Electron cloud and heat loads

G. Iadarola
for the Beam Induced Heat Load Task Force
and the e-cloud Working Group

With input from:
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G. Rumolo, V. Petit, B. Salvant, G. Skripka, M. Taborelli, L. Tavian, E. Wulff

Outline

Introduction

Effects on the beam

- Injection energy
- Top energy

Heat loads

- Issues, mitigation and evolution in Run 2
- Differences among the sectors
- Underlying mechanism

Outlook for Run 3

- Plans for LS2
- e-cloud dependence on bunch intensity
- Expected intensity reach
- First thoughts on scrubbing after LS2

Introduction

Run 2 marked an **important milestone** with respect to **e-cloud effects** in the LHC, i.e. the **usage of the 25 ns bunch spacing** for most of the p-p physics operation

- With 25 ns spacing **e-cloud effects are much stronger than with 50 ns** spacing (used for luminosity production in Run 1)

Main lessons learnt in two points:

e-cloud can be mitigated to a large extent: beam-induced **scrubbing** allows mitigating e-cloud effects to an extent that allows a **satisfactory exploitation of 25 ns beams** in physics

- Scrubbing is mostly **preserved over Year-End Technical Stops** in regions that are not vented → recovery in ~1 day of conditioning at 450 GeV

…but it was not possible to fully get rid of it: even after years of conditioning of the beam chambers, we keep seeing:

- Impact on beam quality (instabilities, losses, emittance growth)
- Heat loads in cryogenic magnets (with puzzling differences among sectors)

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- Run 1 vs Run 2

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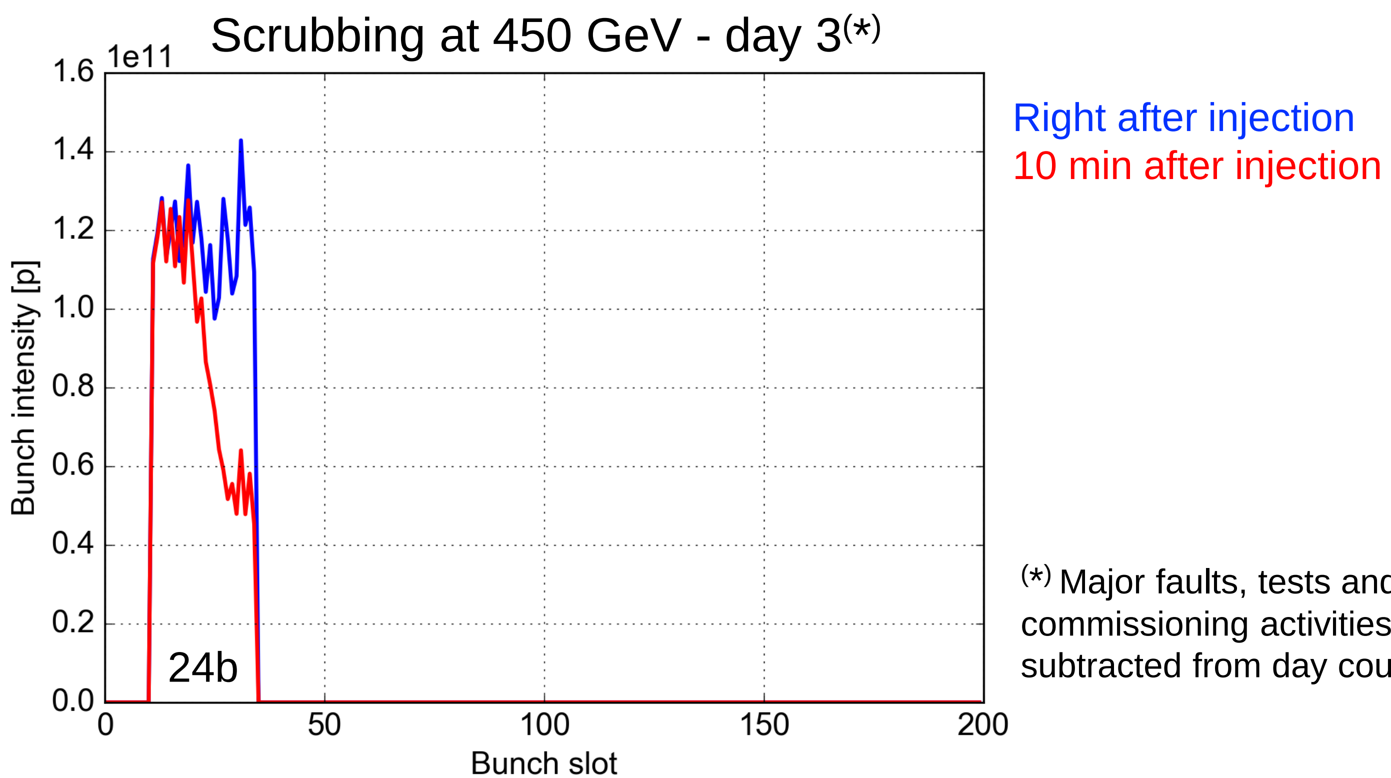
Beam degradation at 450 GeV: the first impression

At the very beginning of Run 2 it was quite **difficult to get the beams under control:**

- Violent **e-cloud instabilities** causing **severe losses** even with short bunch trains
- Beams could be stabilized only after **several days of scrubbing**



(*) Major faults, tests and commissioning activities are subtracted from day counting

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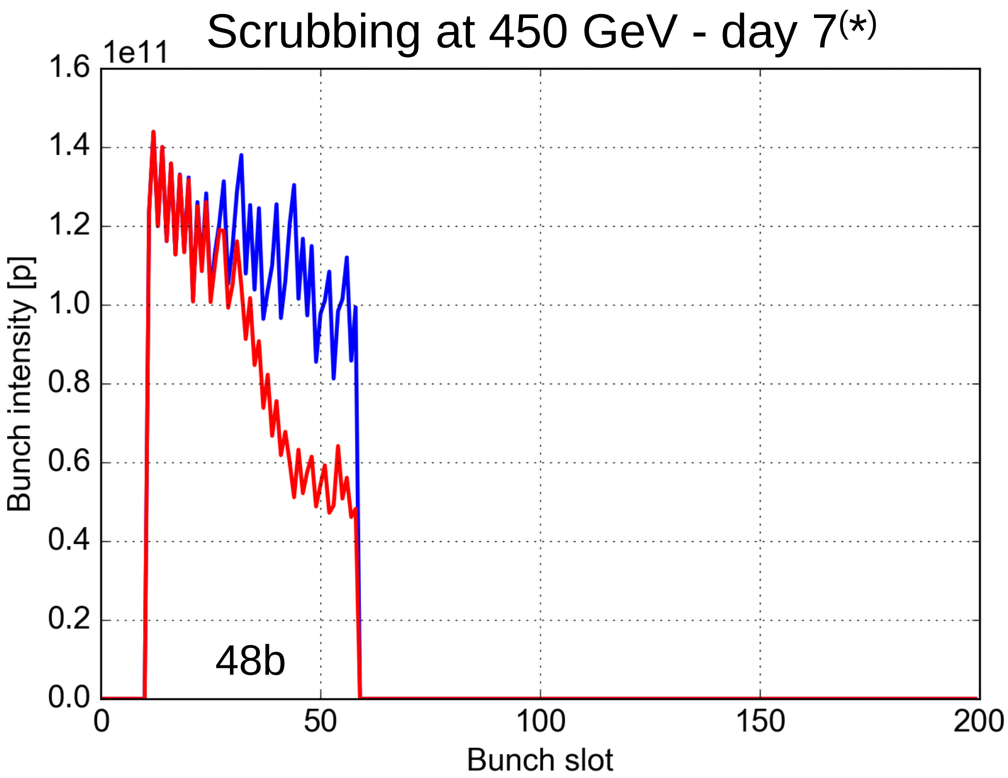

Right after injection
10 min after injection

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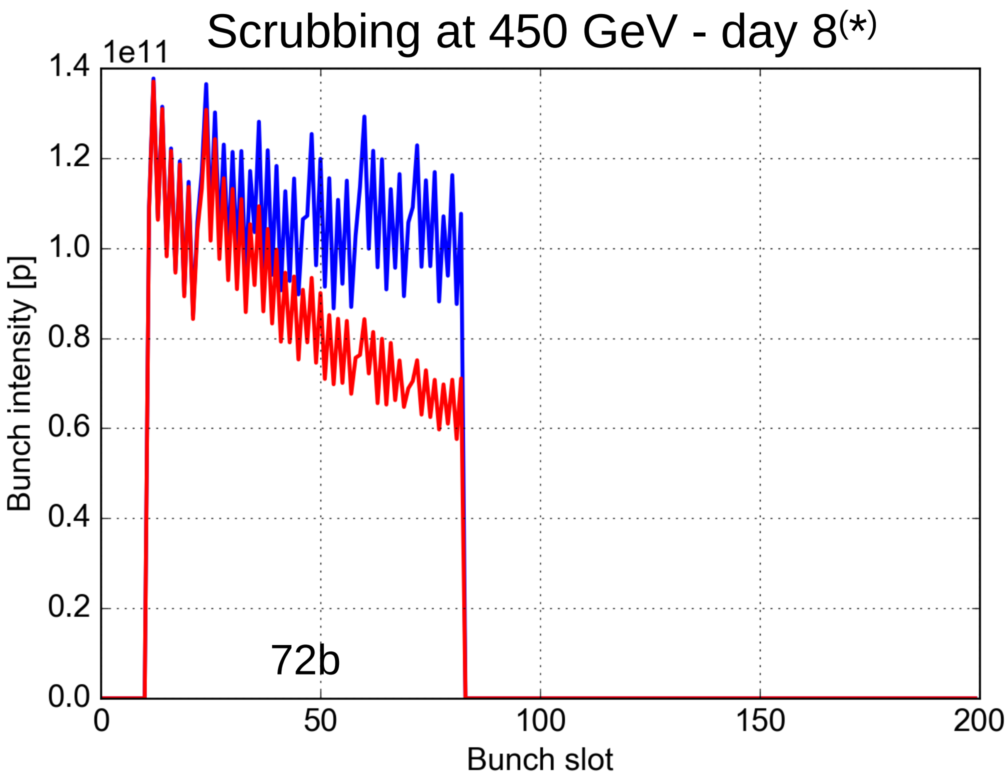

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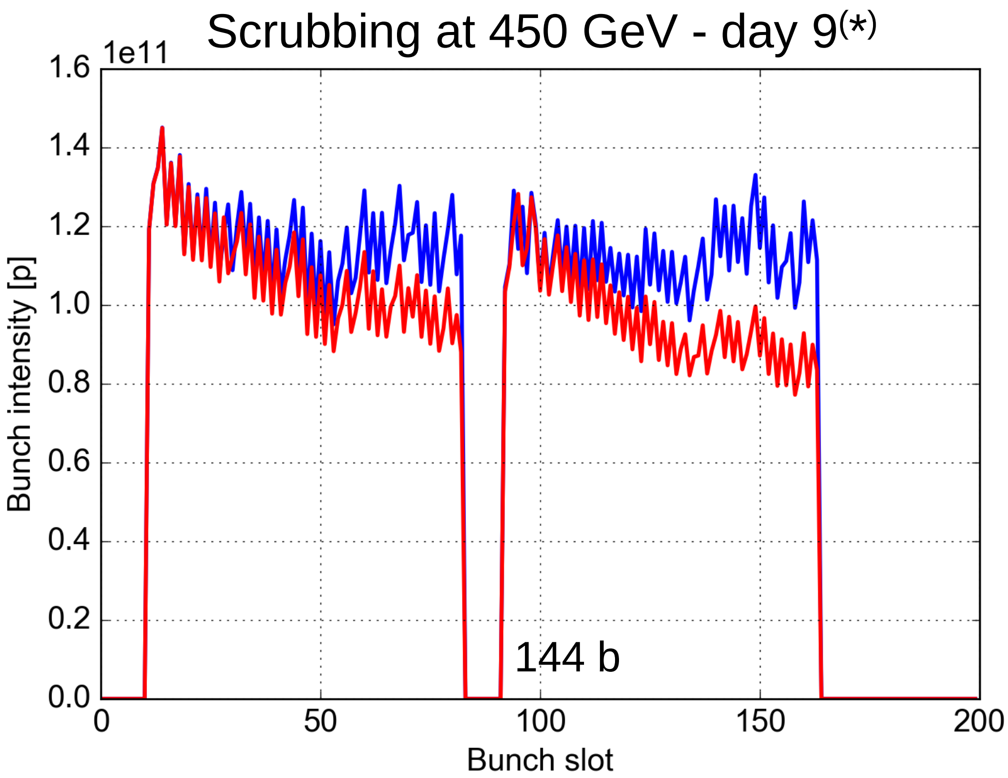

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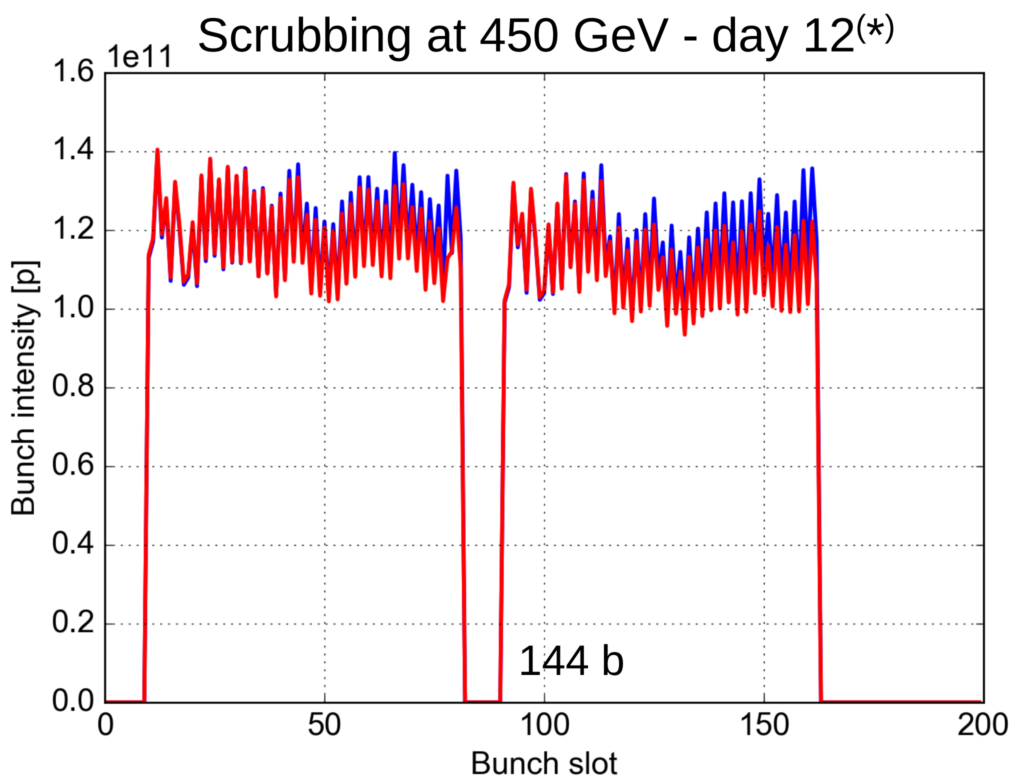

Right after injection
10 min after injection

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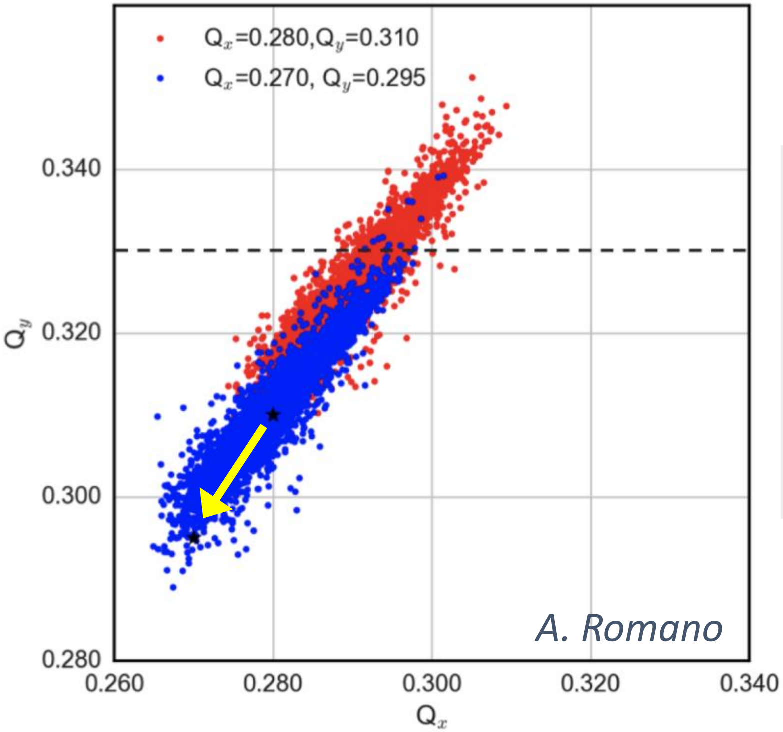
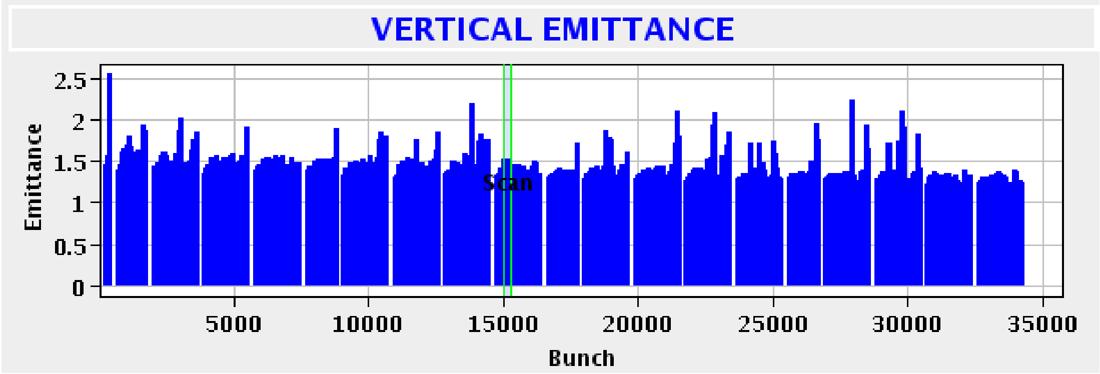
Beam degradation at 450 GeV: beam stability

- Still, during all Run 2, to **stabilize 25 ns beams** we needed to use **high chromaticity** (Q'_{xy} >15) and **high octupole currents** (I_{oct} > 50 A), **high feedback gain and bandwidth**
  - To preserve lifetime, we needed to **optimize tunes at injection** to better accommodate **large tune footprint**
- Beam **still not fully stable** → weak instabilities leading to **some blow-up on a small fraction of bunches** occurred in most of the physics fills

PyECLOUD-PyHEADTAIL sim.



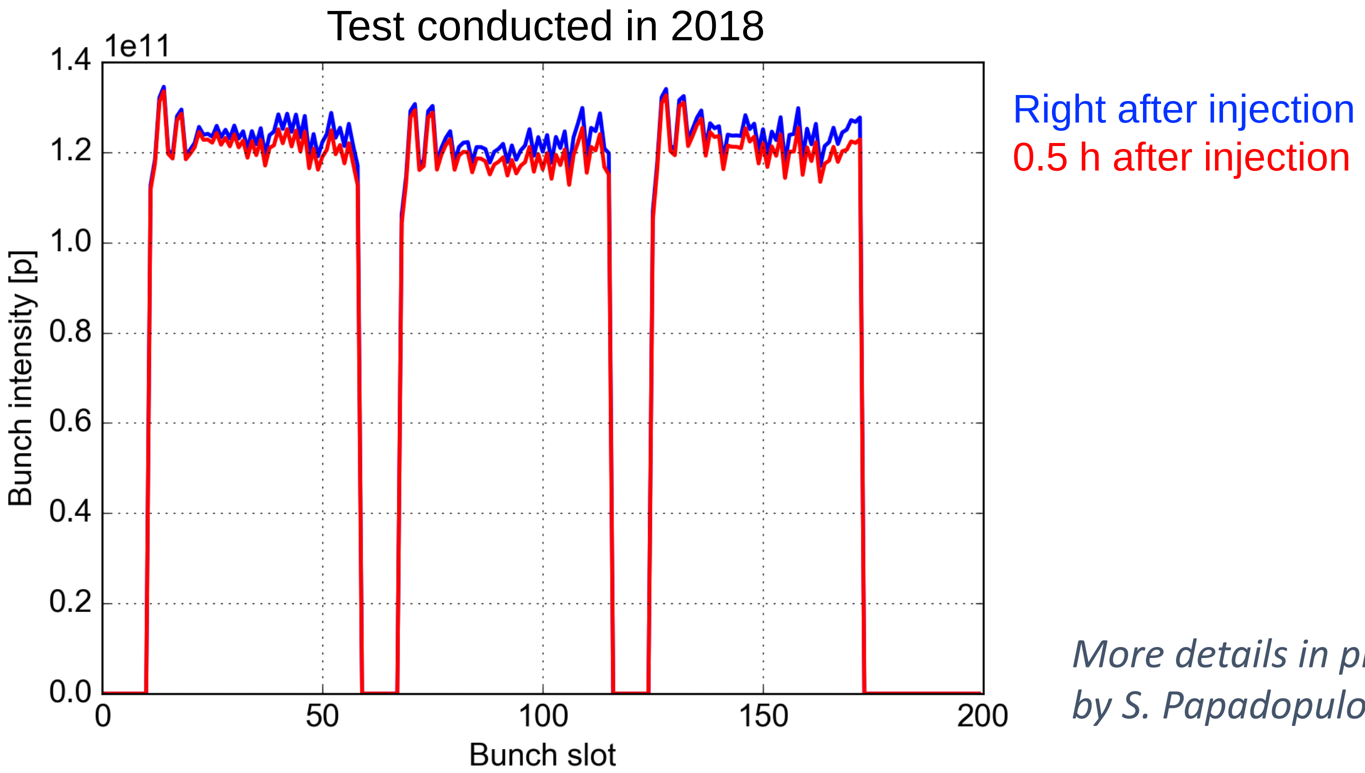
Emittances at start-ramp for a typical 2018 fill



More details on injection instabilities in presentation by X. Buffat

Beam degradation at 450 GeV: slow-degradation

- Even when the beam is kept stable the e-cloud causes a **slow beam degradation (losses and emittance blow-up)**
  - Particularly visible when the beam is stored some time at 450 GeV



More details in presentation by S. Papadopulou

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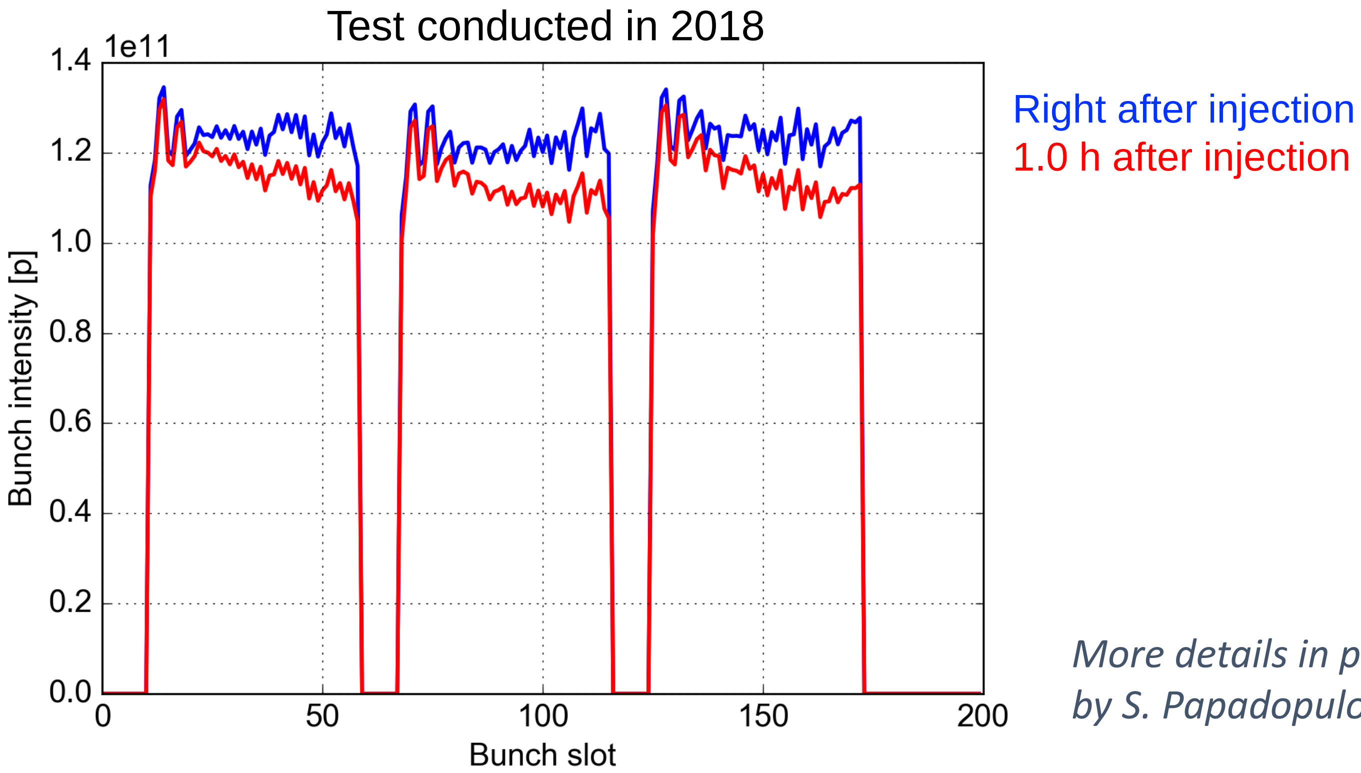

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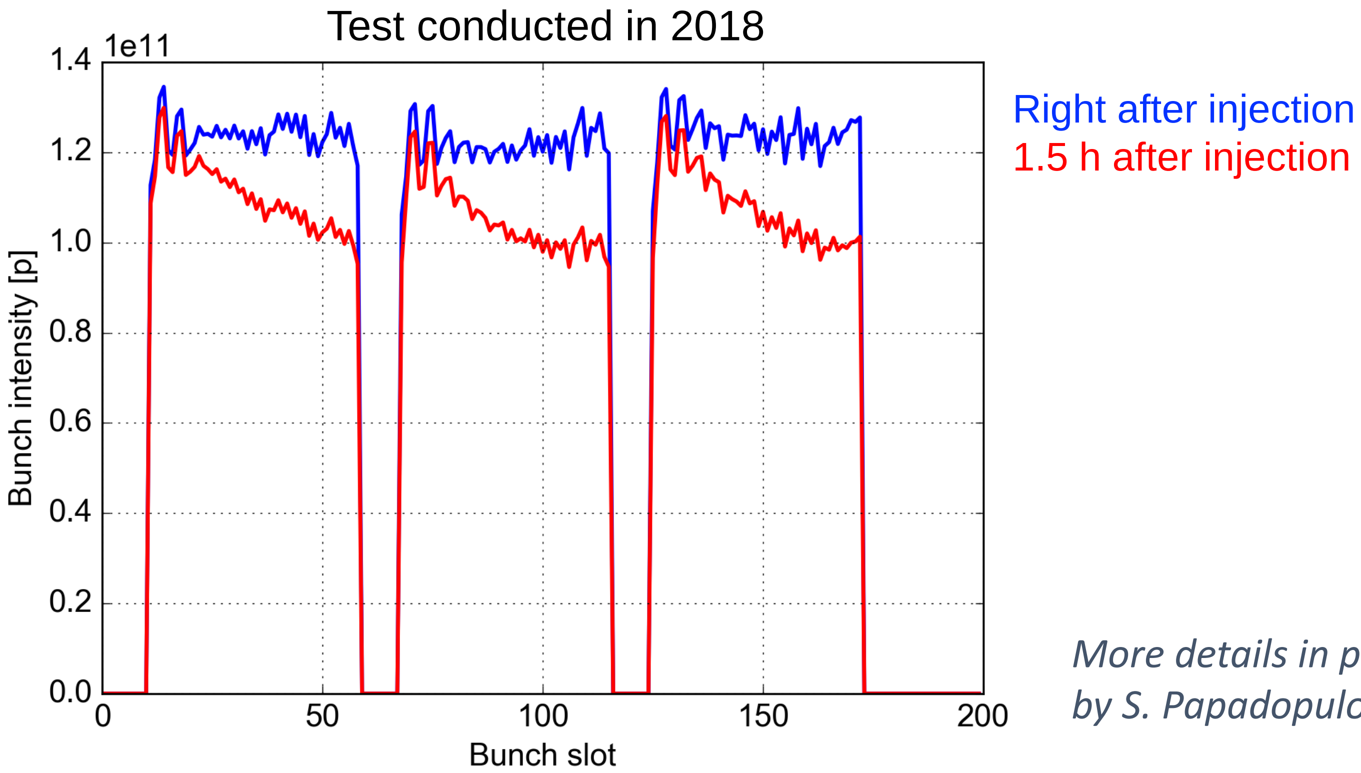

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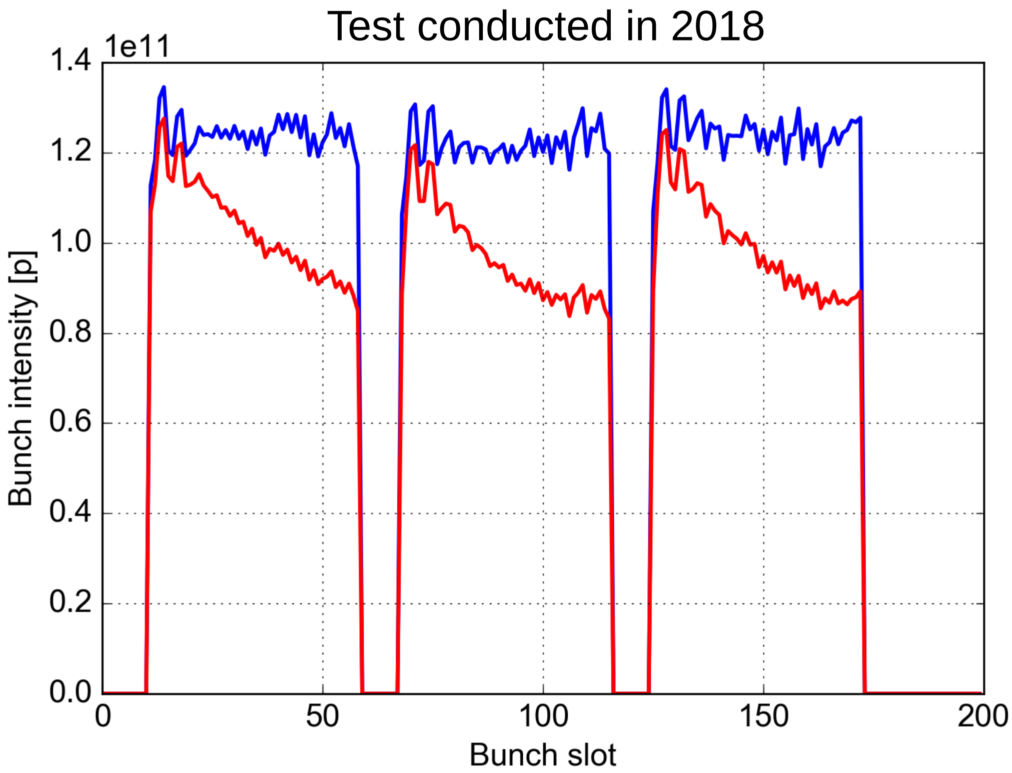


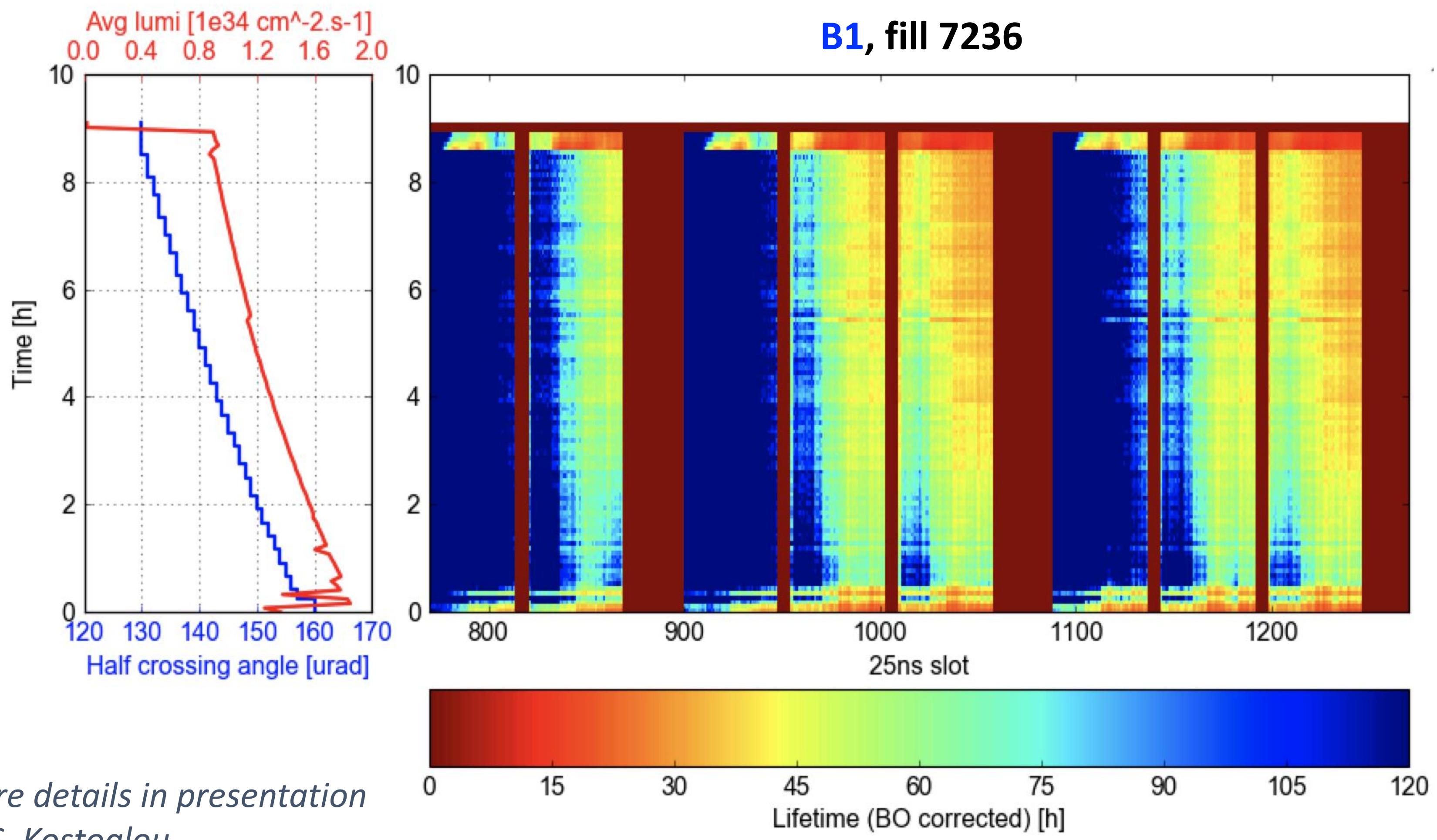
Right after injection
2.0 h after injection

More details in presentation by S. Papadopulou

Effects on beam dynamics: 6.5 TeV

Thanks to the **increased beam rigidity**, effects of the e-cloud on the beam dynamics are much **weaker at 6.5 TeV** but still **clearly visible**

→ e-cloud pattern observed on **losses during the squeeze and in collision**



More details in presentation by S. Kostoglou

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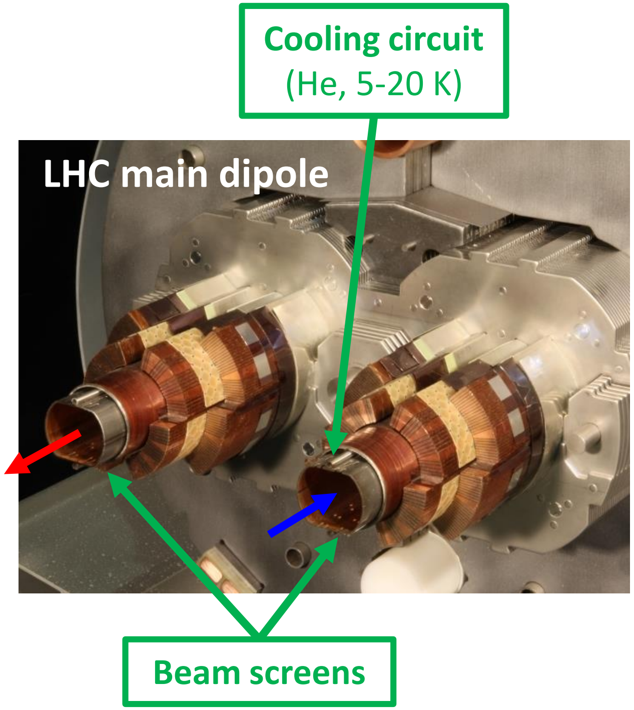
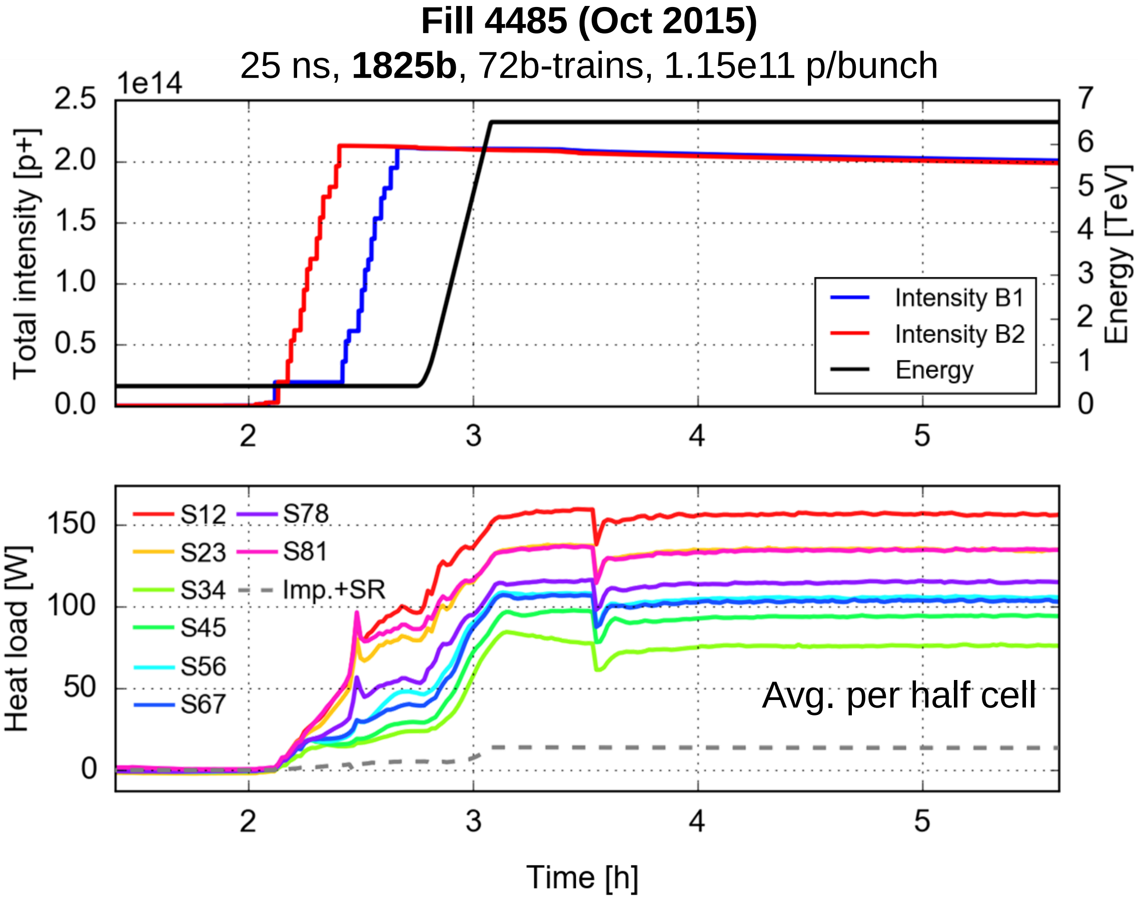
Heat loads on the arc beam-screens

- Electrons deposit **energy on the beam screens** of the LHC arc magnets
  - → **Heat load** that needs to be absorbed by the **cryogenics system**
  - → For some sectors at the **limit of the design cooling capacity** (160 W/half-cell)
- Large **differences observed among sectors**: unexpected!
  - → Object of investigation by dedicated **inter-departmental task force**

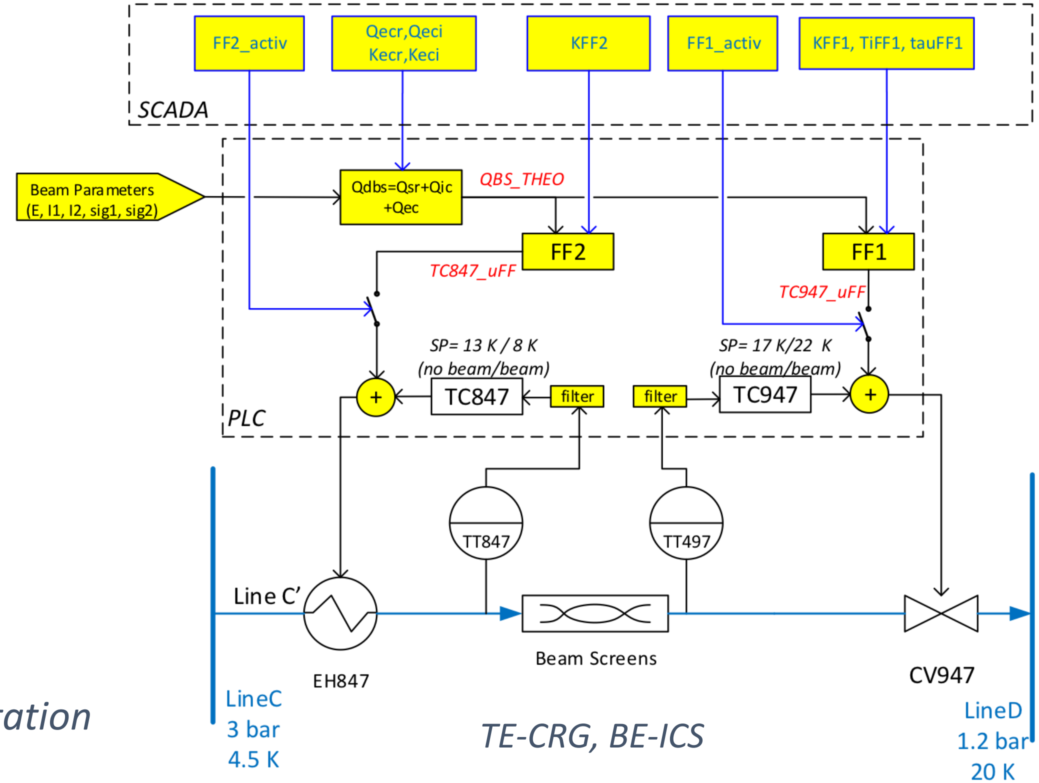




Heat loads: encountered issues and mitigation

Mainly **two types of issues** encountered during Run 2:

1. **Heat load transients** (injection, ramp, beam-dump) → too large **excursions of beam screen temperatures** leading to loss of cryo-conditions. Mitigated by:
   - → **Relaxed CryoMaintain rules** to allow for larger transient (after careful review, moved from **“T>30K for 30 s” to “T>40K for 30 min”**, see LMC#236)
   - → Developed and optimized **cryogenic feed-forward** to anticipate transients based on measured beam properties (see LMC#257)



TE-CRG, BE-ICS

More details in presentation by G. Ferlin

Heat loads: encountered issues and mitigation

Mainly **two types of issues** encountered during Run 2:

2. **Total load on the cryoplants close to the design limit** (especially in 2015 when chambers were not fully conditioned). Mitigated by:

    → Profiting from **flexibility in filling scheme design**

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Never accelerated to 6.5 TeV
with full number of bunches

Heat loads: encountered issues and mitigation

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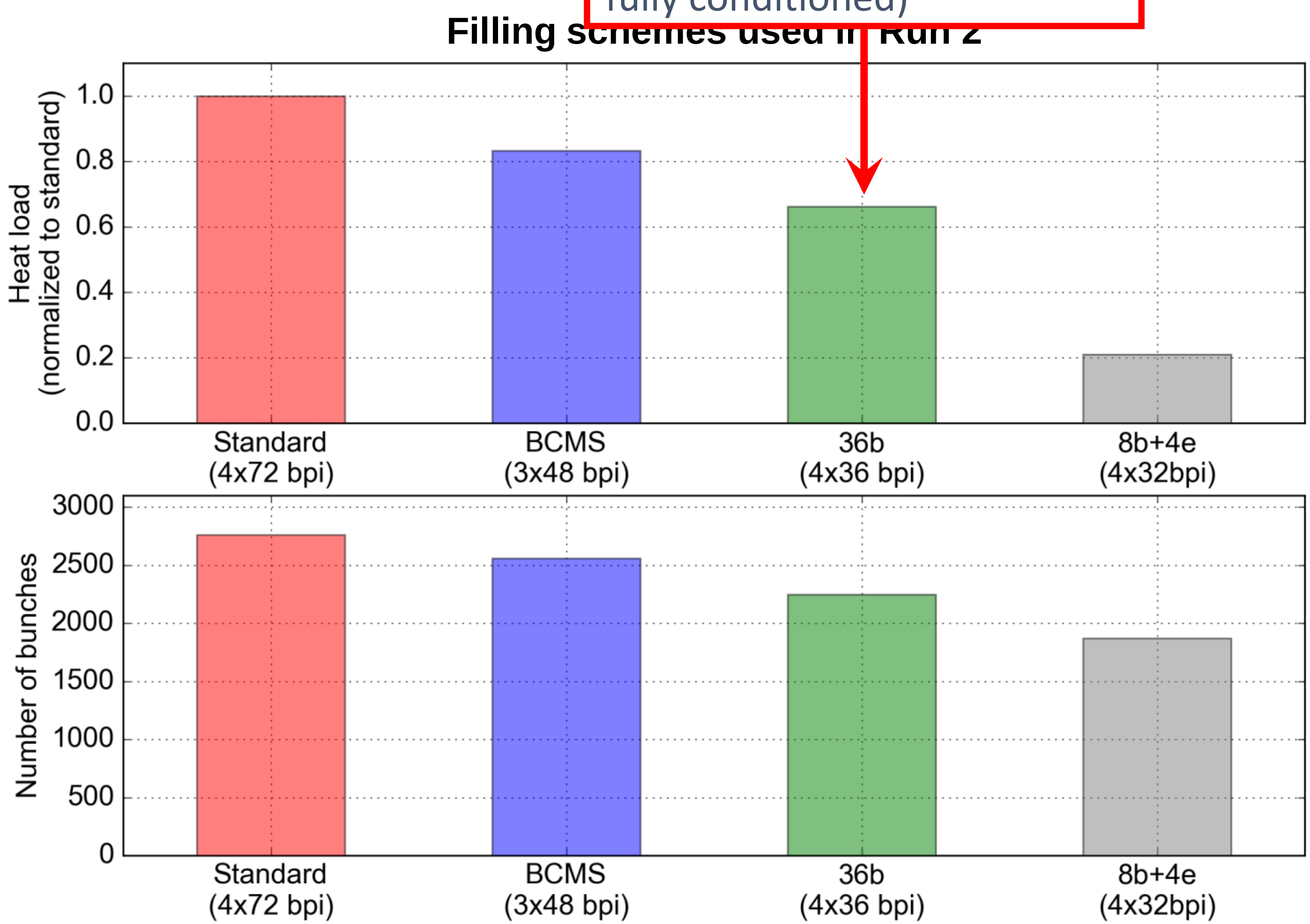
→ Profiting from **flexibility**

First physics fills with >2000b in 2015 (with machine not fully conditioned)



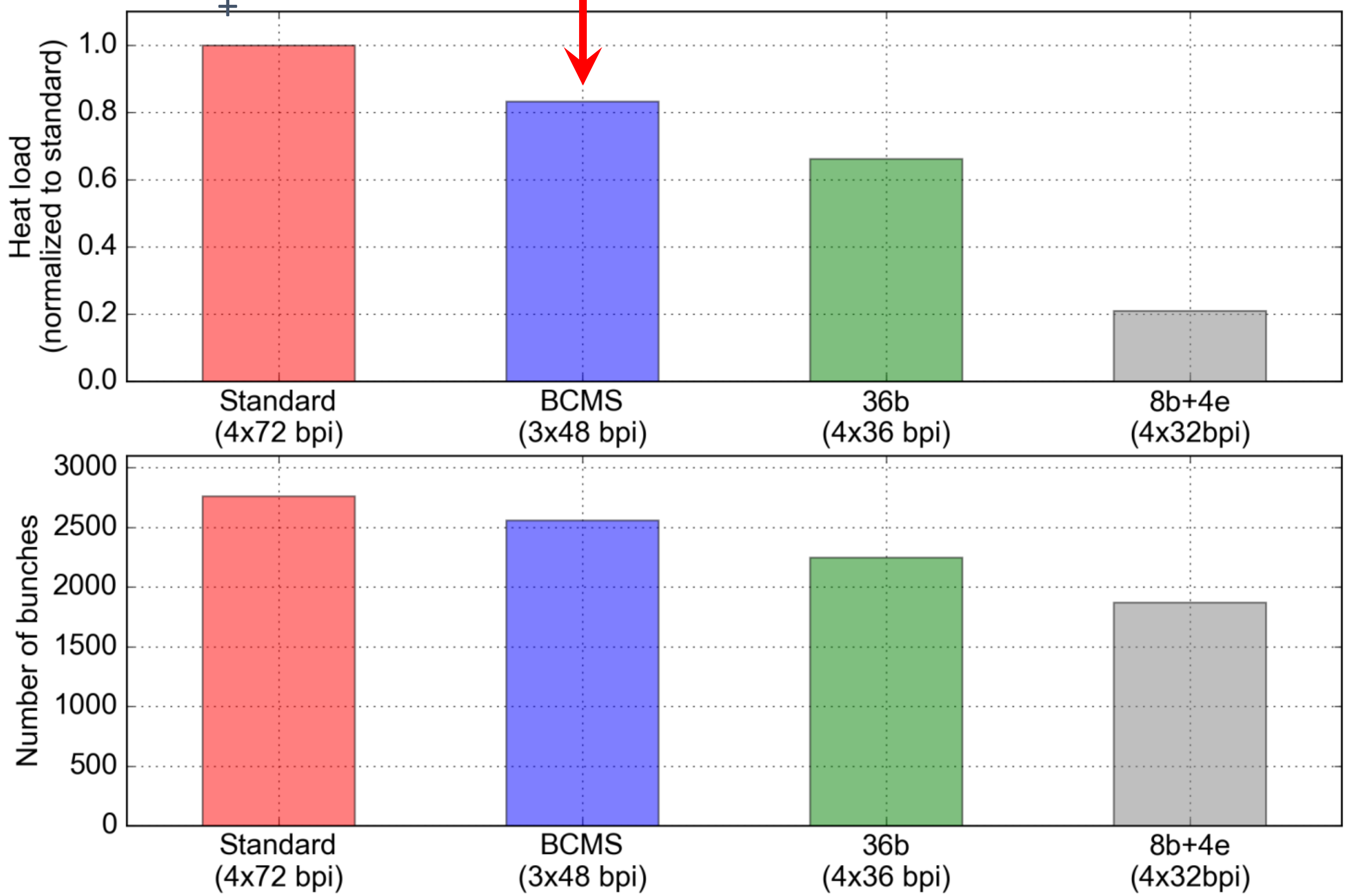
Heat loads: encountered issues and mitigation

Mainly **two types of issues** encountered during Run 2:

2. **Total** … **limit** (especially in 2015 when cham… by:

→ … **sign**

Used for **lumi production in 2016-2018**:
- Max. n. bunches only slightly smaller than standard scheme (-7 %)
+ Lower heat load
+ Higher brightness from the injectors
+

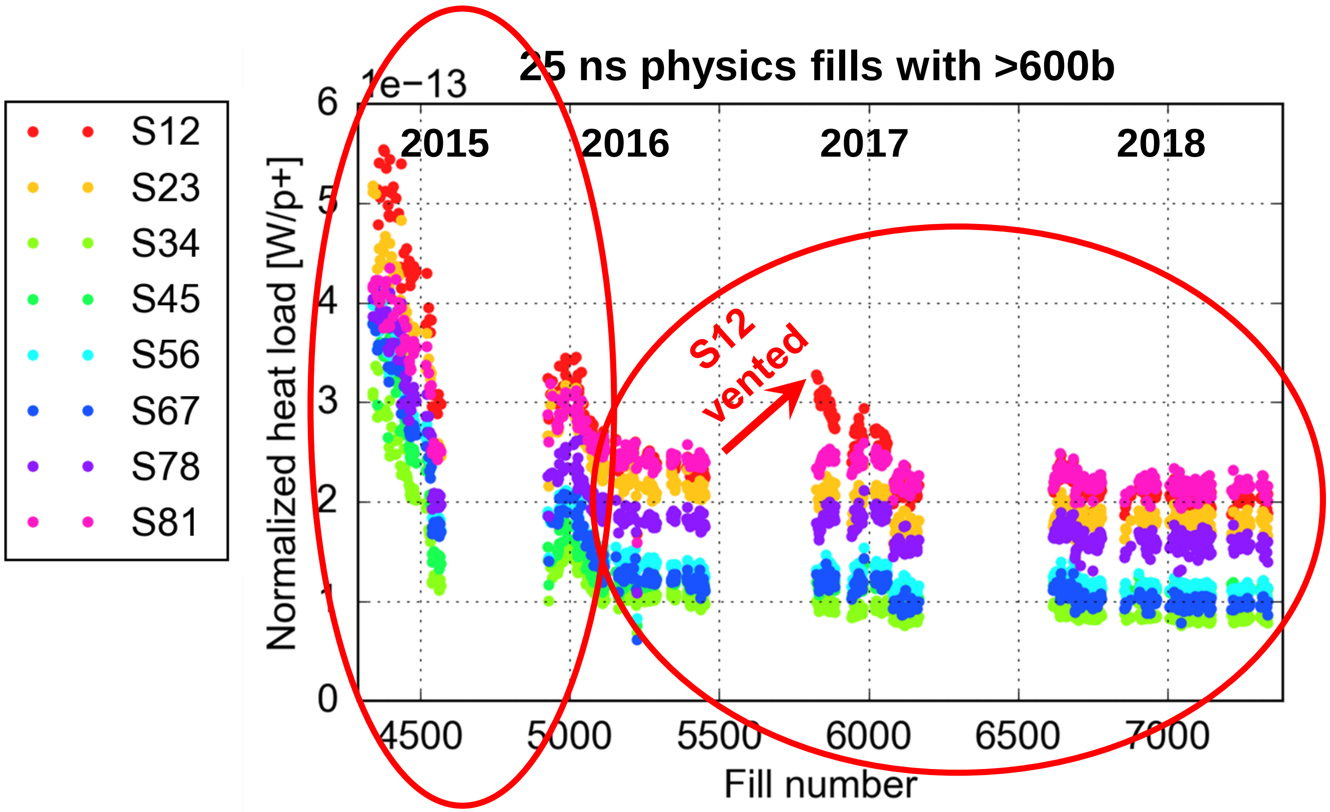


Heat loads: encountered issues and mitigation

Mainly **two types of issues** encountered during Run 2:

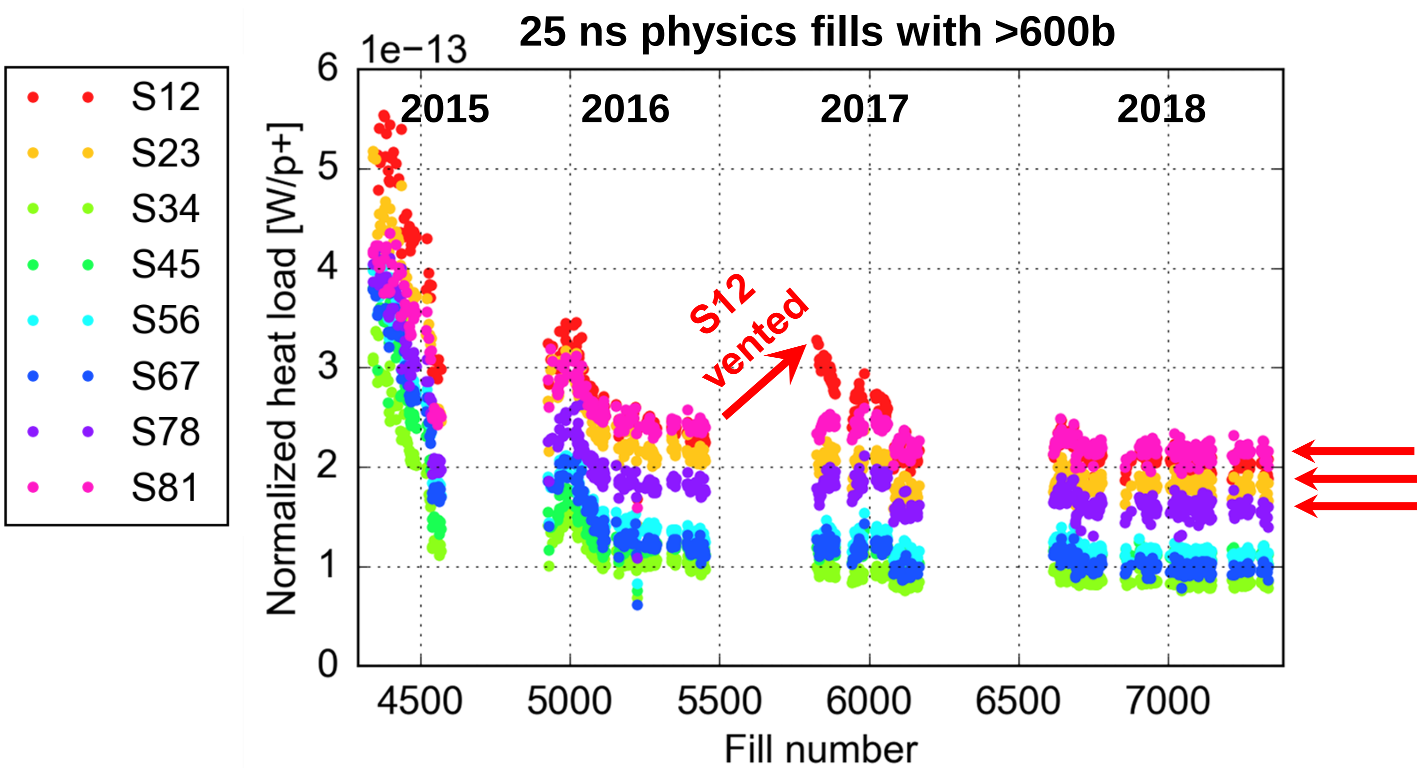
2. **Total load on the cryoplants close to the design limit** (especially in 2015 when chambers were not fully conditioned). Mitigated by:
   - → **Conditioning** accumulated **parasitically during physics operation**
   - → Reduction observed **in 2015-16** but **not later on**

Total heat loads directly affected LHC performance only in 2015. In the following years intensity reach was always limited by other factors (SPS dump in 2016, 16L2 in 2017-18)



Heat loads: differences among sectors

- Heat loads in **S12, S23, S81** much larger than for the other sectors
  - → close to cryo-plant design capacity
- These differences are **very reproducible** and were observed in **all 25 ns fills** over **4 years** (2015-18)



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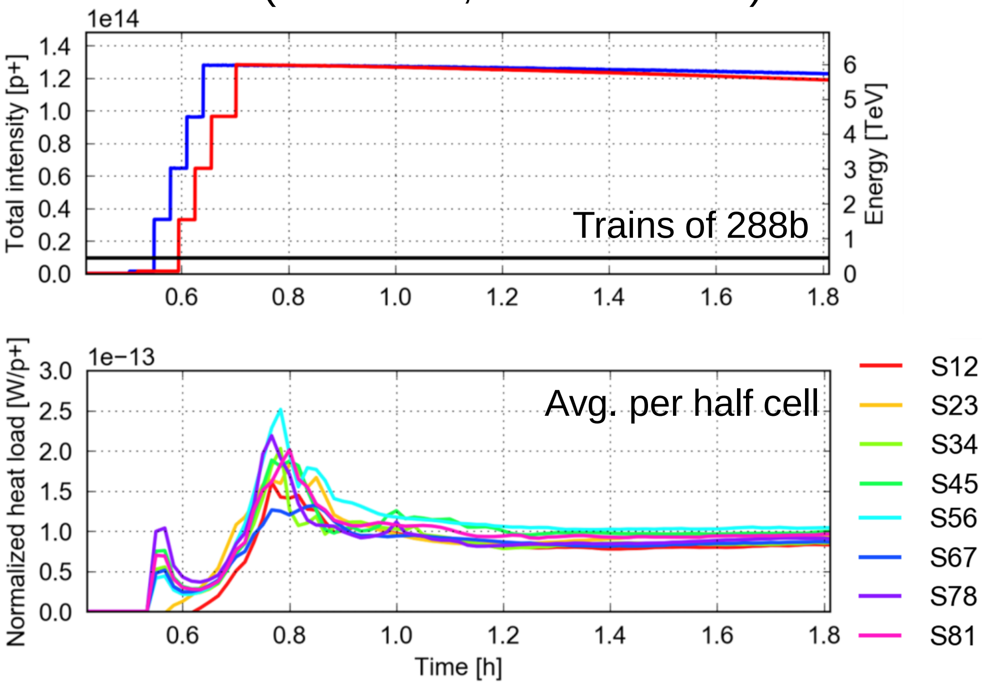
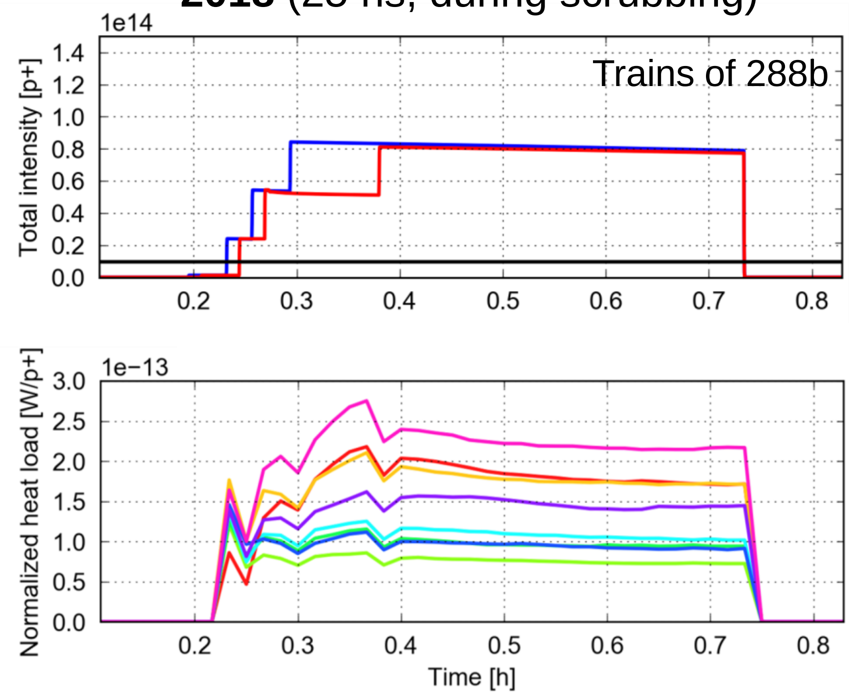
  - → close to cryo-plant design capacity
- These differences are **very reproducible** and were observed in **all 25 ns fills** over **4 years** (2015-18)
- But differences were **not present in Run 1**:
  - → High load sectors experienced a **degradation between Run 1 and Run 2**[(1)]

2012 (25 ns test, end of the run)



2018 (25 ns, during scrubbing)

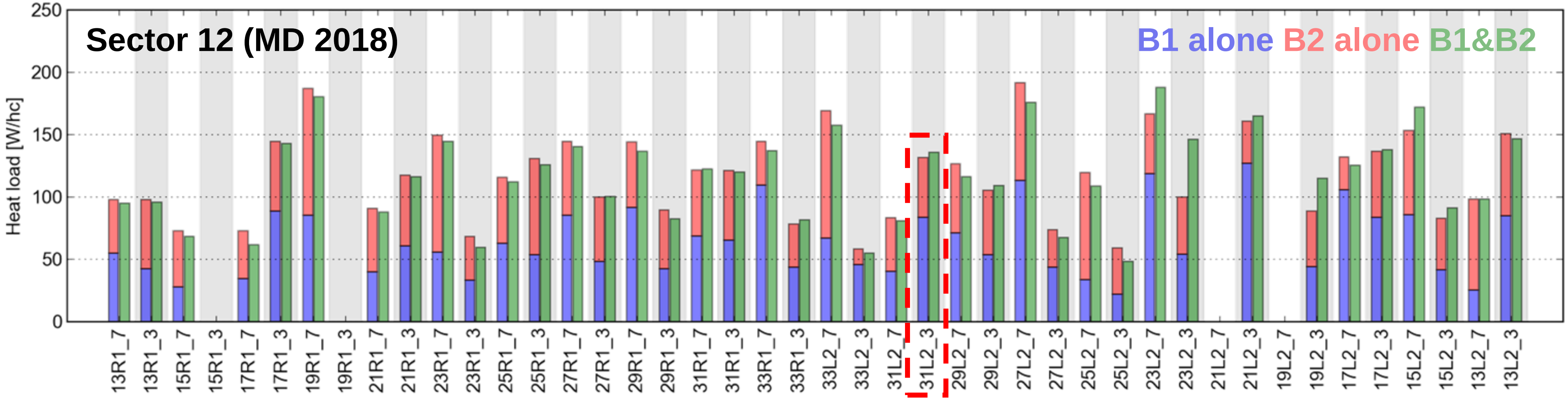


[(1)] It is possible to show that it is not a measurement artefact.

For more details see presentations at LMC#360

Heat loads: distribution along the ring

- Especially in the high load sectors, we observe **large differences from cell to cell**
- Heat loads can be different for the **two apertures of the same cell**
- **Differences** are present even **among magnets of the same cell**

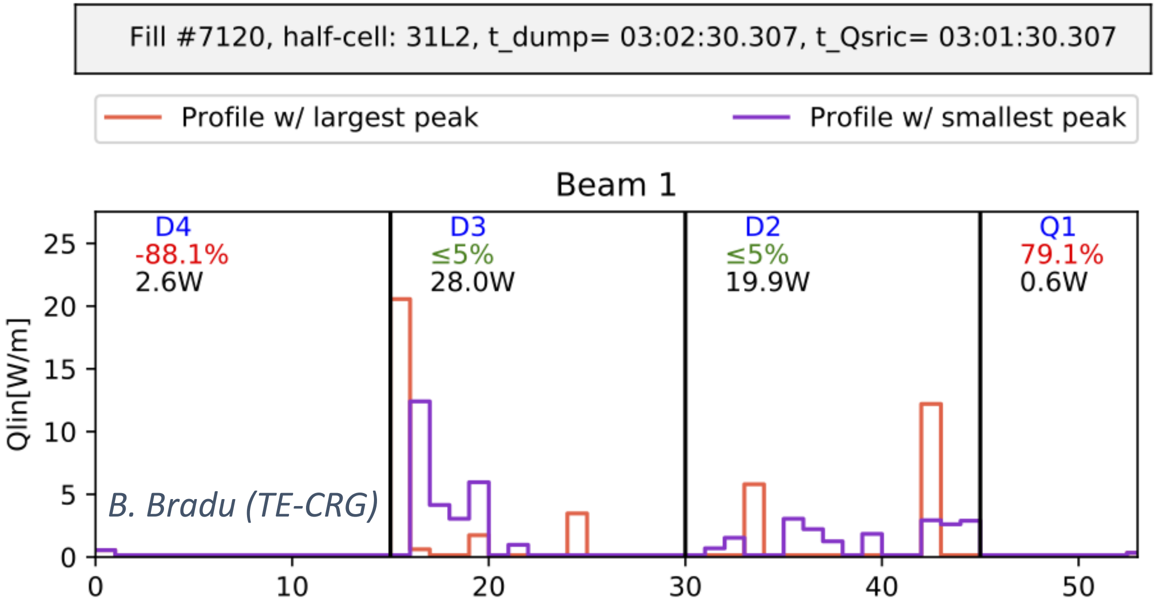


<u>Cell 31L2</u> (equipped with extra thermometers)

	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 loads: distribution along the ring

- Especially in the high load sectors, we observe **large differences from cell to cell**
- Heat loads can be different for the **two apertures of the same cell**
- **Differences** are present even **among magnets of the same cell**
- Technique being developed to **localize heat source within the magnet** (based on temperature evolution at the beam dump)
  - → **Tricky** in the absence of a direct measurement of the helium flow
  - → **Accuracy will improve** with the installation of **flow-meters** during LS2



Automatically generated at each beam dump.

Calculation results available at: http://cryodataanalytics.web.cern.ch/CryoDataAnalytics/Qdistrib/

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Heat loads: underlying mechanisms

How do we know that the **heating source is the e-cloud**?

- We reviewed the **mechanisms** that can **transfer energy** from the beam to the beam-screen and evaluated their **compatibility with observations**

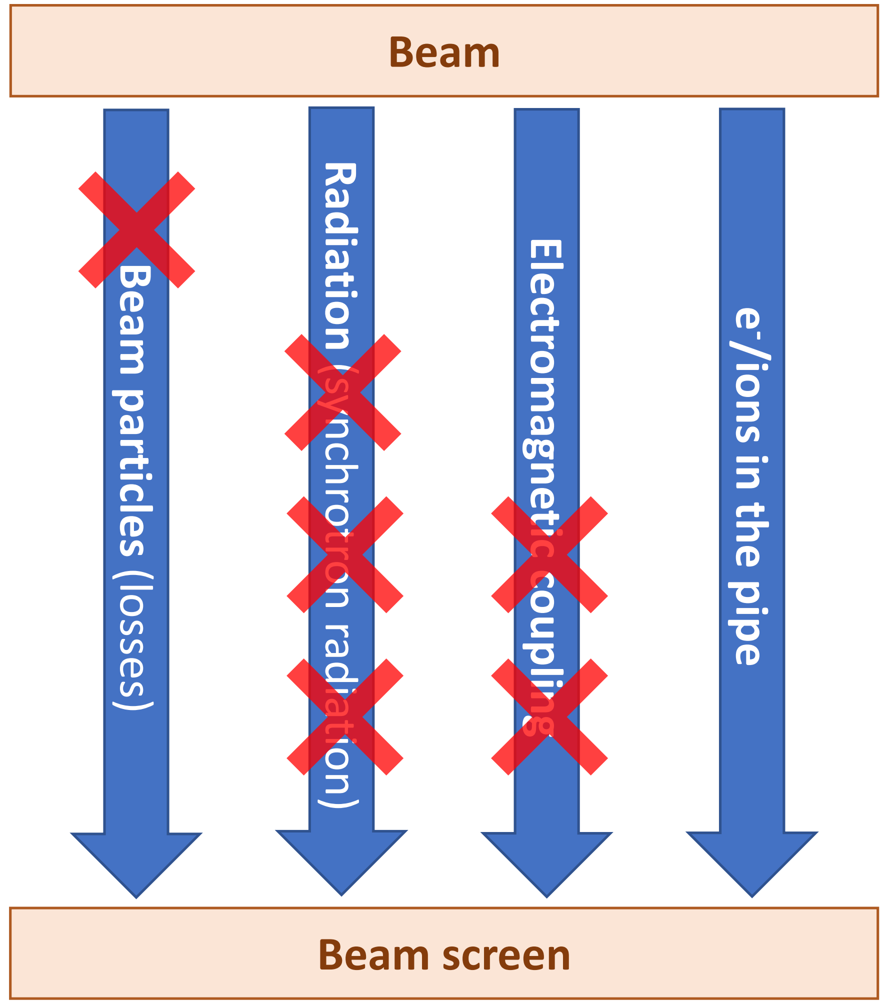
<u>**Observations**</u>

Total power associated to **intensity loss is less than 10% of measured heat load**

Heat load **increases only moderately during the energy ramp**

Heat loads with **50 ns are >10 times smaller than with 25 ns**

Measured **dependence on bunch intensity** is not linear nor quadratic



= Excluded

For more details see presentations at LMC#358 and ABP Forum

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Heat load **increases only moderately**

smaller than with 25 ns

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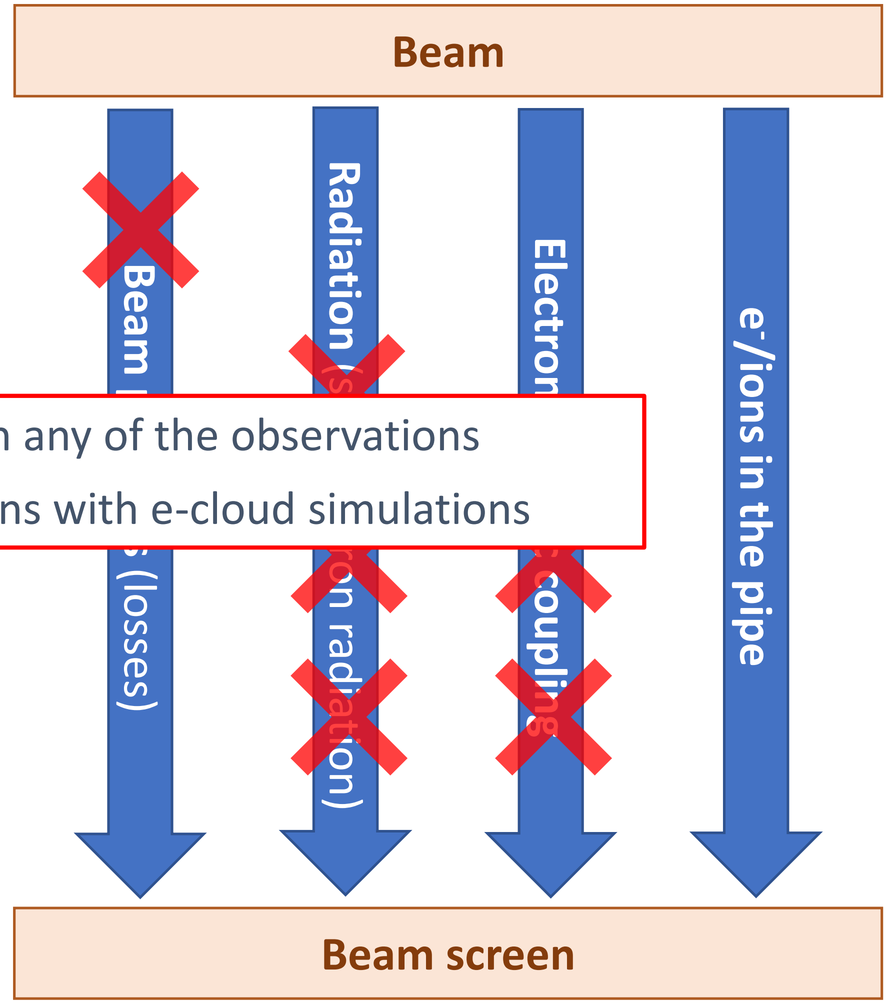

e-cloud effects are not incompatible with any of the observations

→ We try reproduce the observations with e-cloud simulations

✗ = **Excluded**

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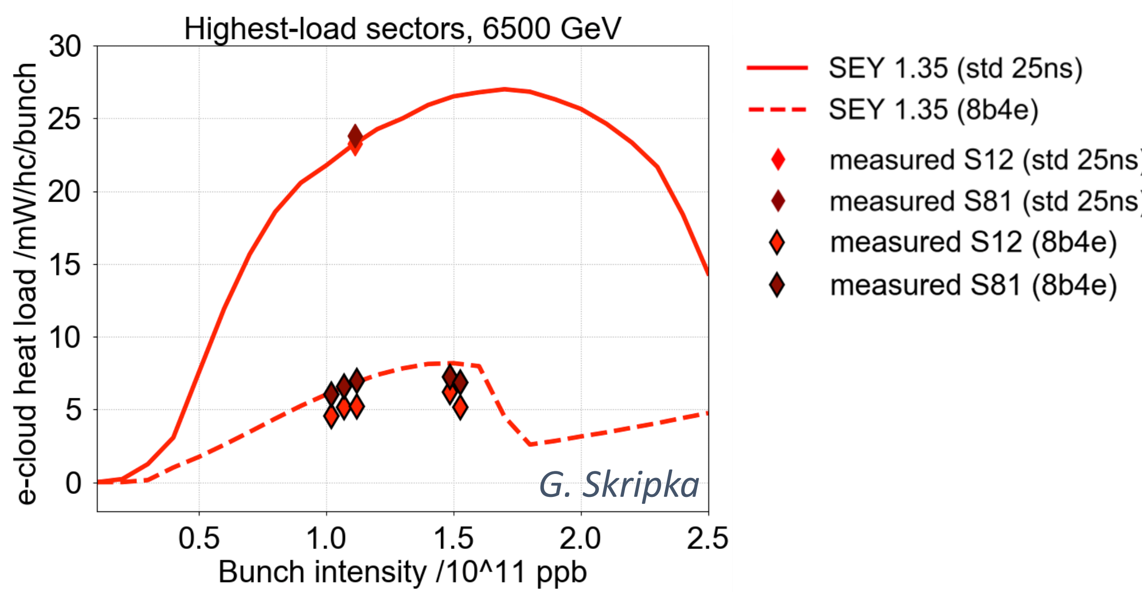
…we attribute the differences in heat load to **different Secondary Electron Yield (SEY)**

Based on heat load measurements taken with **25 ns, 6.5 TeV, 1.1e11 p/b**

Sector	S12	S81	S45	S34
SEY_{max}	1.35	1.35	1.25	1.15

The inferred values could be **validated** using several **independent machine observations** (50 ns, 8b+4e, injection vs high energy, different bunch intensities)

Good agreement especially for high-load sectors



For more details see presentations at e-cloud meeting #62

For more details see presentations at LMC#358 and ABP Forum

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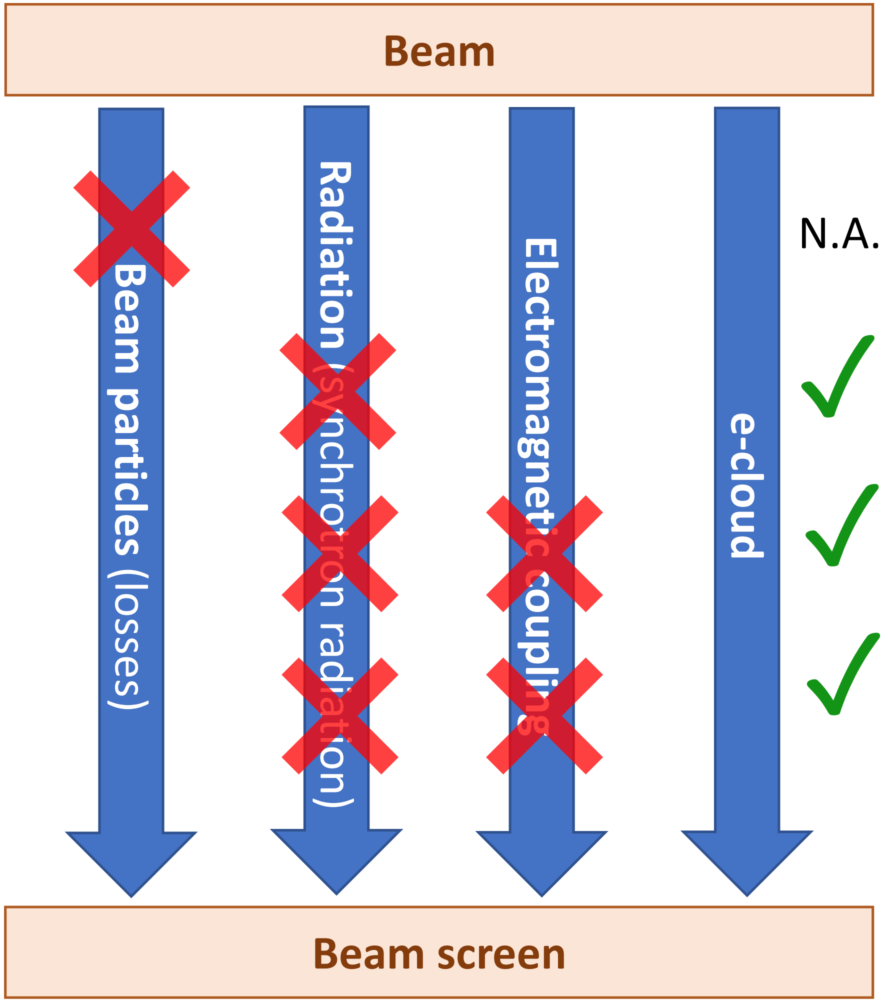

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Measured **dependence on bunch intensity** is not linear nor quadratic

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

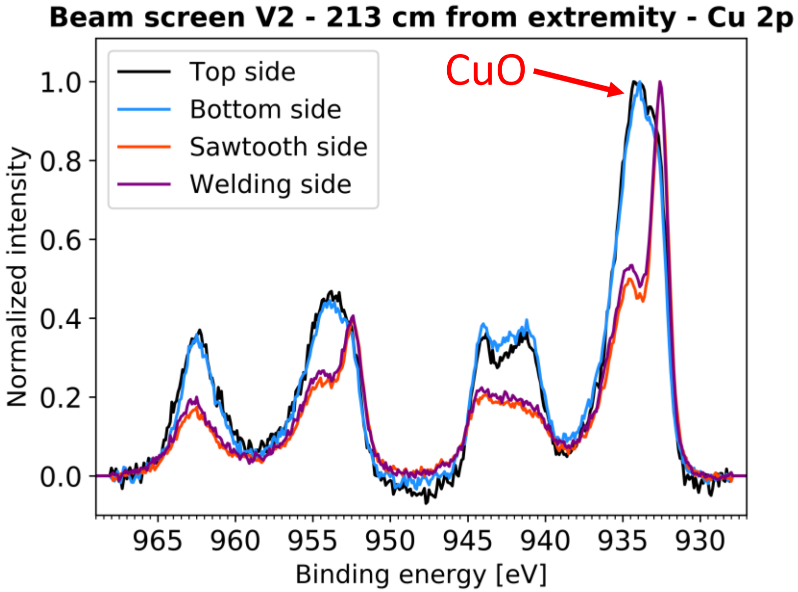
✗ = **Excluded**

For more details see presentations at LMC#358 and ABP Forum

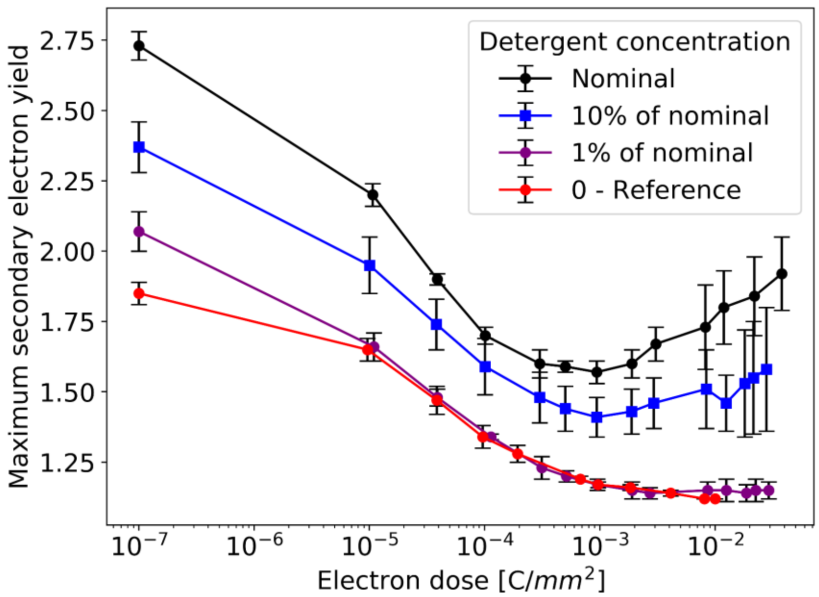
Heat loads: ongoing surface studies

- **Laboratory measurement campaign** launched by TE-VSC to investigate possible causes of SEY alterations:
  - **Analysis** and **tests** on beam screens extracted from the LHC in 2016-17 (MB-A31L2)
  - Several **alteration processes** simulated and studied in lab experiments
- **History** of beam screen **manufacturing, installation and operation** is being analyzed to try to **identify possible causes of degradation**
  - No smoking gun found so far…

Chemical alterations following beam operation



Effect of impurities from cleaning product



V. Petit, M. Taborelli (TE-VSC)

For more details see presentation at LMC#360

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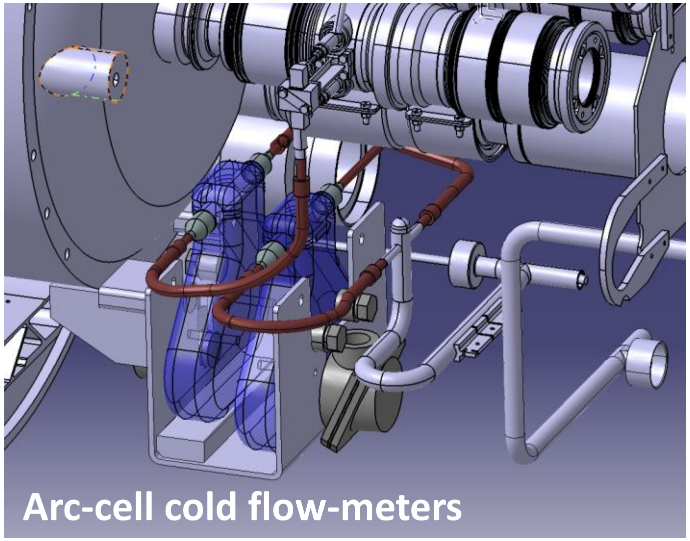
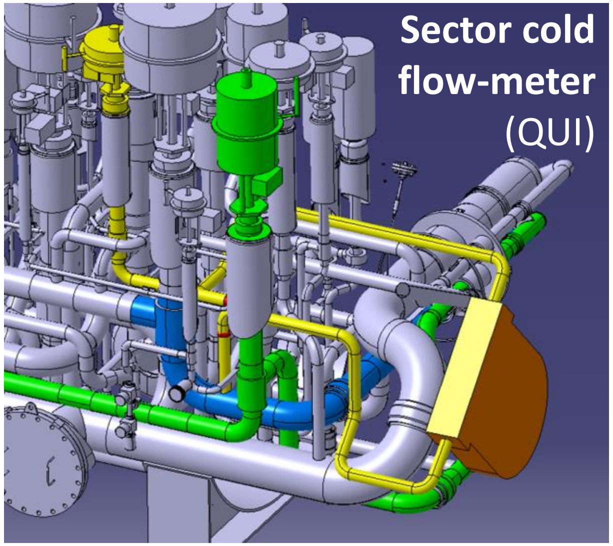
Heat loads: plans for LS2

- A **different gas composition** will be used for the **venting of the arc beam vacuum system** → well controlled and reproducible exposure procedure
- **High-load magnet MB-B31L2** will be **removed from the tunnel** and will undergo extensive **surface analysis.** Comparison will be made with a low-load magnet.
- New **cryogenic instrumentation** will be installed during LS2:
    - After LS2 we will have **10 instrumented cells** (including present 4, which will be upgraded) → better heat load localization
    - Global **sector load measurements** on four sectors (S12, S23, S56, S67)
- BE-BI will continue the development of **microwave measurement technique** for direct e-cloud density measurements





For more details see presentations by L. Tavian at LMC#360

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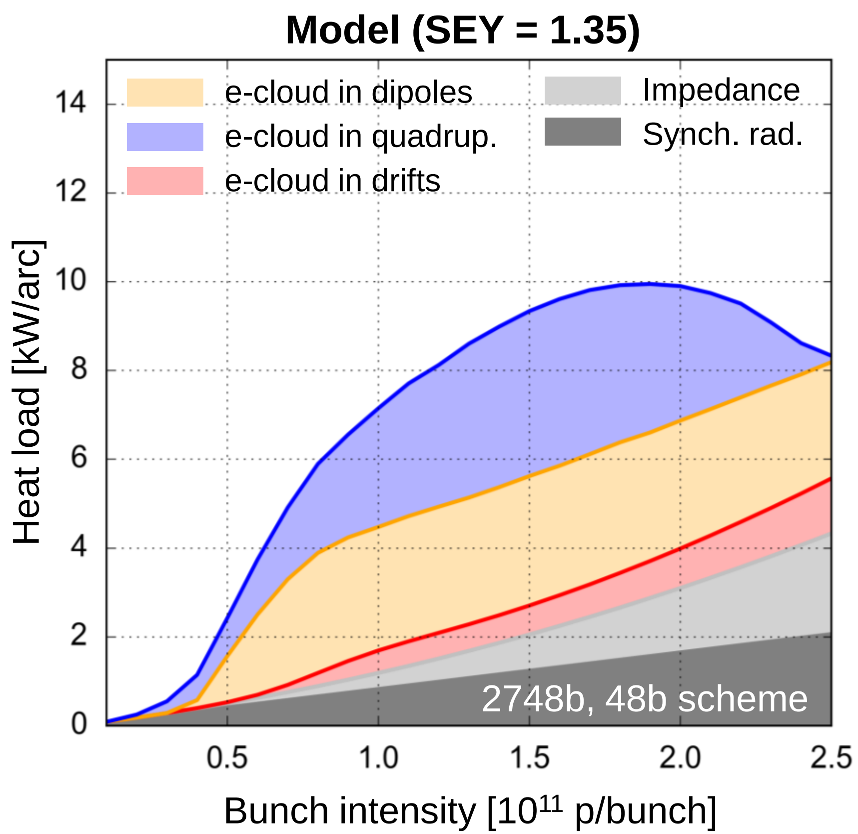
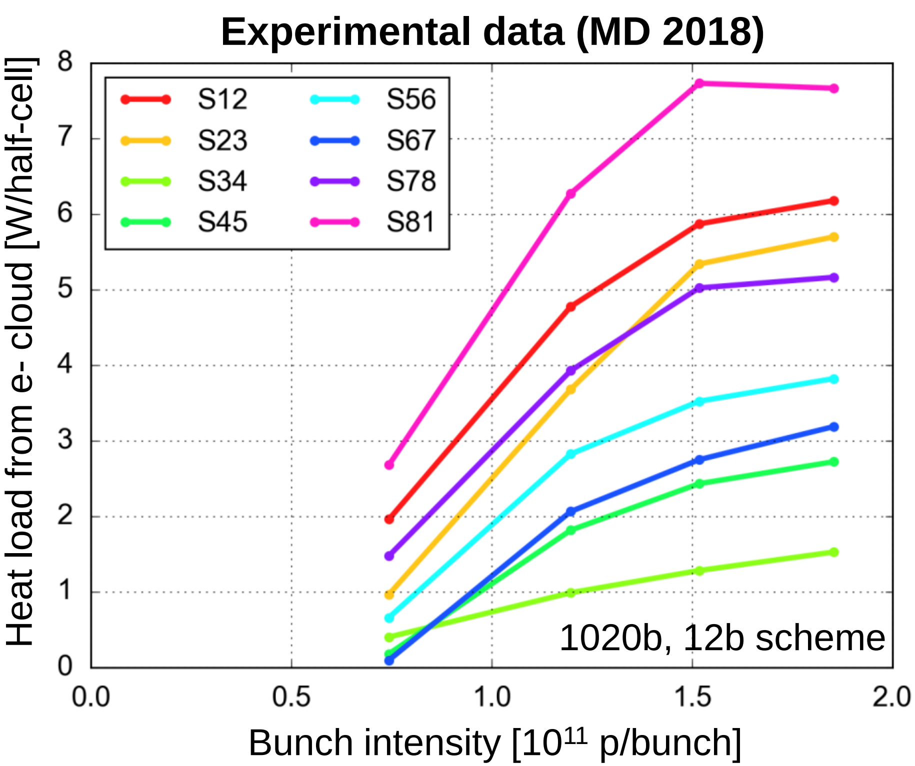
Dependence of e-cloud heat loads on bunch intensity

- **Higher bunch intensity** will become available from the injectors during Run 3
- With the available models, **simulations foresee a relatively mild increase** of the heat load from e-cloud above 1.2x10^{11} p/bunch
- Direct **experimental checks were not possible in Run 2** (RF limitations in the SPS)
- At end 2018, **trains of 12b with high bunch intensity** became available from the SPS

  → Tests done during LHC MD4 **confirmed ~flat dependence above 1.5x10^{11} p/b!**





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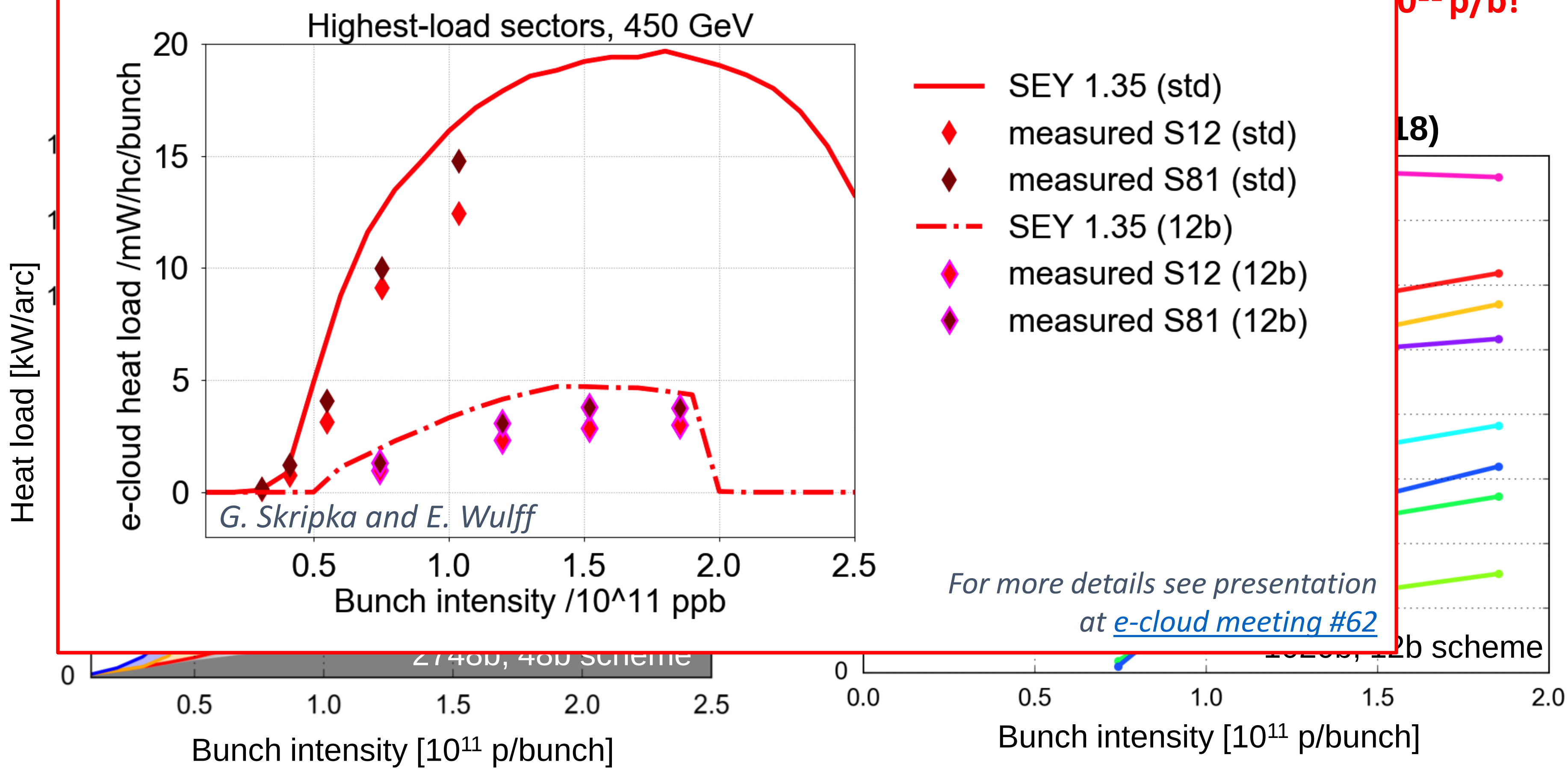
e SPS)

n the SPS

0^{11} **p/b!**

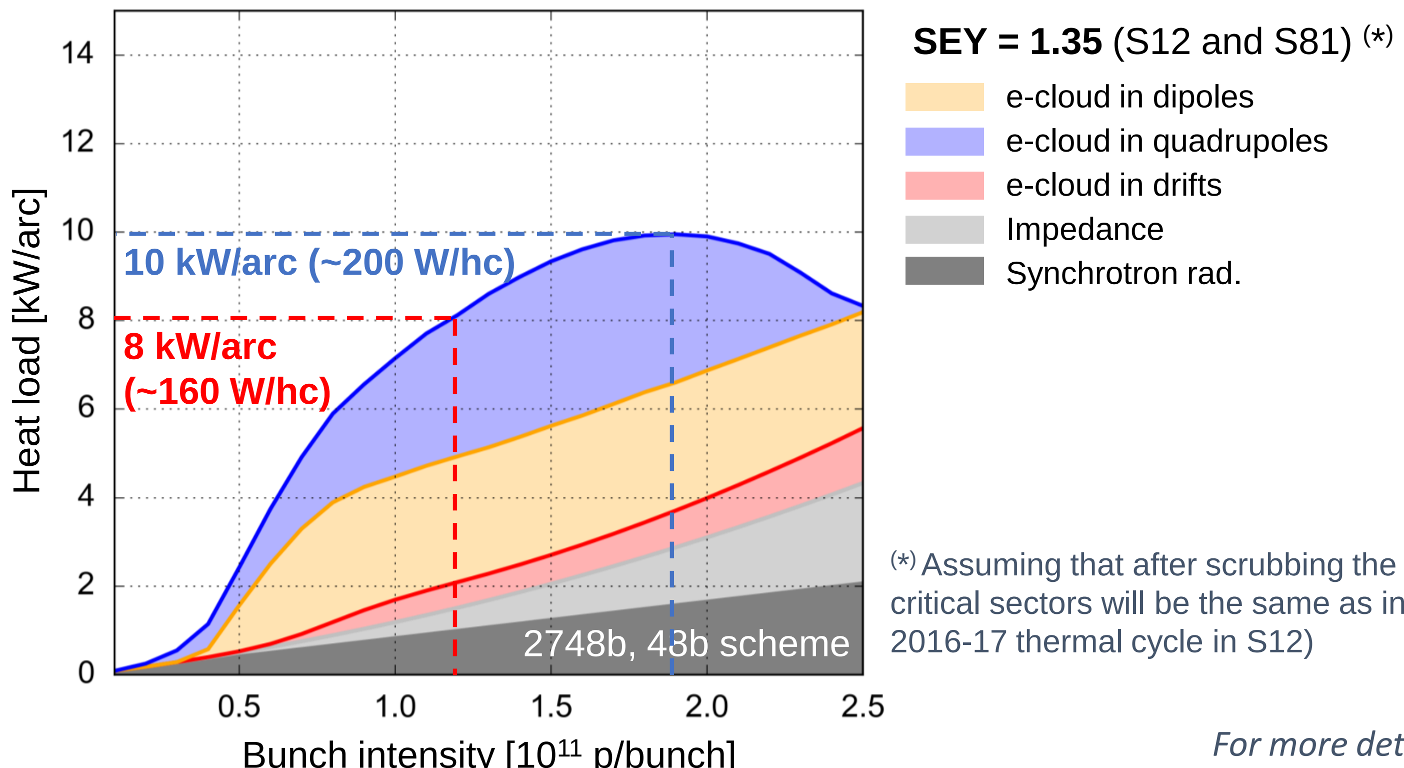
- **Quantitative agreement** of experimental data against simulations is **very good** especially for **high-load sectors**



For more details see presentation at e-cloud meeting #62

Expectations for Run 3

- Counting only on the **nominal cooling capacity** (160 W/hcell) the bunch intensity would be limited **~1.3x10[11] p/bunch**
- **Actual capacity** of the cryoplants was **assessed with measurements** by TE-CRG
  - → In the most **critical sectors** (S12, S23 and S81) we can count on **~200 W/hcell**
  - → **1.8e11 p/bunch should be within reach (with no margin)!**
- In case of problems (further degradation during LS2, lower cryo performance) heat loads can be mitigated using **"mixed filling schemes"** (8b4e inserts in 25 ns beams)



(*) Assuming that after scrubbing the SEY for the critical sectors will be the same as in Run 2 (as for 2016-17 thermal cycle in S12)

For more details see presentation at Run3 config meetings ([#2](#) and [#4](#))

Outline

Introduction

Effects on the beam

- Injection energy
- Top energy

Heat loads

- Issues, mitigation and evolution in Run 2
- Differences among the sectors
- Underlying mechanism

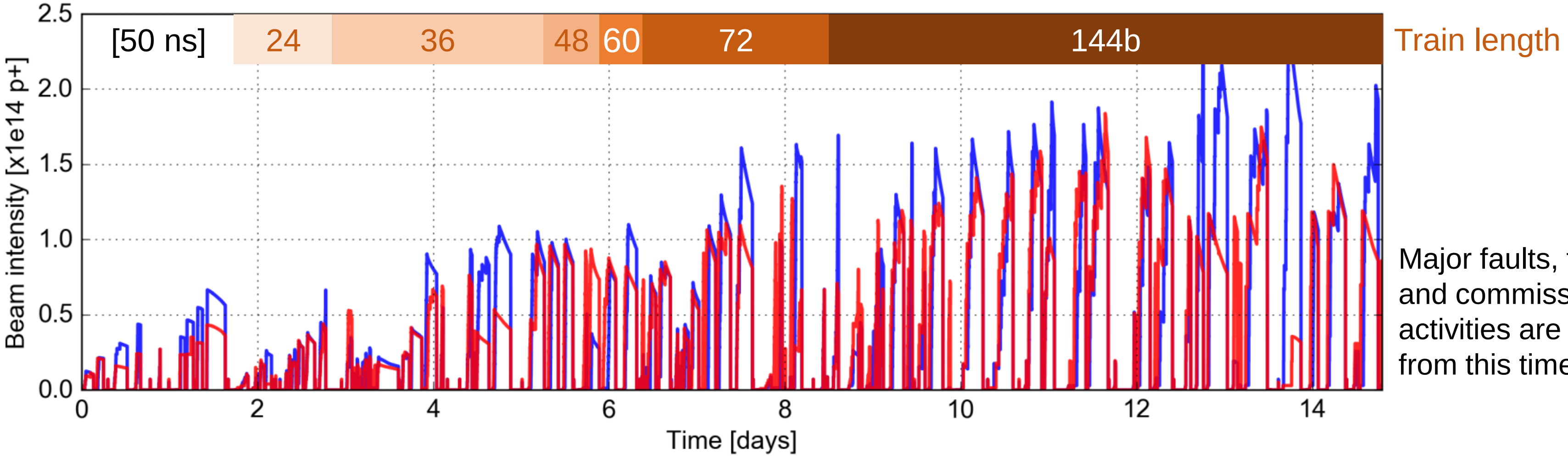
Outlook for Run 3

- Plans for LS2
- e-cloud dependence on bunch intensity
- Expected intensity reach
- First thoughts on scrubbing after LS2

Scrubbing at the beginning of Run 3

- The main goal is to **mitigate instabilities and beam degradation**
- **Heat load mitigation** can be completed **parasitically with 25 ns physics**
- We expect that **arc conditioning will be lost** during LS2 → **2021 similar to 2015**

In 2015 we needed ~16 scrubbing days to allow operation with 25 ns beams



Major faults, tests and commissioning activities are removed from this timeline.

Issues limiting scrubbing pace in 2015 have been **mitigated during Run 2 / LS2:**

Observed issue (2015)	Mitigation deployed in Run 2 / LS2
Vacuum spikes in the **TDI**	- New design (TDIS) to be 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 LS2 - Improved feedforward
Transverse **instabilities**	- More margin in Q’ and octupoles (optimized tunes)

→ We expect to be **more efficient**

→ **Less time should be required in 2021** (if no surprises)

Summary

- **Scrubbing** allowed **mitigating to a large extent** the detrimental effects of e-cloud enabling the **exploitation of 25 ns beams** for luminosity production
- … but **e-cloud effects could not be fully suppressed** and continued affecting beam **stability** and **slow beam parameter evolution** during the entire Run 2

- Electrons caused large **heat loads** on the cryogenics cooling system
  - Partially mitigated by optimizing the **filling scheme** and by the **parasitic conditioning** accumulated during physics fills
- Large **differences** in heat-load are observed **among sectors**. We know that:
  - They were **not present during Run 1** (even with 25 ns)
  - **e-cloud** is the only identified effect **compatible with observations**, assuming some **surface** modification took place in LS1 → being followed-up with lab studies

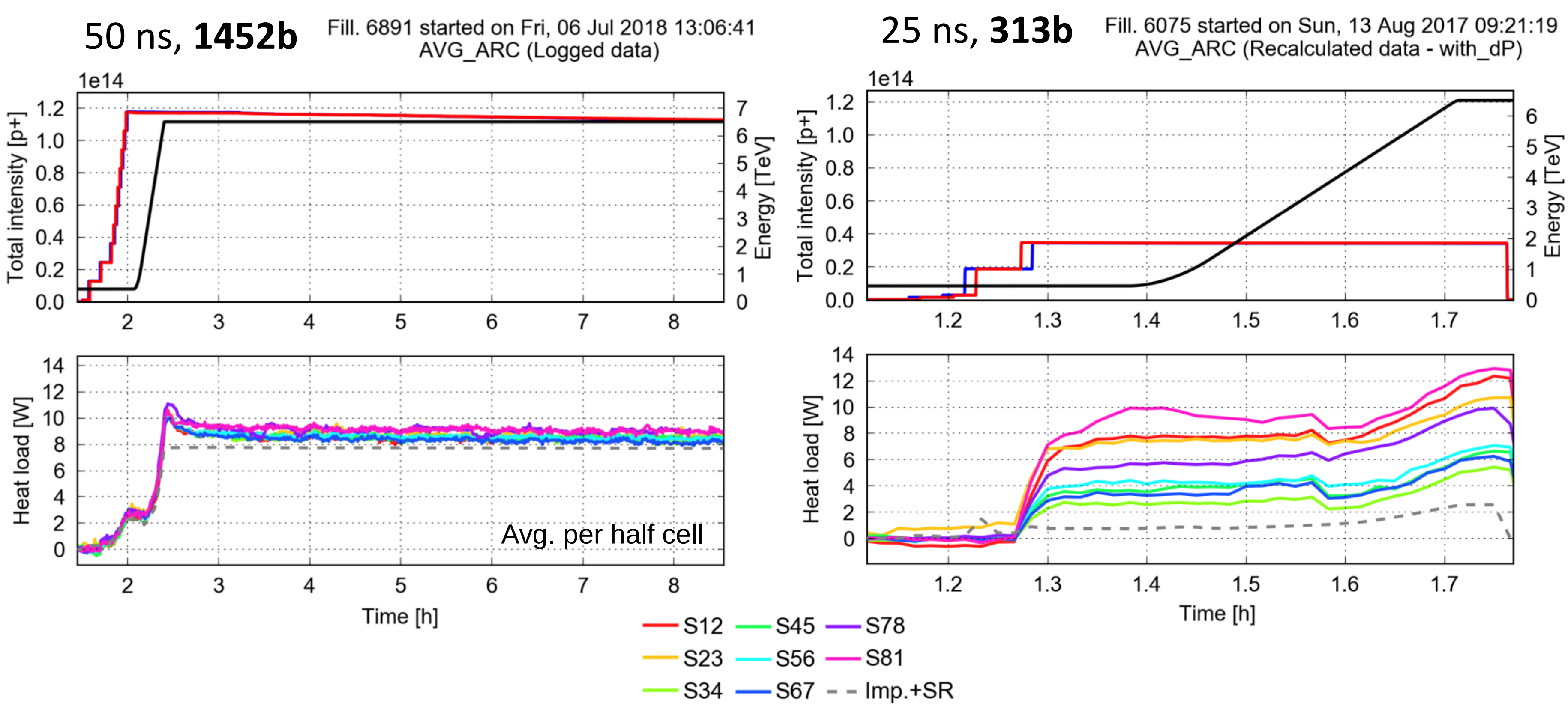
- During **LS2**: **beam-screens** will be extracted and **analyzed**, new **instrumentation** will be installed and **precautions** will be taken to avoid further degradation
- **Dependence of e-cloud on bunch intensity** was probed experimentally with short trains up to 1.9e11 p/b → **trend** was found to be **consistent with models**
  - Assuming no further degradation in LS2 and counting on cryo-plants performing better than design (as measured): **1.8e11 p/bunch could be within reach for Run 3**

Thanks for your attention!

Heat loads: observations with 50 ns

- With **50 ns beams** all sectors agree very well with impedance and synchrotron radiation estimates
- Differences among sectors are observed only with **25 ns**, even with very small number of bunches

  → **Impossible to explain the observations as a measurement artefact** (the measurement system "does not know" about the bunch spacing…)



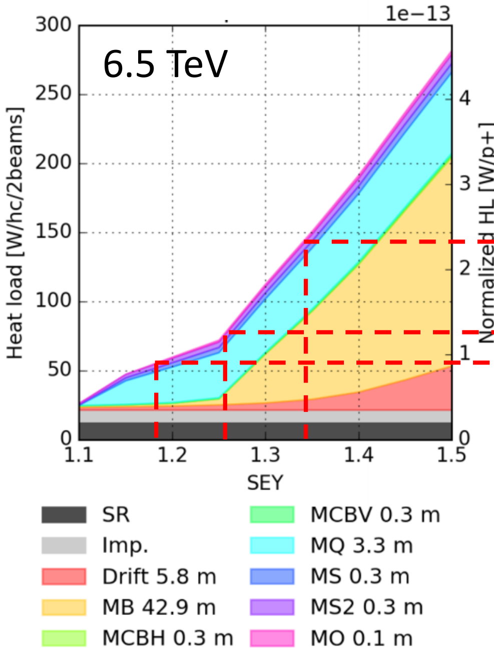
Inferred SEY_{max} range

Hypothesis: we attribute the differences among sectors to differences in SEY_{max}

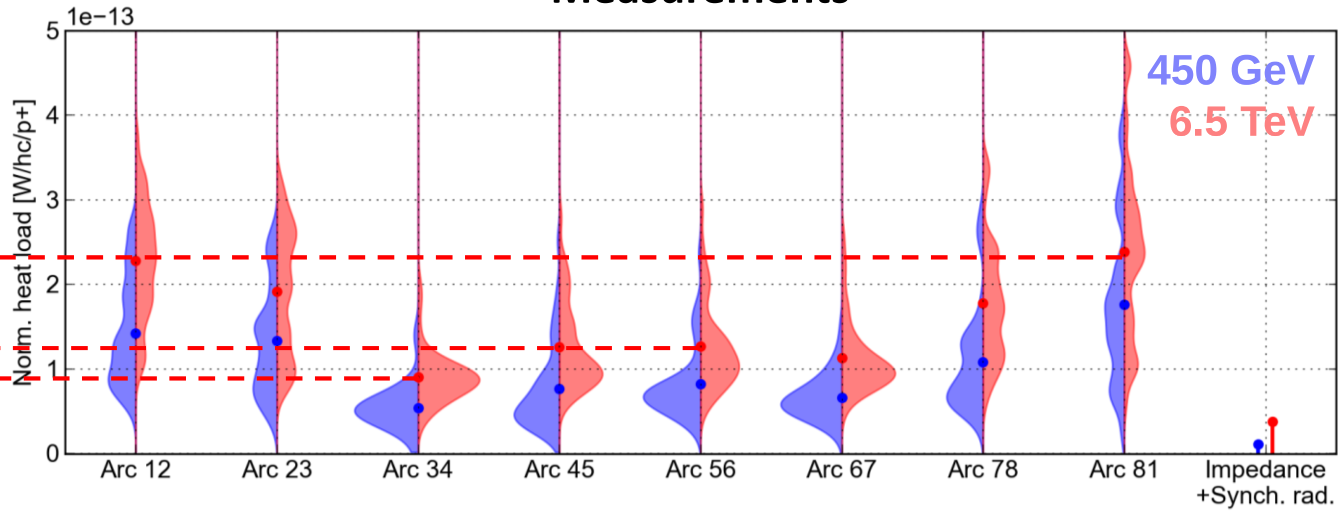
→ first estimate made comparing the average arc loads against simulations

Sector	S12	S81	S45	S34
SEY_{max}	1.35	1.35	1.25	1.15

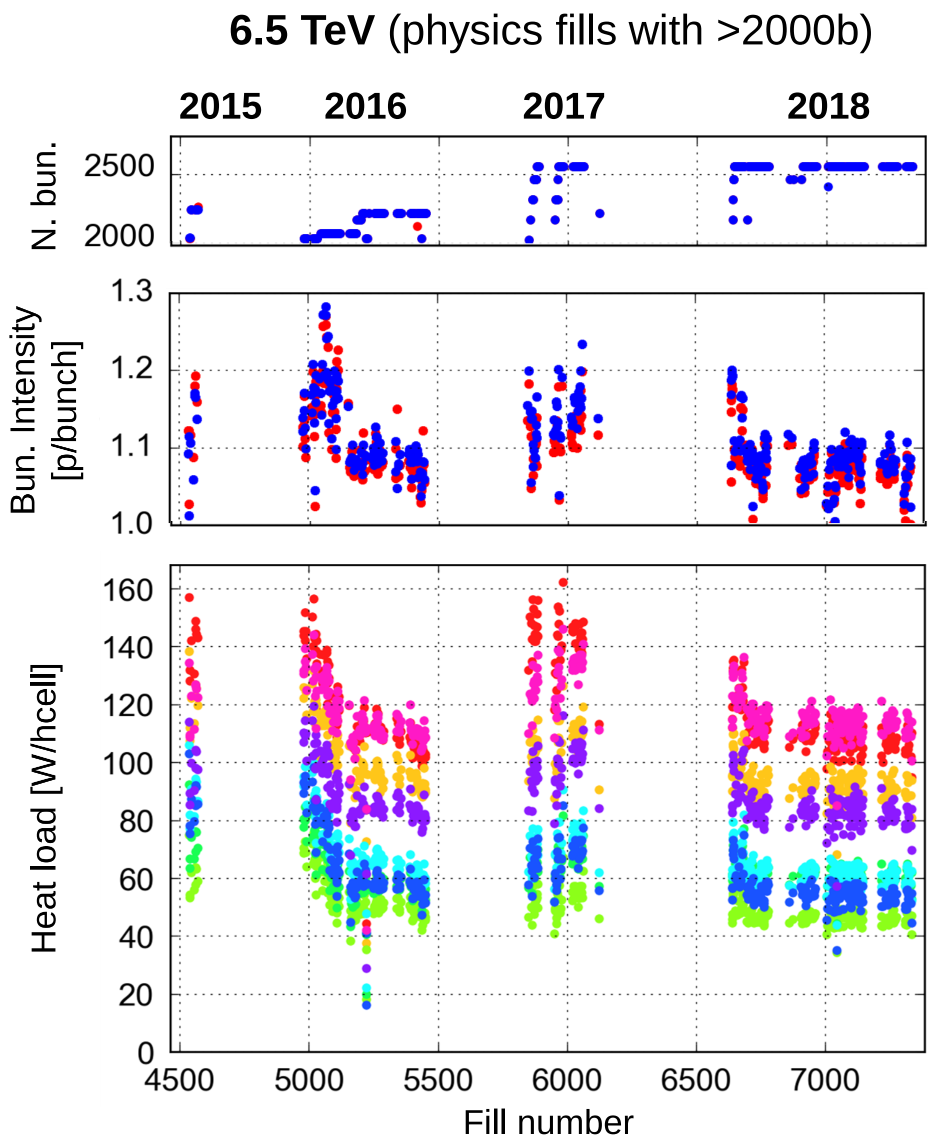
Simulations



Measurements

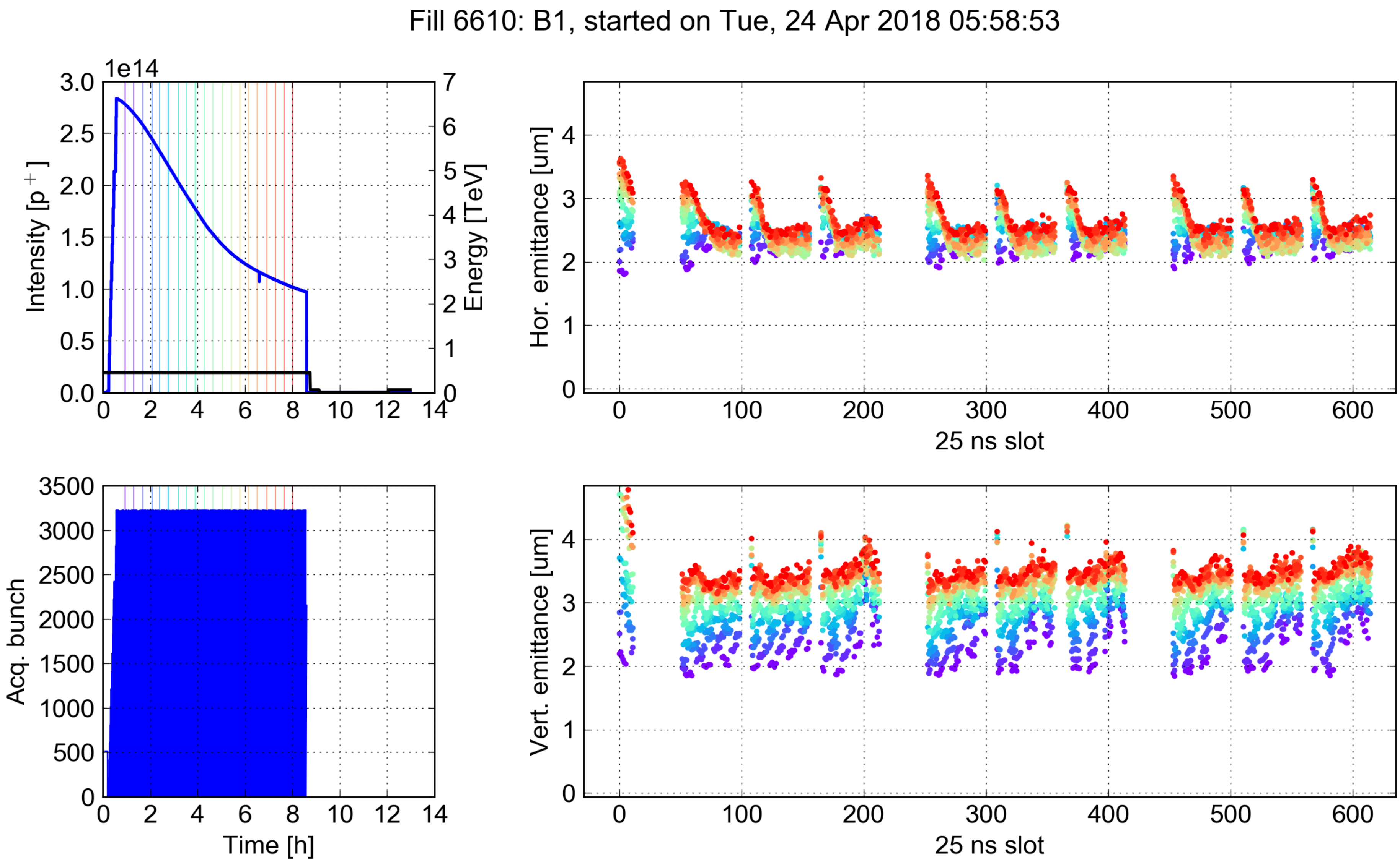


For details see: P.Dijkstal et al., CERN-ACC-NOTE-2017-0057



6.5 TeV (physics fills with >2000b)
2015
2016
2017
2018
N. bun.
2500
2000
Bun. Intensity [p/bunch]
1.3
1.2
1.1
1.0
Heat load [W/hcell]
160
140
120
100
80
60
40
20
0
4500
5000
5500
6000
6500
7000
Fill number

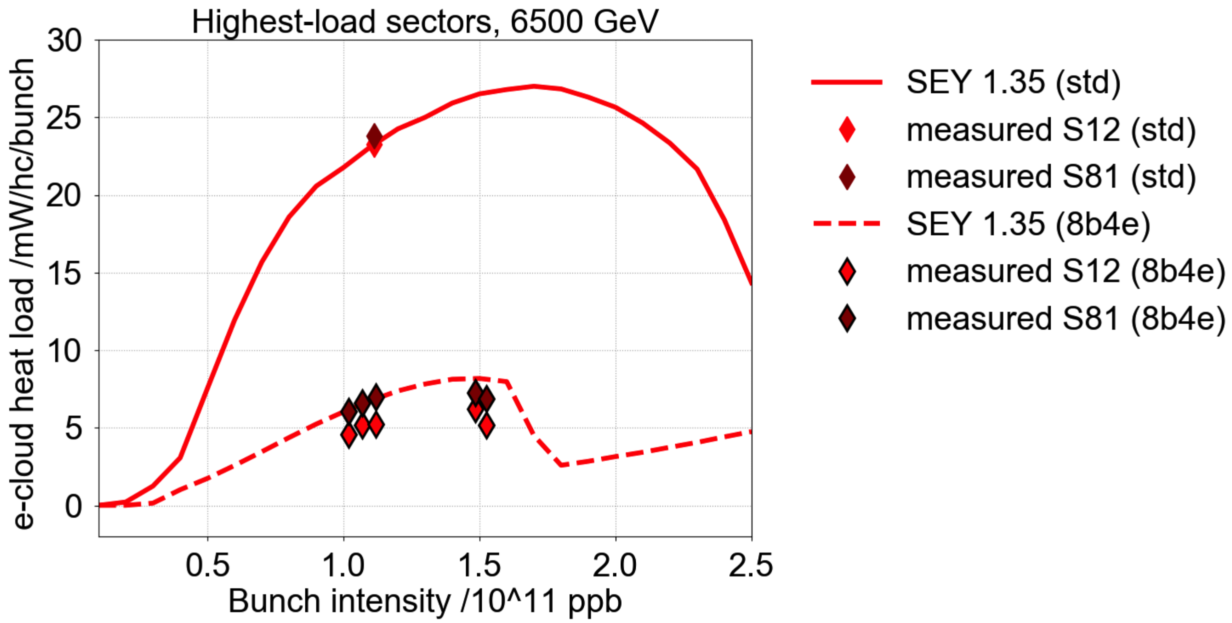
Not calibrated

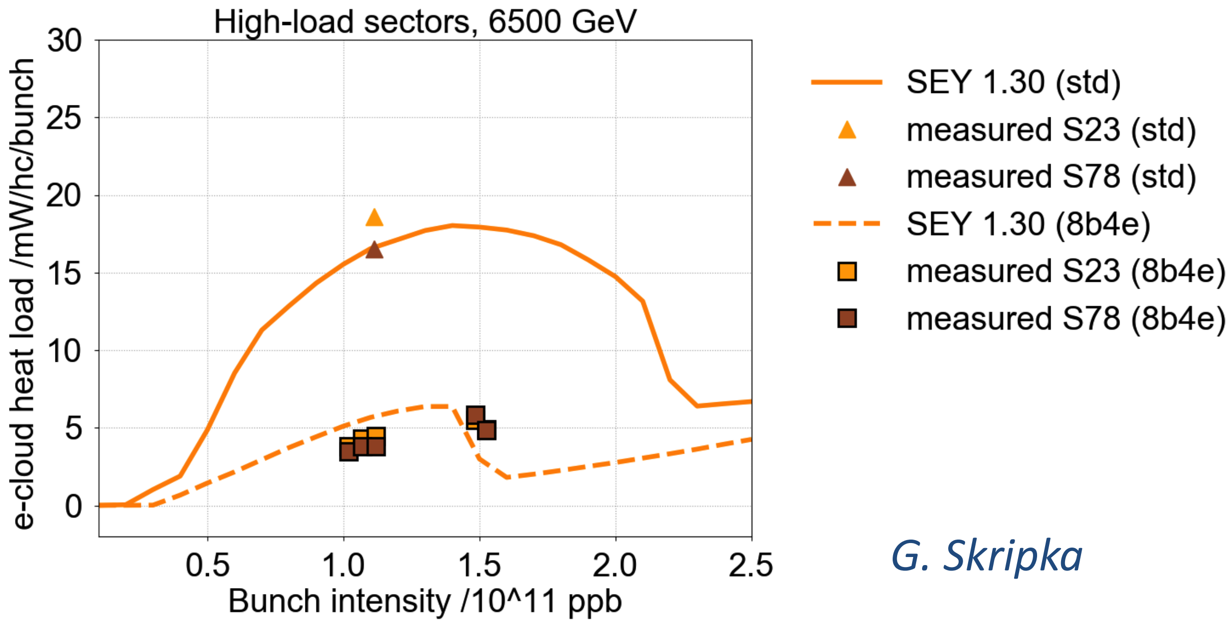


MD2484 - high intensity 8b+4e

First **comparisons against simulations** (made assuming uniform SEY in the arcs)

- Good agreement especially in sectors with higher load
- Next step is to test more complex model where we assume that “degradation” is concentrated in the dipoles





G. Skripka

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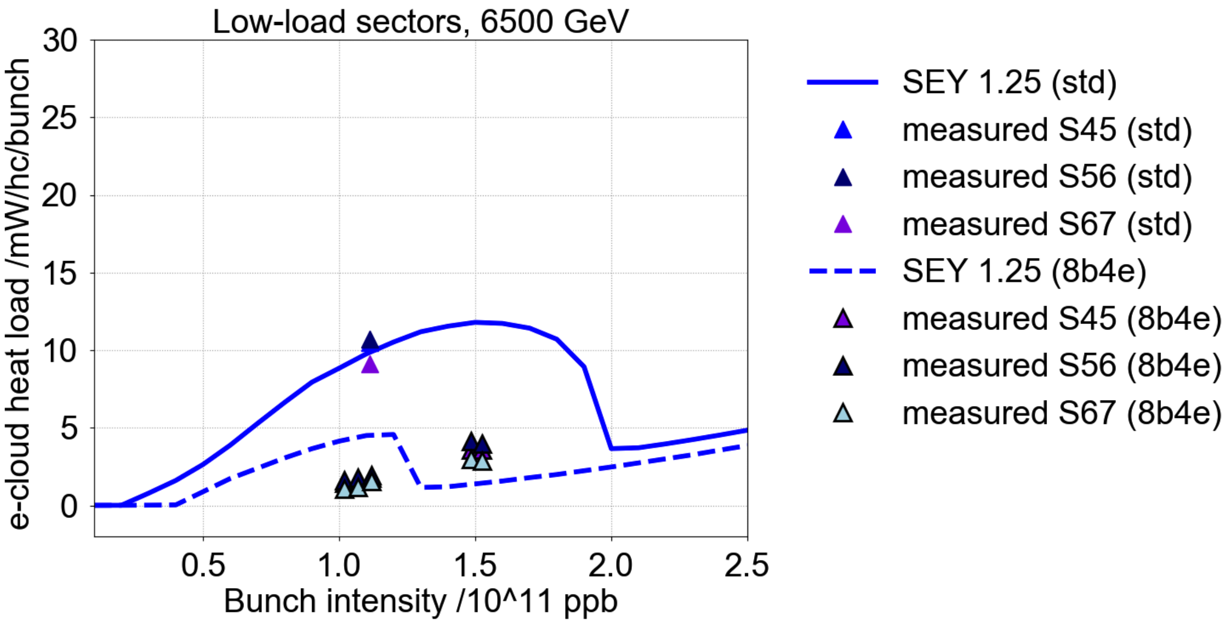
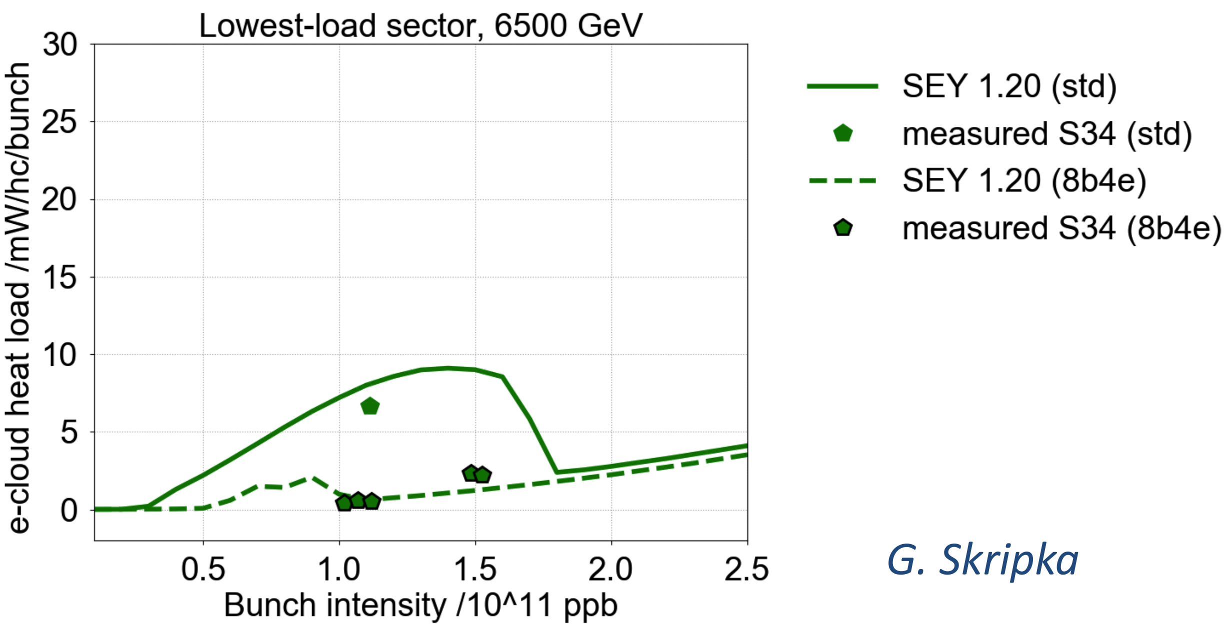


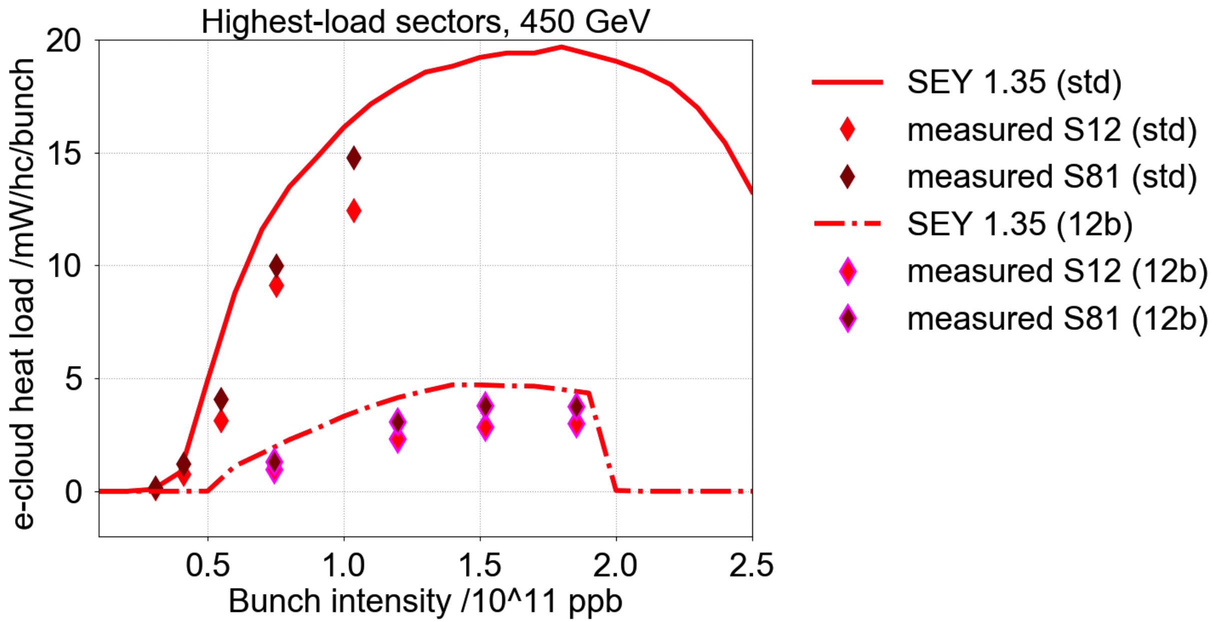


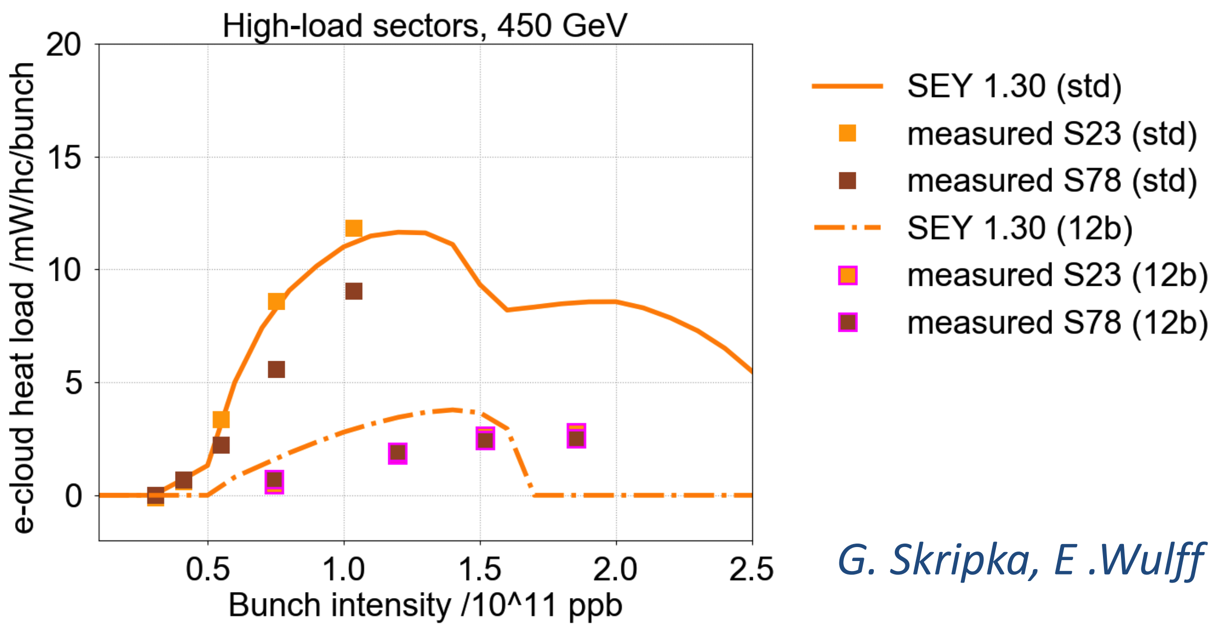
G. Skripka

MD4203 - intensity scan with trains of 12b at 450 GeV

First **comparisons against simulations** (made assuming uniform SEY in the arcs)

- Good agreement especially in sectors with higher load
- Next step it to test more complex model where we assume that "degradation" is concentrated in the dipoles





G. Skripka, E .Wulff

MD4203 - intensity scan with trains of 12b at 450 GeV

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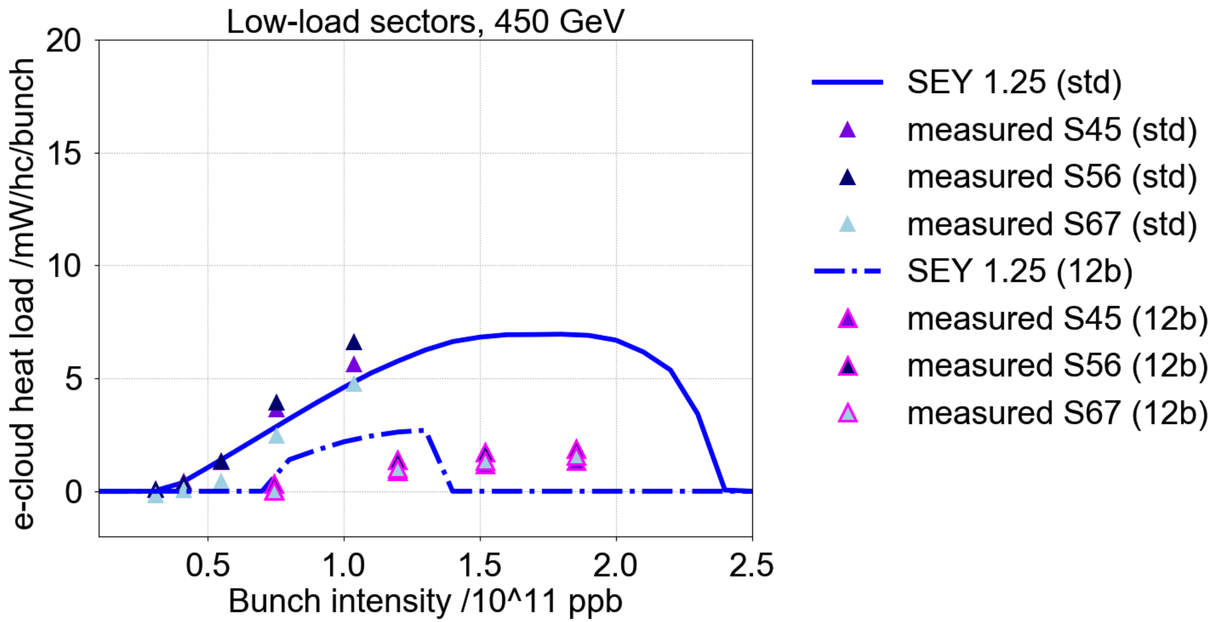
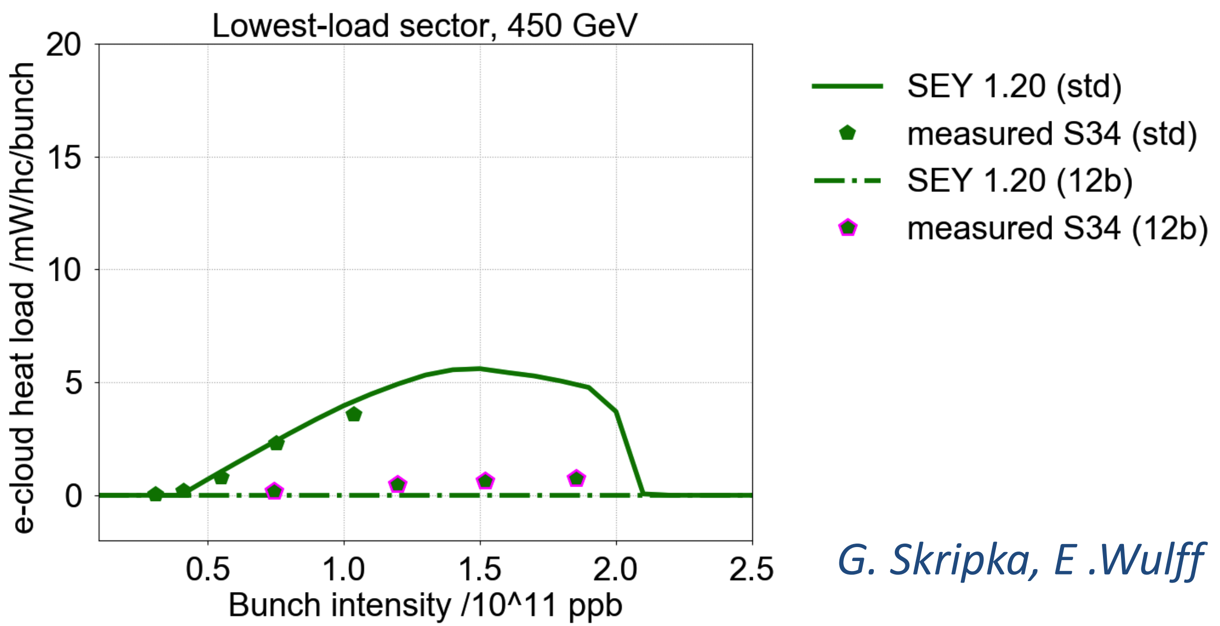




G. Skripka, E .Wulff

Expectations for Run 3

Cooling capacity of the 8 cryoplants was assessed with measurements by TE-CRG

Assumed for Run 3 →

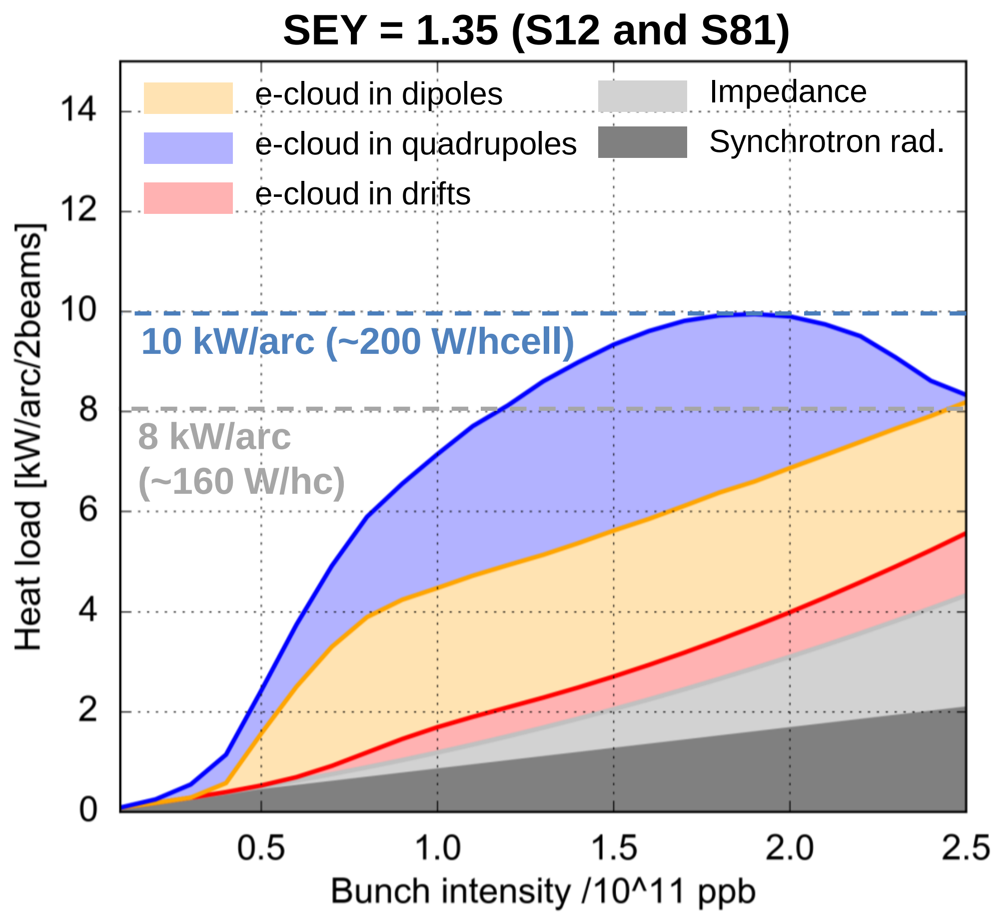
	S1-2	S2-3	S3-4	S4-5	S5-6	S6-7	S7-8	S8-1
Capacity (design conf.) [W/hc]	180	195	125*	160	160	160	175	230
Configuration 2017	200	205	145				195	250

Black – measured value Yellow – default estimated value Grey – estimated value

In the most critical sectors (S12, S23, S81) we can count on a cooling capacity significantly larger than nominal

Assuming that after scrubbing the arc SEY will be the same as in Run 2 (as happened in 2016-18 thermal cycle)

Additional margin in cooling capacity will should allow us to exploit larger than nominal bunch intensity when available from the injectors

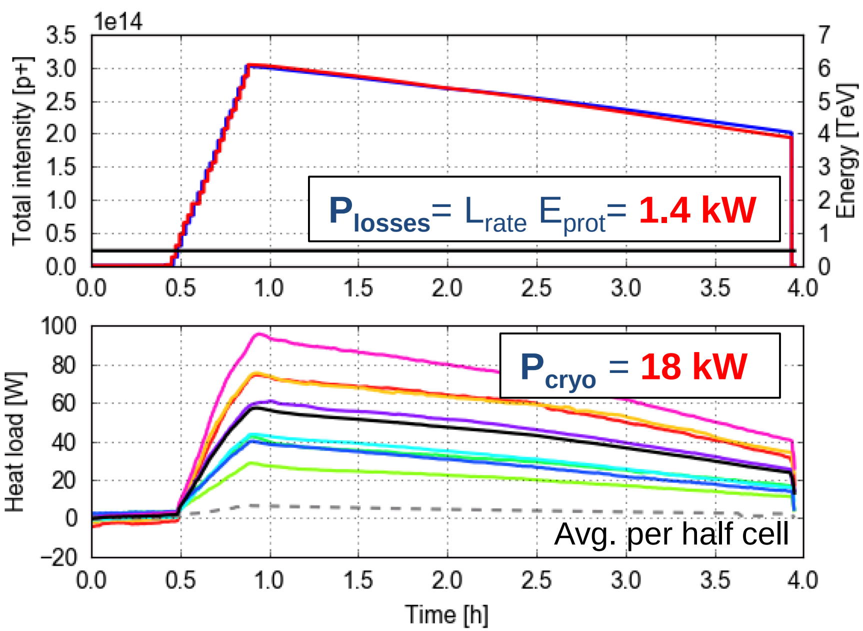


Underlying mechanism

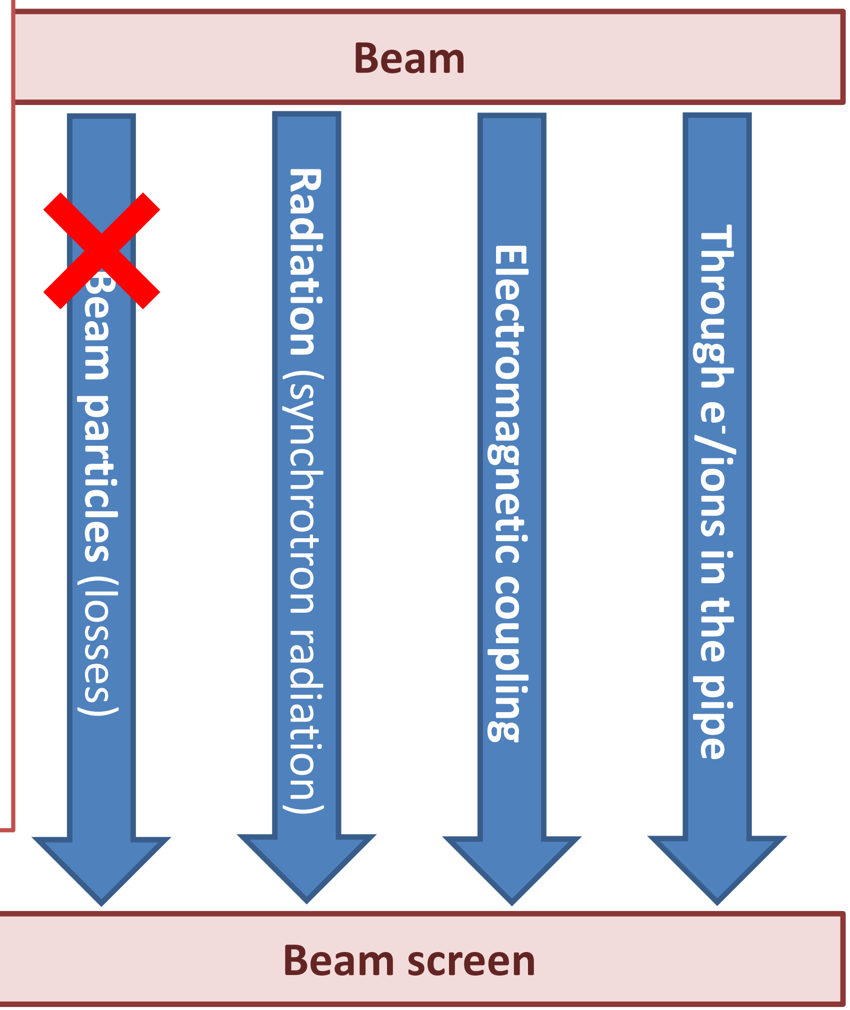
We are looking for a mechanism that **transfers energy from the beam to the beam-screen:**

Beam losses

Power associated to proton losses (including deposition on collimators!) is **less than 10% of the heat load on the arc beam screens**



s that were identified



✗ = Excluded

More info here

We are looking for a mechanism that **transfers energy from the beam to the beam-screen:**

- Here are the possibilities that were identified

Electromagnetic coupling

Bunch intensity — Longitudinal impedance — Normalized beam spectrum

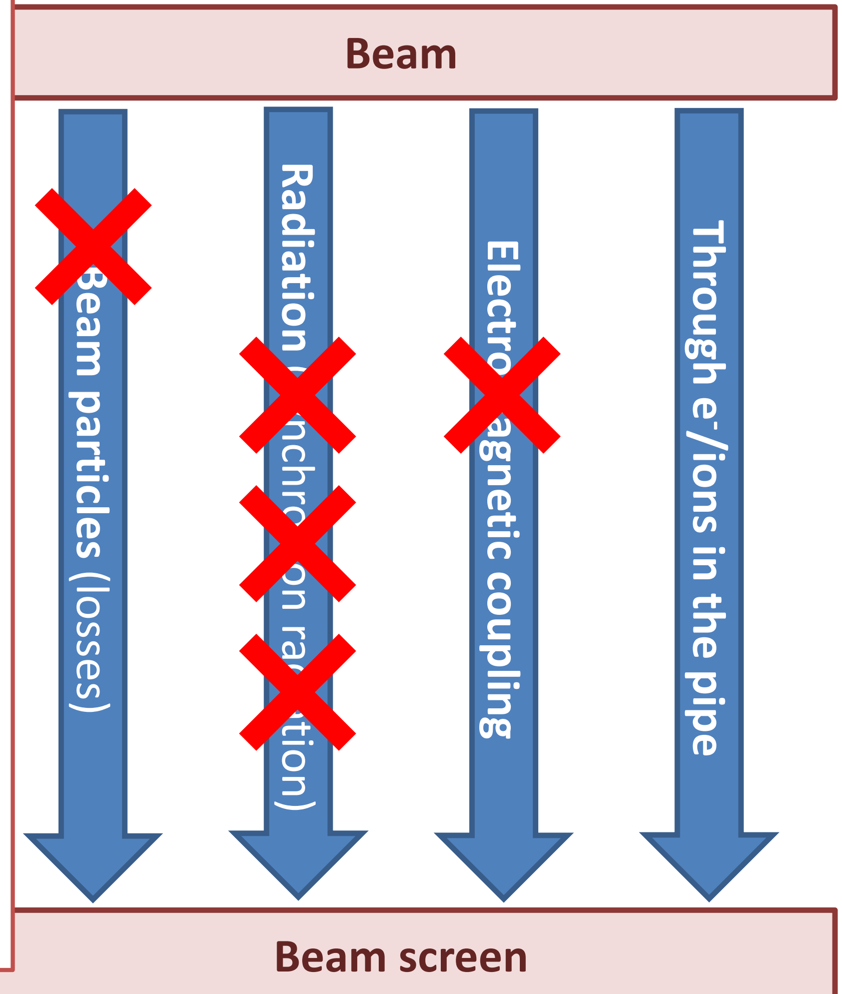
$$P = n_b^2 \sum_{n=0}^{\infty} \mathrm{Re}\left[Z(nf_0)\right] \left|\overline{\Lambda}(nf_0)\right|^2$$

f_0 = revolution frequency

Expected: $$0 \leq \frac{P_{25\mathrm{ns}}}{P_{50\mathrm{ns}}} \leq 4$$

Observed: $$\frac{P_{25\mathrm{ns}}}{P_{50\mathrm{ns}}} \simeq 15$$

More details: F. Giordano and B. Salvant, presentation at Electron Cloud Meeting (link)



More info here

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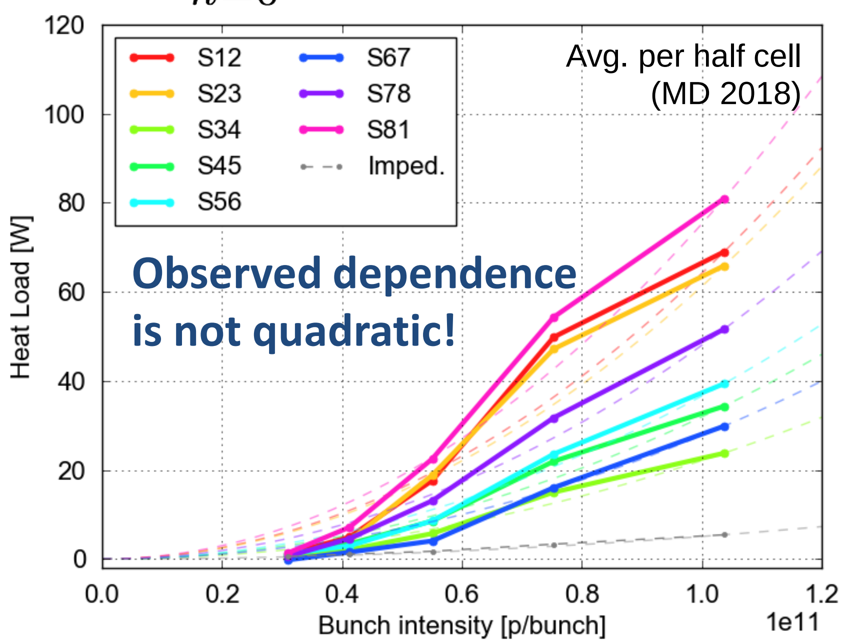
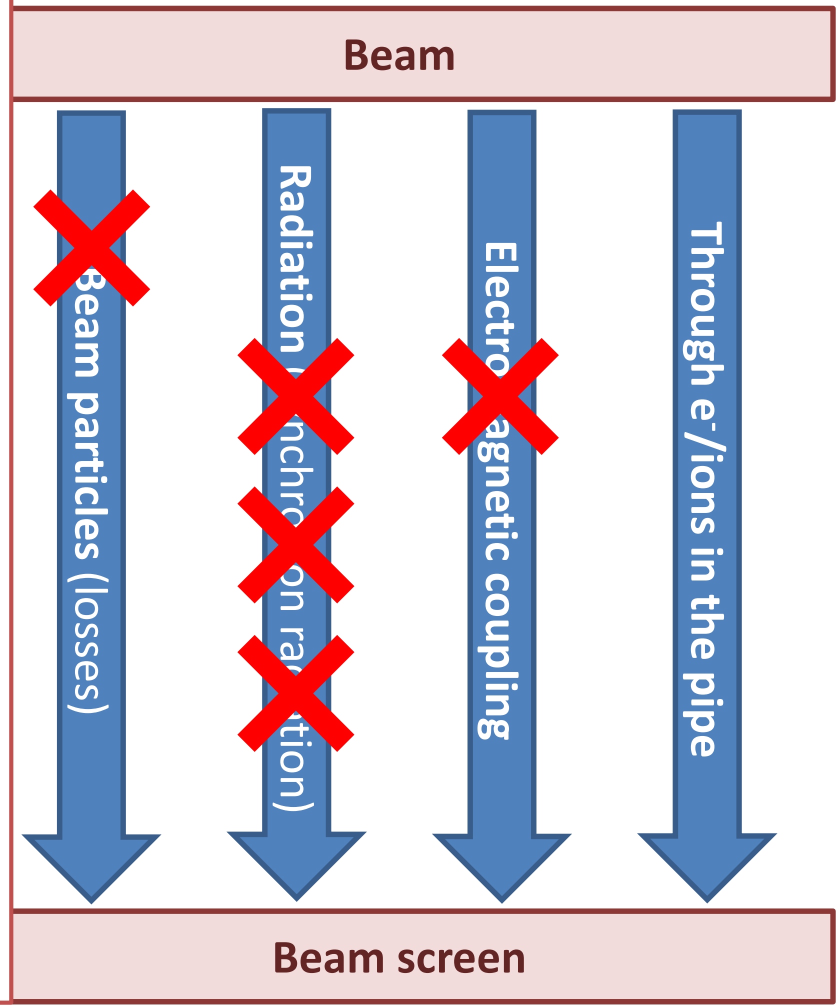




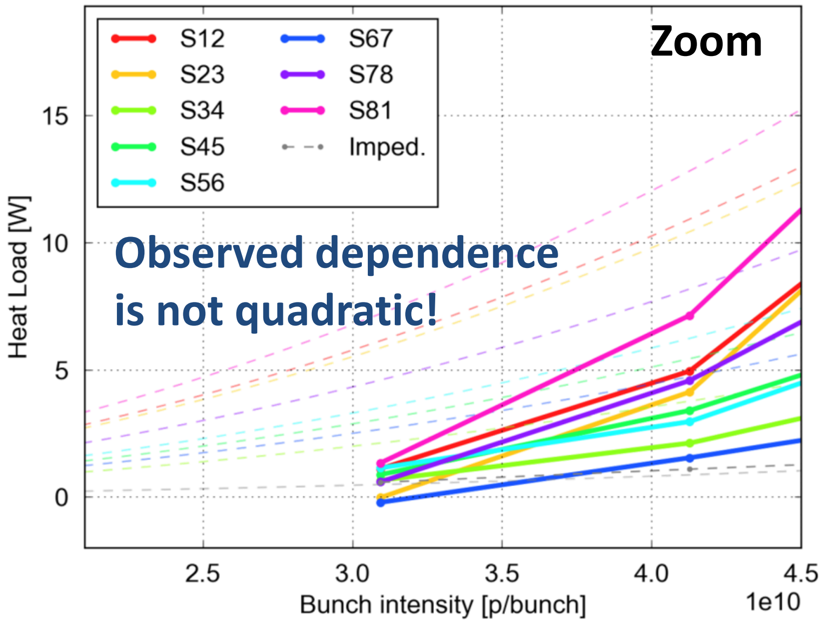
We are looking for a mechanism that **transfers energy from the beam to the beam-screen:**

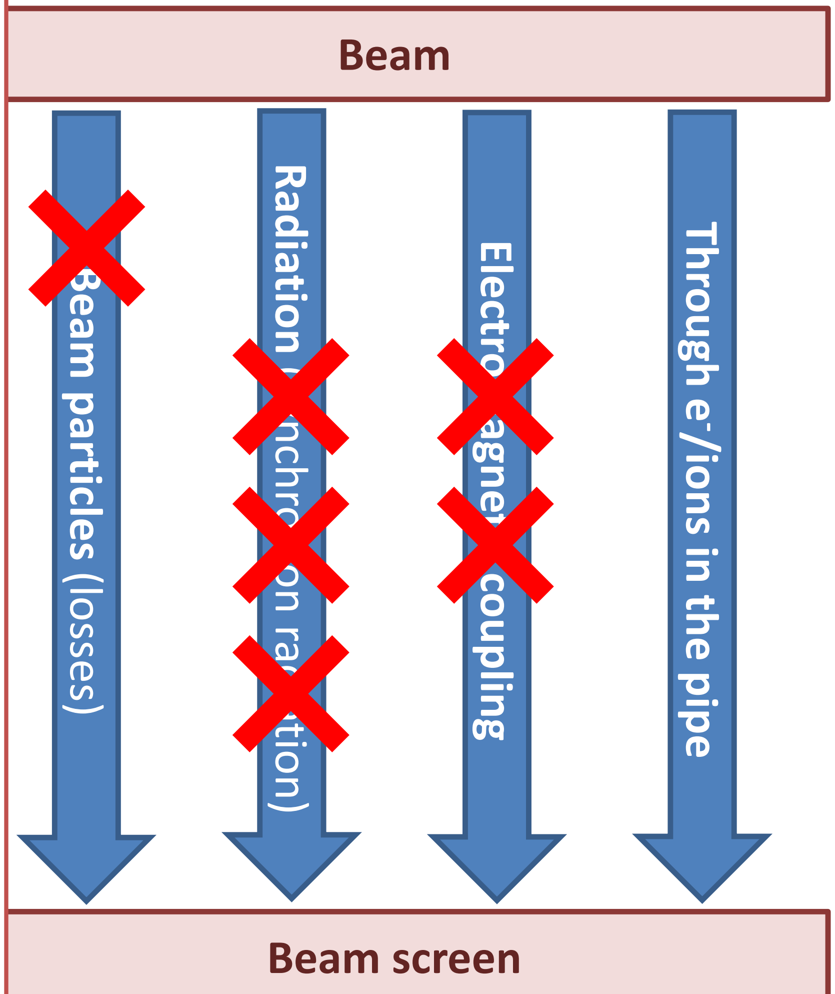
- Here are the possibilities that were identified

Electromagnetic coupling

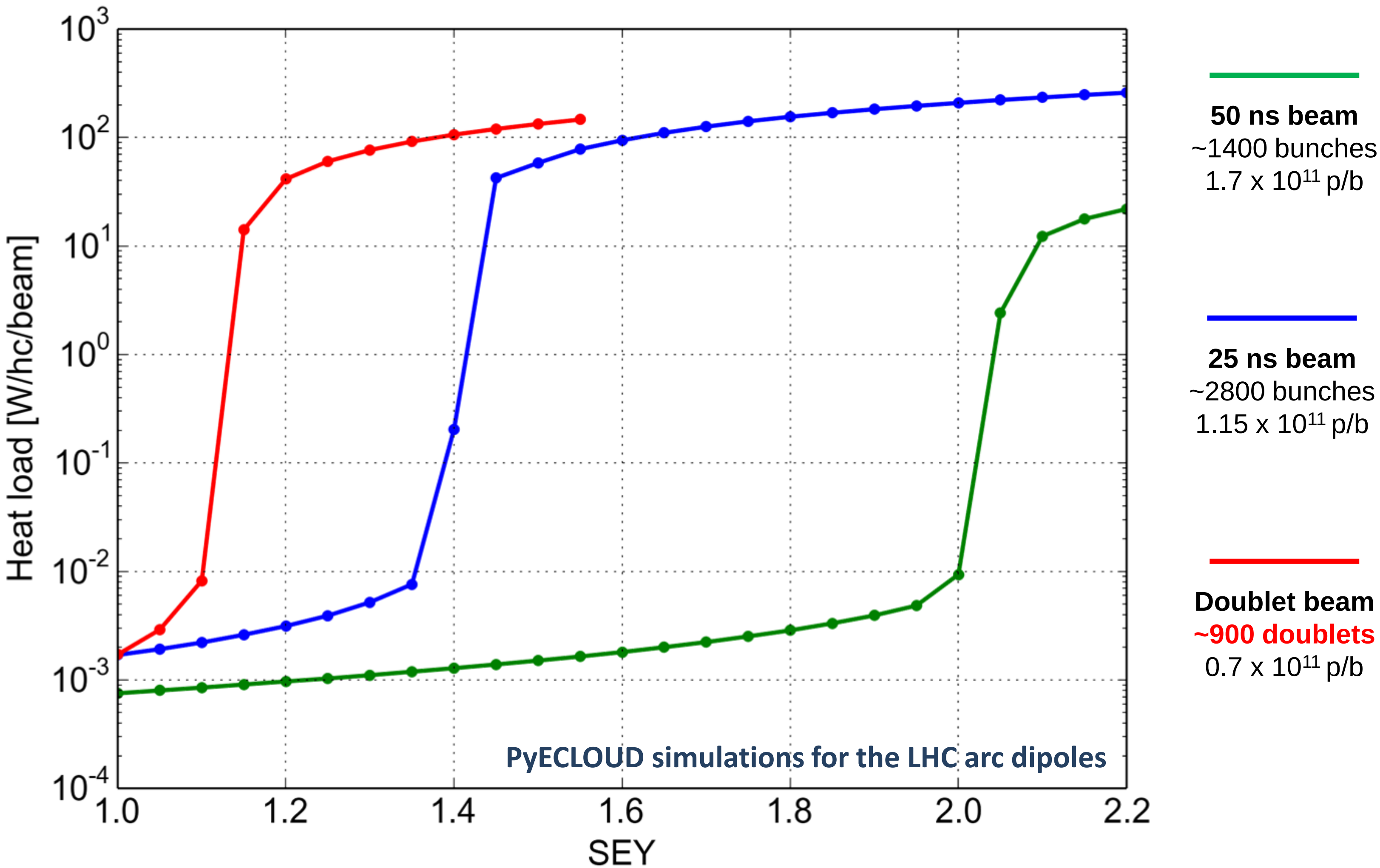
Bunch intensity — Longitudinal impedance — Normalized beam spectrum

$$P = n_b^2 \sum_{n=0}^{\infty} \mathrm{Re}\left[Z(nf_0)\right] \left|\overline{\Lambda}(nf_0)\right|^2$$





More info here


10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
Heat load [W/hc/beam]
1.0
1.2
1.4
1.6
1.8
2.0
2.2
SEY
PyECLOUD simulations for the LHC arc dipoles
50 ns beam
~1400 bunches
1.7 x 10^11 p/b
25 ns beam
~2800 bunches
1.15 x 10^11 p/b
Doublet beam
~900 doublets
0.7 x 10^11 p/b