LHC electron cloud studies

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CERN
for the e-cloud team

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12th HL-LHC Collaboration Meeting
Uppsala, Sweden
22 September 2022

Outline

1. Run 2 experience

2. Outcome of 2022
   a) Scrubbing run and Intensity ramp-up
   b) Implications for HL-LHC

3. Other studies
   a) Heat load in Crab Cavities
   b) Heat load in Inner Triplets
   c) Coating requirement of Insertion Region magnets
   d) Incoherent e-cloud effects (observation and simulation)
   e) Coherent beam instabilities from e-cloud

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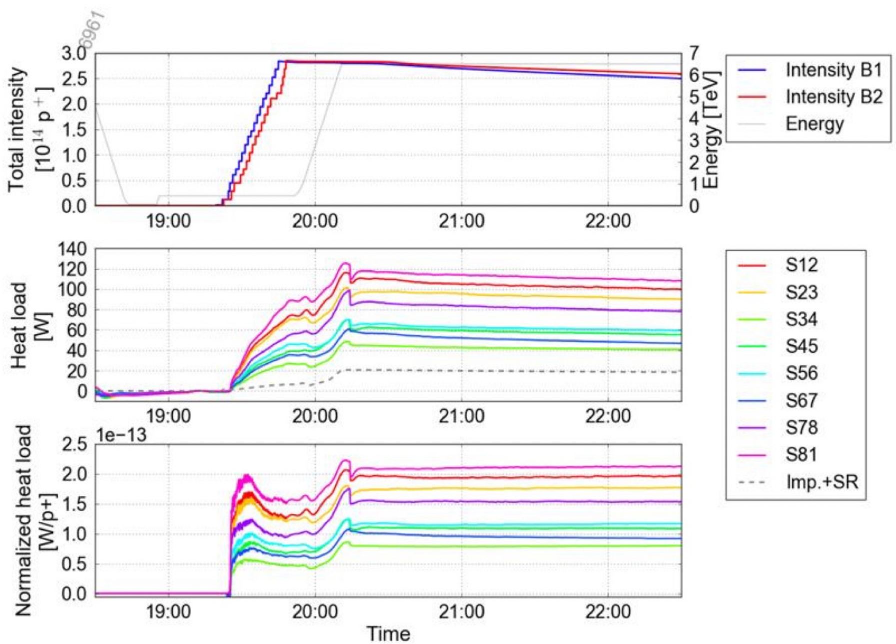
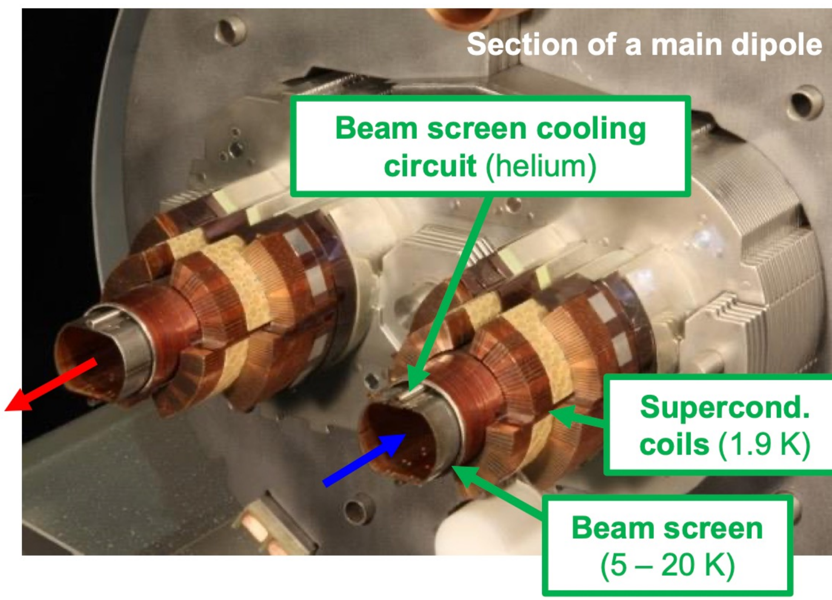
Run 2 experience

Beam induced heat loads on arc beam screens have been a challenge for LHC operation with 25 ns in Run 2: 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 and Run 2
- **CERN Beam-Induced Heat Load Task Force in-place to follow it up**



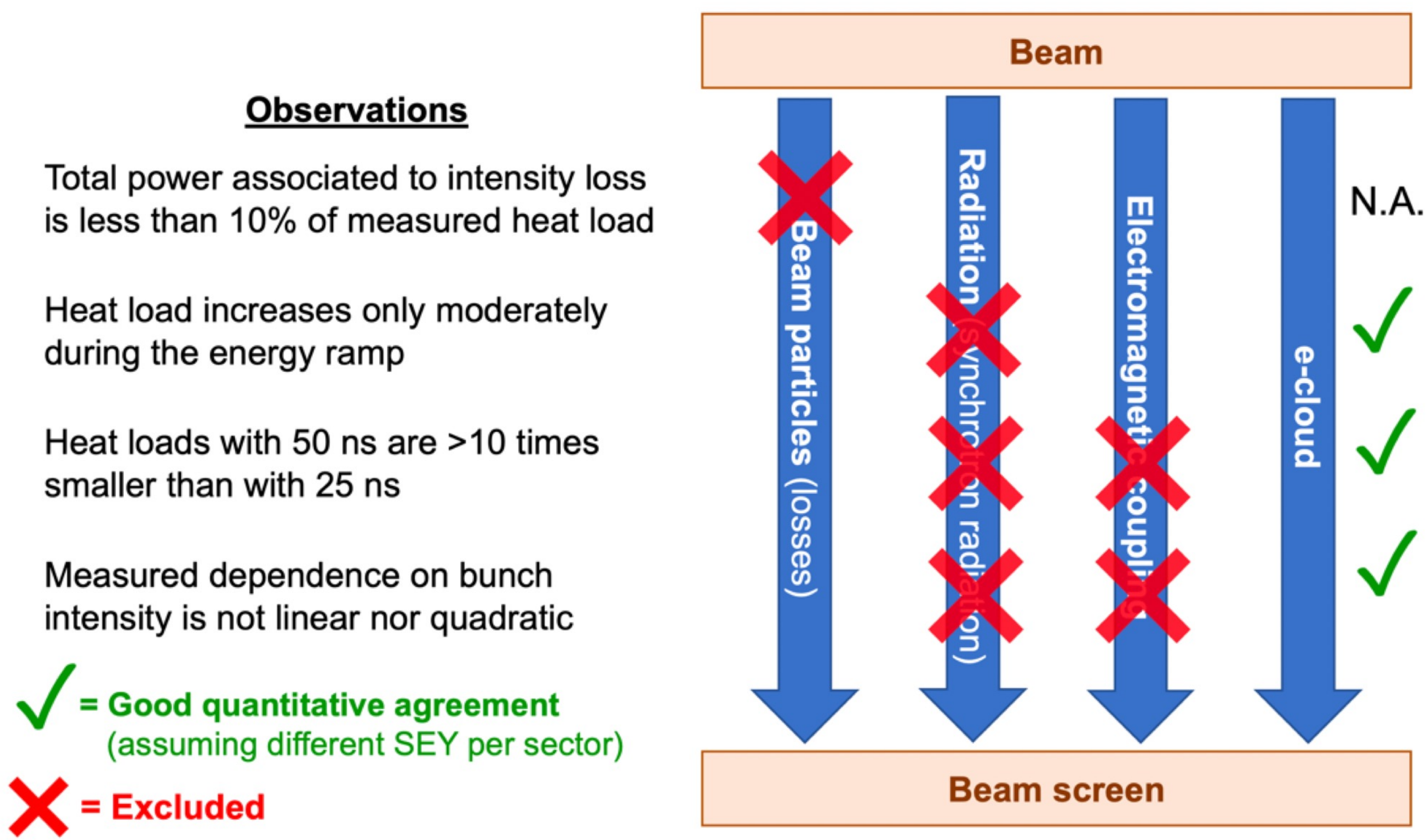


[G. Iadarola, 9th HL-LHC Collaboration meeting]

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)



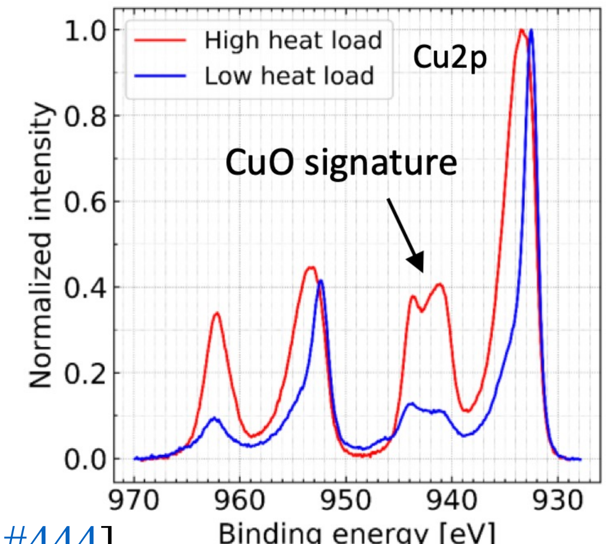
[G. Iadarola, 9th HL-LHC Collaboration meeting]

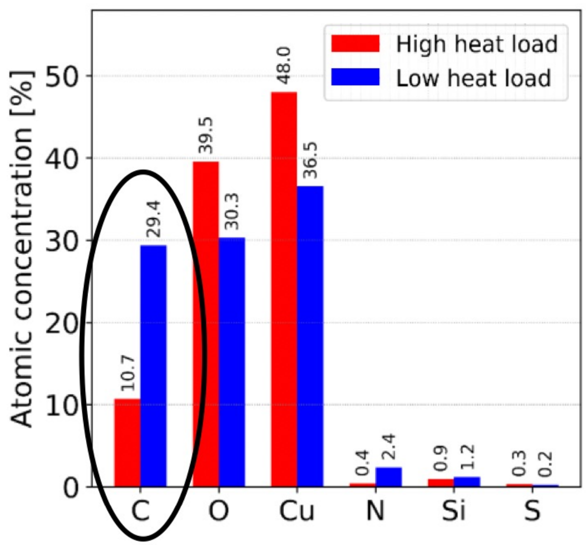
LS2 laboratory analysis

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.

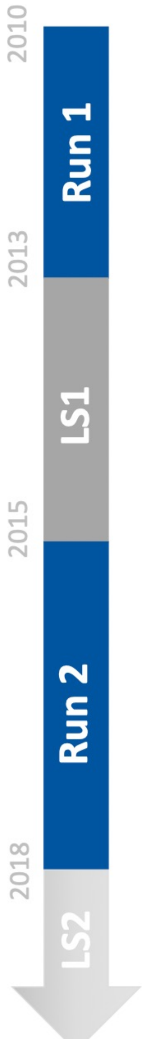
XPS analysis:





[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]

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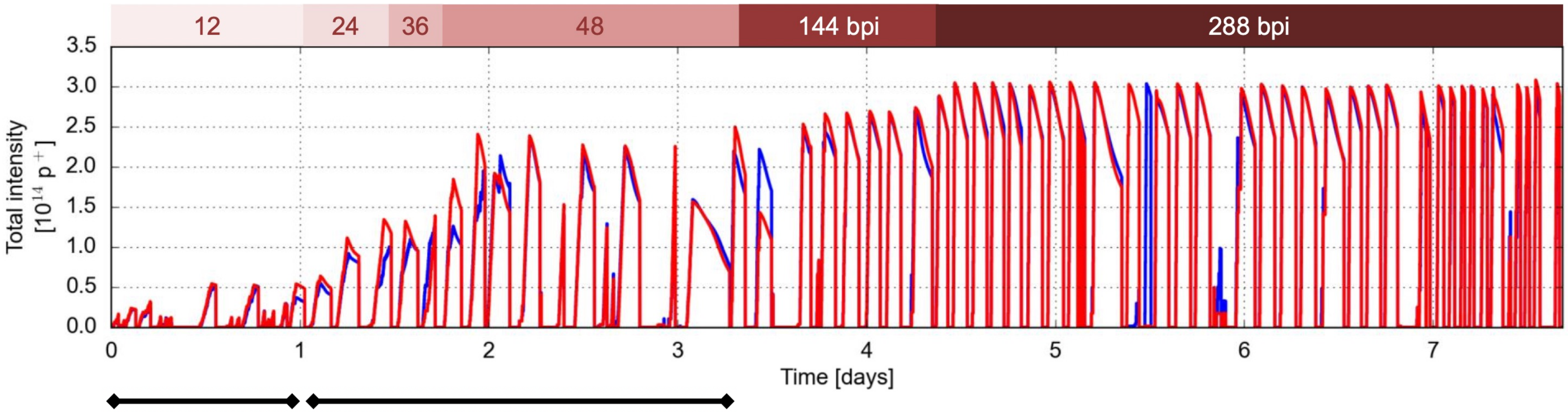
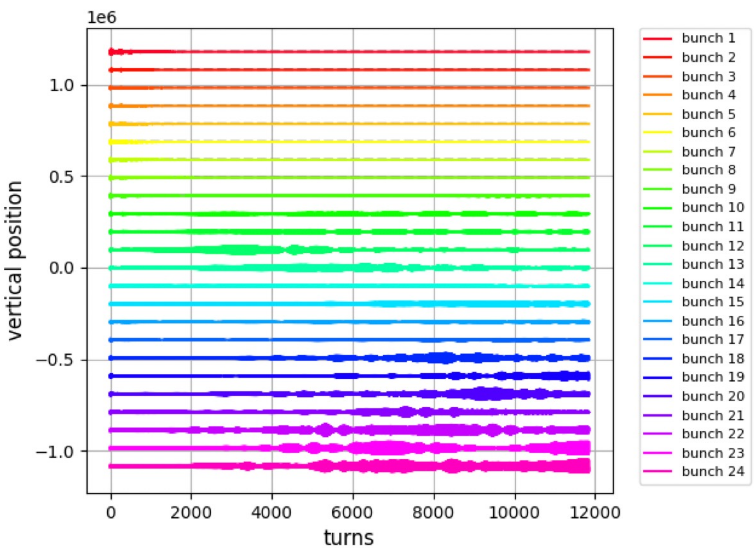
2022 Scrubbing run



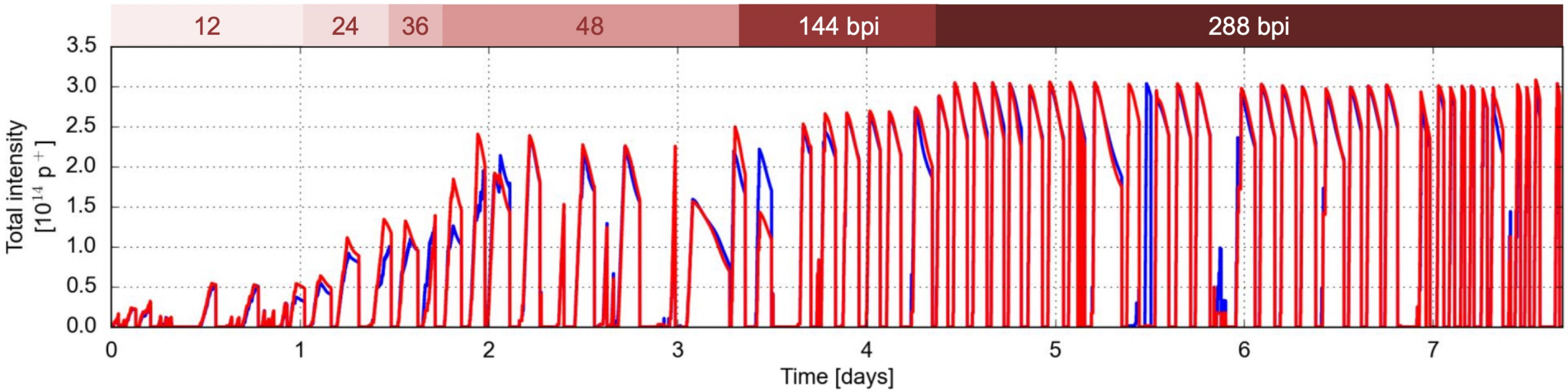
- Around 8 days of dedicated scrubbing took place at the beggining of Run 3.

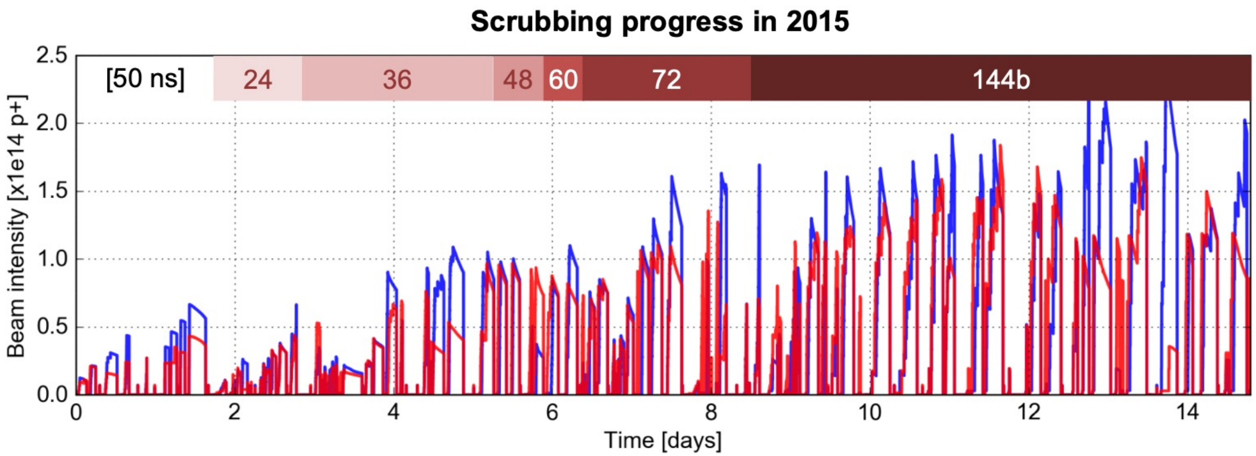
- Early scrubbing was strongly limited by e-cloud instabilities.
- Experience from previous scrubbing runs and simulation studies helped achieving beam control:
    1. Optimized betatron tunes (.27,.293)
    2. Strong transverse feedback
    3. High chromaticity values (Q' = 35)
    4. Strong octupoles (I = 40 A)



[L. Mether, LMC #444]

2022 Scrubbing run



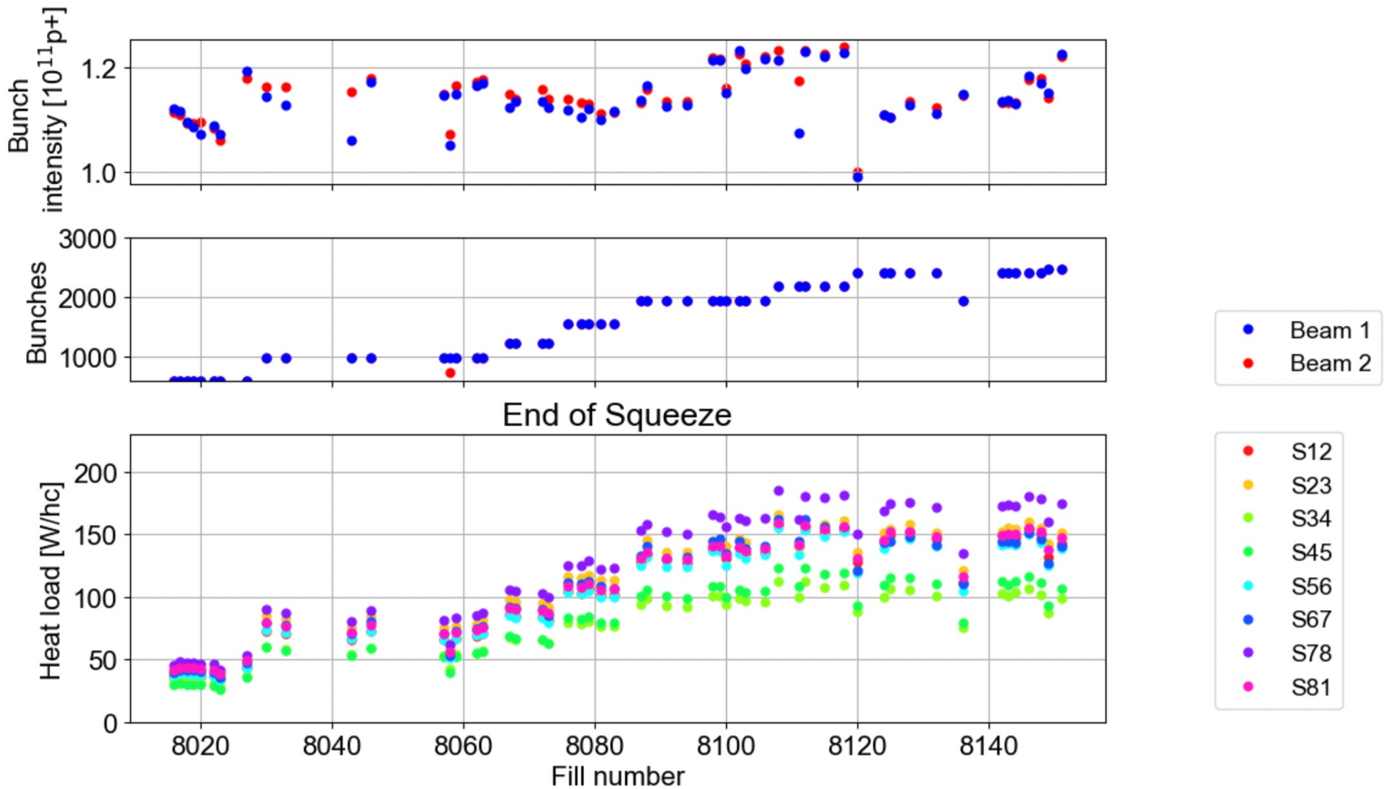


- To reach 144 bunches per injection it took:

2015: ~9 days, 2022: ~4 days

This was also allowed by several improvements including: new TDIS, faster pumping in MKI areas, improved cryogenic feed-forward system.

2022 Intensity ramp-up

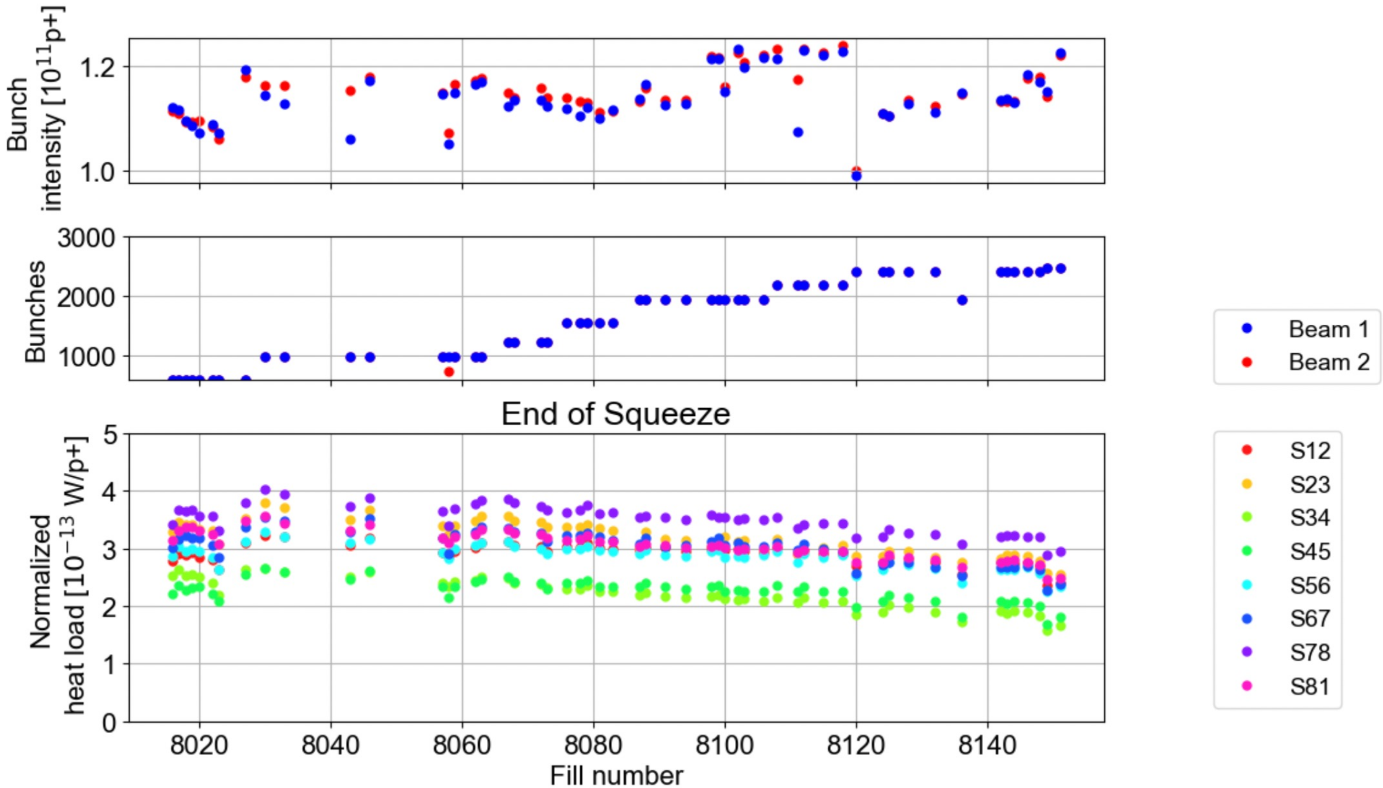


- LHC 2022 intensity ramp-up limited by heat load in sector 78 (not the case in Run 2).
- Limitation reached at 2173 bunches/beam in trains of 5x48b, ~1.2 10^{11} p/b

Ramp-up could continue to increase total intensity with the following steps:

1. 2413 bunches: decrease bunch intensity (1.2 10^{11} p/b → 1.15 10^{11} p/b)
2. 2461 bunches, 1.2 10^{11} p/b: change length of trains (5x48b → 5x36b)

2022 Intensity ramp-up



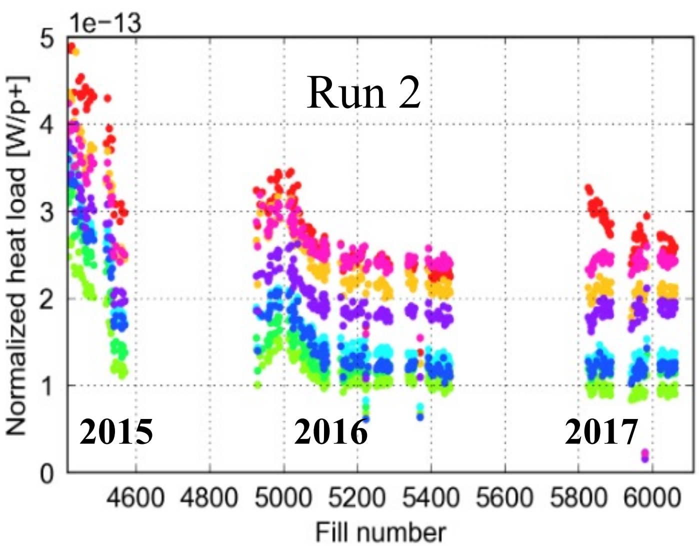
- ~20% Reduction of heat load per proton is visible:
- Partially due to the optimization of beam configuration for max. intensity.
- Partially due to conditioning (scrubbing).

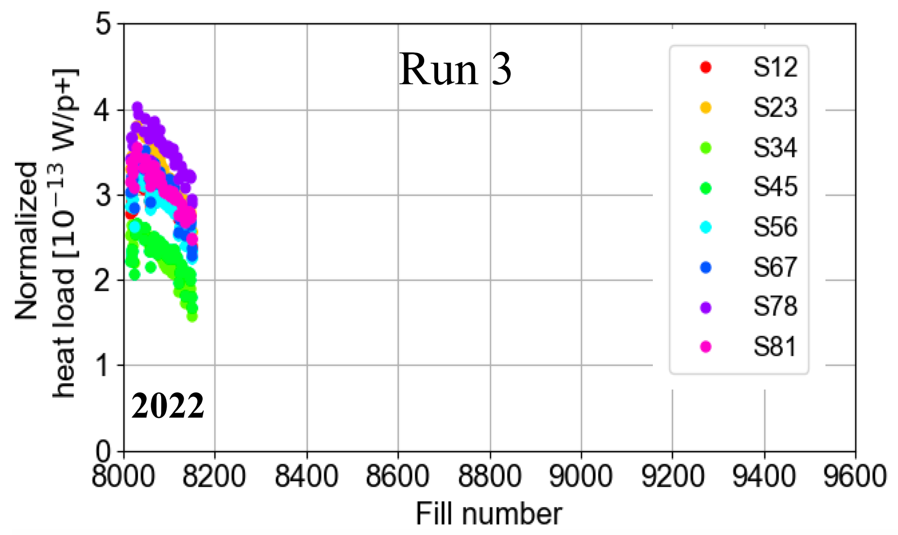
Intensity ramp-up is not finished.

Conditioning is expected to continue well into 2023.

Implications for Run 4

- Conditioning is expected to continue well into 2023.
  - **Until 2023, we cannot know *a priori* what SEY can be achieved and the corresponding intensity reach for HL-LHC.**
  - To achieve baseline parameters, it is necessary to recover Run 2 SEY values.
- Post-LS reconditioning will take place at the beginning of each run.
  - 2022-2023 experience will provide information on **loss of integrated luminosity due to “slow” intensity ramp-up**





Implications for Run 4

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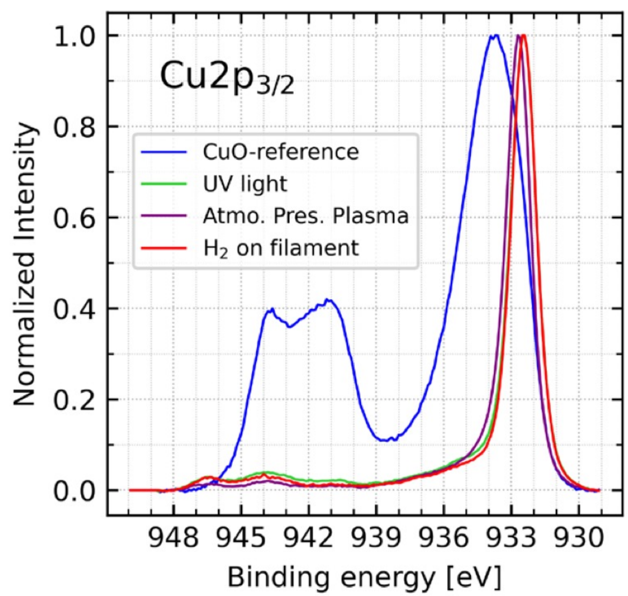
Treatment of the beam screen surface would result in:

1. Faster intensity ramp-up
2. Increased performance reach

Several techniques already in study by the **CERN Beam-Induced Heat Loads Task Force.**

- Promising R&D with test samples.
- Work ongoing to develop methods compatible with an *in-situ* treatment.



[V. Petit *et al*, doi:10.18429/JACoW-IPAC2022-TUOXSP1]

Mitigation schemes

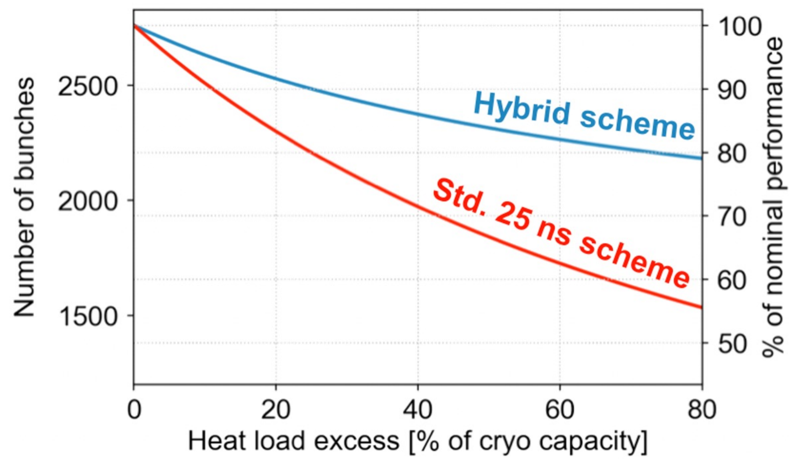
In case intensity reach is limited by heat load in the arcs due to e-cloud, filling scheme can be adapted to partially mitigate the loss of performance.

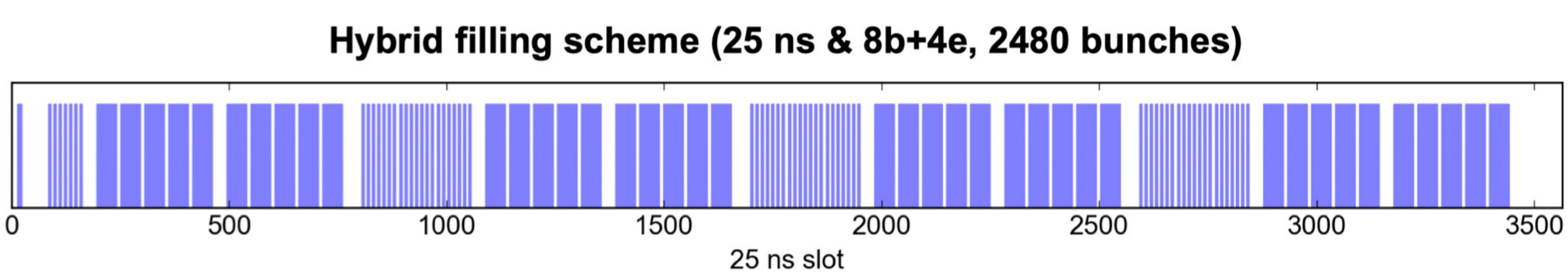
- Some 25 ns trains can be replaced with 8b+4e trains
- The fraction of 8b+4e can be tuned to adapt to the cooling capacity.

A pure 8b+4e beam entails in losing 33% of the number of bunches but:

- Can give reasonable performance with lower heat load.
- Potentially allows running cryo-plants in economy mode.

[G. Skripka, G. Iadarola, CERN-ACC-NOTE-2019-0041]





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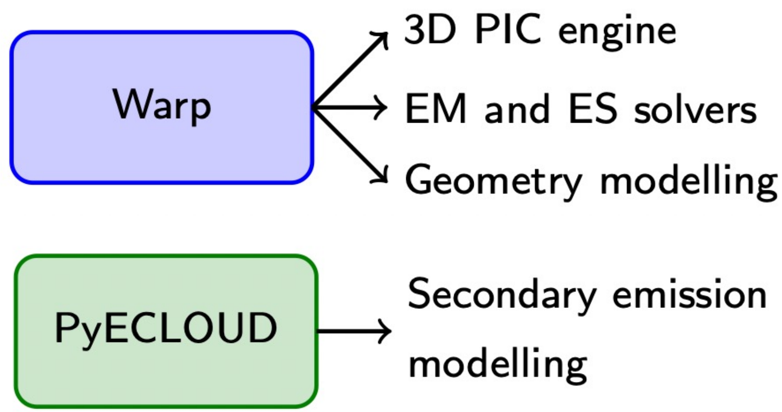
Heat load in crab cavities (Simulation)

Collaboration between CERN and Accelerator Modelling Program of Berkeley Lab (LBNL).

- Electromag netic 3D PIC simulations.
- Interface between Warp and PyECLOUD for simulation of e-cloud in crab cavities.

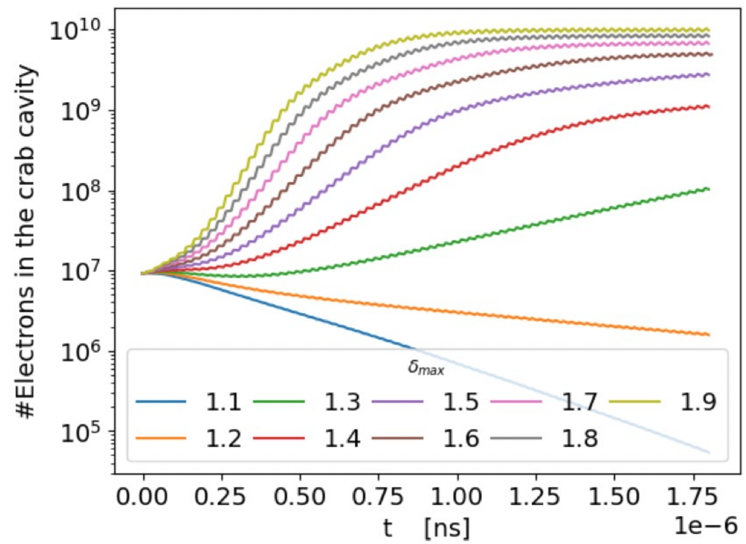


Without any RF voltage:

- Some beam-induced multipacting.
- Heat load is tolerable by cryo.

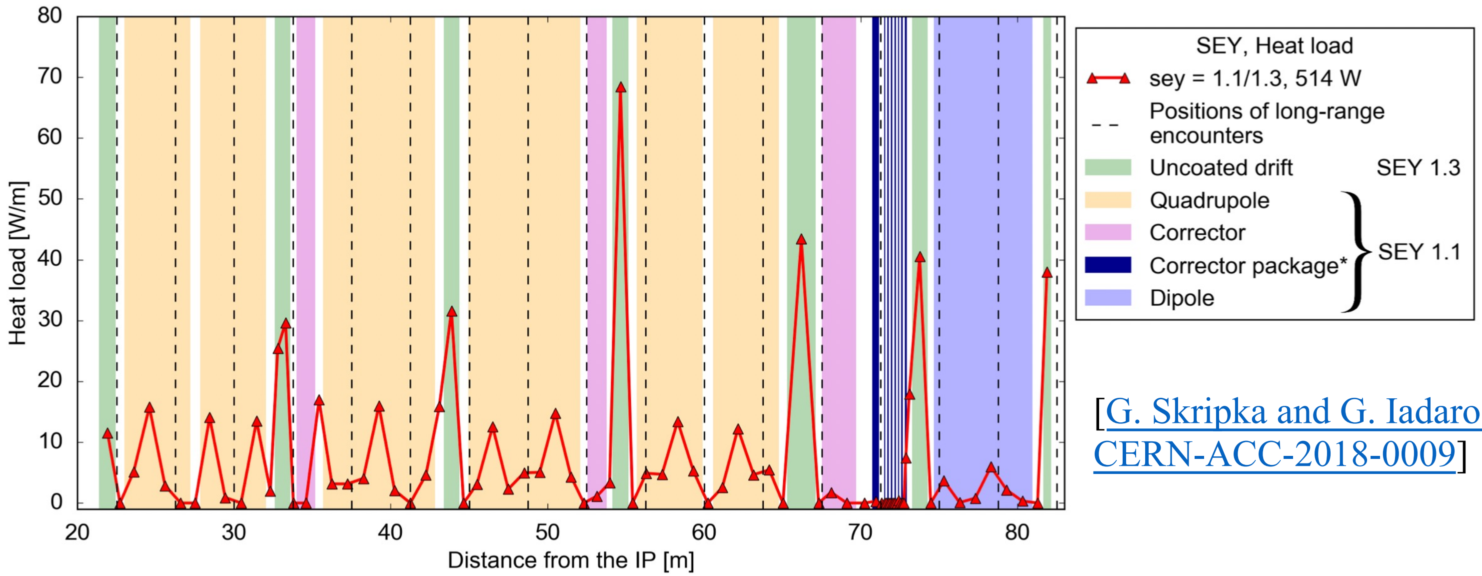
With RF voltage (> 1 MV):

- No beam-induced multipacting.
- RF-induced multipacting observed.
  - Shown to condition in test stands and in the SPS



[L. Giacomel, EDMS 2663141]

Heat load in the Inner Triplets



[G. Skripka and G. Iadarola, CERN-ACC-2018-0009]

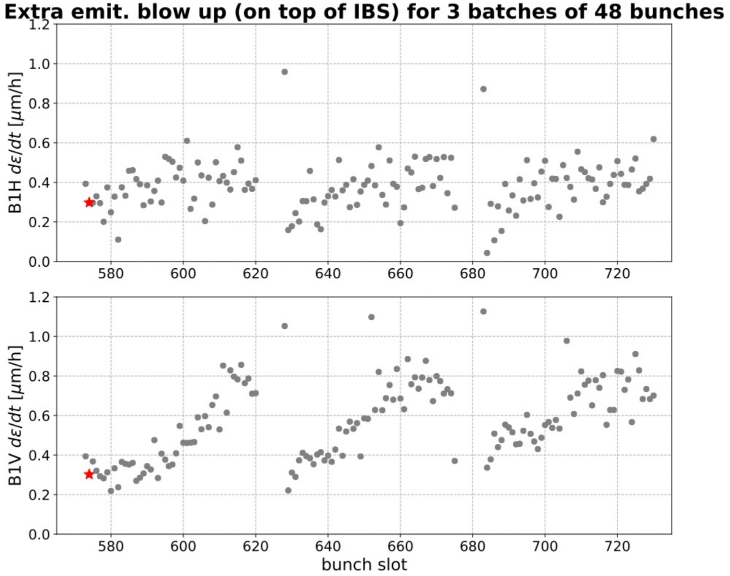
* dodecapole, skew dodecapole, decapole, skew decapole, octupole, skew octupole, sextupole, skew sextupole

- Heat load in the Inner Triplet is dominated by the uncoated drifts (drifts at extremities and Deformable RF finger bellows).
- Refined estimate based on the latest design:
  Total simulated heat load of IT in IR5: 130 W.
- Estimates incorporated in specifications for new cryogenic system upgrade.
  [Heat Loads for HL-LHC scope (P1/P5) – Internal review]

Incoherent electron cloud effect (Run 2 observations)

450 GeV (injection):

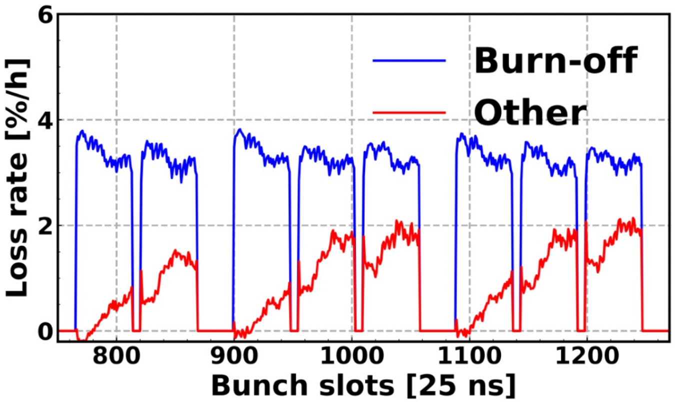
- Most significant effect is slow emittance growth.
- Horizontal: ~ 0.3 um/h
- Vertical: ~ 0.6 um/h



[S. Papadopoulou *et al.*, Evian2019]

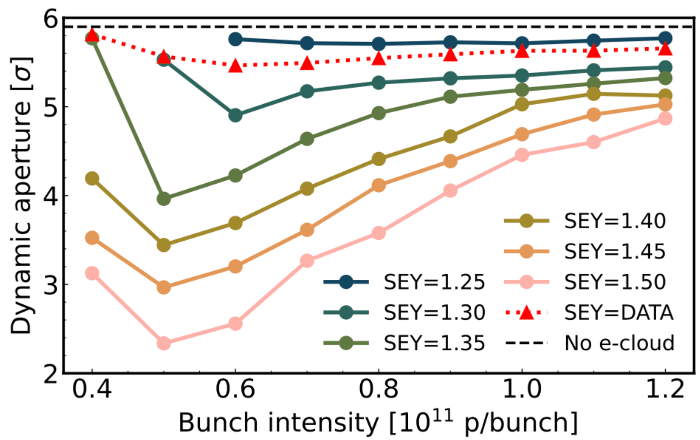
6.5 TeV (stable beams):

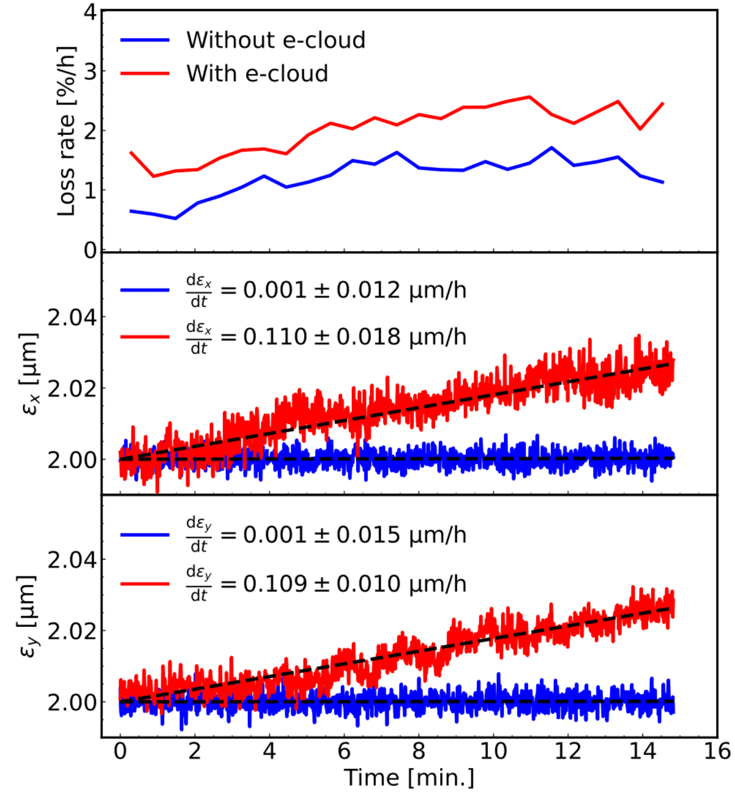
- Significant slow beam loss comparable to luminosity burn-off.
- Effect pinpointed to IR1 & IR5 because it depends:
  1. On crossing angle,
  2. β* / IR β functions,
  3. Presence of the other beam
- But doesn't depend on:
  4. β functions in arcs.



[K. Paraschou *et al.*, MCBI2019]

Incoherent electron cloud effect (Simulation)





- Significant progress in the simulation of e-cloud incoherent effects (XSuite).
- Can use GPUs to simulate observable timescales (15-30 mins).
- **First simulations for LHC at 450 GeV.**

Near future:

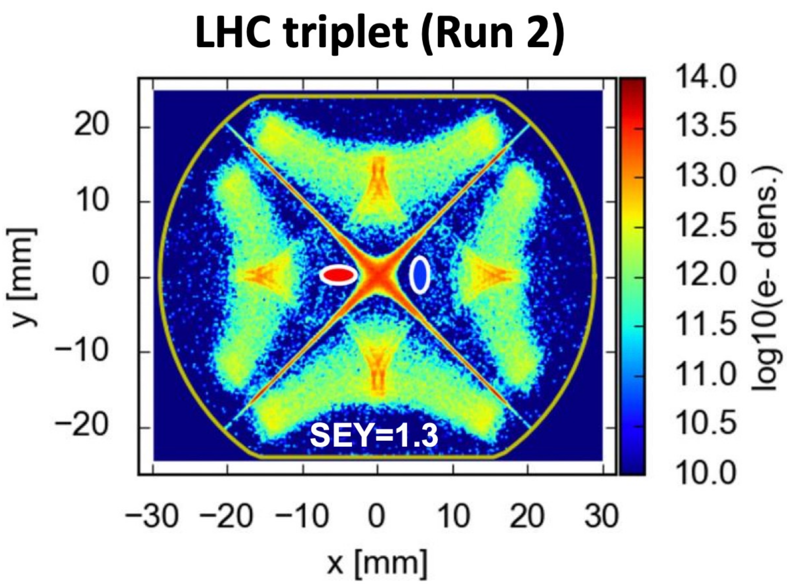
- Specialized MDs necessary (450 GeV) to **verify modelling** with measurements.
- Simulate slow beam loss with Inner Triplet e-cloud at collision energy.

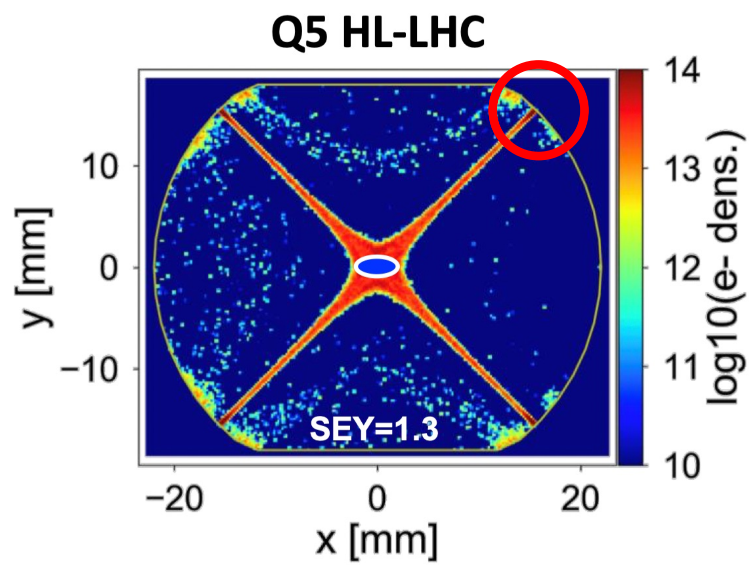
Challenges for simulating the e-cloud in IT:

1. Buildup depends on both beams.
2. Buildup depends on delay between bunches of opposing beams (changes along s position).
3. Beam-beam effect needs to be included.

[K. Paraschou, ABP-CEI meeting]

Coating requirements of the Insertion Region magnets





- New HL-LHC Inner Triplet quadrupoles are planned to be coated with amorphous carbon.
- Q4 and Q5 quadrupoles to be coated to avoid performance degradation, due to large electron density at the beam location and large β functions.
    - Target SEY < 1.10 (full suppression of e-cloud for HL-LHC intensities).
    - No coating necessary on the flat regions of beam screen.

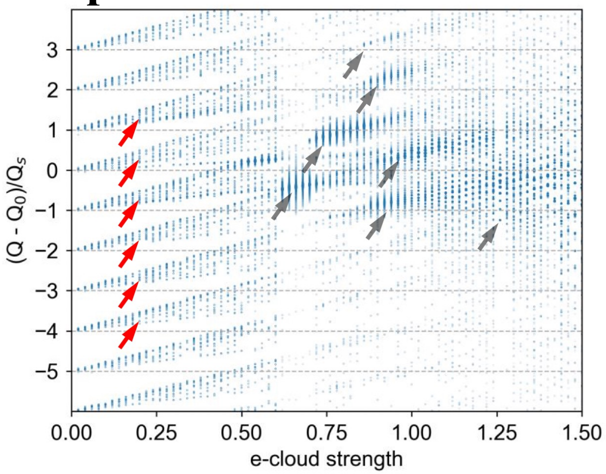
[G. Iadarola, 202nd HiLumi WP2 meeting]

[G. Iadarola, 205th HiLumi WP2 meeting]

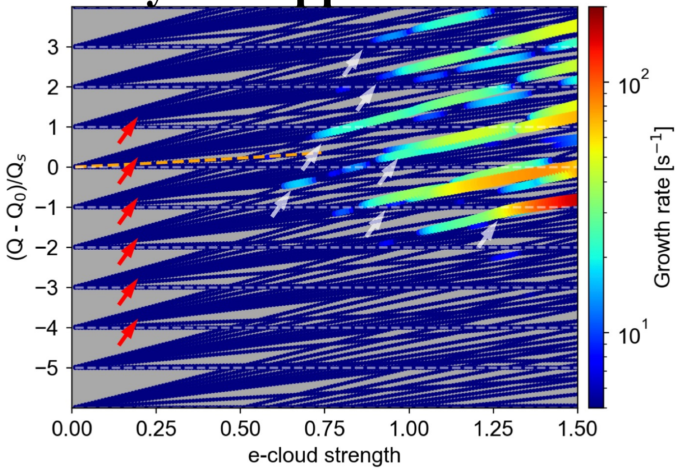
Electron cloud coherent beam instabilities

- "Single-bunch" coherent beam instabilities from e-cloud effects in (HL-)LHC effects extensively studied with PIC simulations [L. Sabato, CERN-ACC-NOTE-2020-0050].
- Effort now dedicated to developing predictive methods with a linearized Vlasov method in order to achieve:
  - Better insight on underlying mechanism.
  - Access longer instability timescales.
- Agreement between macro-particle simulations (PyHEADTAIL) and new analytical approach is remarkable in the absence of chromaticity.
- Presently studying interplay with chromatic detuning.

Macroparticle simulation:



New analytical approach:



More details in:

G. Iadarola *et al.*, PRAB 23, 081002 (2020) and S. Johanesson, ABP-CEI meeting

Conclusion

The e-cloud induced heat load in the LHC arcs can pose a limitation to achieving the HL-LHC target luminosity.

- Deconditioning after long shutdowns causes a prolonged intensity ramp-up → → loss of integrated luminosity.
- Each long shutdown brings risk of further irreversible degradation to the beam screen in terms of SEY.
- Important to develop surface treatment to reduce SEY in the arc beam screens (dedicated Task Force in place).
- Hybrid schemes (25ns + 8b4e) possible to partially mitigate loss of luminosity.

Several other e-cloud studies for HL-LHC:

- Simulation studies of e-cloud in crab cavities reveal no concerns. Many thanks to the collaboration with LBNL.
- Heat load studies in Inner Triplets provided input for cryogenic upgrade.
- Slow losses from Inner Triplets observed in Run 2. Coating of IT is expected to mitigate them. Important to reduce SEY in Q4 and Q5 as well.
- Ongoing progress in simulating (incoherent) slow losses and emittance growth from e-cloud.
- Effort ongoing to develop predictive methods of coherent beam instabilities with a linearized Vlasov method to achieve better insight on underlying mechanism and access longer instability timescales.

Thank you for your attention!

Konstantinos Paraschou