E-cloud, scrubbing and heat load after LS2

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with input from:

Electron Cloud Working Group

Beam Induced Heat Load Task Force

10th LHC Operations "Evian" Workshop
25.11.2021

Outline

- Experience from Run 2
  - Introduction
  - Conditioning through scrubbing
  - E-cloud instabilities
  - Heat loads
- Understanding the heat loads
  - Beam observations
  - Main results from surface analysis
- Prospects for Run 3
  - Scrubbing
  - Heat loads
  - Instabilities

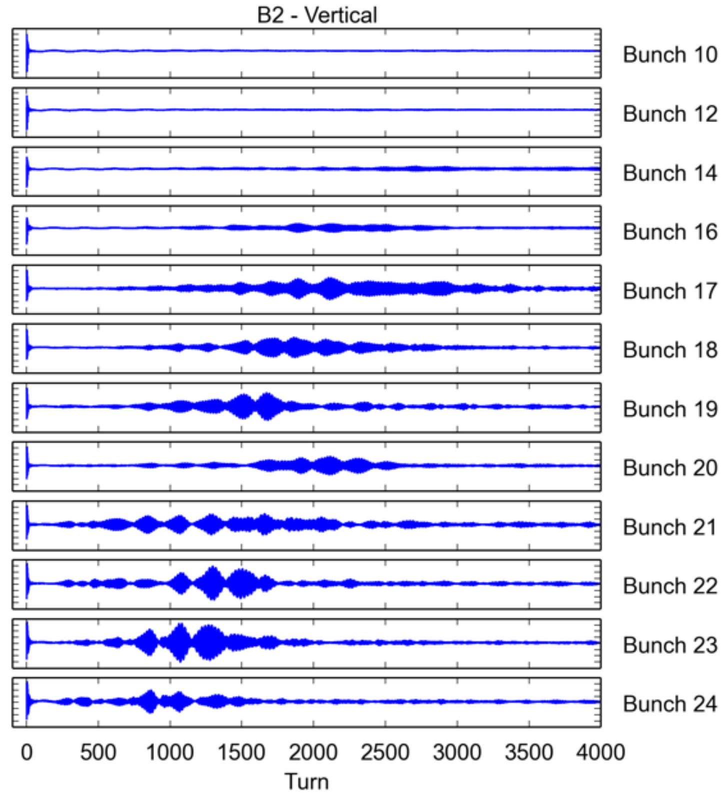
Introduction

In Run 2, the LHC was routinely operated with 25 ns beams for the first time

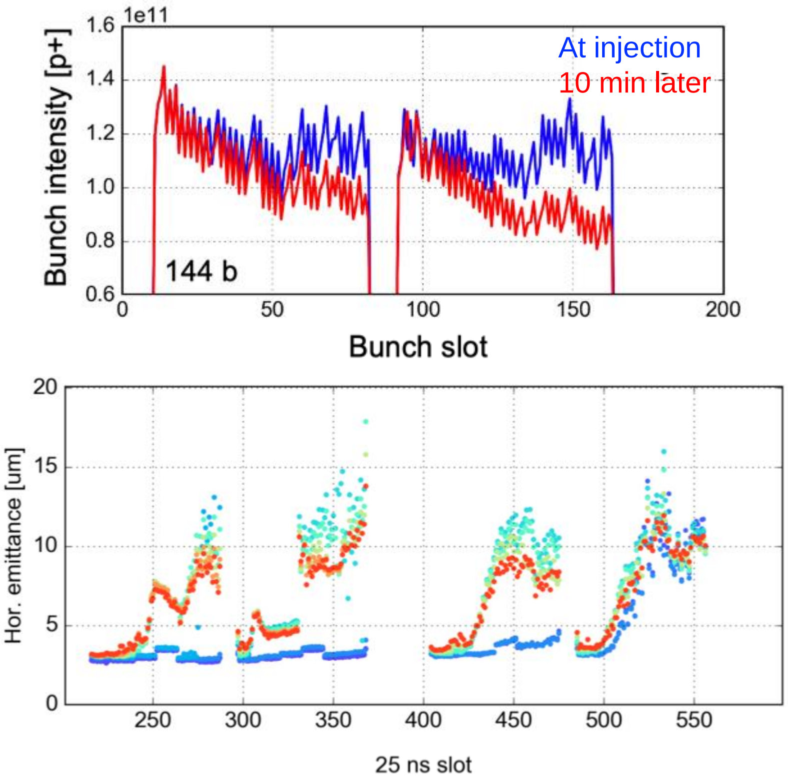
→ Significantly increased electron cloud production compared to Run 1

→ Degradation of beam quality

Transverse instabilities



Beam loss and emittance growth



Introduction

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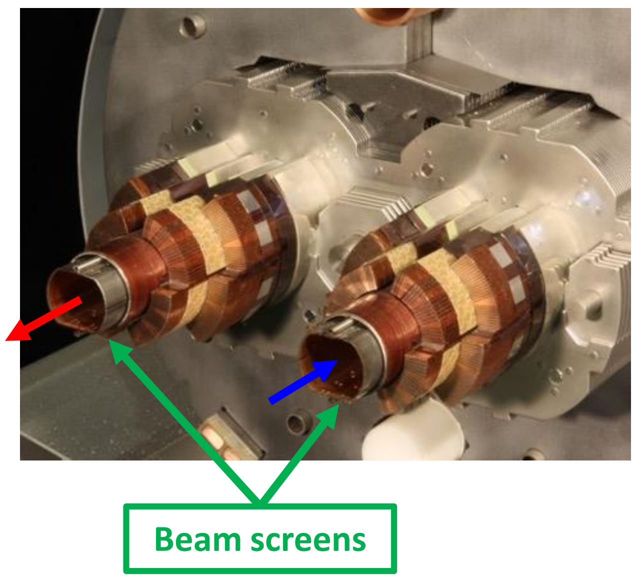
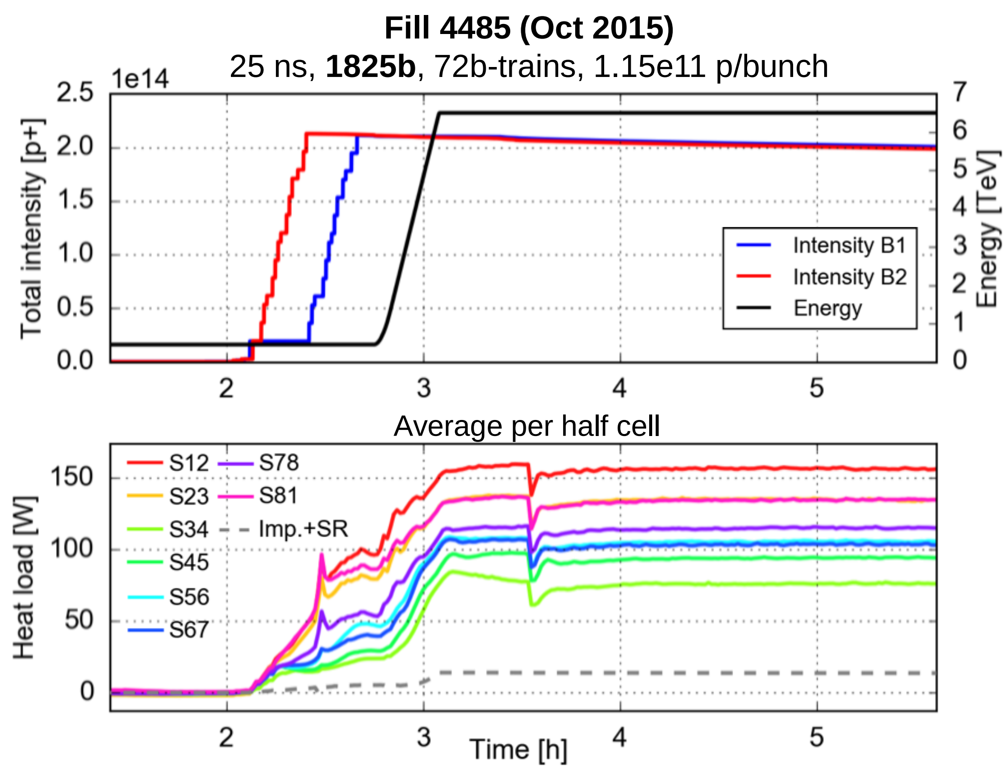
→ Significantly increased electron cloud production compared to Run 1

→ Degradation of beam quality

→ Power deposition on the arc beam screens

Heat load in the cryogenic magnets



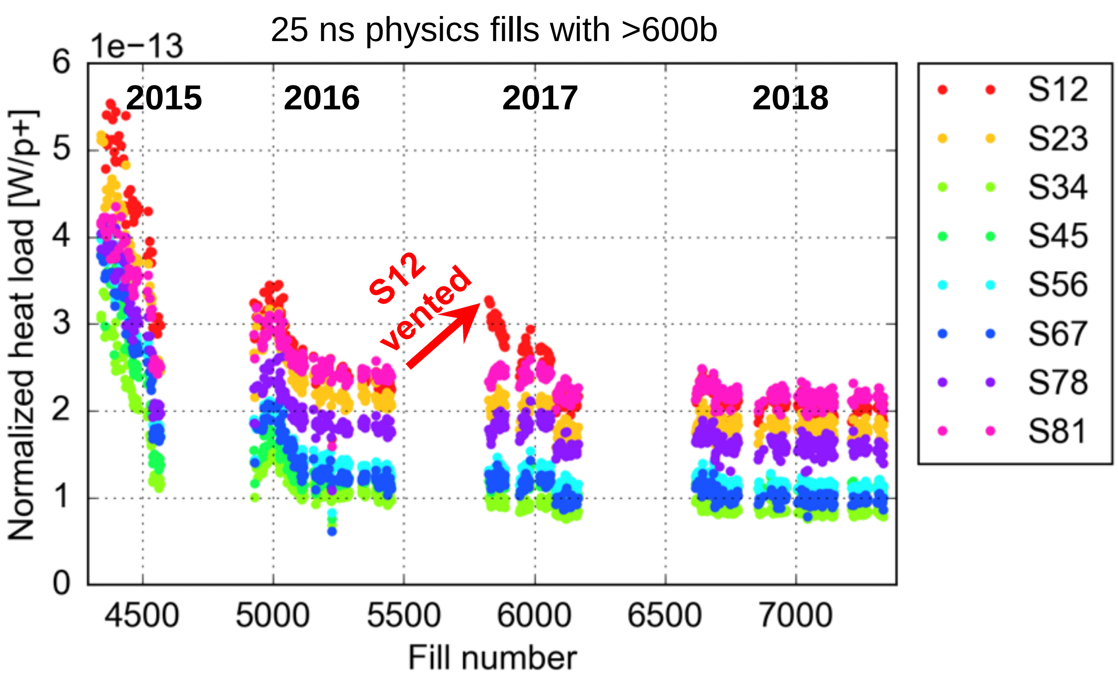


Conditioning through scrubbing

Beam-induced scrubbing was able to mitigate electron cloud to a large extent

- A strong reduction of the arc heat loads was observed in 2015 and the first part of 2016
  - Allowed a satisfactory exploitation of 25 ns beams for physics

- However, it was not possible to fully mitigate electron cloud through scrubbing
  - From the second part of 2016 until the end of Run 2, the heat loads stayed practically constant and e-cloud effects remained present in the machine

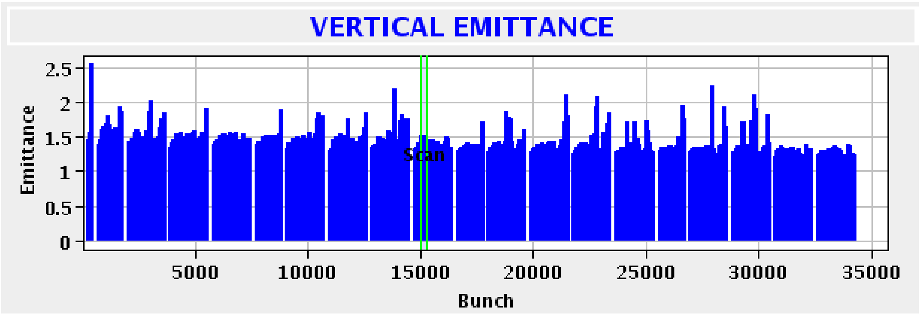


Beam degradation at 450 GeV

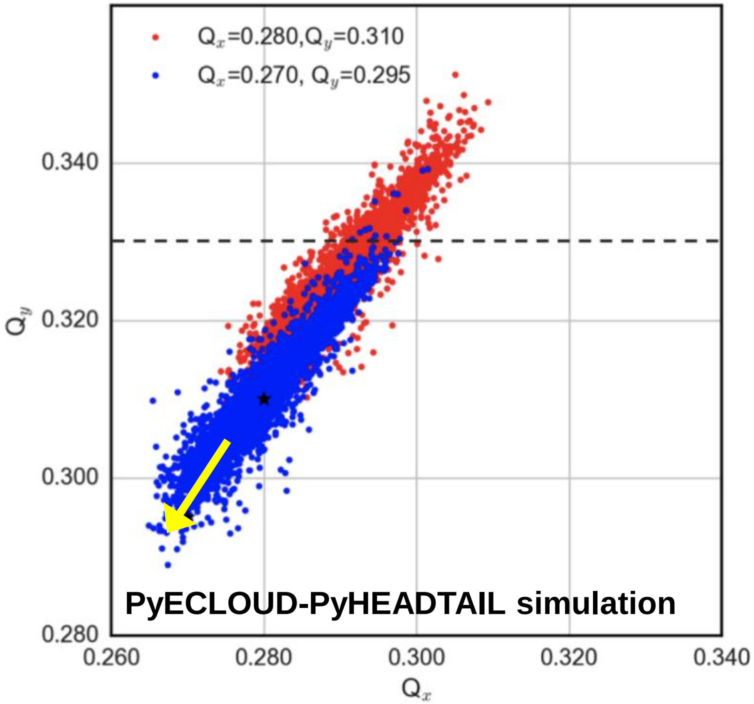
- Instabilities could be mitigated by using high chromaticity, strong octupoles and high feedback gain and bandwidth, but could not be fully suppressed

$Q'_{xy} > 15$, $I_{oct} > 50$ A
~20 turns damping time

Emittances at start-ramp for a typical 2018 fill



- Throughout the run, the tunes at injection needed to be shifted to accommodate the large tune footprint caused by the e-cloud, in order to preserve the beam lifetime

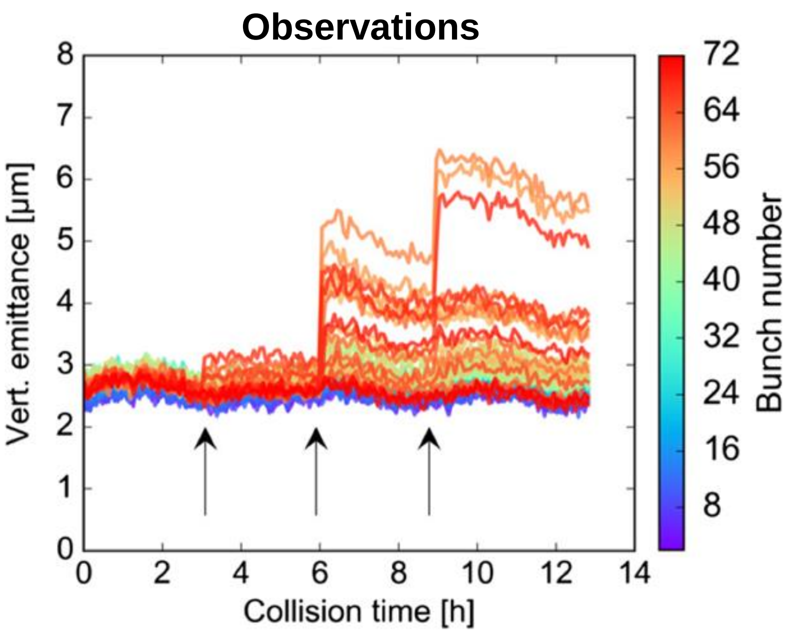


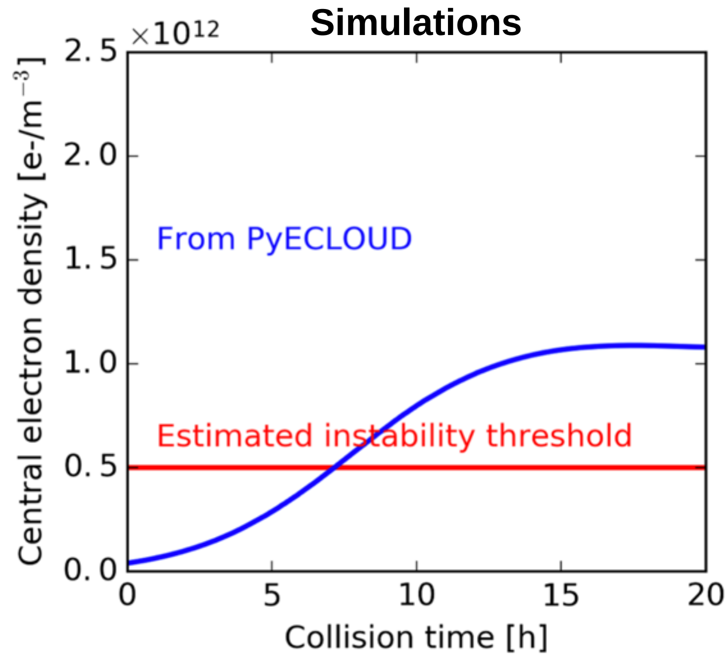
For more details, see: A. Romano et al, IPAC2017 (TUPVA018)

Beam degradation at collision energy

At collision energy the effects of the e-cloud on the beams are much weaker, thanks to the increased beam rigidity

- In 2016, instabilities at end of fills occurred due to growth of central electron stripe in dipoles with decreasing bunch intensity – not observed later with shorter bunch trains





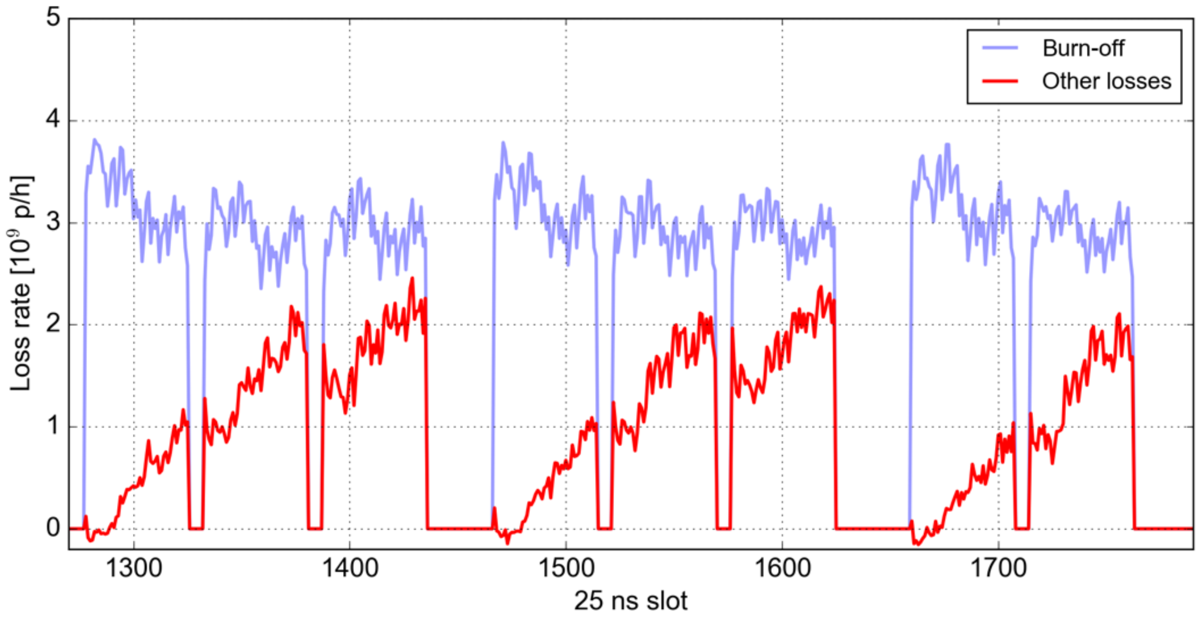
For more details, see: A. Romano et al, [Phys. Rev. Accel. Beams 21, 061002]

Beam degradation at collision energy

At collision energy the effects of the e-cloud on the beams are much weaker, thanks to the increased beam rigidity

- In 2016, instabilities at end of fills occurred due to growth of central electron stripe in dipoles with decreasing bunch intensity – not observed later with shorter bunch trains

- Even when beams were stable, slow beam losses were observed in collision
  - Caused mainly by e-cloud in the Inner Triplets, enhanced by the large beta functions



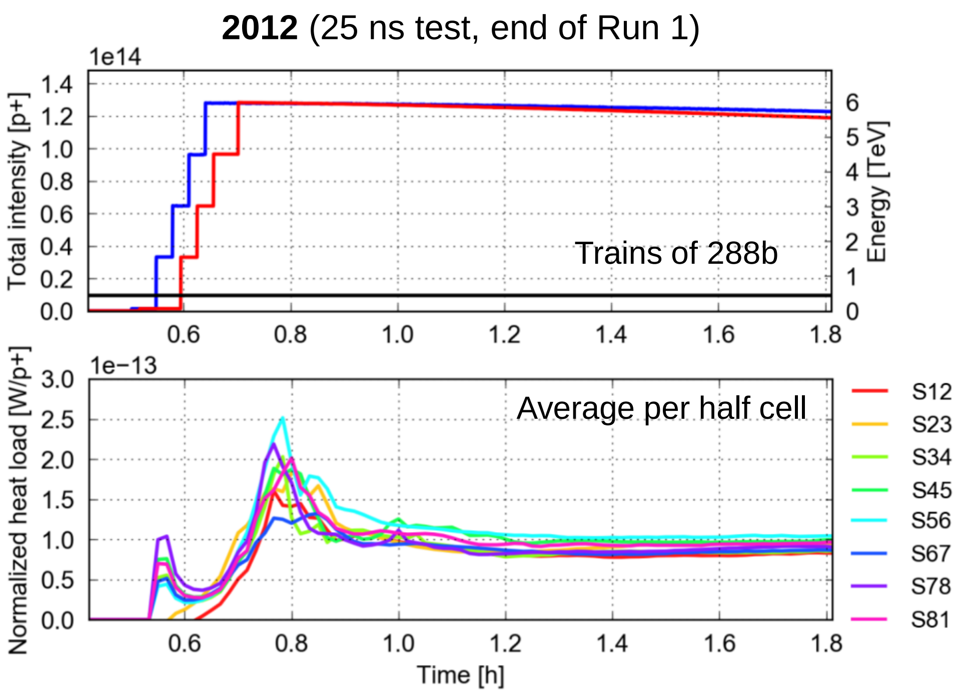
For more details, see: K. Paraschou et al., *DOI: 10.23732/CYRCP-2020-009.249*

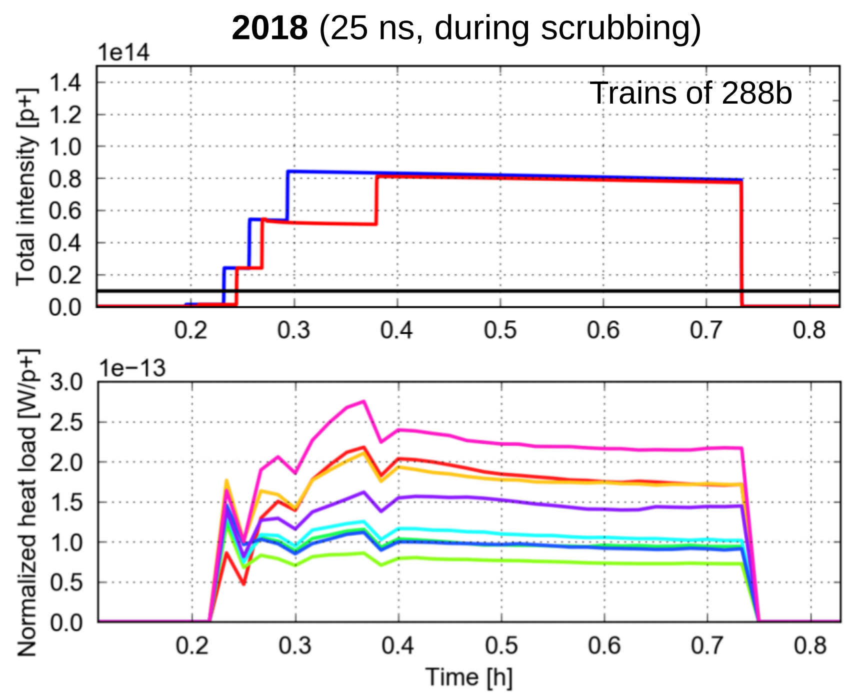
Heat load differences

Unexpectedly, the heat loads measured in the eight sectors showed large differences

- The heat loads in S12, S23 and S81 were much larger than in the other sectors
- The differences were highly reproducible over all 25 ns fills in Run 2, but were not present in Run 1 → degradation occurred between Run 1 and Run 2

→ Addressed by dedicated Beam-Induced Heat Load Task Force since 2017





For more details, see: G. Iadarola, LMC 12 Sep 2018

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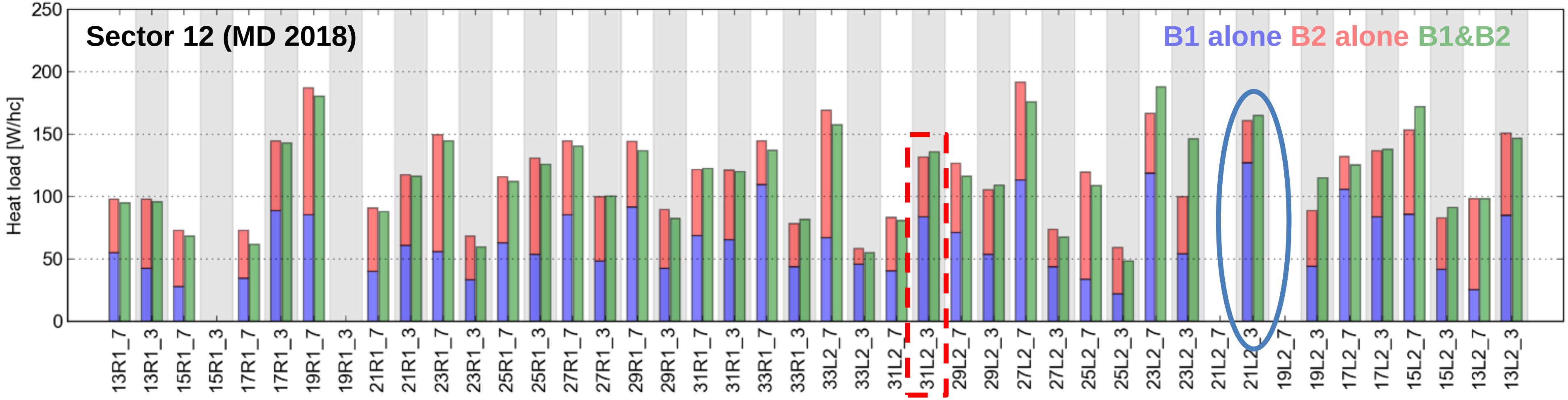
    - Instabilities

Heat load distribution

- Differences in heat load were not only observed between sectors, they also appeared:
  - From cell to cell, especially in the high load sectors
  - For the two apertures in a single cell
  - Among magnets in a single cell



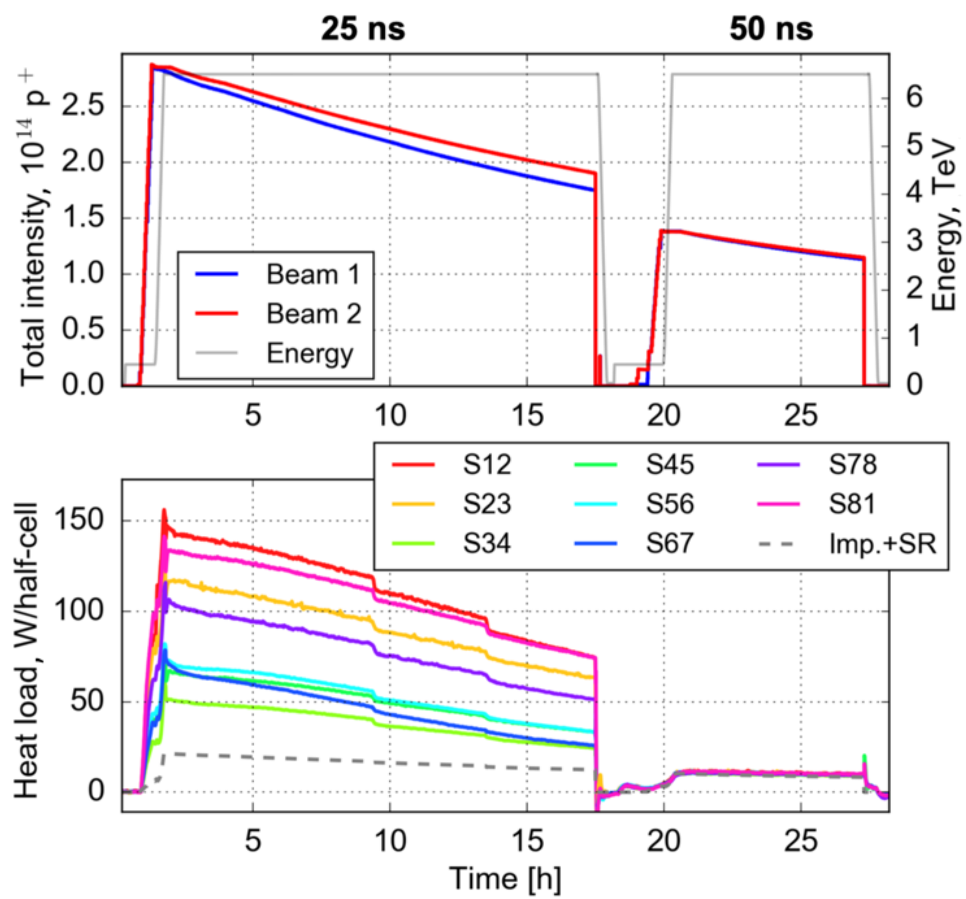
<u>Cell 31L2</u> (equipped with extra thermometers within the cell)

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

Beam observations

Several studies with beam were performed in 2017-2018 to investigate the behaviour of the heat loads

- While the heat load differences were observed with 25 ns bunch spacing, they disappeared with 50 ns bunch spacing
  - → Clear electron cloud signature!
- With the 25 ns beam, the measured heat loads were much larger than estimated for impedance and synchrotron radiation in all sectors
  - → Significant contribution from electron cloud

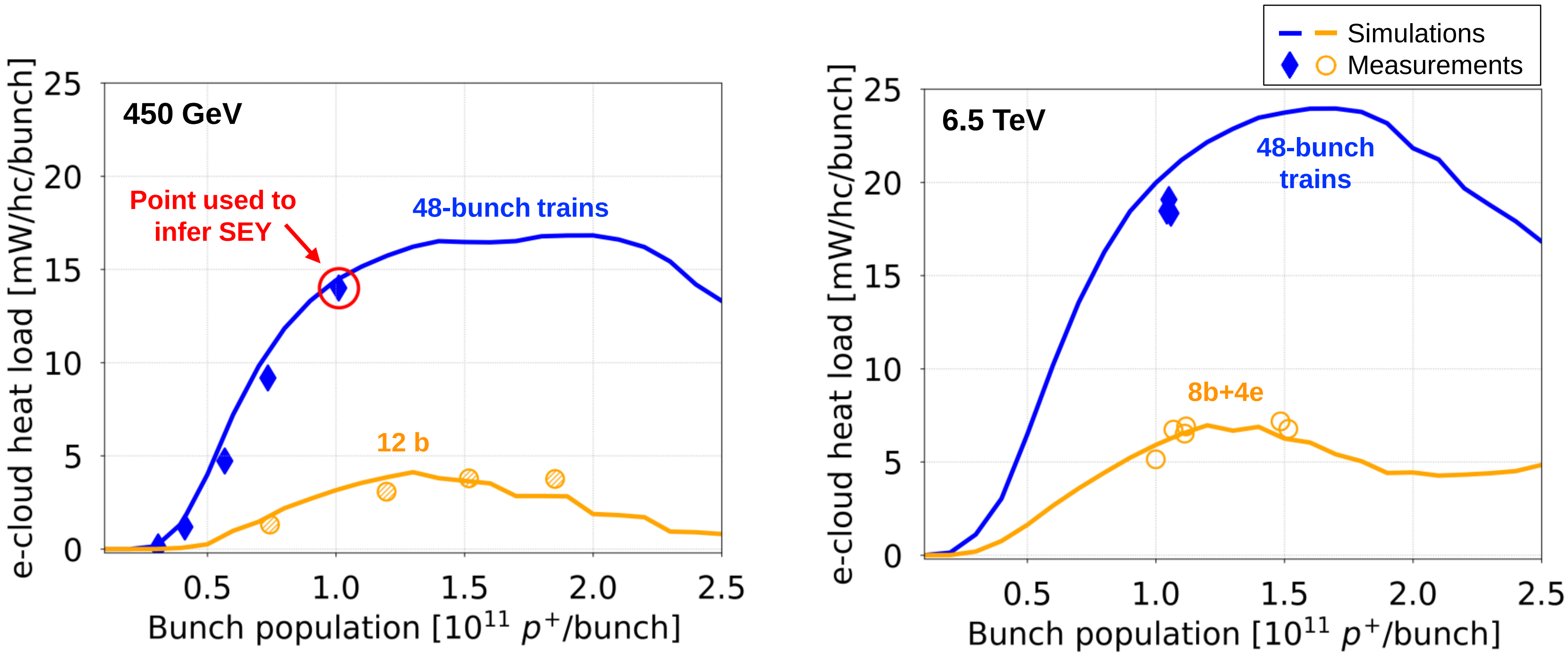


For more details, see: G. Skripka et al., [CERN-ACC-NOTE-2019-0041]

Comparing simulations with measurements

Simulations were compared against measurements to assess whether the high heat loads could be ascribed to a larger Secondary Emission Yield (SEY) of the corresponding surfaces

- A single measurement point was used to infer the SEY for the simulations (cell by cell)
- All other measurements, covering several different beam conditions: energy, bunch intensity and bunch-train length, were used as a crosscheck
  - → Very good agreement found!
  - → Observations are compatible with a larger SEY in the high-load arcs!



For more details, see: G. Iadarola et al., CERN-ACC-NOTE-2019-0057

Beam screen extraction and analysis

During LS2, the hypothesis that the high heat loads are driven by a higher SEY could be investigated by direct inspection of beam screens removed from the tunnel

- Among the magnets extracted during LS2, two were initially selected for analysis: one showing a high heat load and one showing a low heat load

- The beam screens were extracted, cut in shorter sections, stored under vacuum and then underwent lab analysis (led by TE-VSC)

For more results and details, see:
V. Petit, presentation at [10th HL-LHC Collaboration Meeting 2020]
L. Tavian, presentation at [LBOC meeting #126,19 Jan 2021]

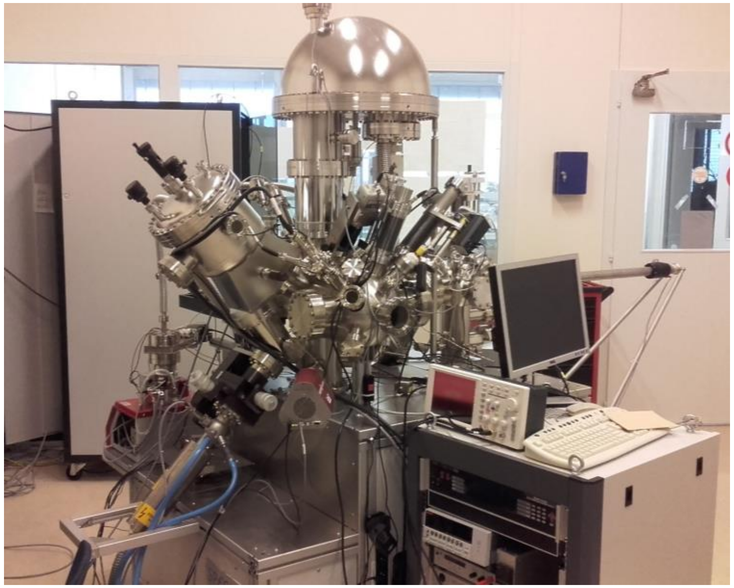
Results from SEY and conditioning analysis

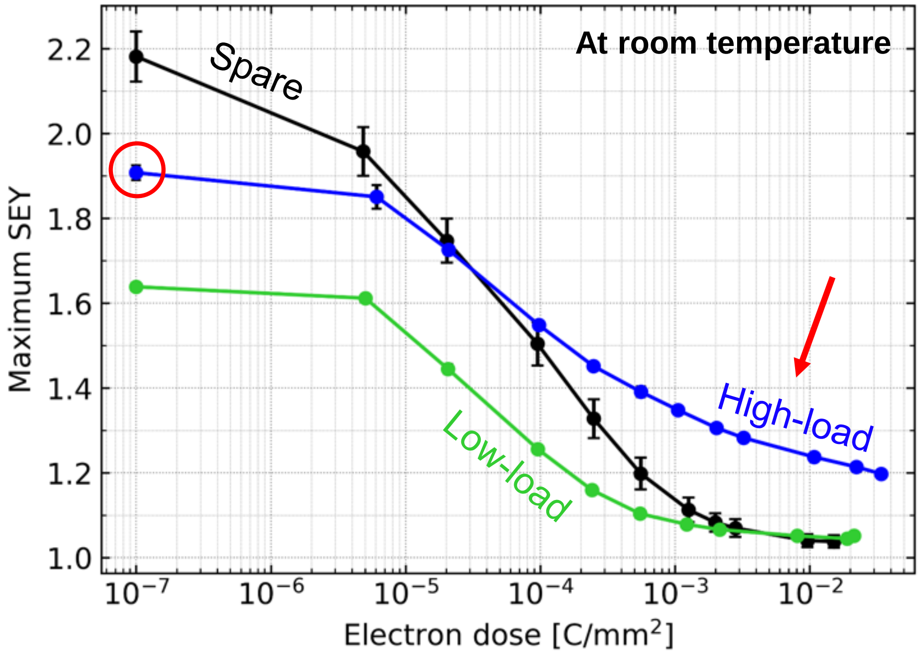
The SEY and conditioning behaviour at room temperature of the two beam screens were measured and compared

→ The high-load beam screen shows a higher SEY after air exposure

→ The high-load beam screen shows worse conditioning behaviour with electron irradiation (compared both to the low-load one and to a spare beam screen)

SPECS measurement system (TE-VSC)



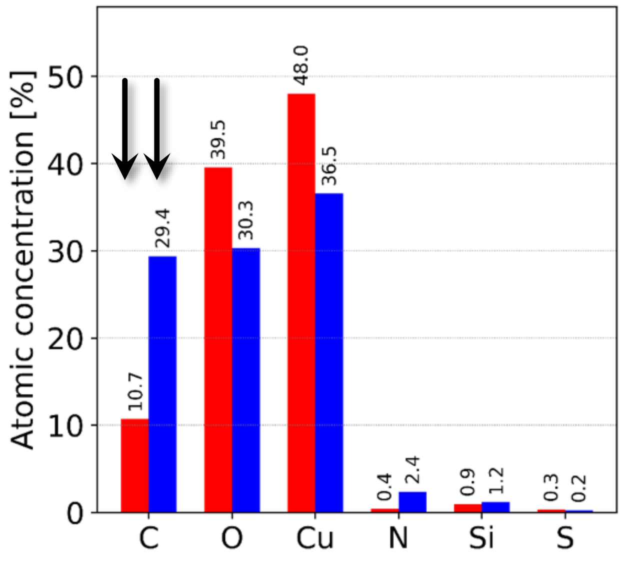


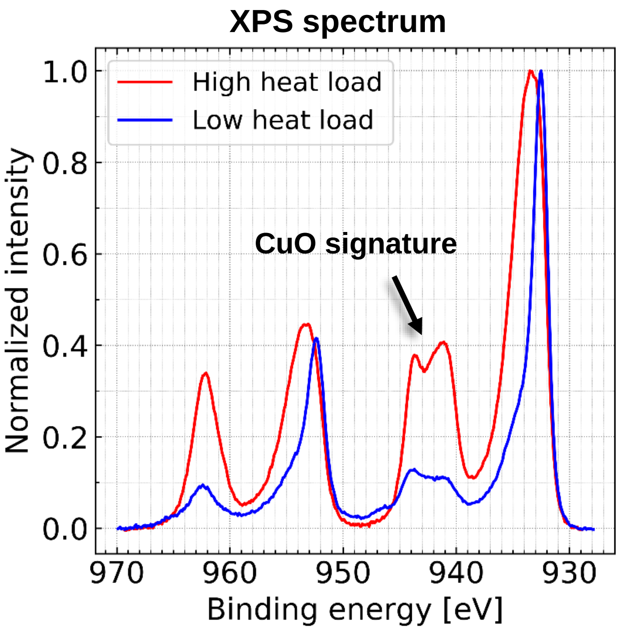
For more details, see: V. Petit, [10th HL-LHC Collaboration Meeting 2020]

Results from XPS analysis

- Surface chemistry analysis using X-ray photoelectron spectroscopy (XPS) revealed different oxidation states in the low- and high-load magnets
  - Low-load magnets show Copper(I) oxide (Cu_2O) → native copper oxide
  - High-load magnets show Copper(II) oxide (CuO) → unexpected!
- High-load beam screens also show a surprisingly low concentration of carbon

→ These chemical alterations, observed on several high-load beam screens, but not found on beam screens extracted during LS1, are very likely the cause of the different SEY and conditioning behaviour!





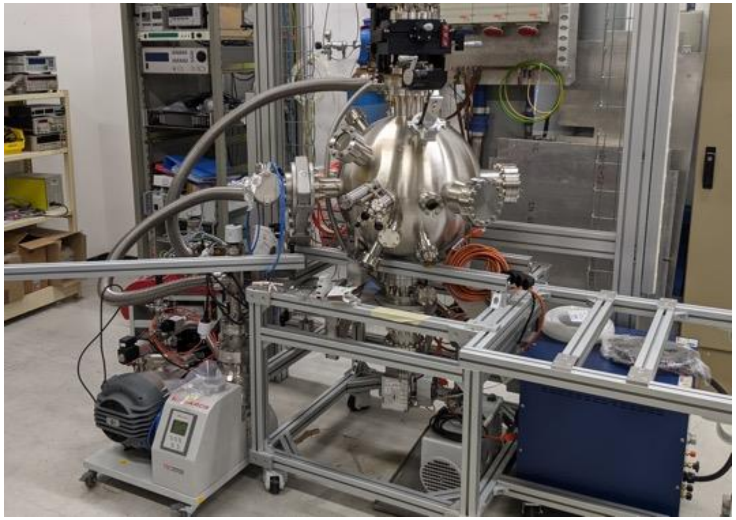
For more details, see: V. Petit, 10th HL-LHC Collaboration Meeting 2020, L. Tavian, LBOC #126,19 Jan 2021

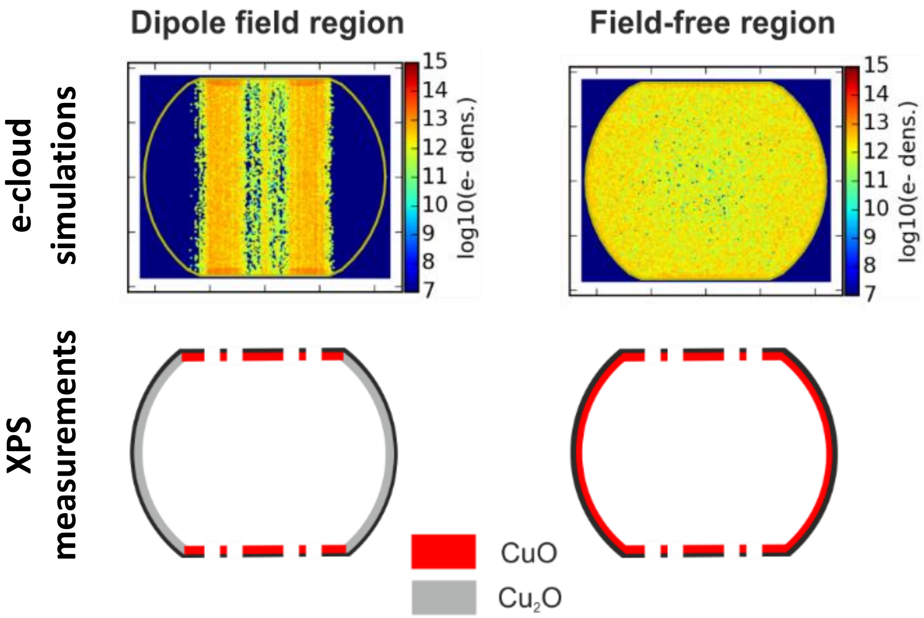
Results from XPS analysis

The angular distribution of CuO matches the expected distribution of the e-cloud in both dipole fields and field-free regions

→ Likely formed under the effect of electron bombardment during post-LS1 beam operation

- CuO production under electron irradiation is not expected based on conditioning studies in the lab at room temperature
  → New dedicated cryogenic XPS/SEY measurement system being commissioned to study effects at low temperature





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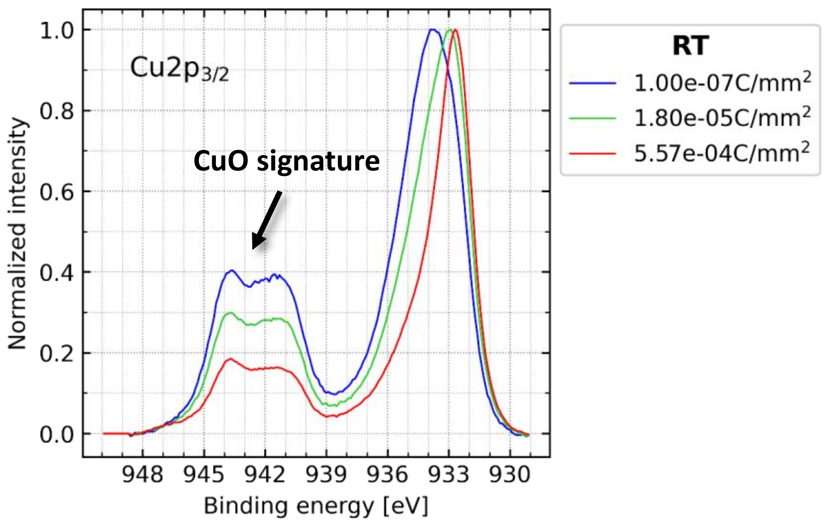
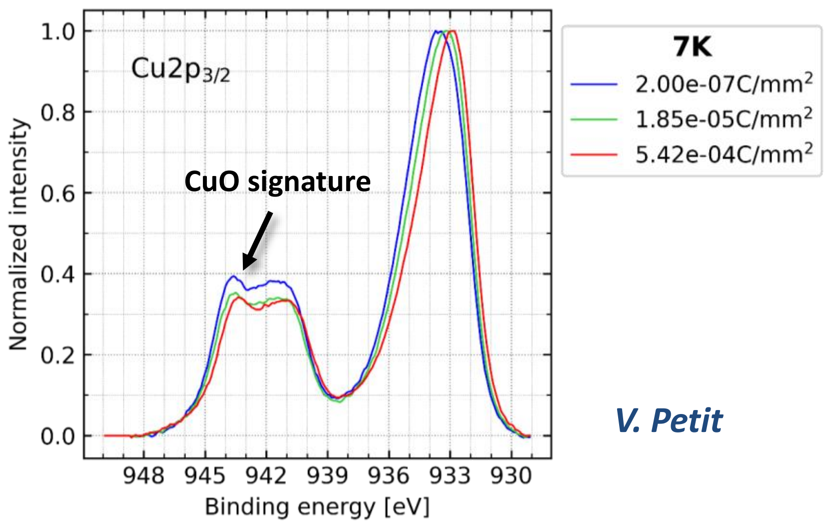
- CuO production under electron irradiation is not expected based on conditioning studies in the lab at room temperature
  - → New dedicated cryogenic XPS/SEY measurement system being commissioned to study effects at low temperature
  - ○ First results show strong suppression of CuO reduction under electron bombardment at cryogenic temperatures





V. Petit

Implications for Run 3

Once formed, CuO is very stable → there is very little hope for a spontaneous improvement

- Methods for actively removing or covering the CuO in-situ are under investigation
  - Possible test on half-cell in LS3

- Precautions were taken during LS2 to minimize risk of further degradation e.g.,
  - Initial venting with controlled gas composition
  - Attention to cooldown slope to avoid condensation on the beam screens

- However, many open questions remain regarding the degradation process e.g.,
  - Why were some sectors/magnets affected by CuO formation and others not
  - Why did degradation occur during/after LS1, but not during/after installation, nor during/after the venting of Sector 12 in EYETS 2016-2017

- As long as our understanding of the full process is incomplete, it is difficult to predict whether the taken precautions are guaranteed to prevent further CuO formation

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Scrubbing run

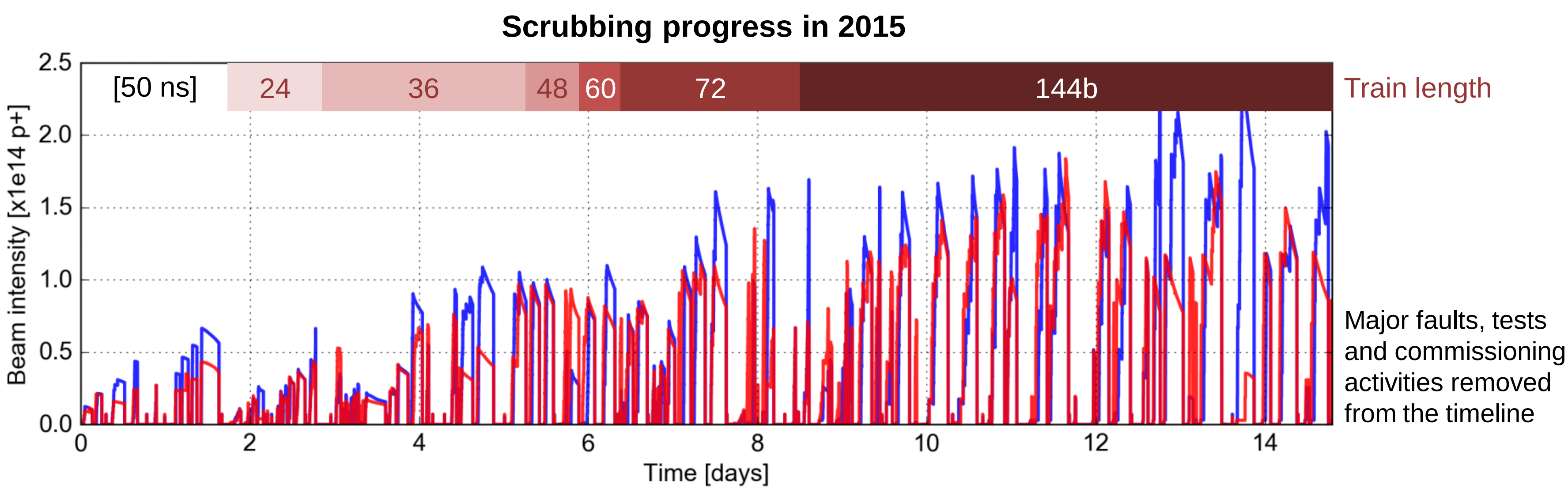
The main goal of the scrubbing run will be to mitigate instabilities and beam degradation to the extent necessary to allow the intensity ramp-up for physics to proceed

- Further conditioning to reduce the heat loads can be completed parasitically with 25 ns beams for physics, in order to maximise the luminosity production

- At the beginning of 2022 operation, all beam screen surfaces are expected to be deconditioned due to air exposure during LS2, similarly to the beginning of Run 2

  → All beam screens will initially have a high SEY and show high heat loads

  → We can use our experience from 2015 to predict how scrubbing will progress



Mitigations impacting scrubbing pace

Several issues limiting the scrubbing pace in 2015 have been mitigated during Run 2 or LS2

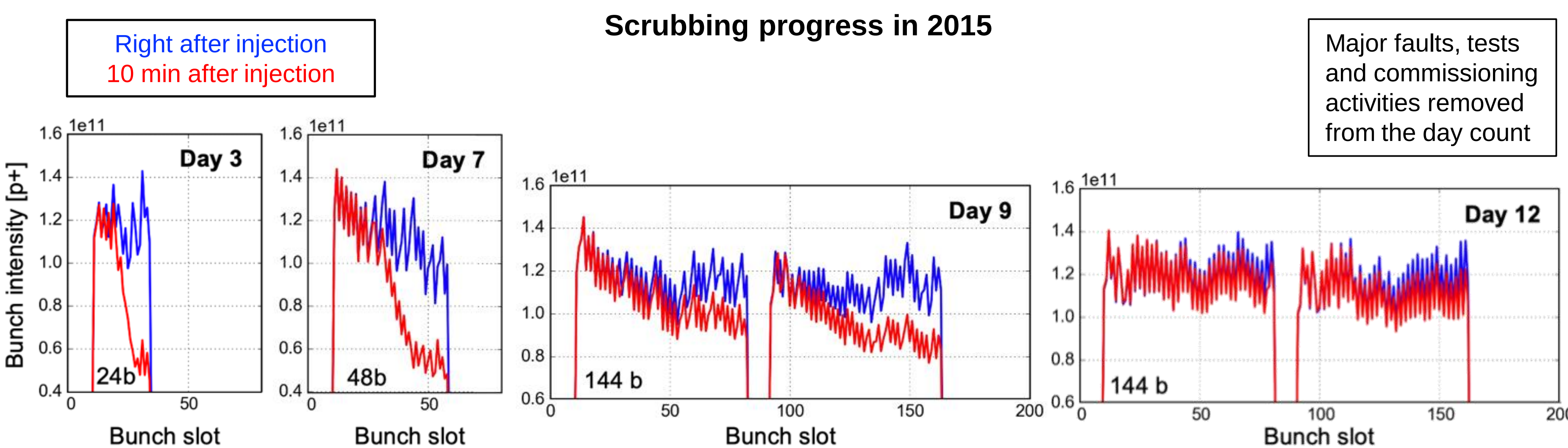
Observed issue (2015)	Mitigation deployed in Run 2 / LS2
Vacuum spikes in the **TDI**	- New design (TDIS) installed in LS2
Outgassing in **MKI** areas	- Pumping speed upgraded during Run 2 - Coated alumina tubes in some of the modules
Beam-screen temperature transients	- Cryo-condition rules relaxed during Run 2 - Improved feedforward
Transverse **instabilities**	- More margin in Q' and octupoles (optimized tunes)

→ In 2022 we should be more efficient and thus need fewer days of scrubbing to achieve the same level of conditioning as in 2015

Plan for scrubbing 2022

- The standard 25 ns beam with 1.2×10^{11} p/b and up to 4×72 bunches per train will be used for scrubbing
  - Experience from Run 2 shows that doublets are not efficient for scrubbing, given the slow conditioning behaviour of the LHC

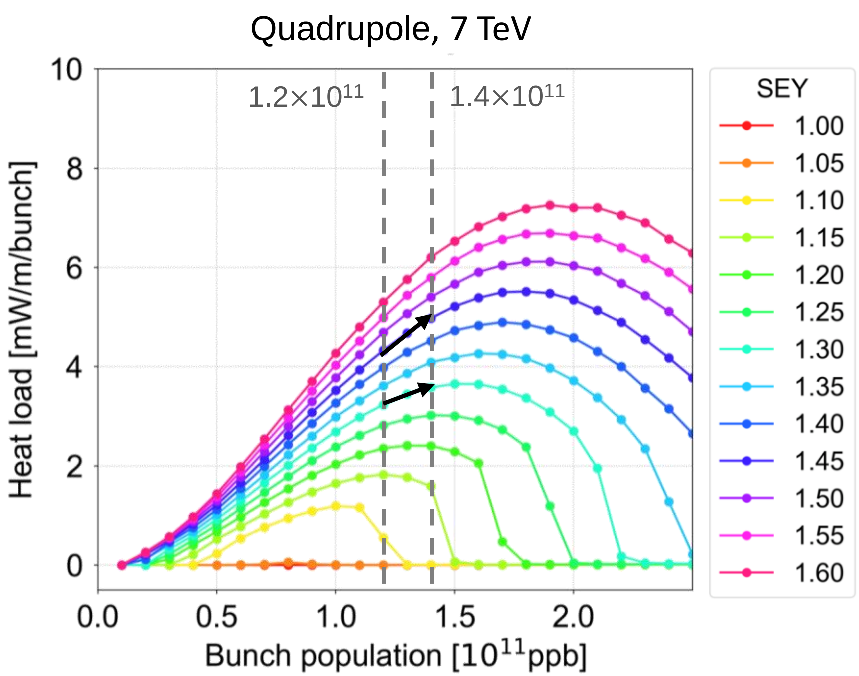
- In 2015, 16 days of dedicated scrubbing took place, after major faults, tests and commissioning activities are discounted
  - With the mitigations implemented since then, expect to need 10-12 days of dedicated scrubbing in 2022



Intensity ramp-up

Even after the dedicated scrubbing run, the beam screens will not be fully scrubbed

- In Run 2, scrubbing levelled off after roughly four months of operation
- Since heat load increases steeply with SEY, the heat load increase with bunch intensity will be steeper before the machine is scrubbed
- Proposal for intensity ramp-up: constant intensity of 1.2×10^{11} p/b during the entire ramp-up to 2748 bunches
  - Facilitate ramp-up in number of bunches
  - Allow for heat load benchmarking with Run 2 data
- A subsequent gradual increase in bunch intensity to 1.4×10^{11} p/b should be possible without further scrubbing, as long as there is margin for the heat loads
  - Request for periodic fills with bunch intensity of 1.2×10^{11} p/b for heat load benchmarking



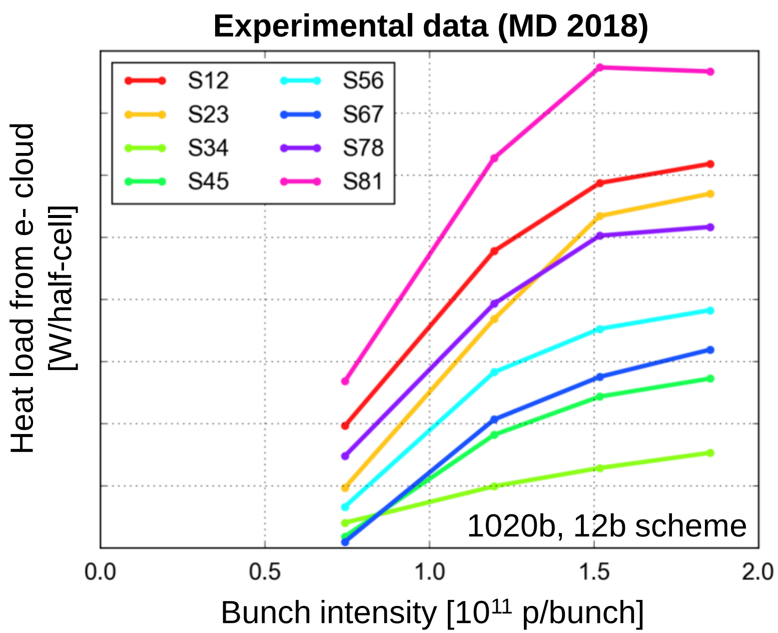
Heat load with LIU beams

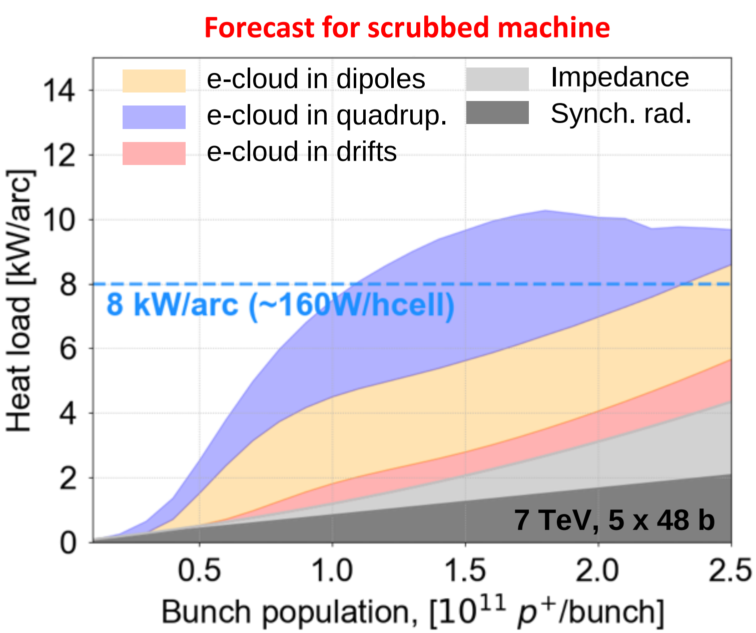
Run 3 will see the available bunch intensity ramped up as the LIU commissioning progresses

- Allows to confirm/improve our knowledge of e-cloud dependence on bunch intensity

- With the available models, simulations foresee a relatively mild increase of the heat load from e-cloud above 1.2×10^{11} p/b, for a fully scrubbed machine (to Run 2 level)

→ First tests with high-intensity 25 ns beams in trains of 12 bunches at the end of 2018 confirm flat intensity dependence above 1.5×10^{11} p/b!





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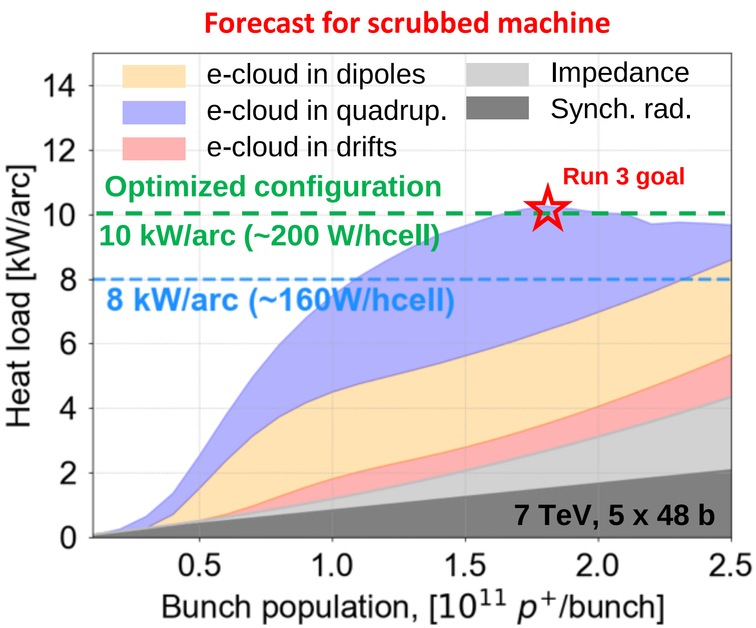
- With the available models, simulations foresee a relatively mild increase of the heat load from e-cloud above 1.2×10^{11} p/b, for a fully scrubbed machine (to Run 2 level)

→ We should be able to avoid performance limitation, provided that:
  - There is no further degradation of the high-load sectors (known only after end of 2022)
  - We can count on optimized cryogenic configuration, already used in Run 2
  - The surface model used in simulations is accurate enough

→ Additional mitigation will be needed in case any of these conditions are not fulfilled

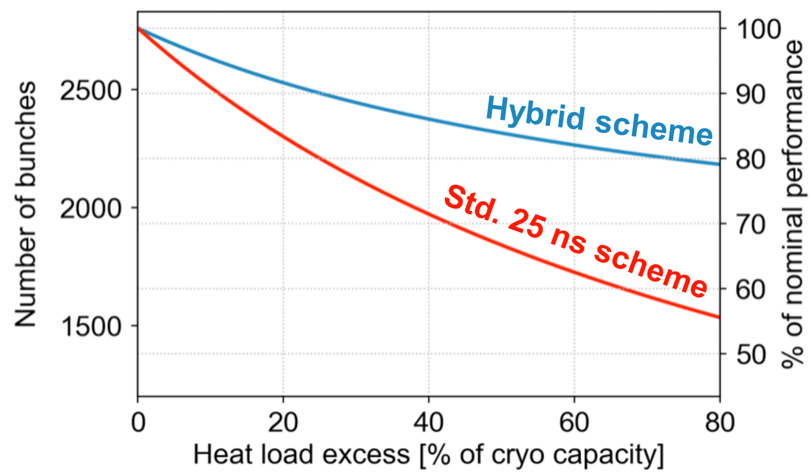


For more details, see:
*G. Skripka, [HL-LHC WP2 meeting, 26 Feb 201](), *
K. Brodzinski, [LMC meeting #376]()

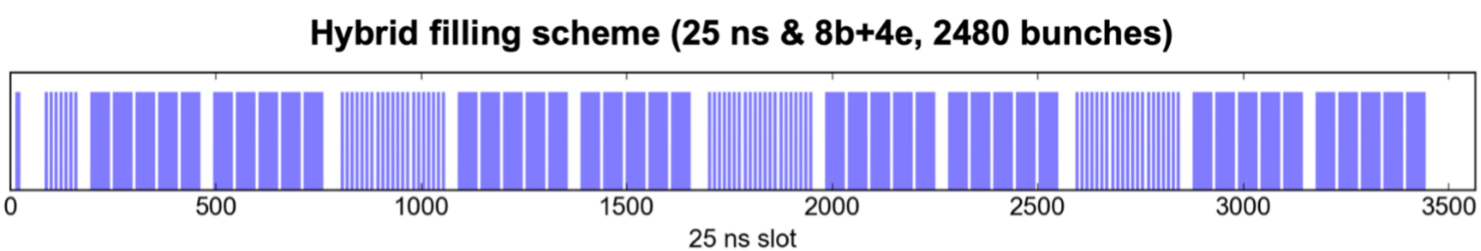
Mitigation schemes

In Run 3, possible intensity limitations from e-cloud will have to be mitigated by acting on the beam configuration (exploiting the flexibility of the injectors)

- The best compromise for maximising performance while keeping the heat loads within acceptable limits is obtained with hybrid schemes
  - Replace some 25 ns trains with 8b+4e trains
  - Fraction of 8b+4e beam can be tuned to adapt to the cooling capacity



- If very strong beam screen degradation occurs, also beam stability could become an issue that requires mitigation schemes

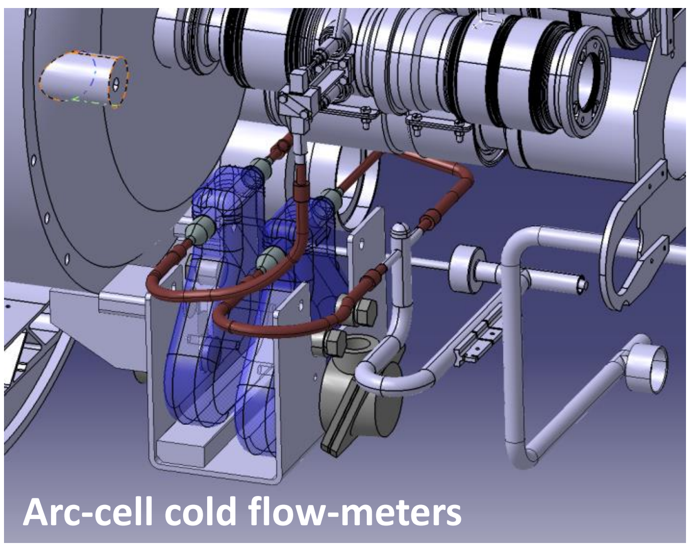


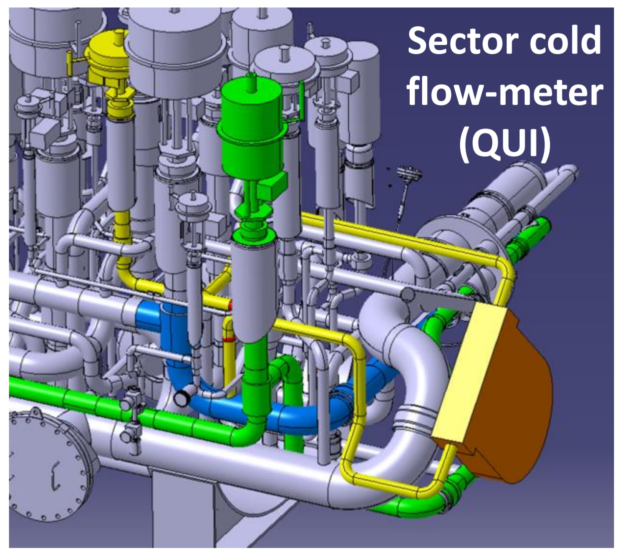
For more details, see: G. Skripka et al., CERN-ACC-NOTE-2019-0041

Improved instrumentation

New cryogenic instrumentation was installed during LS2 to improve heat load diagnostics

- Additional temperature probes and flowmeters were installed in individual half-cells, including upgrades to the instrumented cells of Run 2, and at the level of entire sectors
  - 9 instrumented half-cells: 6 high-load, 2 low-load and 1 field-free cell
  - 3 sectors with global load measurements: S12, S23, S56





For more details, see: L. Tavian, [LBOC #126,19 Jan 2021]

Instability forecast for 2022

With initial bunch intensities of 1.2 - 1.4 $\times$ 10^{11} p/b, beam stability is expected to be similar to the situation in Run 2

- Weak instabilities at injection
  - Strong chromaticity, octupole and damper settings needed
  - Optimised tunes to allow for large footprint to gain margin for stability

- Instabilities at flat top
  - Instabilities at end of fills with low bunch intensity observed in 2016 may return (although they were never seen with trains of 48 bunches in Run 2)
  - Can be suppressed with chromaticity

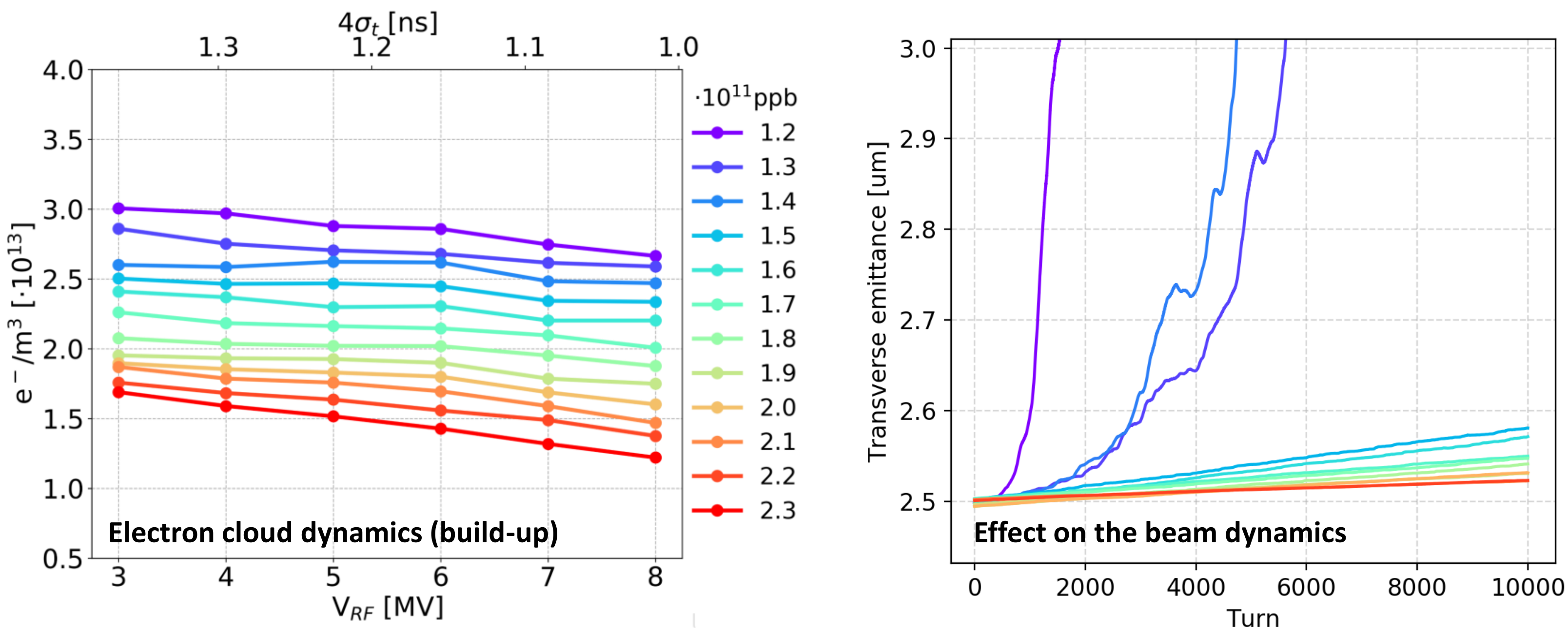
- Beam quality degradation at collision
  - Slow beam losses in collision expected mostly for lower beta*

Instabilities with LIU beams

- Simulations predict that the electron density at the beam location decreases with increasing bunch intensity, both in the main dipoles and in the quadrupoles
  → Instabilities are mitigated rather than aggravated by higher bunch intensities

- The associated changes in bunch length (RF voltage) and transverse emittance are not expected to significantly impact the scaling of beam stability with bunch intensity

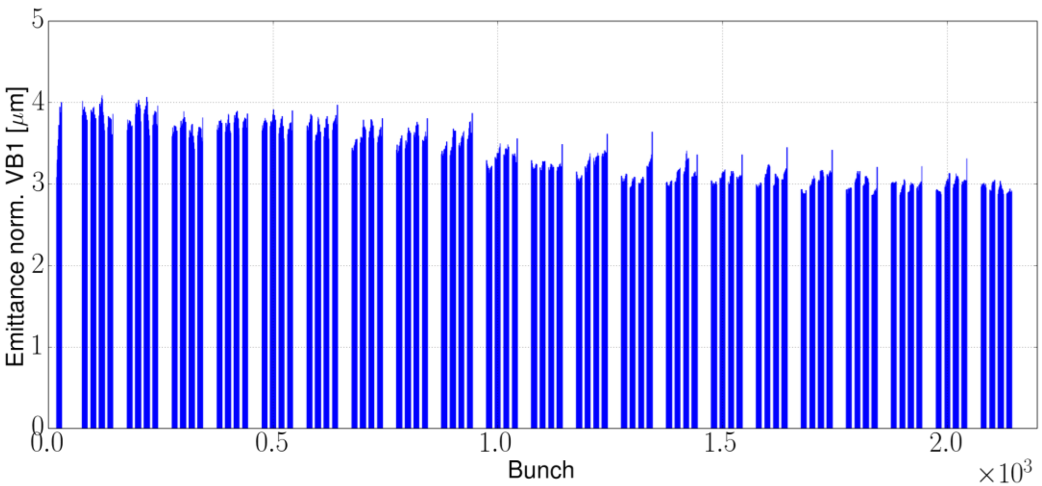
Simulations of quadrupoles at 450 GeV



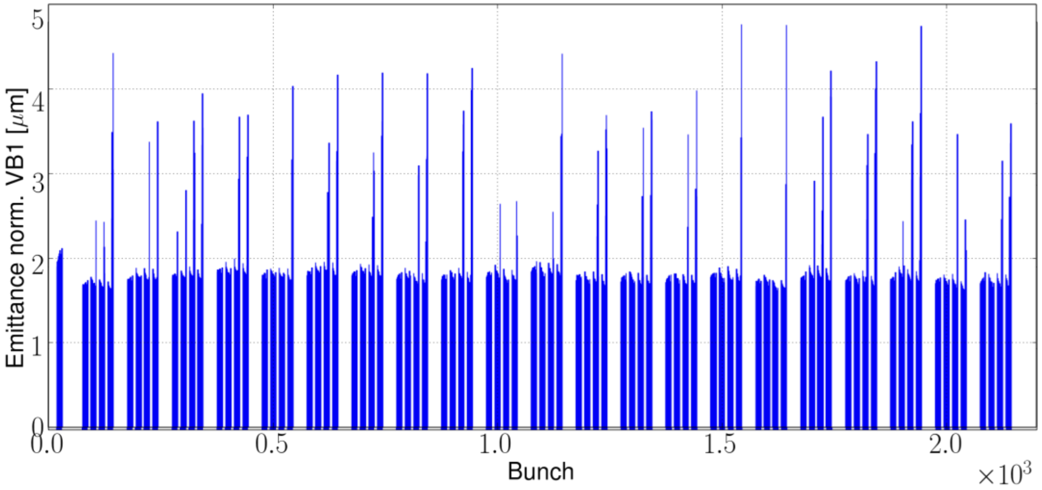
For more details, see: L. Sabato et al., CERN-ACC-NOTE-2020-0050

Instabilities with LIU beams

First tests with high-intensity 25ns beams in trains of 12 bunches in 2018 are consistent with expectations from simulations → high-intensity beam stable even without octupoles



1.8 x 10^{11} p/b
Stable without octupoles



0.7 x 10^{11} p/b
Unstable with I_{oct} = 56 A

Conclusions

- Measurements indicate that the high heat loads due to e-cloud, observed in some sectors, cells and magnets, are due to higher SEY and poor conditioning behaviour
  - Caused by different surface characteristics: low carbon content and non-native CuO oxide, formed during operation with beam after LS1
  - No improvement expected without active intervention (under investigation for LS3)
  - Precautions taken to avoid further degradation in LS2, to be confirmed after 2022

- Beam screens are expected to be fully deconditioned at the beginning of 2022
  - With mitigations compared to 2015, 10-12 days of dedicated scrubbing should be sufficient to enable intensity ramp-up
  - Propose to perform ramp-up to max number of bunches at constant intensity of 1.2×10^{11} p/b
  - Continue scrubbing parasitically during luminosity production along the year

- Without further degradation of the beam screens, e-cloud is not expected to significantly impact Run 3 performance with intensities up to 1.8×10^{11} p/b
  - With optimised cryogenics configuration, heat loads (barely) within cooling capacity once scrubbing has tapered off
  - Instabilities predicted to scale favourably with increasing bunch intensity
  - If needed, customised hybrid filling schemes (25 ns/8b+4e) can be used as mitigation

Thank you for your attention!

Underlying mechanisms

Several mechanisms that could transfer energy from the beam to the beam-screen were reviewed and their compatibility with observations was evaluated

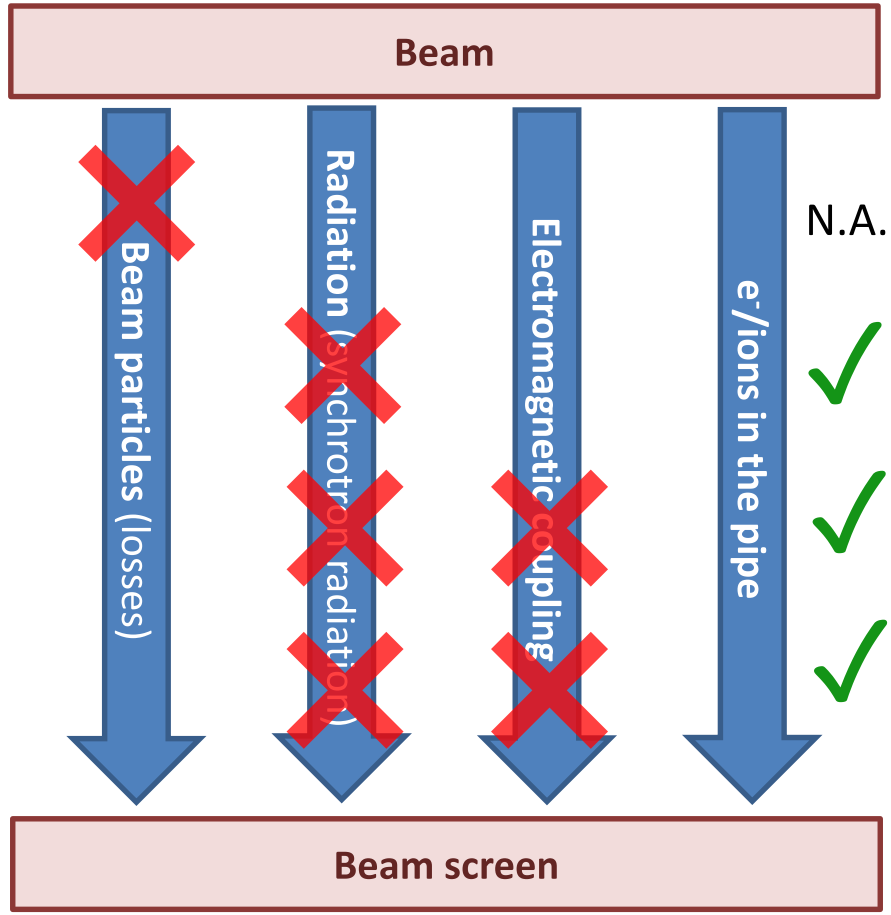
→ Only e-cloud effects cannot be excluded based on the observations

Observations

- Total power of intensity loss is less than 10% of measured heat load
- Heat load increases only moderately during the energy ramp
- Heat loads with 25 ns are more than 10 times larger than with 50 ns
- Measured dependence on bunch intensity is not linear nor quadratic

✓ = **Good quantitative agreement** (assuming different SEY per sector)

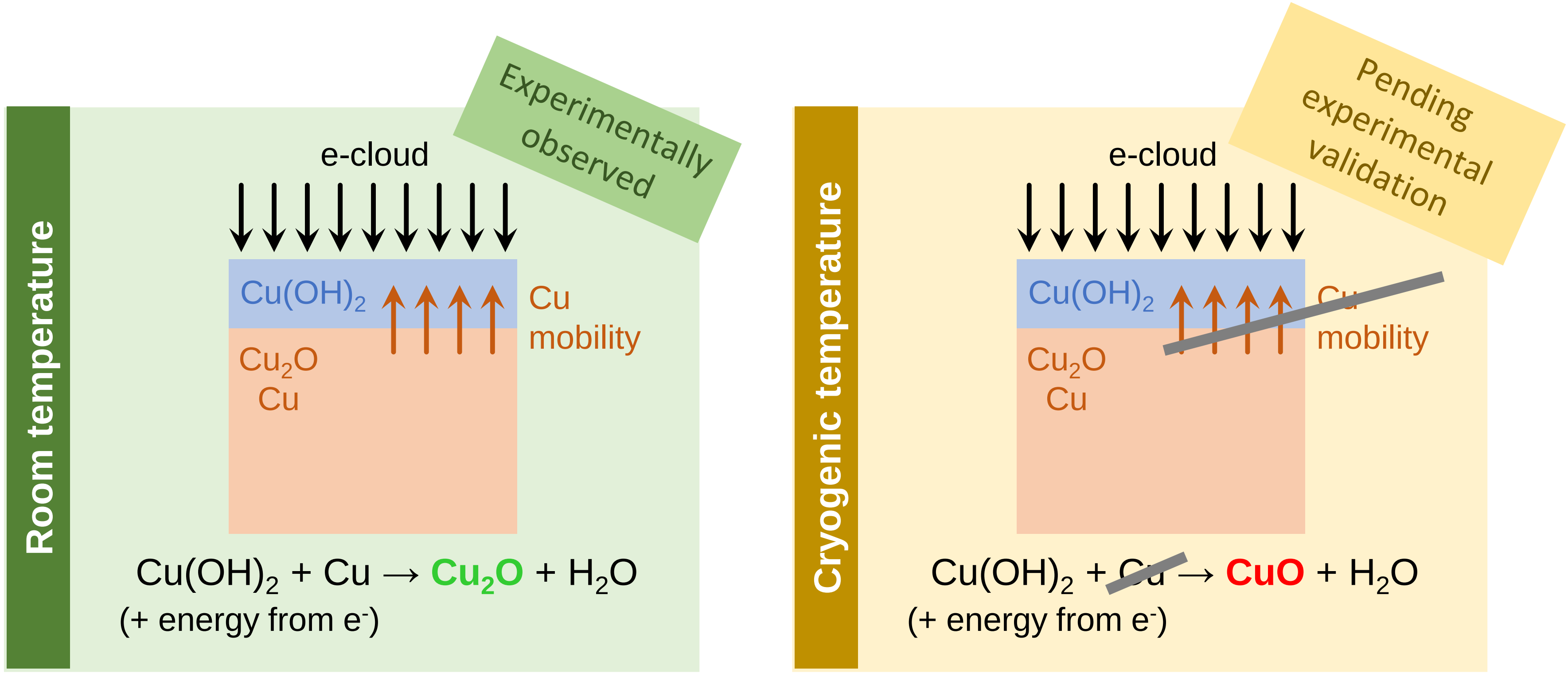
✗ = **Excluded**



CuO formation

Whereas several hypotheses for CuO formation have been considered, the most probable formation process is through the conversion of copper hydroxide $Cu(OH)_2$

- Under electron irradiation at room temperature $Cu(OH)_2$ transforms into Cu_2O
  - A process involving atom mobility from the underlying layer
- Low temperatures can block the diffusion process, leading to the formation of CuO instead
  - Direct validation at cold should be possible using a new cryogenic SEY/XPS setup



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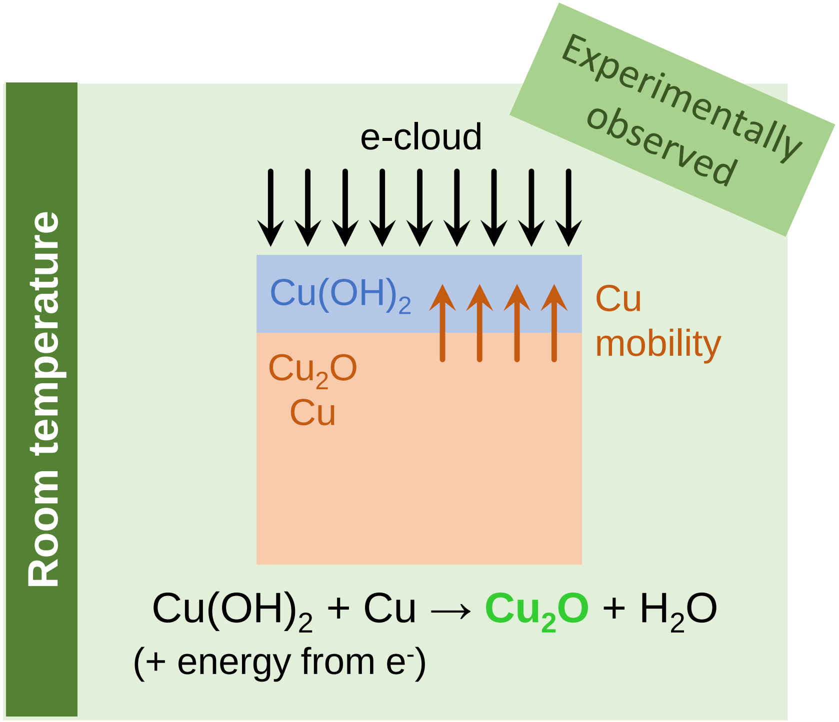
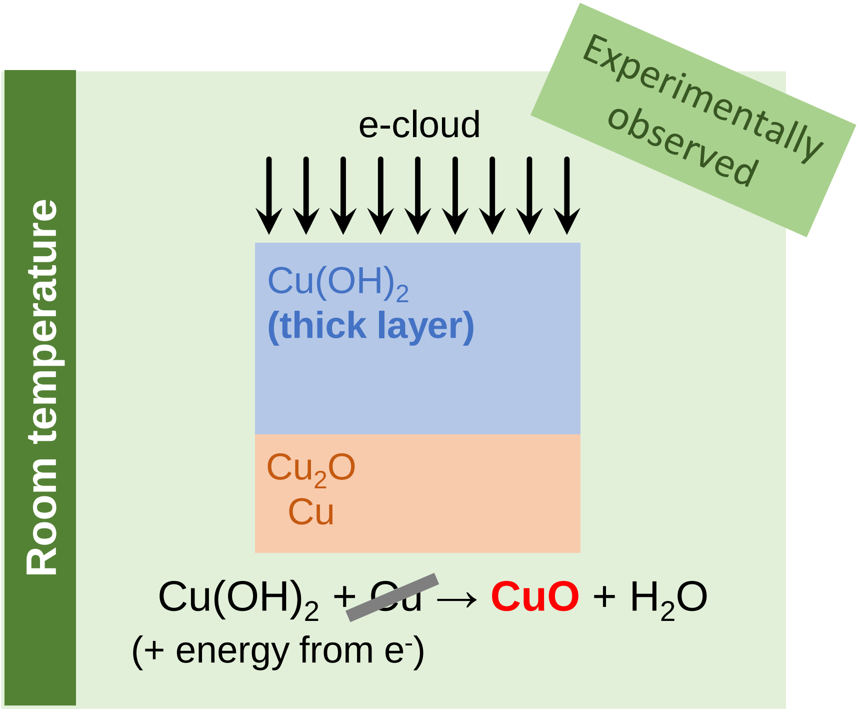
  - Indirect check with thick $Cu(OH)_2$ layers at room temperature support the hypothesis





Cooling capacity

Cryogenics configuration fully optimized to cope with large beam induced heat loads

→ Cooling capacity in the high-load sectors is significantly larger than expected by design

- All sectors were measured to confirm available cooling power for BS cooling
- LS2 HiLumi upgrade of LHCA refrigerator at P4 was done and after preliminary results gives capacity of 210 W/hc

Cryogenic plant type	AL-B	AL-A	L-A	AL-B	L-B	L-A	AL-A	L-B
LHC sector	S1-2	S2-3	S3-4	S4-5	S5-6	S6-7	S7-8	S8-1
Capacity (design conf.) [W/hc]	180	195	210	180	240	175	175	230
Configuration Run2 [W/hc]	200	205	220	200	260	195	195	250

All above measurements with input from reference fill in 2017 F5979

Black – measured value

Grey – recalculated value (contingency of 10 W/hc considered)

K. Brodzinski, Beam Induced Heat Load Task Force 25 August 2021