The electron cloud and its impact on the LHC and future colliders

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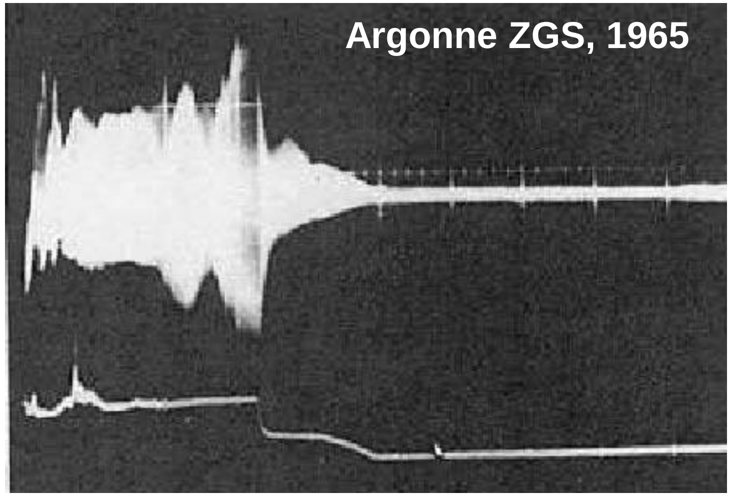
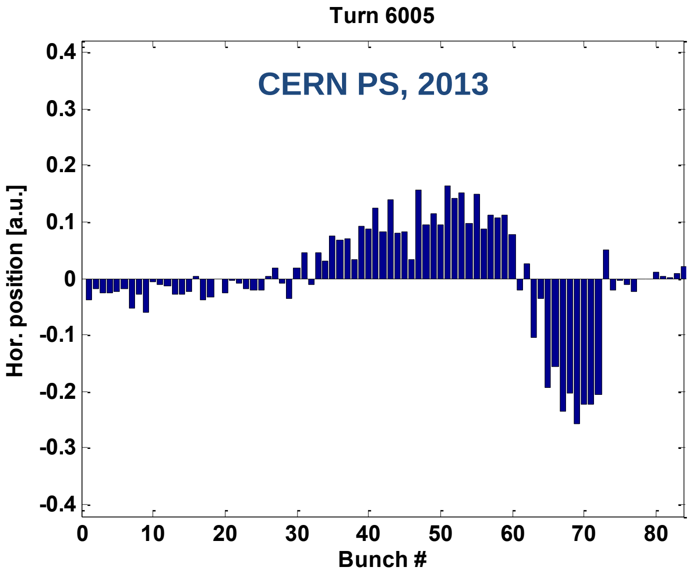
The electron cloud

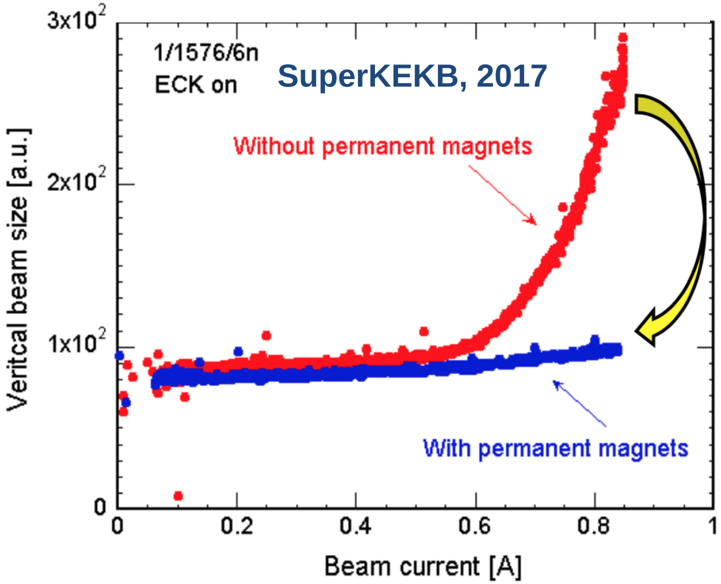
- Electron clouds can build-up due to an avalanche multiplication of electrons in the beam chamber
    - Lead to several detrimental effects on the beam and on the accelerator environment

- Electron cloud effects have been observed in many accelerators since the 1960’s
    - Affect mainly machines operating with positively charged particle bunches (p+, e+, positive ions…)

- In currently running machines, electron cloud effects have occurred to varying degrees e.g., in DAΦNE, SuperKEKB, RHIC, and CERN PS, SPS and LHC, which is very strongly impacted by the effects

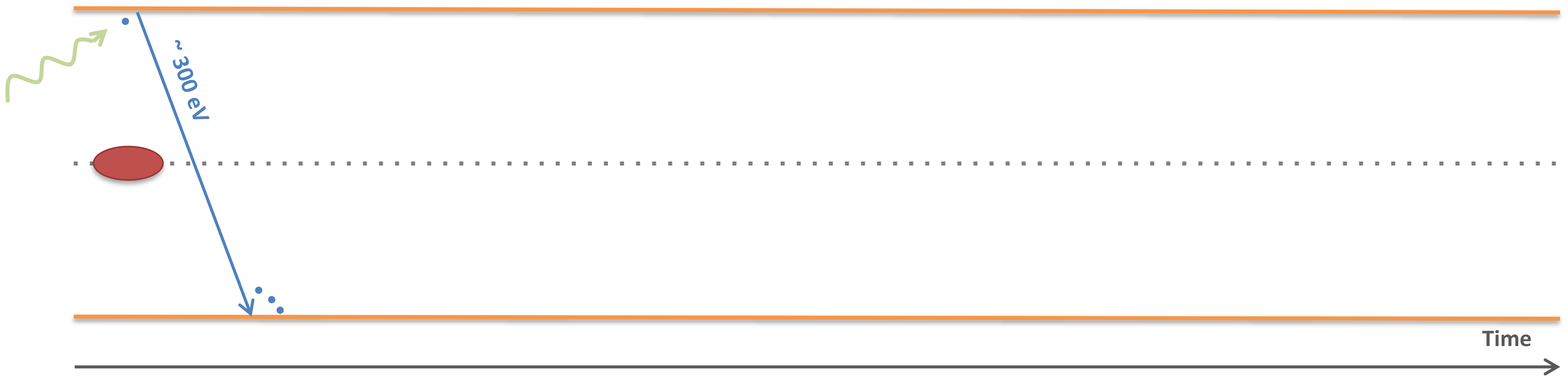






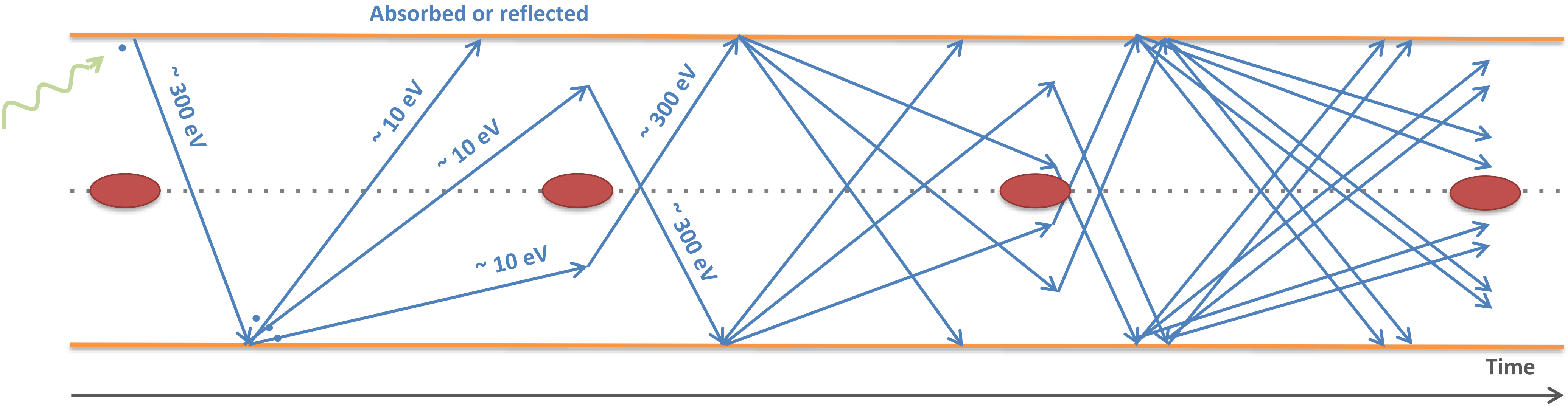
[H. Koiso, IPAC’17]

Electron cloud build-up



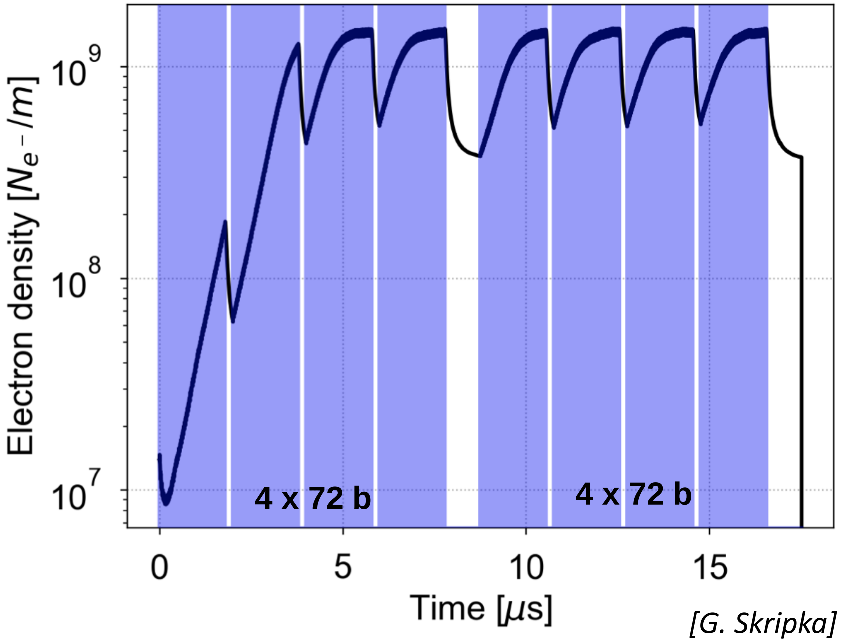
- Seed electrons, generated by e.g. photoemission, are accelerated by the beam field
    - When the accelerated electrons hit the wall, secondary emission of low-energy electrons can occur

Electron cloud build-up



- When the secondary electrons reach the wall, they are most likely absorbed
  - Electrons that survive until the next bunch passage are accelerated and can emit more secondaries

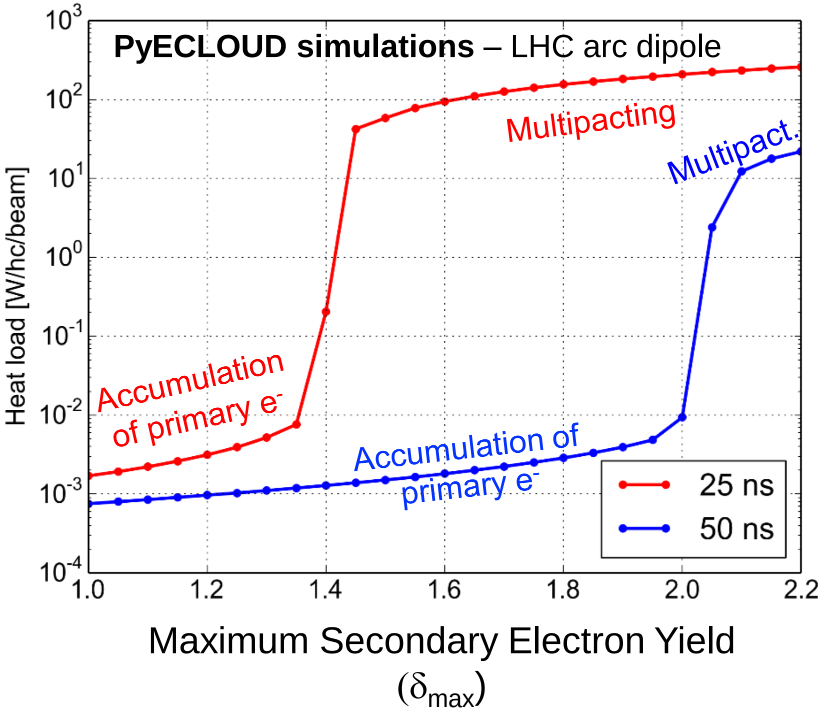
- After several bunch passages, a dynamic equilibrium is reached: the electron cloud
  - Bunches towards the end of trains are more affected



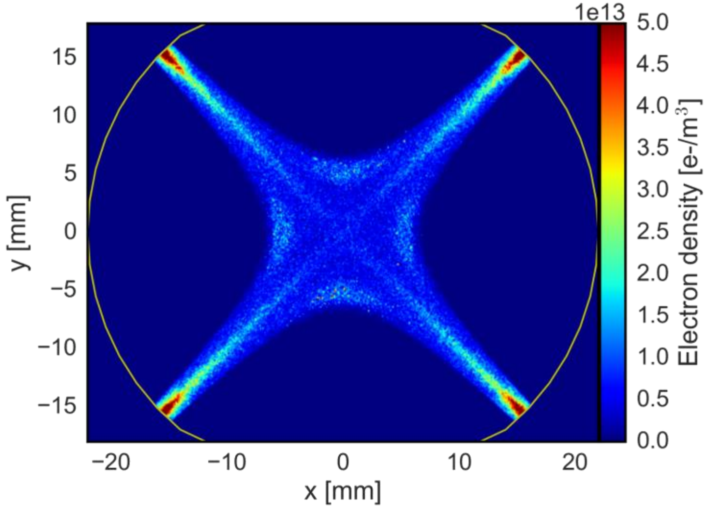
[G. Skripka]

Main factors in electron cloud build-up

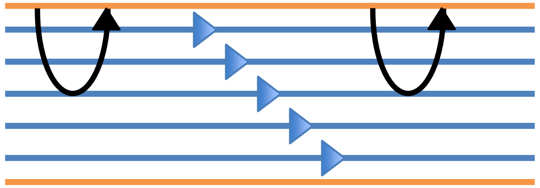
1. The survival rate of low-energy electrons between successive bunch passages
   - Depends strongly on the **chamber dimensions** and the **bunch spacing**
   - Can also be influenced by magnetic fields



Magnetic trapping in quadrupoles and higher order multipoles can extend the electron lifetime



Longitudinal solenoid fields can bend emitted electrons back towards the surface reducing their lifetime

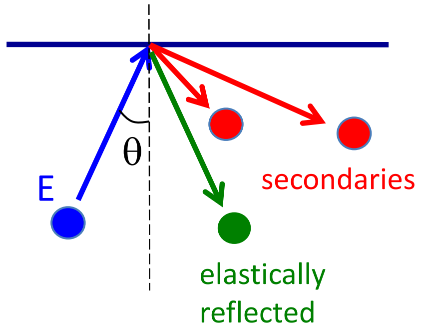


Main factors in electron cloud build-up

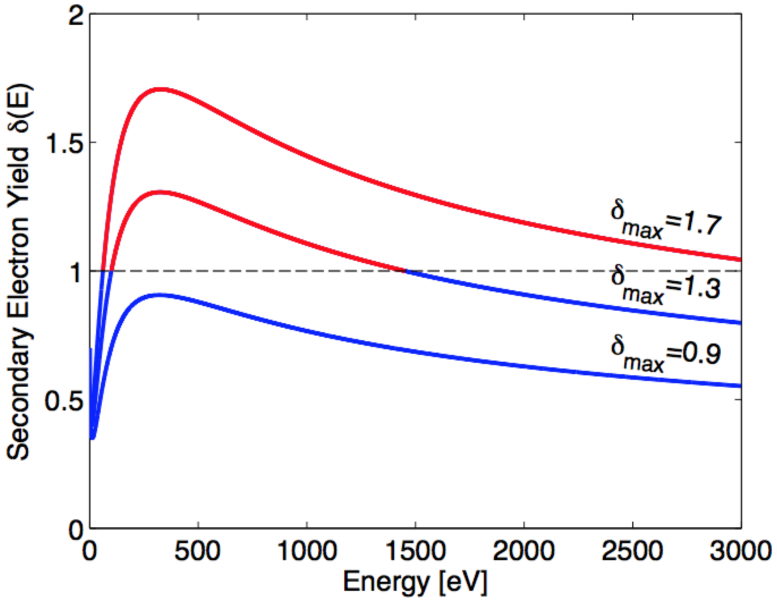
2. The Secondary Emission Yield (SEY) of electrons

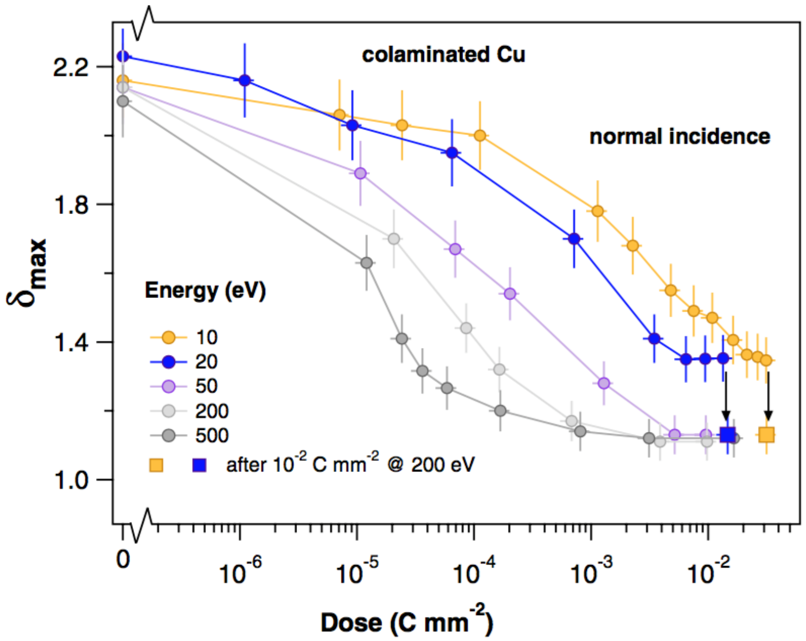
- Defined as the ratio between emitted and impacting electrons
- A function of the energy and incidence angle of the impacting electrons

$$\delta(E,\theta) = \frac{I_{\mathrm{emit}}}{I_{\mathrm{imp}}(E,\theta)}$$



The SEY is often parameterised by its maximum value δ_{max}





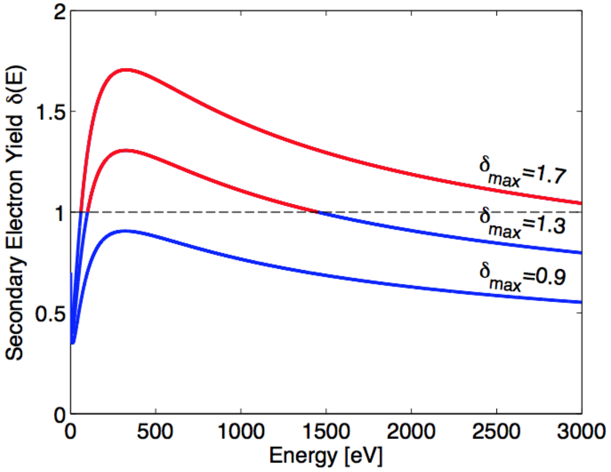
[R. Cimino et al. Phys. Rev. Lett. ***109****, 064801 – 2012]*

δ_{max} is usually high for air-exposed surfaces, but reduces with electron irradiation

→ Irradiation by the electron cloud itself: beam-induced conditioning (scrubbing)

Main factors in electron cloud build-up

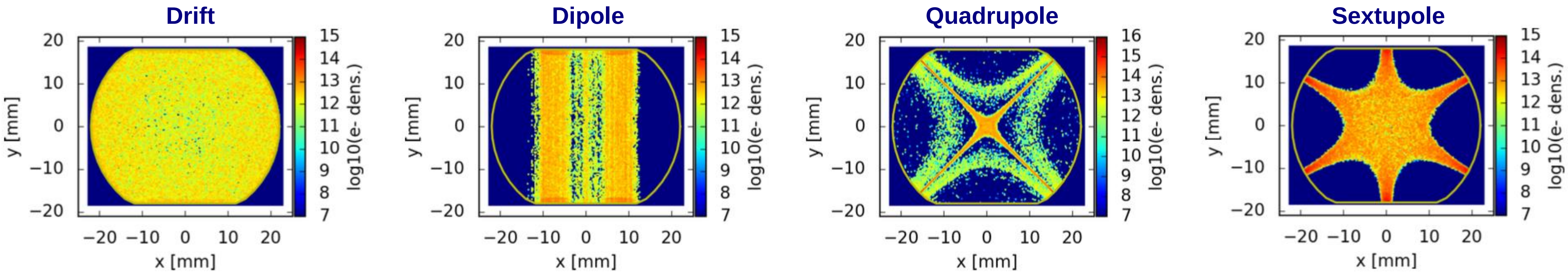
2. The Secondary Emission Yield (SEY) of electrons



- ○ Due to the non-monotonic dependence on the electron energy, the surface acts as a net emitter over a limited energy range

→ Build-up depends strongly on **bunch intensity** and **bunch length**, which both impact the instantaneous beam field that determines the electron acceleration

→ Together with the trapping of electrons around magnetic field lines, the energy dependence of the SEY curve leads to the characteristic electron cloud patterns for each magnetic multipole


Drift **Dipole** **Quadrupole** **Sextupole**

[P. Dijkstal]

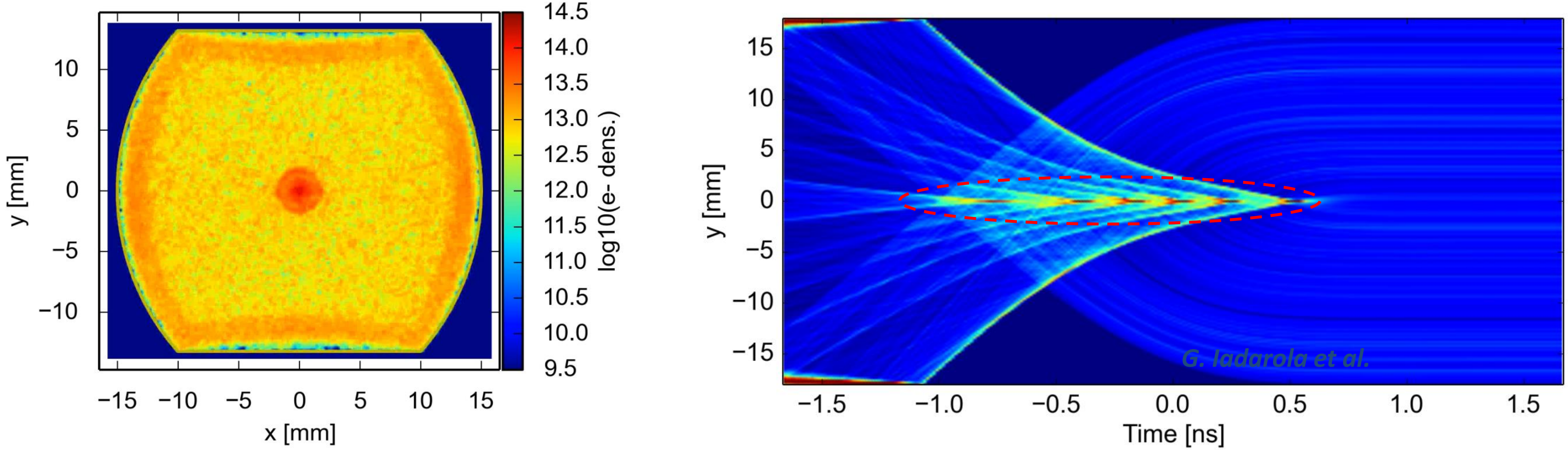
The electron cloud pinch

- If the magnetic field lines allow it, the electrons attracted by the beam field are pulled into the bunch where they oscillate in the beam field during the bunch passage
    - ○ The accumulated effect of the electron cloud pinch around the machine can lead to significant consequences for the beam dynamics

Electron density during the passage of an LHC-like bunch

Transverse view

Longitudinal view



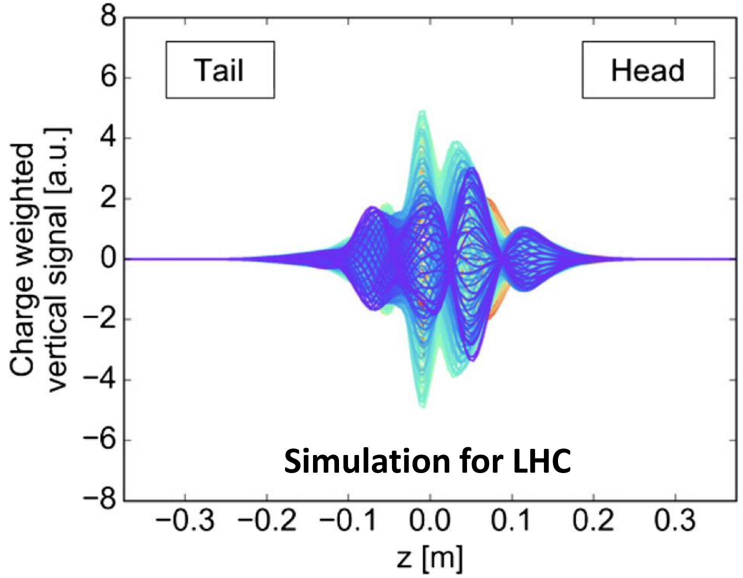
G. Iadarola et al.

Impact on beam dynamics

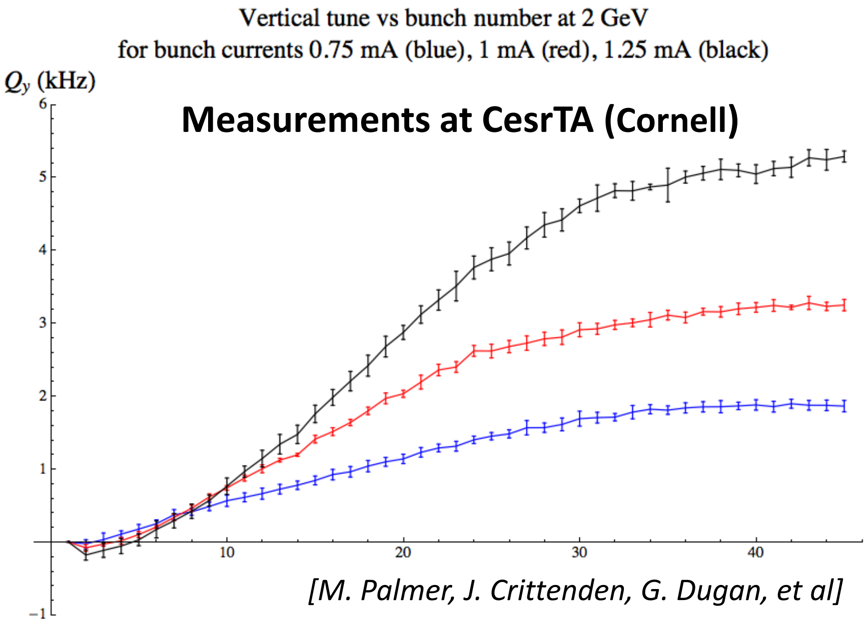
- Single-bunch instabilities
  - Causing fast emittance growth and beam losses
  - Characterized by fast intra-bunch motion → Difficult to damp with conventional bunch-by-bunch feedback systems

- Tune shift along the bunch train

- Tune spread leading to resonance excitation, emittance growth and slow beam losses



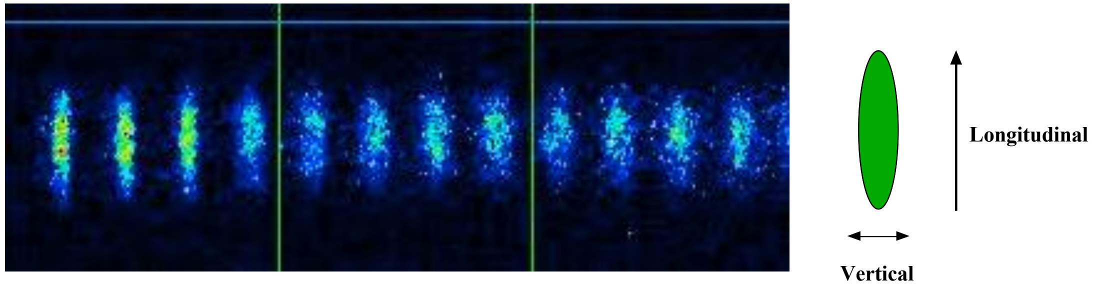
[A. Romano et al, Phys. Rev. Accel. Beams 21, 061002]



Measurements at CesrTA (Cornell)

[M. Palmer, J. Crittenden, G. Dugan, et al]

Vertical emittance blow up at KEK-LER

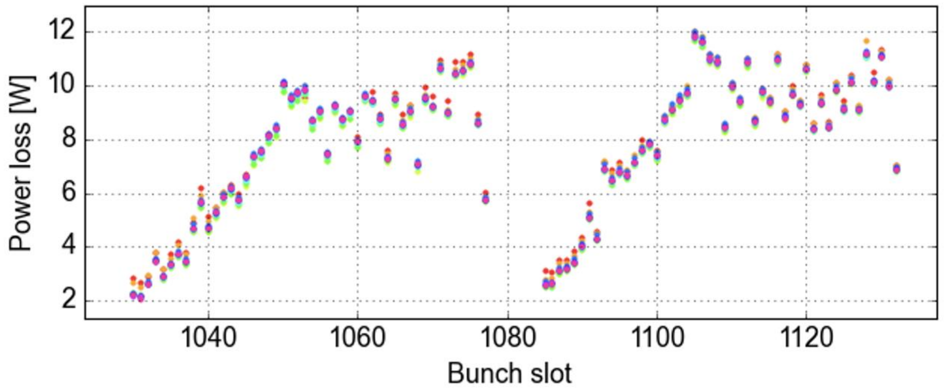


[K. Ohmi, K. Oide, F. Zimmermann, et al]

Impact on local accelerator environment

- Beam energy loss
  - The acceleration of the electrons transfers energy away from the beam, resulting in a synchronous phase shift that must be compensated for by the RF system

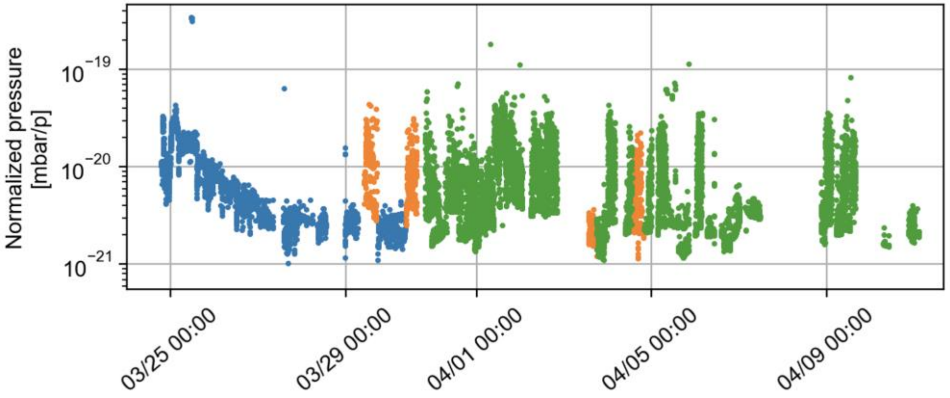
Measurement in LHC



- Heat load
  - Most of this energy is eventually deposited on the chamber, causing a heat load which can be difficult to manage in cryogenic machines, where low temperature is crucial, but the cooling capacity is limited

- Dynamic pressure rise
  - Outgassing through electron-stimulated desorption can lead to e.g., beam loss, equipment irradiation, increased background in experimental areas
  - Risk of vacuum breakdown in high-voltage devices, like kickers

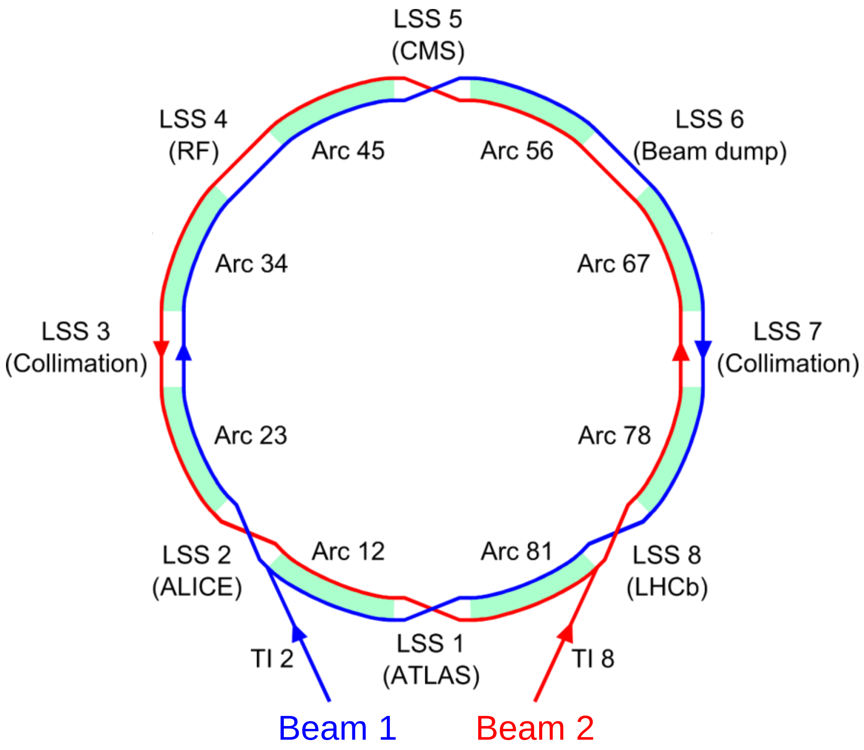
Electron cloud induced pressure rise in SPS injection kicker

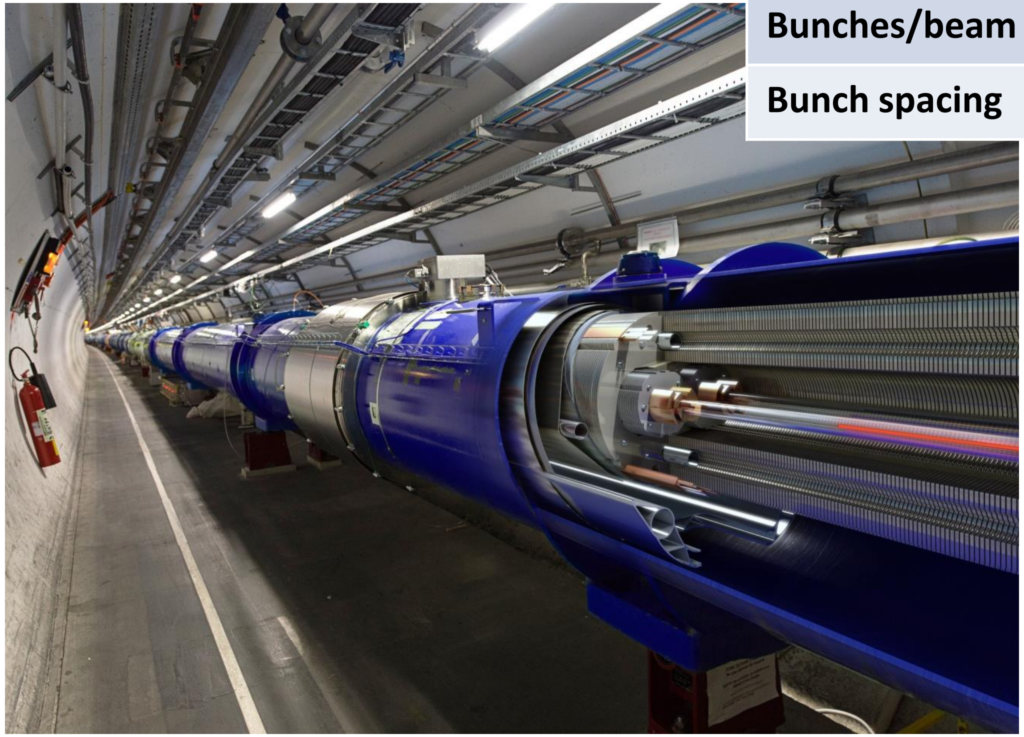


The Large Hadron Collider (LHC)

The LHC is a 27-km proton (and ion) collider that consists of 8 arcs containing the periodic superconducting magnet lattice and 8 long straight sections (LSS) for detectors and other equipment

Main design parameters	
Circumference	27 km
Injection energy	450 GeV
Collision energy	7 TeV
Bunches/beam	2800
Bunch spacing	25 ns

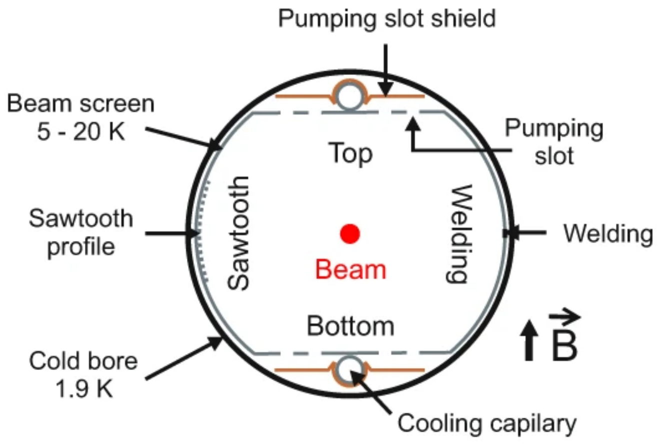




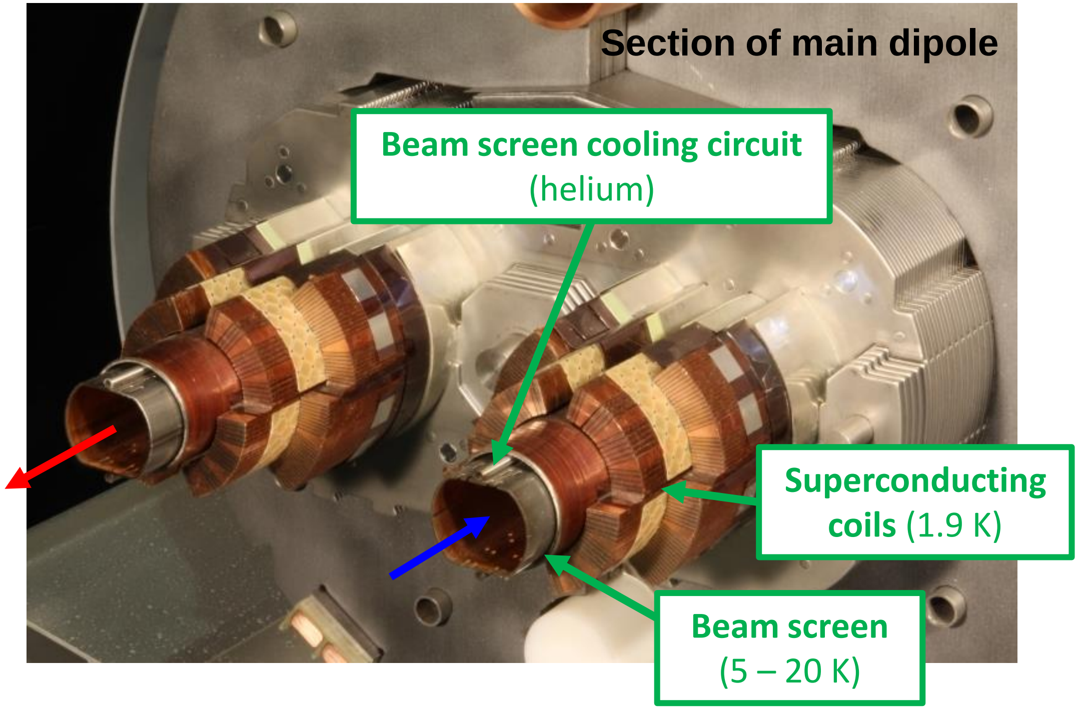
The LHC beam-screen

The superconducting magnets are equipped with a beam screen to protect the cold bore from heating due to e.g., impedance, synchrotron radiation and electron cloud

- Relies on beam-induced scrubbing for electron cloud mitigation

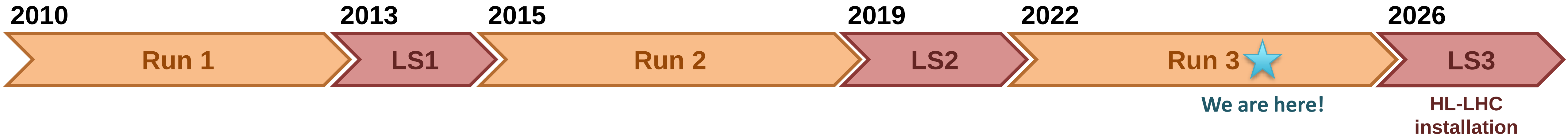


co-laminated Cu on StSt



Overview of LHC operation

- The LHC schedule alternates between physics runs and long shutdown (LS) periods
  - Run: Typically, 6-8 months/year of luminosity production
  - LS: Extended maintenance period without beam, where the arcs are warmed up and exposed to air



2010 Run 1

2013 LS1

2015 Run 2

2019 LS2

2022 Run 3

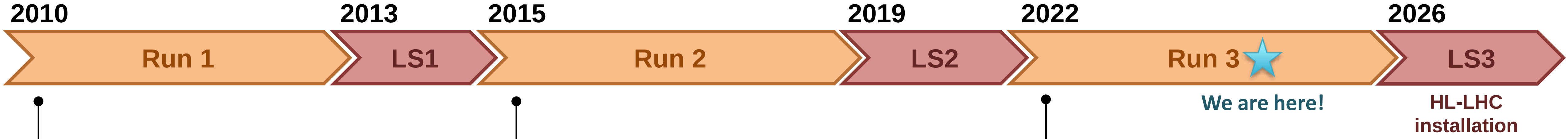
We are here!

2026 LS3

HL-LHC
installation

Overview of LHC operation

Long Shutdown 2:
- Selected beam screens extracted for lab analysis
- LHC Injectors Upgrade to produce 25 ns beam with 2.3e11 p and high brightness for HL-LHC



Run 1:
- Bunch spacing: **150 – 50 ns**
- Bunch intensity: **1.7e11 p**
- Max # of bunches: **1380**
- Beam energy: **3.5 - 4 TeV**

- **Mild electron cloud effects**, except for short **pilot periods** with **25 ns** beams

Run 2:
- Bunch spacing: **25 ns**
- Bunch intensity: **1.2e11 p**
- Max # of bunches: **2556**
- Beam energy: **6.5 TeV**

- **Systematic electron cloud effects, stronger than with 25 ns beams in Run 1**

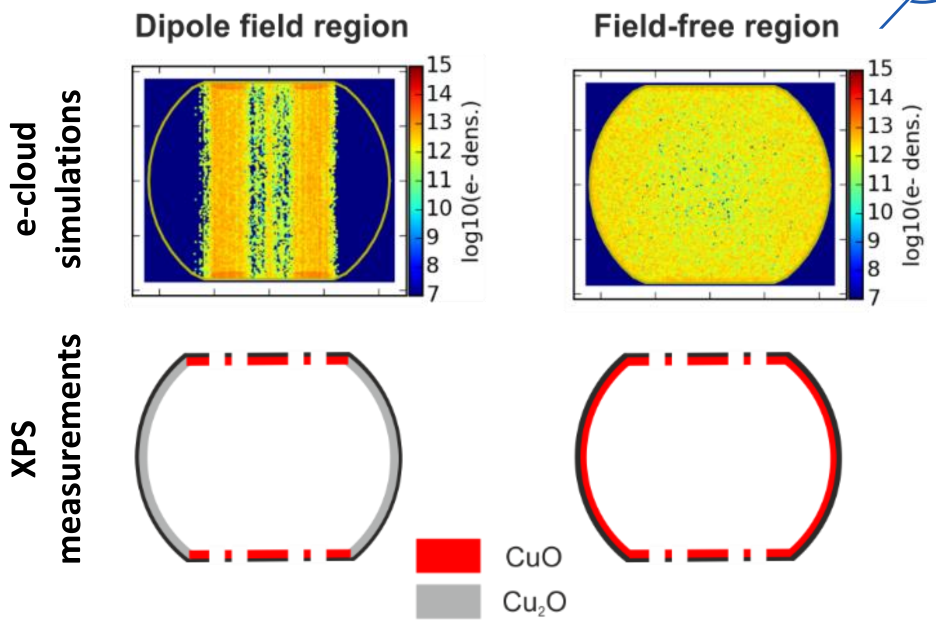
Run 3:
- Bunch spacing: **25 ns**
- Bunch intensity: **1.6e11 p** (goal: 1.8e11)
- Max # of bunches: ~**2500**
- Beam energy: **6.8 TeV**

- **Systematic electron cloud effects, stronger than in Run 2**

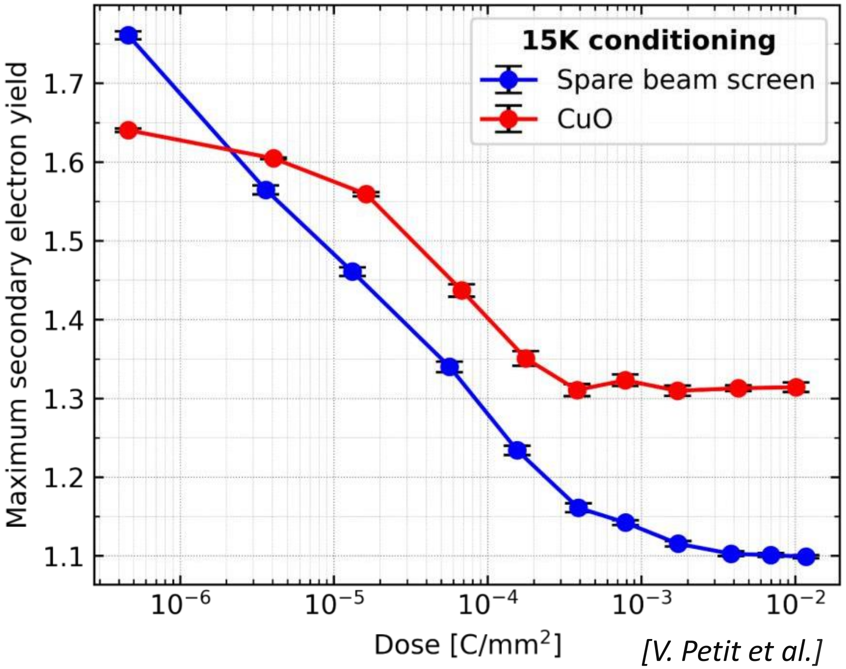
Beam screen degradation

- Lab analysis showed a different copper oxide (CuO) in areas irradiated by the electron cloud on some of the extracted beam screens

- CuO surfaces show a different SEY curve and worse conditioning behaviour with electron irradiation compared to the regular beam screen surfaces



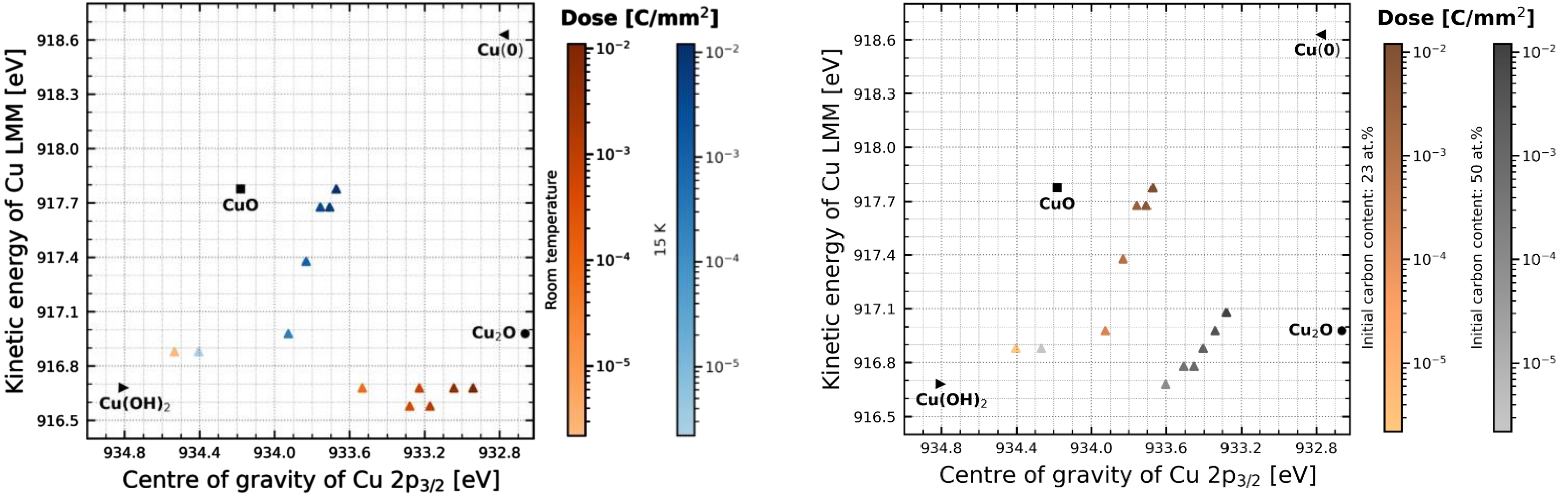
*[V. Petit et al., Commun Phys **4**, 192 (2021)]*



[V. Petit et al.]

Beam screen degradation

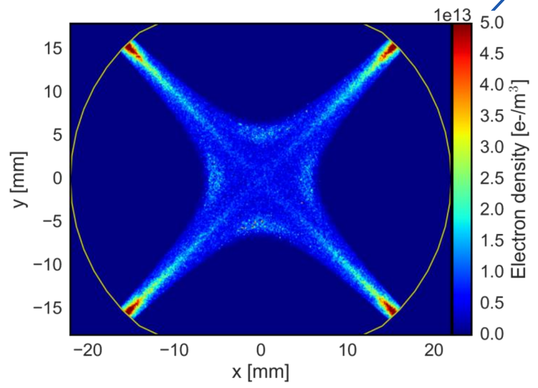
- Based on extensive further lab measurements, the probable ingredients for CuO formation have been identified as:
  - Exposure to humid air during the long shutdowns
  - A low surface carbon content
  - Exposure to an electron flux under cryogenic conditions



[V. Petit et al., IPAC'22]

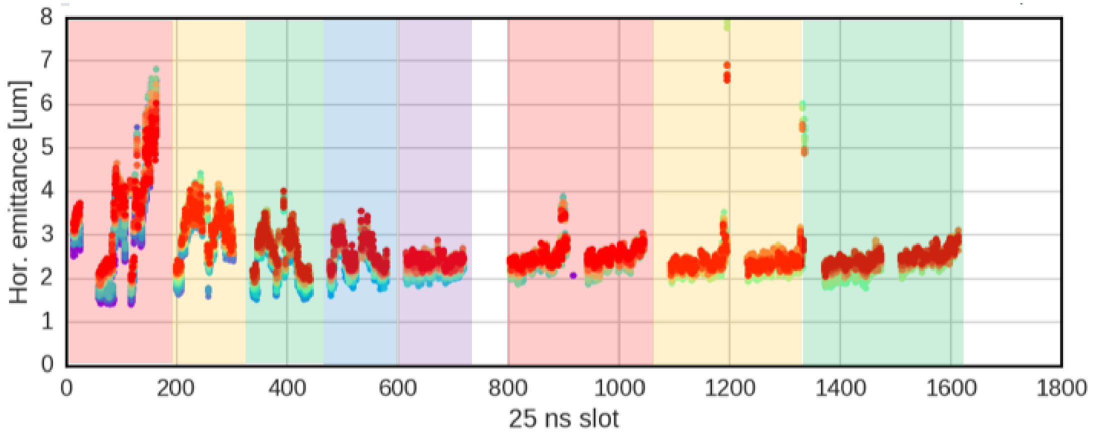
Single-bunch instabilities at injection

- Single-bunch instabilities systematically occur at injection energy
  - Caused by e-cloud in the arc quadrupoles, where the electron density at the beam location is high during the pinch



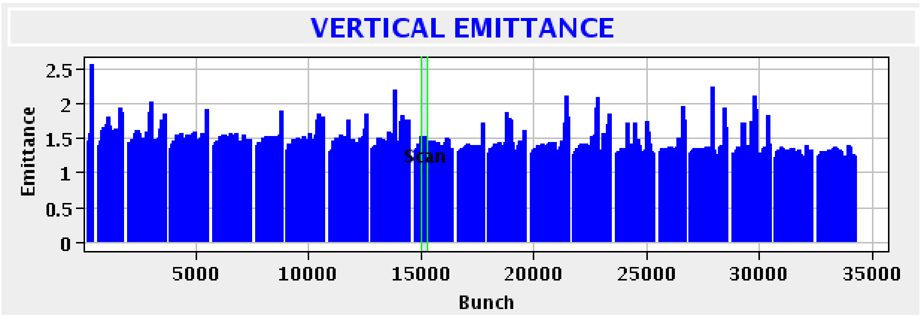
Can be controlled, although not cured, by high chromaticity, high octupole current and the transverse feedback

Oct [A]	6.5	13	13	13	26	52	52	52
Q’	5/5	5/5	10/10	15/15	15/15	15/15	10/15	20/15



[A. Romano et al.]

Lead to moderate emittance growth



[See S. Johannesson, IPAC’24 MOZD2]

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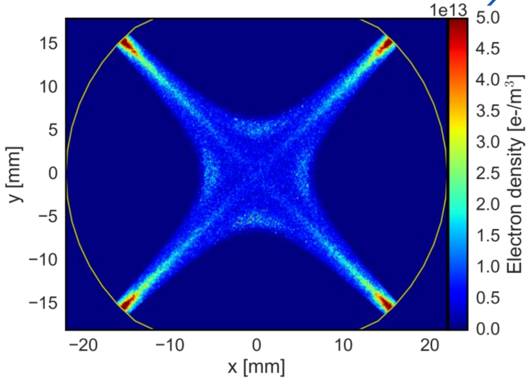
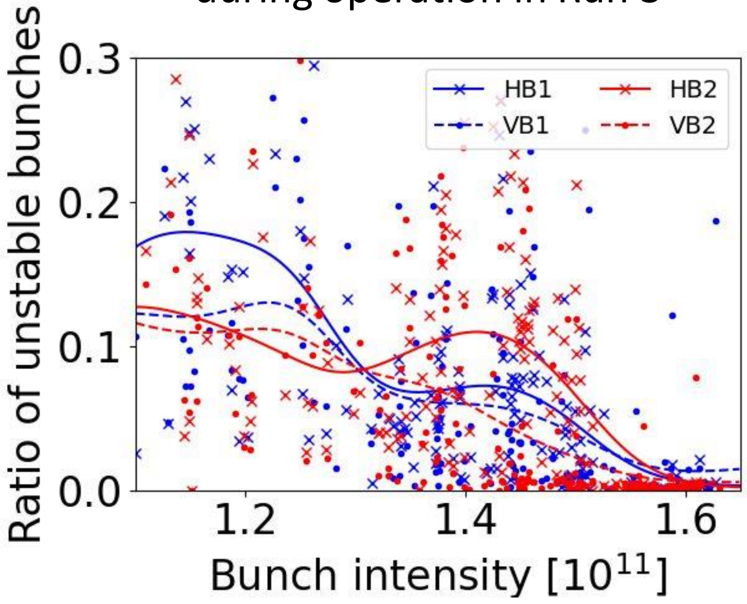
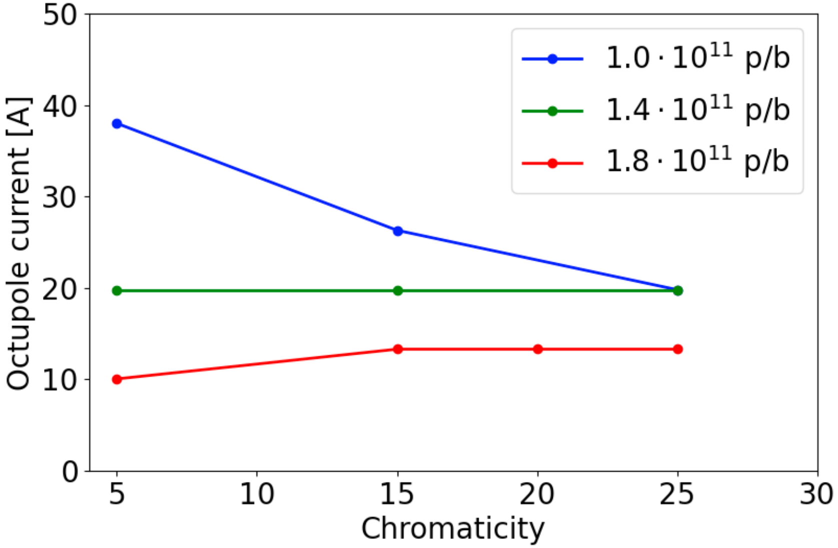


A favourable scaling with bunch intensity has been observed during operation in Run 3

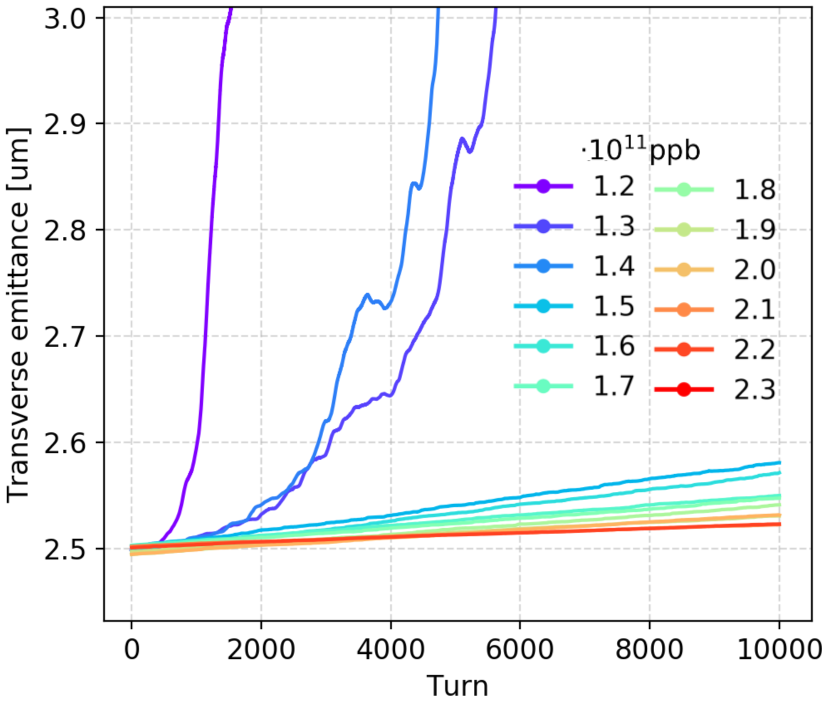


[X. Buffat]

Scaling confirmed in dedicated measurements

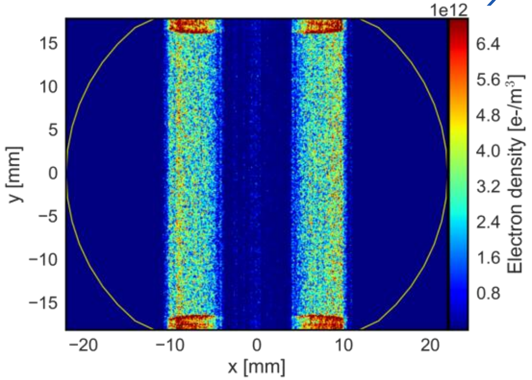


Consistent with predictions from macro-particle simulations

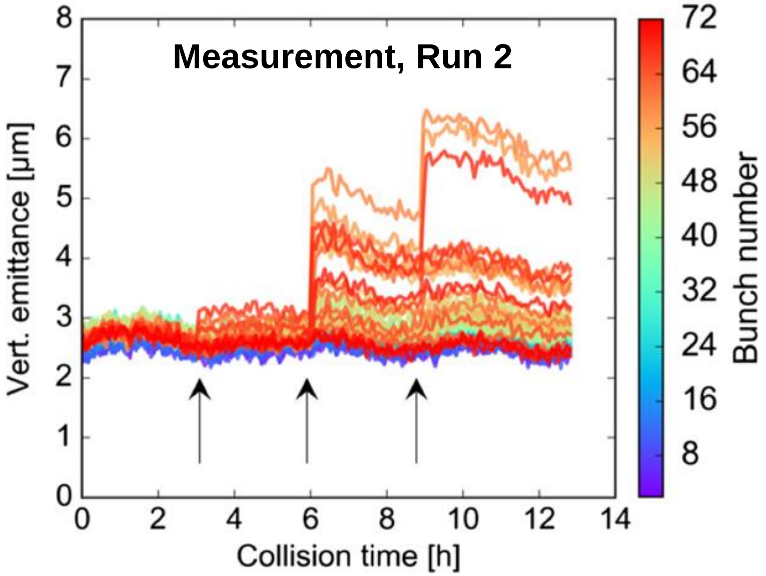


Single bunch instabilities at collision energy

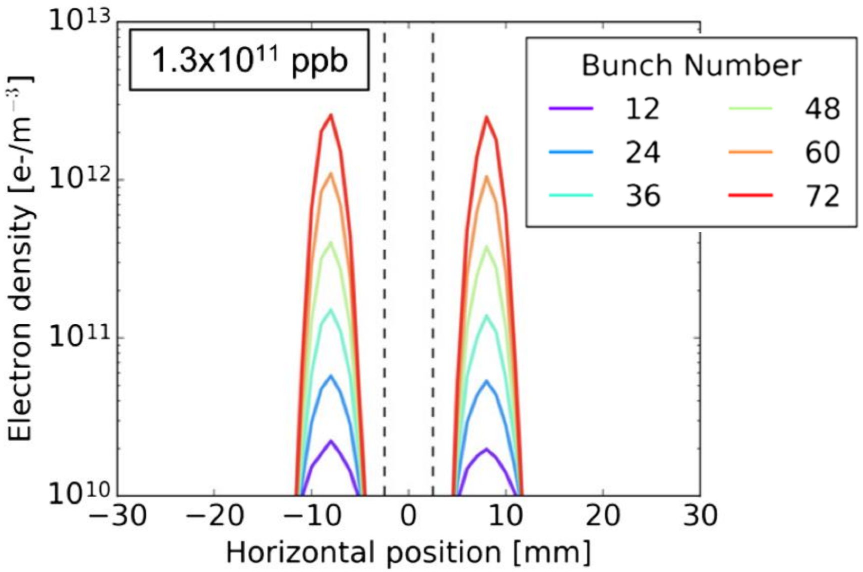
- Single bunch instabilities in the vertical plane are observed also at collision energy
  - Caused by electron cloud in the arc dipoles
  - In Run 2, the instabilities could be fully suppressed with high chromaticity and were eventually cured through scrubbing

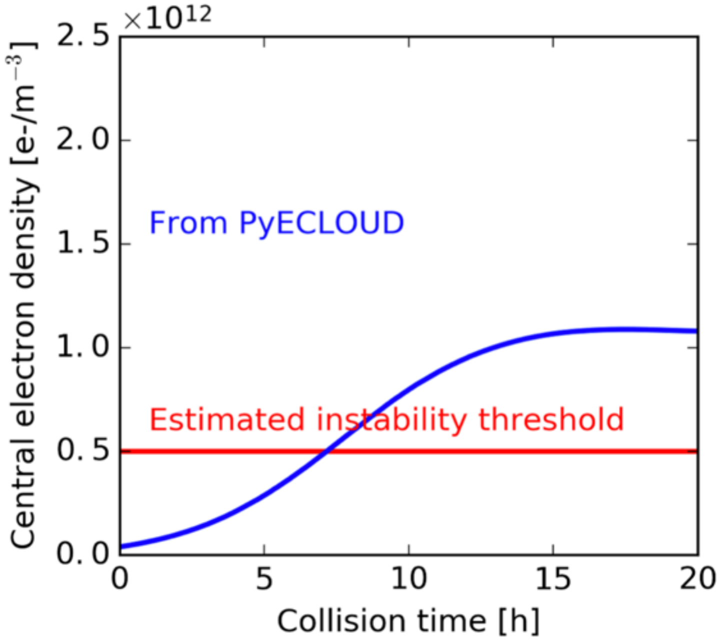


Appear only at the end of stores for luminosity production, due to luminosity burn-off



When the bunch intensity decreases, the electron density at the beam location increases

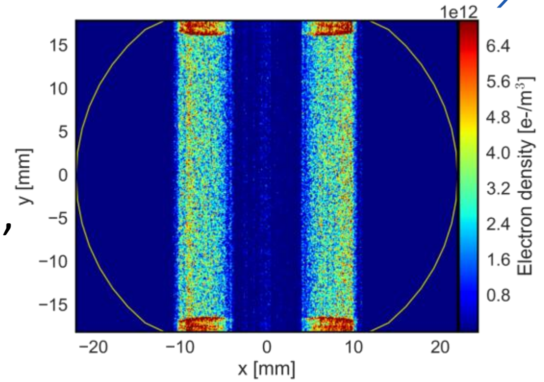


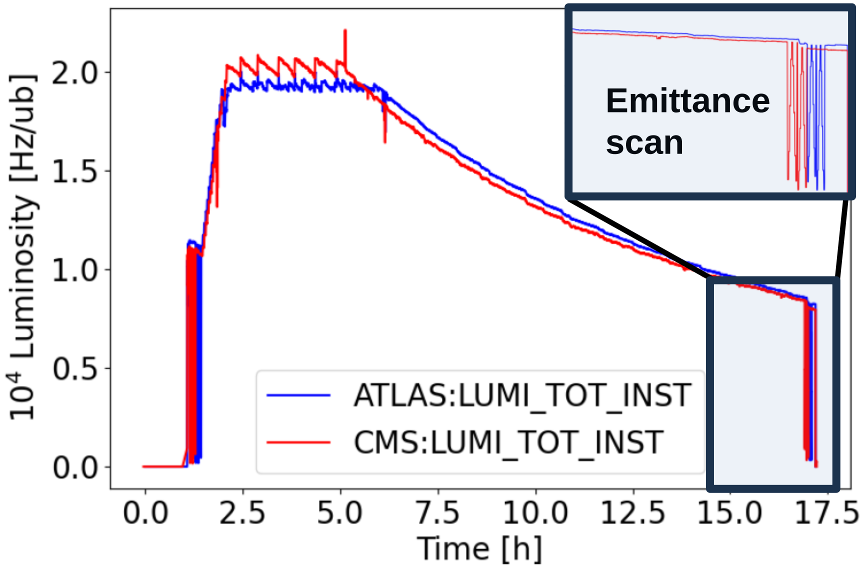


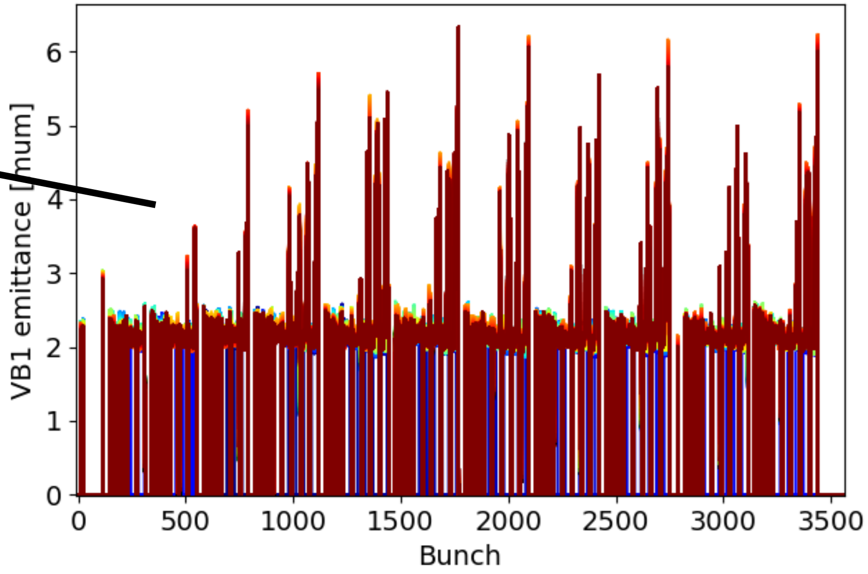
[A. Romano et al, Phys. Rev. Accel. Beams 21, 061002]

Single bunch instabilities at collision energy

- Single bunch instabilities in the vertical plane are observed also at collision energy
  - Caused by electron cloud in the arc dipoles
  - In Run 3, the instabilities are systematically present, especially during luminosity scans, when the beam-beam interactions and the tune spread they induce are reduced
  - The intensity at which instabilities appear has also increased from Run 2 to Run 3, likely due to the different SEY curve for the degraded surfaces



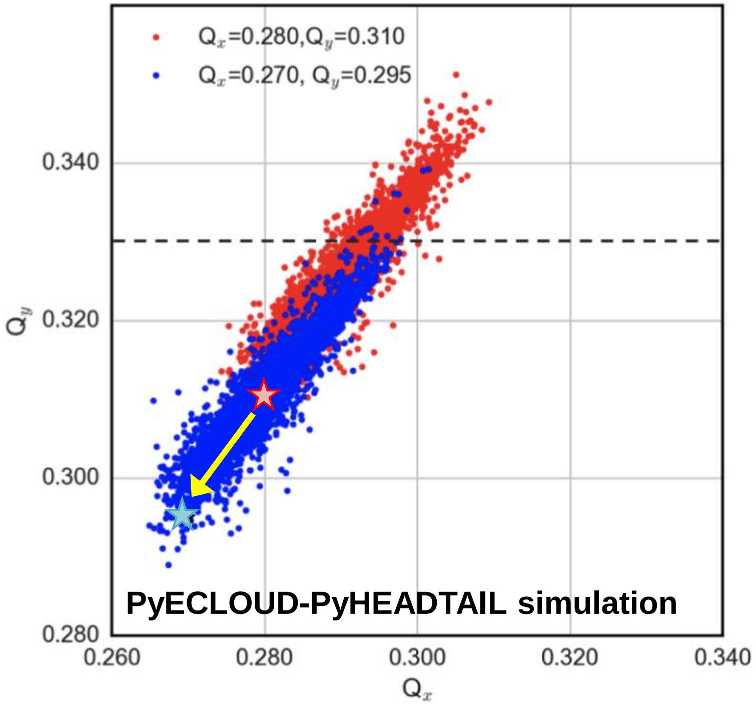




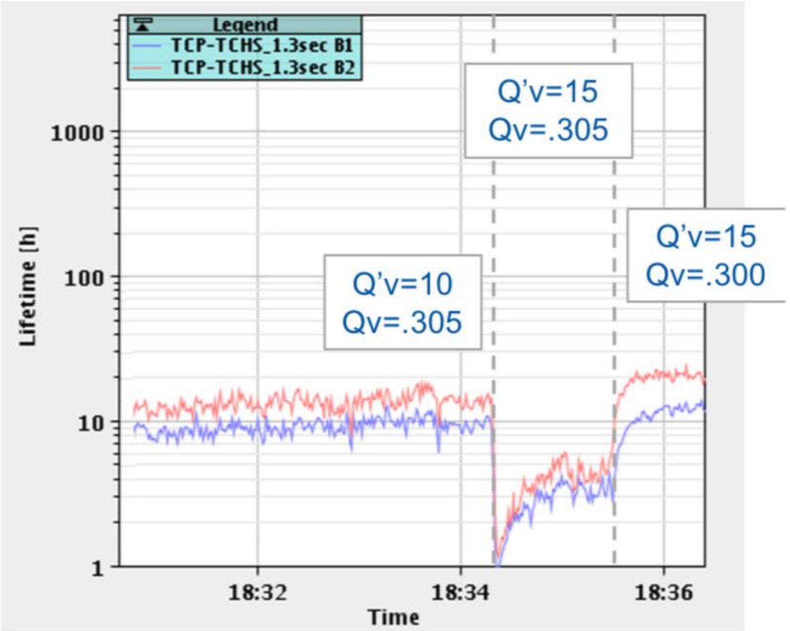
Not a strong performance limitation, but affect lifetime indirectly through the high chromaticity required for their mitigation

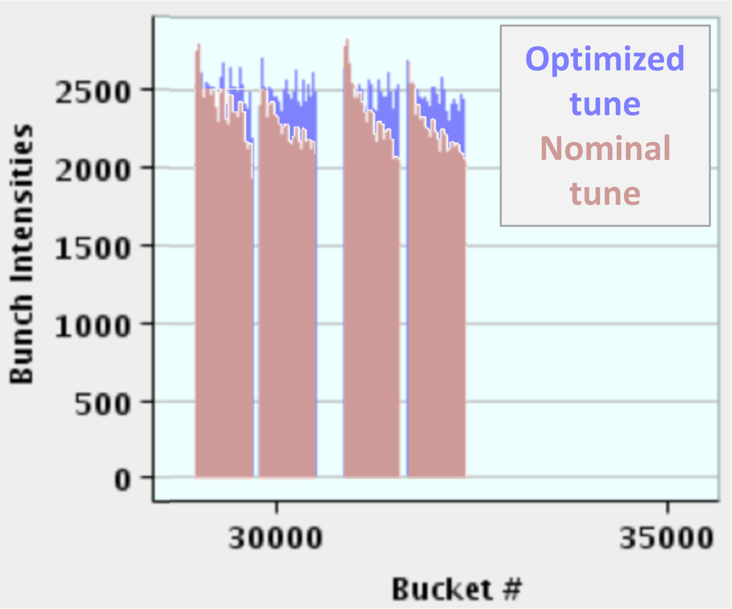
Tune shift and spread

- Together with the chromaticity and octupole currents needed for stability, the e-cloud introduces a significant tune spread
    - To preserve the beam lifetime, modified betatron tunes are used at injection energy when operating with trains of bunches



Measurements at LHC in Run 2 (450 GeV)

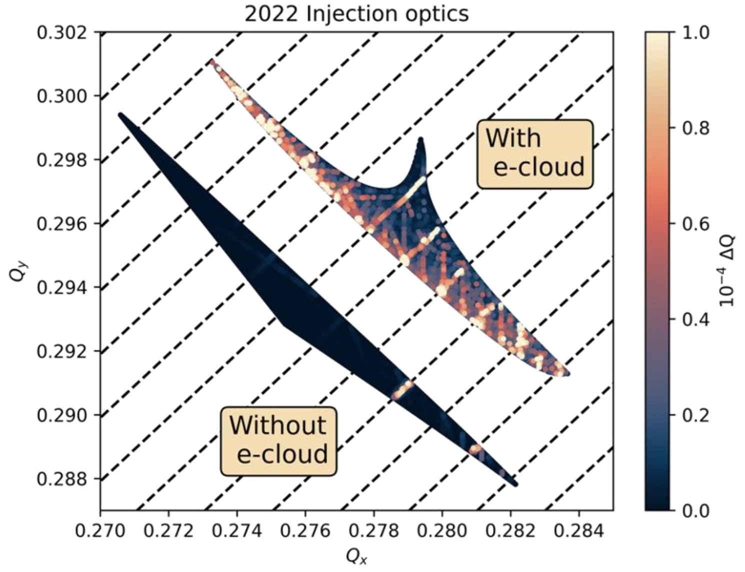




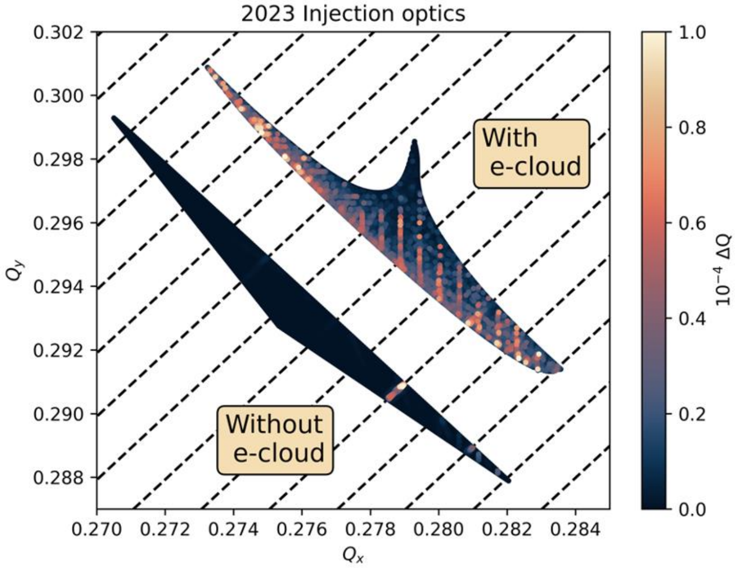
[A. Romano et al, IPAC'17]

Emittance growth at injection

- Electron cloud in the arc quadrupoles drives emittance growth at injection
  - Long-term tracking simulations with electron cloud have identified synchro-betatron resonances as cause ($2Q_x - 2Q_y + mQ_\zeta = 4$)
  - LHC injection optics modified in 2023 to correct octupolar resonances:
    1. From lattice octupoles (in arcs)
    2. From electron clouds in quadrupoles



Synchro-betatron resonances are greatly reduced in simulations



[K. Paraschou et al, HB2023]

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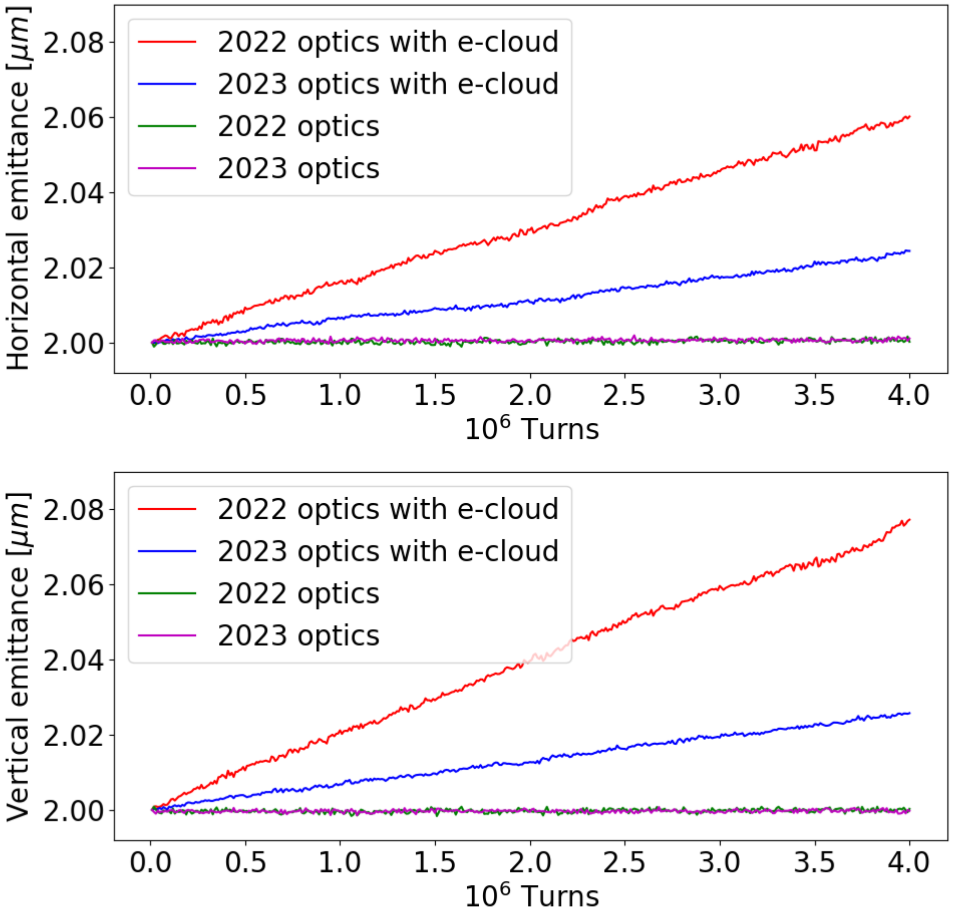
Simulations show significant reduction of emittance growth with 2023 optics

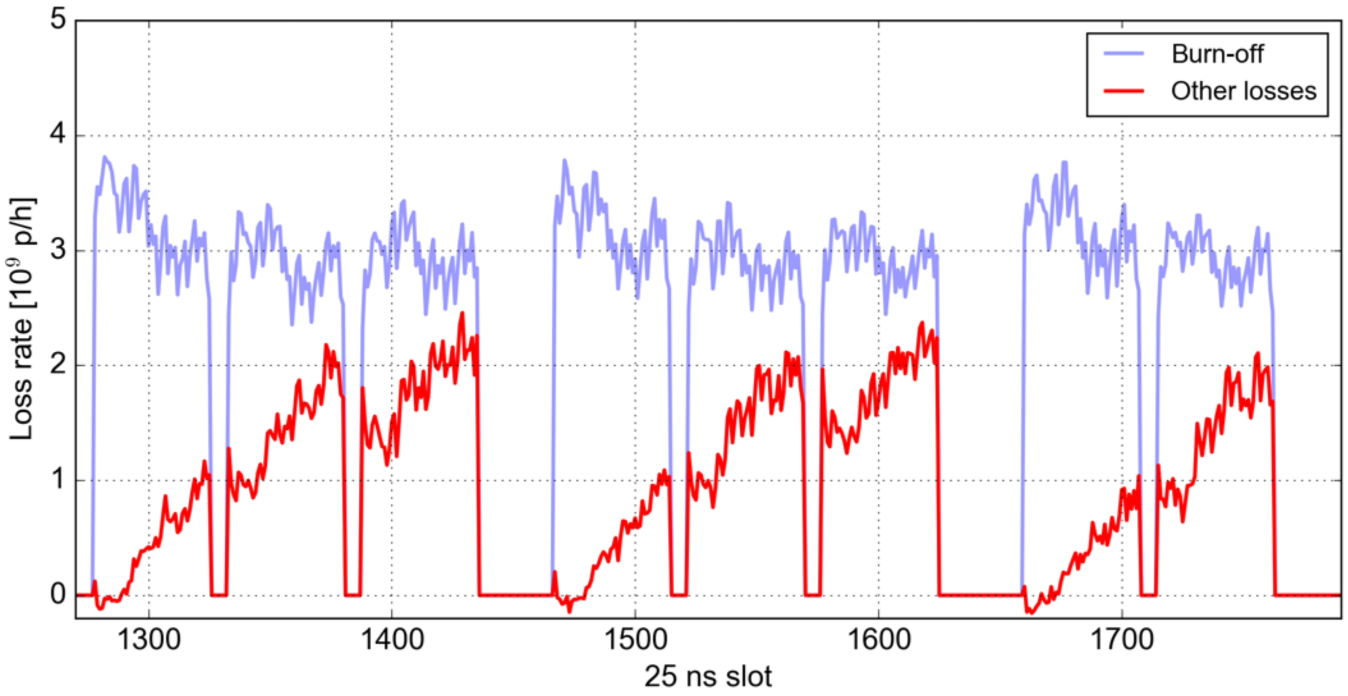


[K. Paraschou et al, HB2023]

Dedicated measurements scheduled in 2 weeks!

Beam loss during collisions

- With the beams in collision, slow losses in addition to losses from burn-off (BO) are observed
  - Caused by e-cloud in the final focusing quadrupoles, Inner Triplets, enhanced by the large beta functions



Beam loss during collisions

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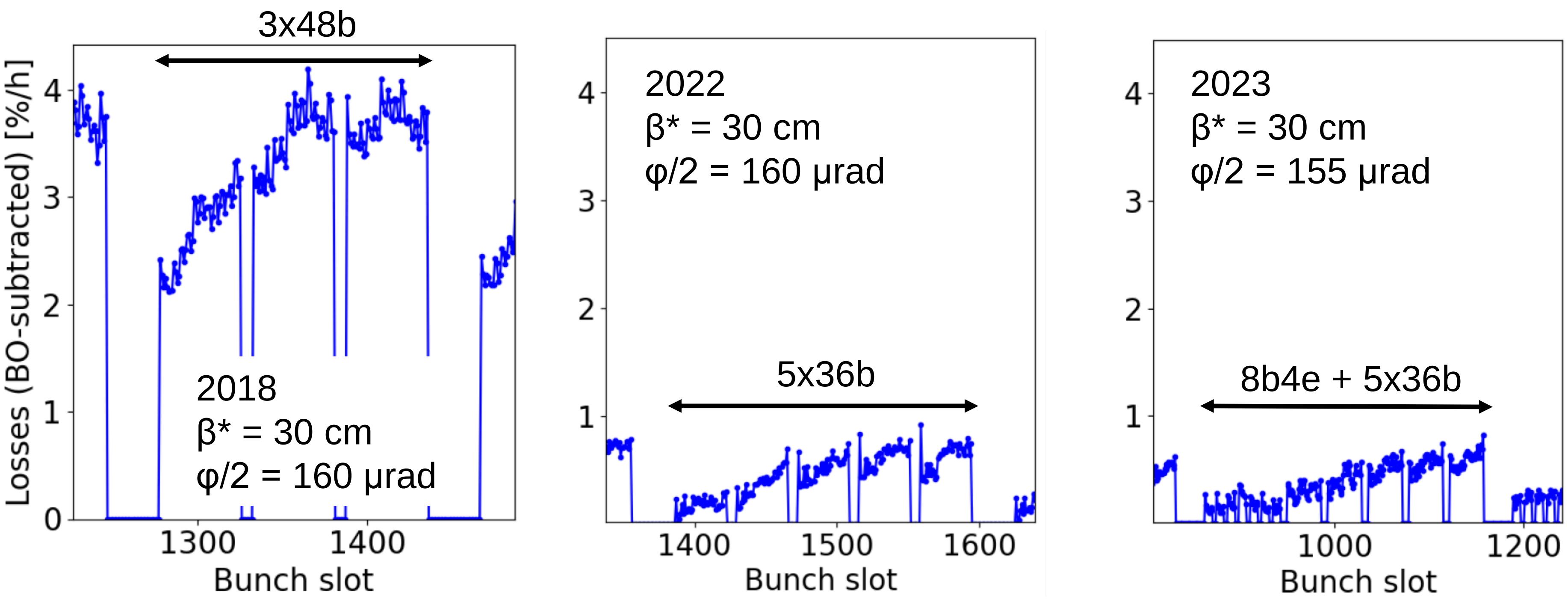


The relative losses are smaller in Run 3 than in Run 2

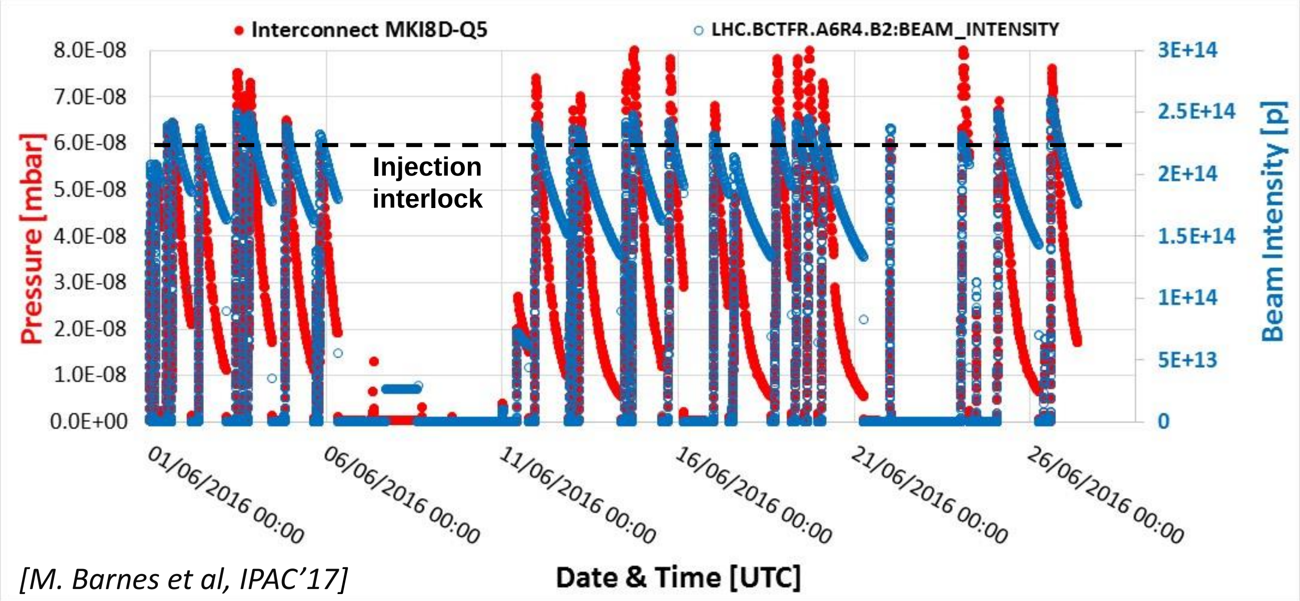
  - Long-term tracking simulations including longitudinally resolved electron cloud in the triplets and beam-beam effects have recently been performed for the first time. They suggest that the increase in bunch intensity in Run 3 is at least partly responsible for the improvement

[See K. Paraschou, IPAC'24 WEPR57]

Vacuum degradation

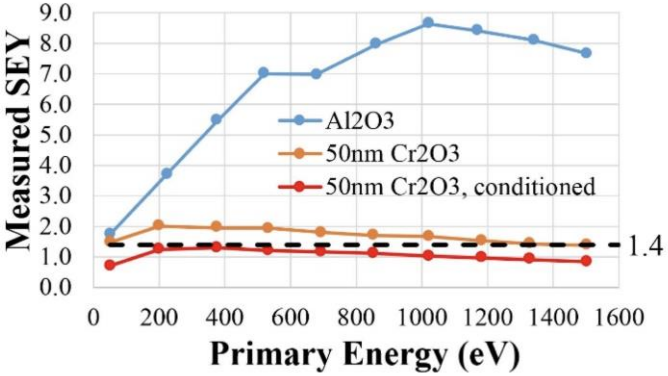
- Dynamic pressure rise from e-cloud doesn’t cause problems in most of the machine, but the injection kickers are an exception, due to the low acceptable vacuum level

At the beginning of Run 2, the bunch intensity in the LHC was limited by this dynamic pressure rise



[M. Barnes et al, IPAC’17]

Increased pumping capacity and a Cr_2O_3-coated alumina beam screen in some modules alleviated the issue



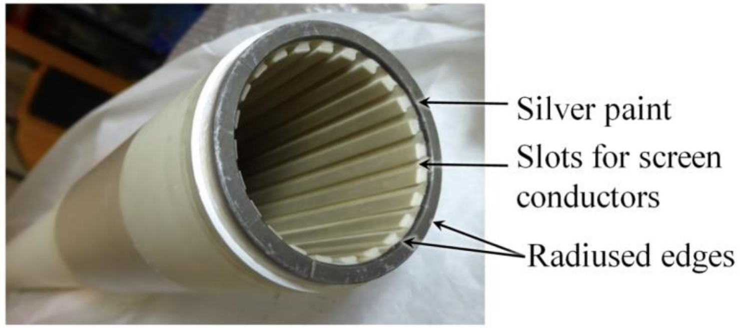


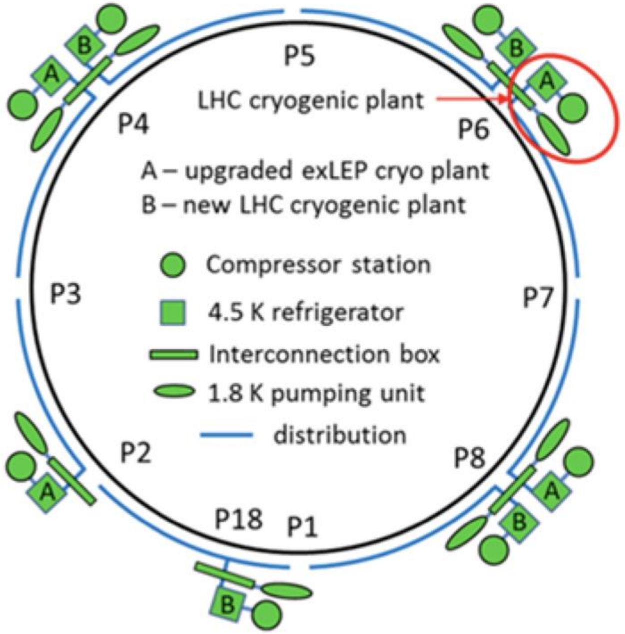
Figure 2: Photograph of one end of the alumina tube, with silver paste and Cr_2O_3 coating by magnetron sputtering.

[M. Barnes et al, IPAC’17, IPAC’18]

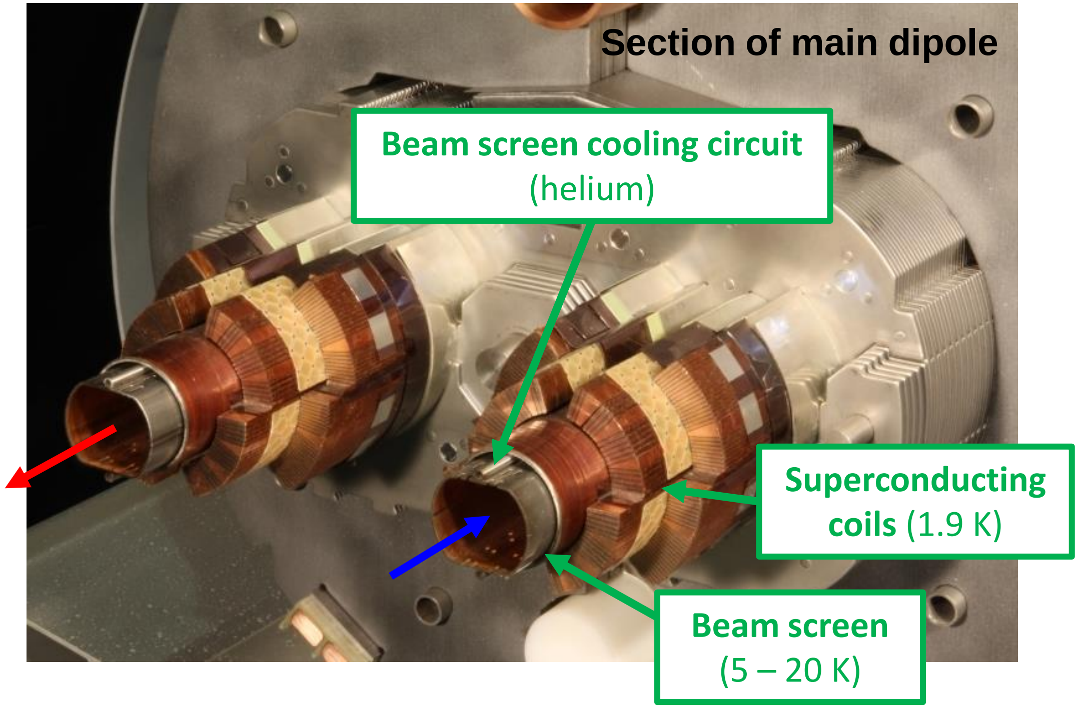
- A few days of beam-induced scrubbing are still needed after every air-exposure to recover the vacuum performance

Heat load

- The strongest limitation due to electron cloud on LHC performance comes from the heat load
  - The heat load must be efficiently extracted by the cryogenics system to protect the superconducting magnets and ensure a stable vacuum
  - The cryogenics system consists of 4 pairs of cryoplants, each responsible for cooling 2 arcs, with a cooling capacity that varies from arc to arc between 190 W and 260 W per lattice half-cell



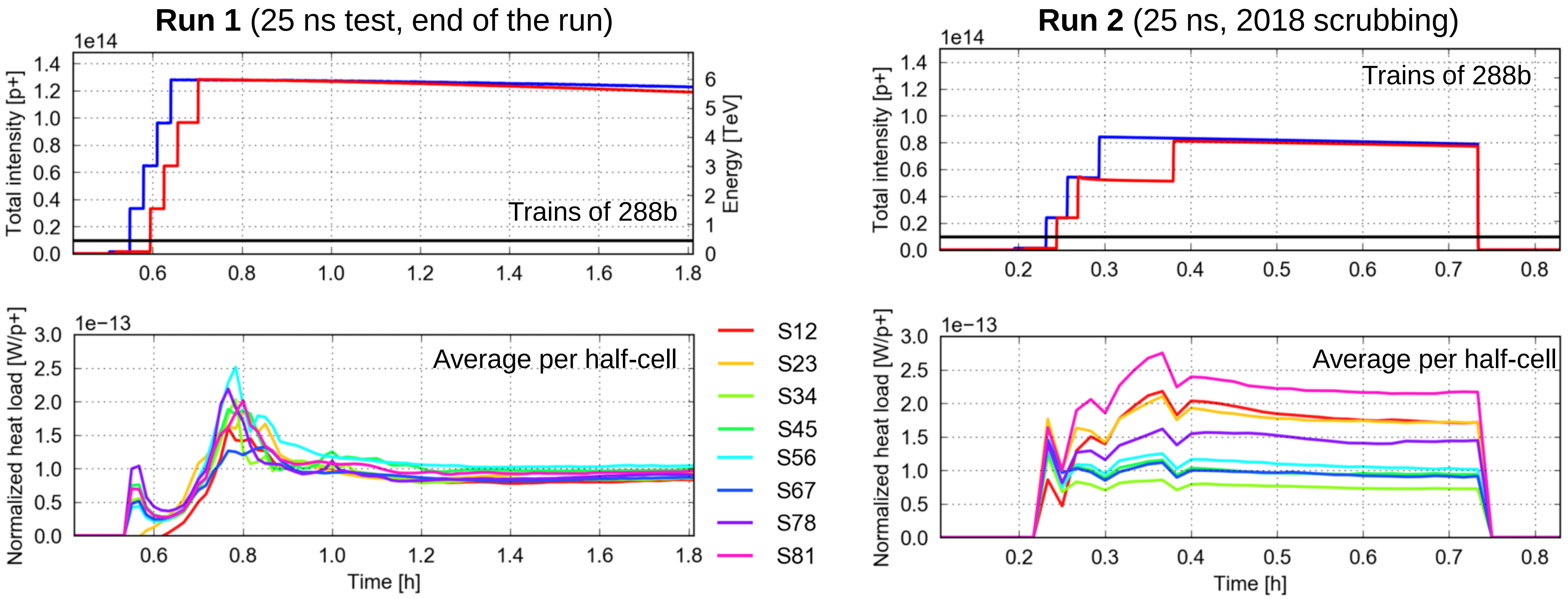
[B. Bradu et al, ECLOUD'18]



Heat load

- In Run 2, unprecedentedly large heat loads were observed with a large spread among sectors

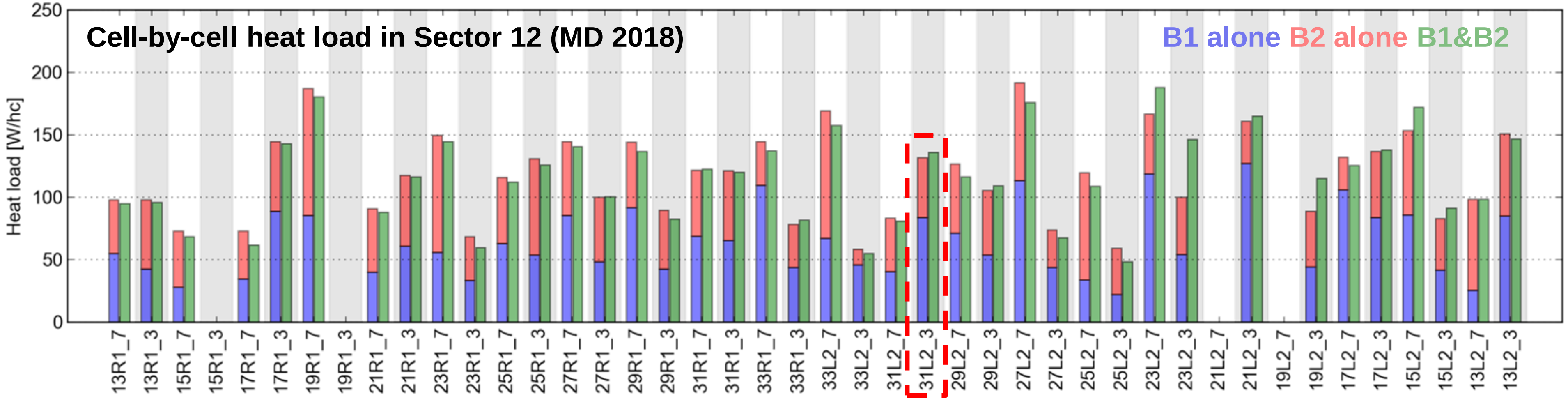
First **indication** of
beam screen
degradation


Run 1 (25 ns test, end of the run)

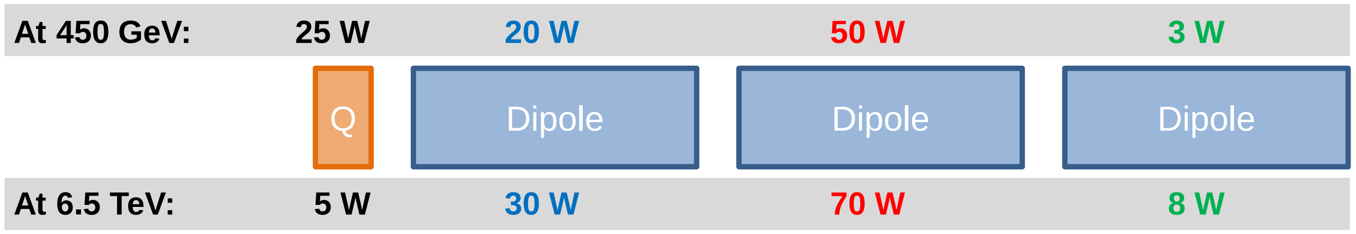
Run 2 (25 ns, 2018 scrubbing)

Heat load

- In Run 2, unprecedentedly large heat loads were observed with a large spread among sectors
  - Large variations are observed also between half-cells, magnets and apertures
  - After becoming accustomed to the large heat load transients during operation, no limitations from cryogenics were encountered despite heat loads up to 160 W/half-cell



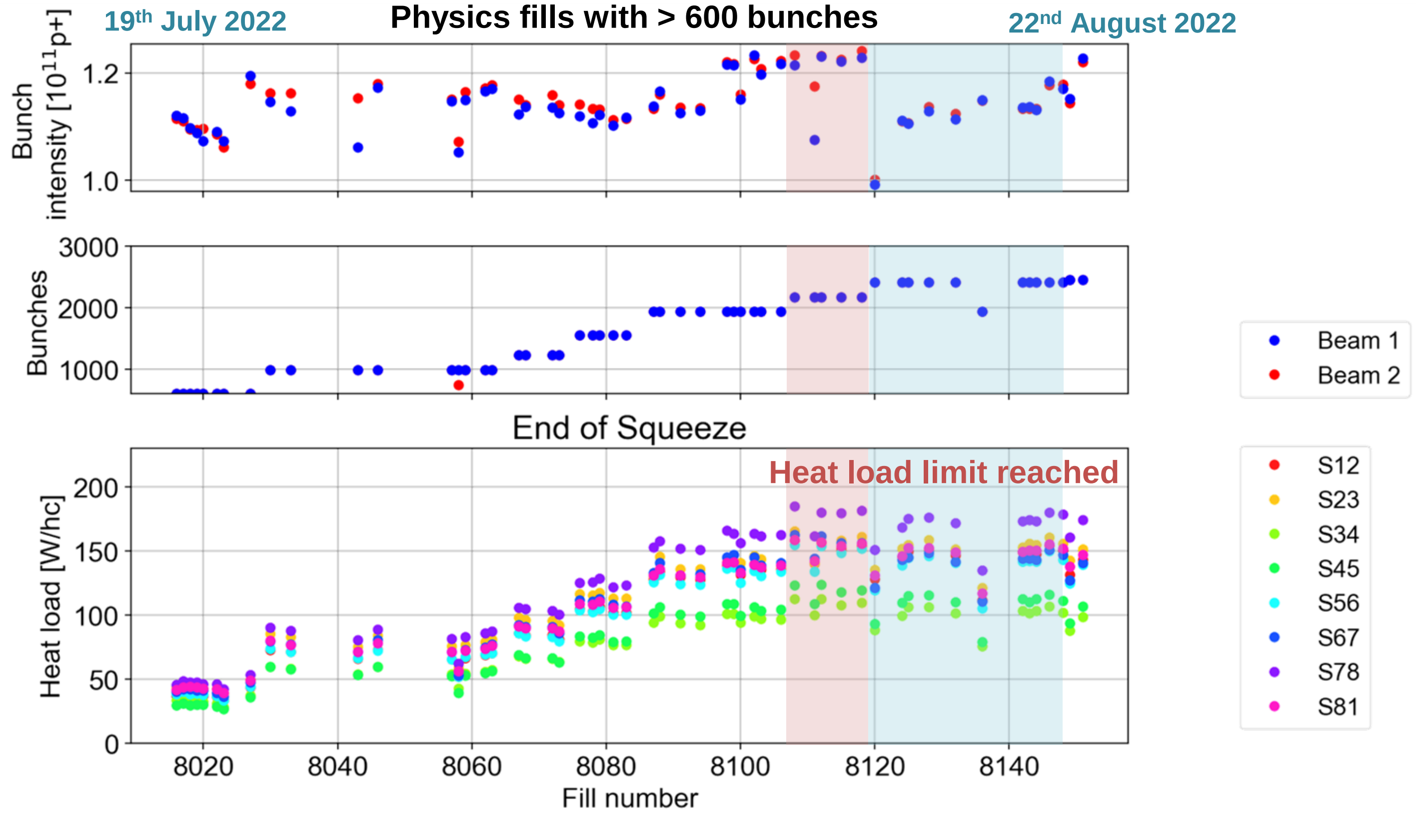
Cell 31L2 (equipped with extra thermometers within the cell)



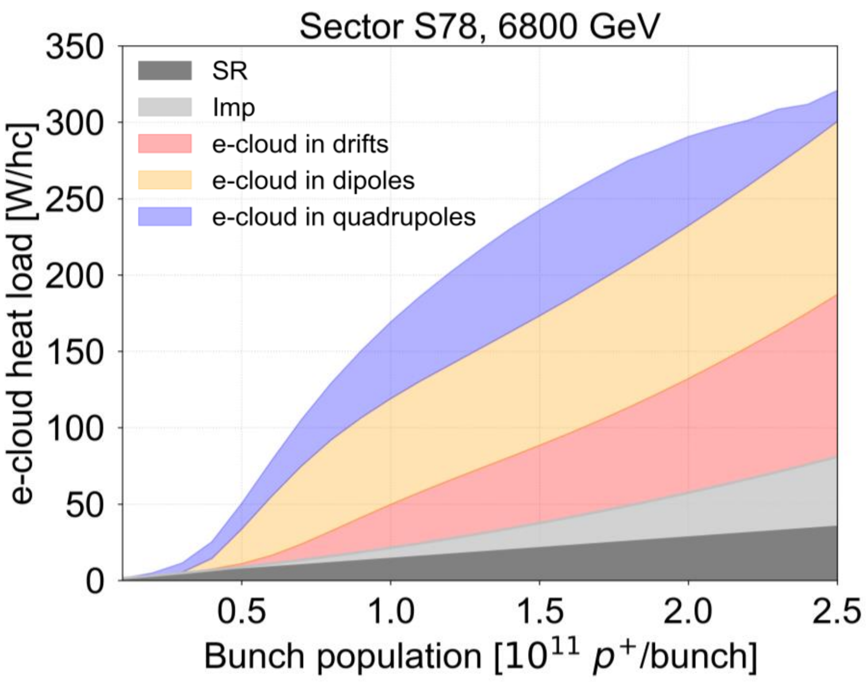
	Q	Dipole	Dipole	Dipole
At 450 GeV:	**25 W**	**20 W**	**50 W**	**3 W**
At 6.5 TeV:	**5 W**	**30 W**	**70 W**	**8 W**

Heat load limitation

- In Run 3, the total intensity has been limited by the heat load since the beginning of the run
  - Due to strong degradation after LS2 in one sector (S78) with the lowest available cooling capacity

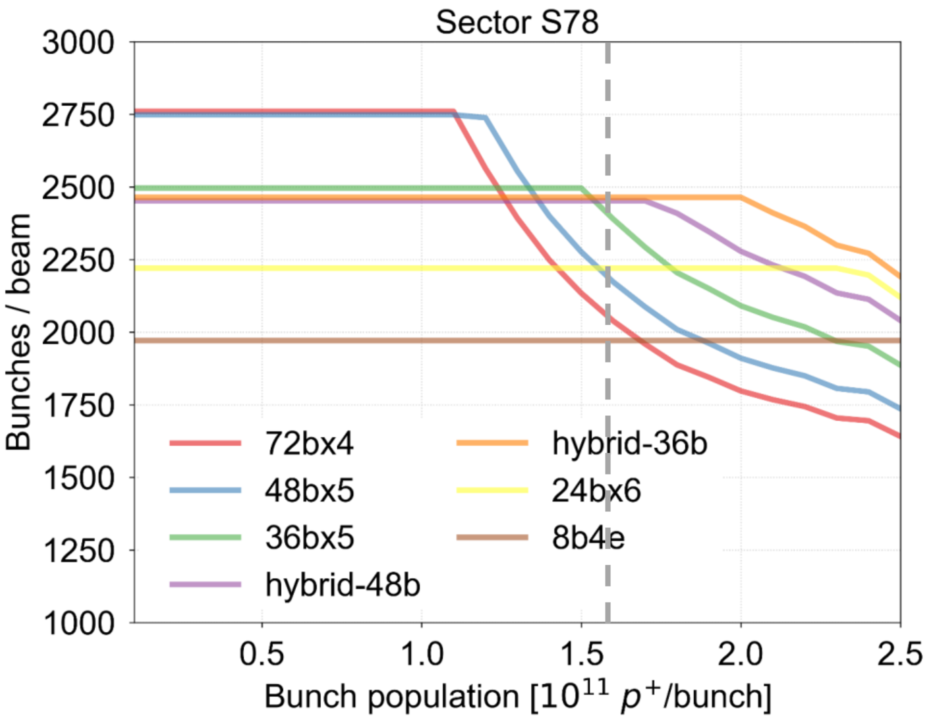


Aggravated by bunch intensity increase, since the heat loads from e-cloud and other sources increase with intensity



Mitigation with filling schemes

- Only mitigation measure available short term is reducing the train length to lower the average heat load per bunch
  - The drawback is a reduction in the number of bunches that can fit in the machine – need to find best balance between heat load and number of bunches



With 1.6e11 p/bunch, trains of 36 bunches are well suited, limiting the number of bunches by around 10%

With the nominal bunch pattern (4 x 72b), only 2000 bunches are allowed

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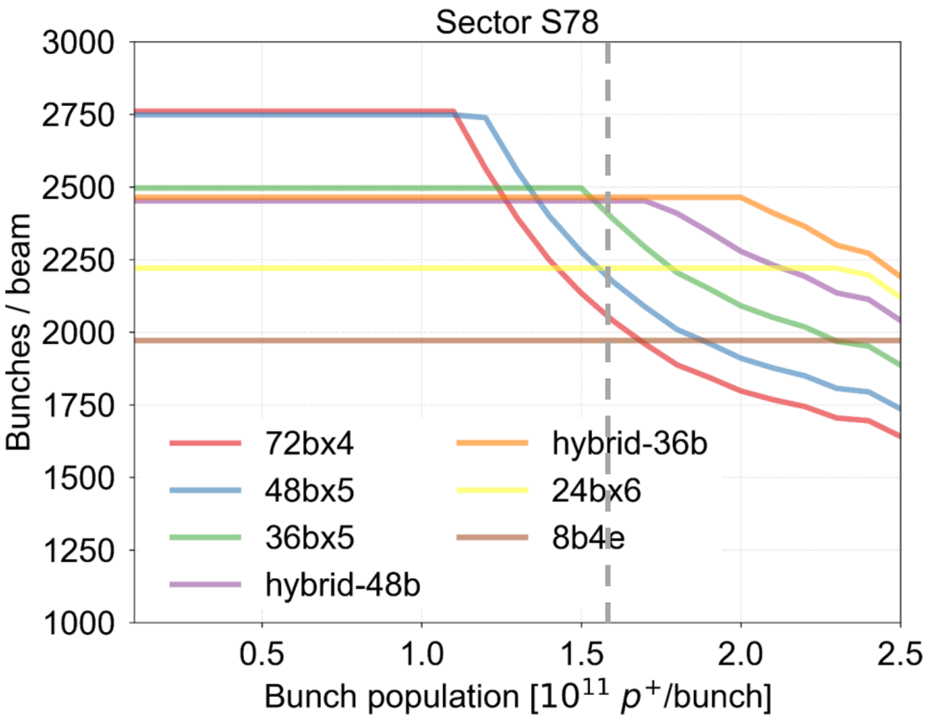
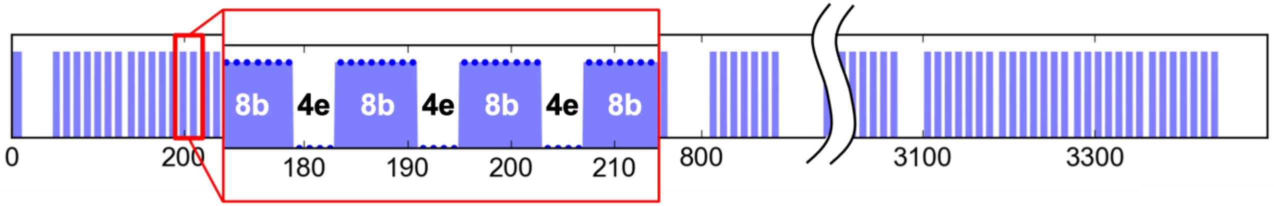


To increase bunch intensity further, strong suppression can be achieved with the "8b+4e" filling scheme, at the expense of 30% of the bunches

8b+4e filling scheme



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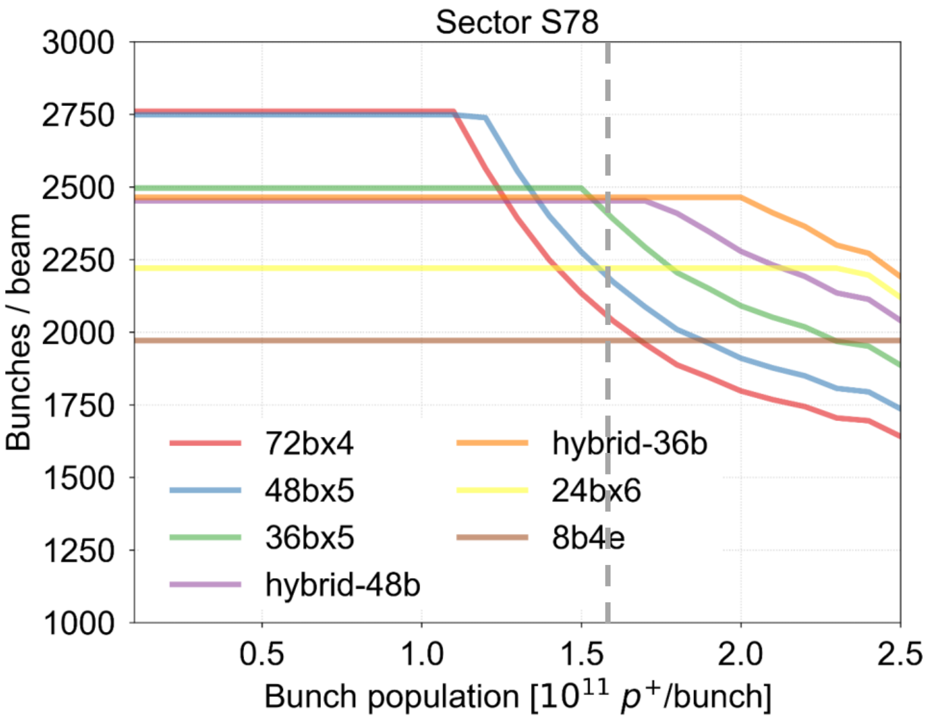
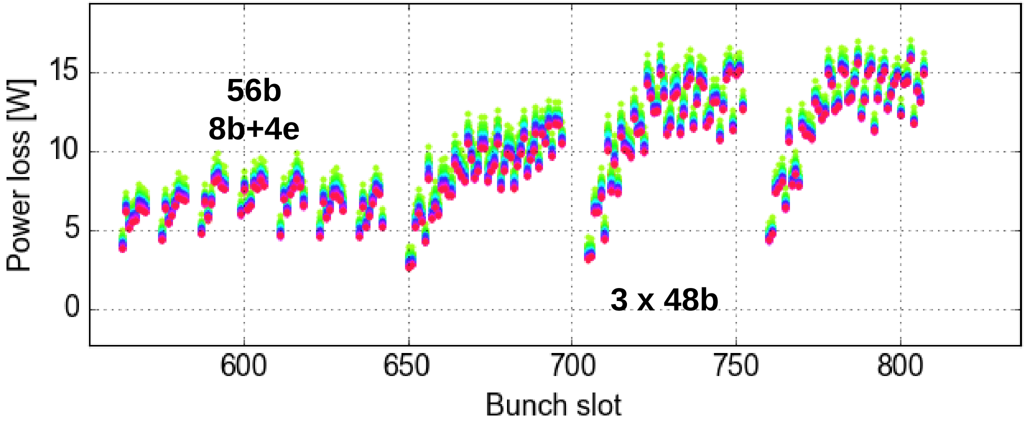


Hybrid filling schemes, where 8b+4e and 25 ns beam can be combined at an optimal ratio give a better performance



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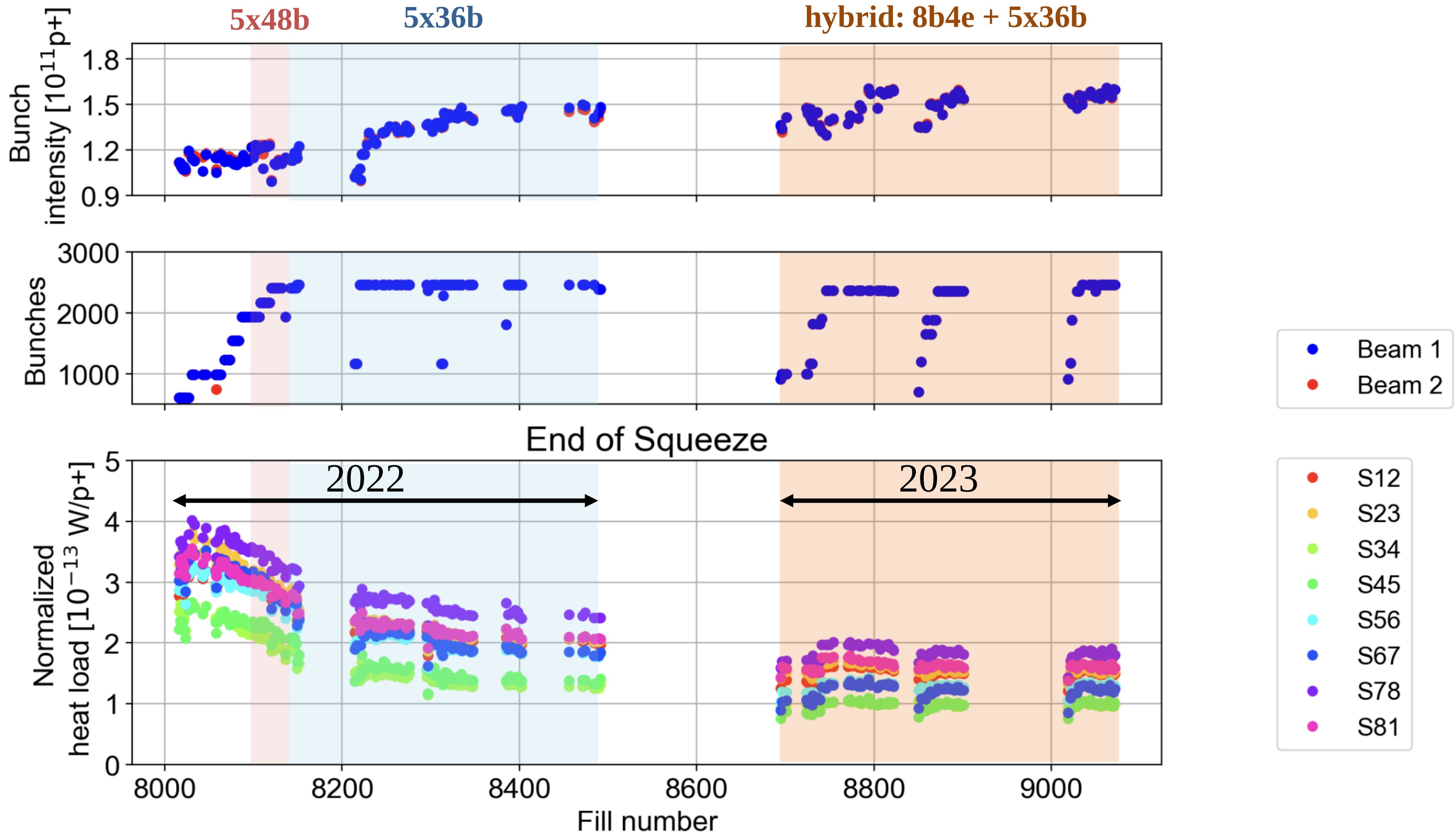
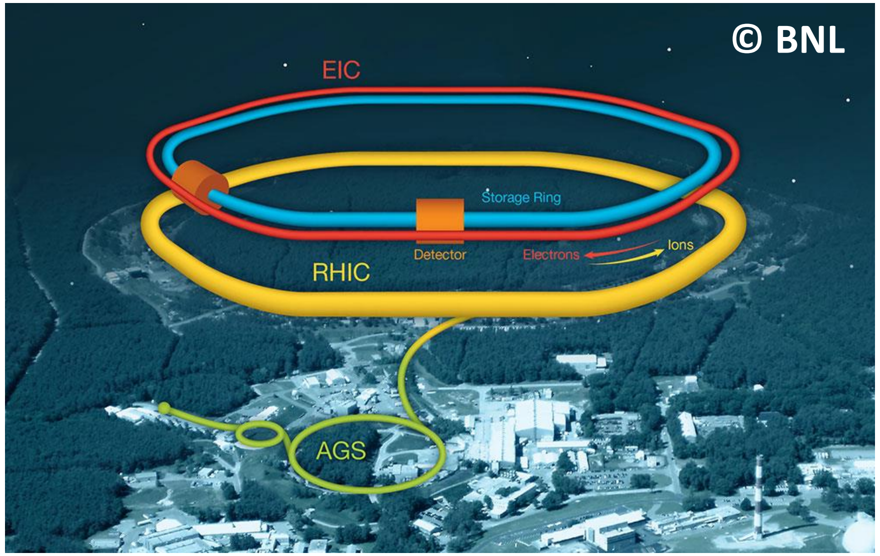
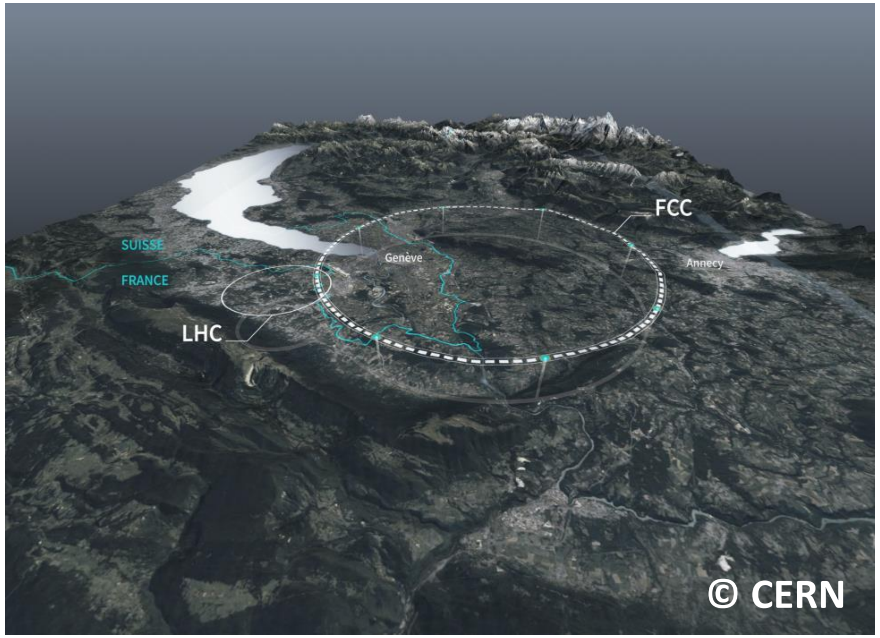


Lessons for future collider projects

- Electron cloud can strongly limit the machine performance
  - Suppressing the build-up is the only way to fully mitigate its effects
- Electron cloud must be considered already when the machine and beam parameters are defined, due to the strong dependence on many essential parameters
  - Parameter dependences can be non-monotonic → consider full range of parameters during operation
  - Evaluate need for mitigation in as much of the machine as possible, including interaction regions, and other short areas that may cause limitations due to local effects
- Mitigation measures may impact other aspects, such as impedance, vacuum system, magnet specifications etc.





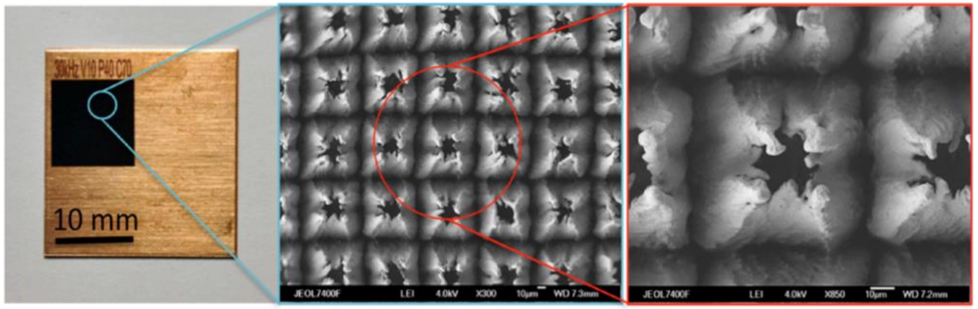
Mitigation measures

- Reduce the secondary emission yield
    - Surface coating with low SEY: a-C, NEG, TiN
    - Increased surface roughness: grooves, laser-engineering
    - Scrubbing, but achievable SEY material dependent with levels often higher than with above measures

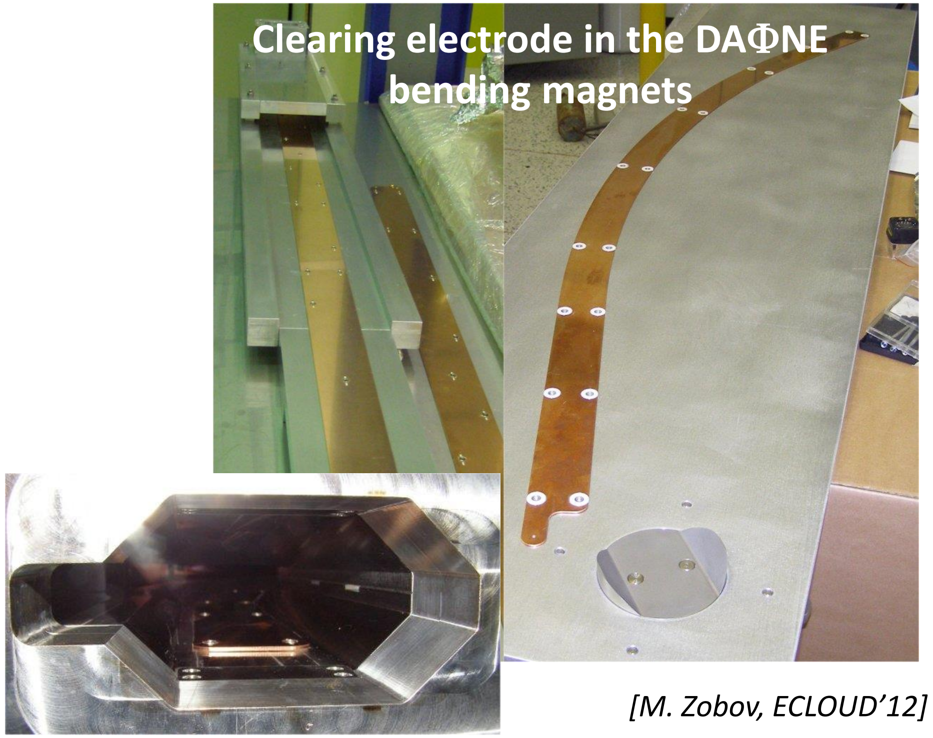
- Reduce electron survival rate by modifying electron dynamics with external fields
    - Longitudinal solenoid fields
    - Clearing electrodes
    - Permanent magnets

- Control synchrotron radiation reflection and absorption, important especially in lepton machines
    - Absorbers, grooves, material reflectivity
    - Consider photoemission yield of chamber material

Laser engineered surface



[G. Tang et al, Appl. Phys. Lett. 101, 2319021 (2012)



Clearing electrode in the DAΦNE bending magnets

[M. Zobov, ECLOUD'12]

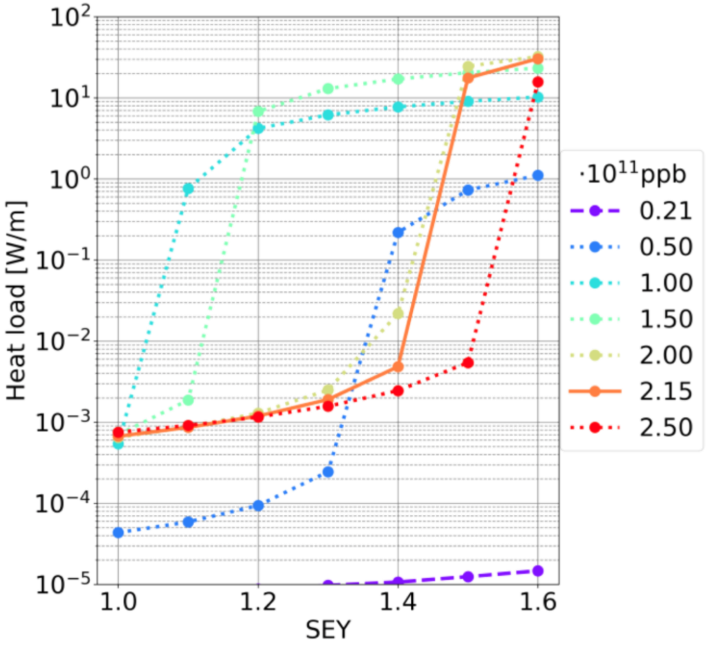
Electron cloud mitigation in FCC-ee Z-mode

For entirely new machines, mitigation is feasible with the available methods, but may constrain other design choices

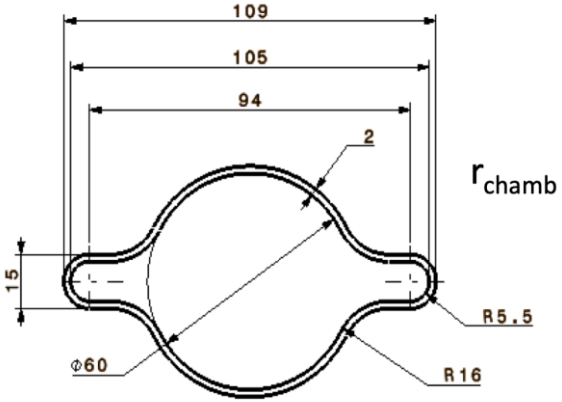
- Suppressing build-up sets strong constraints on the bunch spacing (≥ 20 ns)
  → Higher bunch intensity needed to achieve design current, which makes beam-beam effects more critical

- The tightest constraints come from intermediate intensities that will be crossed due to the top-up injection
  - The low SEY needed to ensure suppression is not quite compatible with a NEG coating that is foreseen for the vacuum system

- Suppression of synchrotron radiation in main chamber is needed to limit photoelectron emission and ensure stability
  - Larger winglets on beam chamber would help, but would set stricter constraints on magnet specifications



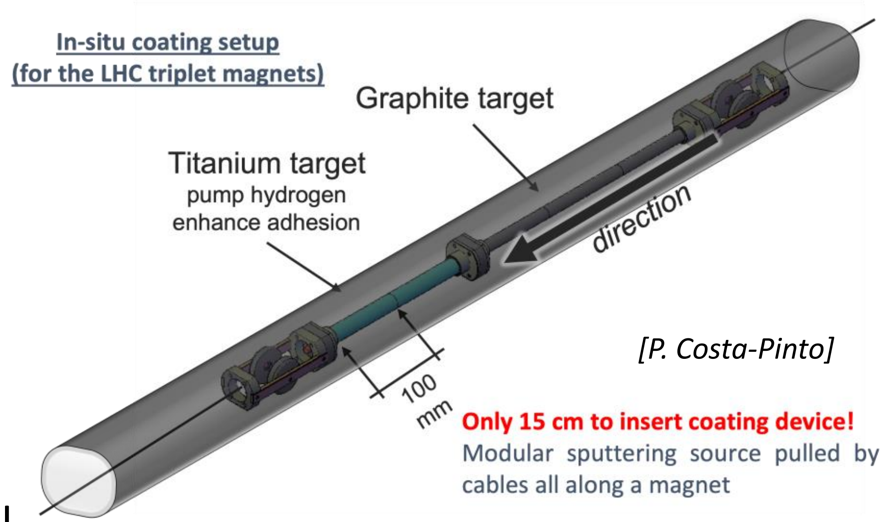
[See F. Zimmermann, IPAC’24 WEPR14]



Electron cloud mitigation in HL-LHC

In machines that rely primarily on existing installations the feasible mitigation measures may be more limited

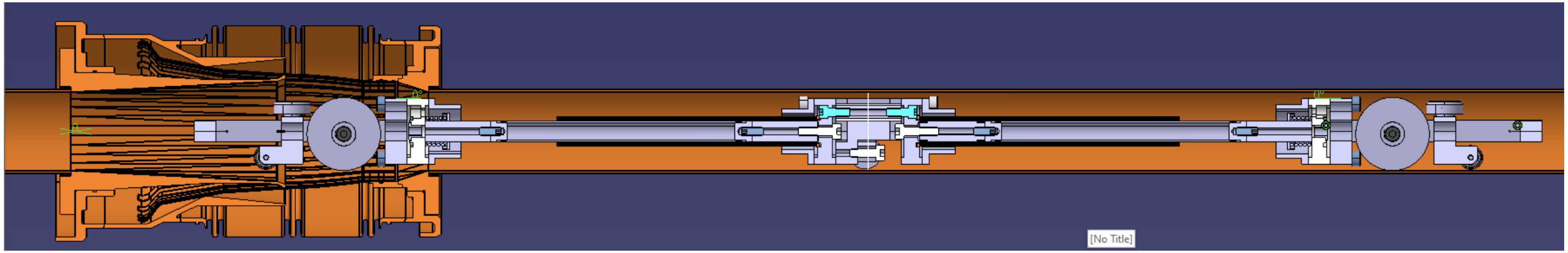
- The HL-LHC Inner Triplets will be completely replaced and treated with an a-C coating
  - The arcs, however, are likely to cause even stronger limitations with the bunch intensity increase and further degradation from coming shutdowns



[P. Costa-Pinto]

Only 15 cm to insert coating device!
Modular sputtering source pulled by cables all along a magnet

- To avoid such limitations, a project is underway to develop a system for applying coating to entire half-cells at a time, in-situ, in the LHC tunnel
  - Aim to treat around a quarter of all half-cells in LS3 before the start of HL-LHC, with the prospect to treat more in coming shutdowns if needed



[G. Rosaz]

Summary and outlook

- Electron cloud build-up leads to a wide range of effects that can considerably impact the beam quality and accelerator environment
  - Particularly evident in the LHC, where increasingly strong e-cloud is significantly limiting the performance

- We start having a very good understanding of the various effects, with advanced tools now allowing to quantitatively study also the more subtle effects
  - Provides the means to mitigate effects as much as possible through fine-tuning machine and beam parameters

- Together with the growing evidence of effective mitigation measures, this makes the prospects for future colliders promising, if electron cloud build-up and mitigation are comprehensively considered as part of the design process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