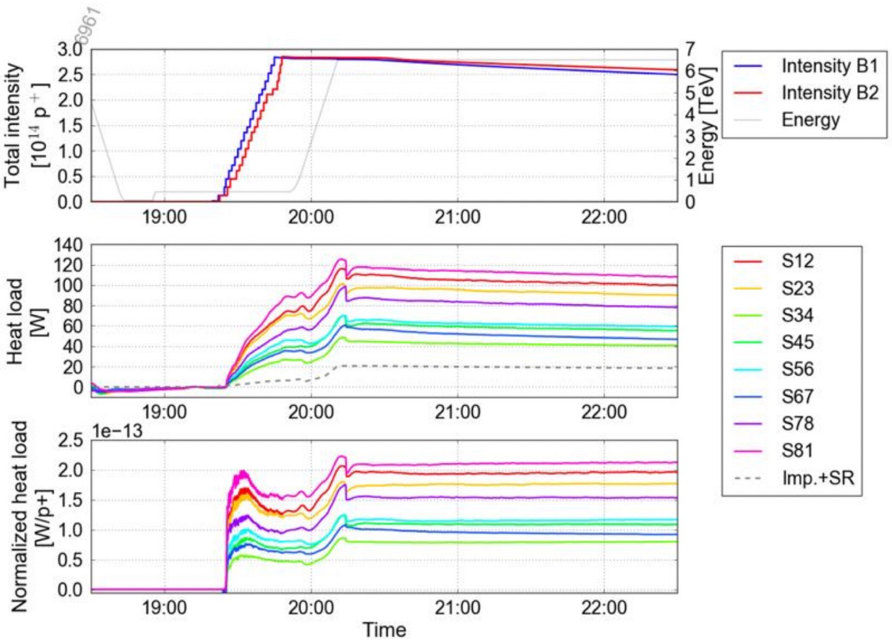


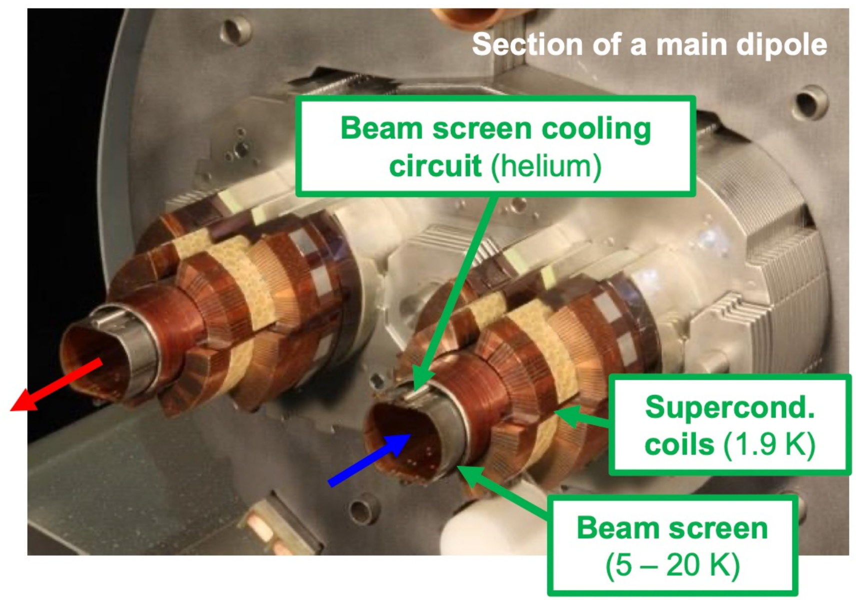
At cryogenic temperatures, it can get more complicated.

Beam-induced scrubbing: Run 2 experience

Beam induced heat loads on arc beam screens have been a challenge for LHC operation with 25 ns in 2015-2018: dominating total heat load on the cryo-plants

- Much larger than expected from impedance and synchrotron radiation
- Large differences between sectors and between consecutive cells in the same sector
- Degradation has been observed between Run 1 (2010) and Run 2 (2015)
- **CERN Beam-Induced Heat Load Task Force in-place to follow it up**



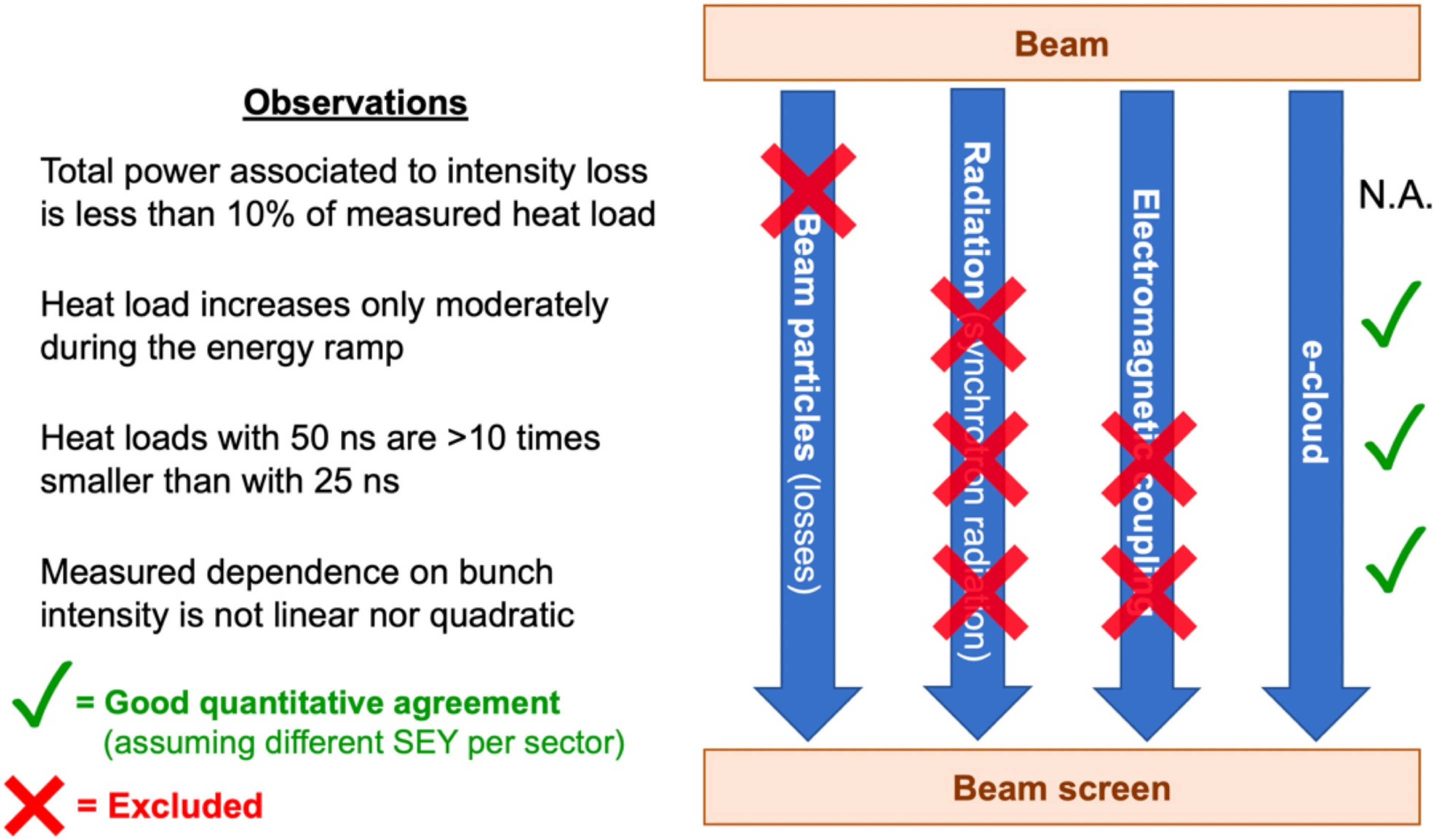


[G. Iadarola, 9th HL-LHC Collaboration meeting]

Beam-induced scrubbing: Run 2 experience

Beam observations in Run 2 indicated that:

- The additional heat load comes from electron cloud effects
- It is compatible with modifications in the beam-screen surface leading to higher Secondary Emission Yield (SEY)



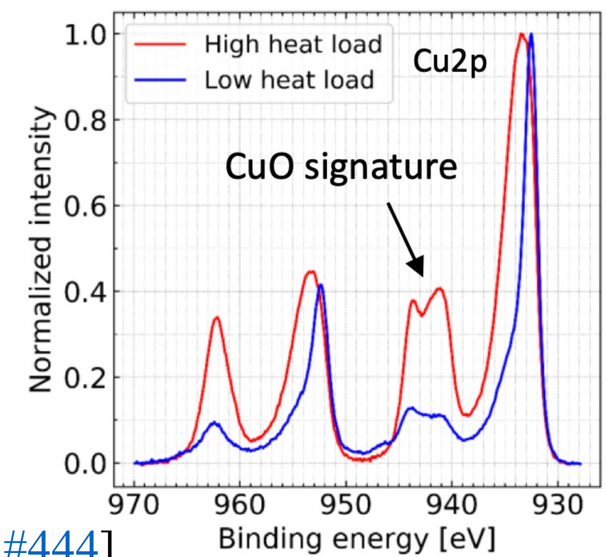
[G. Iadarola, 9th HL-LHC Collaboration meeting]

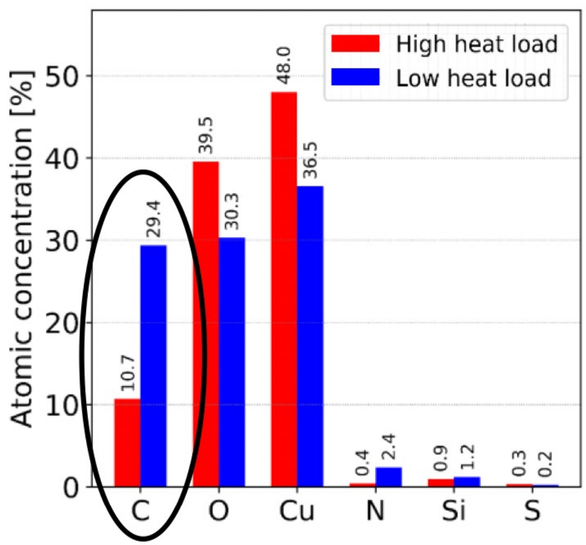
LS2 laboratory analysis

Laboratory analysis of beam screens extracted from high-load magnets identified:

- Presence of cupric oxide (CuO) instead of the native cuprous oxide (Cu_2O).
- When venting: $Cu(OH)_2$ can build up (long shutdown), acts as precursor for the formation of CuO.
- Low concentration of Carbon on high-heat load beam screen.
  - Carbon plays key role in achieving low SEY values.

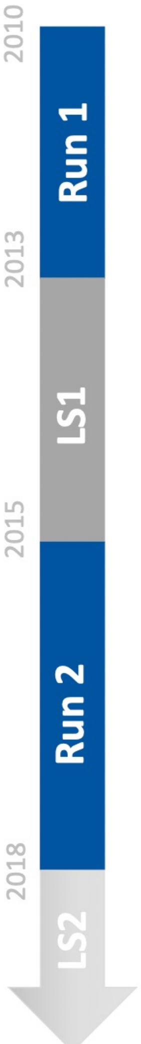
XPS analysis:





[V. Petit *et al*, LMC #444]

Underlying mechanism



Low $Cu(OH)_2$ coverage
and/or
Enough carbon to compensate for the presence of $Cu(OH)_2$
↓
CuO-free conditioning: low heat load

Venting for maintenance
$Cu(OH)_2$ uptake ↔ ambient conditions, surface state at venting

High $Cu(OH)_2$ coverage
(e.g. high humidity and/or increased surface reactivity)
and/or
Low carbon amount
↓
CuO build-up: high heat load sectors

Low $Cu(OH)_2$ coverage
(e.g. low humidity and/or “passivation”)
and/or
High carbon amount
↓
No CuO build-up: low heat load sectors

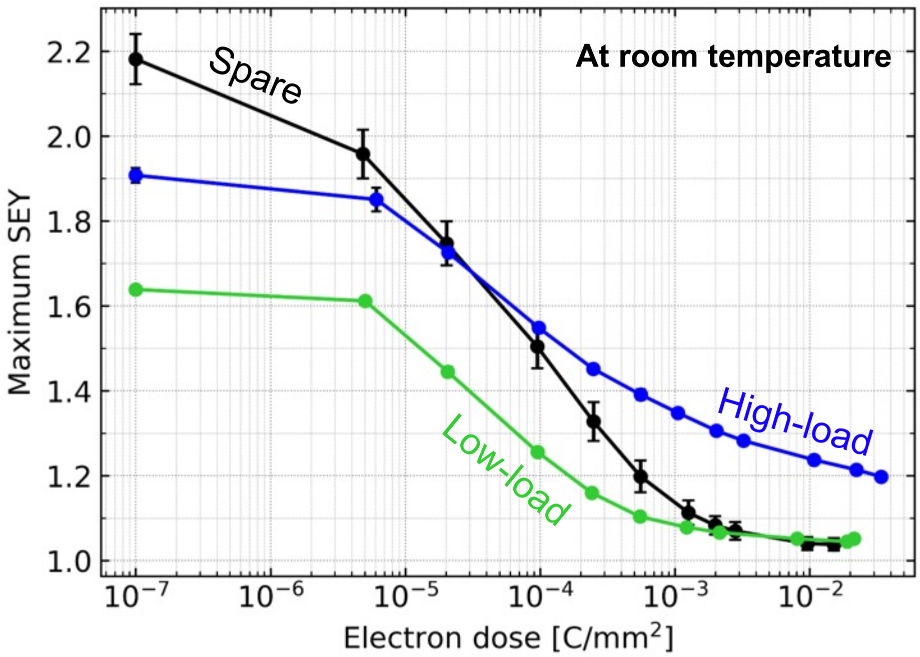
[V. Petit *et al*, LMC #444]

Remarks about beam-induced scrubbing

- After each cycle of conditioning → de-conditioning → re-conditioning, **SEY may not reach the same value.**
- Cryogenic conditions played vital role in evolution of SEY.
- SEY degraded and is expected to degrade even further due to the chemical alteration of the chamber's surface (formation of CuO, deplection of C).

- Best mitigation strategy: prevent electron clouds by acting directly on chamber surface. (Coating, surface treatment)

- Expensive



More details, see: V. Petit, presentation at LHC Performance Workshop 2022; V. Petit et al., Commun Phys **4**, 192 (2021)

Conclusion

Key parameter is Secondary Emission Yield of surface

Disclaimer:

- Electron cloud formation depends on many parameters.
- Different accelerators can have completely different types of electron clouds.
- Difficult to predict without simulations.
- Several simulation codes available (among which PyECLOUD, see appendix)

In context of dust-charging:

- Mostly low-energy electrons: O(10 eV)
- Intense beams can accelerate electrons to higher energies: O(1 keV)
- Current densities of up to O(1 A/m^2)
- Electron current is heavily directed by external magnetic fields

Dealing with electron clouds:

- Several techniques: surface coating, surface modifications, beam-induced scrubbing, clearing electrodes, solenoids.
- Cryogenic temperatures can influence evolution of SEY.
- Secondary Emission Yield is not guaranteed to be stable if left alone.

Thank you for your attention!

Konstantinos Paraschou

Backup slides

Modeling of electron cloud effects

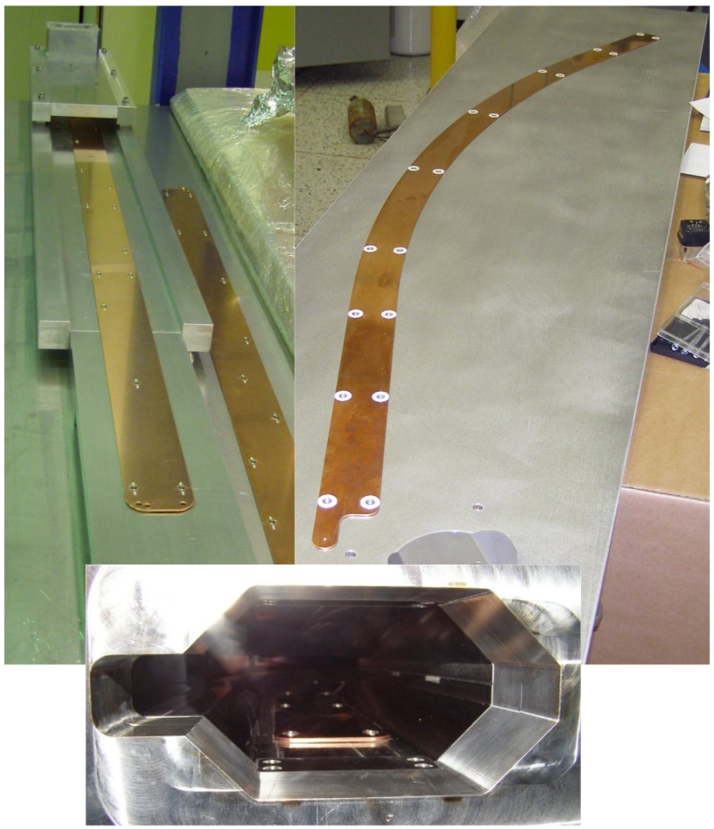
- **E-cloud build-up →** Solely focuses on electron dynamics with an unperturbed beam distribution to determine how the e-cloud forms and where it saturates
- Many codes developed over the years
  - ECLOUD [*CERN*, Zimmermann *et al*., Crittenden (*Cornell*)]
  - POSINST [*LBNL*, Furman, Pivi]
  - CLOUDLAND [*BNL-SLAC*, Wang]
  - CSEC [*BNL*, Blaskiewicz]
  - PEI [*KEK*, Ohmi]
  - FAKTOR2 [*CERN*, Bruns]
  - PyECLOUD [*CERN*, Iadarola, Mether, Belli, Dijkstaal, Wulf, ...] – an evolution of ECLOUD able to deal also with ions and several species
  - WARP-PyECLOUD [*CERN-LBL*, Giacomel, Vay, Iadarola] – to include RF fields

Mitigation strategies

The e-cloud can be mitigated by **perturbing the electrons dynamics**:

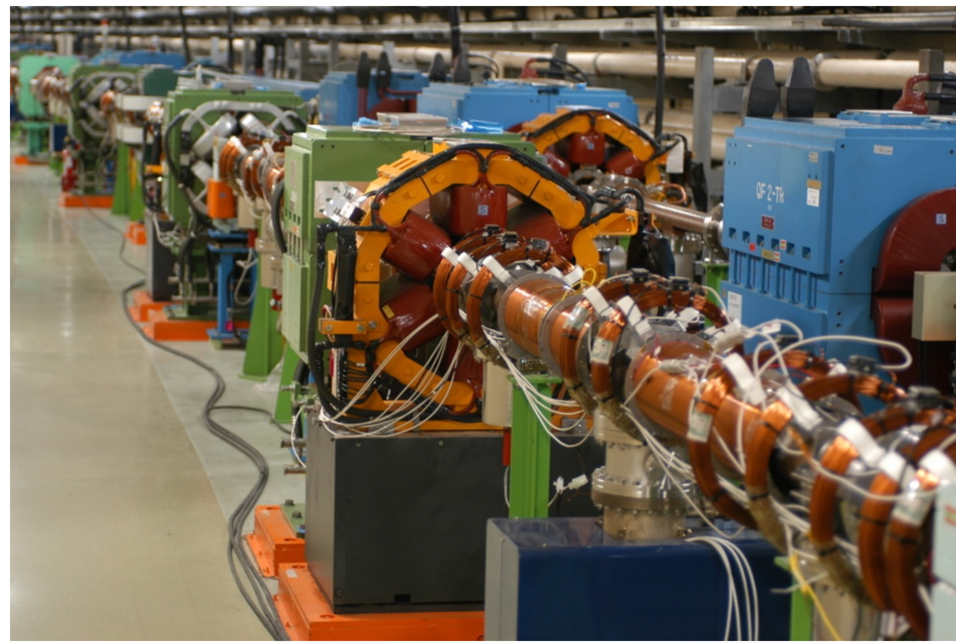
- **Electric fields** → cleaning electrodes
- Weak **axial magnetic fields** → solenoids, permanent magnets

Cleaning electrode in the DAΦNE bending magnets



M. Zobov, "Operating Experience with Electron Cloud Clearing Electrodes at DAFNE", ECLOUD12

Anti e-cloud solenoids at SuperKEKB



H. Koiso, Commissioning Status of High Luminosity Collider Rings for SuperKEKB, IPAC17

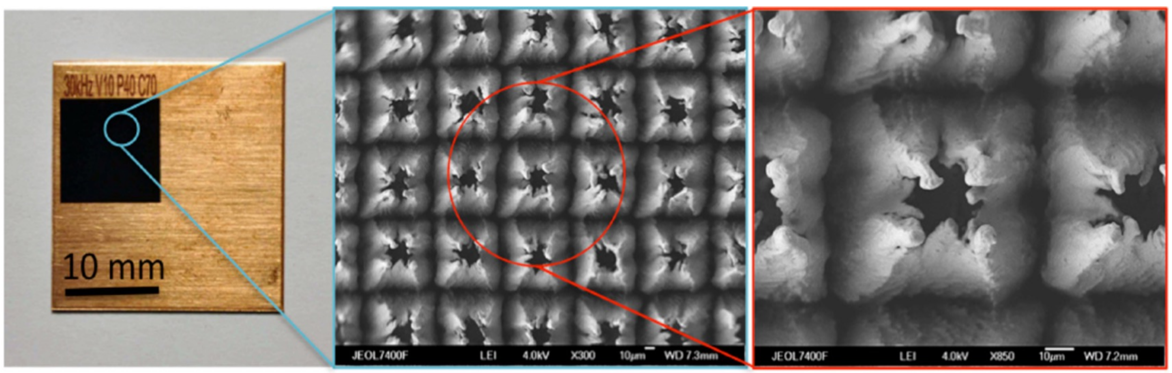
Courtesy of G. Iadarola

Mitigation strategies

The e-cloud can be mitigated by acting on **surface properties**:

- Decrease Secondary Electron Yield (SEY) by surface **conditioning (beam scrubbing)**
- Surface **morphological changes**:
    - Artificially induced **roughness**, **laser ablation**
    - Macroscopic **grooves**

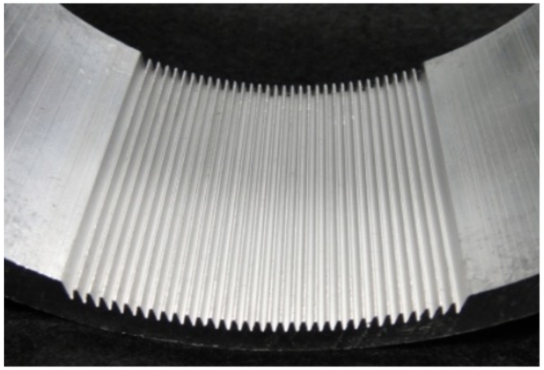
Ongoing development for HL-LHC upgrade

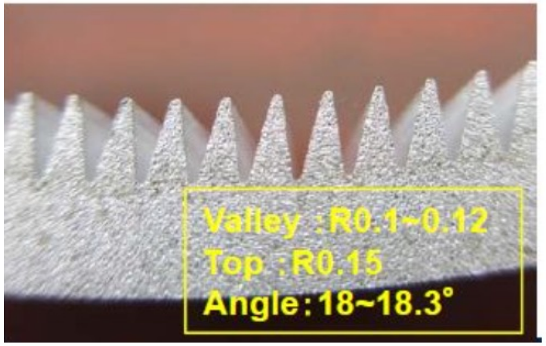


Appl. Phys. Lett. 101, 2319021 (2012).
Physics Highlights – Physics Today (February 2013).
Opt. Mater. Exp. 1,1425 (2011).

University of Dundee

Installed in SuperKEKB





Courtesy of G. Iadarola