Electron Cloud Effects

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Many thanks to: G. Arduini, E. Metral,
LHC Coordination, BE-BI, BE-RF, BE-OP, EN-ICE, EN-STI, TE-ABT, TE-CRG, TE-VSC
for the invaluable support

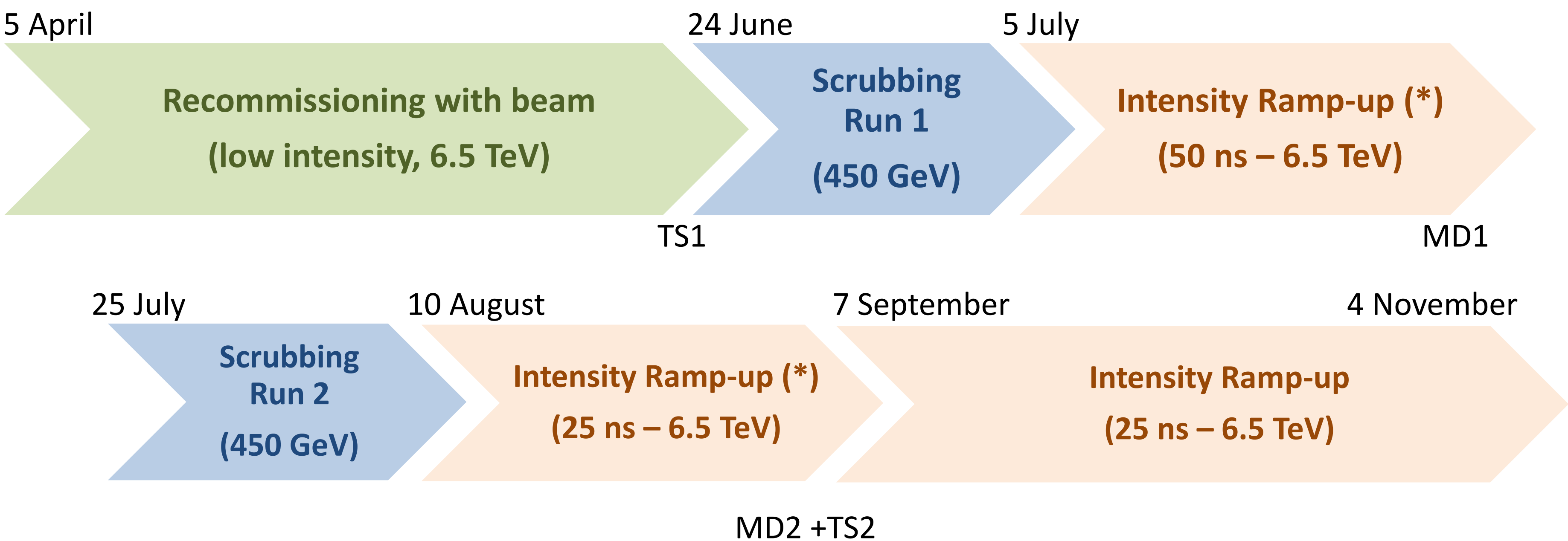
Chamonix 2016

Outline

- **Introduction**
- **Scrubbing at 450 GeV**
- **Intensity ramp-up with 25 ns beams**
  - Beam dynamics observations
  - Heat loads
  - Conditioning observations
- **De-conditioning and re-conditioning observations**
  - Effect of Technical Stops and Special Runs
- **Experience with exotic bunch patterns**
  - Doublets
  - 8b+4e
- **First lessons to retain and possible strategy for 2016**

Introduction

- One of the **main goals** of the 2015 run was to explore operation with **25 ns** beams
- Expected **challenges from e-cloud effects** (as anticipated from 25 ns pilot run in 2012)
  - → Decided to operate with **~nominal bunch parameters** (1.1 x 10^{11} ppb in 2.5 um injected)
  - → Significant time allocated for **scrubbing**



(*) Limited to ~450b. by radiation induced faults in QPS electronic boards (fixed during TS2)

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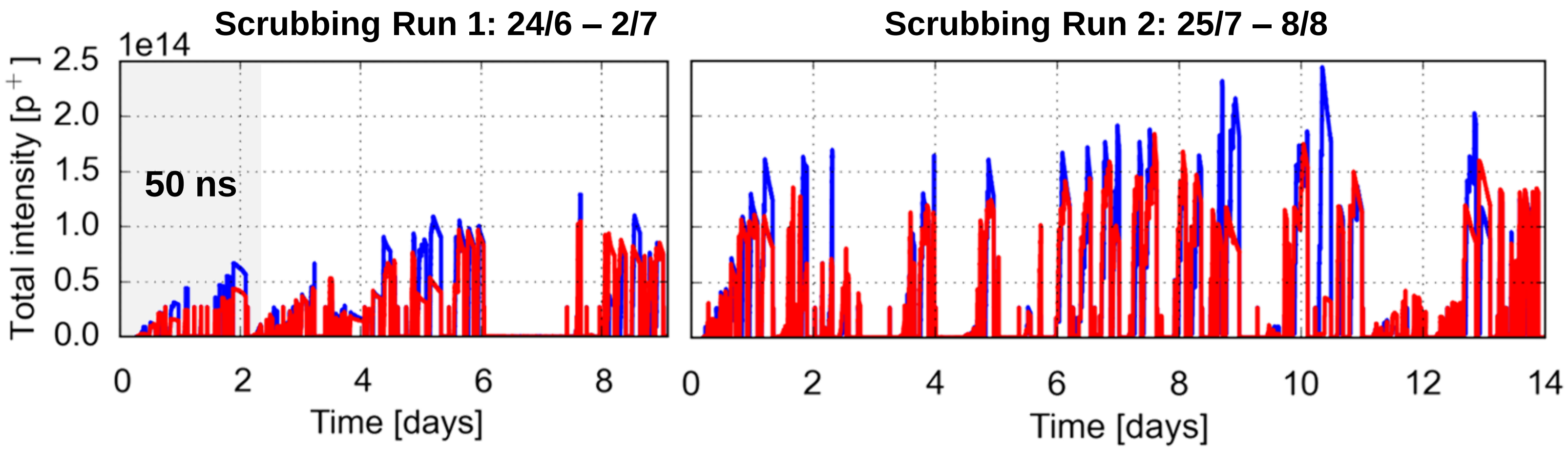
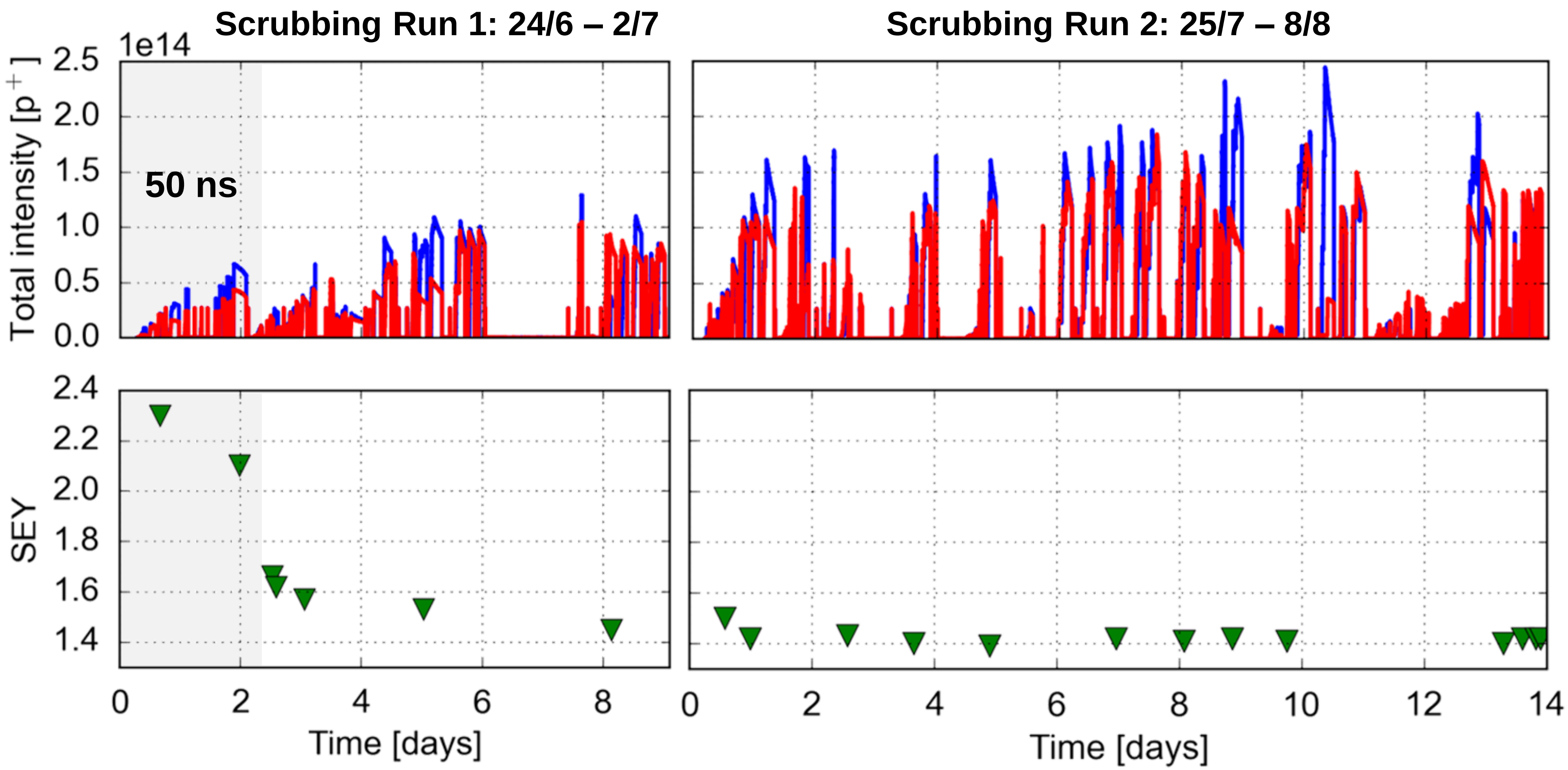
Scrubbing for 25 ns operation



- **After LS1 the Secondary Electron Yield (SEY) was practically reset** (same as beginning of Run 1)
  - e-cloud induced instabilities were observed even with 50 ns
- During **(1+2) weeks** of scrubbing at 450 GeV
  - Regularly filling the machine with **up to ~2500b. with 25 ns spacing** at 450 GeV
- Main **limitations to the scrubbing efficiency**:
  - **e-cloud instabilities** → evidently **improving with scrubbing**
  - **Transients on beam screen temperatures** → less critical now with the **new Cryo-Maintain rules**
  - Vacuum spikes at the **TDI8** injection absorber → **exchanged during YETS**
  - Pressure rise in the **MKIs** → close follow-up by TE-ABT and TE-VSC team (interlock changes)

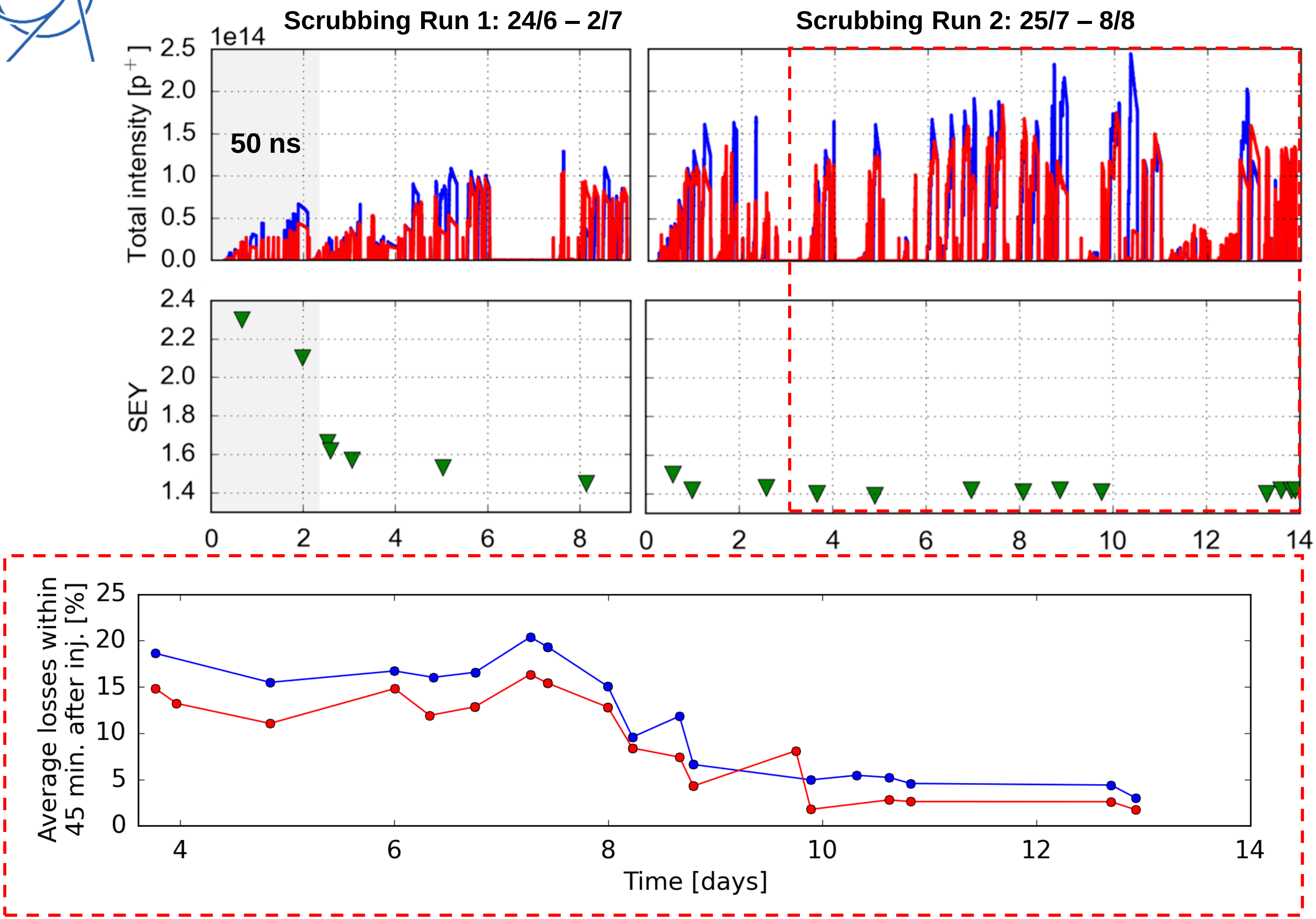
Scrubbing for 25 ns operation



Secondary Electron Yield (SEY) was reconstructed comparing **heat load** and **RF stable phase** measurements against **PyECLOUD simulations**

→ **Observed reduction of the SEY** confirmed by steadily **improving beam quality**

Scrubbing for 25 ns operation



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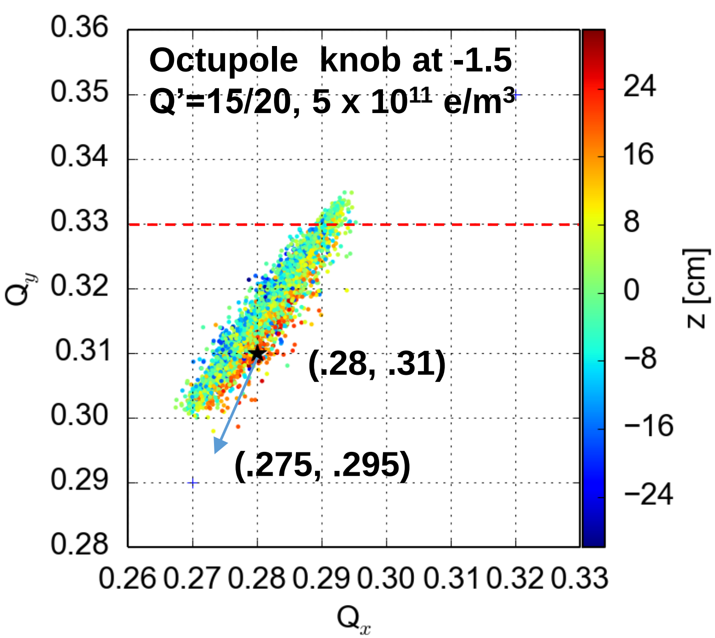
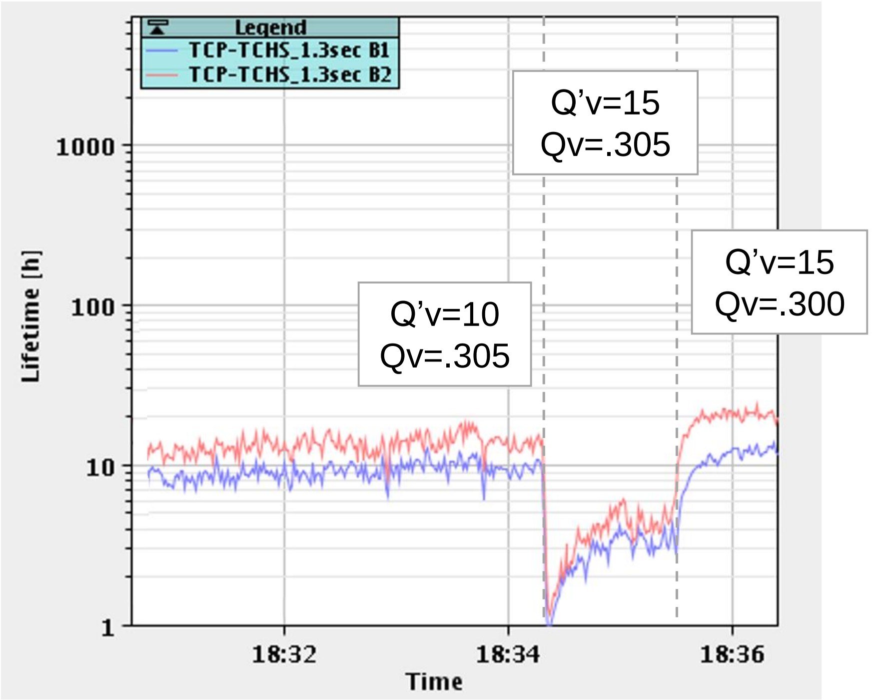
Intensity ramp-up with 25 ns beams: beam dynamics

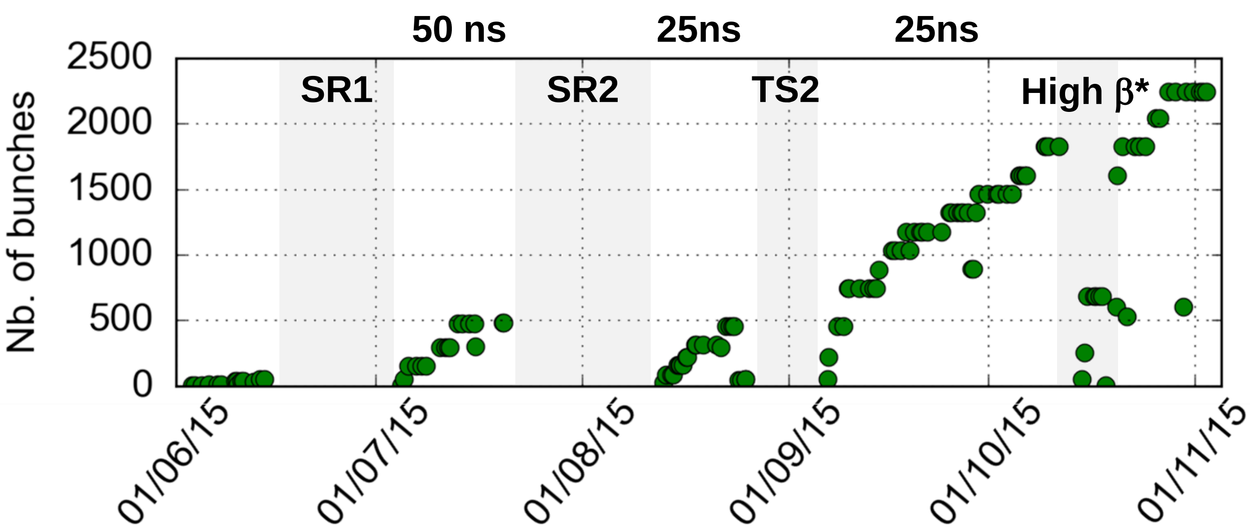
- Scrubbing Run provided **sufficient mitigation against beam degradation** at 450 GeV but **full suppression of the e-cloud was not achieved**
  - → During the physics intensity ramp-up we had to learn how to **run the machine in the presence of the e-cloud**
- **Tricky to ensure beam stability at 450 GeV**: need for high chromaticity and octupoles settings and for full transverse damper performance (see talk by K. Li)
- Slightly **changed working point at injection** to better accommodate large tune footprint from Q', octupoles and e-cloud





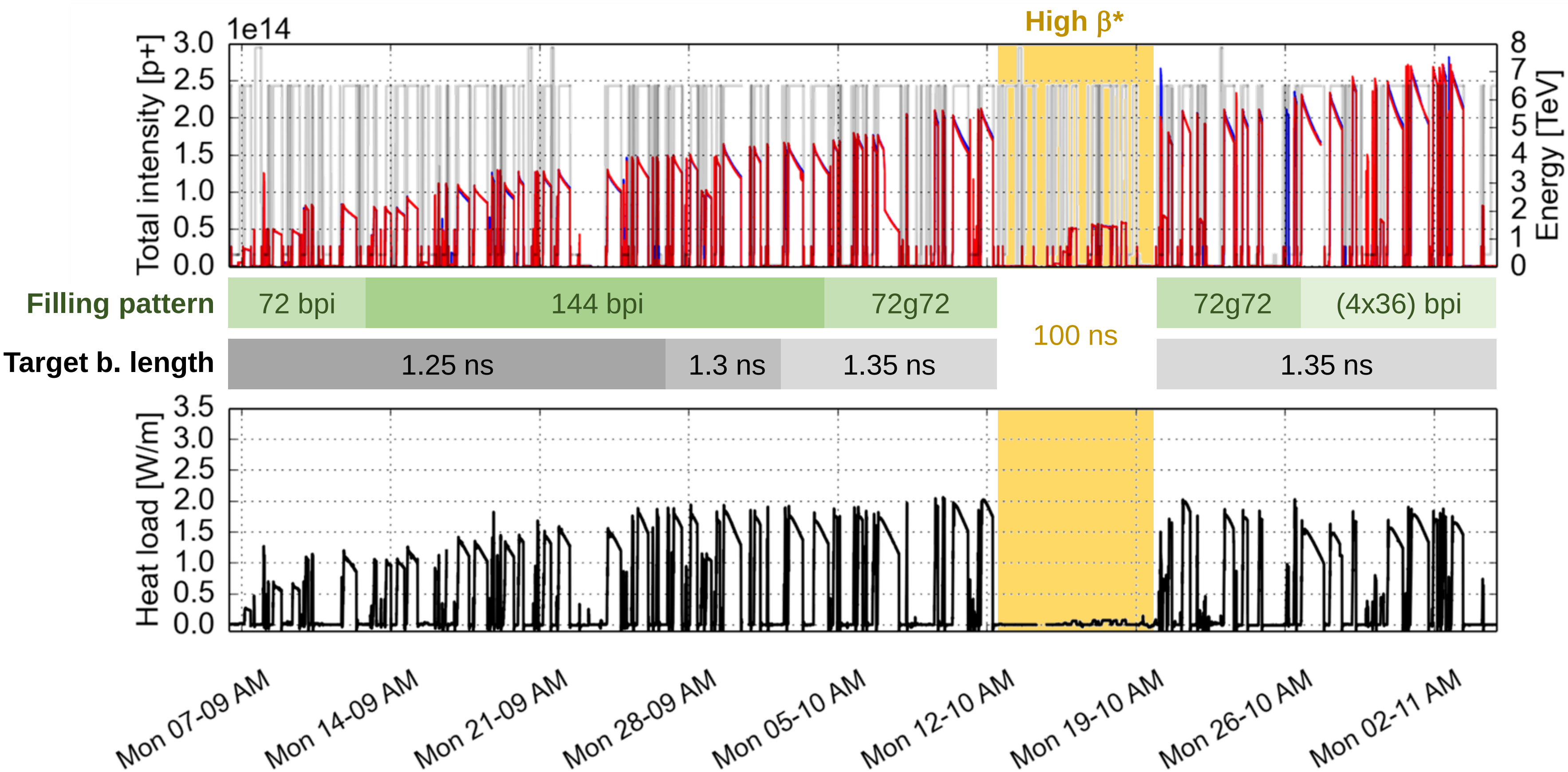
Intensity ramp-up with 25 ns beams: heat loads

- In the first stages, even with relatively low number of bunches, strong **transients of the beam screen temperatures** were observed, leading to loss of cryo-conditions :
  - Intensity ramp-up performed in **“mini-steps”** for fine tuning of cryo-regulations
  - During the first stages, **injection speed often decreased** to control beam screen temperatures
  - Limitation from transients strongly **mitigated over the year by**:
    - → **Modified Cryo Maintain rules** to allow for larger temperature excursion
    - → Improvement on **cryogenic feed-forward** control



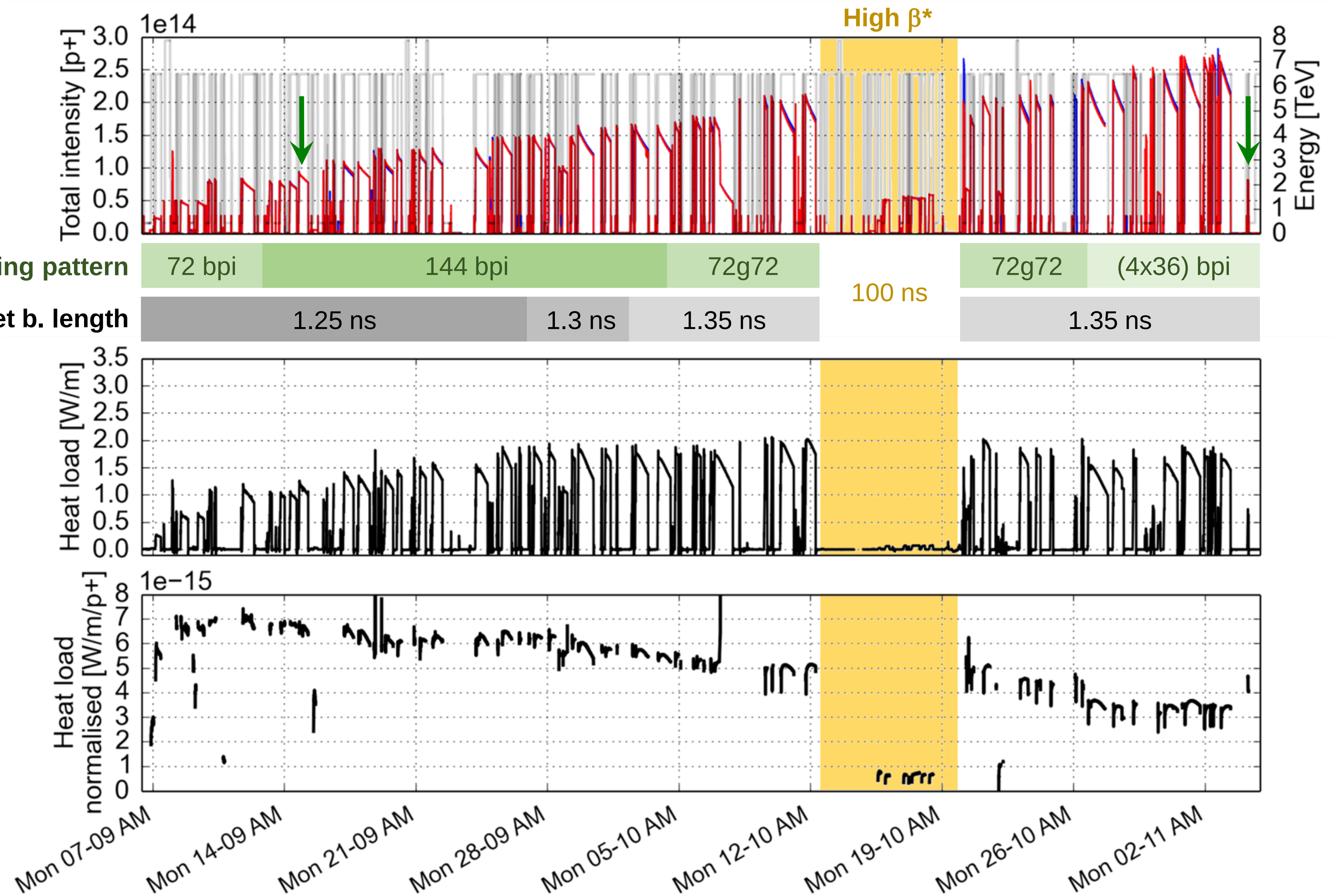
Intensity ramp-up with 25 ns beams: heat loads

- Around ~1450b. (1.5×10^{14} p) we started approaching the **limit of the available cooling capacity** on the arc beams screens. Additional margin gained by:
  - → Increased **longitudinal emittance blow-up** on the ramp
  - → **optimized filling scheme** to gain additional margin
- By the end of the proton run **reached 2244b.** (in trains of 36 b.) with **1.2×10^{11} ppb**



Scrubbing accumulated during the physics run

- Heat load per bunch **significantly decreased during the physics run**
  → **Reference fill** performed at the end of the run in order to disentangle contributions from scrubbing and beam tuning



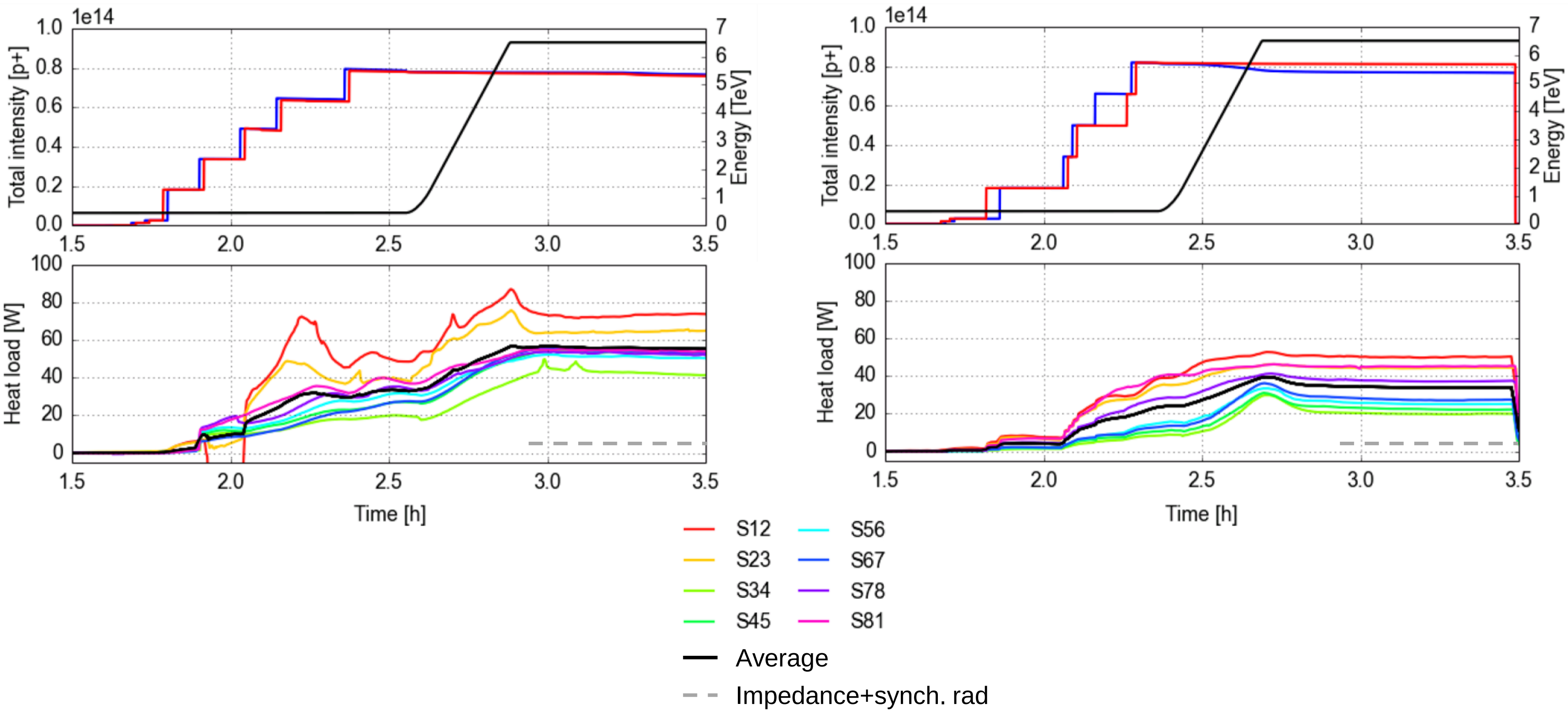
Scrubbing accumulated during the physics run

At the end of the p-p run we repeated an early fill of the intensity ramp-up

- **Very similar beam conditions** (filling pattern, bunch intensity, bunch length)
- After 2 months, significant **reduction visible in all arcs** (30% to 60% depending on the sector)

14 September – Average arc half cells

4 November – Average arc half cells



Scrubbing accumulated during the physics run

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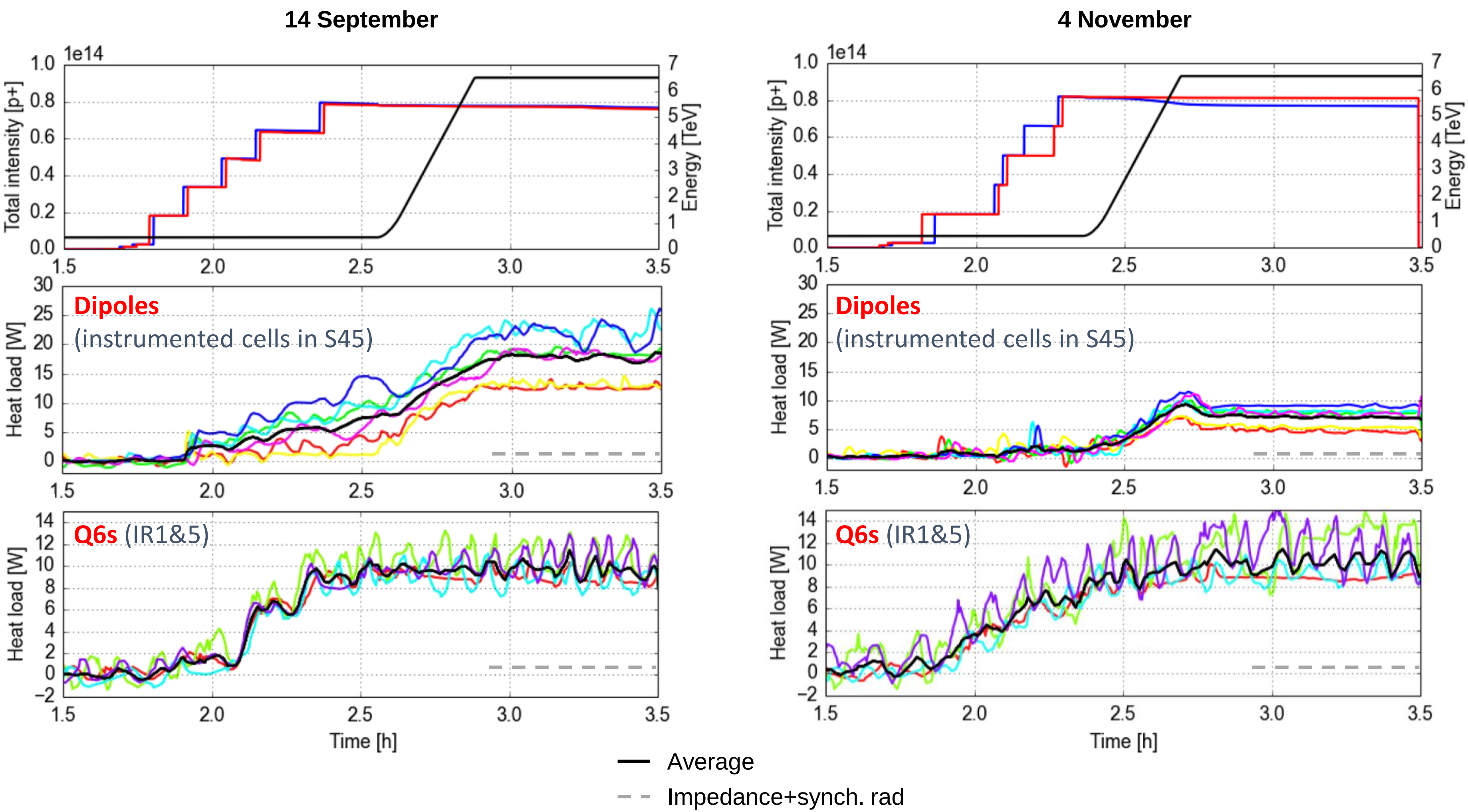
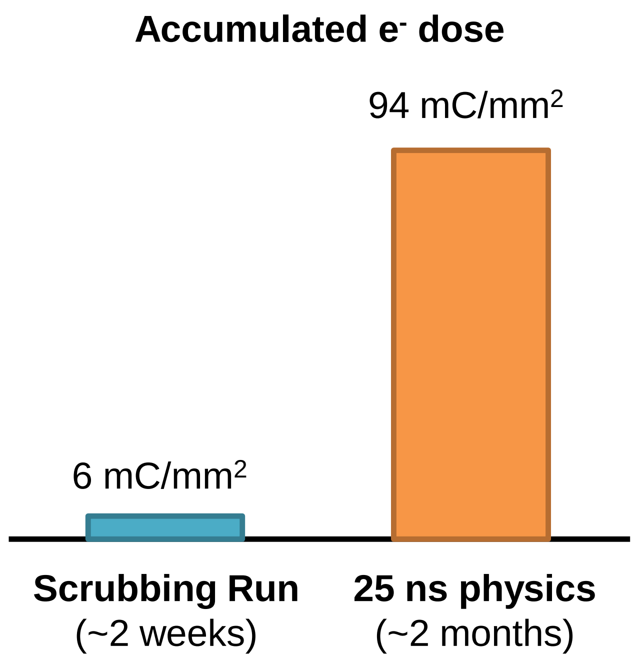
- Reduction observed **mainly in dipole magnets** (higher SEY threshold compared to quadrupoles)

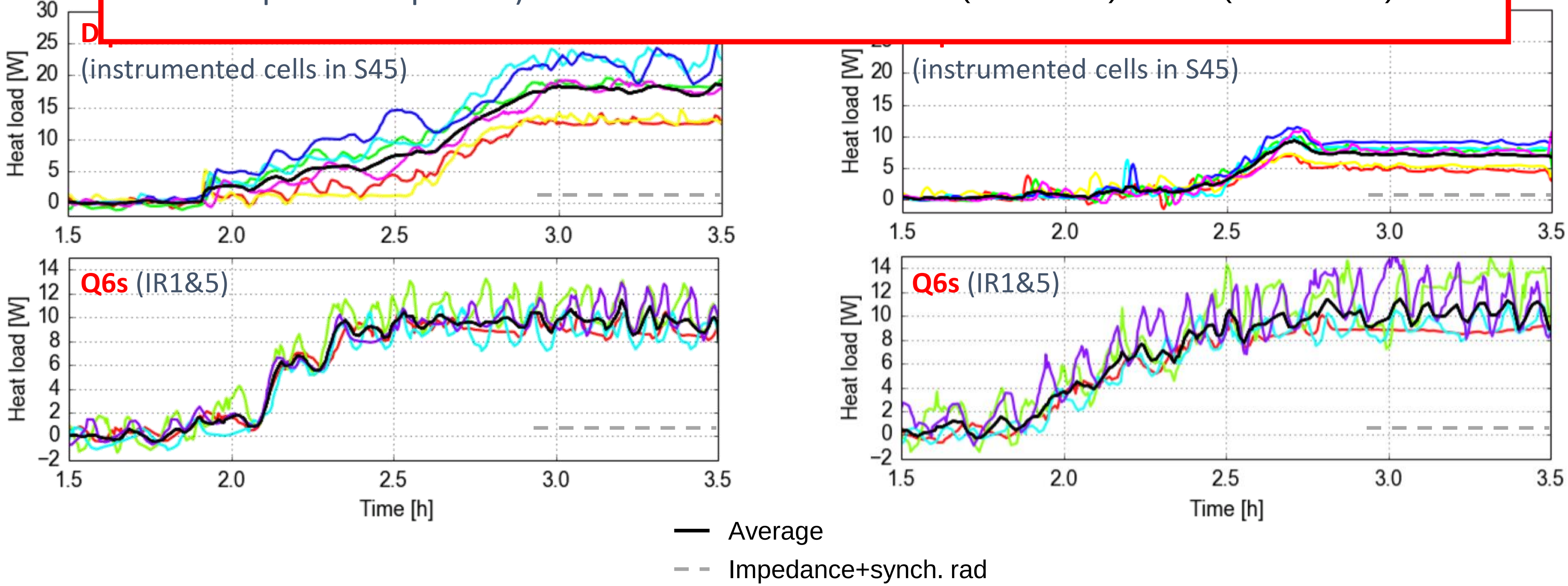


Scrubbing accumulated during the physics run

Electron dose needed to achieve factor two reduction of the heat load at flat top is **very large**:

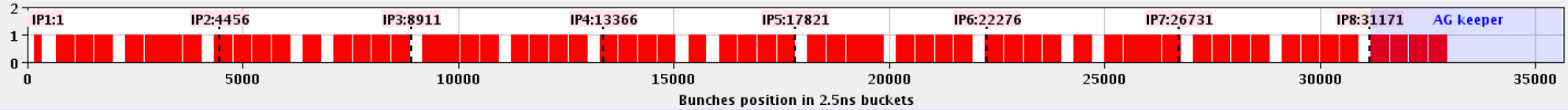
- Difficult to accumulate in a reasonable time with dedicated scrubbing run
- Possible future strategy (e.g. after LS2):
  - **Shorter scrubbing period,** to achieve acceptable beam quality
  - Accumulate **further dose in parallel with physics** (but slower intensity ramp up to be expected)

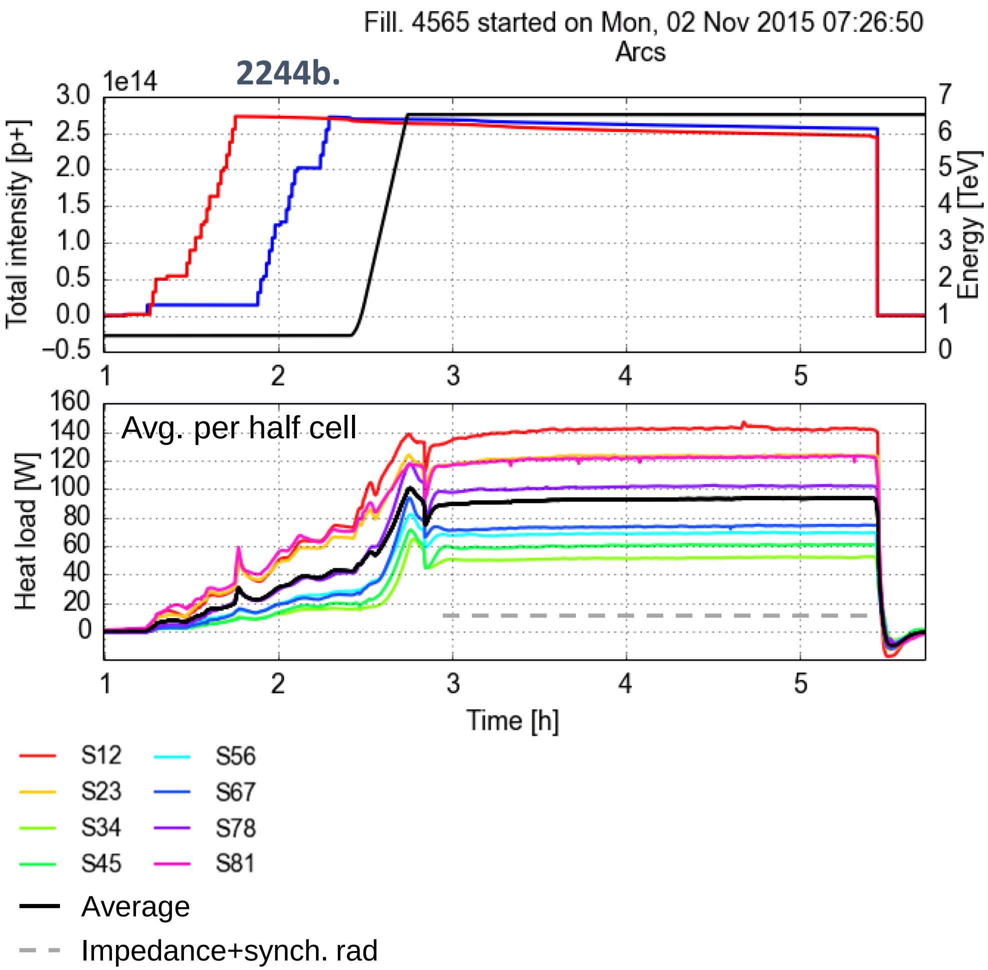




Situation at the end of the p-p run

Achieved in 2015: 2244b. in trains of 36b.





Factor 3 spread among heat loads in different sectors

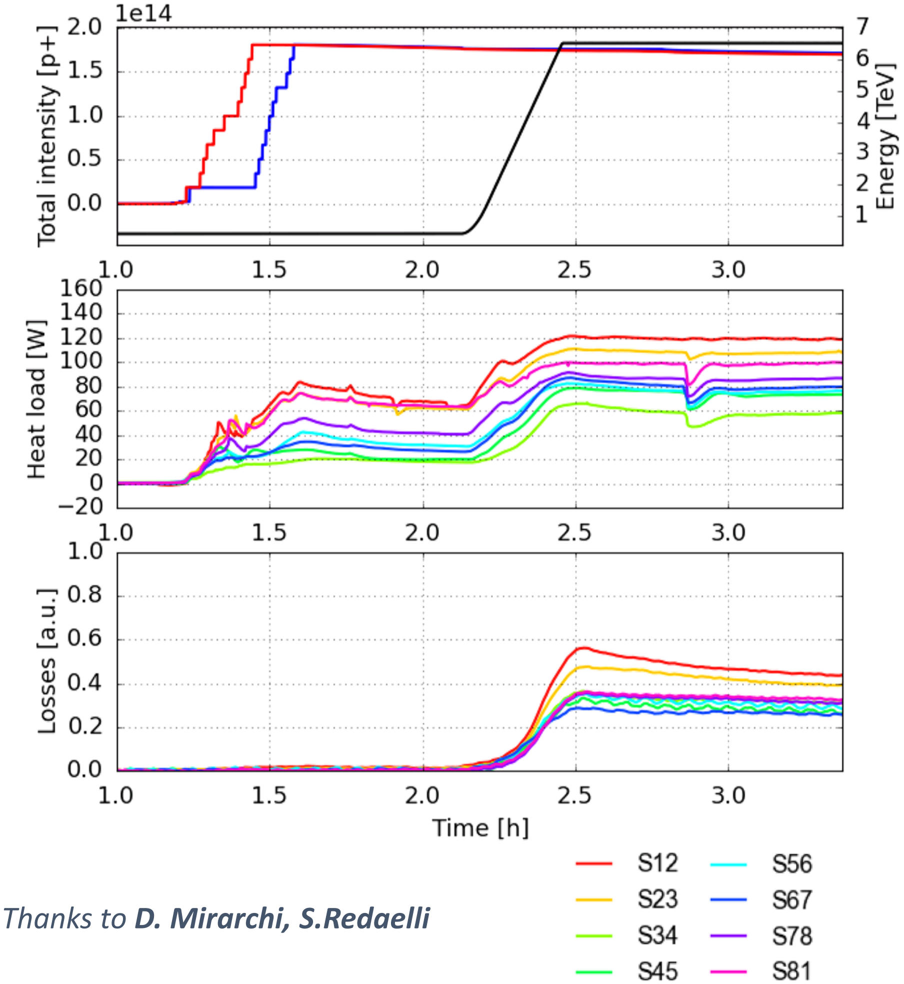
- Sectors **81, 12 and 23 close to the limit** with this filling scheme
- Sectors **34, 45, 56, 67 (and cold magnets in IRs) have already enough margin** to accommodate the nominal beam(1)

(1) Analysis **by D. Berkowitz and S. Claudet**

Different heat loads along the LHC

The **difference among sectors** seems **not to be a measurement artefact**

- Test cells were **calibrated with heaters**
- Sectors with high heat load also show **larger BLM signals in the arcs**



*Thanks to **D. Mirarchi, S.Redaelli***

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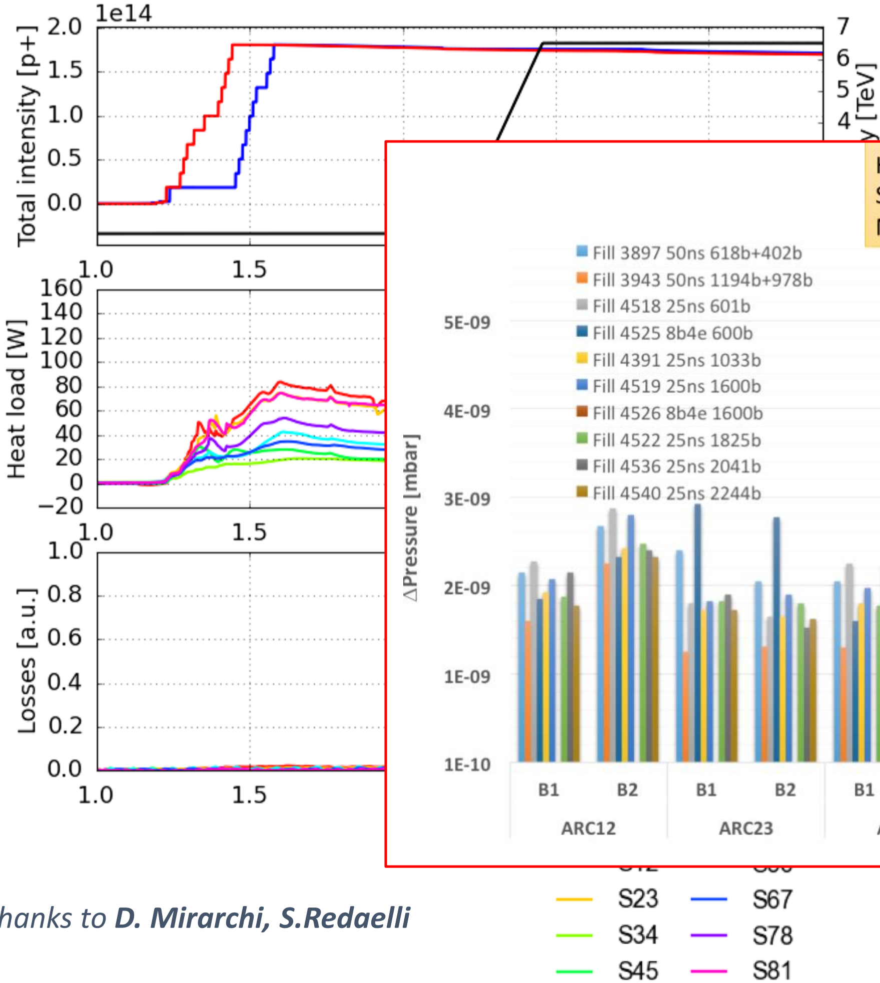
  - → Compatible with worse vacuum due to a stronger e-cloud activity?
  - → Not visible on the localized gauges in the arcs, but number of gauges is limited



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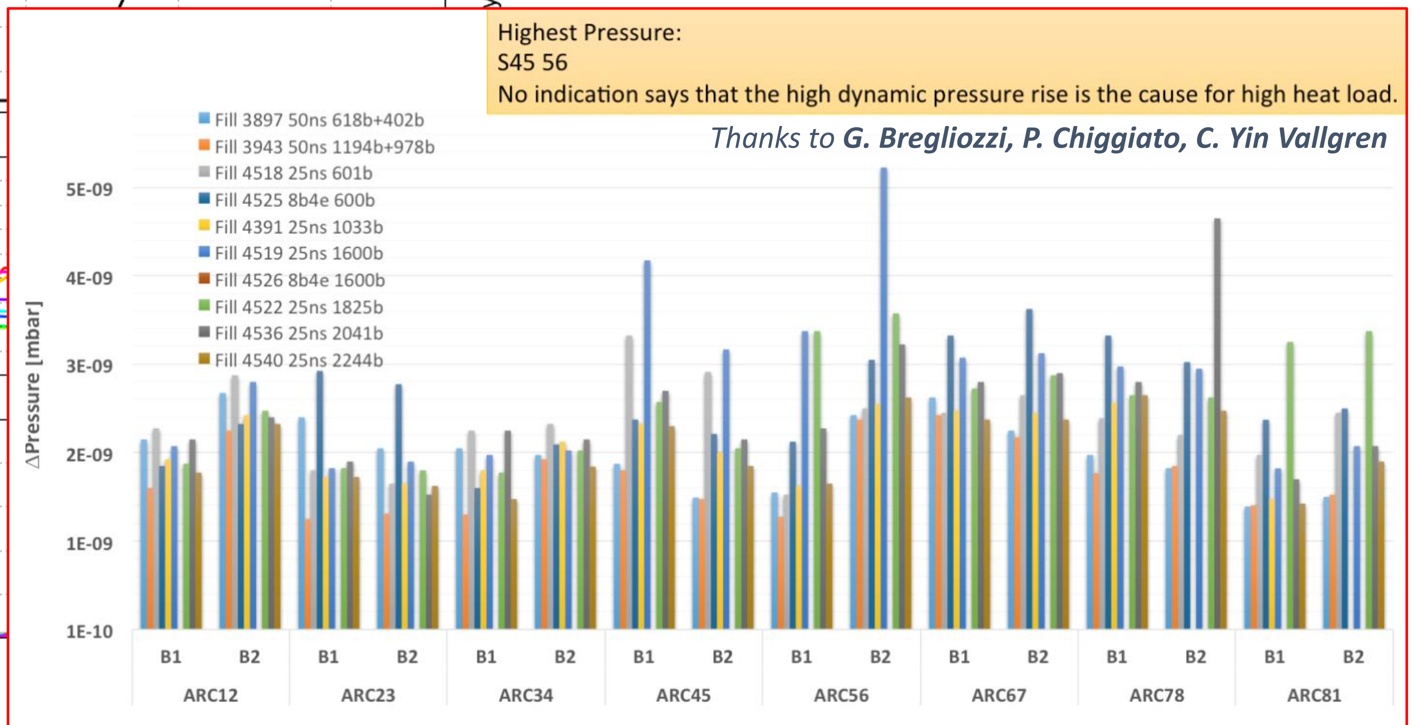

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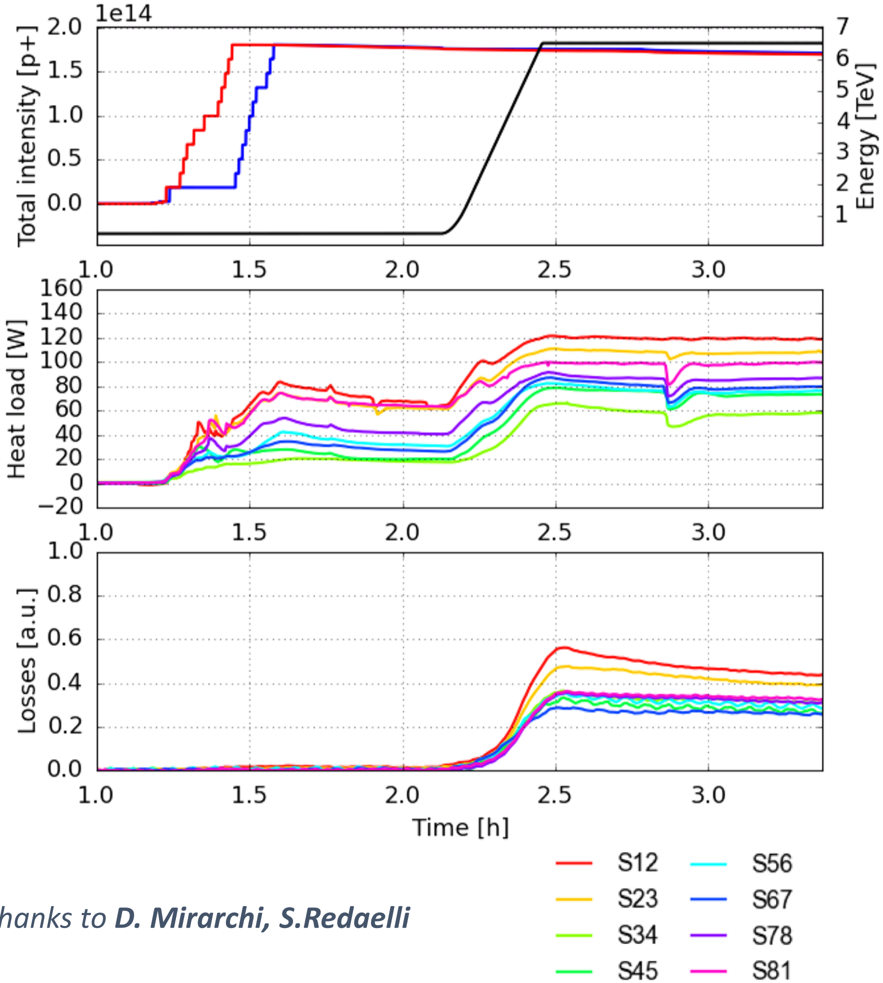


Several **tests and analysis performed/ongoing**:

- It is there with **only one beam**
- It was observed also with **50 ns**, then disappeared with scrubbing
- It was observed with **doublets**
- Difference is **increasing with time**
- Unaffected by **radial position** of the beam
- **Thermal cycle** of the beam screen has **no effect** on the heat load

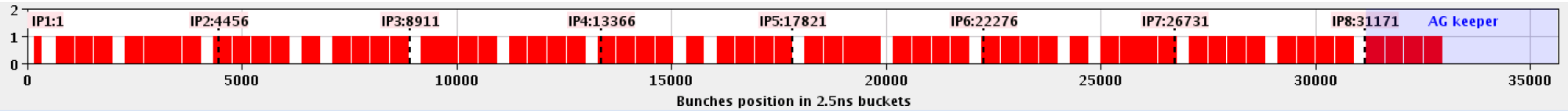
… but **origin of different behaviour is still unclear**

Spread **not related to construction differences** since heat load distribution in the ring was **different in 2012**

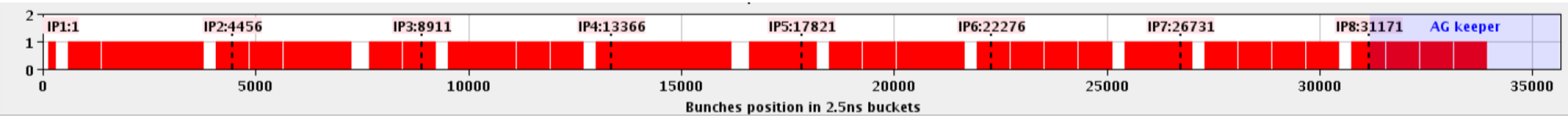
*Thanks to **D. Mirarchi, S.Redaelli***

Looking at 2016

Achieved in 2015: 2244b. in trains of 36b.
no margin for heat load increase (S12-23)



Nominal: 2748b. in trains of 72b.



22% more bunches but **40% less gaps**
→ expected **~50% more heat load**

Still some way to go…

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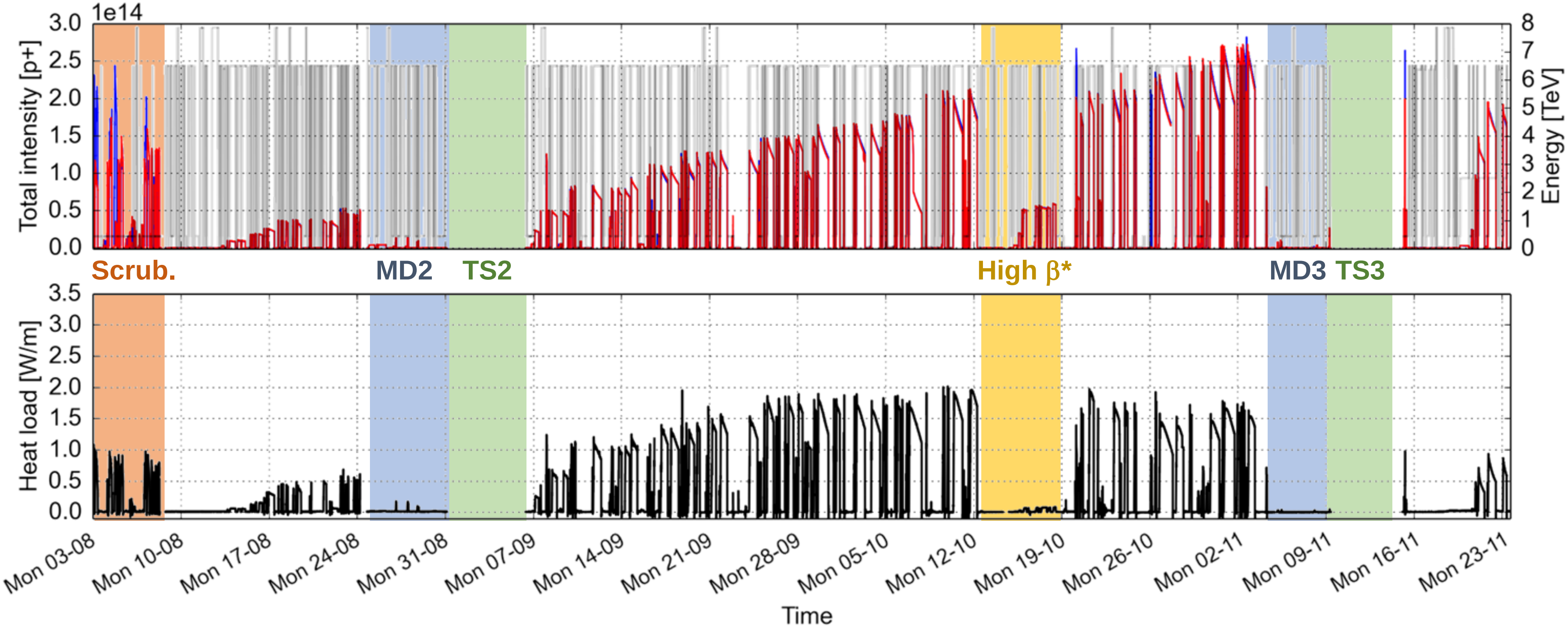
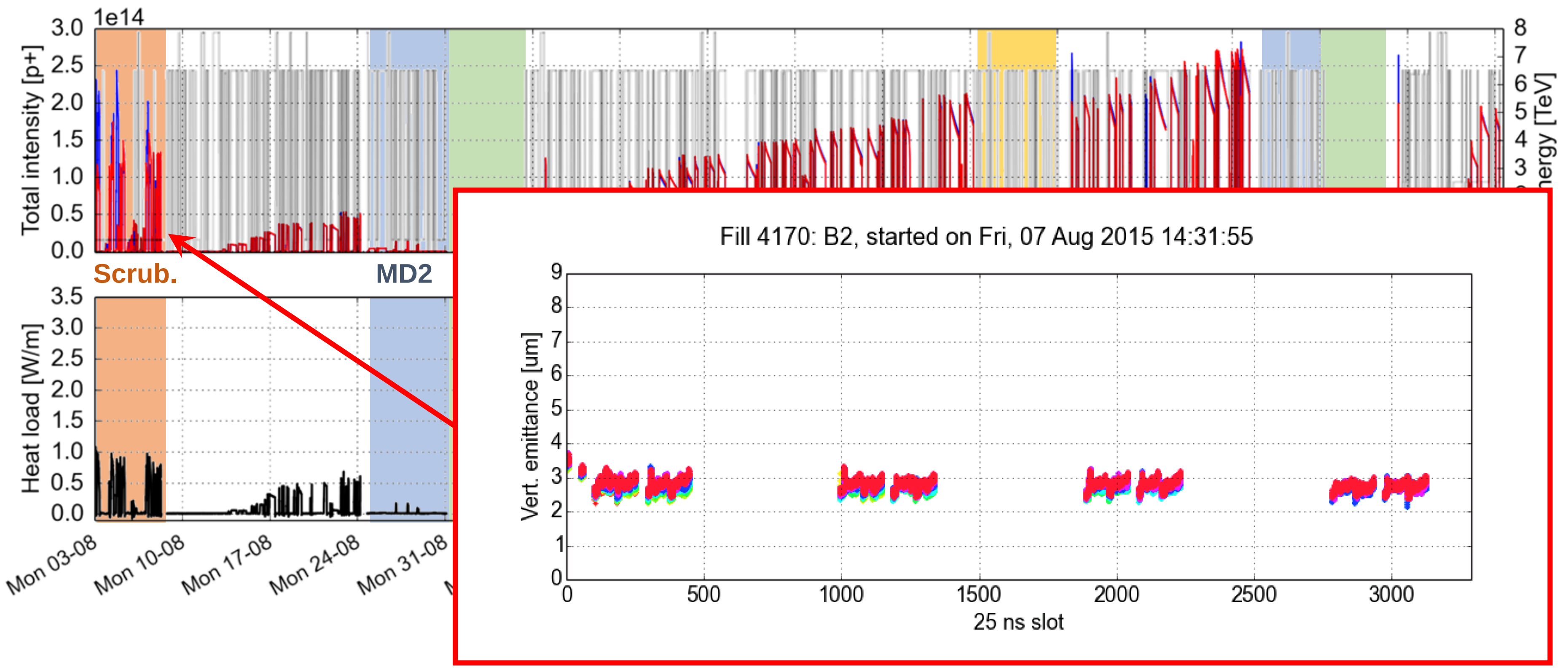
Deconditioning & reconditioning

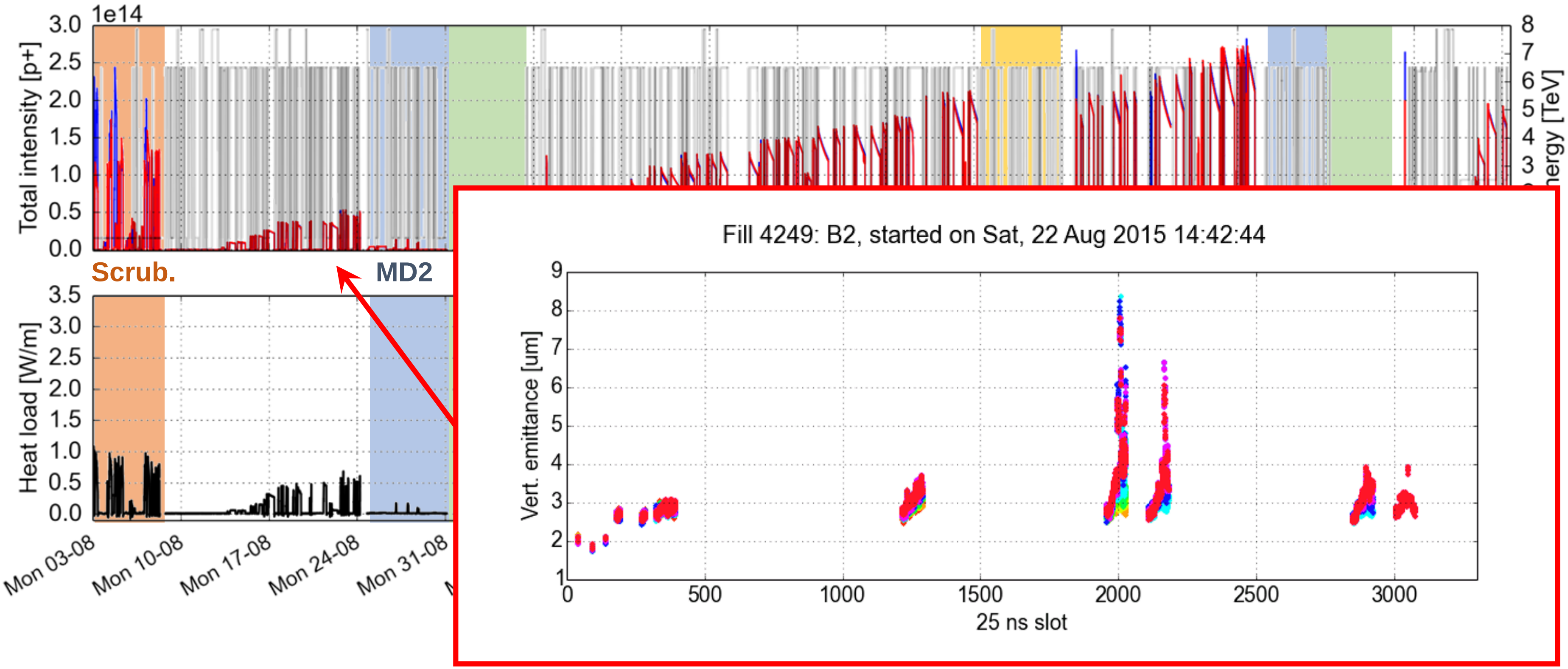


Deconditioning & reconditioning



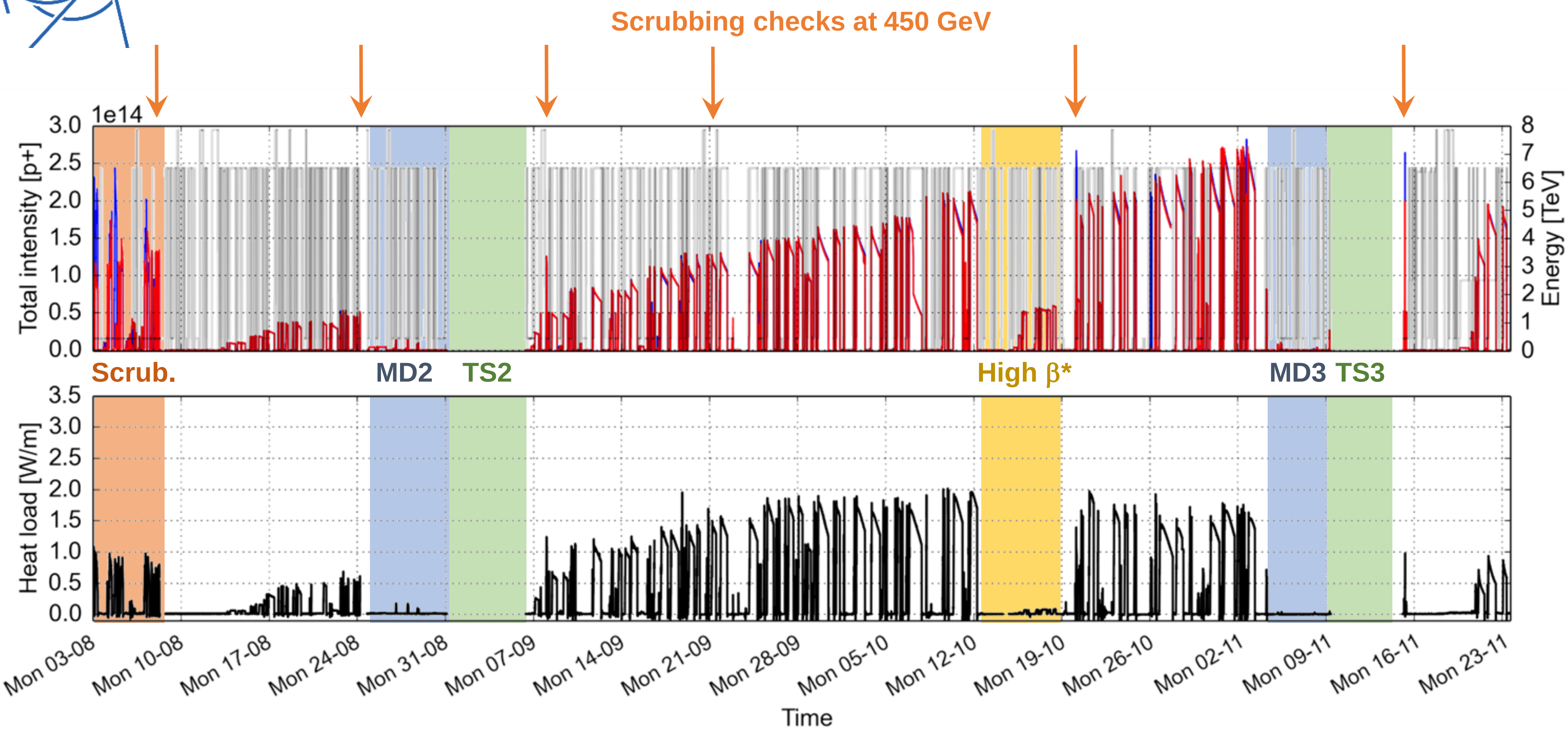
- By the **end of the scrubbing run** it was **possible to store 1177b.** with injections of 144b. without significant beam degradation from the electron cloud

Deconditioning & reconditioning



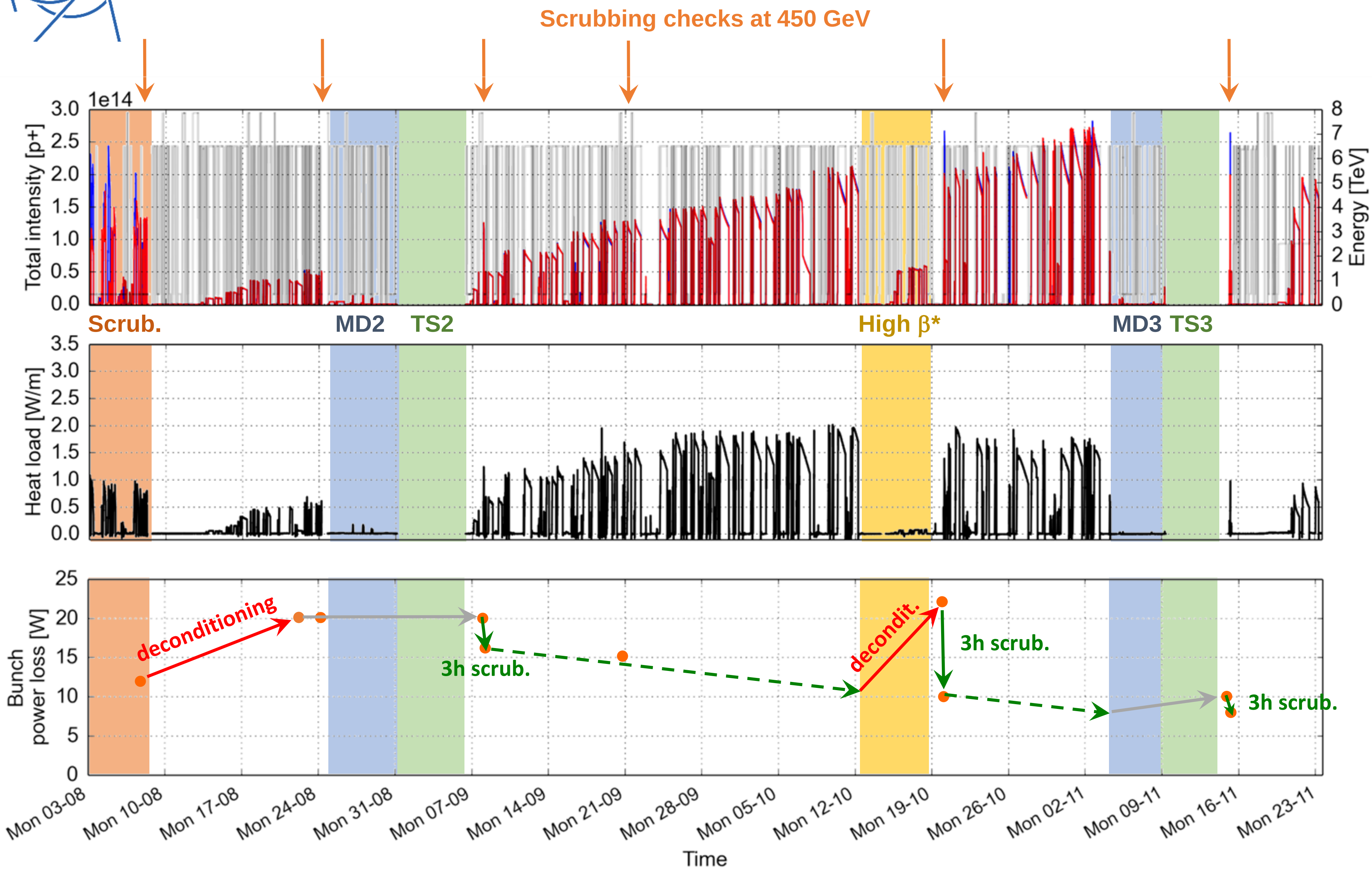
- By the **end of the scrubbing run** it was **possible to store 1177b.** with injections of 144b. without significant beam degradation from the electron cloud
- **Two weeks later**, strong **emittance blow-up** was observed **with 459b.** with injections of 72b.

Deconditioning & reconditioning



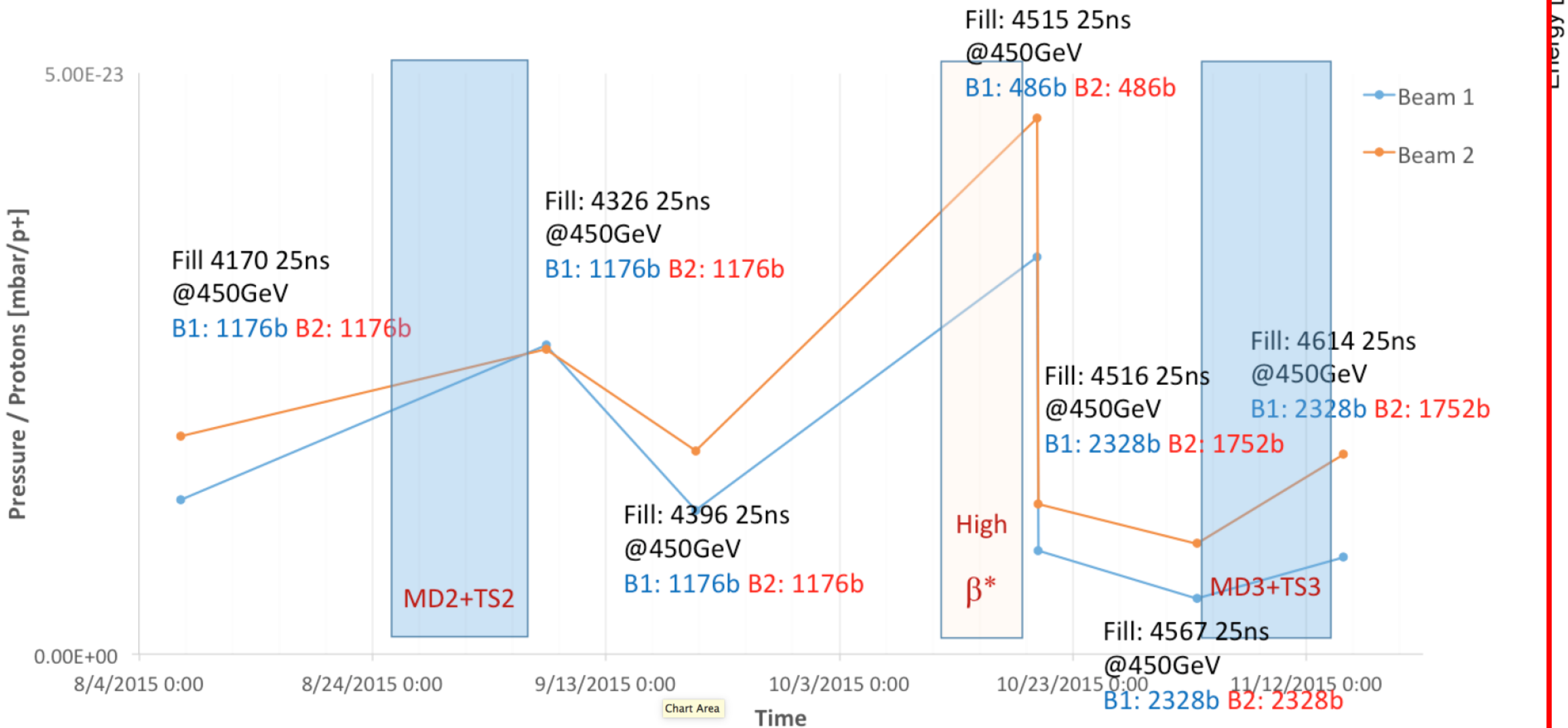
- By the **end of the scrubbing run** it was **possible to store 1177b.** with injections of 144b. without significant beam degradation from the electron cloud
- **Two weeks later**, strong **emittance blow-up** was observed **with 459b.** with injections of 72b.
  - → Decided to perform **check fills at 450 GeV** to monitor more precisely the e-cloud evolution

Deconditioning & reconditioning



Scrubbing checks at 450 GeV

From vacuum gauges



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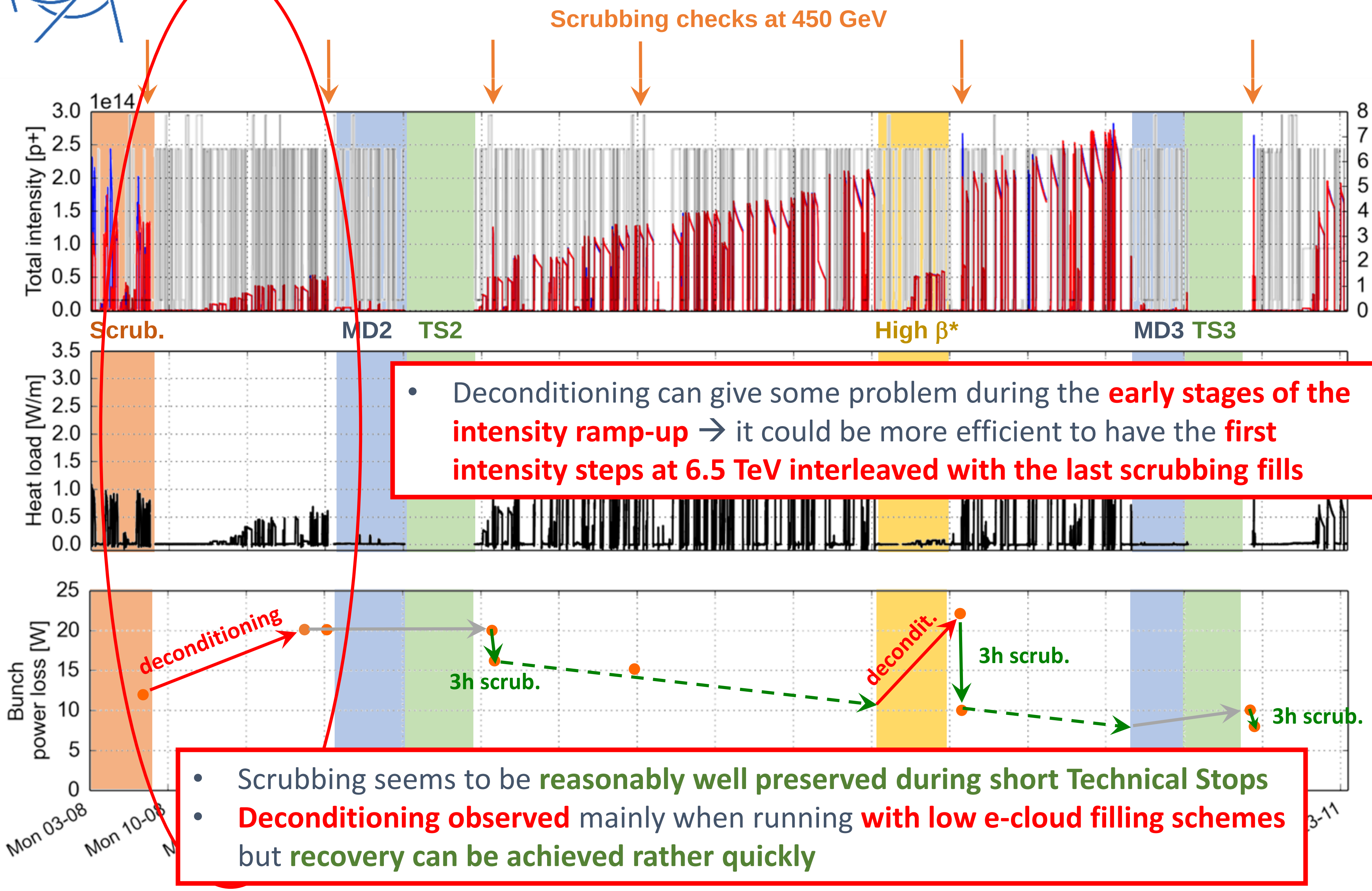
Deconditioning & reconditioning



- Deconditioning can give some problem during the **early stages of the intensity ramp-up** → it could be more efficient to have the **first intensity steps at 6.5 TeV interleaved with the last scrubbing fills**

- Scrubbing seems to be **reasonably well preserved during short Technical Stops**
- **Deconditioning observed** mainly when running **with low e-cloud filling schemes** but **recovery can be achieved rather quickly**

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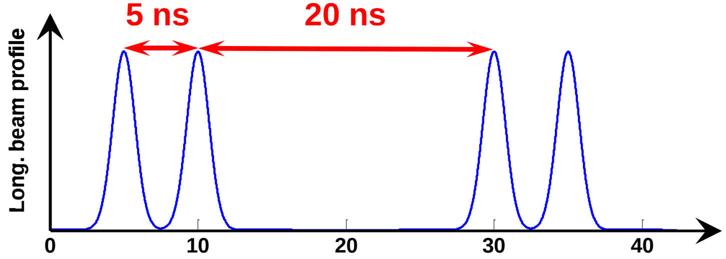
Doublets

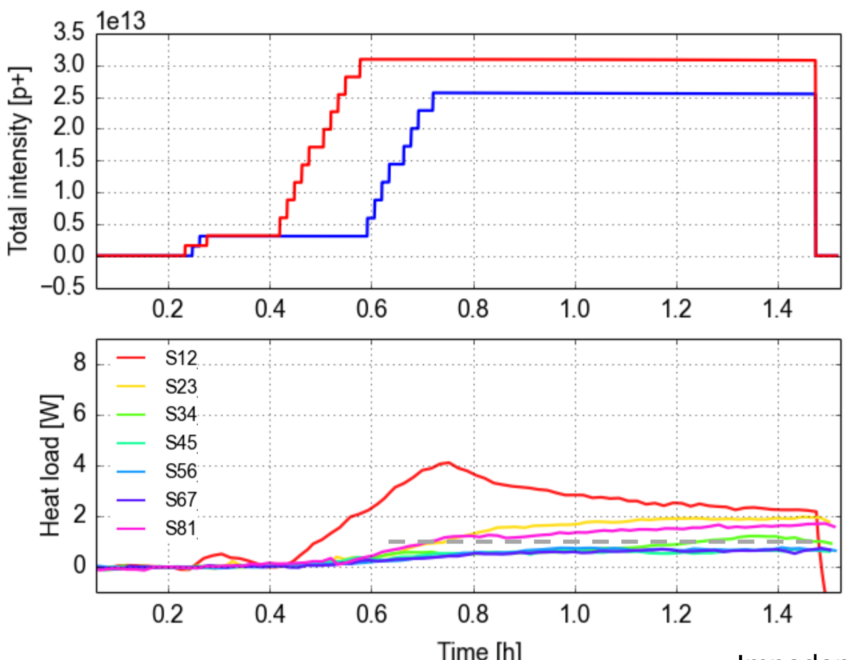


Similarly to scrubbing with 25 ns beams to ensure ecloud-free with 50 ns beams, the **doublets boost scrubbing for 25 ns beams**

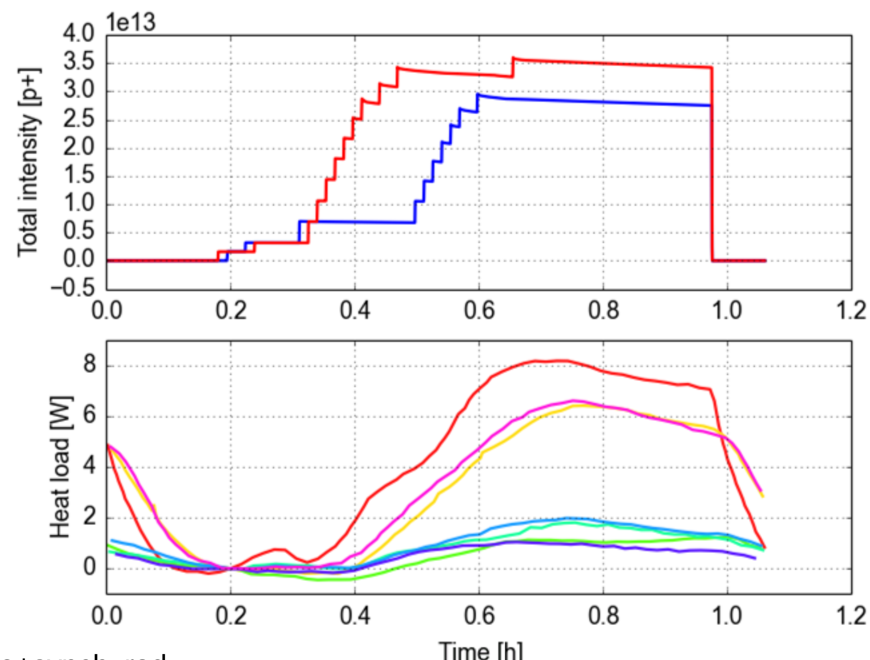
Doublet trains were **tested** for the first time in the LHC during the Scrubbing Run

- e-cloud enhancement could be **confirmed experimentally**

Standard 25 ns beam

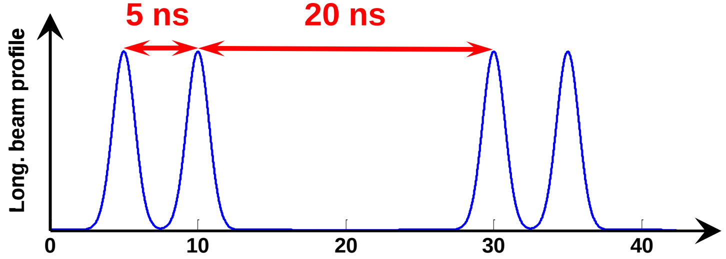


"Doublet" beam



Impedance+synch. rad

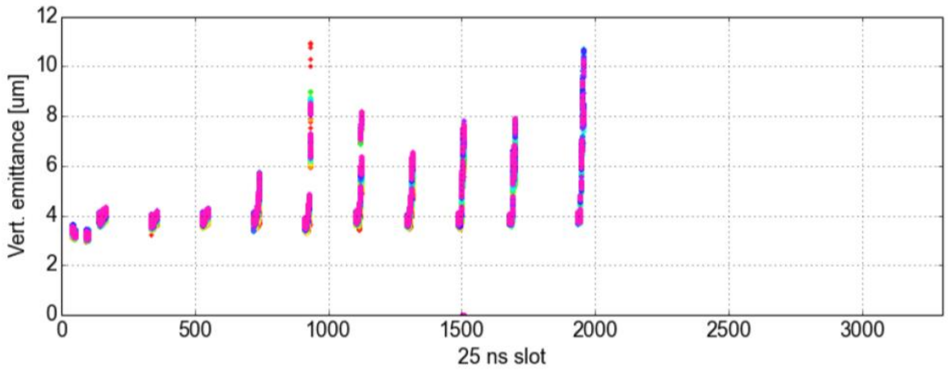
Doublets

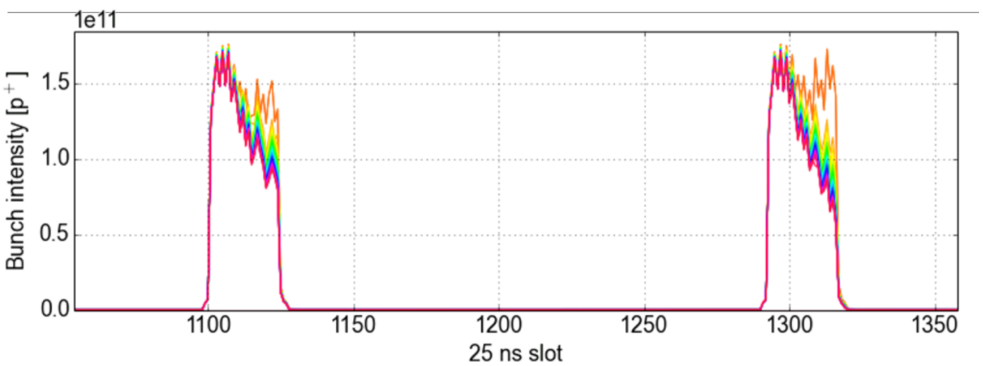


Similarly to scrubbing with 25 ns beams to ensure ecloud-free with 50 ns beams, the **doublets boost scrubbing for 25 ns beams**

Doublet trains were **tested** for the first time in the LHC during the Scrubbing Run

- e-cloud enhancement could be **confirmed experimentally**
- But, due to **violent e-cloud instabilities**, it was **impossible to inject enough beam** and keep sufficient beam quality **for efficient scrubbing** with doublets





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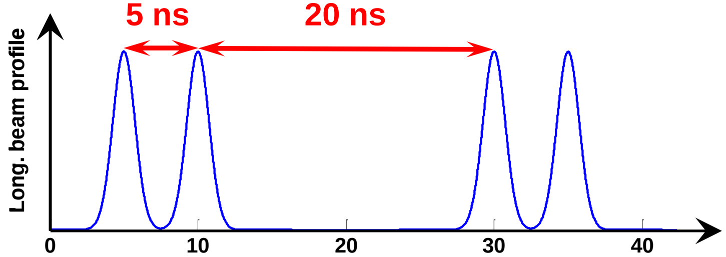
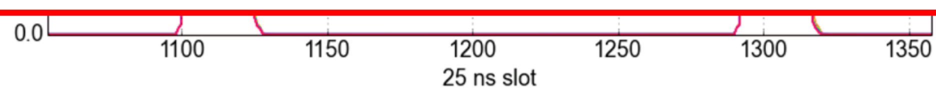


Similarly to scrubbing with 25 ns beams to ensure ecloud-free with 50 ns beams, the **doublets boost scrubbing for 25 ns beams**

Considerations for 2016

- As long as in physics we are **running at the cryogenics limit** (with strong load in the dipoles) by definition there is **no way to increase the scrubbing efficiency**
- On the other hand, when we will have lowered significantly the SEY in the dipoles, doublets **could become interesting** to **bring the SEY below the threshold for 25 ns**
- To achieve a good efficiency with doublets **we need better control of e-cloud instabilities** → more bunches in longer trains
- For this purpose:
  - → Doublet should be tested **after having accumulated enough scrubbing** with nominal beam (i.e. not at the beginning of the run)
  - → Operate with **high Q' to stabilize** and **lower tunes to preserve lifetime**
  - → Optimize **ADT configuration** for doublet intensity and working point



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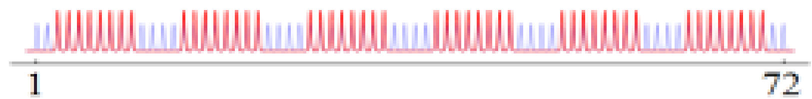
8b+4e scheme

- Filling pattern designed to **suppress the e-cloud build-up** (lower thresholds expected from simulations, and verified in SPS MD)

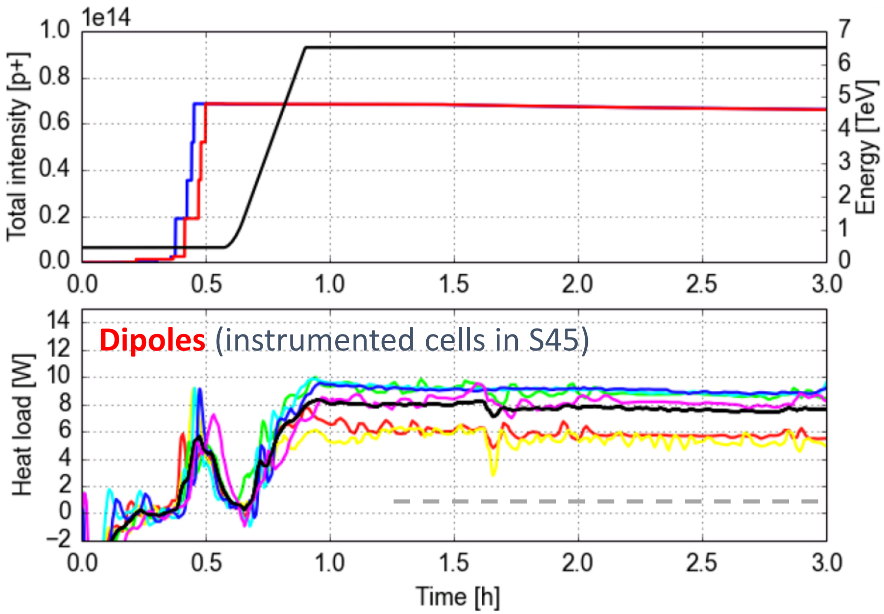
  → **Confirmed experimentally in the LHC** in 2015

  → Validated as **alternative scenario** in case of strong e-cloud limitations

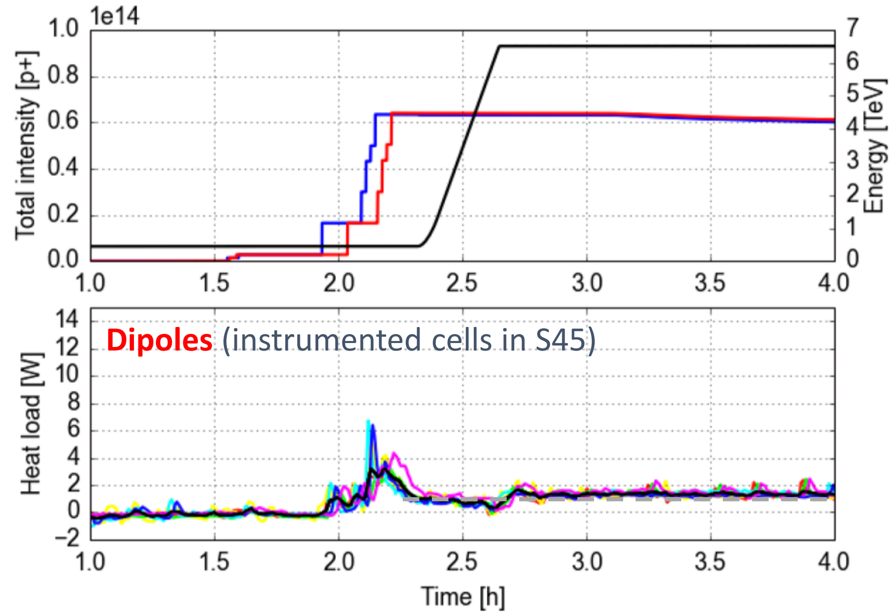
Up to ~1850b. in the LHC



Standard 25 ns beam



"8b+4e" beam



— Average
- - Impedance+synch. rad

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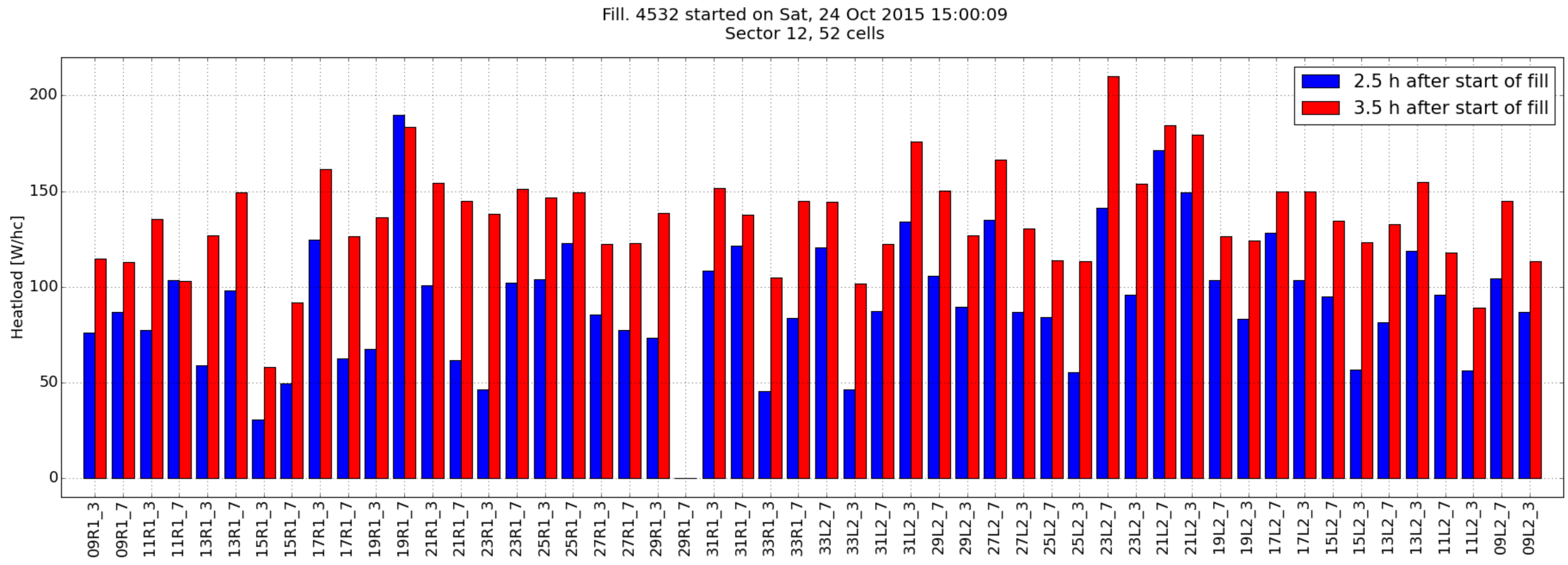
First lessons to retain

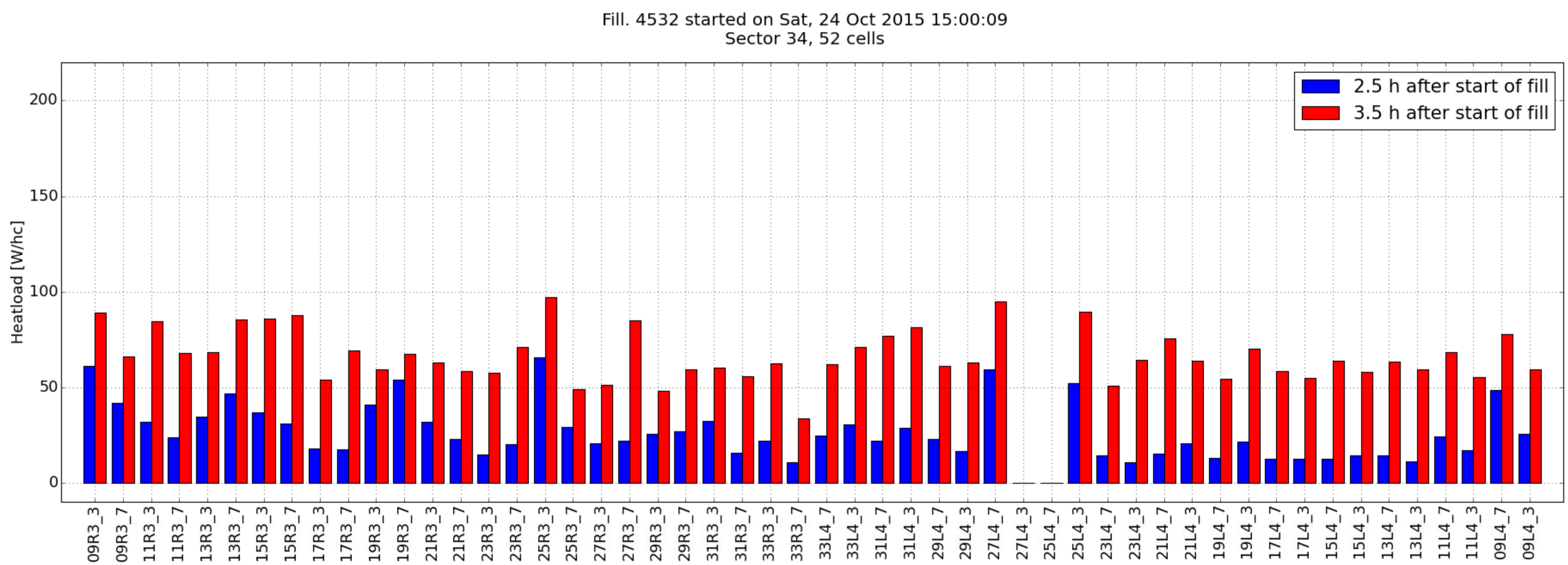
- **Scrubbing** at 450 GeV allows to **mitigate e-cloud instabilities** and **beam degradation** occurring at low energy
- After this stage, relying on ADT and high Q' and octupoles, it is **possible to preserve good beam quality from injection to collision** in spite of the e-cloud still present in the machine → high heat load in the arcs
- **Parasitic scrubbing** accumulated during the physics run has **lowered the heat load** in the dipoles by roughly a factor two (in two months)
  - → The **doses needed** to see an evolution at this stage are **very large**, practically incompatible with a dedicated scrubbing run
  - → Possible **recipe for the future** (e.g. after LS2): relatively **short scrubbing at injection** to get the beam under control, then accumulate **further dose in parallel with physics** (but slower intensity ramp up)

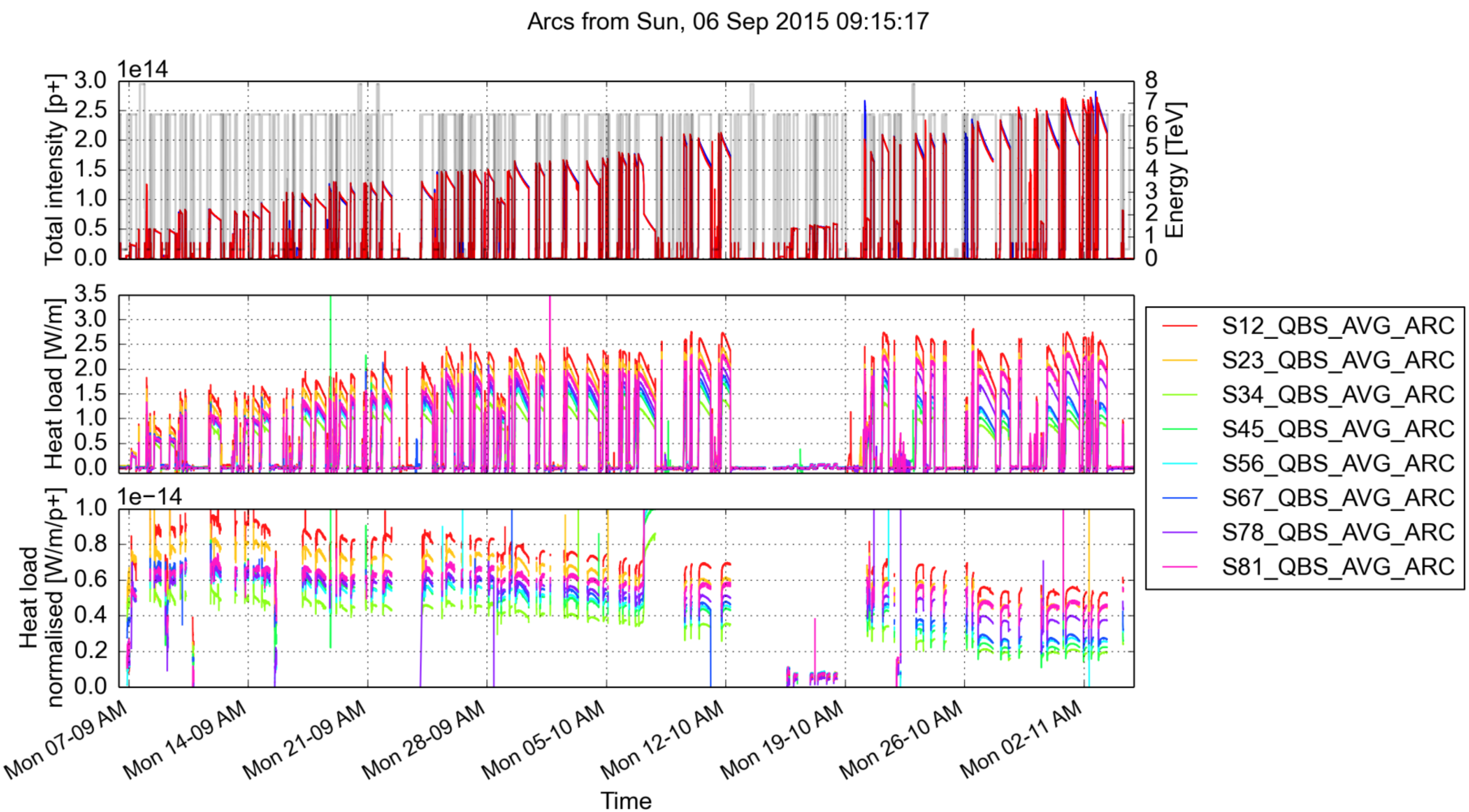
Proposal for the 2016 start-up

- Arcs will be kept under vacuum → **scrubbing should be at least partially preserved** during the YETS
- Scrubbing **proposal for 2016**:
  - **4 days scrubbing run** should be reasonable to recover high intensities at 450 GeV (assuming setup for high intensity is done before, e.g. injection, ADT)
  - A few **"refresh" scrubbing fills during first 1-2 weeks of intensity ramp up** in physics (to avoid problems with deconditioning)
  - **During intensity ramp up**:
    - → As long as no limitation is encountered, try to **maximize electron dose** by using long trains (up to 288b. per injection) → **it will pay off later**
    - → If/when cryo limit is reached, move to **optimized filling scheme** to gain luminosity
    - → Use **physics fills to accumulate more scrubbing** for further intensity increase
- **Doublet test** to be performed when **SEY is sufficiently low** (e.g. at least after recovering the end-2015 situation) to check whether good beam quality can be preserved
  - → In case of positive outcome, **first scrubbing stores with doublets**

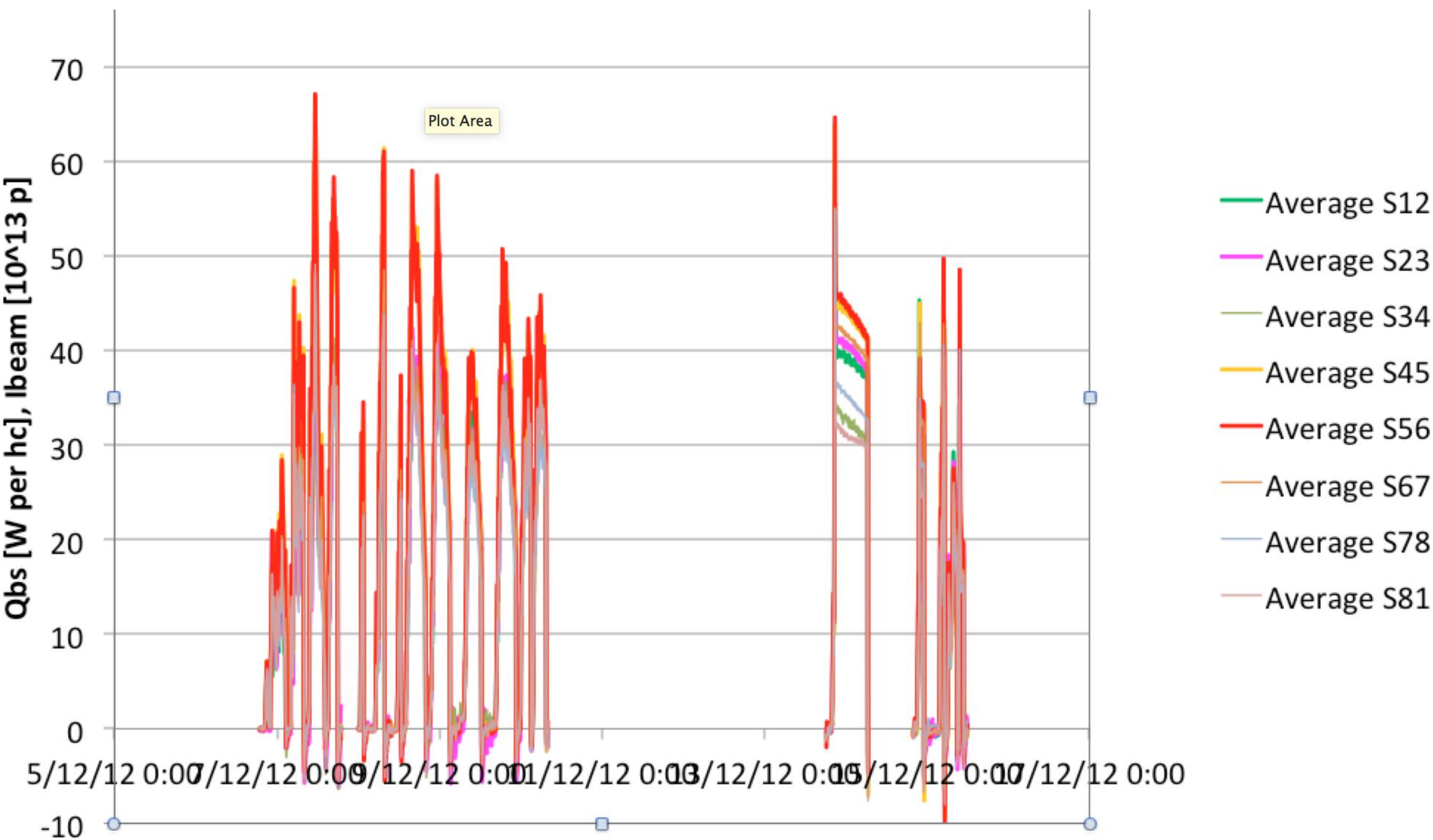
Thanks for your attention!

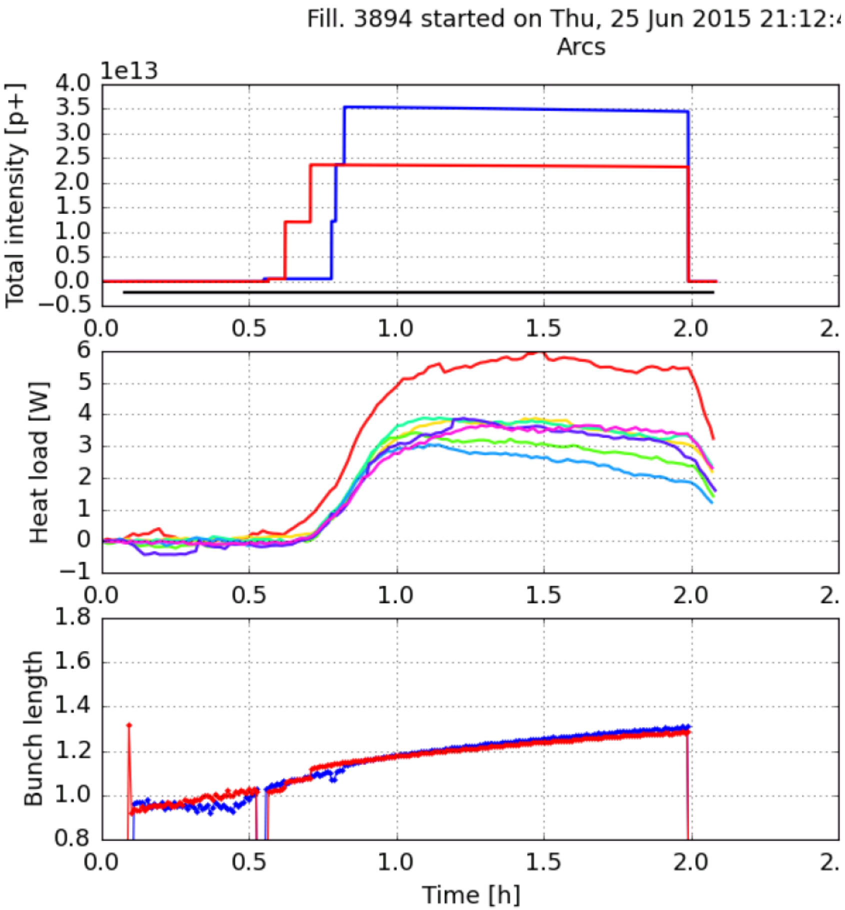

Fill. 4532 started on Sat, 24 Oct 2015 15:00:09
Sector 12, 52 cells
Heatload [W/hc]
2.5 h after start of fill
3.5 h after start of fill


Fill. 4532 started on Sat, 24 Oct 2015 15:00:09
Sector 34, 52 cells
Heatload [W/hc]
2.5 h after start of fill
3.5 h after start of fill

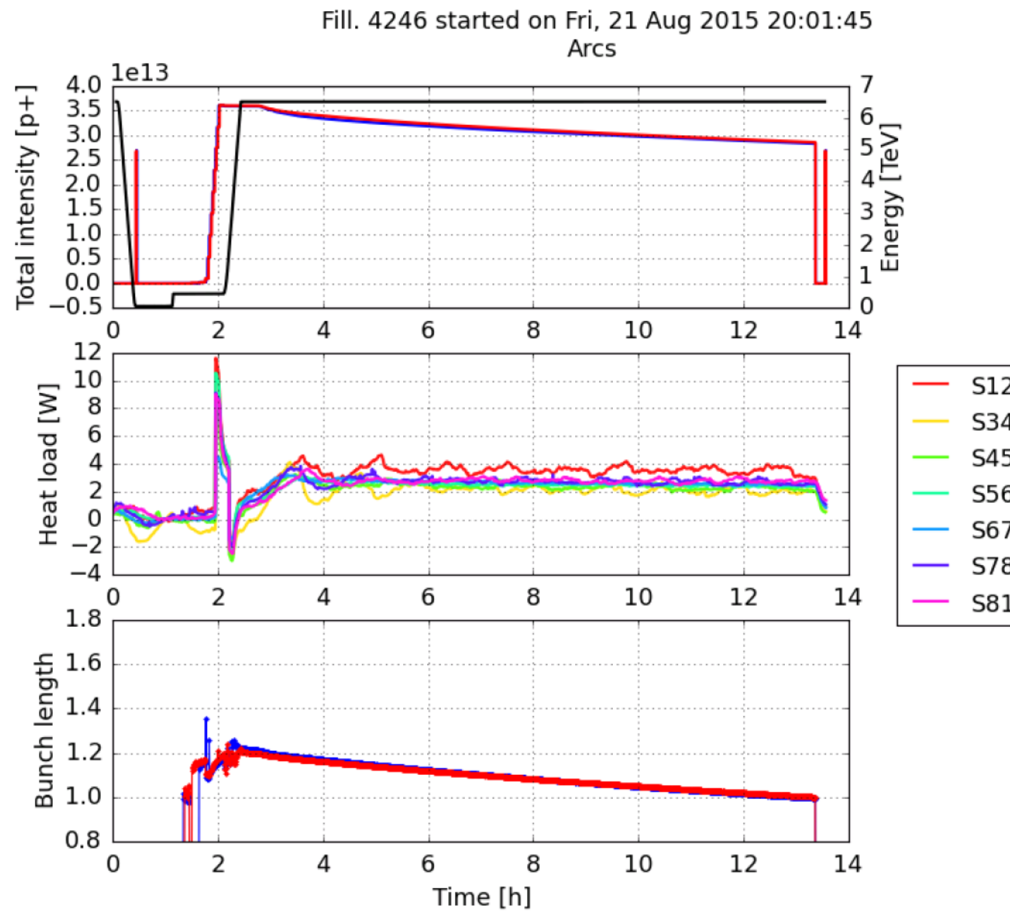


Arcs from Sun, 06 Sep 2015 09:15:17
1e14
Total intensity [p+]
Energy [TeV]
Heat load [W/m]
1e−14
Heat load
normalised [W/m/p+]
S12_QBS_AVG_ARC
S23_QBS_AVG_ARC
S34_QBS_AVG_ARC
S45_QBS_AVG_ARC
S56_QBS_AVG_ARC
S67_QBS_AVG_ARC
S78_QBS_AVG_ARC
S81_QBS_AVG_ARC
Mon 07-09 AM
Mon 14-09 AM
Mon 21-09 AM
Mon 28-09 AM
Mon 05-10 AM
Mon 12-10 AM
Mon 19-10 AM
Mon 26-10 AM
Mon 02-11 AM
Time

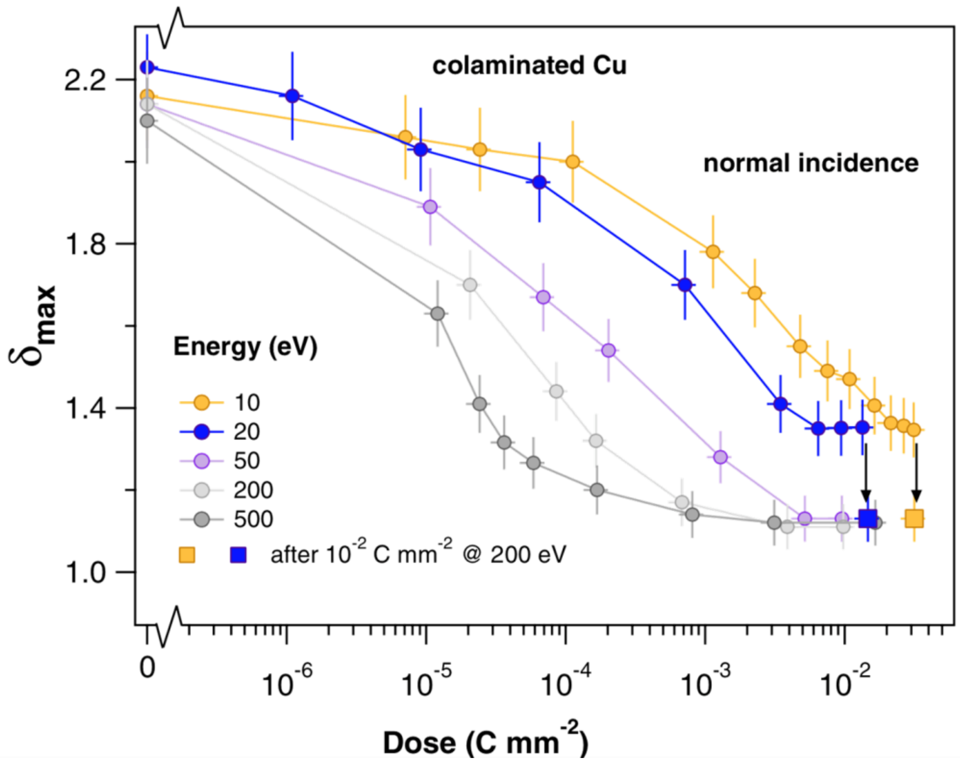

Plot Area
Qbs [W per hc], Ibeam [10^13 p]
70
60
50
40
30
20
10
0
-10
5/12/12 0:00
7/12/12 0:00
9/12/12 0:00
11/12/12 0:00
13/12/12 0:00
15/12/12 0:00
17/12/12 0:00
Average S12
Average S23
Average S34
Average S45
Average S56
Average S67
Average S78
Average S81



Fill. 3894 started on Thu, 25 Jun 2015 21:12:
Arcs
1e13
Total intensity [p+]
Heat load [W]
Bunch length
Time [h]



Fill. 4246 started on Fri, 21 Aug 2015 20:01:45
Arcs
1e13
Total intensity [p+]
Energy [TeV]
Heat load [W]
Bunch length
Time [h]
S12
S34
S45
S56
S67
S78
S81



colaminated Cu
normal incidence
Energy (eV)
10
20
50
200
500
after 10^-2 C mm^-2 @ 200 eV
δmax
2.2
1.8
1.4
1.0
0
10^-6
10^-5
10^-4
10^-3
10^-2
Dose (C mm^-2)

Scrubbing accumulated during the physics run

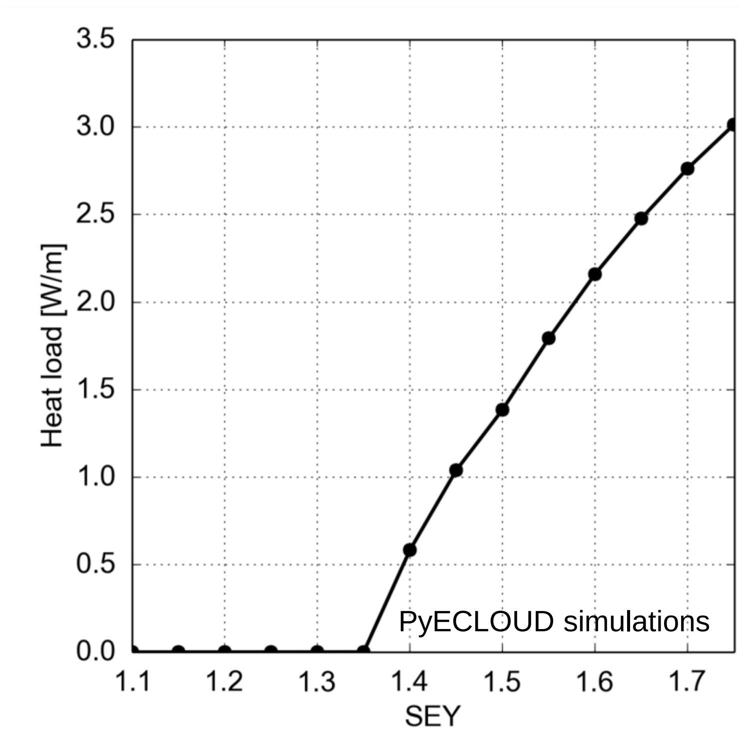
At the end of the p-p run we repeated an early fill of the intensity ramp-up

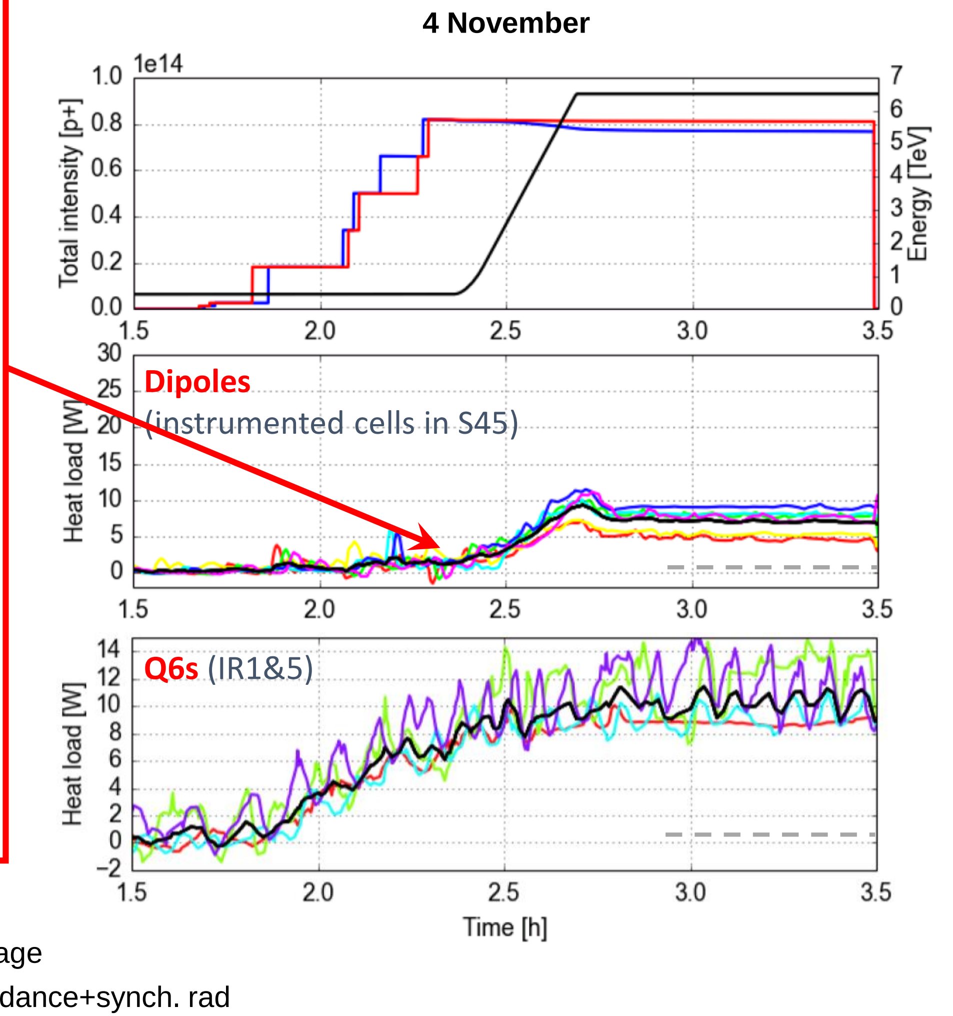
- **Very similar beam conditions** (filling pattern, bunch intensity, bunch length)
- After 2 months, significant **reduction visible in all arcs** (30% to 60% depending on the sector)

magnets (higher SEY threshold compared to quads)

Practically **no measurable heat load in the dipoles at 450 GeV** (at least in S45)

→ **SEY** should be below **1.4**

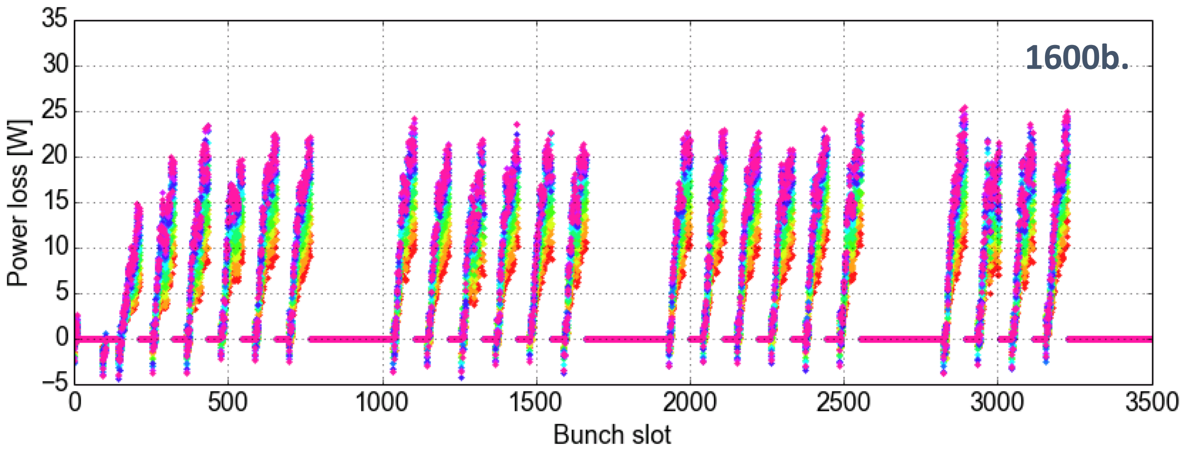




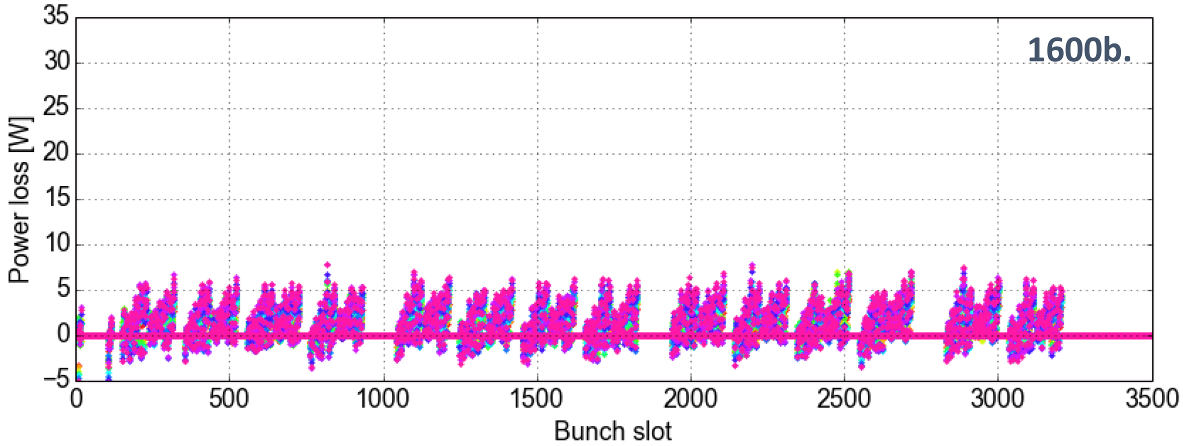
8b+4e scheme

- Filling pattern designed to **suppress the e-cloud build-up** (lower thresholds expected from simulations, and verified in SPS MD) → **confirmed experimentally in the LHC** in 2015

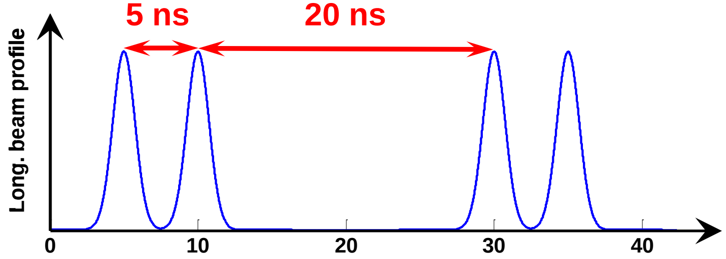
Standard 25 ns beam



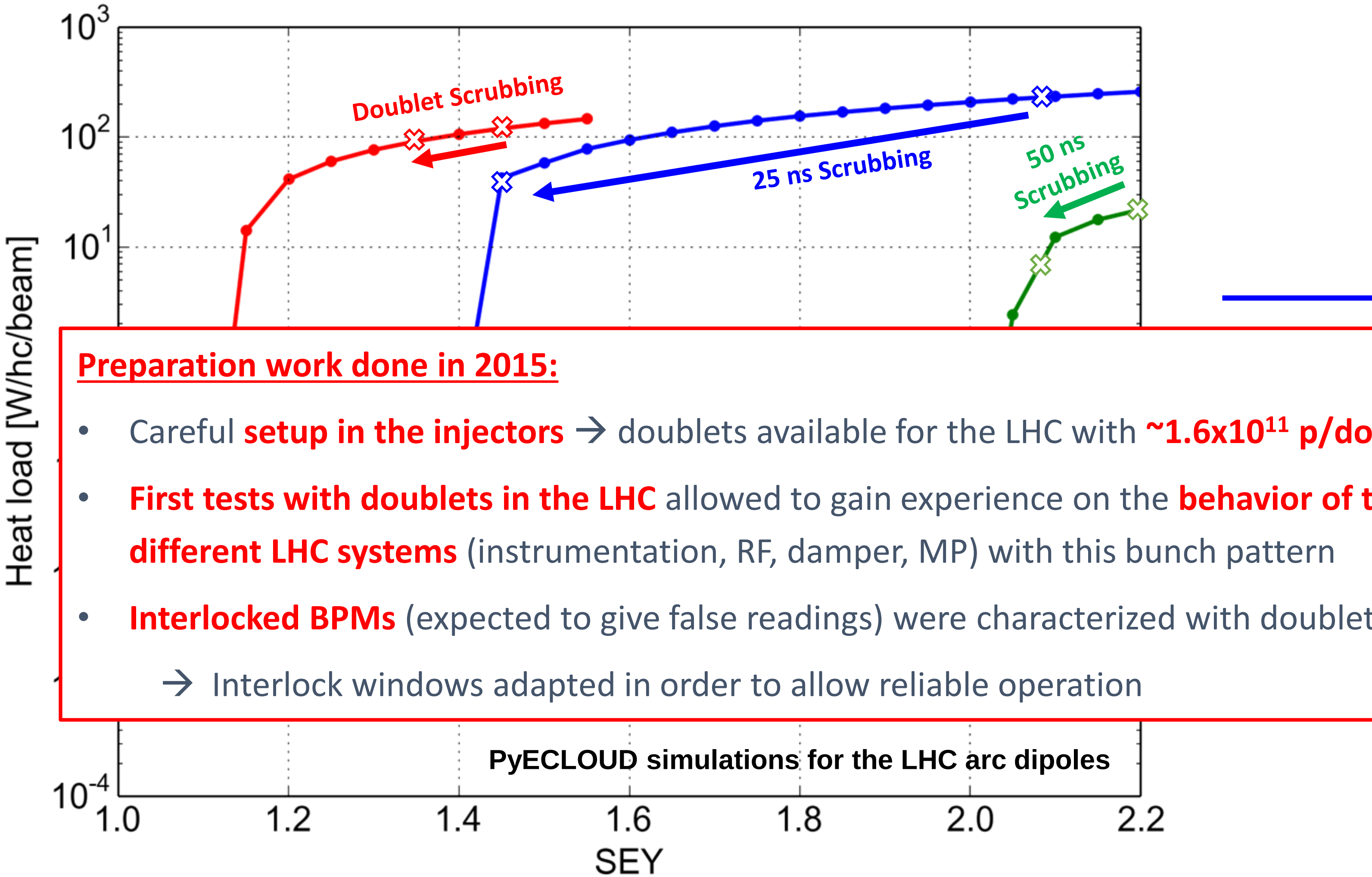
"8b+4e" beam



Doublets



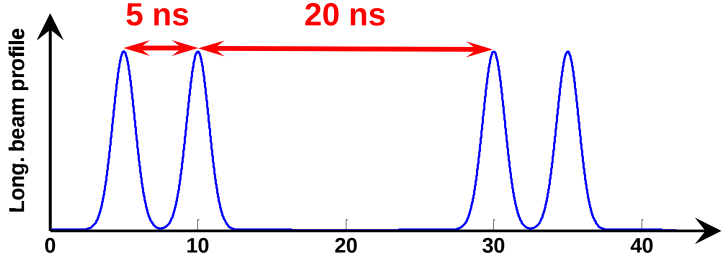
Similarly to scrubbing with 25 ns beams to ensure ecloud-free with 50 ns beams, the **doublet** would **boost scrubbing for 25 ns beams**



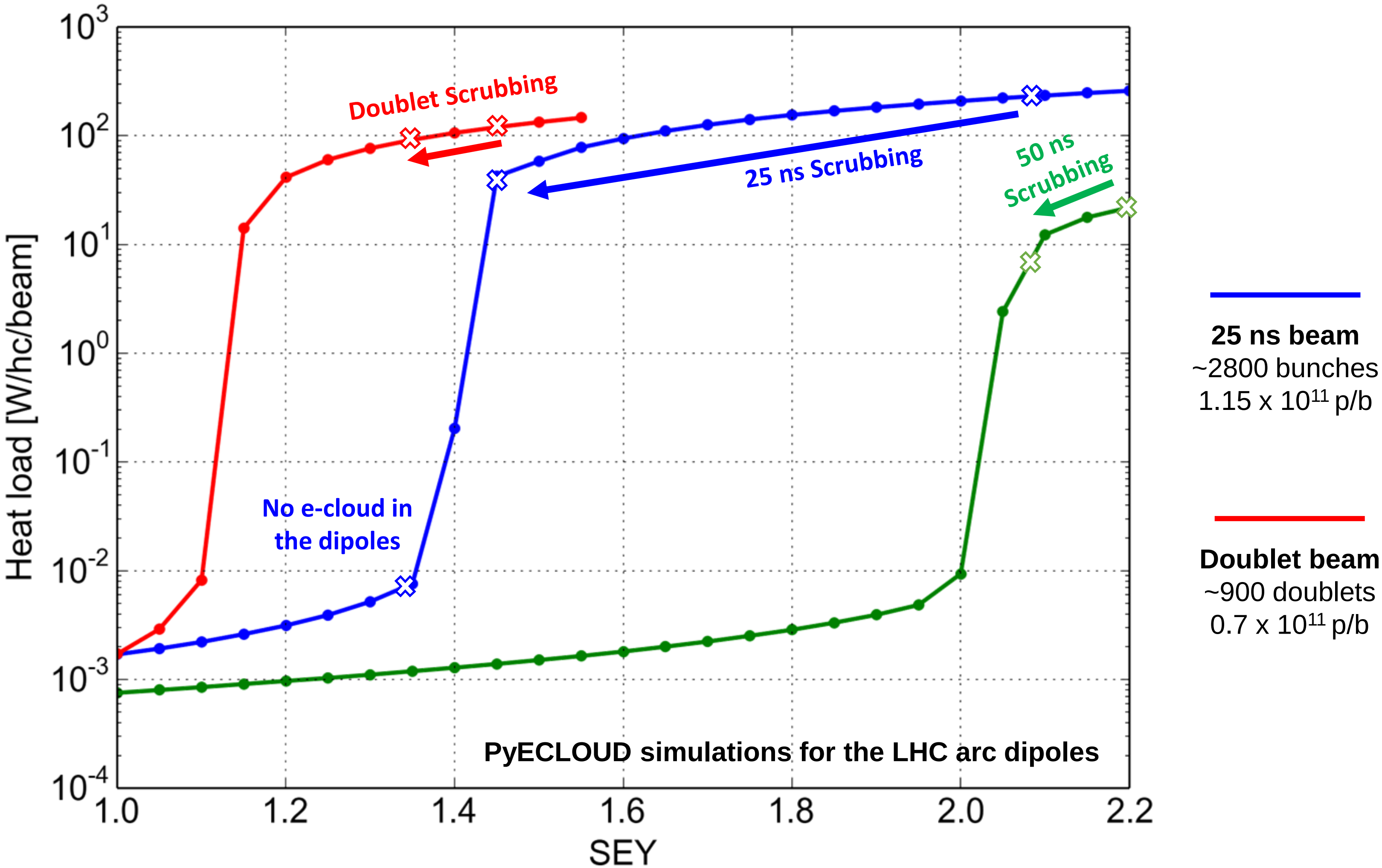
Preparation work done in 2015:

- Careful **setup in the injectors** → doublets available for the LHC with **~1.6x10^{11} p/doublet**
- **First tests with doublets in the LHC** allowed to gain experience on the **behavior of the different LHC systems** (instrumentation, RF, damper, MP) with this bunch pattern
- **Interlocked BPMs** (expected to give false readings) were characterized with doublets
  → Interlock windows adapted in order to allow reliable operation

Doublets



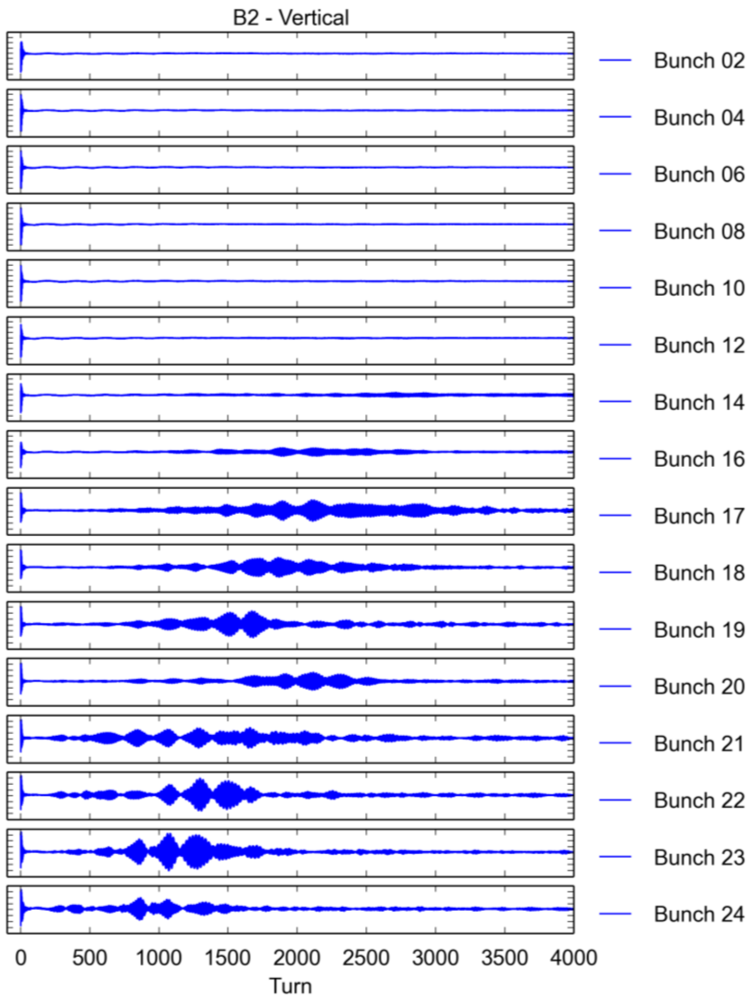
Similarly to scrubbing with 25 ns beams to ensure ecloud-free with 50 ns beams, the **doublet** would **boost scrubbing for 25 ns beams**

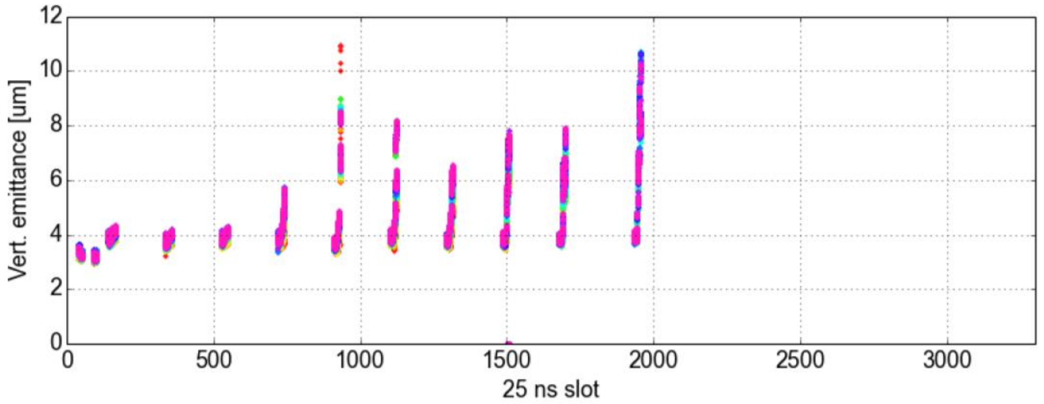


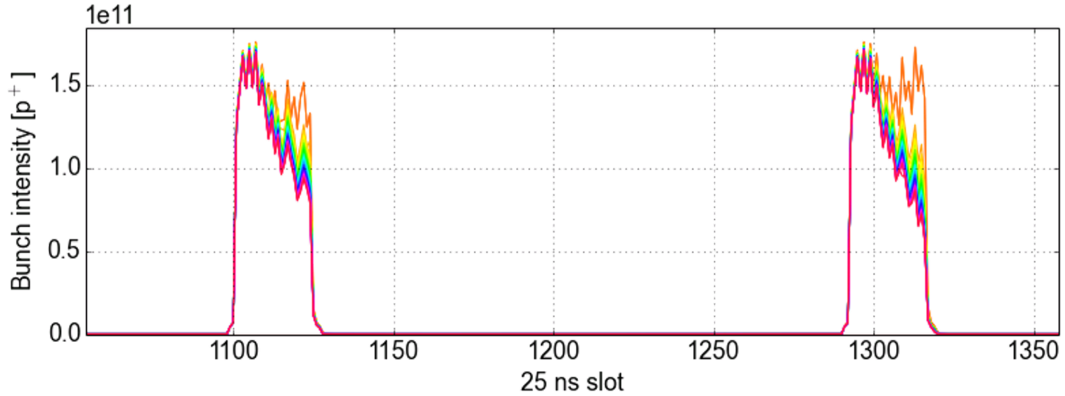
Doublets: instabilities and beam degradation

With doublets, **fast e-cloud induced instabilities** were observed, difficult to control even with high Q' and octupole settings and ADT ON

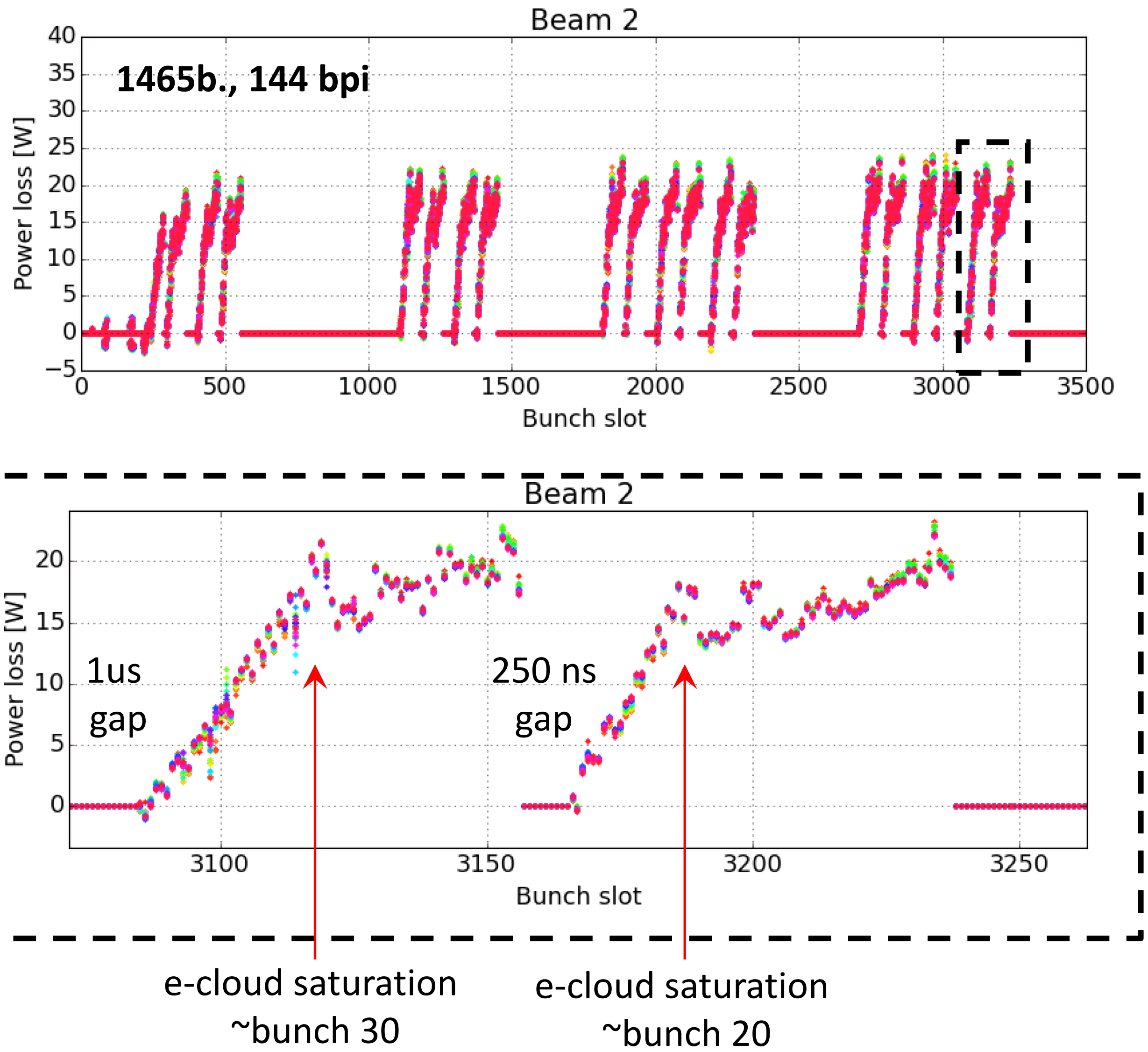
→ **strong emittance blow-up** and particle **losses**

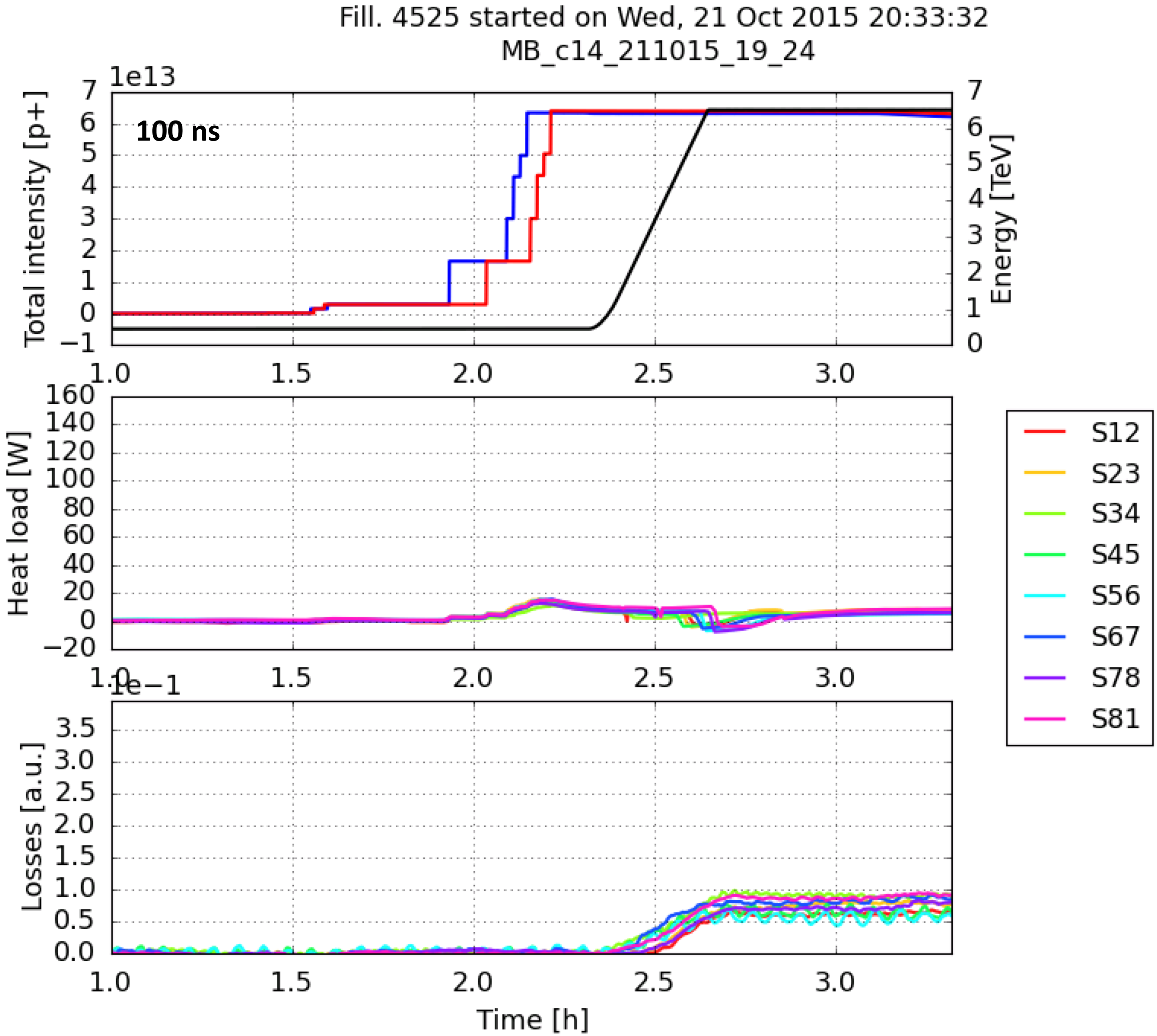




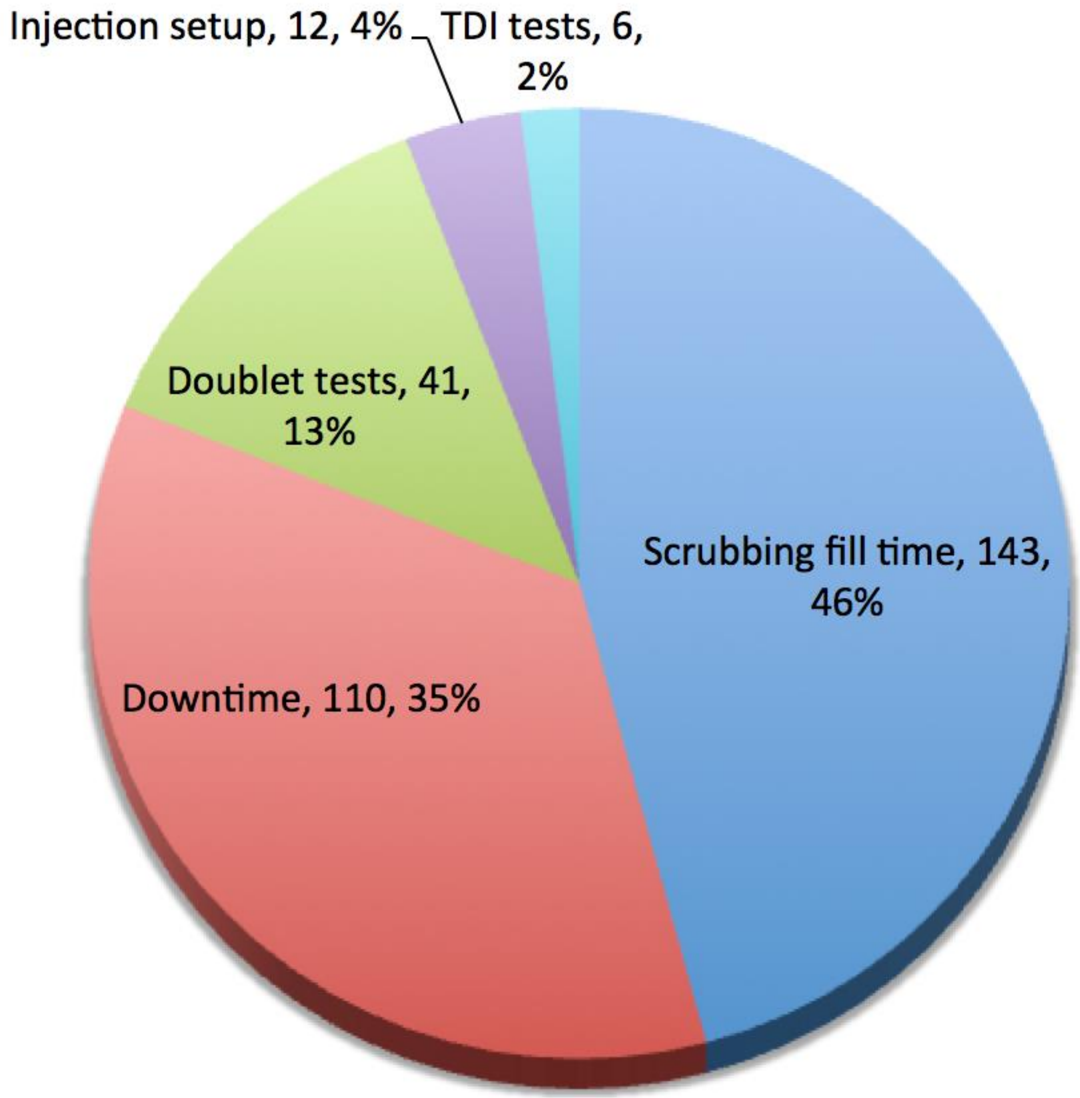


Effect of the bunch pattern





Fill. 4525 started on Wed, 21 Oct 2015 20:33:32
MB_c14_211015_19_24
100 ns
1e13
Total intensity [p+]
Energy [TeV]
Heat load [W]
1e−1
Losses [a.u.]
Time [h]
S12
S23
S34
S45
S56
S67
S78
S81


Injection setup, 12, 4%
TDI tests, 6, 2%
Doublet tests, 41, 13%
Scrubbing fill time, 143, 46%
Downtime, 110, 35%