Electron Cloud Effects

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LHC Coordination, BE-BI, BE-RF, BE-OP, EN-ICE, EN-STI, TE-ABT, TE-CRG, TE-VSC
for the invaluable support

Evian 2015 – 16 December 2015

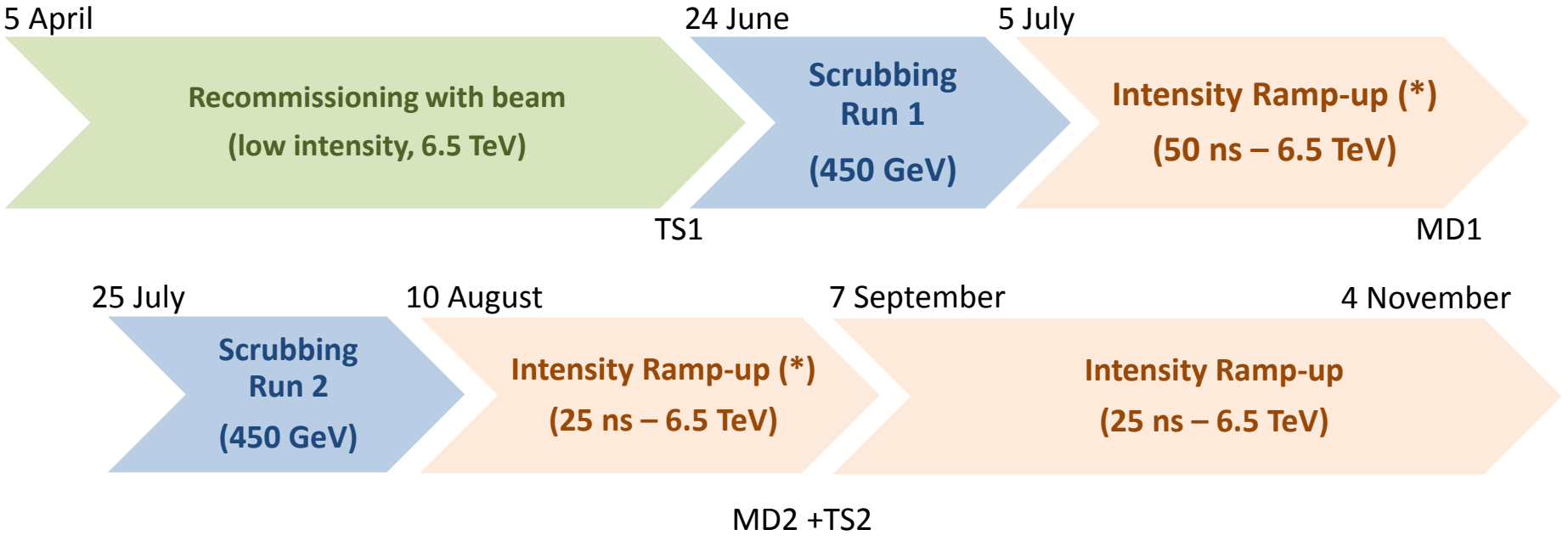
Outline

- **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 at **6.5 TeV** with **25 ns** beams
- Expected **challenges from e-cloud effects** (as anticipated from 25 ns pilot run in 2012)

  → Plenty of time allocated for **scrubbing**
- Decided to operate with **~nominal bunch parameters** (injecting 1.1 x 10^{11} ppb in 2.5 um)



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

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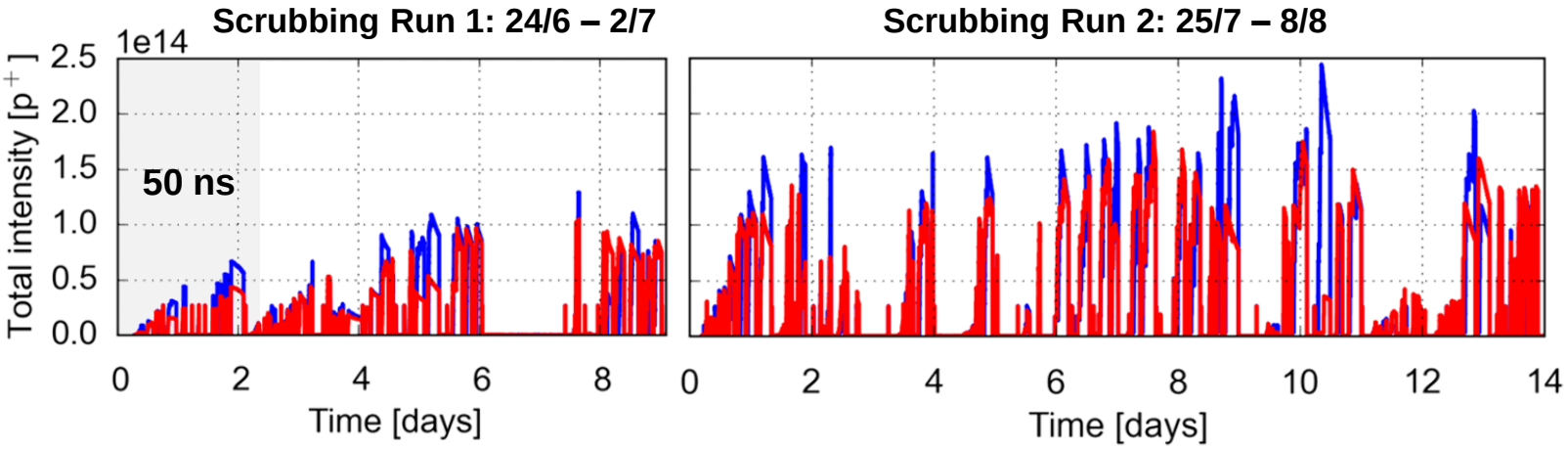
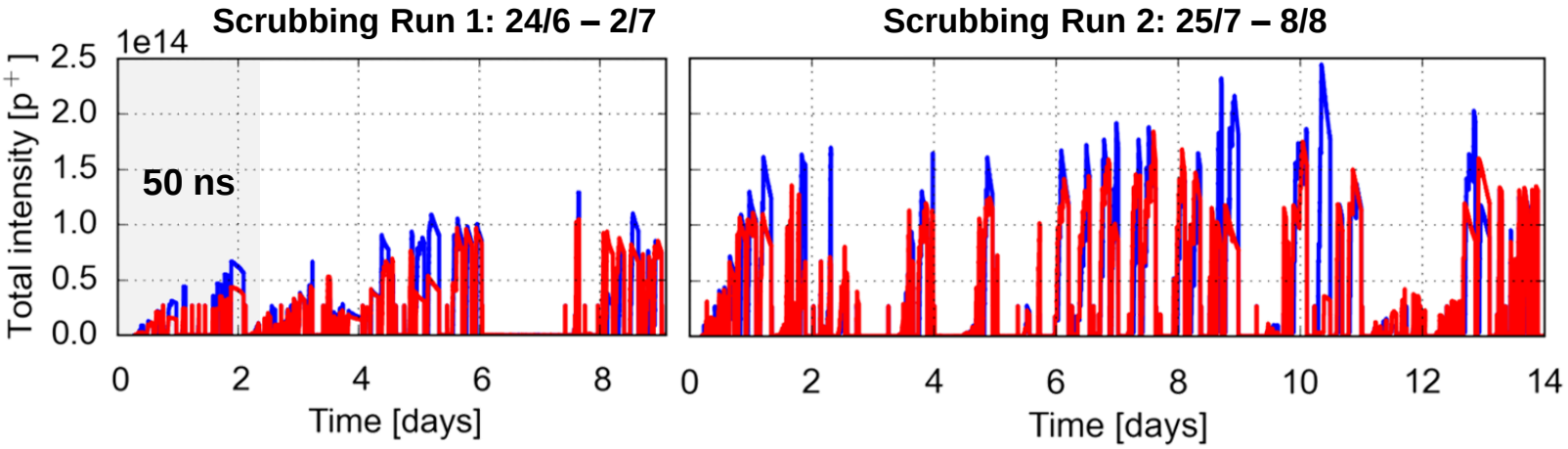
Scrubbing for 25 ns operation



- **After LS1 the SEY was practically reset** w.r.t what was observed at the 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** (dump from BLM or interlocked BPM dumps), evidently getting better with scrubbing
  - **Transients on beam screen temperatures** → long waiting time between injections (should be better now with the new CM rules)
  - Vacuum spikes at the **TDI8** limiting the intensity for beam 2 (see talk by A. Lechner)
  - Pressure rise in the **MKIs** (required close follow-up by TE-ABT and TE-VSC team, interlock changes)

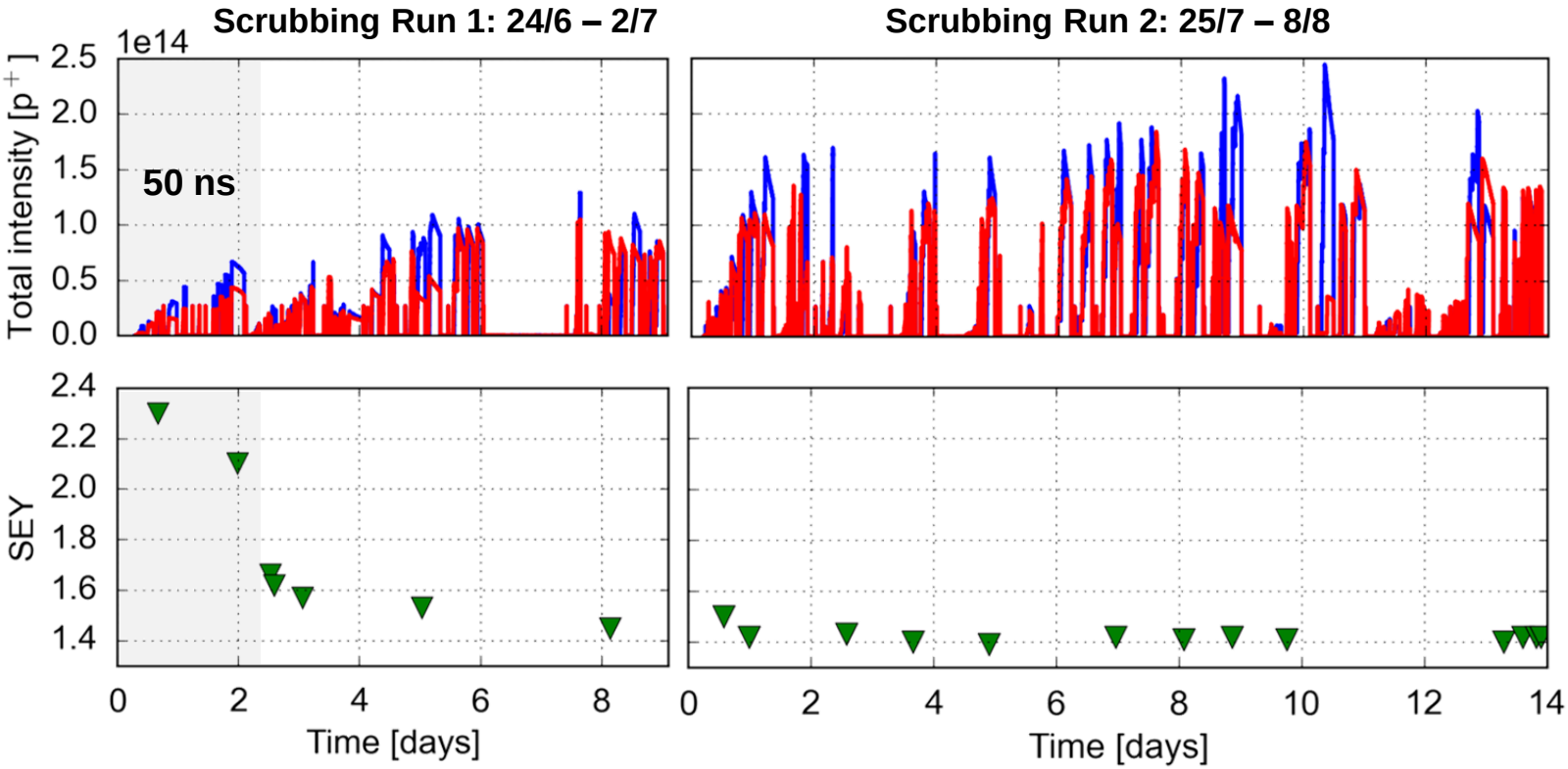
Scrubbing for 25 ns operation



Follow-up and **optimization** of the process heavily based on lost of **non-standard diagnostics** (heatload, RF stable phases, data from ADT pickups)

→ **many thanks** to the different teams for the **great preparation work!**

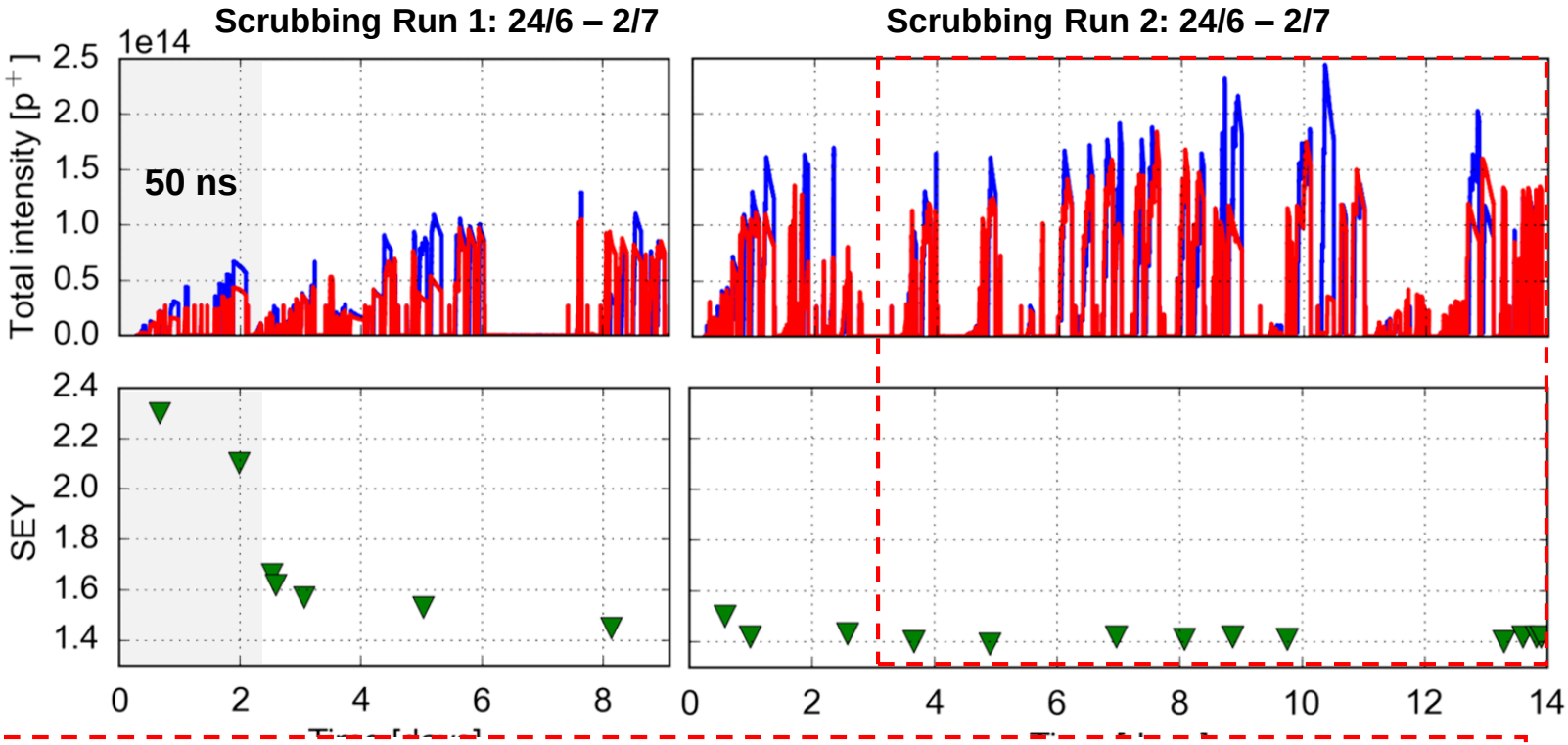
Scrubbing for 25 ns operation

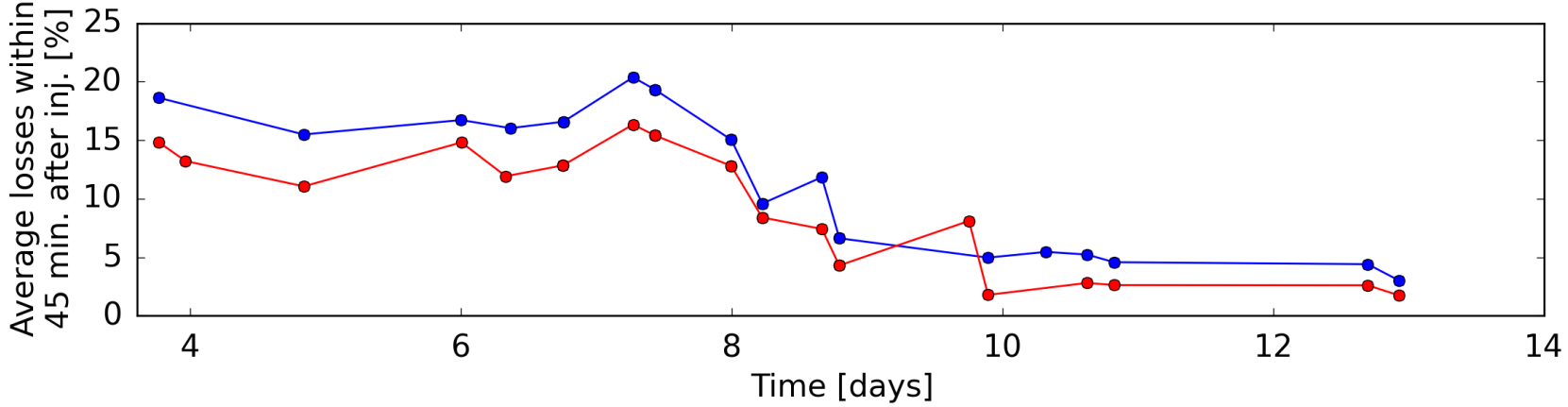


SEY was reconstructed comparing **heat load** and **RF stable phase** measurements against **PyECLOUD simulations**

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

Scrubbing for 25 ns operation





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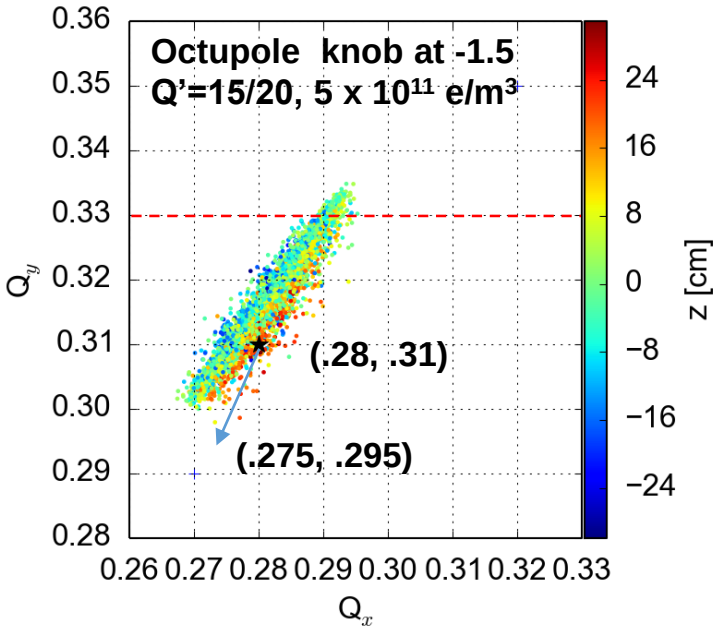
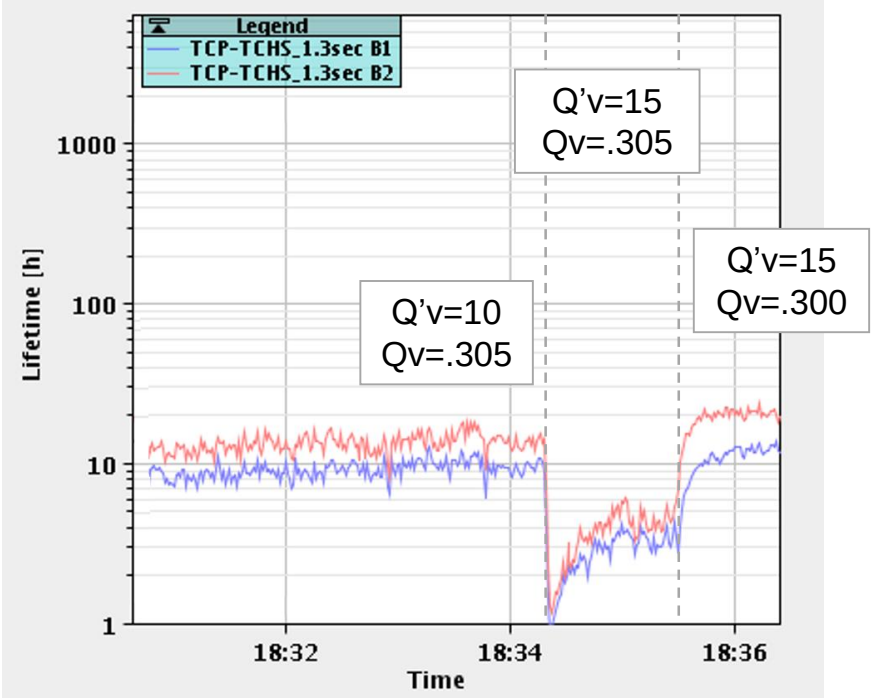
Intensity ramp-up with 25 ns beams: beam dynamics

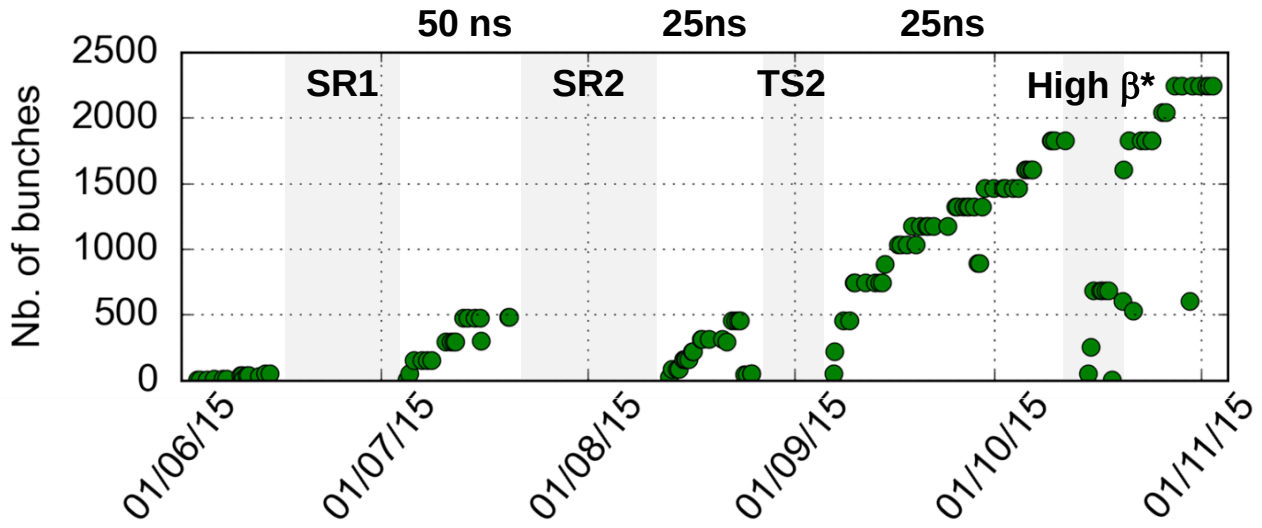
- Scrubbing Run provided **sufficient mitigation against beam degradation** at 450 GeV but **full suppression of the e-cloud was not achieved**
  - → During the physics intensity ramp-up we had to learn how to **run the machine in the presence of the e-cloud**
- **Tricky to ensure beam stability at 450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





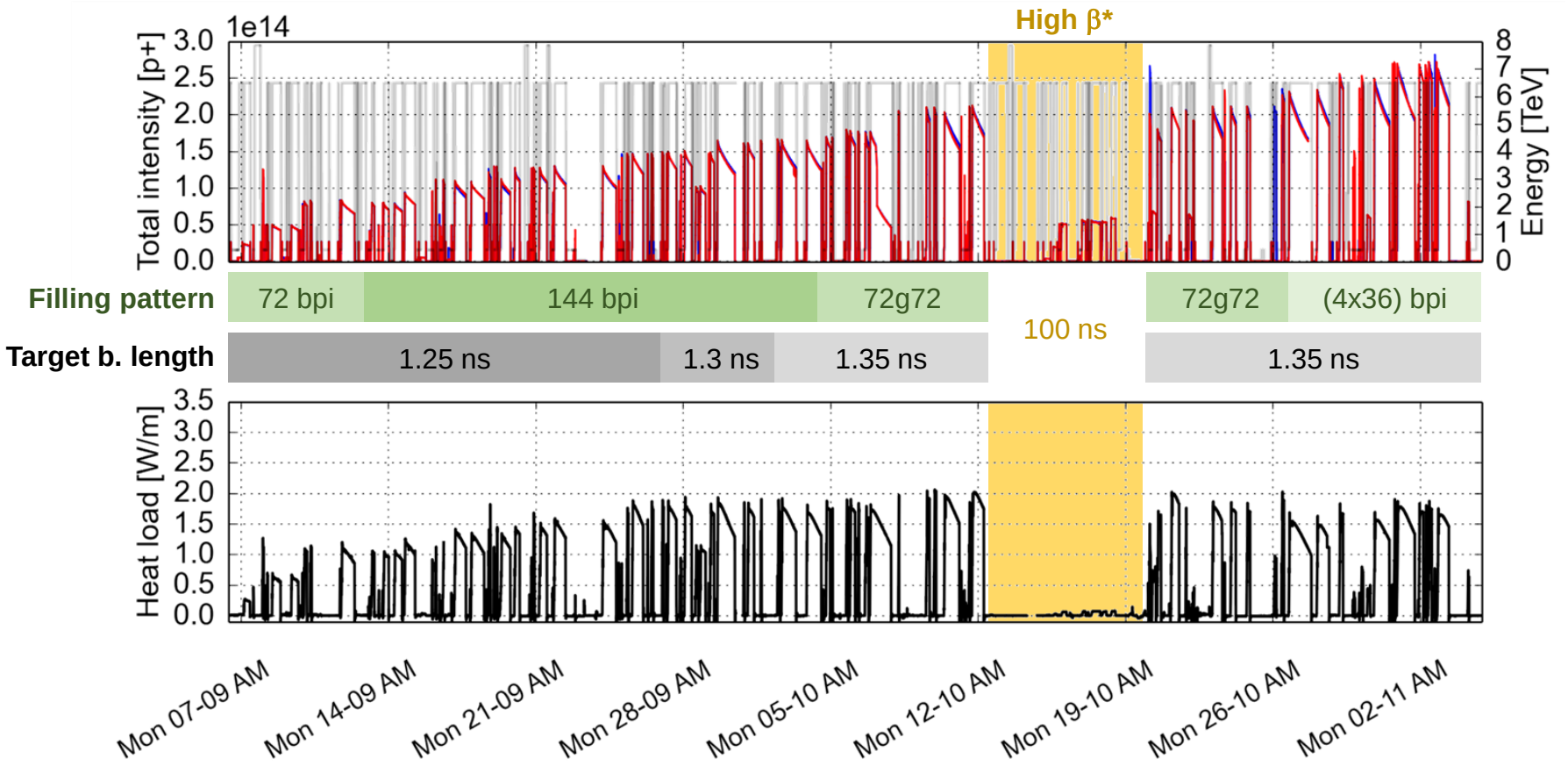
Intensity ramp-up with 25 ns beams: heat loads

- 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** (see talk by K. Brodzinsky):
    - → **Modified Cryo Maintain rules** to allow for larger temperature excursion
    - → Improvement on **cryogenic feed-forward** control



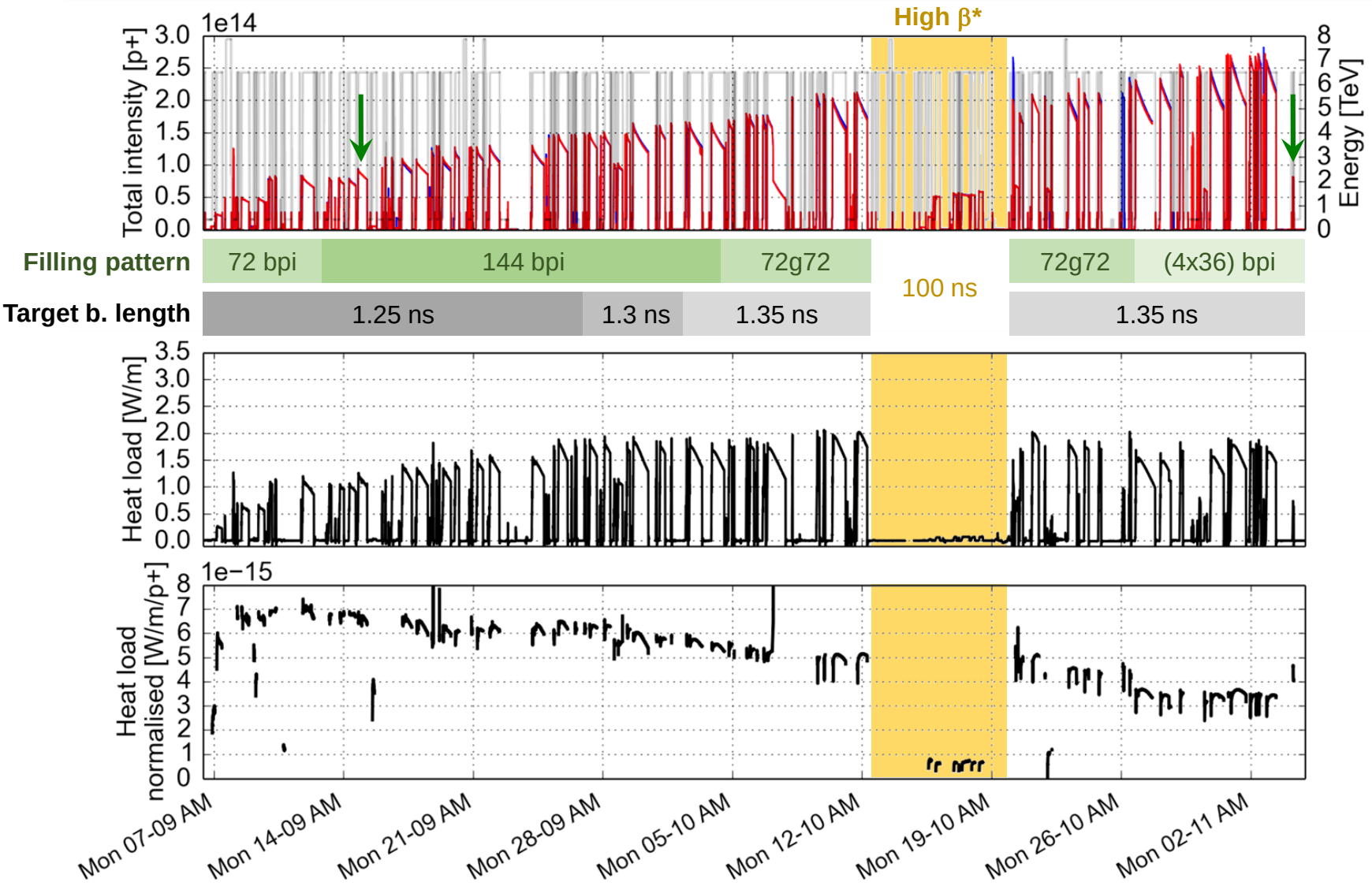
Intensity ramp-up with 25 ns beams: heat loads

- 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

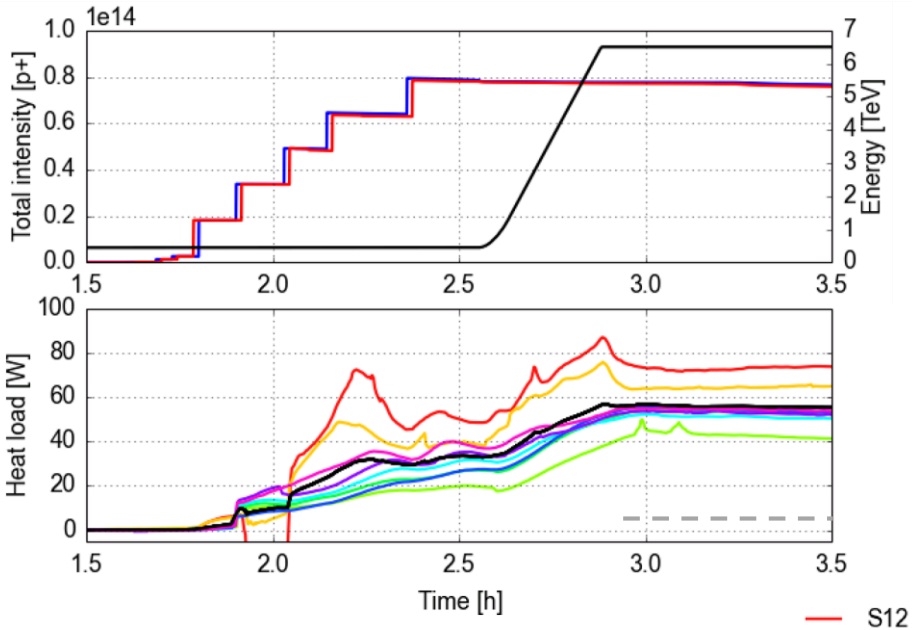


Scrubbing accumulated during the physics run

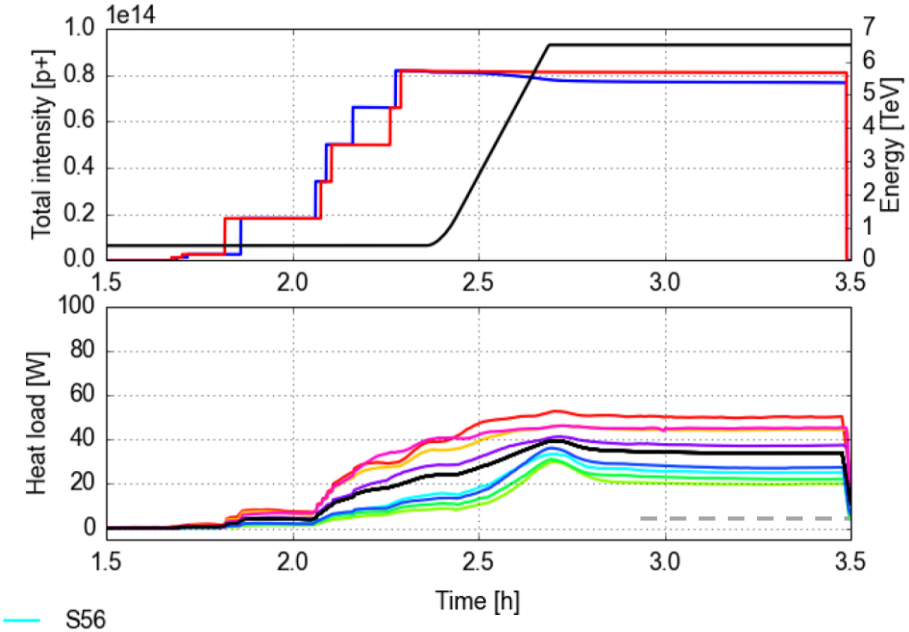
At the end of the p-p run we repeated an early fill of the intensity ramp-up

- **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



S12
S23
S34
S45
S56
S67
S78
S81
Average
Impedance+synch. rad

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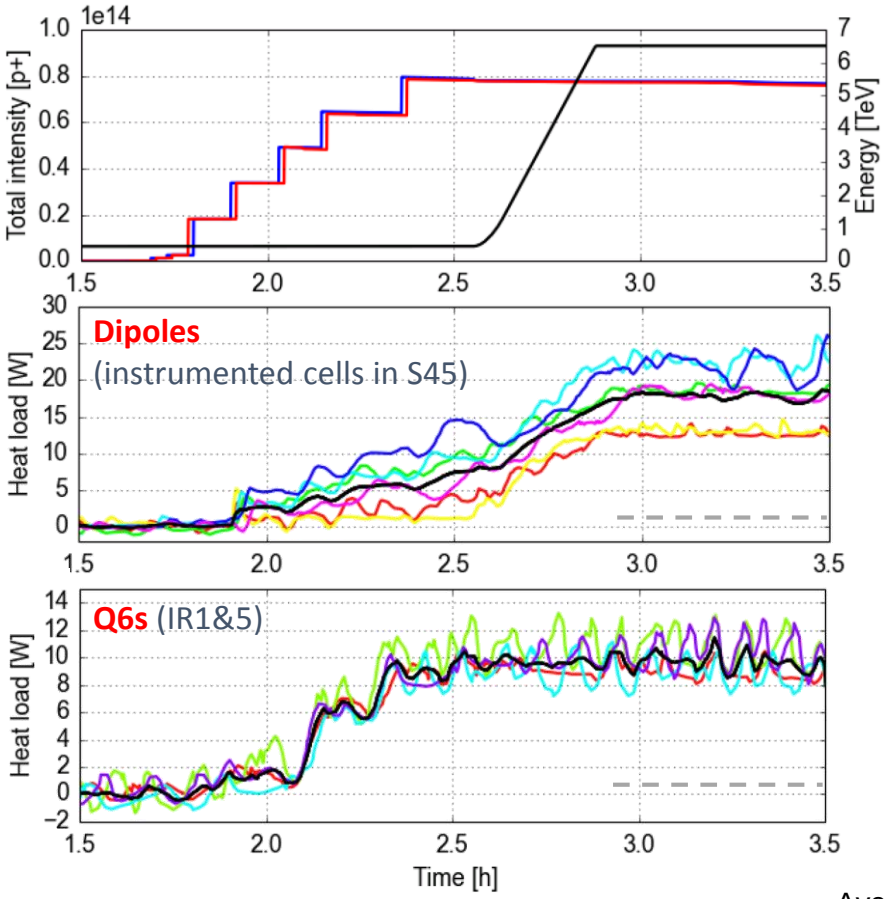
- After 2 months, significant **reduction visible in all arcs** (30% to 60% depending on the sector)
- Reduction observed **mainly in dipole magnets** (higher SEY threshold compared to quads)

14 September



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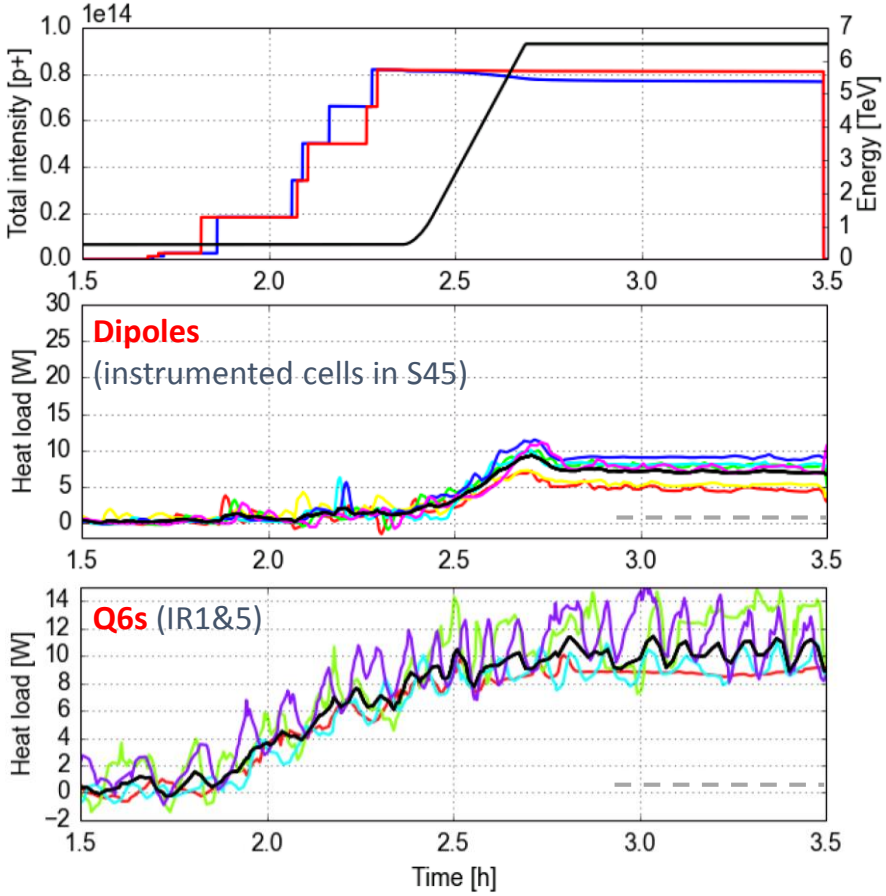

Average

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Scrubbing accumulated during the physics run

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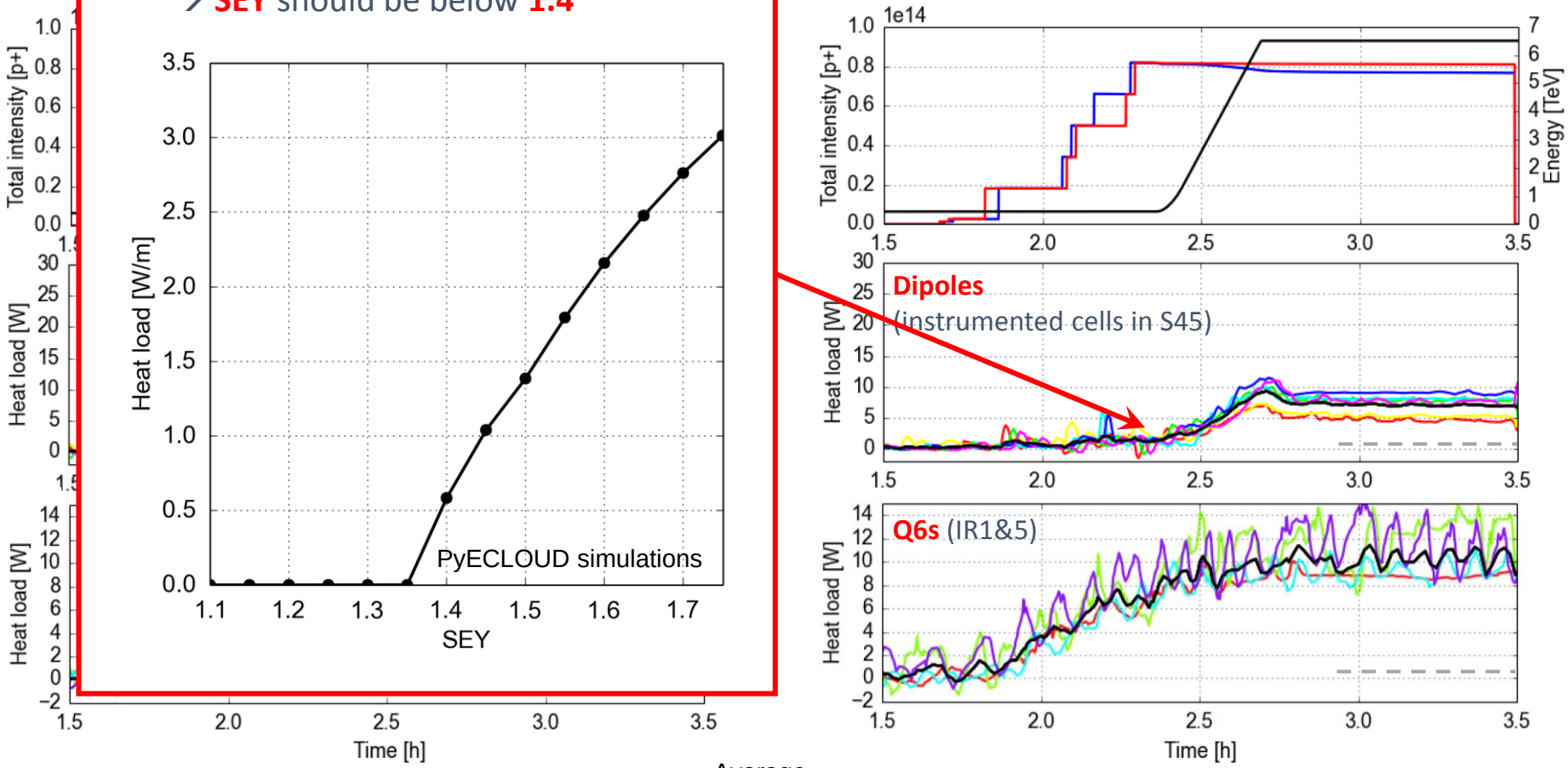
Practically **no measurable heat load in the dipoles at 450 GeV** (at least in S45)

→ **SEY** should be below **1.4**

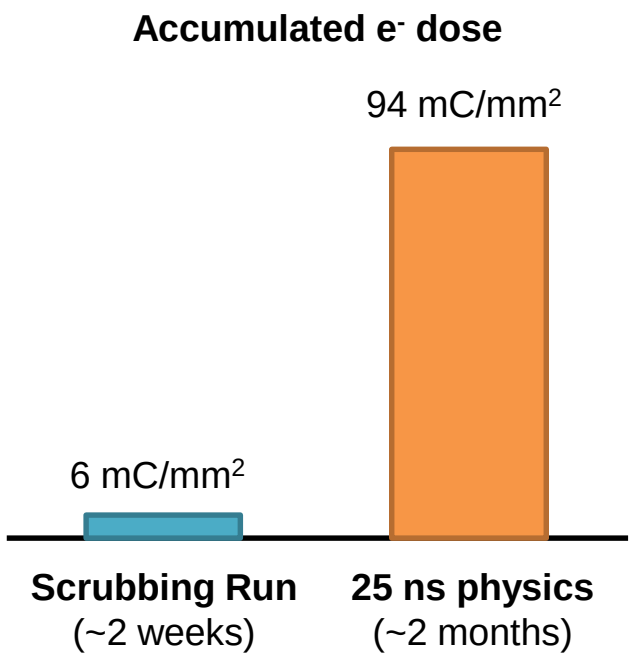
4 November

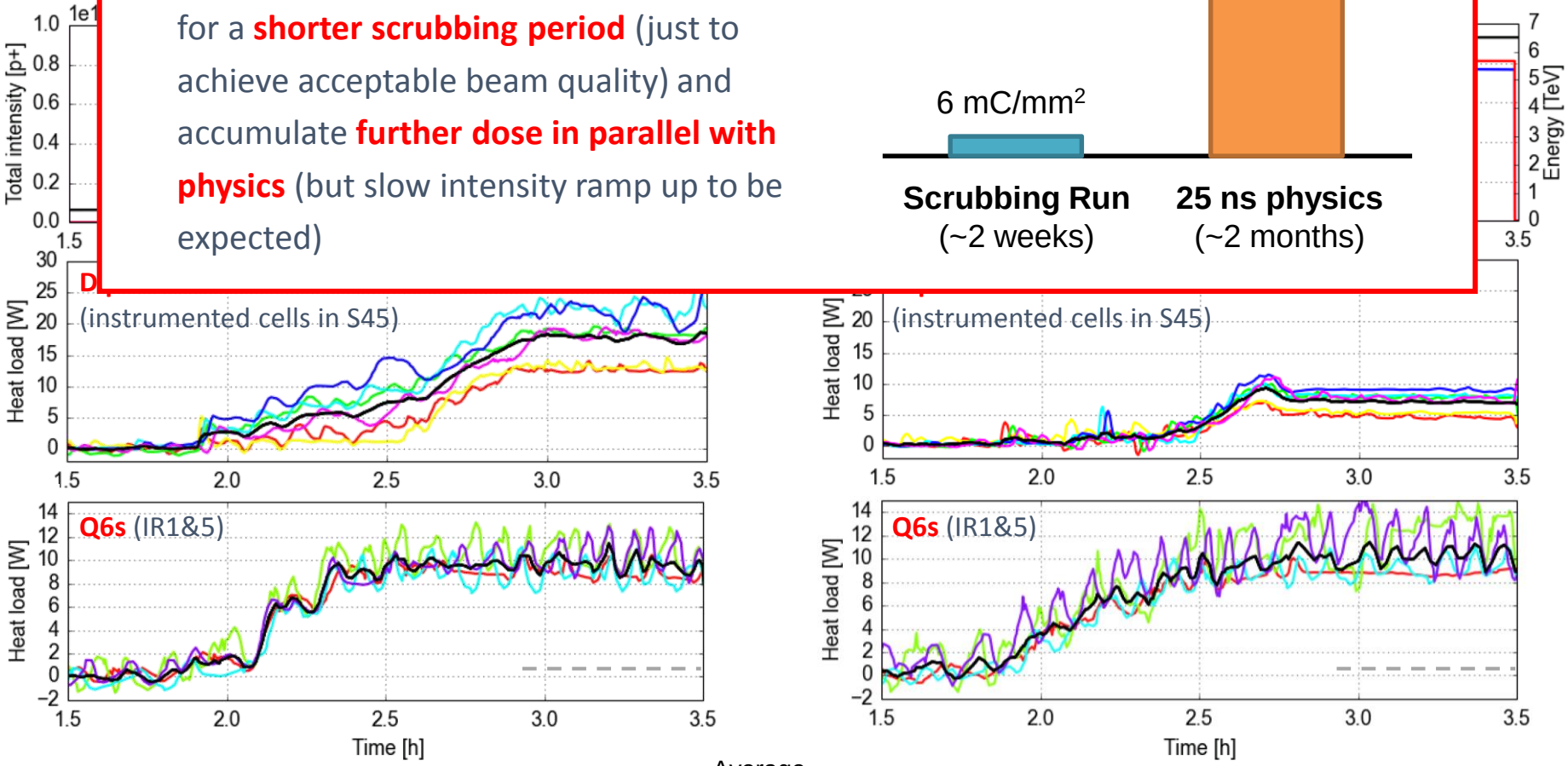


Scrubbing accumulated during the physics run

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

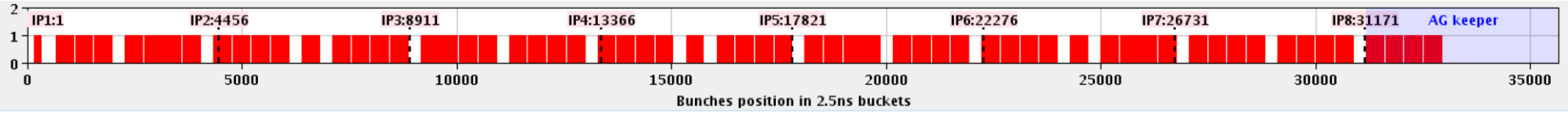
- Difficult to accumulate in a reasonable time with dedicated scrubbing run
- In the future (e.g. after LS2) we might go for a **shorter scrubbing period** (just to achieve acceptable beam quality) and accumulate **further dose in parallel with physics** (but slow intensity ramp up to be expected)



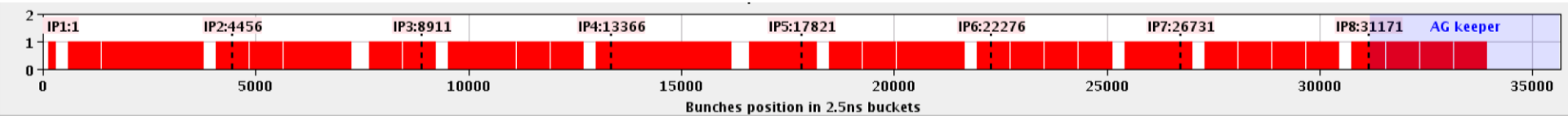


Situation at the end of the p-p run

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



Nominal: 2748b. in trains of 72b.



22% more bunches but **40% less gaps**

→ expected **~50% more heat load**

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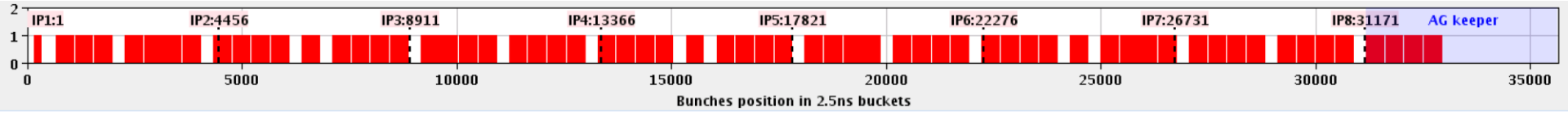
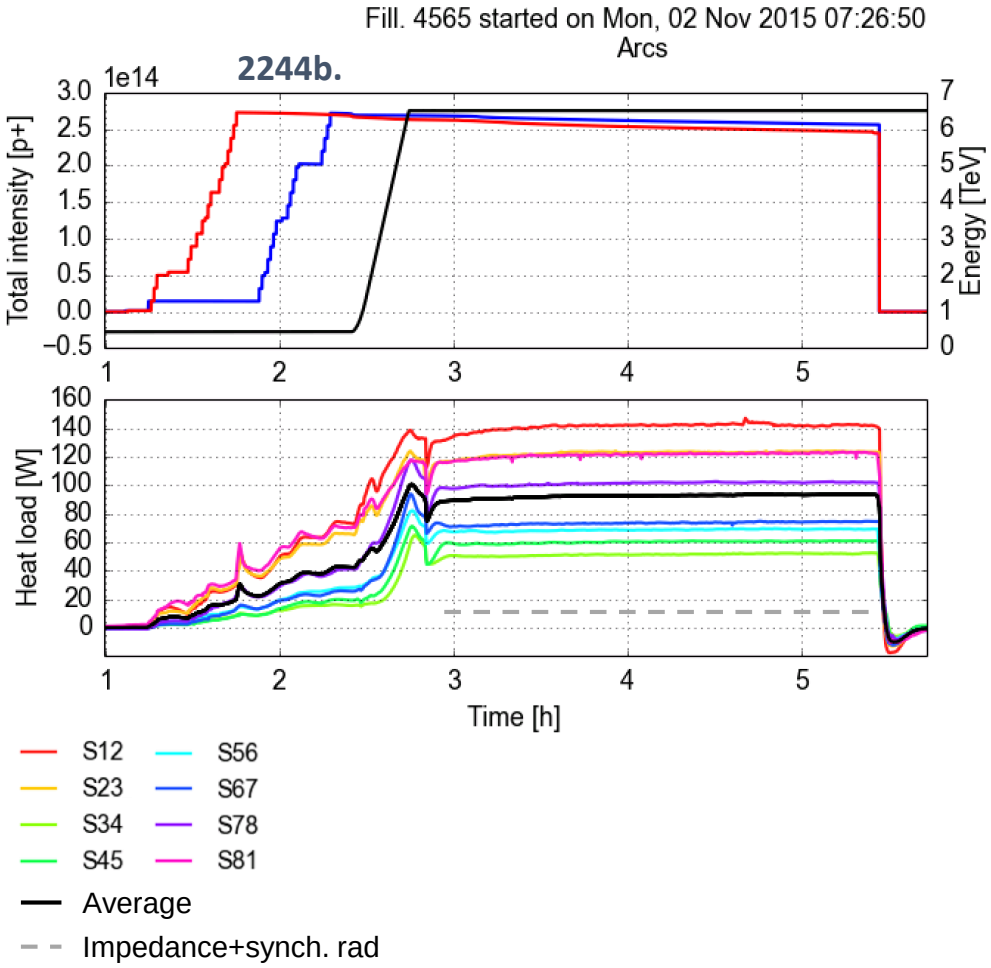


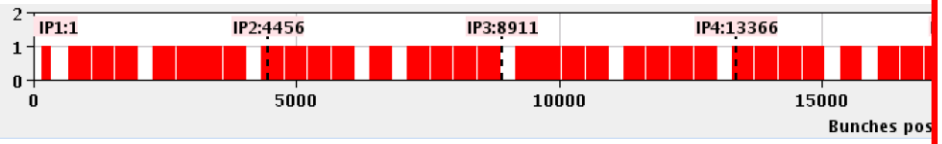


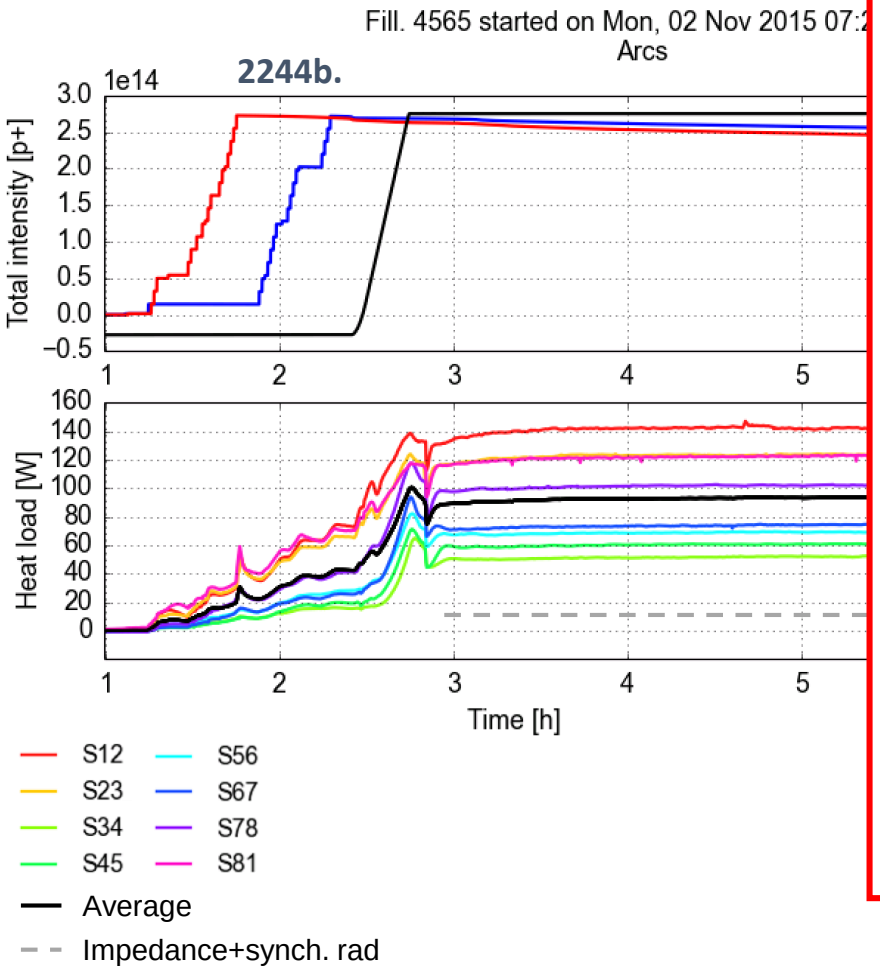
Factor 3 spread among heat loads in different sectors! - reason not clear

- Sectors **81, 12 and 23 close to the limit** with this filling scheme
- Sectors 34, 45, 56, 67 have already enough margin to accommodate the nominal beam

Situation at the end of the p-p run

Achieved in 2015: 2





On the **difference among sectors:**

- It is **not a measurement artefact** (test cells calibrated with heaters)
- In **2012** distribution was different (S45 and S56 were the worse at the time)
- It is there with **only beam 1** (and gives half the value)
- It was observed also with **50 ns**, then disappeared with scrubbing
- It was observed with **doublets** (see later)
- Difference is **increasing with time** (good sectors condition faster)
- There is **no dependence on the radial position** of the beam (tested +/- 0.2 mm)
- **Thermal cycle** of the beam screen has **no effect** on the heat load
- High heat load sectors seem to have **larger integrated BLM signals**

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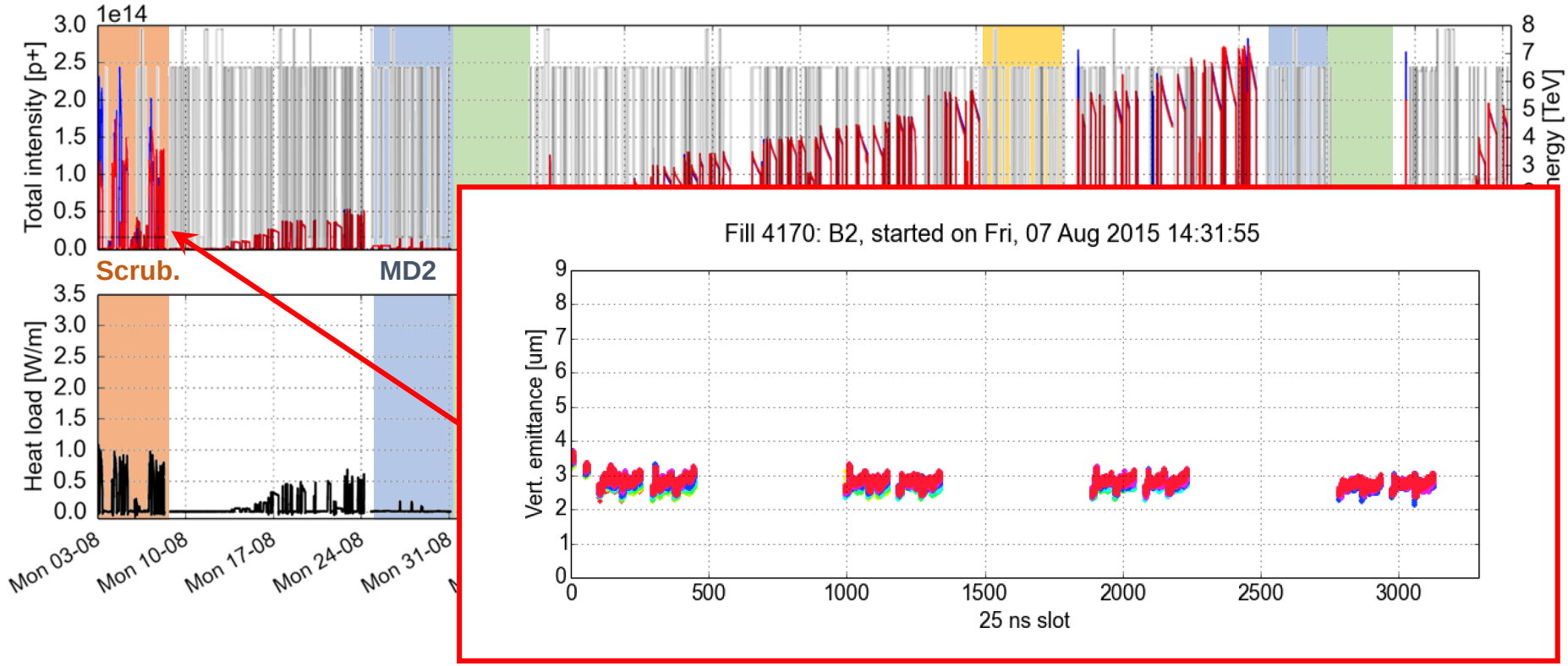
Deconditioning & reconditioning



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

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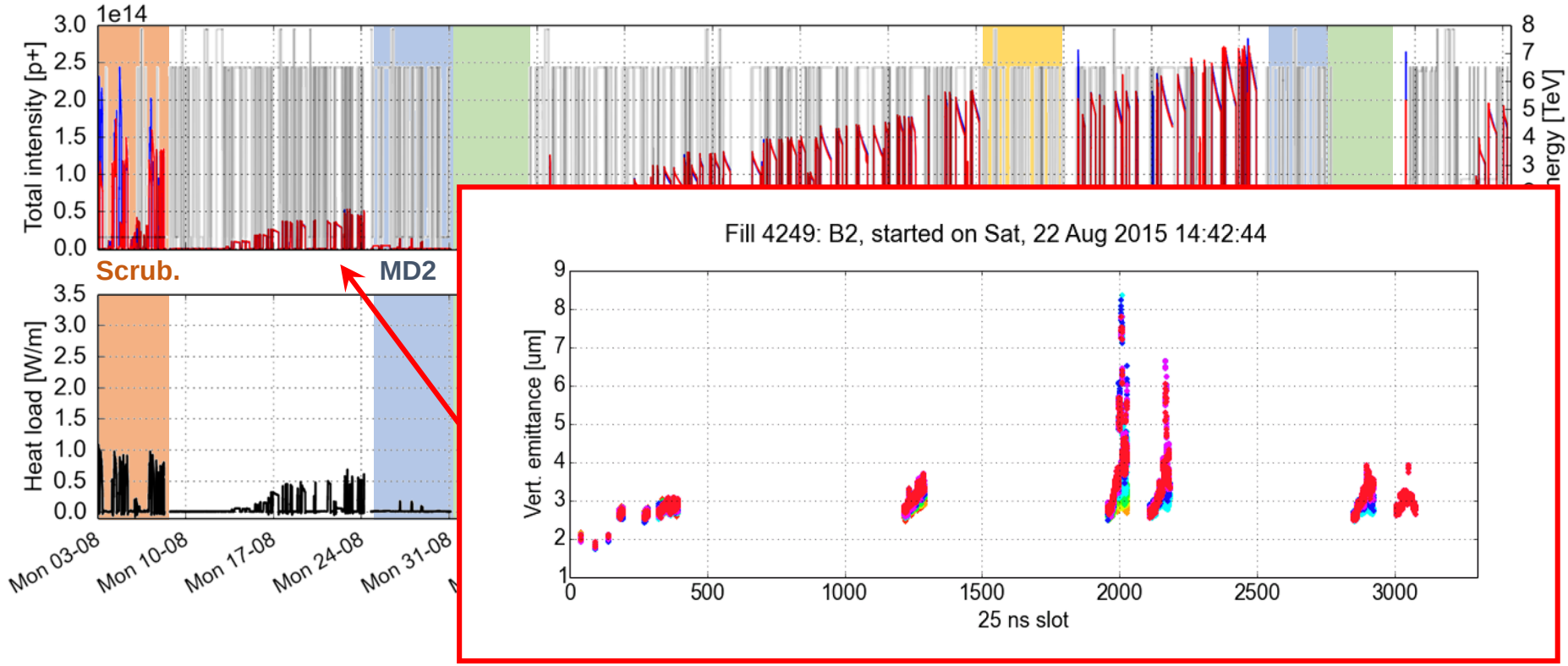

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- **Two weeks later**, strong **emittance blow-up** was observed **with 459b.** In injections of 72b.

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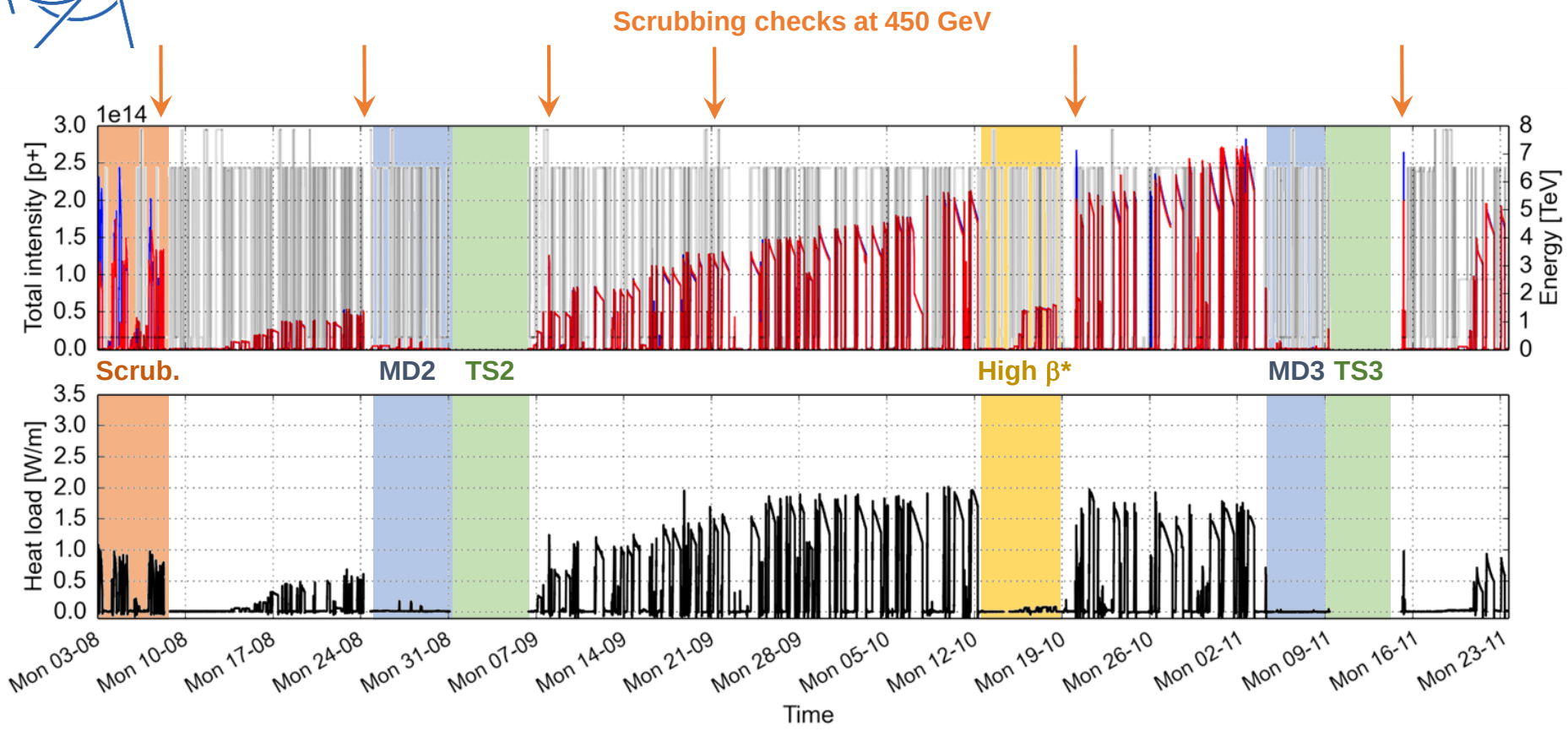

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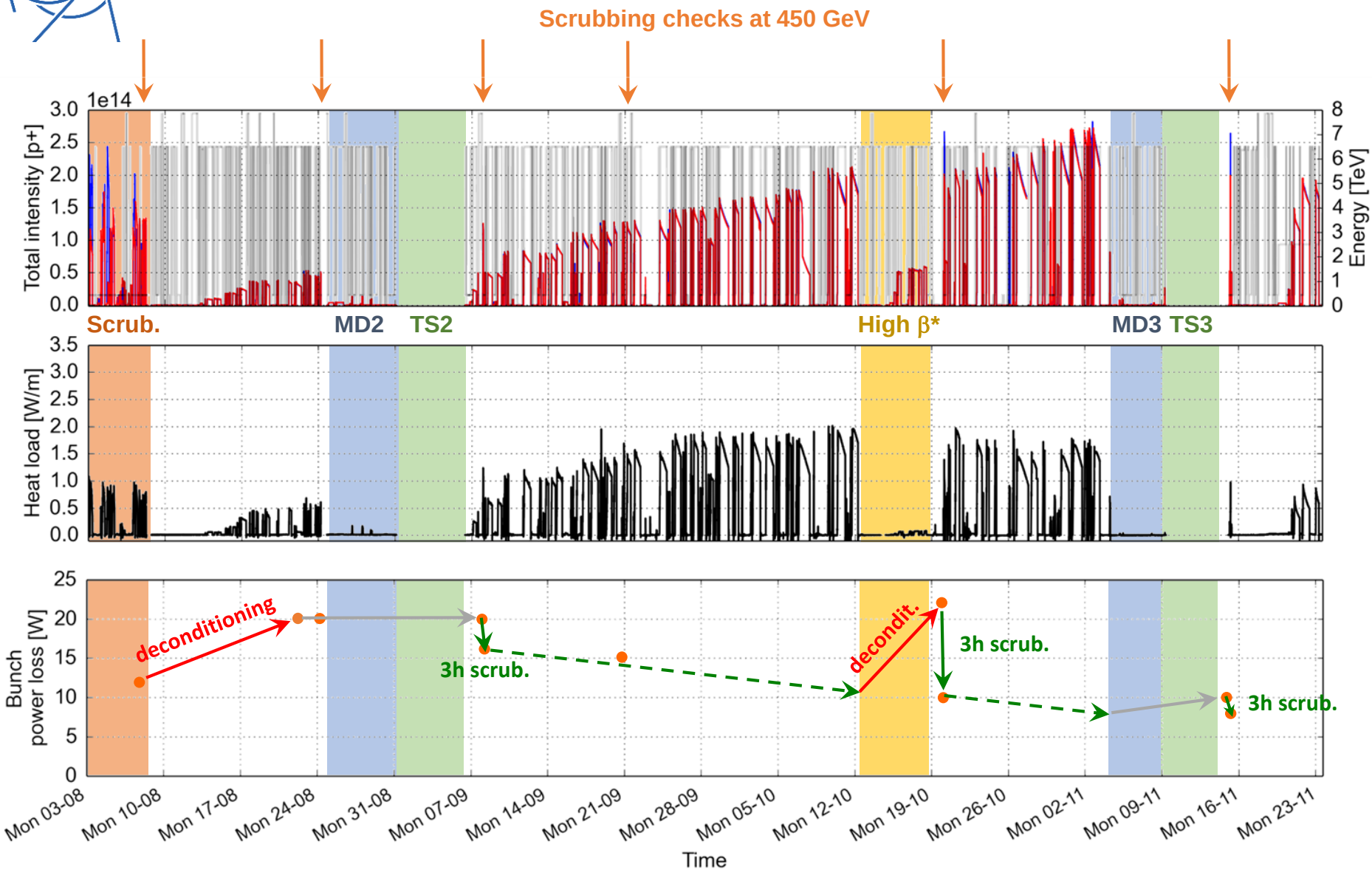
- **Two weeks later**, strong **emittance blow-up** was observed **with 459b.** In injections of 72b.

  → Decided to perform **check fills at 450 GeV** to monitor more precisely the e-cloud evolution

Deconditioning & reconditioning



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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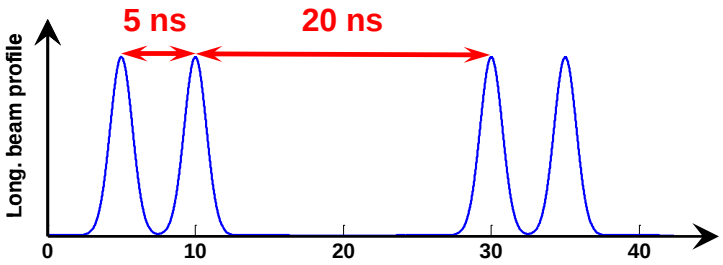
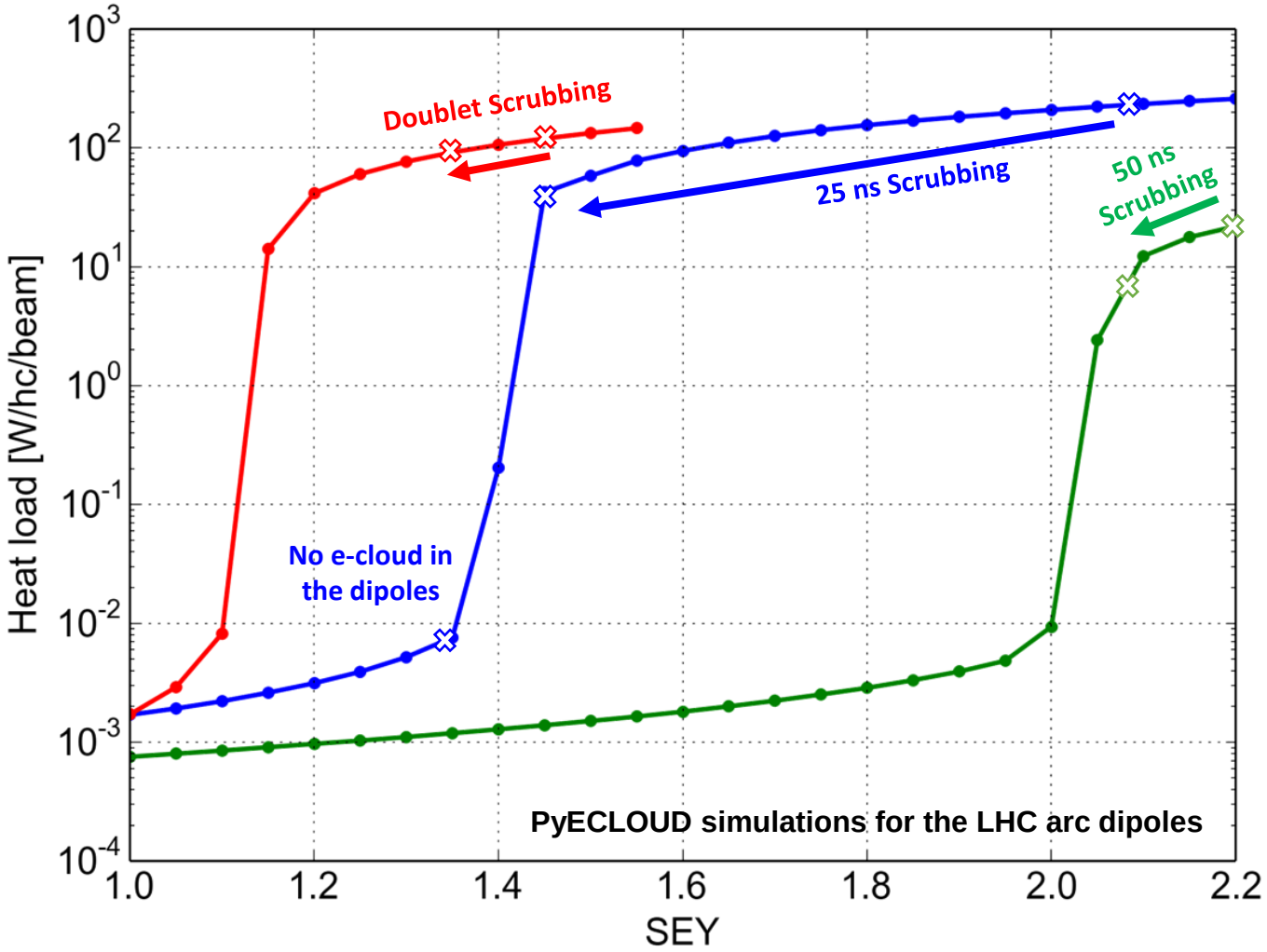
Doublets



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

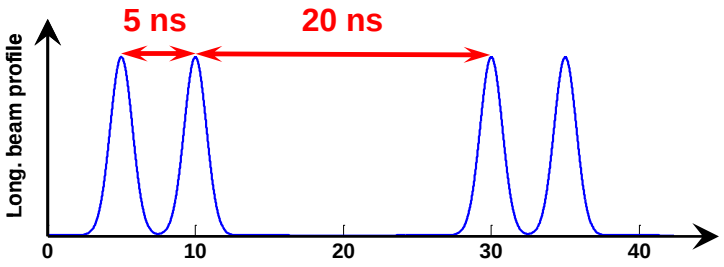


50 ns beam
~1400 bunches
1.7 x 10^{11} p/b

25 ns beam
~2800 bunches
1.15 x 10^{11} p/b

Doublet beam
~900 doublets
0.7 x 10^{11} p/b

Doublets



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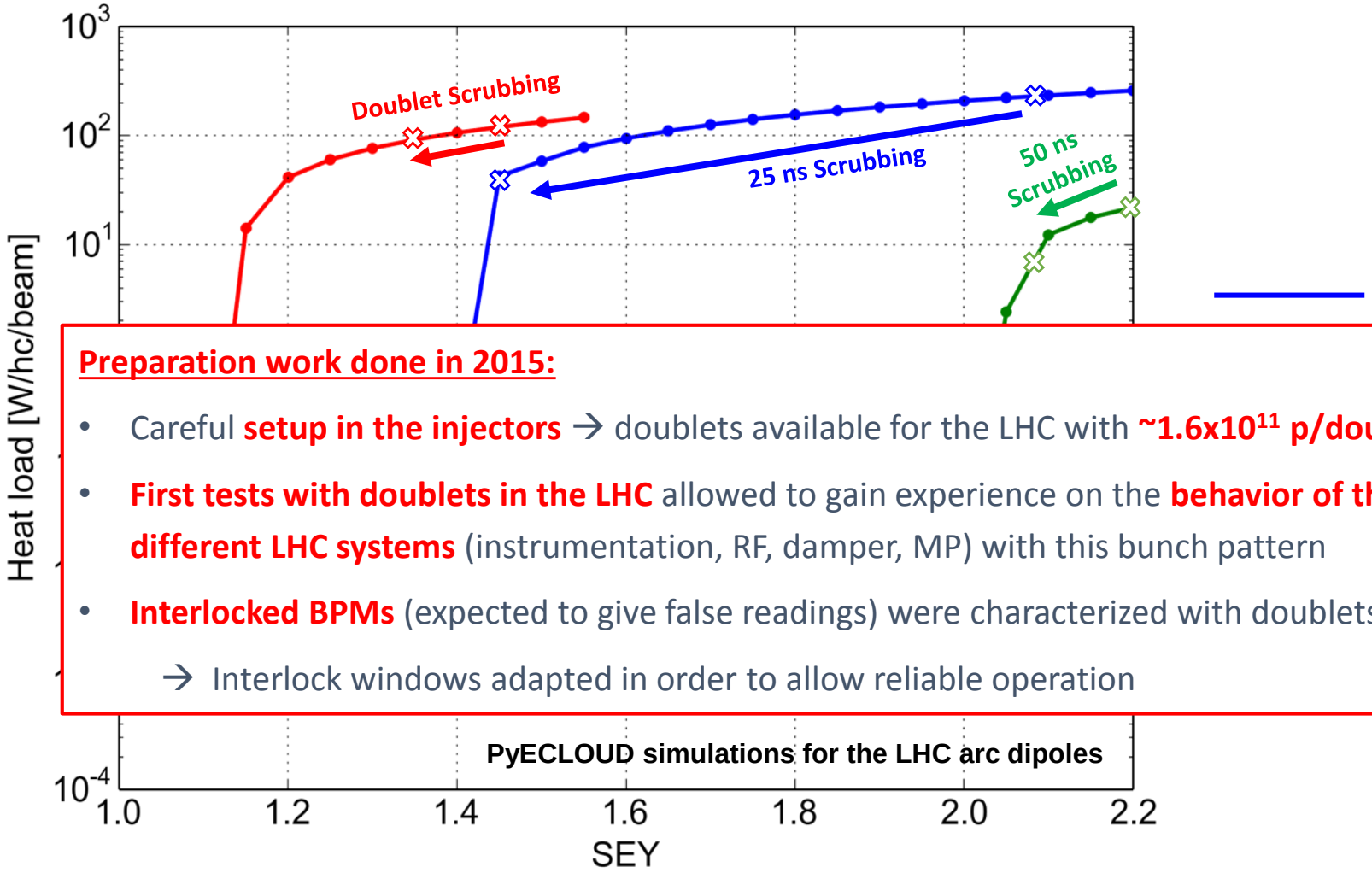


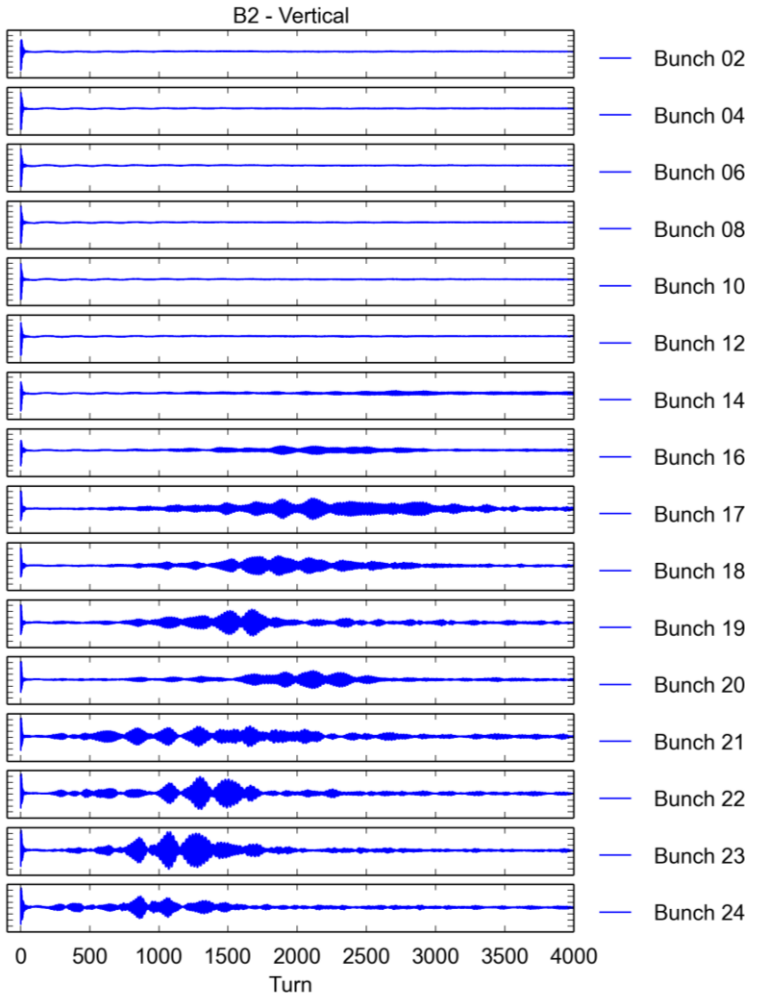
Preparation work done in 2015:

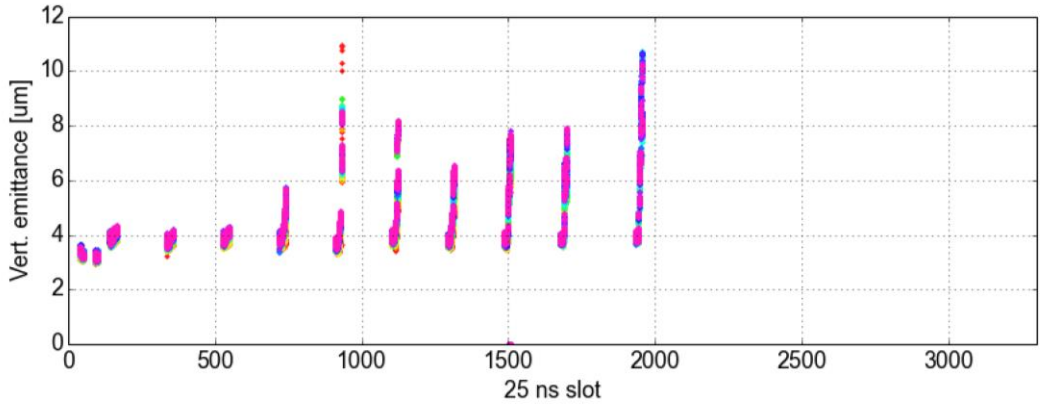
- Careful **setup in the injectors** → doublets available for the LHC with **~1.6x10^{11} p/doublet**
- **First tests with doublets in the LHC** allowed to gain experience on the **behavior of the different LHC systems** (instrumentation, RF, damper, MP) with this bunch pattern
- **Interlocked BPMs**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

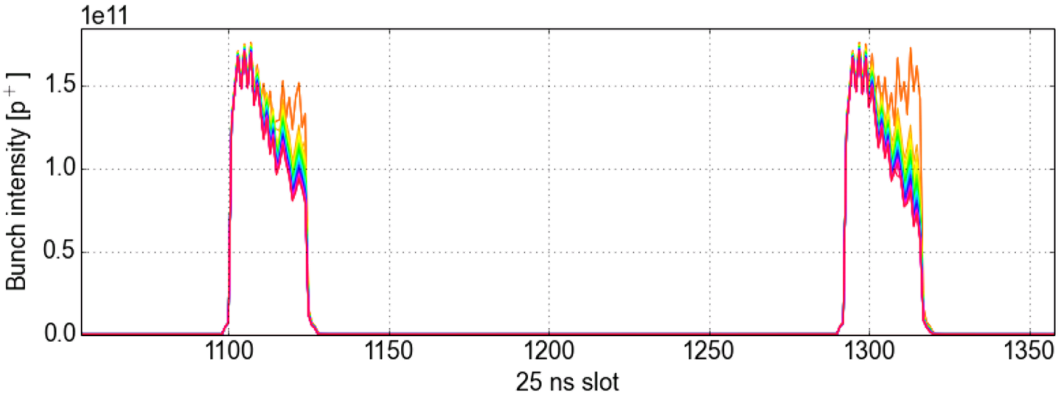
Doublets: instabilities and beam degradation

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**



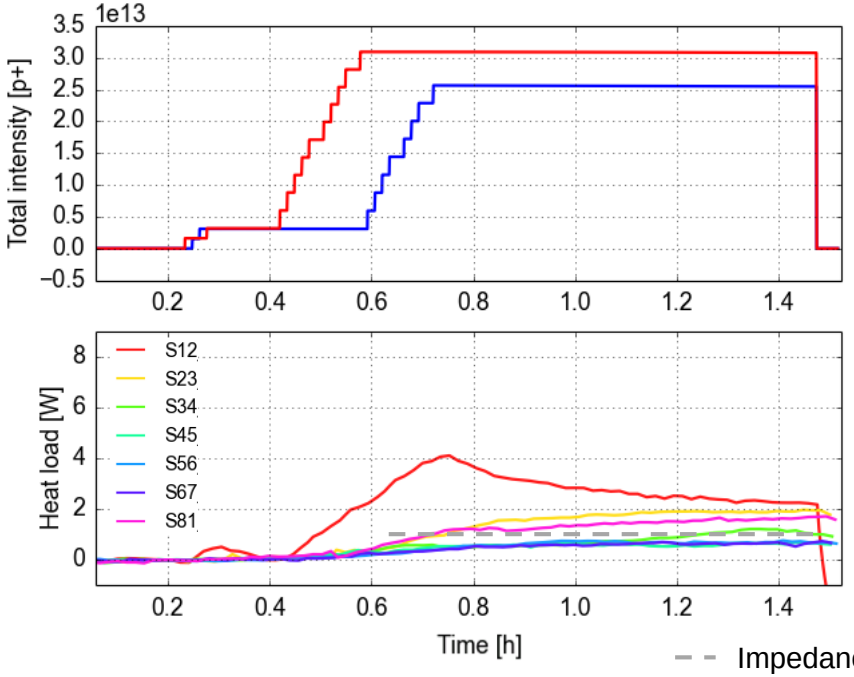




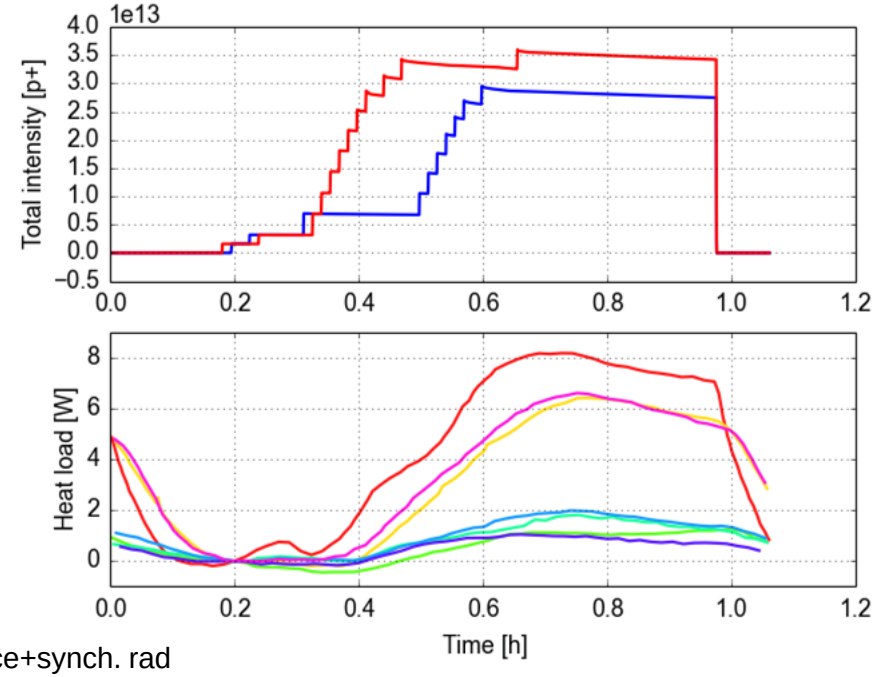
Doublets: heat loads

- Trains **up to 48 doublets could be injected** in the LHC but, due to the instabilities, it was possible to **accumulate only trains of 24 doublets** (up to ~250 doublets in total)
- Despite the strong beam degradation, the **e-cloud enhancement could be observed** on the arc heat load
- But **impossible to inject enough beam** and keep sufficient beam quality **for efficient scrubbing** with doublets

Standard 25 ns beam



"Doublet" beam



Impedance+synch. rad

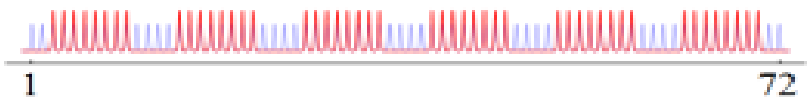
Doublets: considerations for 2016

- 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 a better control on e-cloud instabilities** and to achieve acceptable beam lifetimes → 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

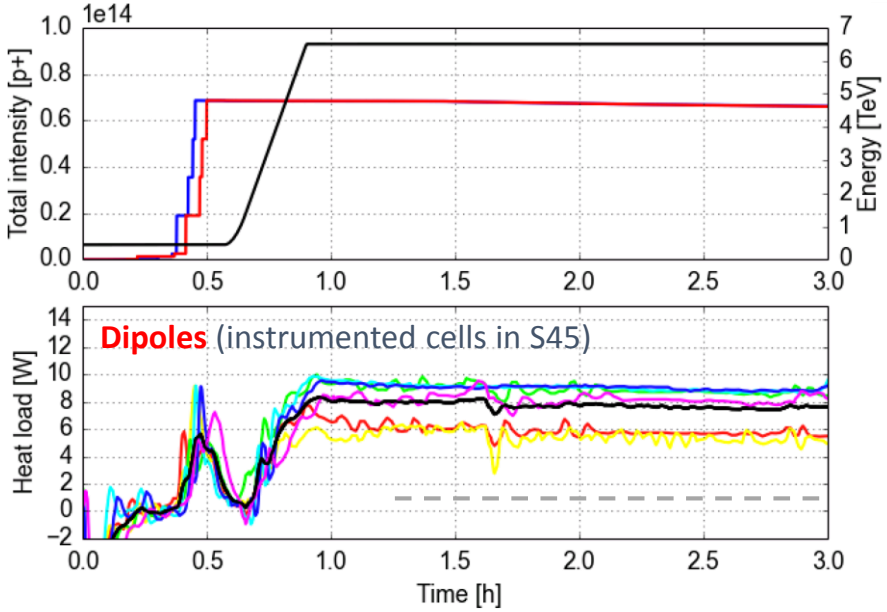
8b+4e scheme

- 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

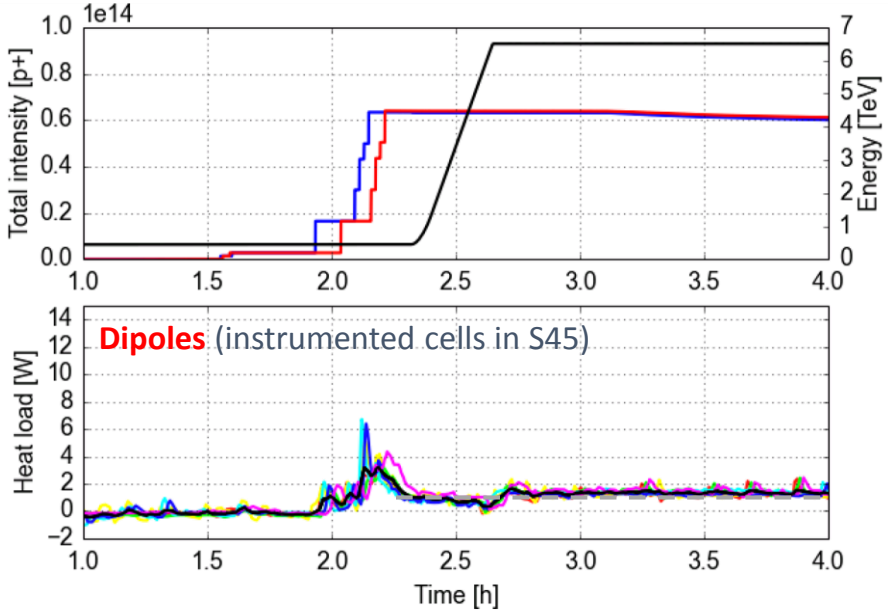
Up to ~1850b. in the LHC



Standard 25 ns beam



"8b+4e" beam



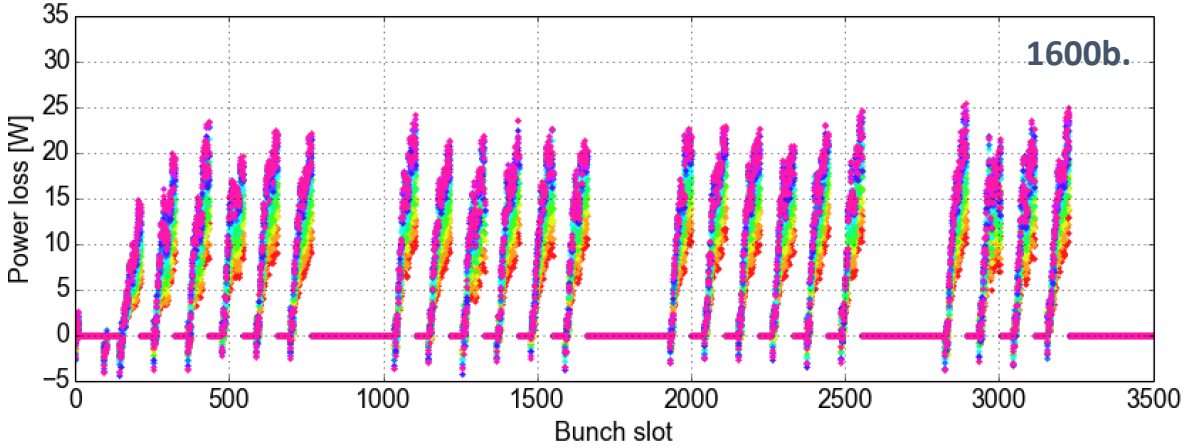
Average

Impedance+synch. rad

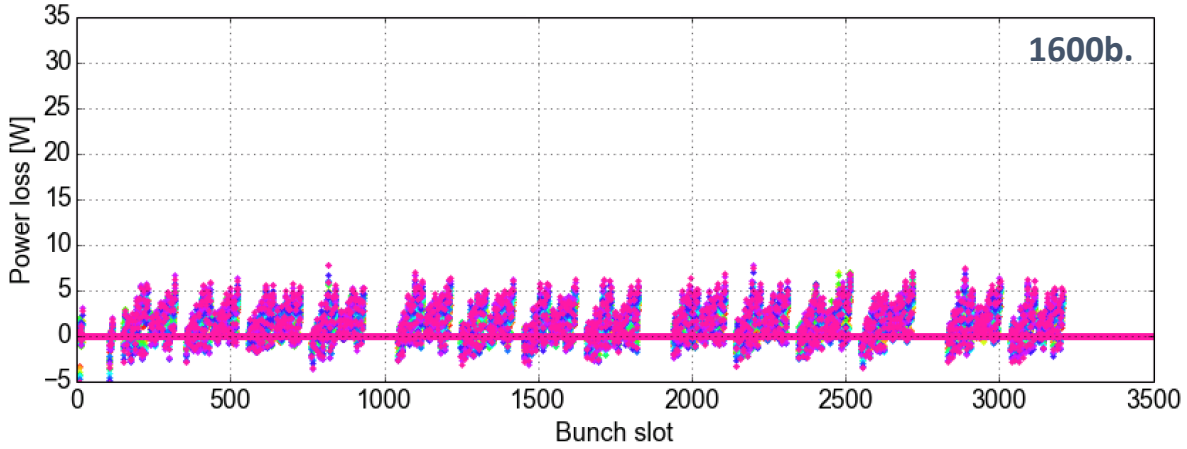
8b+4e scheme

- 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



Outline

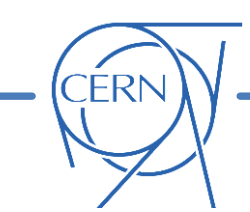
- Introduction
- Scrubbing at 450 GeV
- Intensity ramp-up with 25 ns beams
  - Beam dynamics observations
  - Heat loads
  - Conditioning observations
- De-conditioning and re-conditioning observations
  - Effect of Technical Stops and Special Runs
- Experience with exotic bunch patterns
  - Doublets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

First lessons to retain

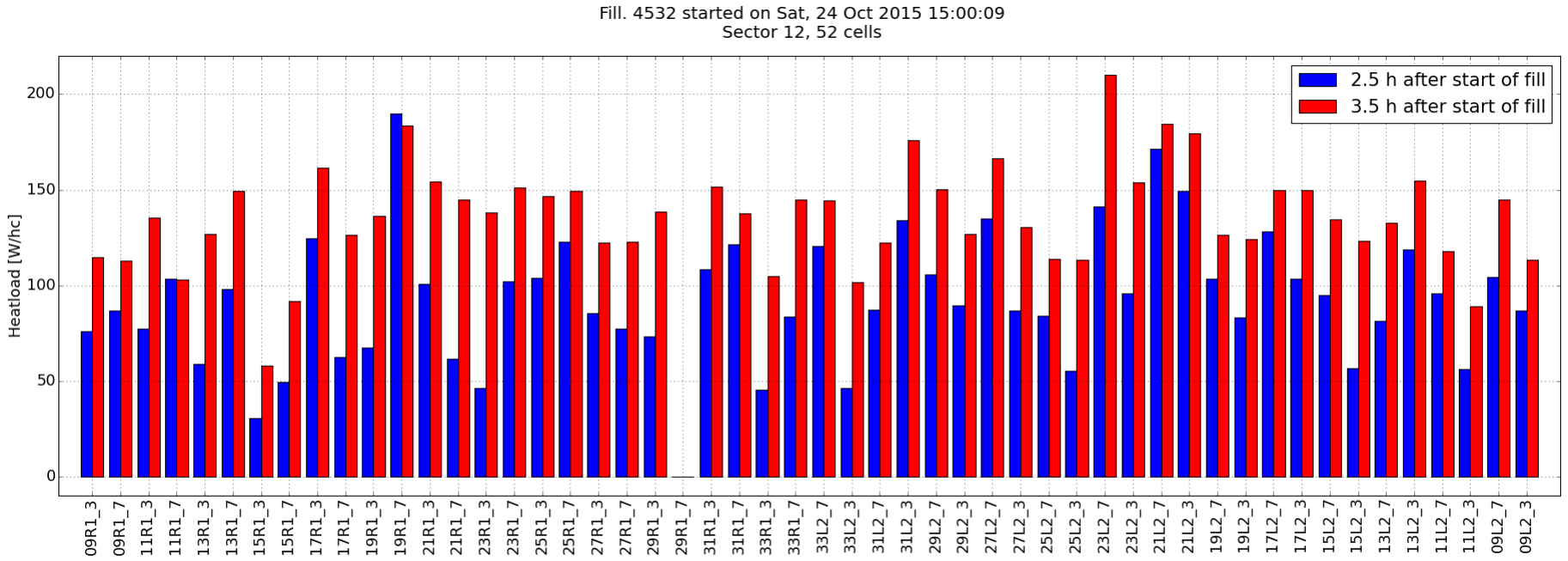
- **Scrubbing** at 450 GeV allows to **mitigate e-cloud instabilities** and **beam degradation** occurring at low energy
- After this stage, relying on ADT, and high Q' and octupoles, it is **possible to preserve good beam quality from injection to collision** in spite of the e-cloud still present in the machine as witnessed by the 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**: 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 **requirements for 2016**:
  - **4 days scrubbing run** should be reasonable to recover high intensities at 450 GeV
  - A few **"refresh" scrubbing fills during first 1-2 weeks of intensity ramp up** in physics (to avoid problems with deconditioning)
  - Accumulate **further scrubbing in physics:**
    - → **"aggressive" filling scheme**, with up to **288b. per injection**, should be used until we hit again limitations from cryo
  - **Doublet test** to be performed when **SEY is sufficiently low** (e.g. after recovering the 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
2.5 h after start of fill
3.5 h after start of fill
Heatload [W/hc]
0
50
100
150
200
09R1_3
09R1_7
11R1_3
11R1_7
13R1_3
13R1_7
15R1_3
15R1_7
17R1_3
17R1_7
19R1_3
19R1_7
21R1_3
21R1_7
23R1_3
23R1_7
25R1_3
25R1_7
27R1_3
27R1_7
29R1_3
29R1_7
31R1_3
31R1_7
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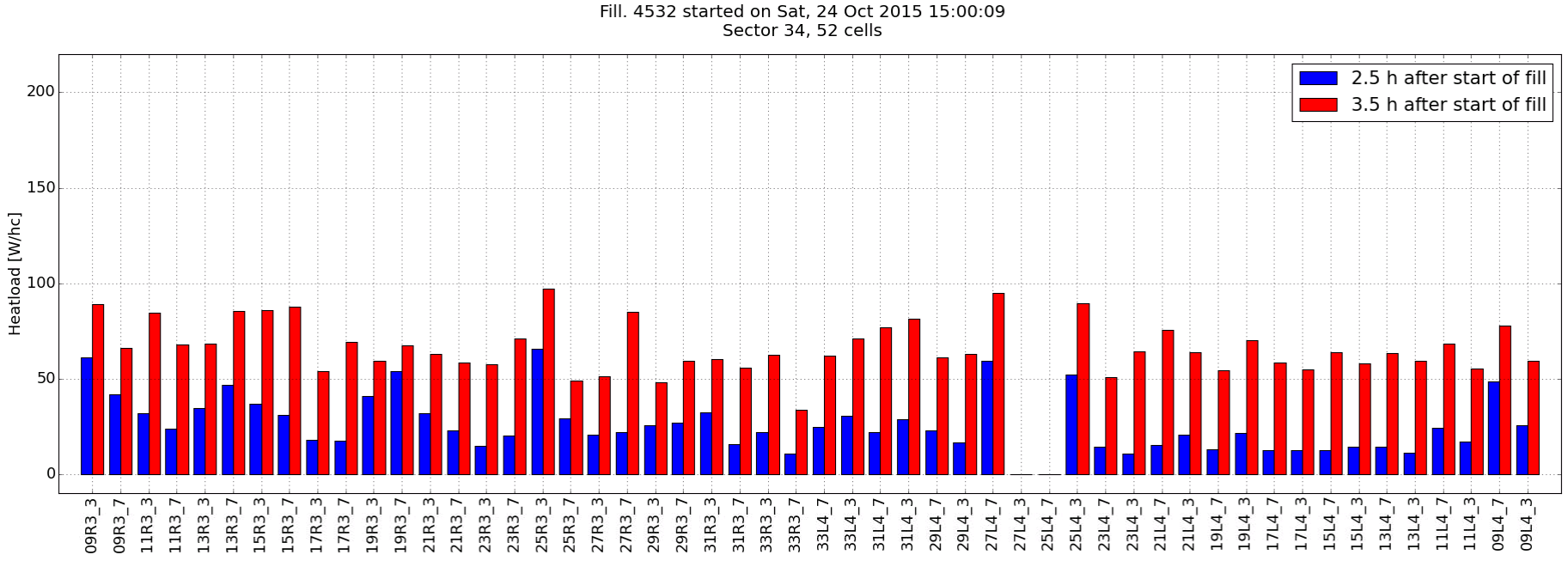
09L2_3


Fill. 4532 started on Sat, 24 Oct 2015 15:00:09
Sector 34, 52 cells
2.5 h after start of fill
3.5 h after start of fill
Heatload [W/hc]
0
50
100
150
200
09R3_3
09R3_7
11R3_3
11R3_7
13R3_3
13R3_7
15R3_3
15R3_7
17R3_3
17R3_7
19R3_3
19R3_7
21R3_3
21R3_7
23R3_3
23R3_7
25R3_3
25R3_7
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29R3_3
29R3_7
31R3_3
31R3_7
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33R3_7
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17L4_7
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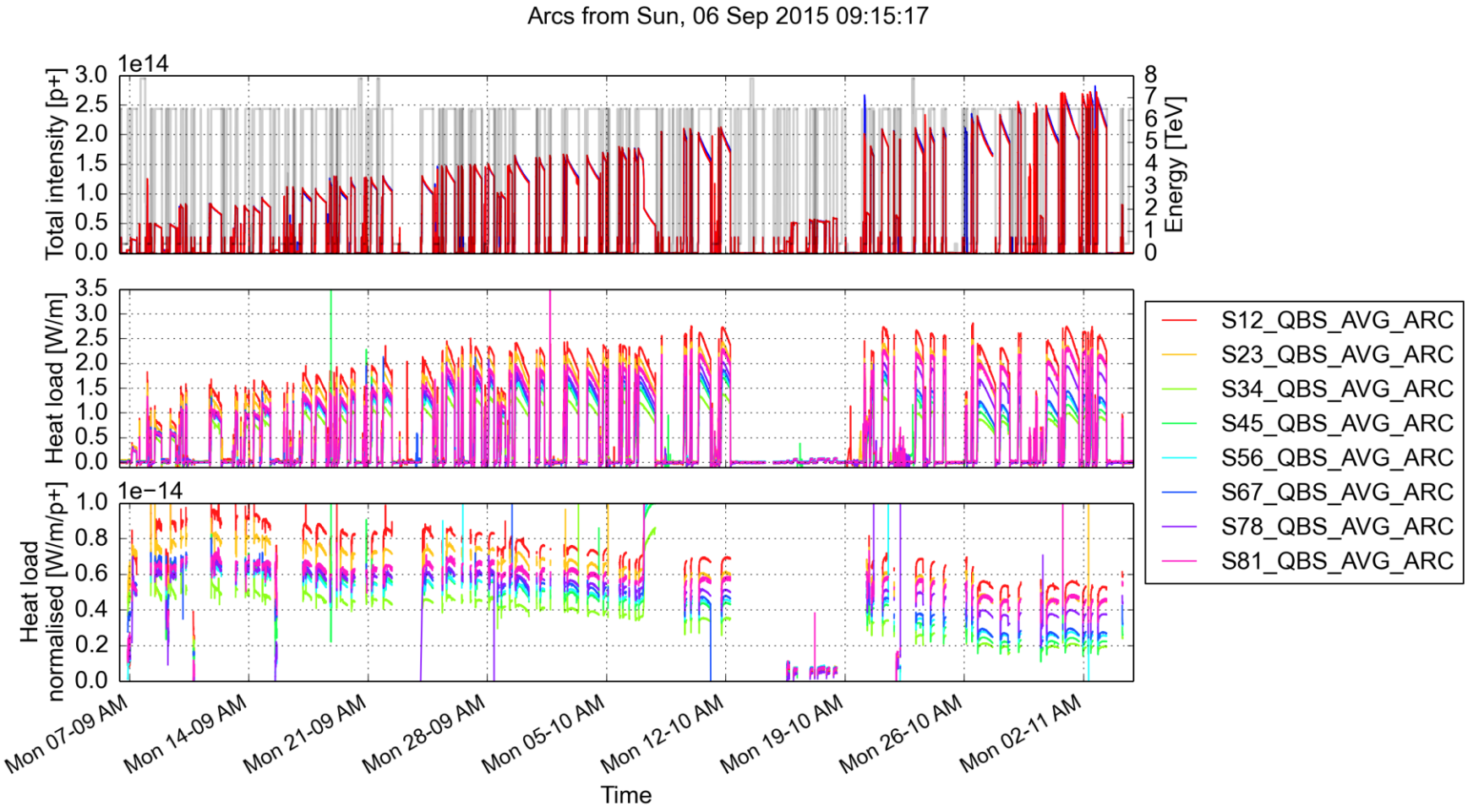
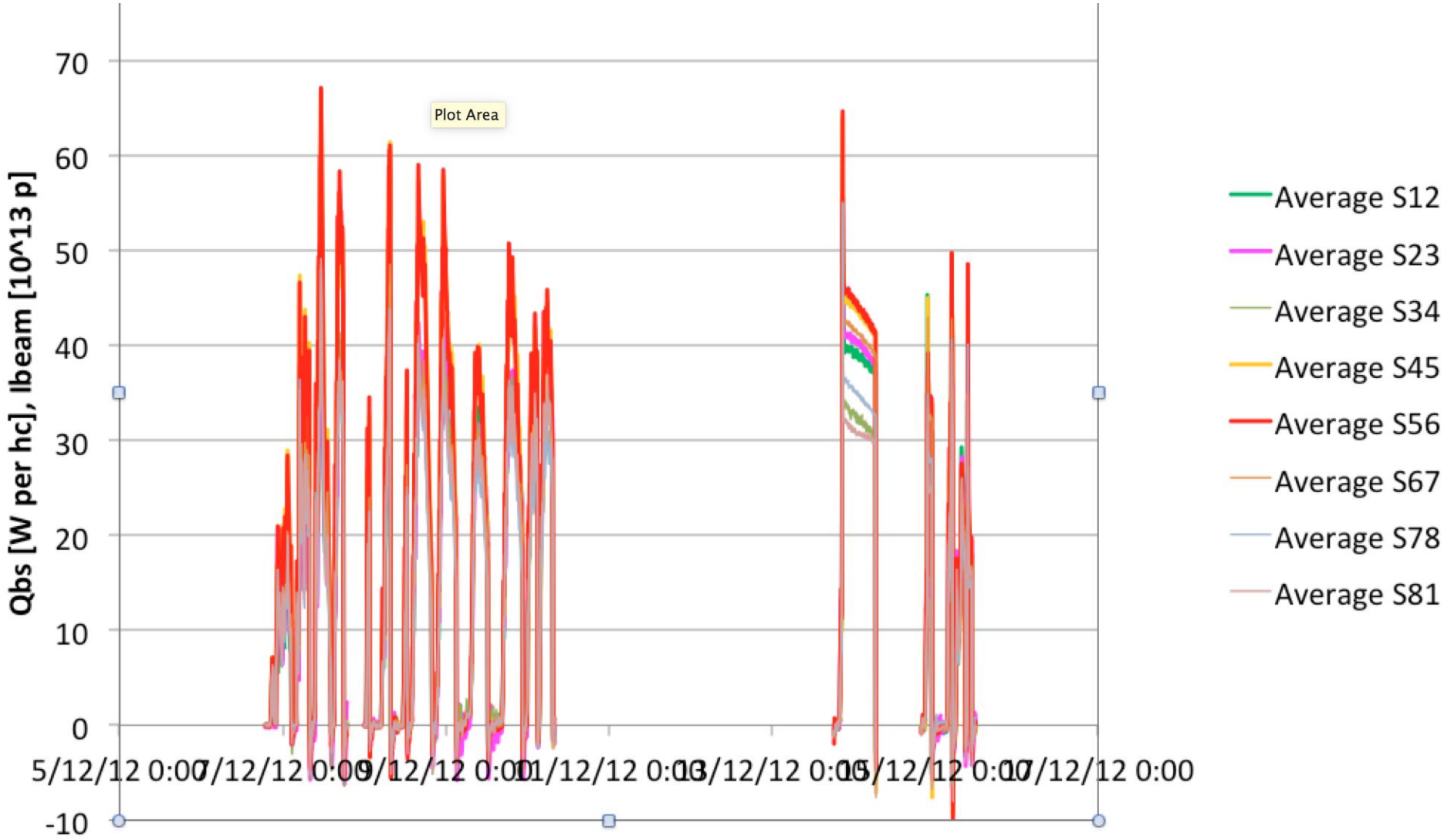
09L4_3

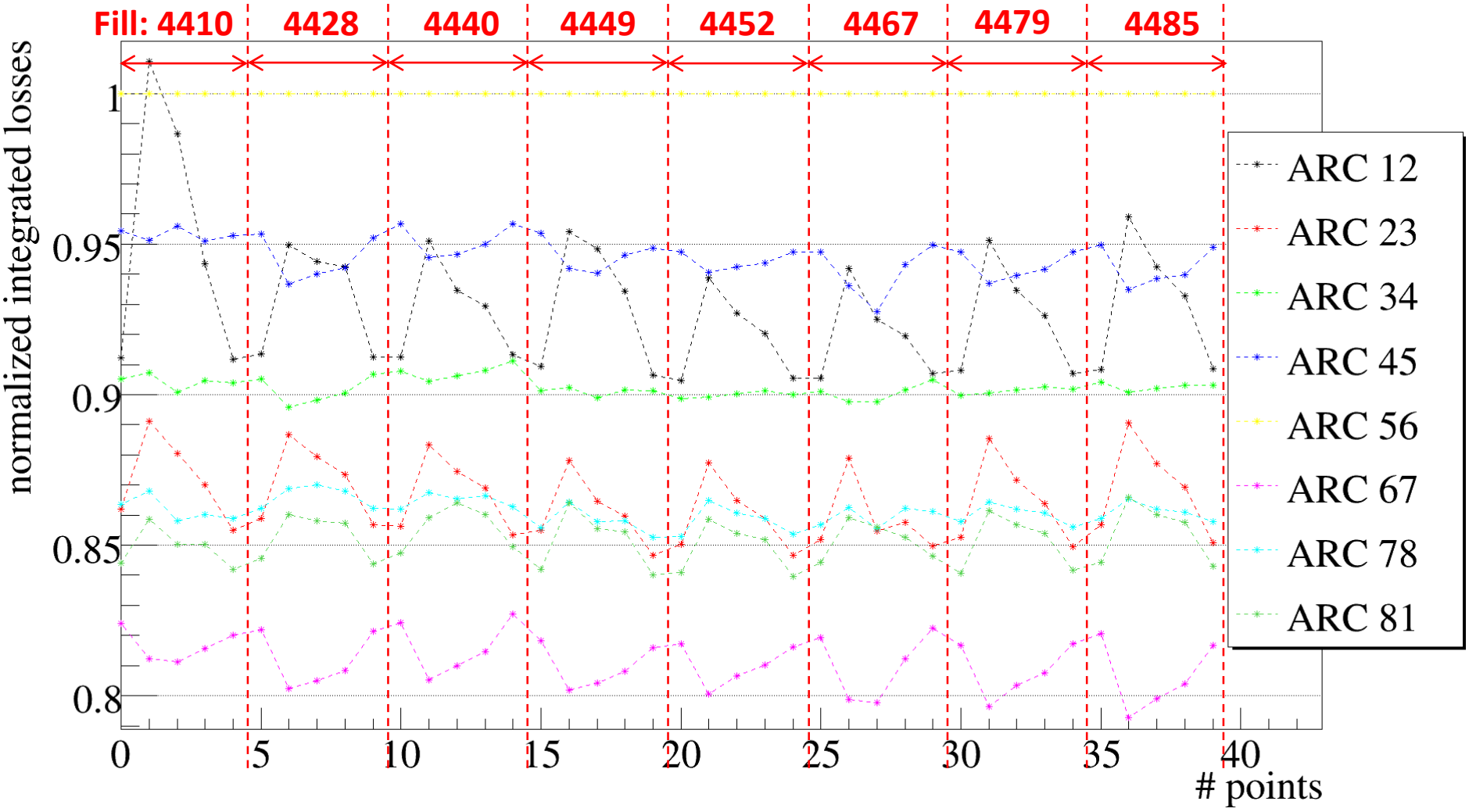

Arcs from Sun, 06 Sep 2015 09:15:17
1e14
Total intensity [p+]
Energy [TeV]
Heat load [W/m]
1e−14
Heat load normalised [W/m/p+]
S12_QBS_AVG_ARC
S23_QBS_AVG_ARC
S34_QBS_AVG_ARC
S45_QBS_AVG_ARC
S56_QBS_AVG_ARC
S67_QBS_AVG_ARC
S78_QBS_AVG_ARC
S81_QBS_AVG_ARC
Mon 07-09 AM
Mon 14-09 AM
Mon 21-09 AM
Mon 28-09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

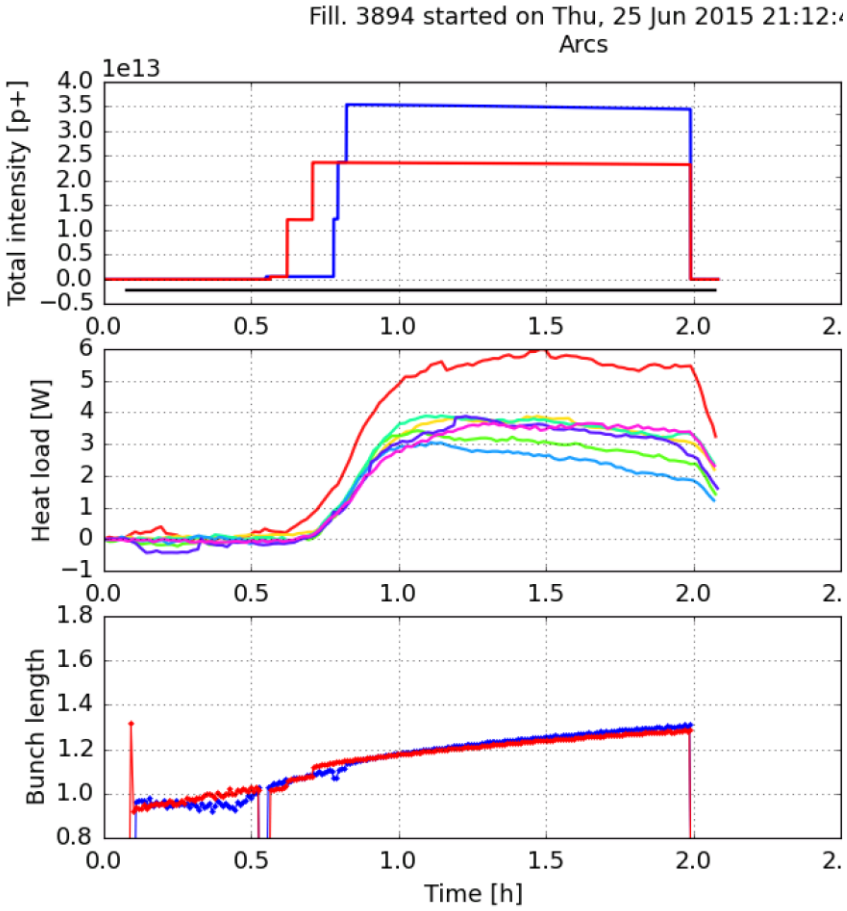

Plot Area
Qbs [W per hc], Ibeam [10^13 p]
70
60
50
40
30
20
10
0
-10
5/12/12 0:00
7/12/12 0:00
9/12/12 0:00
11/12/12 0:00
13/12/12 0:00
15/12/12 0:00
17/12/12 0:00
Average S12
Average S23
Average S34
Average S45
Average S56
Average S67
Average S78
Average S81

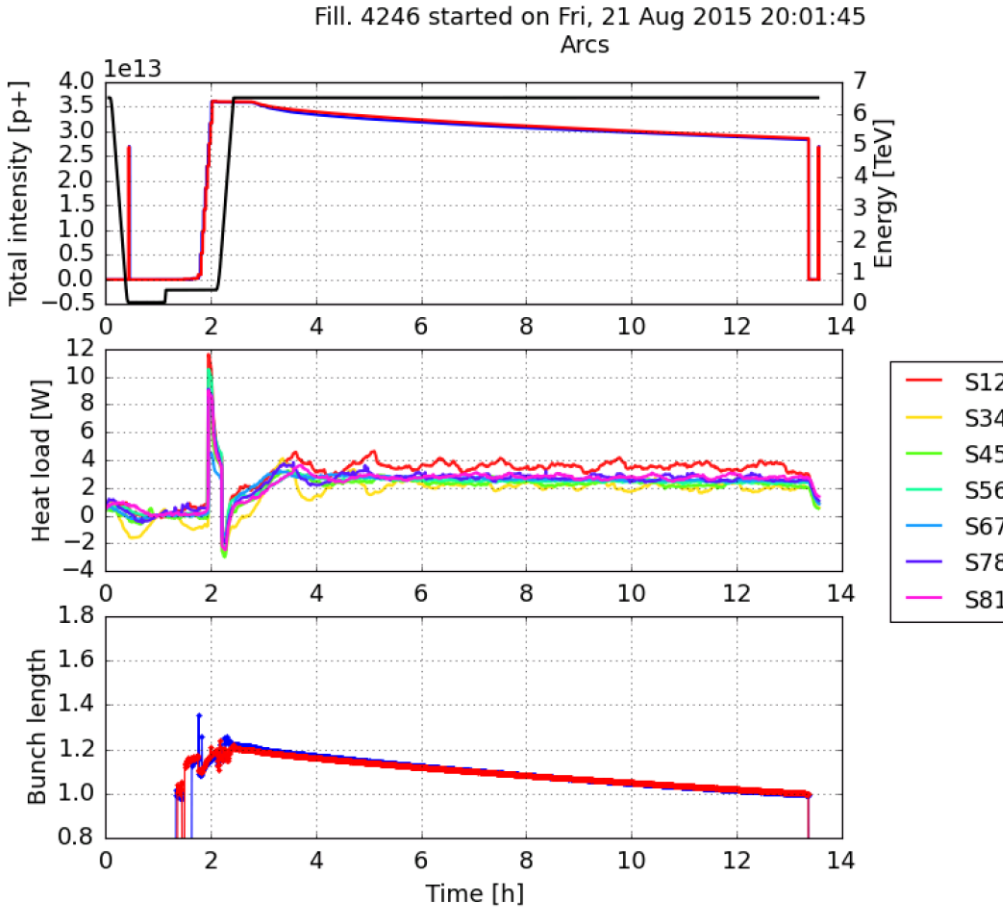
Normalized integrated losses (ARCs)

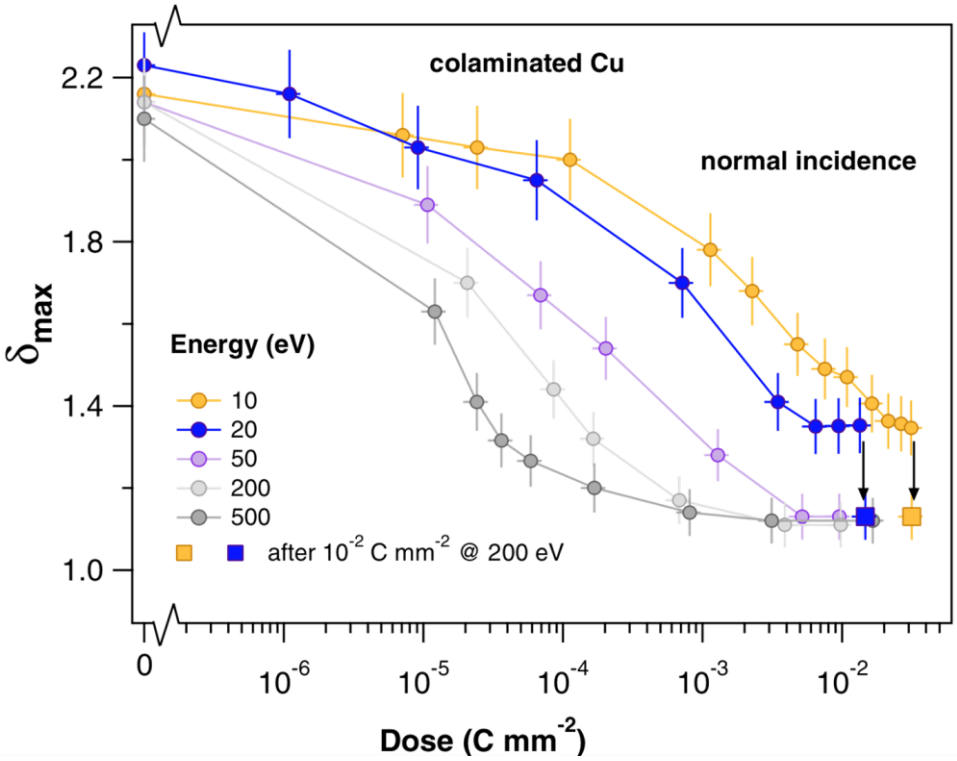
Beam loss integrated over 1h in five points and normalized w.r.t. S56 (smooth loss along cycle)

First and last points refer to bkg without beam, and the other three are in stable beam




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
δ_{max}
2.2
1.8
1.4
1.0
Energy (eV)
10
20
50
200
500
after 10^{-2} C mm^{-2} @ 200 eV
0
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Dose (C mm^{-2})