Update on the LHC heat-load and projection for HL-LHC

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and the e-cloud Working Group

8th HL-LHC Collaboration Meeting, CERN, 15-18 Oct 2018

Outline

Introduction

- Heat load observations
- Comparison against Run 1

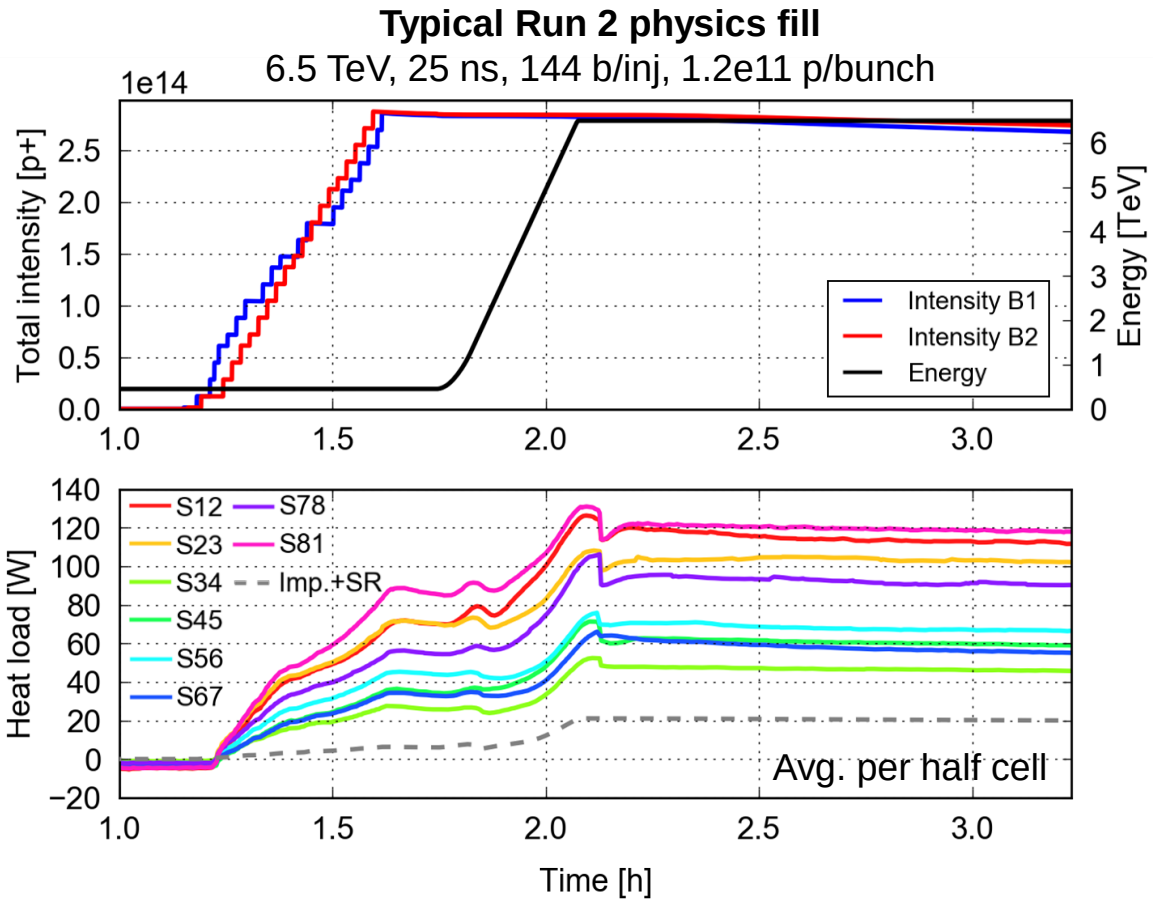
Analysis and comparison against models

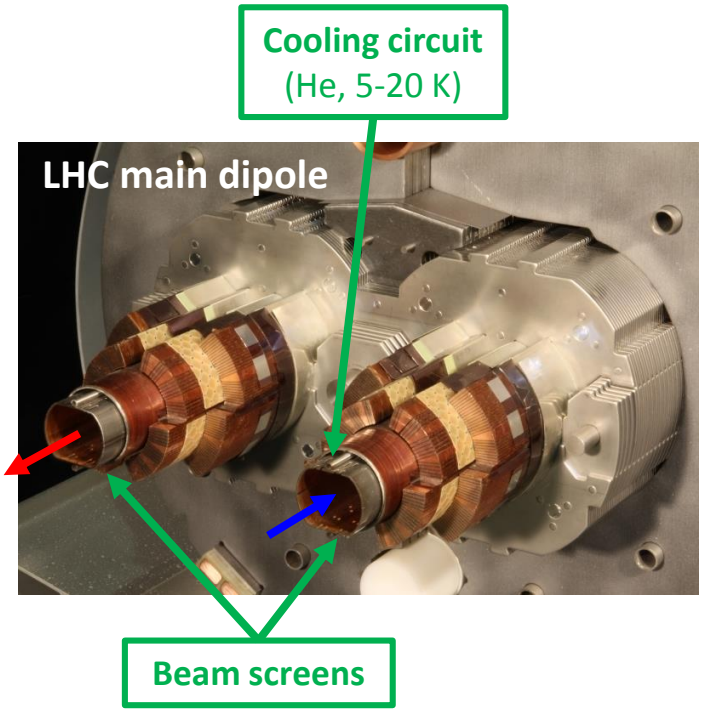
- Is it a measurement artefact?
- Underlying mechanism
- Comparison against e-cloud simulations

Projections for HL-LHC

- Expected heat loads for larger bunch intensity
- Scaling comparison against experimental data
- 8b+4e backup scenario

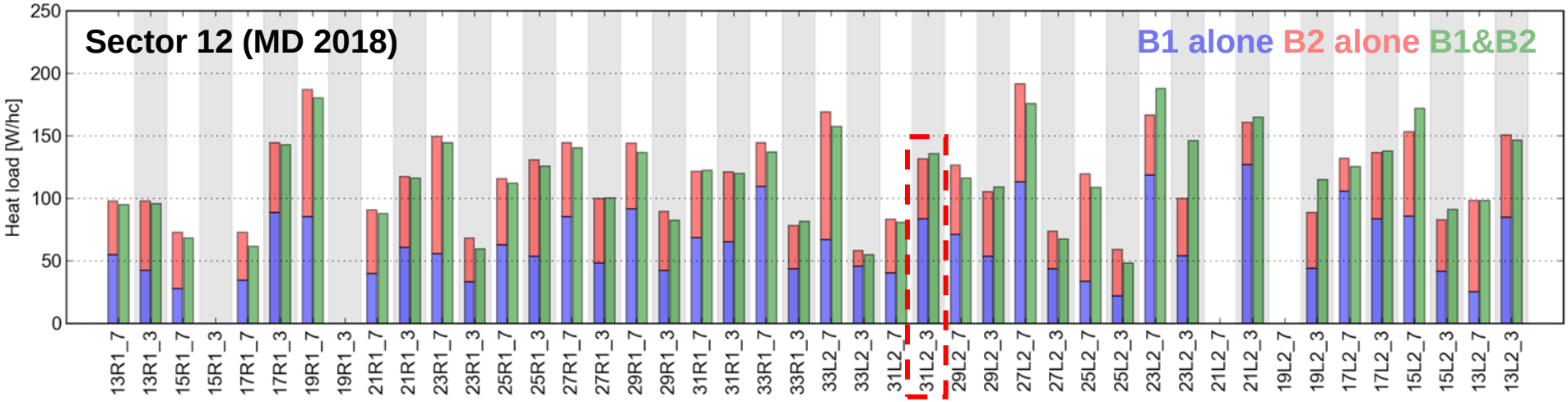
- In Run 2 **large beam-induced heat loads** (>100 W/hcell) are observed on **the beam screens** of the **LHC arcs** → Much larger than impedance and synchrotron radiation
- Very **large differences among the eight** arcs (up to a factor of 3), not at all expected!





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**



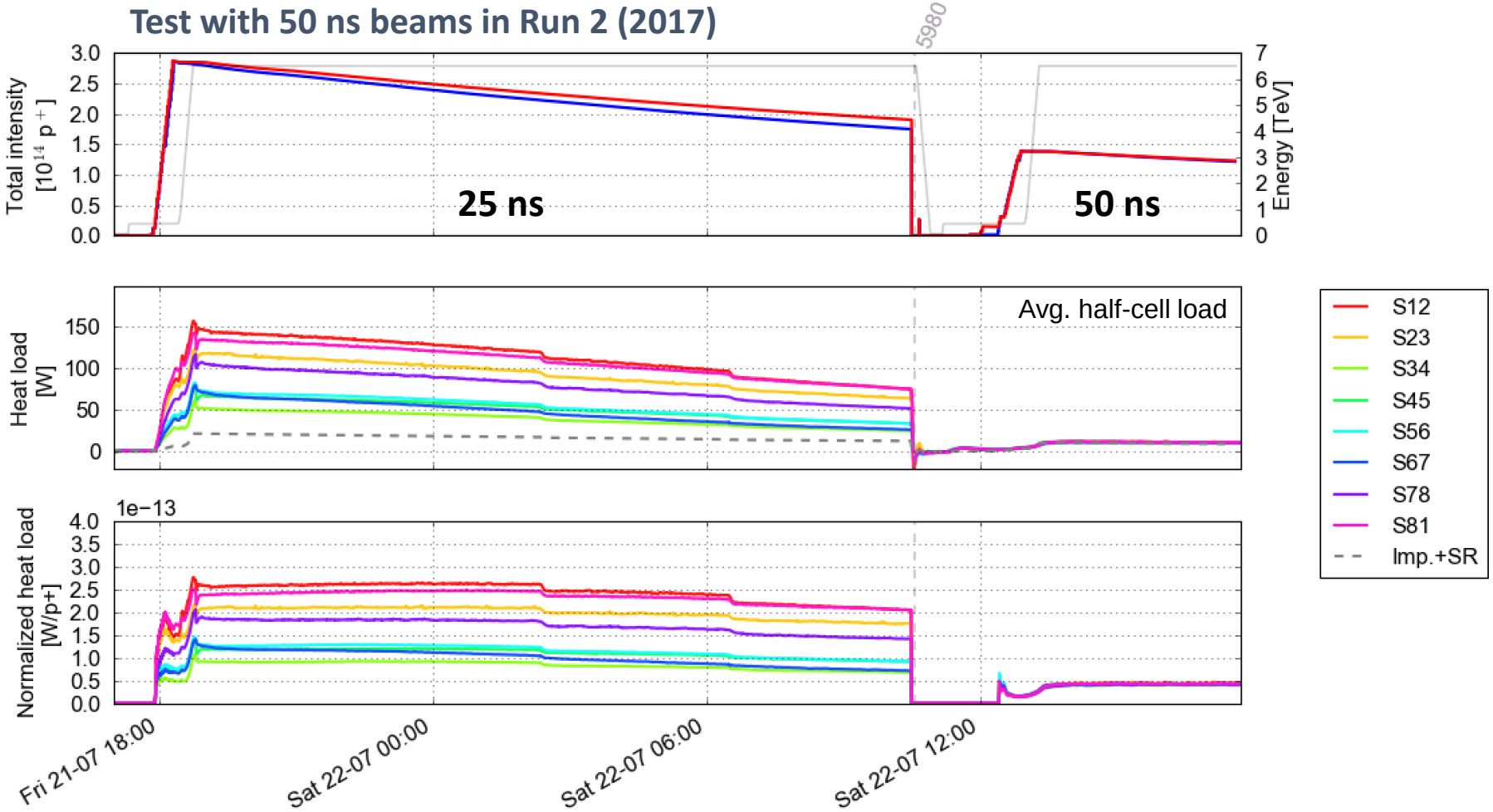
Cell 31L2 (equipped with extra thermometers)

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

Dependence on the bunch spacing

Heat loads show a very strong dependence on the **bunch spacing**:

→ Particularly evident when comparing **50 ns** and **25 ns** beams

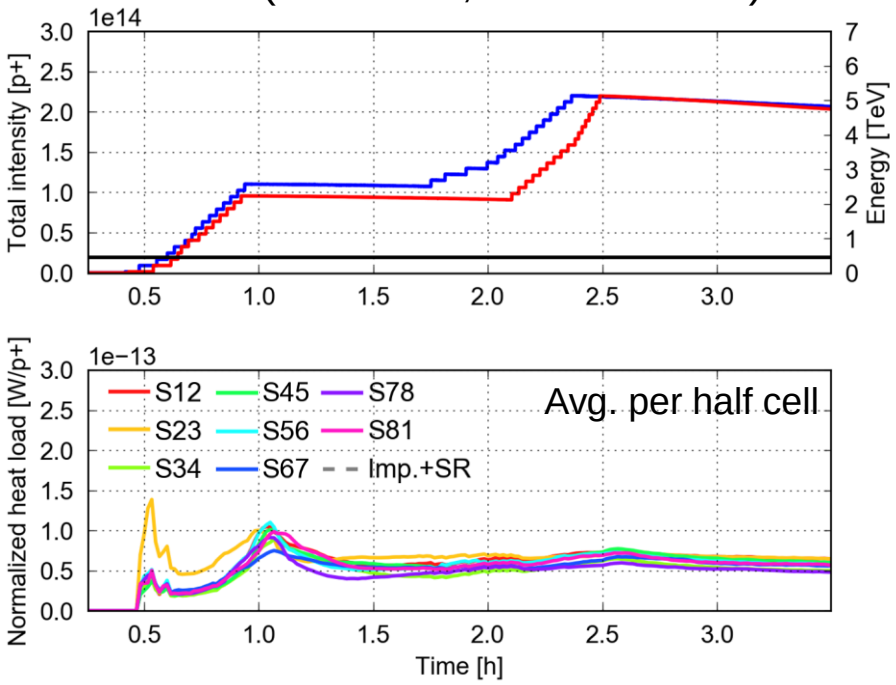


Comparison 2012 vs 2018

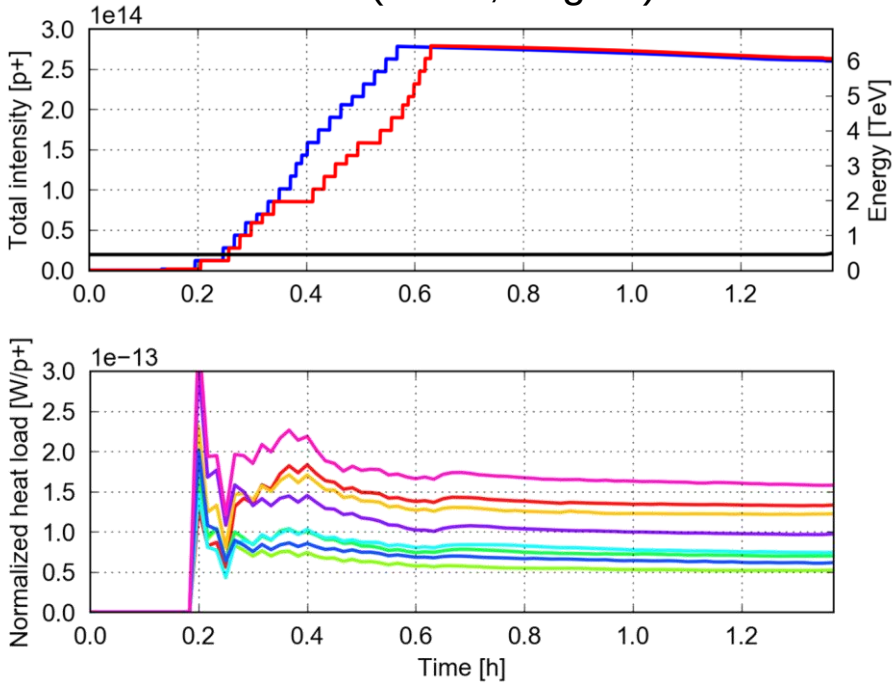
- **No differences** among sectors were present **in 2012** (before the 2013-14 long shutdown, LS1)
- In 2012 heat loads were **comparable to present low-load sectors**

  → The situation has globally degraded from Run 1 to Run2

2012 (25 ns test, end of the run)



2018 (25 ns, August)



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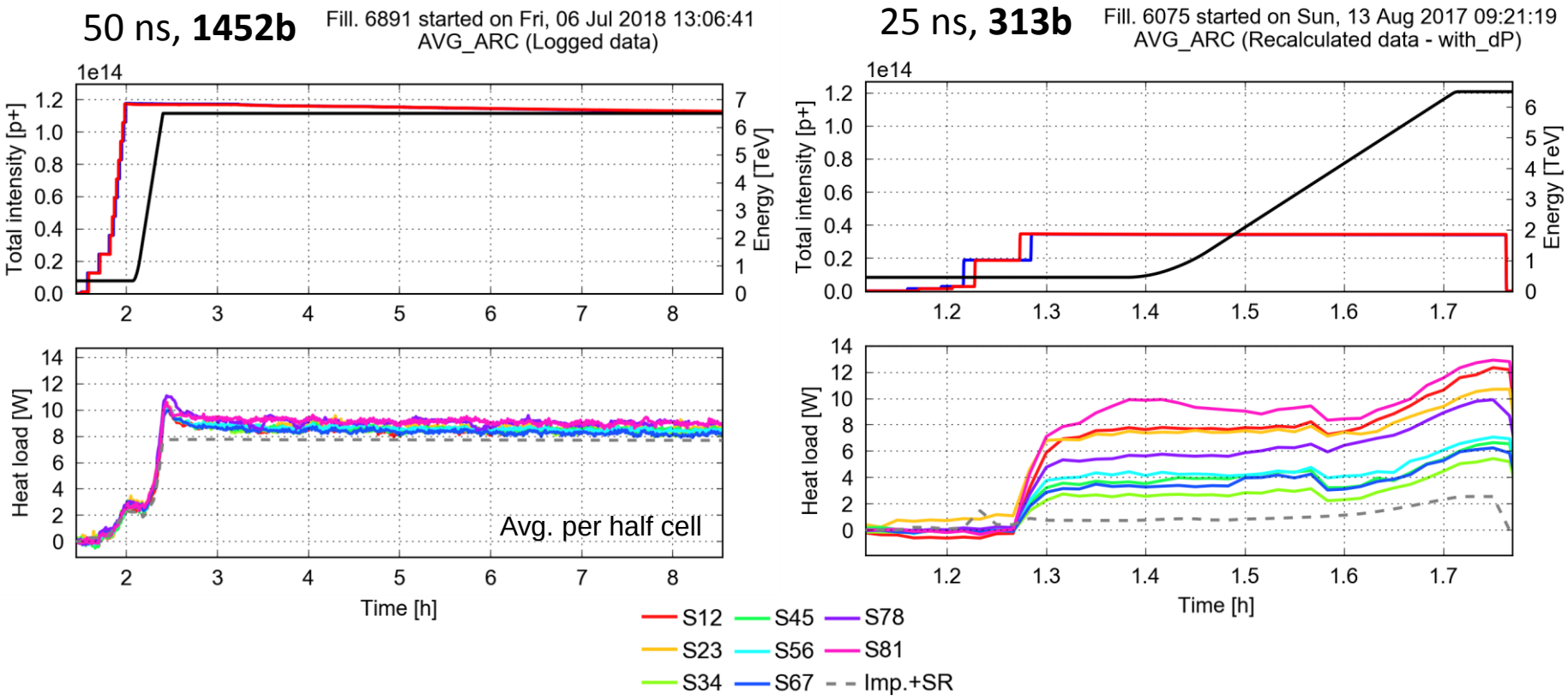
Is it a measurement artefact?

- With **50 ns** all sectors agree very well with impedance and synchrotron radiation estimates → **The measurement is well calibrated**
- Differences among sectors are observed with **25 ns** even with very small number of bunches

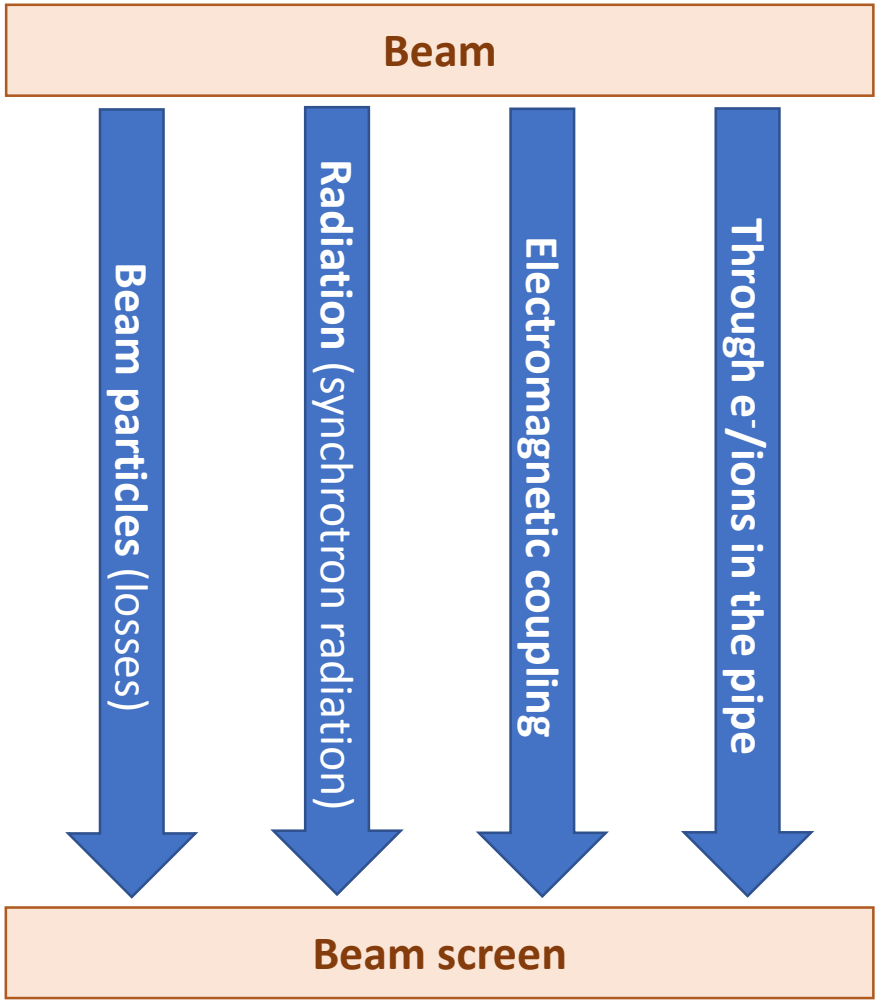
→ **Impossible to explain as a measurement artefact** (the measurement system "does not know" about the bunch spacing…)



Underlying mechanism

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

- Here are the possibilities that were identified



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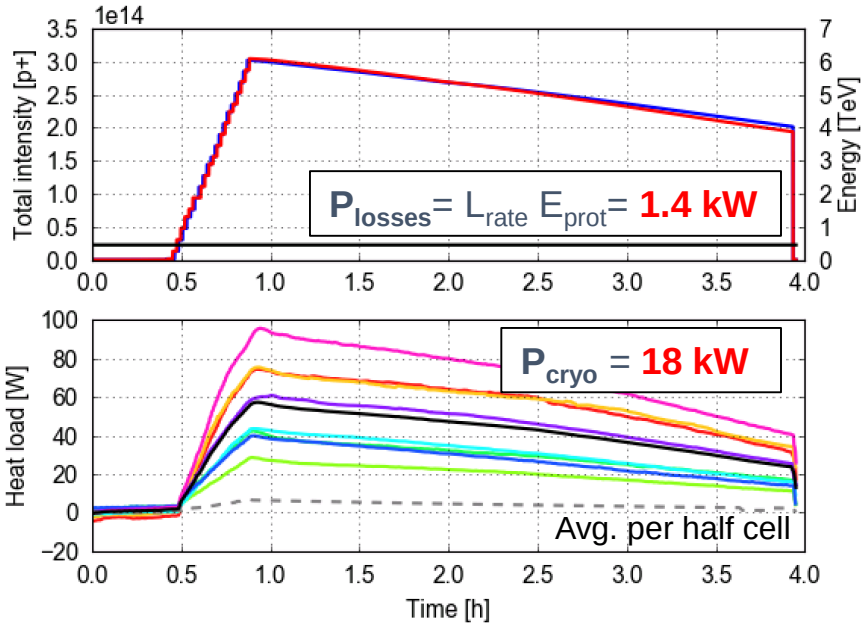
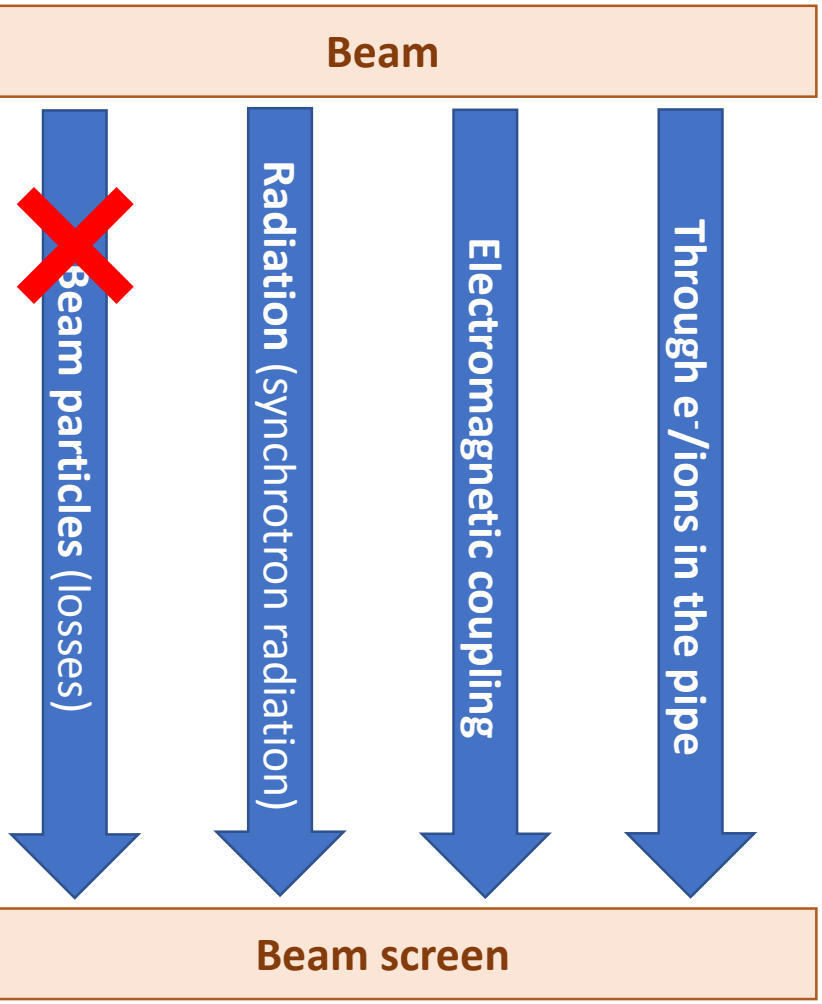
Beam losses

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





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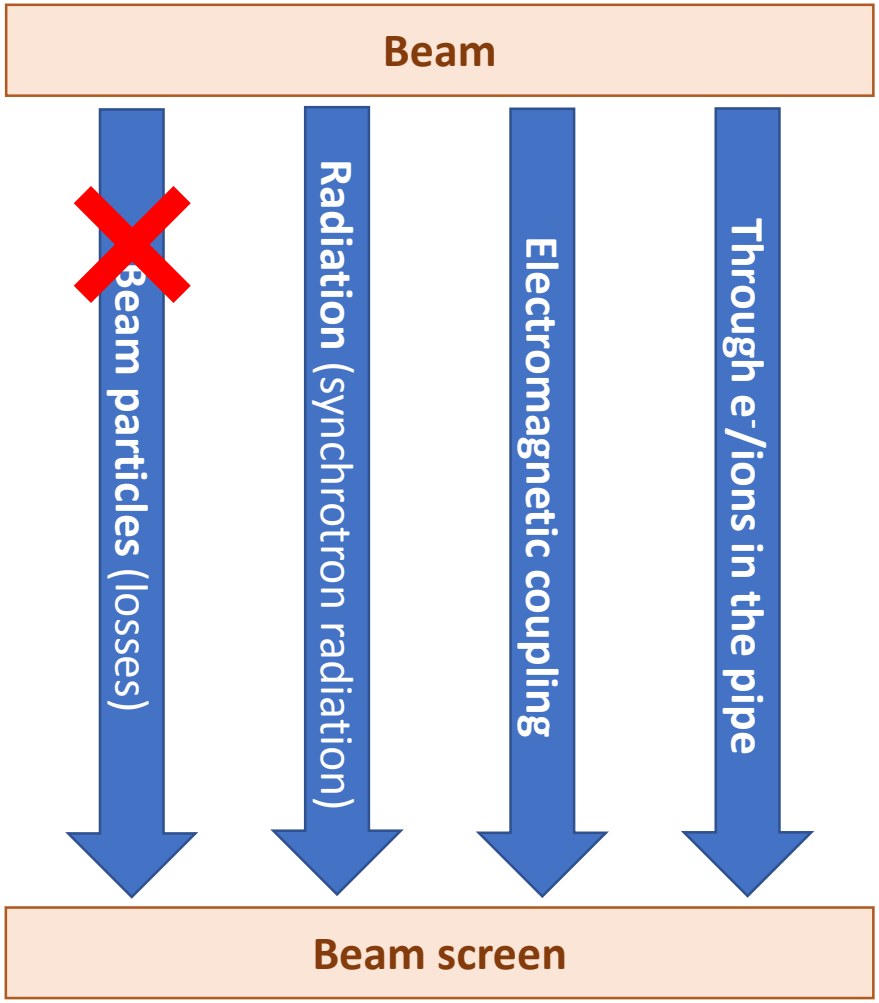
Compatible with **measured intensity loss**



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Synchrotron radiation

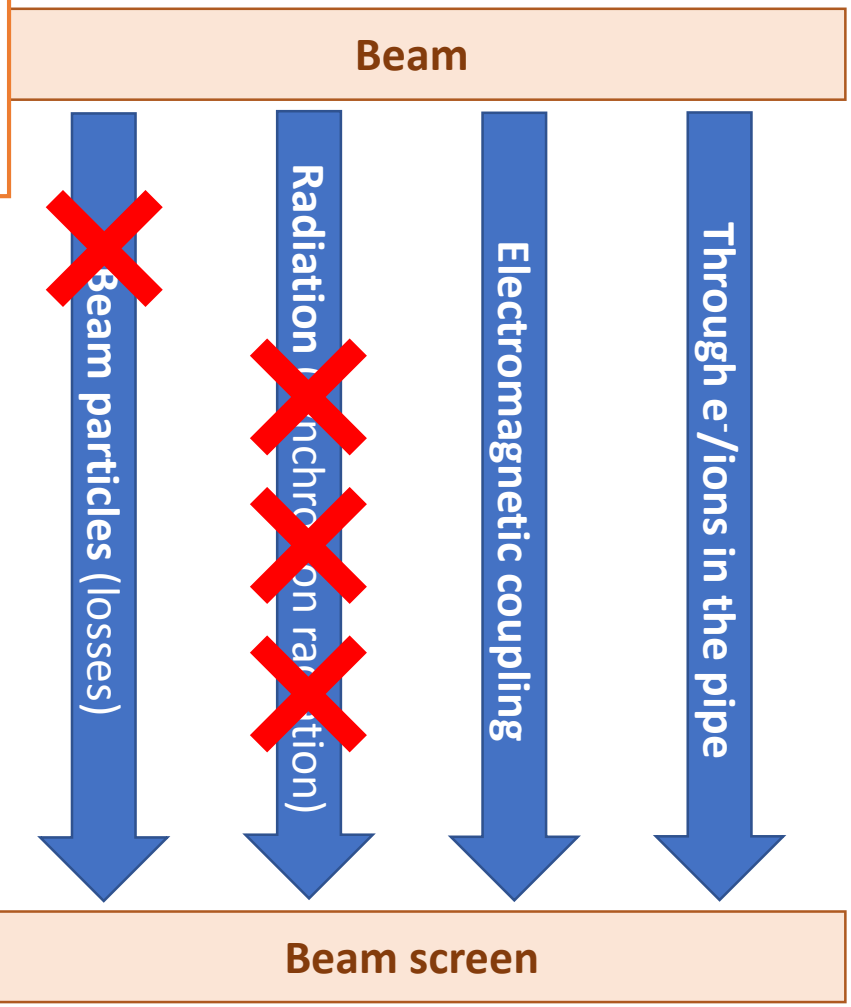
- Scales linearly with the total intensity independently on the bunch pattern
- Scales like E^4

Compatible with **measured intensity loss**

Compatible with **measured dependence on bunch spacing**

Compatible with **measured dependence on bunch intensity**

Compatible with **measured dependence on beam energy**



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Underlying mechanism

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

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Electromagnetic coupling

Bunch intensity — Longitudinal impedance — Normalized beam spectrum

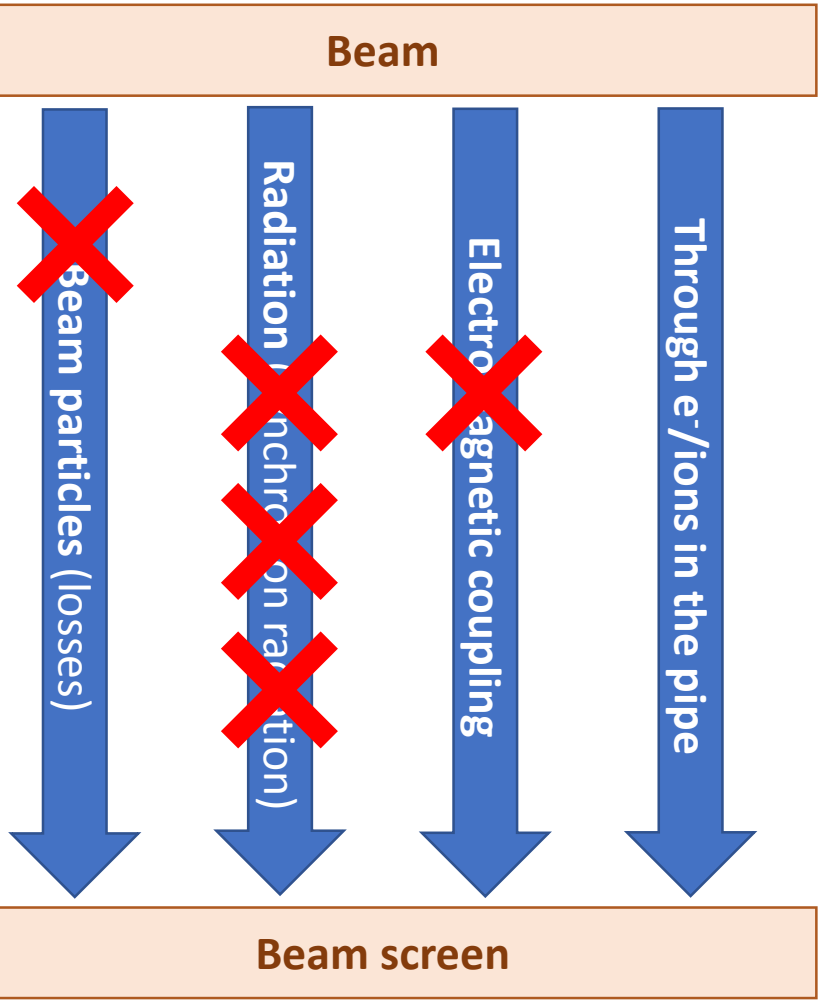
$$P = n_b^2 \sum_{n=0}^{\infty} \mathrm{Re}\left[Z(nf_0)\right] \left|\overline{\Lambda}\left(nf_0\right)\right|^2$$

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)



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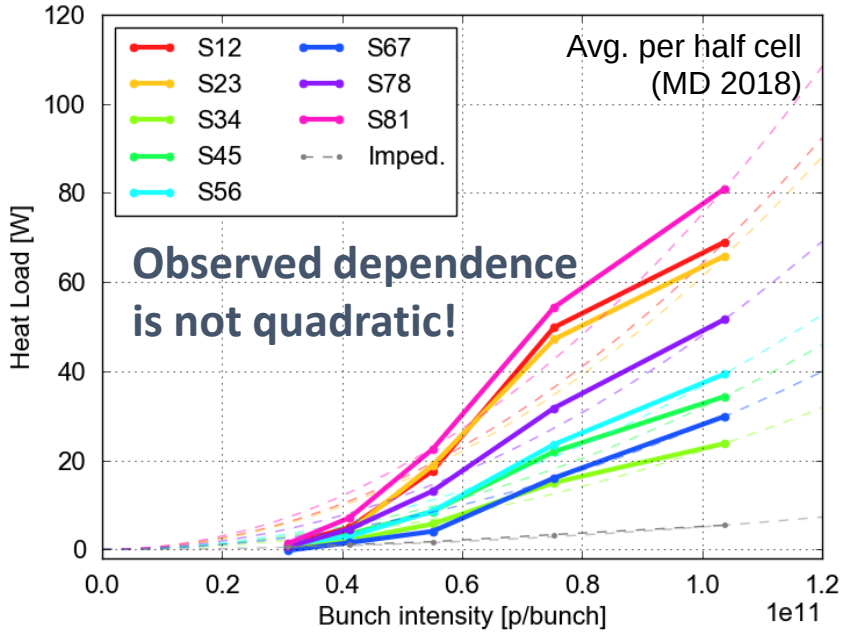

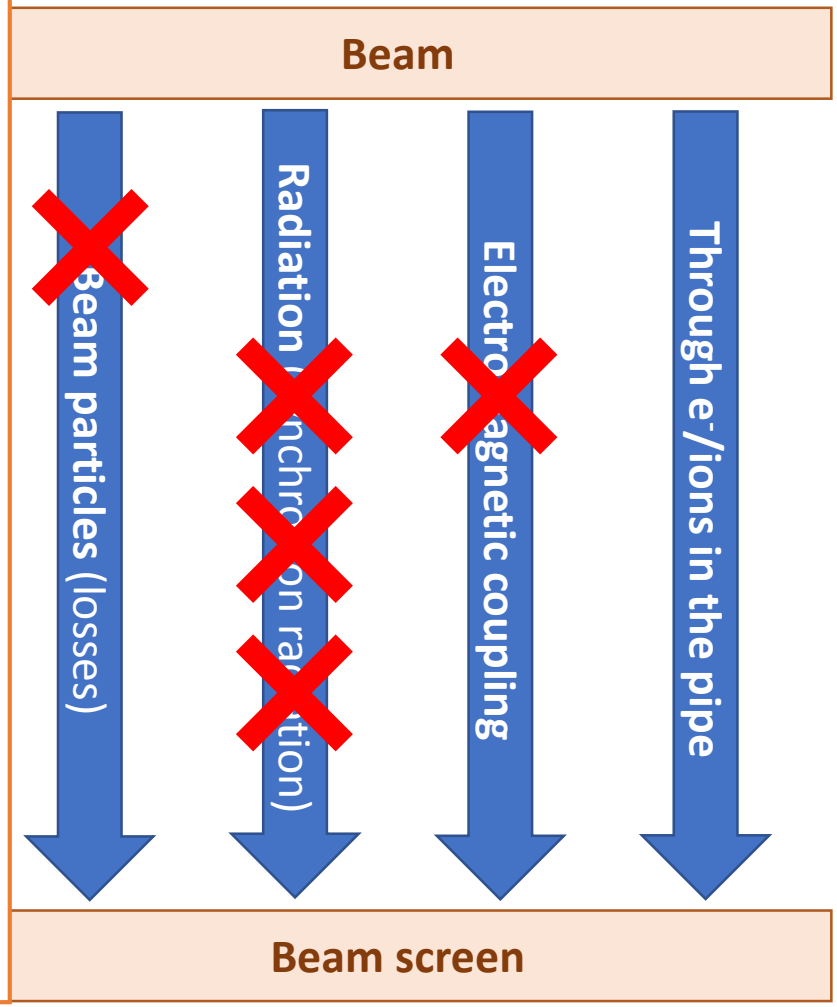

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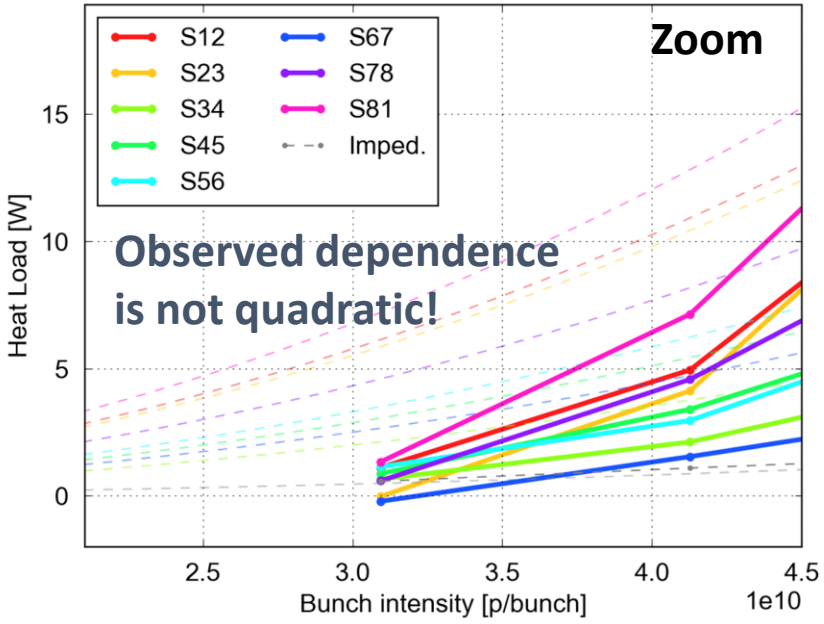

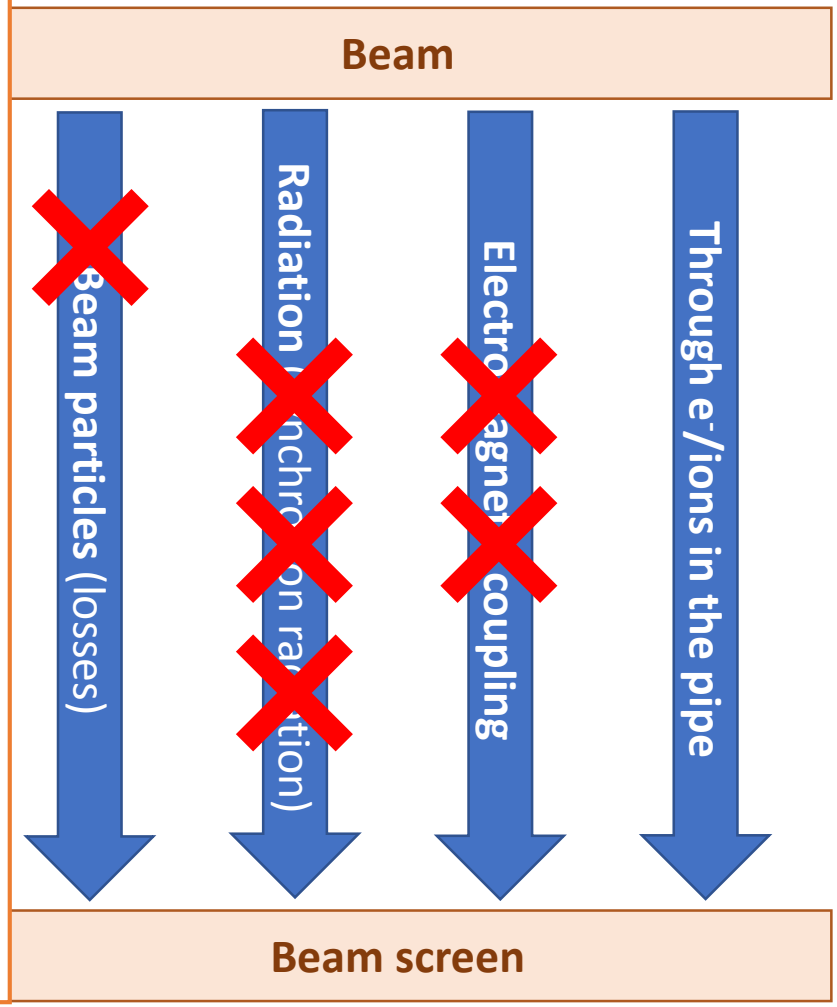

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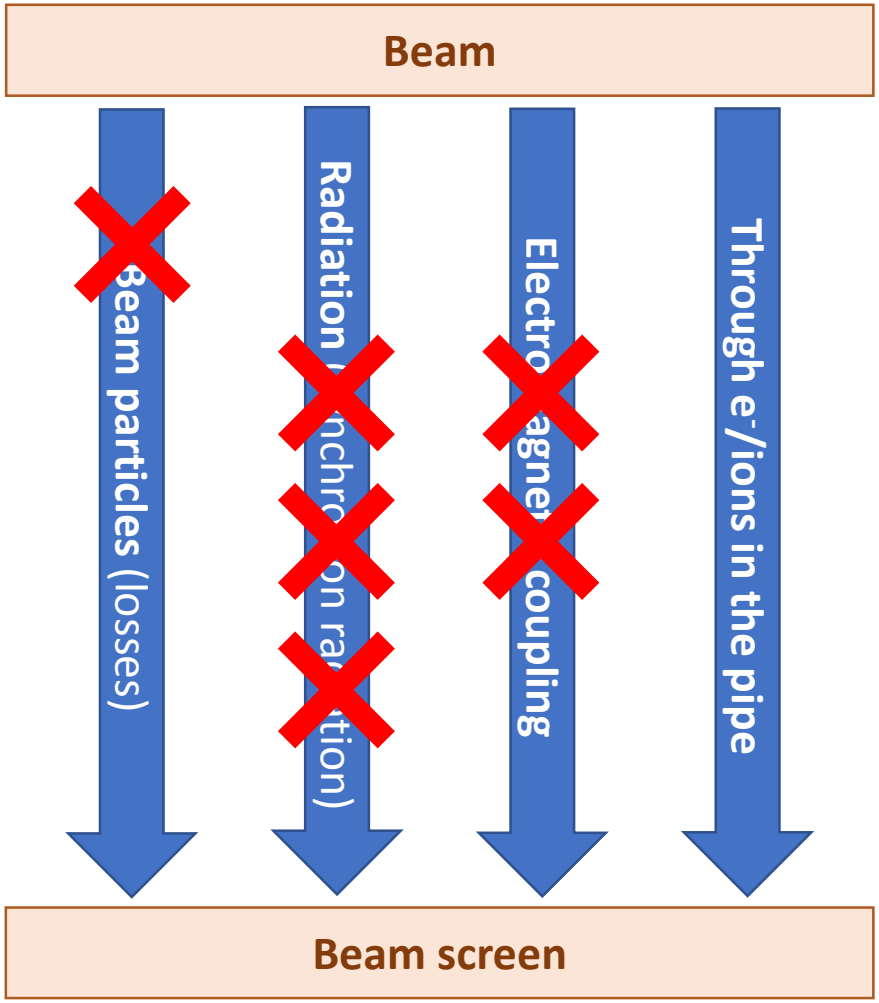
Compatible with **measured intensity loss**

Compatible with **measured dependence on bunch spacing**

Compatible with **measured dependence on bunch intensity**

Compatible with **measured dependence on beam energy**



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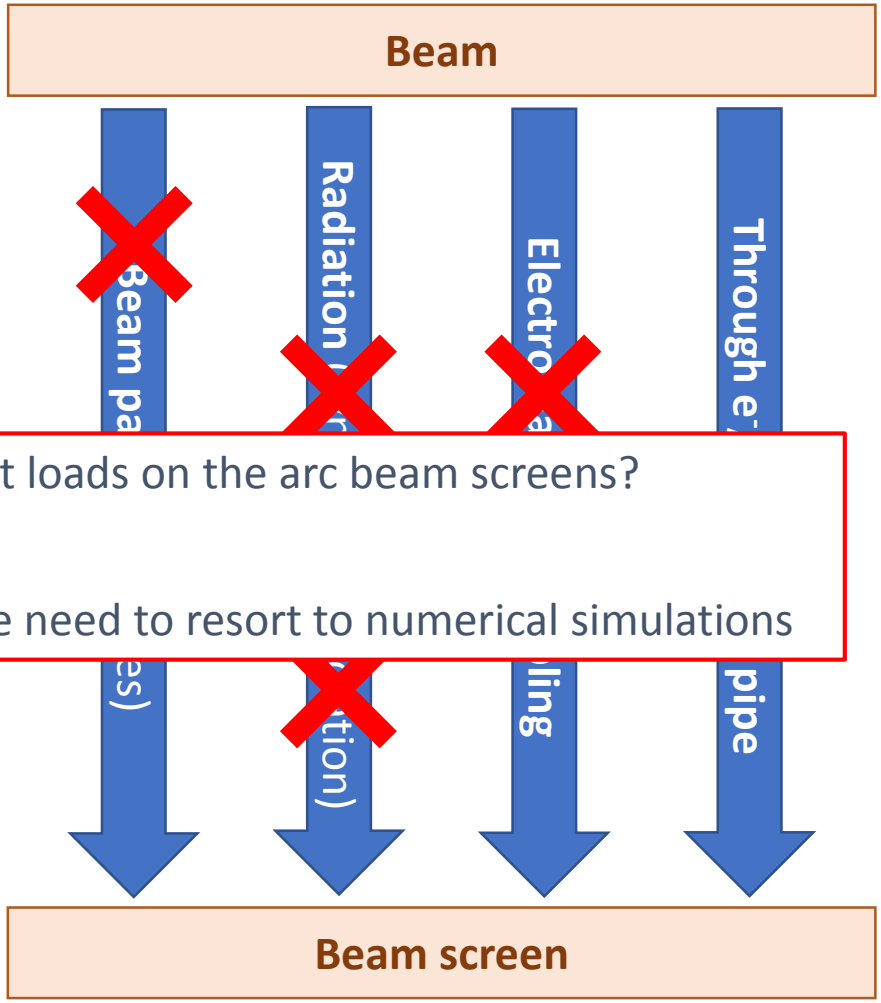

Can **e-cloud** be the **source** of the heat loads on the arc beam screens?

→ Qualitatively yes

→ For quantitative estimates we need to resort to numerical simulations

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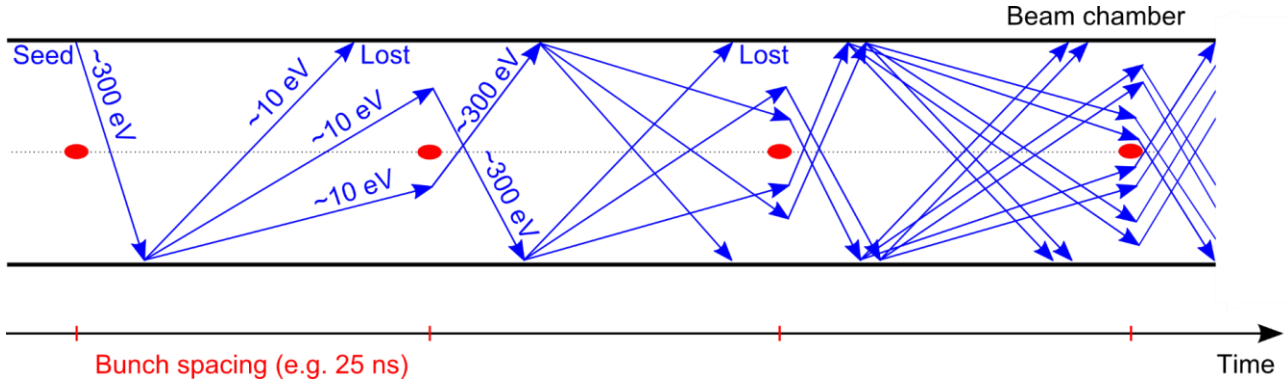
More info here

Modeling of e-cloud effects



Surface properties have a primary role in the e-cloud formation

The main quantity involved is **Secondary Electron Yield (SEY).**

Ratio between emitted and impacting electron current

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

In the following we use the **Secondary Emission Model** for the LHC beam-screen, developed at the time of the LHC design based on **laboratory measurements** (see for example in [1])

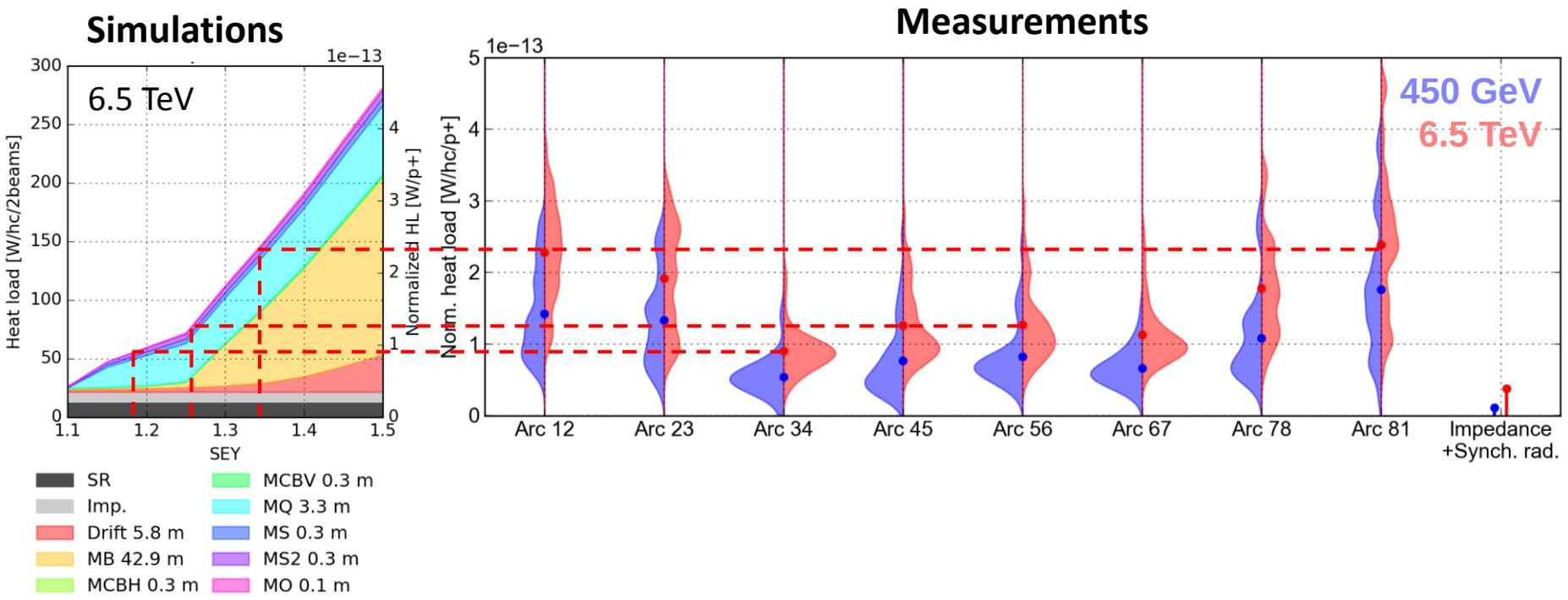
[1] R. Cimino, I. R. Collins, et al. , Phys. Rev. Lett. 93, 014801

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



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

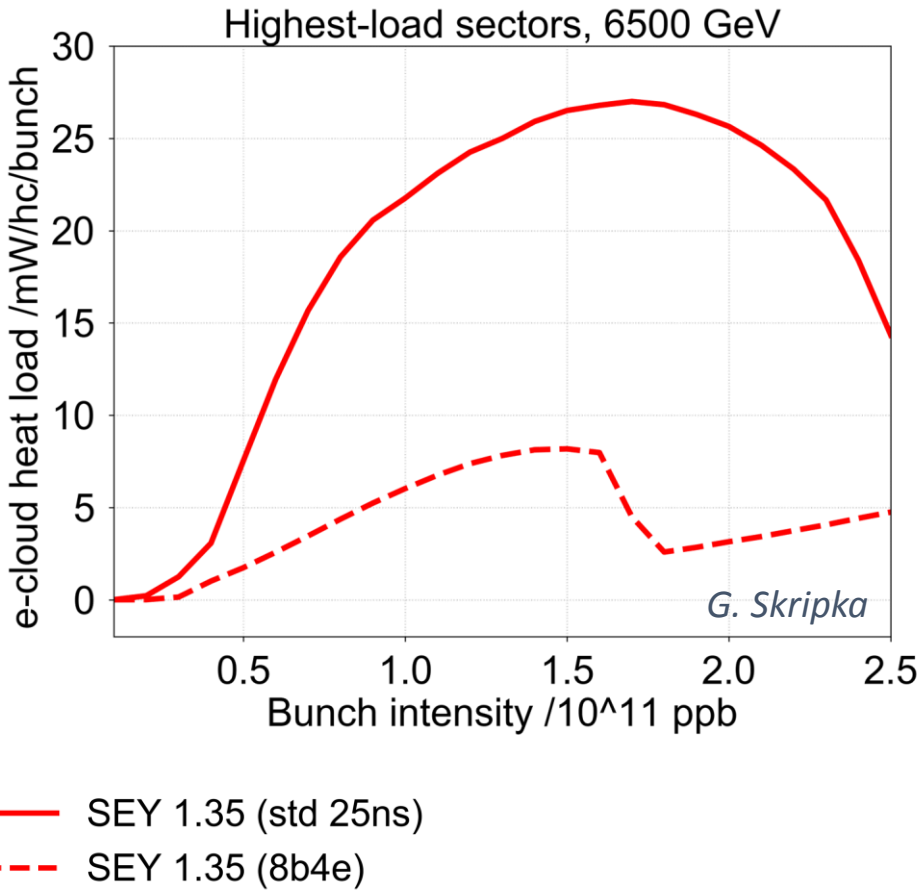
Independent crosschecks

Estimated with:
25 ns, 6.5 TeV, 1.1e11 p/bun

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

The inferred values could be **validated** using **independent machine observations**:

1. 50 ns spacing
2. 8b+4e pattern
3. Data at injection energy
4. Different bunch intensity



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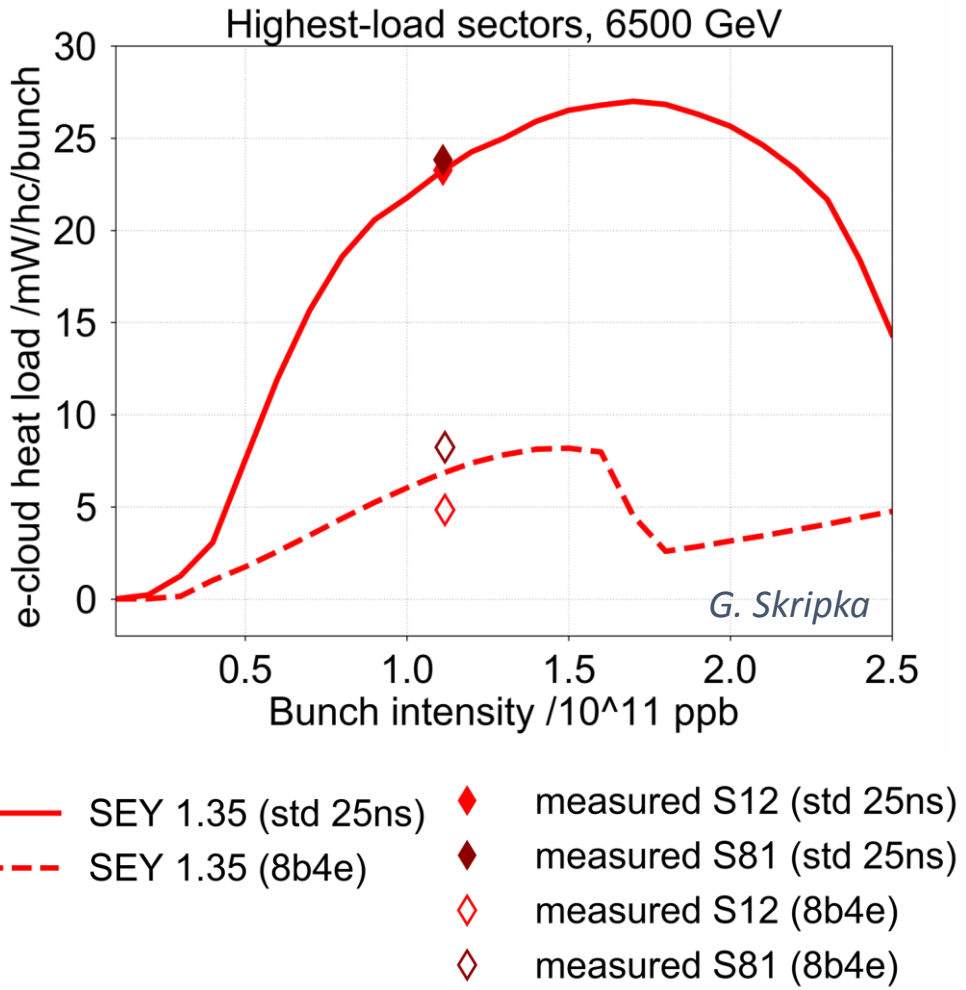

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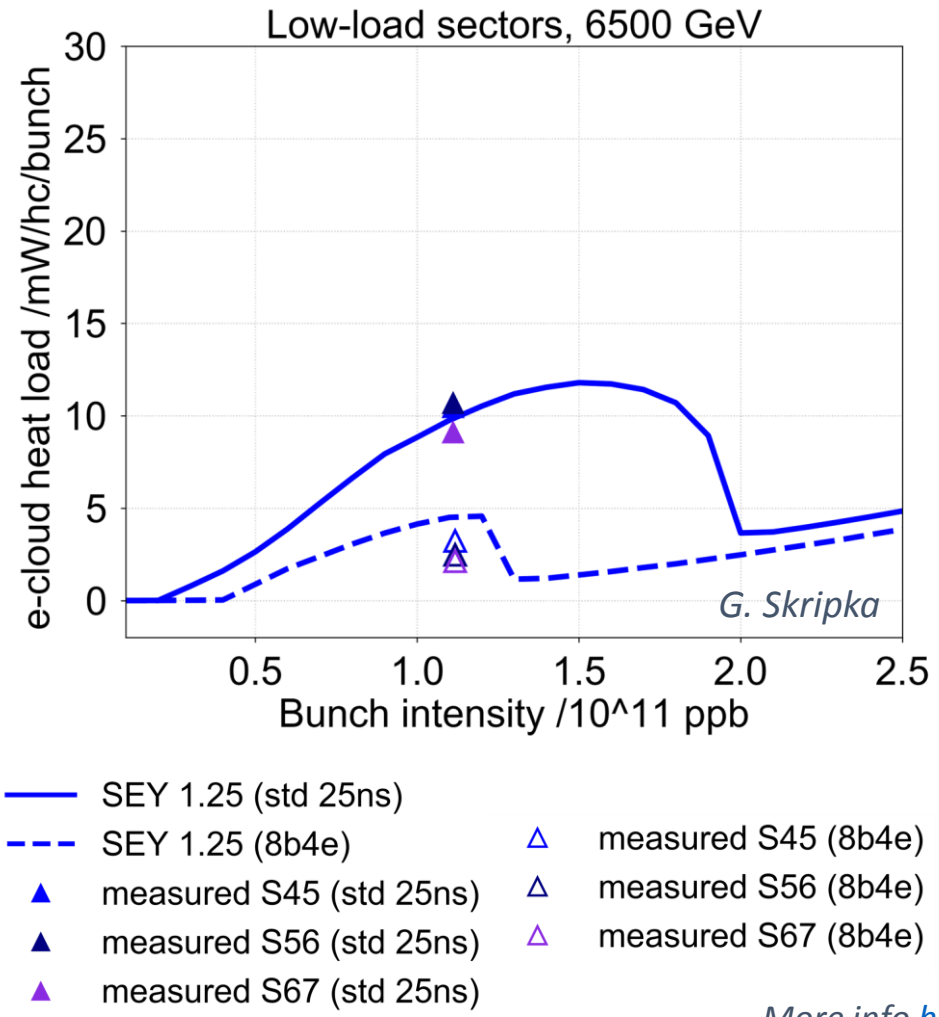

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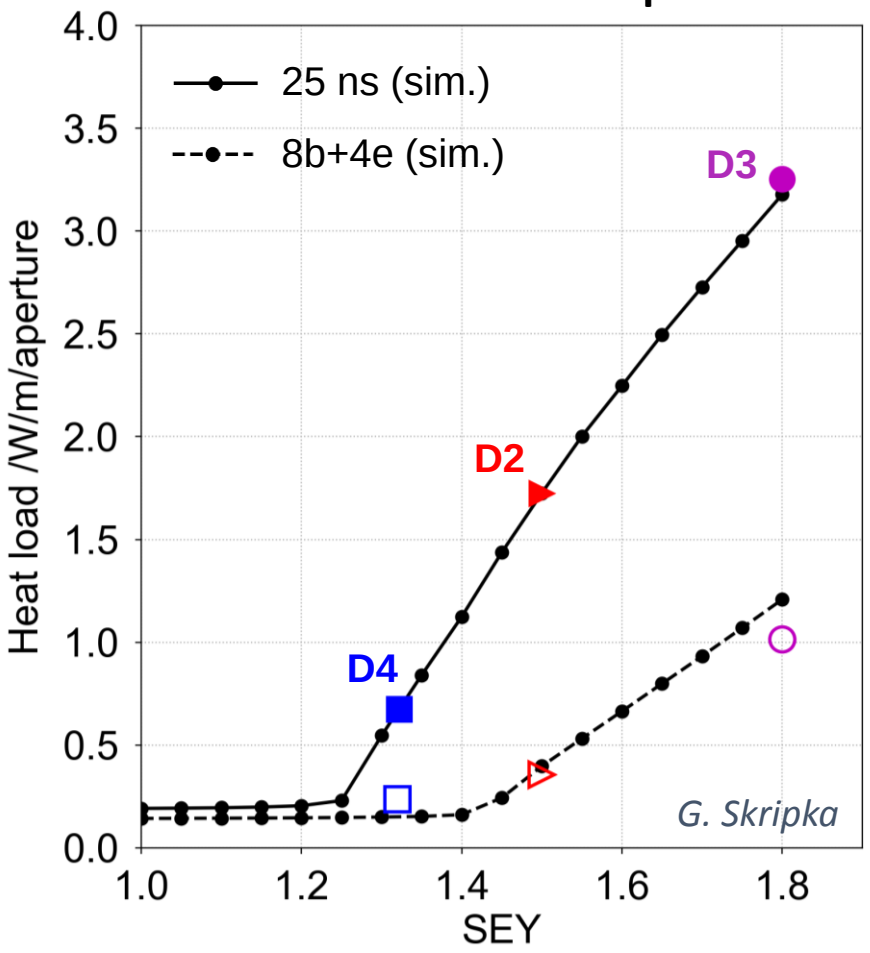
Instrumented arc dipoles



More info here

Underlying mechanism

- **e-cloud** is the only heating channel that is **not excluded**
- Is in **quantitative agreement** with different **independent observations** assuming **different SEY for the different arcs**

→ The cause of these surface differences is under investigation by the Task Force

Compatible with **measured intensity loss**

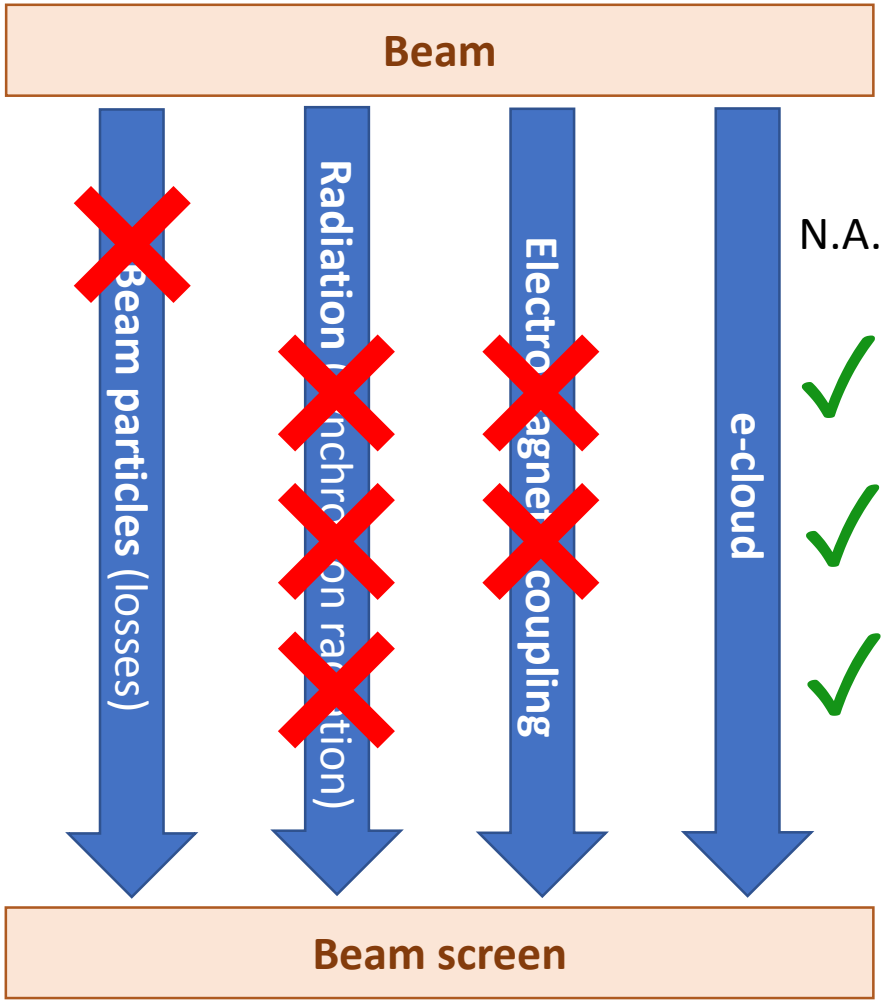
Compatible with **measured dependence on bunch spacing**

Compatible with **measured dependence on bunch intensity**

Compatible with **measured dependence on beam energy**

✓ = **Good quantitative agreement**

✗ = **Excluded**



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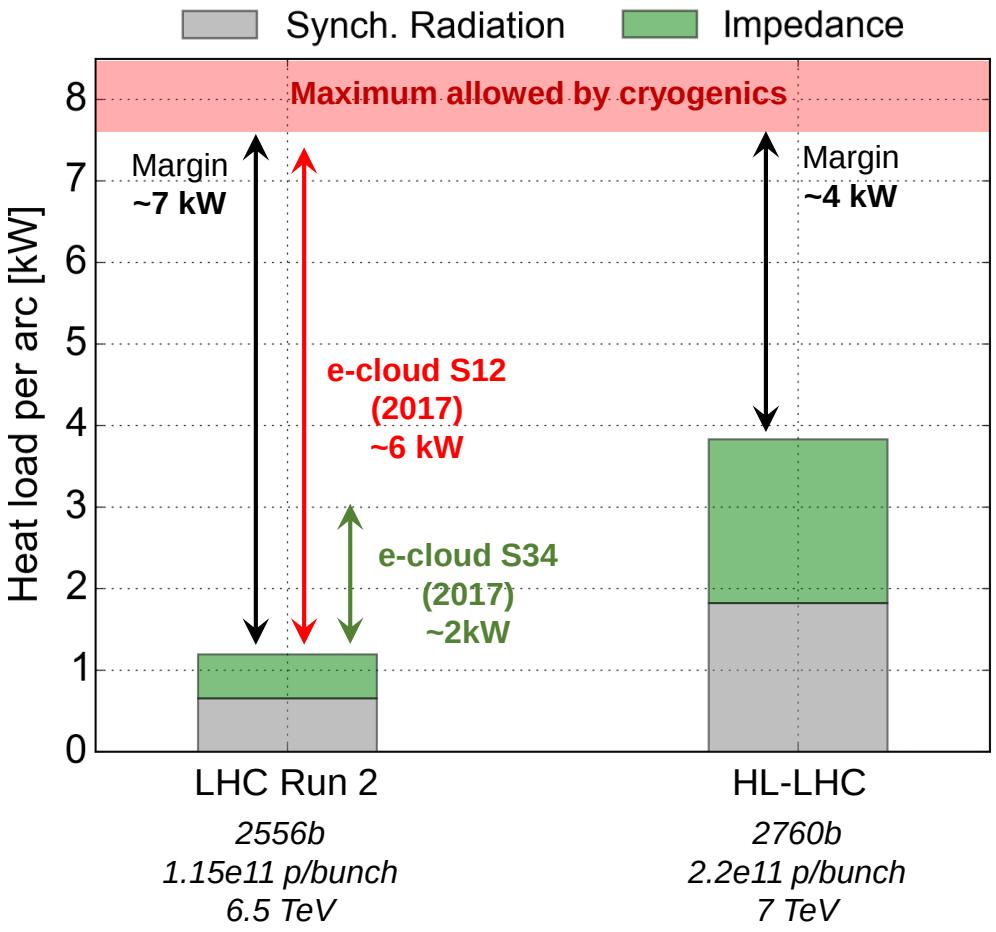
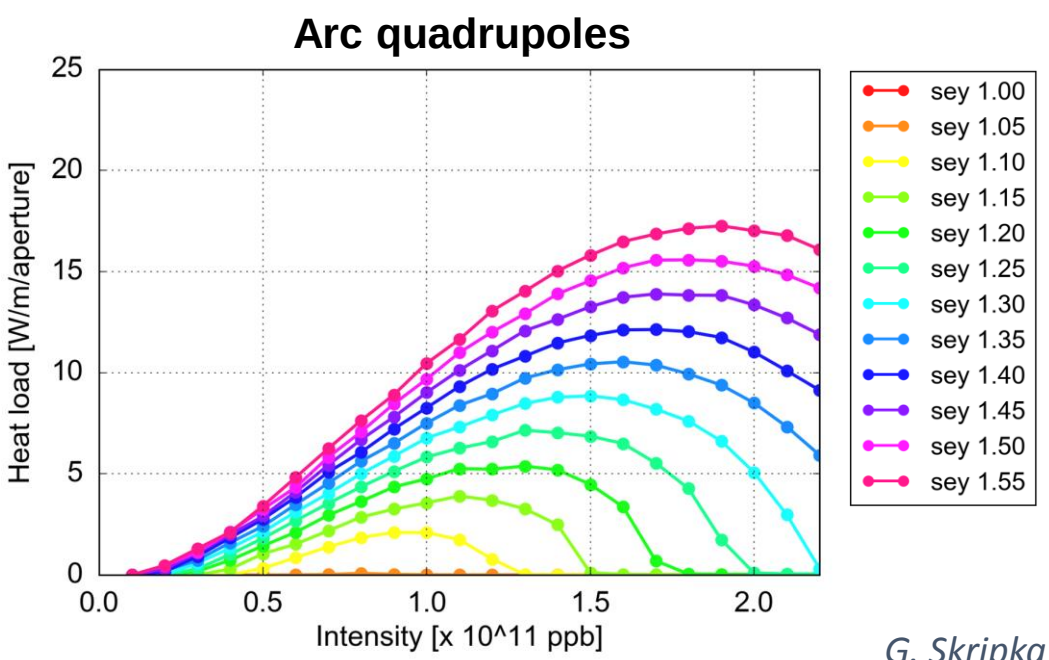
Arc heat loads - outlook for HL-LHC

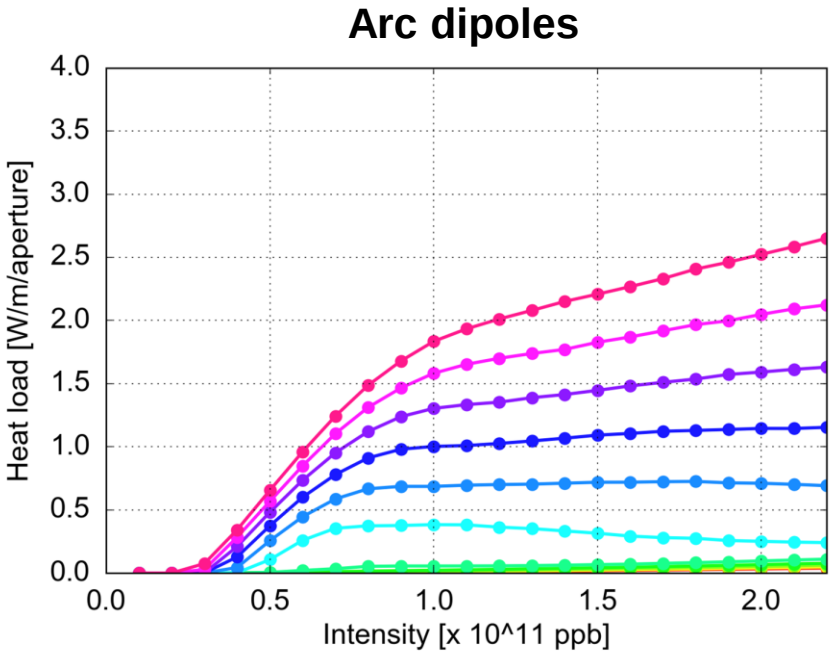
- In **Run 2** configuration: small contributions from **impedance and synchrotron radiation** → used large available **margins to cope with e-cloud**
- When moving to **larger beam intensities** (and to 7 TeV) the **margin reduces strongly**



Arc heat loads - scaling with bunch intensity

- With the available model, **simulations foresee a relatively mild increase** of the heat load from e-cloud when increasing the bunch intensity to HL-LHC values



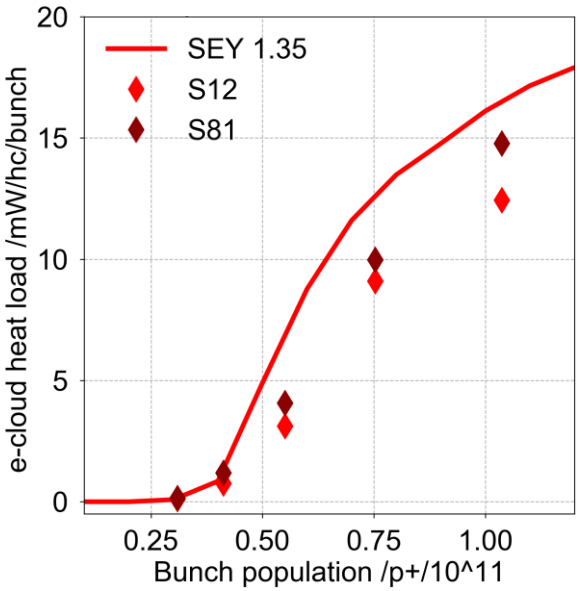


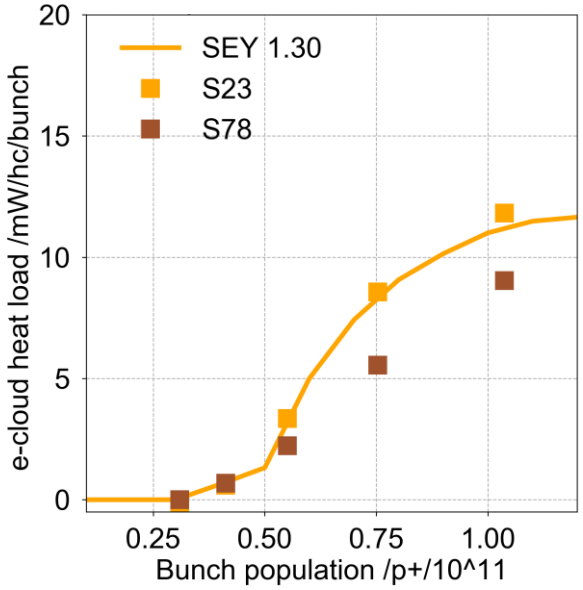
G. Skripka

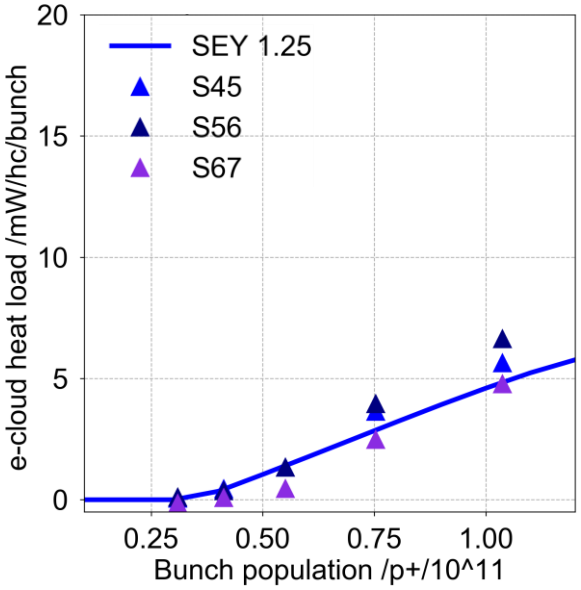
Arc heat loads - scaling with bunch intensity

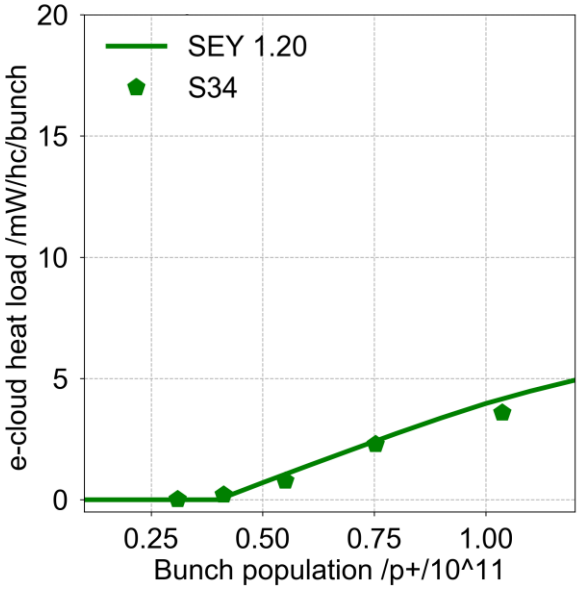
- The dependence of the heat loads with the bunch population was **confirmed experimentally in the LHC intensity range** (SEY as estimated before)
- Direct verification for the **HL-LHC intensity range** will be possible **only after the injectors upgrade** (LS2)

Data from 2018 MD









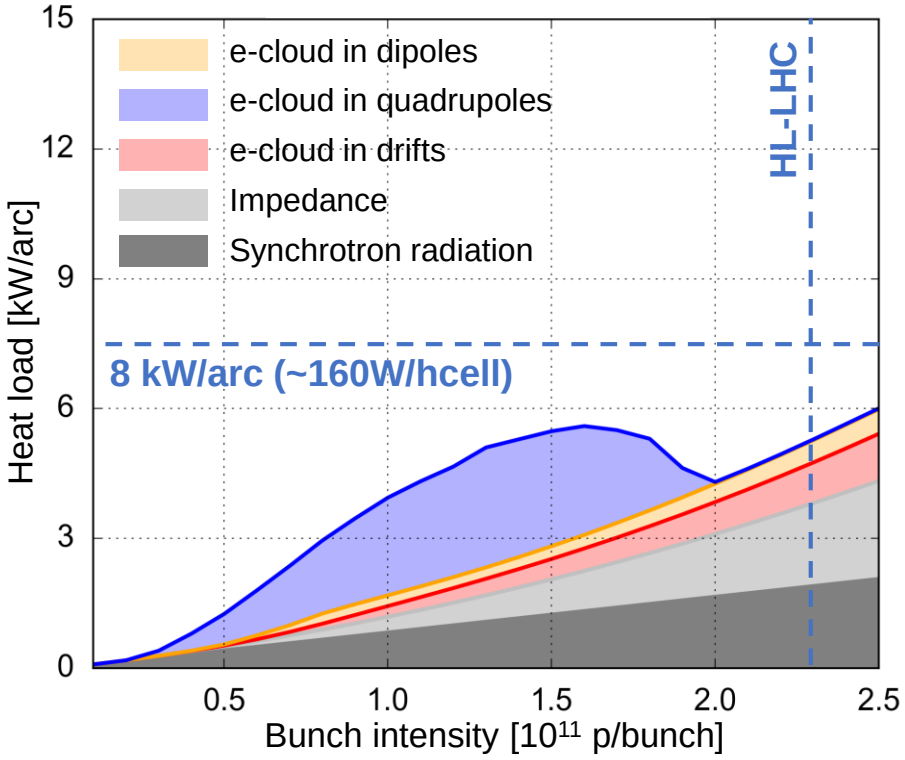
G. Skripka

Arc heat loads - scaling with bunch intensity

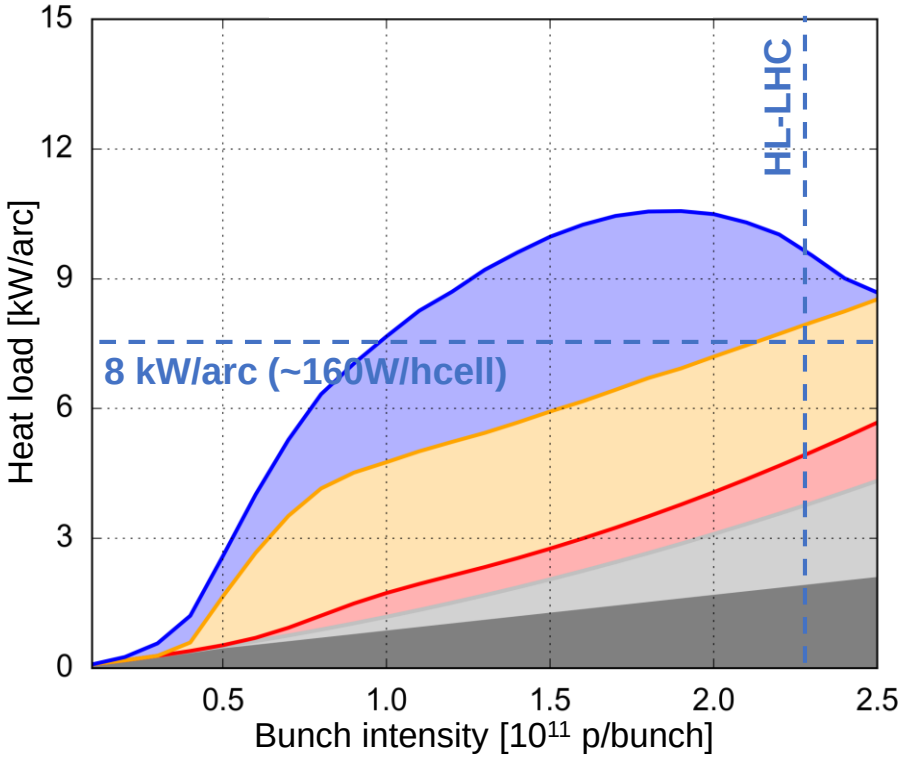
Assuming surface properties assumed above

- Present conditioning achieved in the **low-load sectors** is **compatible with HL-LHC**
- Expected heat load for the **high-load sectors** is **~10 kW/arc → not acceptable**
  - → Ongoing work to **identify and suppress the source** of differences among arcs is **very important for HL-LHC**
  - → A **solid backup plan** must be available…

Present state of the low-load sectors
(SEY = 1.25)

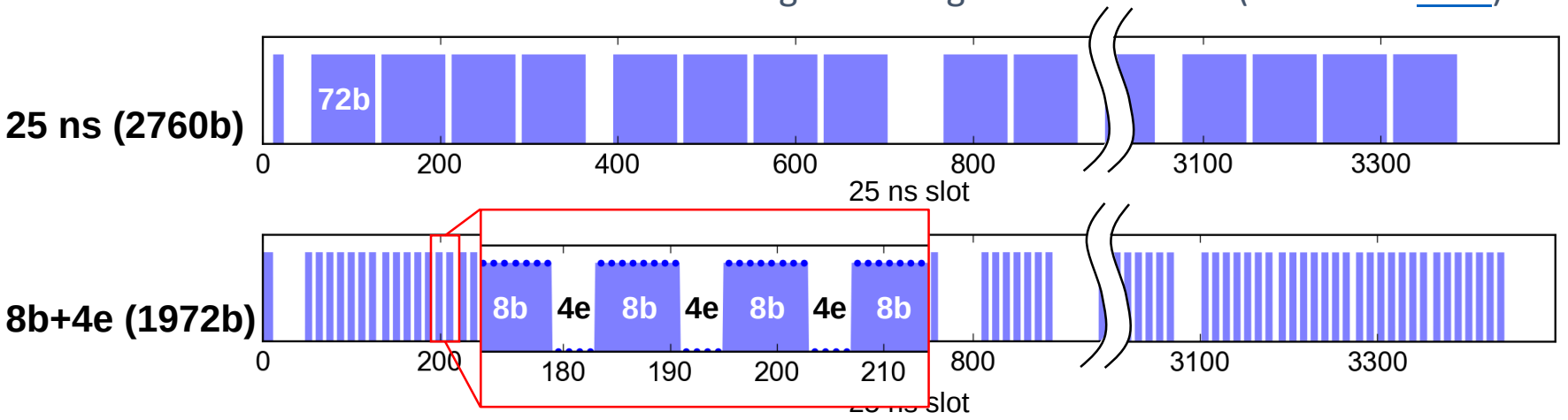


Present state of the high-load sectors
(SEY = 1.35)

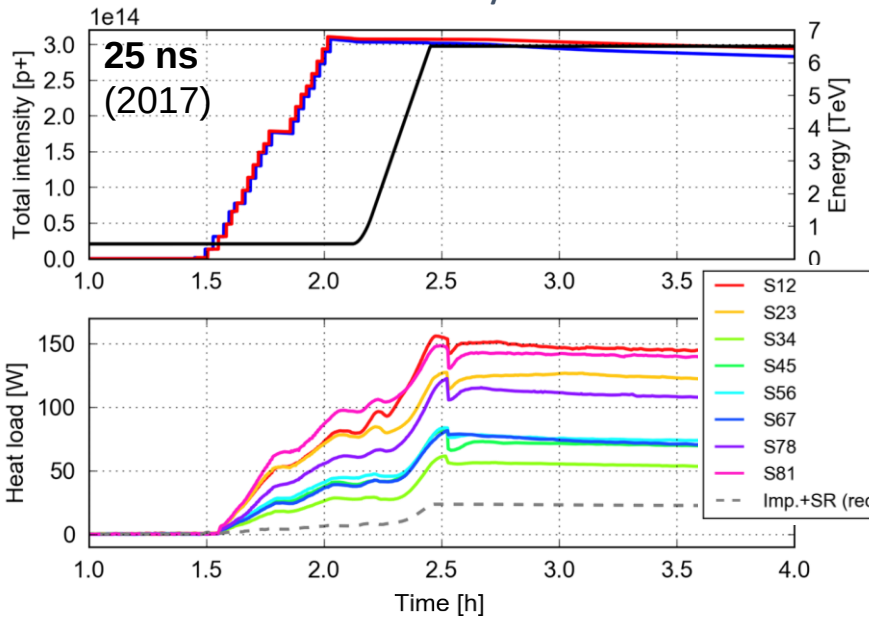


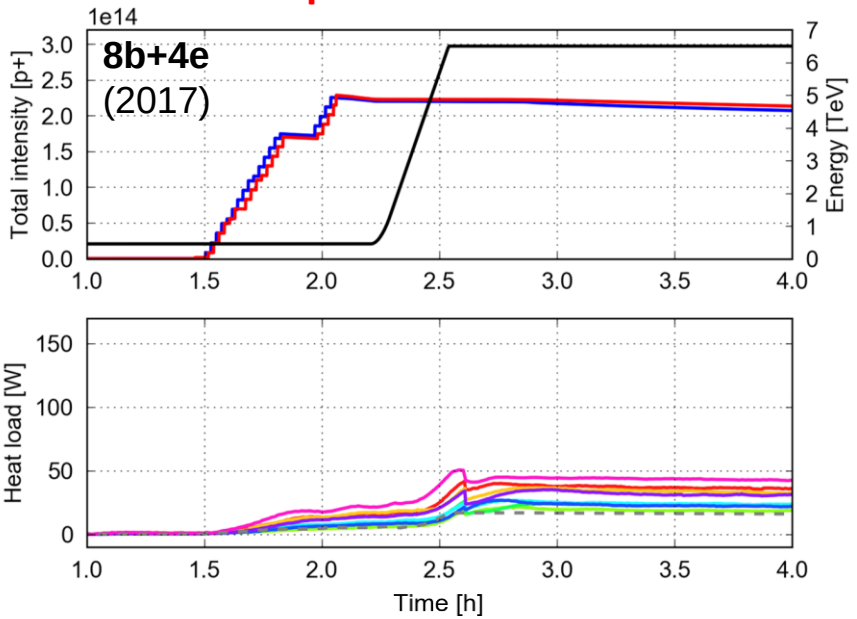
Arc heat loads - 8b+4e backup scheme

- **8b+4e: filling pattern** conceived to **suppress the e-cloud** and hence reduce the heat loads. Price to pay: **30% less bunches**.
- Performance loss can be mitigated using **mixed schemes** (more info here)



Successfully **tested** in the LHC in **2015** and **used in operation** in **2017**





Conclusions and next steps

- In Run 2 **heat loads** on beams screens are significantly **larger than expected** with **large differences** observed among sectors and half-cells cells
- Heating from **electron cloud** is the only known mechanism that is **compatible** with heating observations. Machine data are well **reproduced by e-cloud simulations**
- For the **high load sectors**, the heat load predicted for **HL-LHC** intensities is **more than present cryogenics capacity**
- A **dedicated Task Force** is working on identifying the **root cause** of the increased heat loads, presently focusing on surface alterations

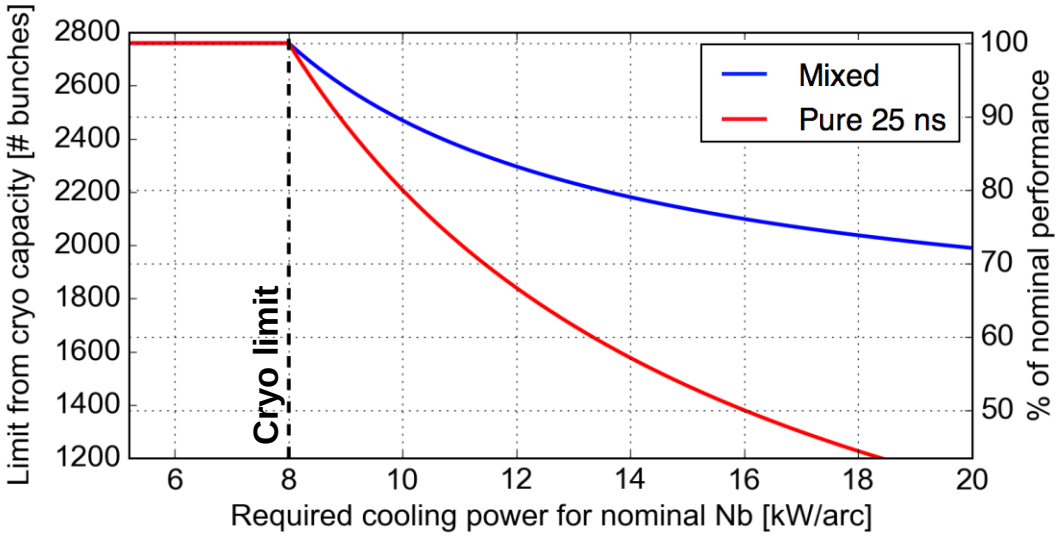
Next steps:

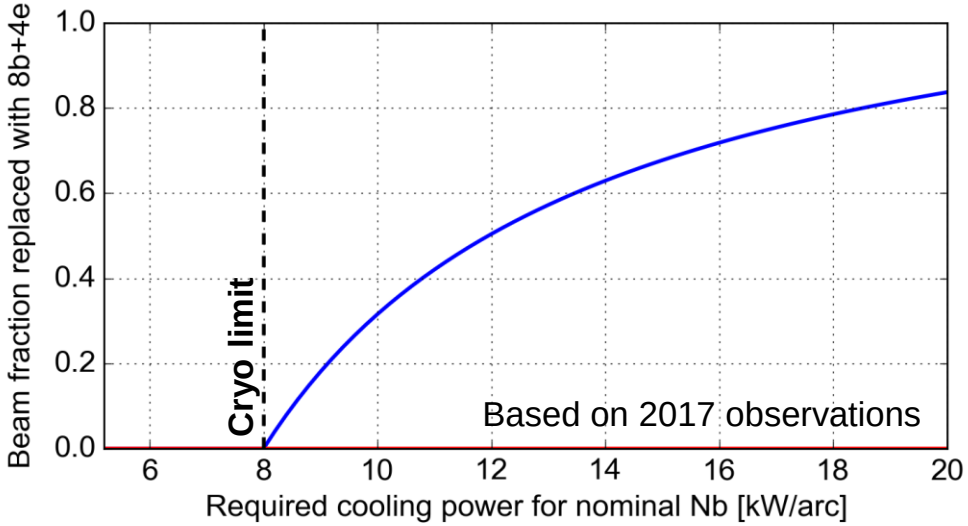
- Important tests will be performed during the **upcoming LHC MD period**:
  - Measurements with short bunch **trains with high bunch intensity** (2×10^{11} p/b)
  - Validation of the **HL-LHC backup scheme (8b+4e)** with large bunch intensity
- During the **Long Shutdown** (LS2, 2019-20):
  - Apply **reviewed venting procedures** in order to minimize further degradation
  - **Cryogenics instrumentation** will be substantially improved (more info here)
  - One **high-load magnet** will be **removed** and **analyzed in the laboratory**

Thanks for your attention!

Arc heat loads - mixed schemes

- With no manipulation on the bunch pattern the **achievable performance is inversely proportional** to the heat load excess
- With mixed schemes **performance reduction is much less severe**





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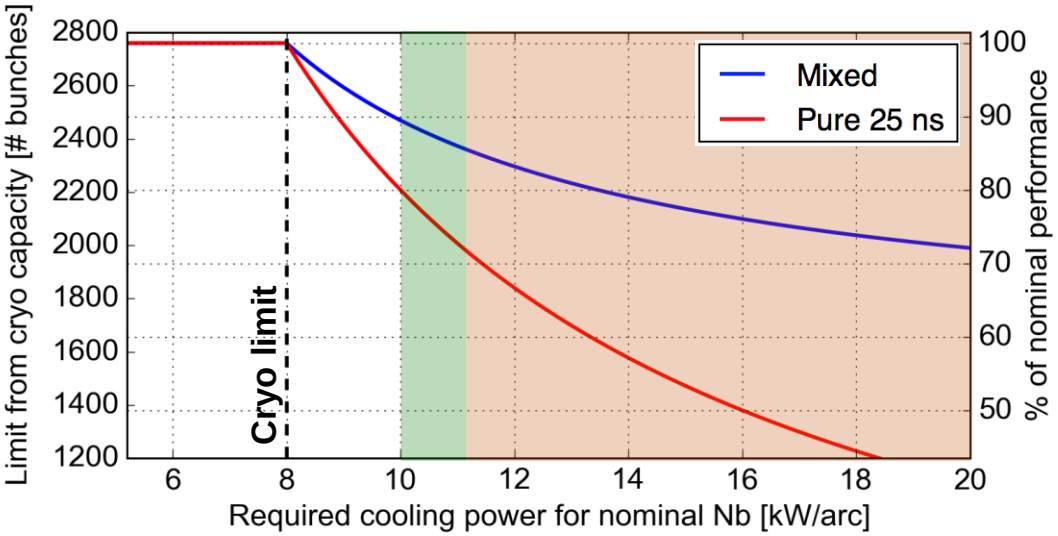

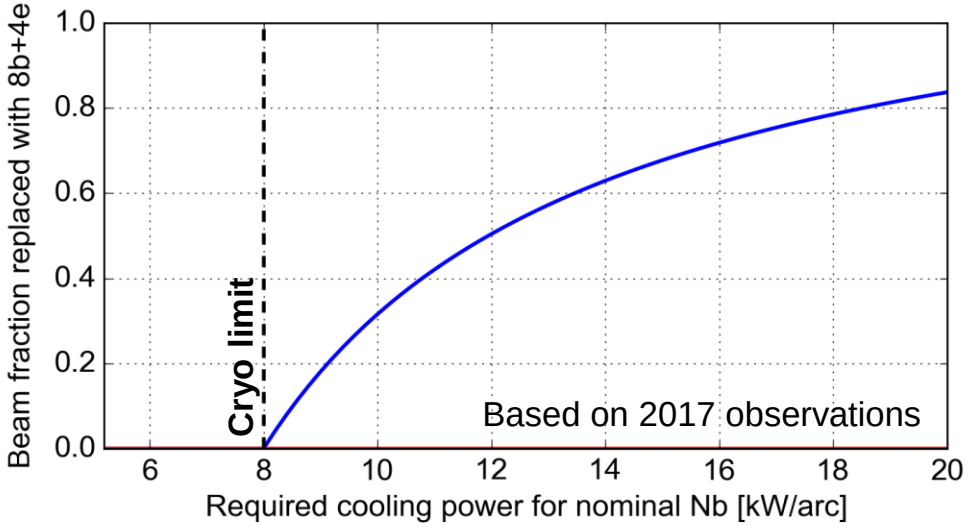

Failure scenario A:

- e-cloud scaling with intensity is confirmed by experiment
- Present LHC conditioning state cannot be improved

Perf. loss with pure 25ns: **~25 %**

Perf. loss with mixed: **~12 %**

Failure scenario B

- e-cloud scaling with intensity is found to be worse than expected
- Present LHC conditioning state cannot be improved

Perf. loss with pure 25ns:
from **~25%** to **very bad**

Perf. loss with mixed:
from **~12% to 30%**

Evolution in in Run 2

- **Conditioning** observed **until mid-2016**
- After that heat loads stayed **practically constant for 2.5 years**
- Heat loads in **S12, S23, S81** much larger than at the end of 2012

Differences are **very reproducible**:

- Observed in **all 25 ns fills** with >800b
- Quite **insensitive to day-by-day changes/fluctuations** in beam parameters:
  - Bunch intensity
  - Bunch length
  - 72b vs 48b trains