Electron cloud in the LHC: lessons learnt from 2015 experience with 25 ns beams

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CERN, 26-30 October 2015

Outline

- **Introduction**
- **Scrubbing runs in 2015**
  - Main limitations
  - Beam observations
  - Evolution of the Secondary Electron Yield (SEY)
- **Intensity ramp-up in physics**
  - Optimal working point at 450 GeV
  - Dealing with high heat load on the cryogenic system
  - Losses and emittance preservation
- **Experience with different beam variants**
  - “Doublet” beam
  - 8b+4e scheme
  - “Tailored” filling schemes
- **Simulation study on impact of baffle plates**
- **Summary**

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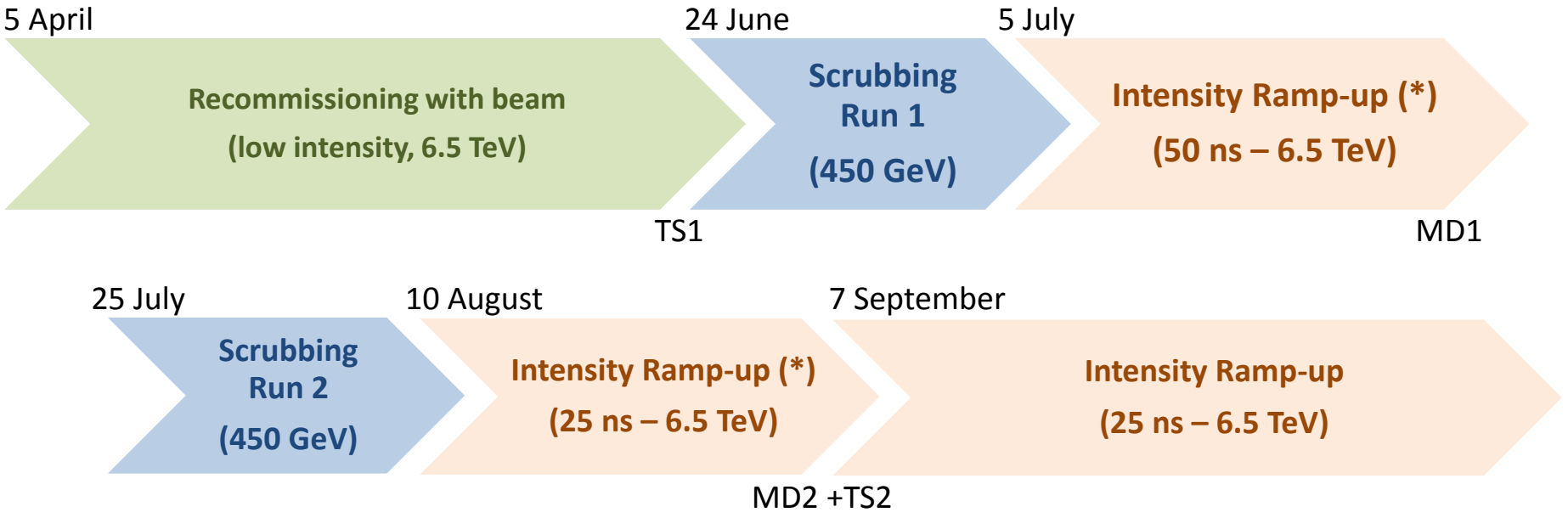
Introduction

- The **main goals** of the 2015 run were to **re-commission** the machine after the Long Shutdown 1 (LS1) and 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), relaxed machine configuration: **β^* = 80 cm** in IP1 and IP5, relatively **large crossing angles**



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

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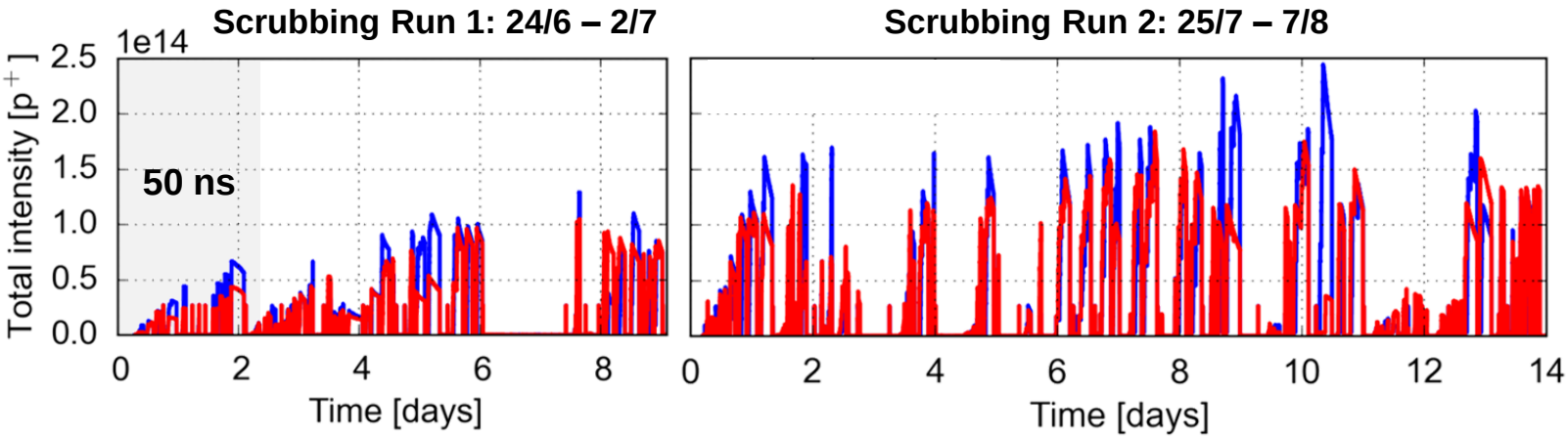
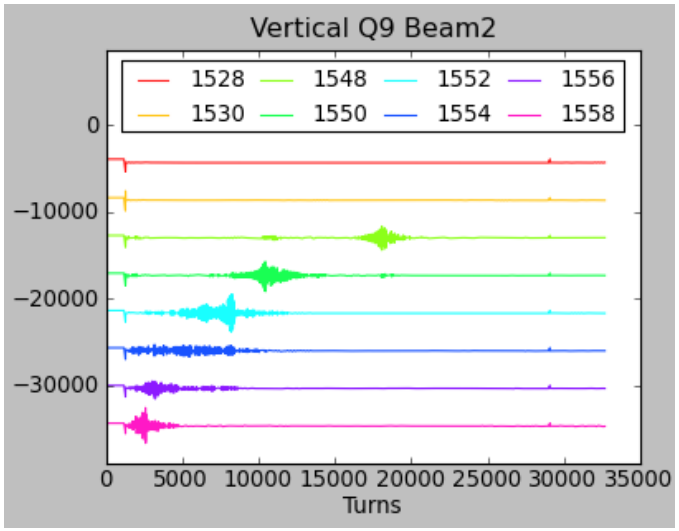
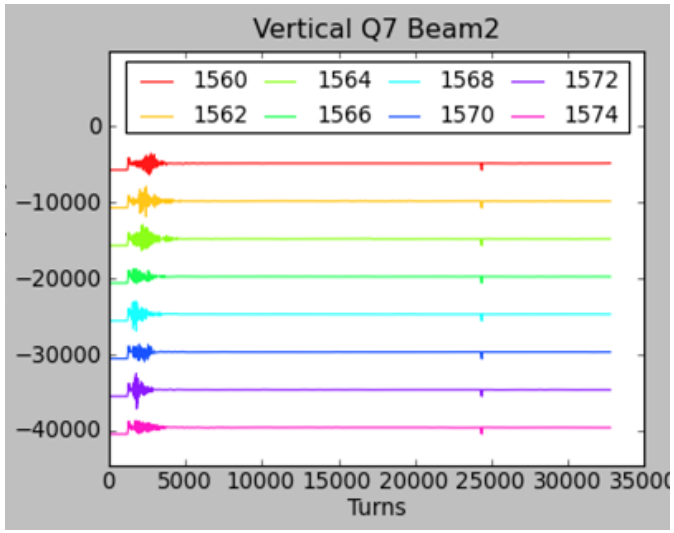
Scrubbing for 25 ns operation



- **After LS1 the SEY was practically reset** to what was observed at the beginning of Run 1
- During (1+2) weeks of scrubbing, regularly **filling the machine with up to ~2500b. with 25 ns spacing** (at 450 GeV) in order to lower the Secondary Electron Yield (SEY) of the beam chambers
- Main **limitations**:
  - Vacuum spikes at the injection collimator in IR8 (**TDI8**)
  - Pressure rise in the injection kickers (**MKIs**)
  - Time required by cryogenics to handle **transients on beam screen temperatures**

Scrubbing for 25 ns operation: beam degradation





Vertical position

During scrubbing with 25 ns beams **instabilities occurring very often at injection** (mainly V, but few dumps also from H)

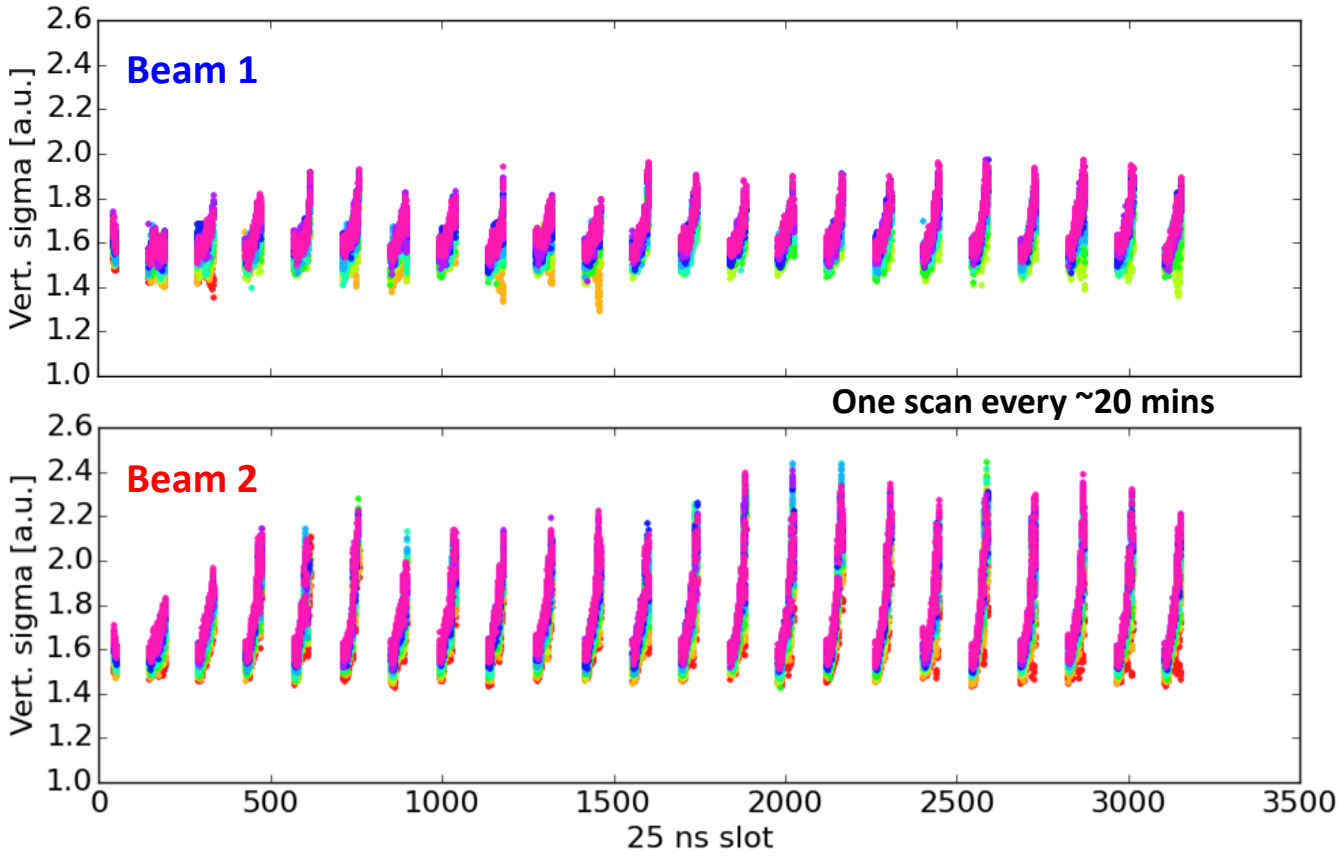
Managed to keep the beam (though instabilities not fully suppressed) using:

- Full performance of the **transverse feedback**
- High **chromaticity** settings ($Q'_{H,V} \approx 15$)
- **High Octupoles** settings

When **not injecting chromaticity trimmed to $Q'_{H,V} \approx 10$** to improve beam lifetime

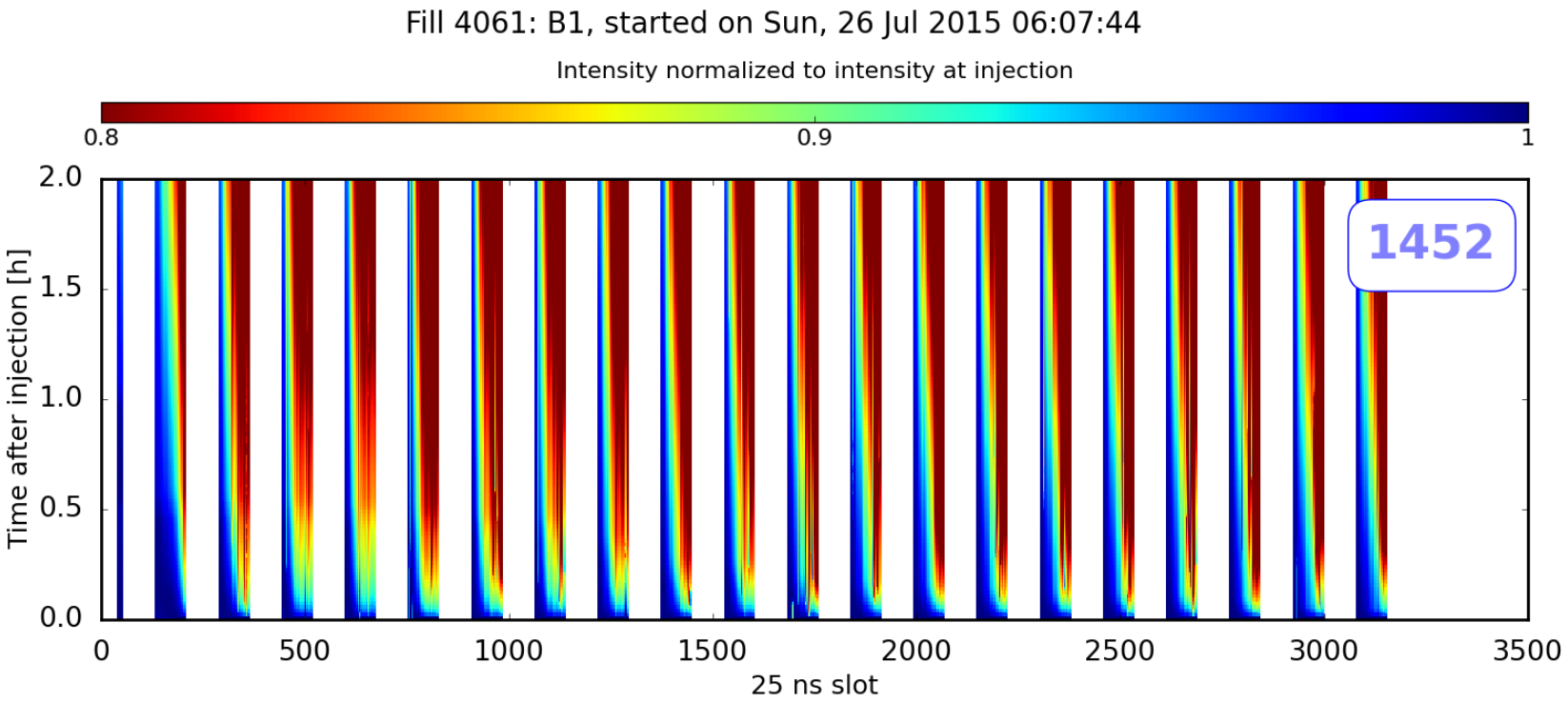
Scrubbing for 25 ns operation: beam degradation

- e-cloud was driving **slow beam degradation** on the circulating beam:
  - Transverse **emittance blow-up**

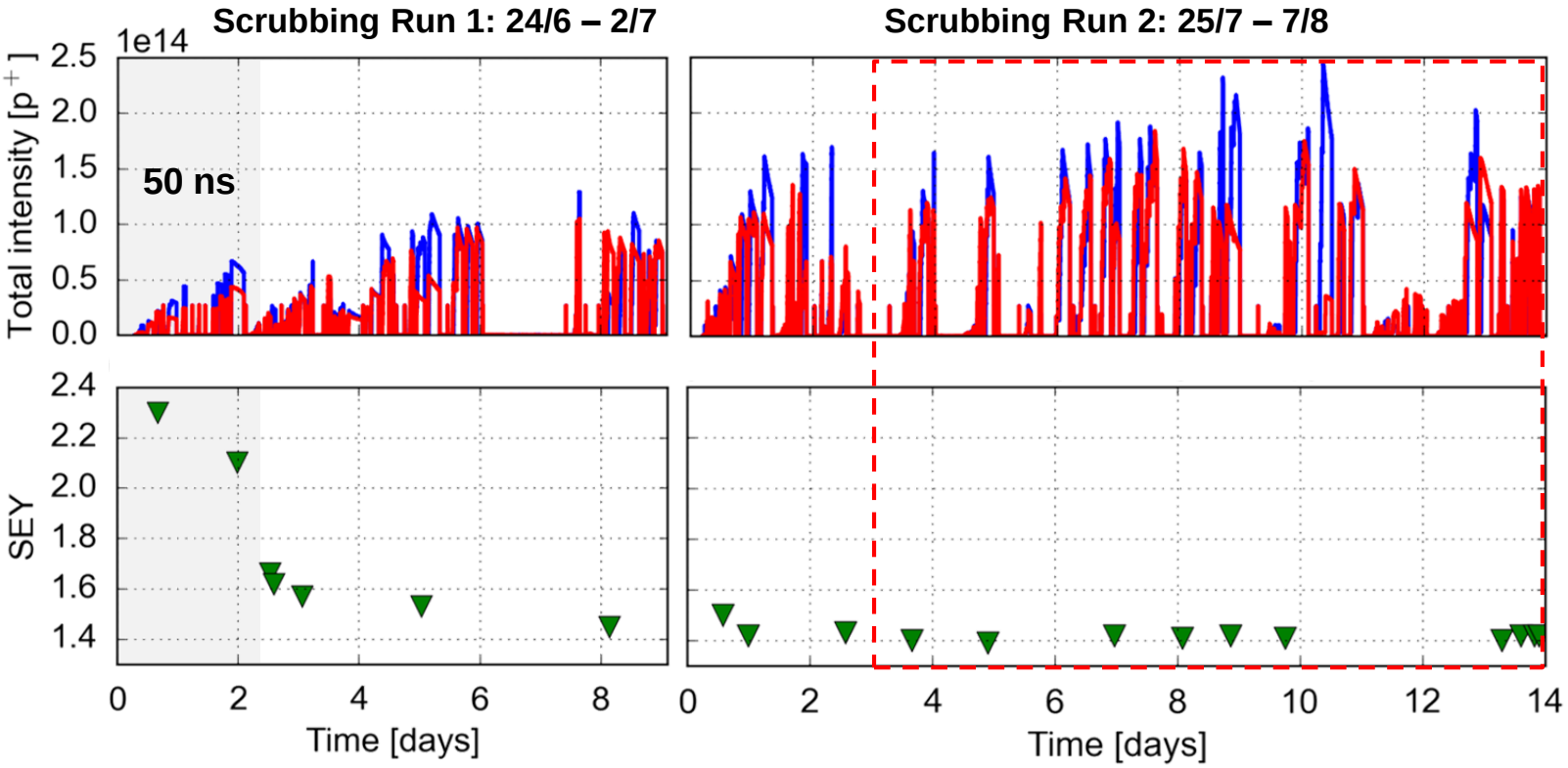


Scrubbing for 25 ns operation: beam degradation

- e-cloud was driving **slow beam degradation** on the circulating beam:
  - **Beam losses**

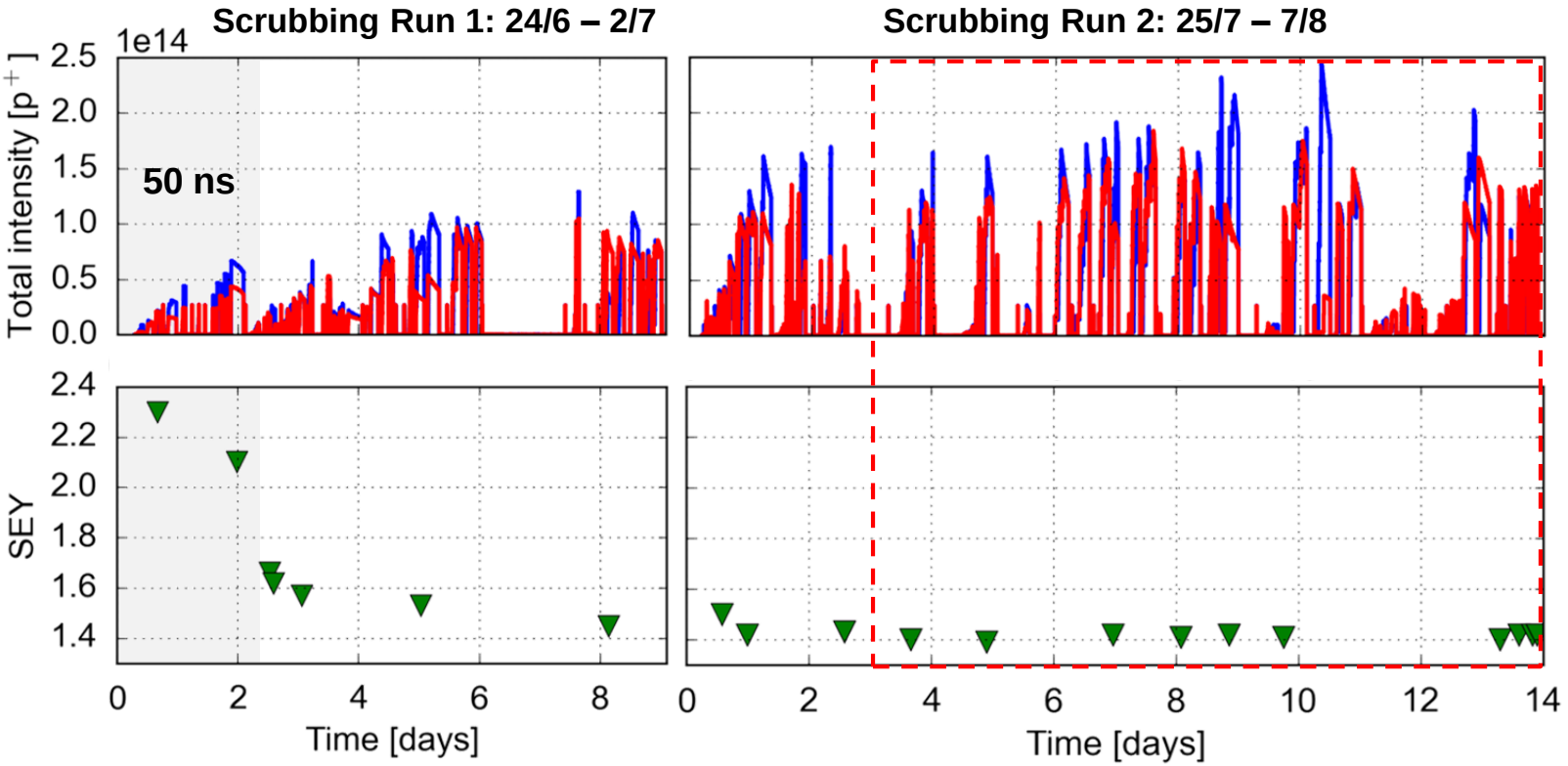


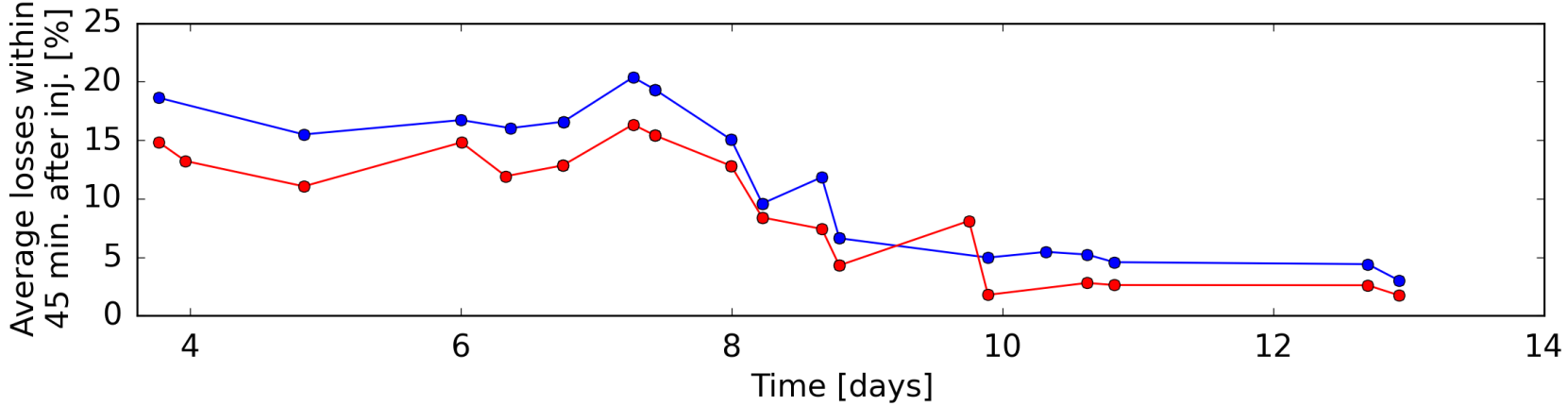
Scrubbing for 25 ns operation: evolution



- **Reduction of the SEY** could be **inferred from heat load measurements** and confirmed by steadily **improving beam quality**

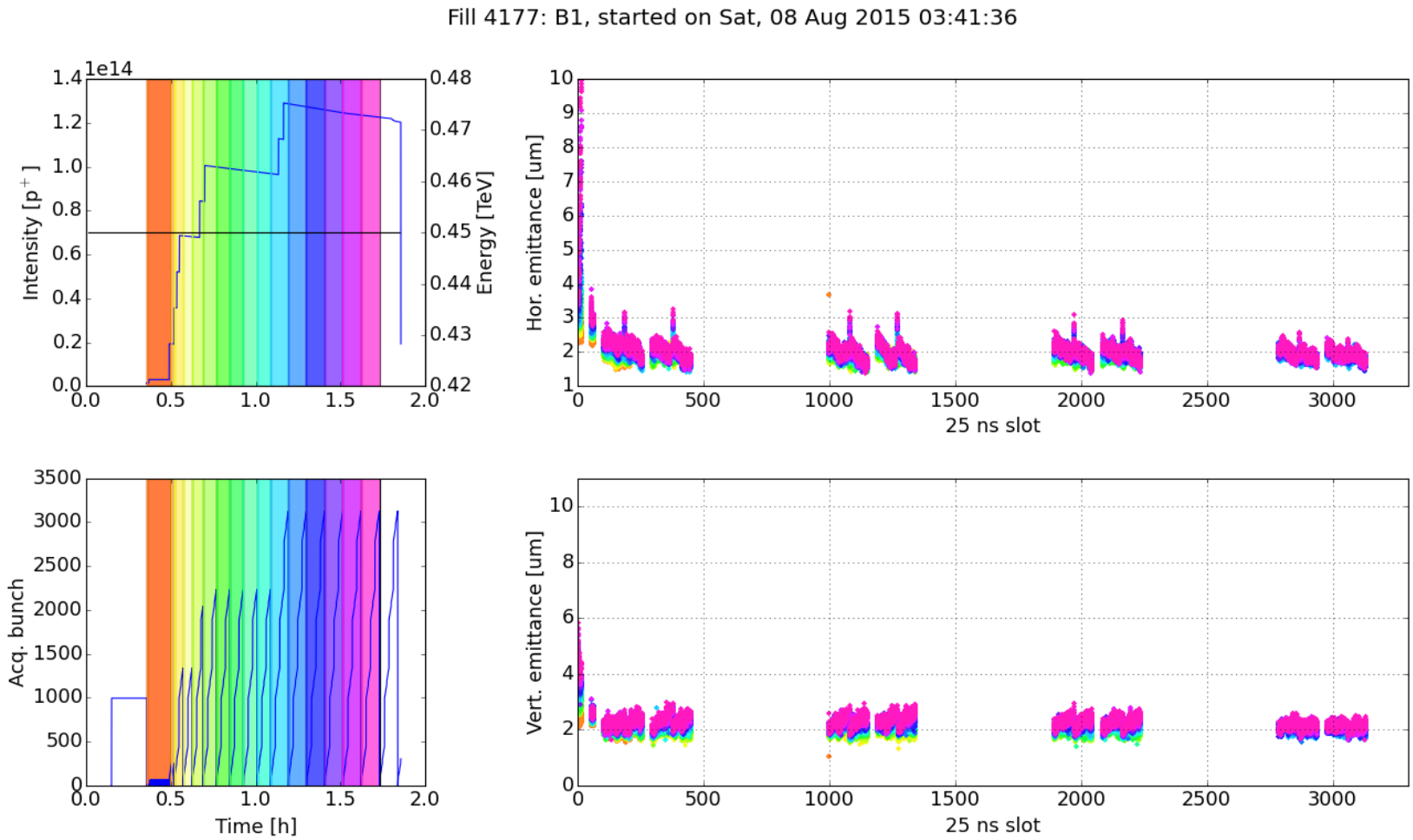
Scrubbing for 25 ns operation: evolution





Scrubbing for 25 ns operation: evolution

- By the end of the scrubbing **instabilities were under control** and **emittances could be well preserved** at 450 GeV (qualification done with ~1200 b.)



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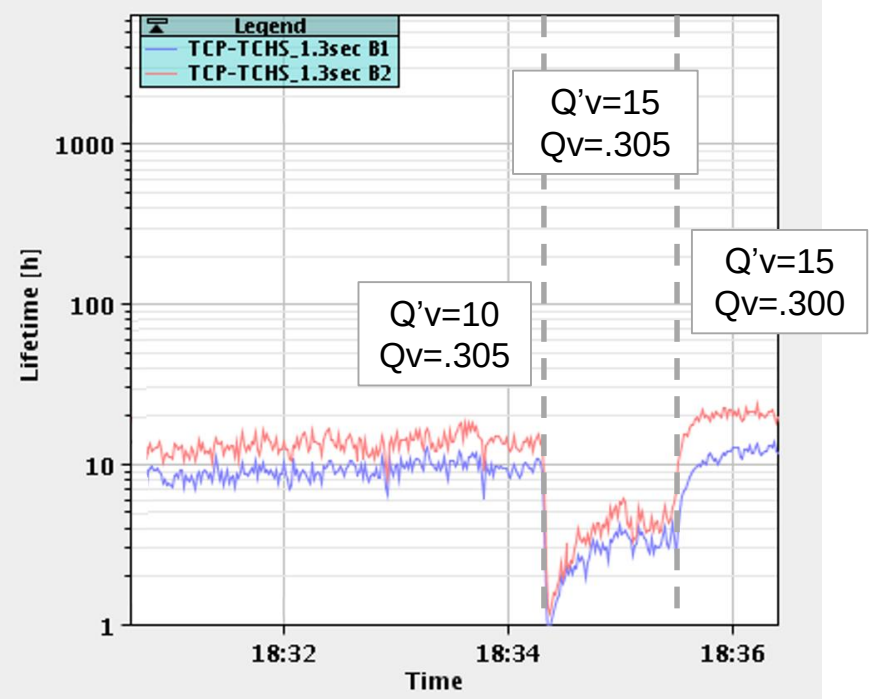
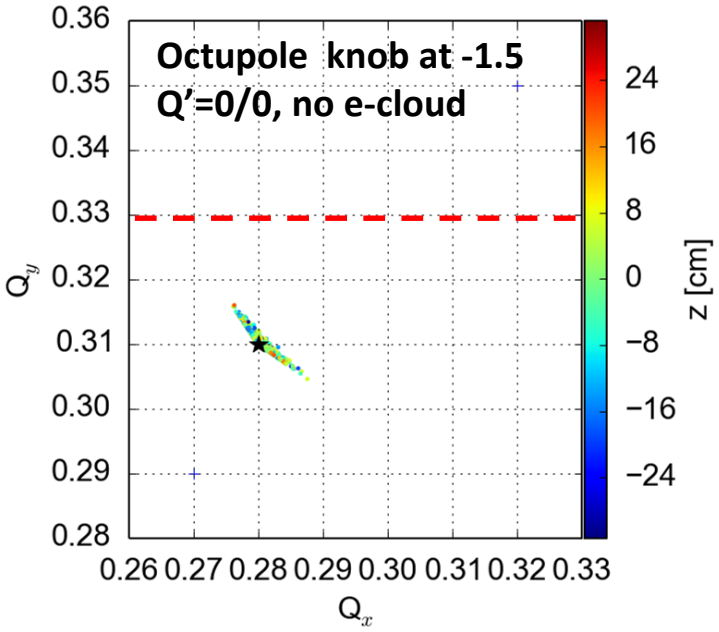
Working point at 450 GeV

- 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
- Slightly **changed working point at injection** to better accommodate large tune footprint from Q', octupoles and e-cloud



Tune footprint simulated with PyECLOUD-PyHEADTAIL



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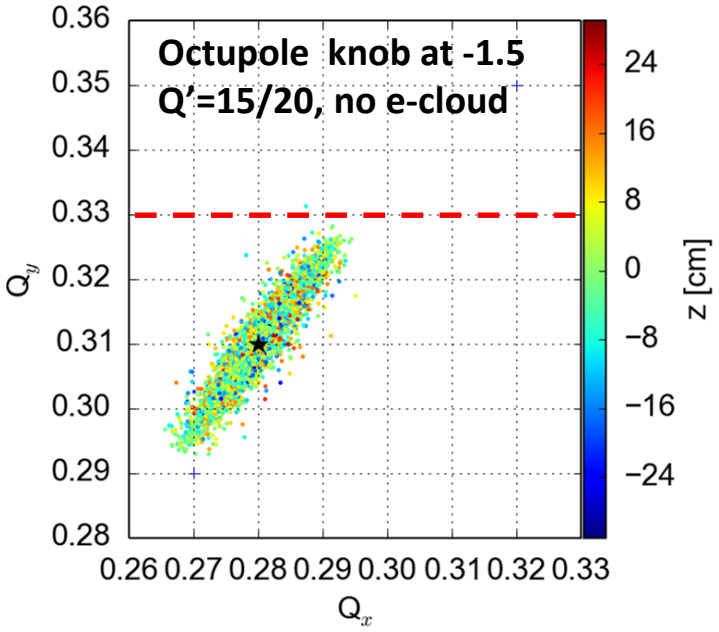
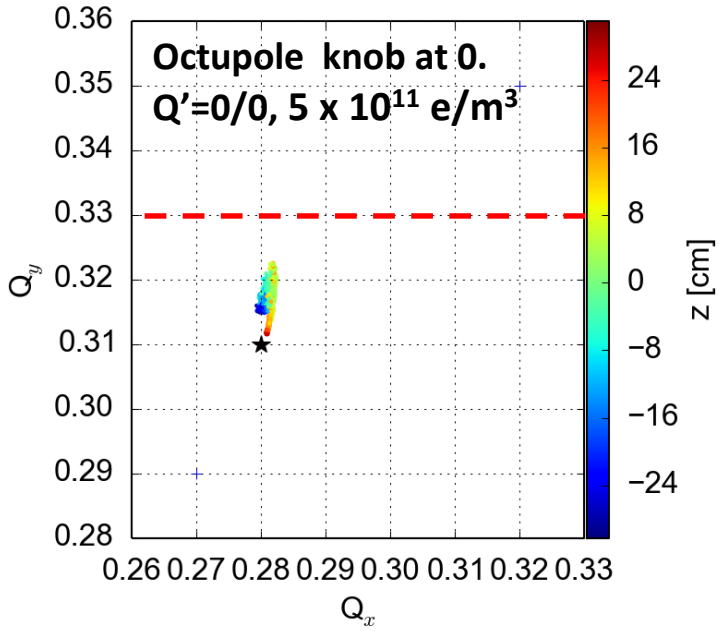
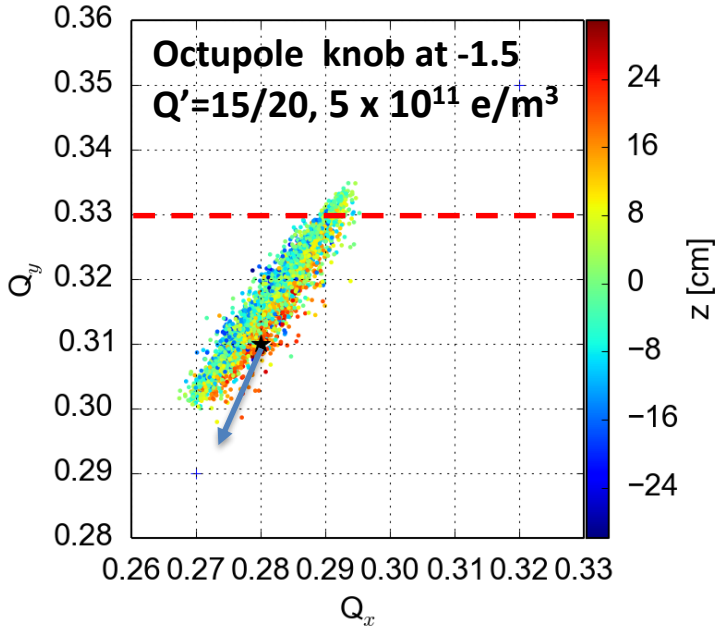
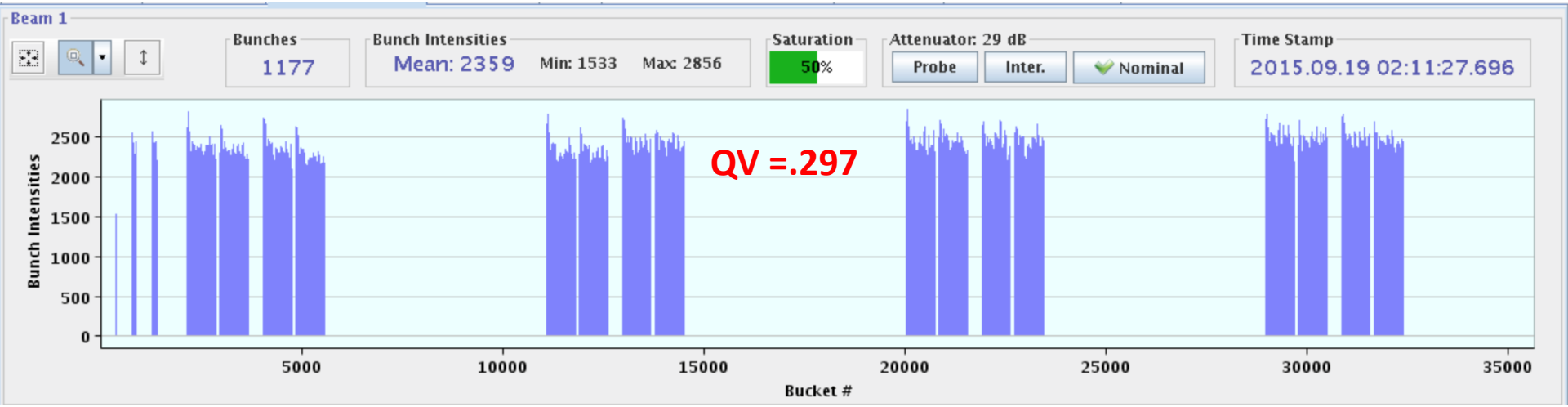


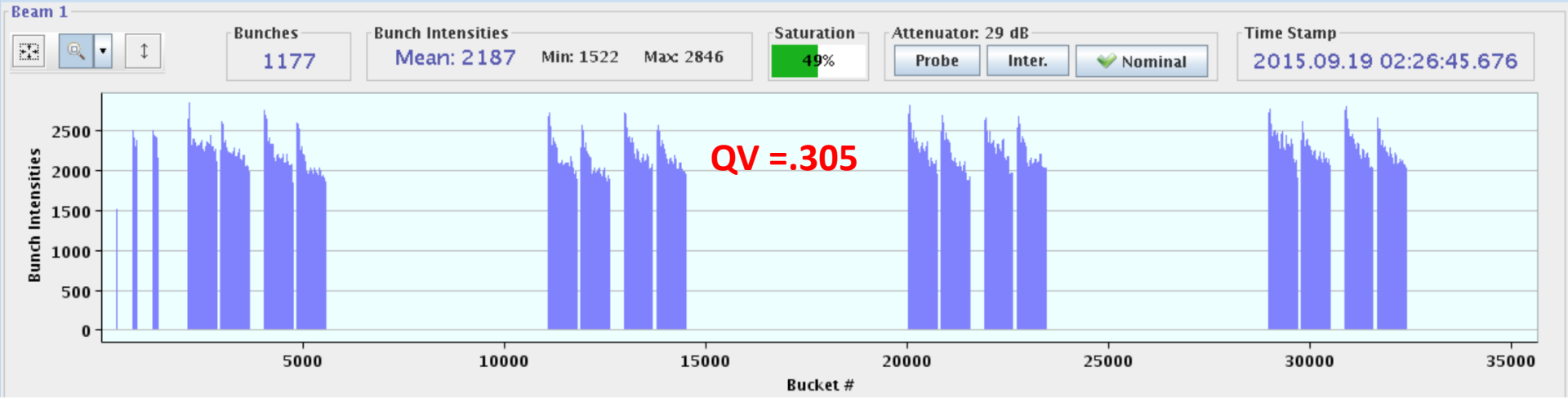




Machine observations

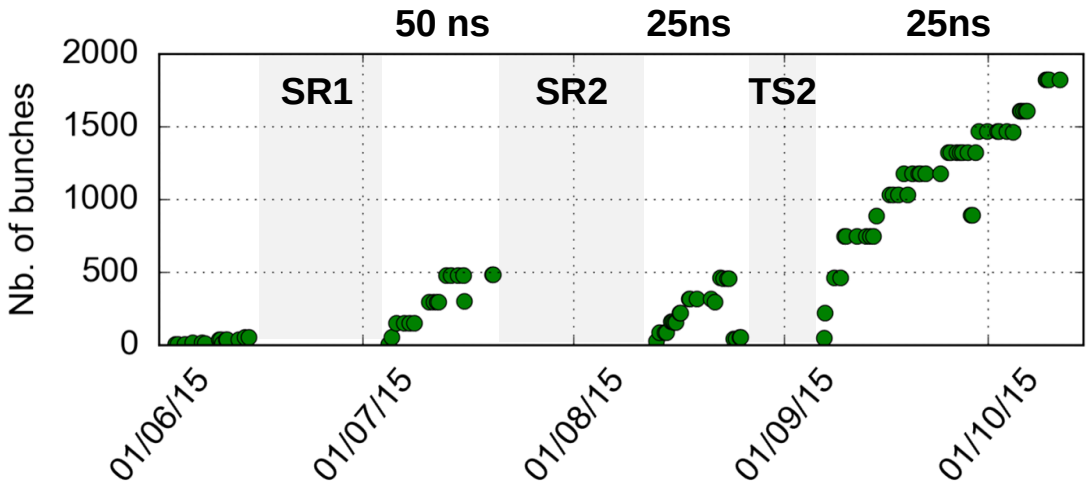
- **Only trailing bunches** (which see stronger e-cloud) have large enough tune spread to reach the resonance





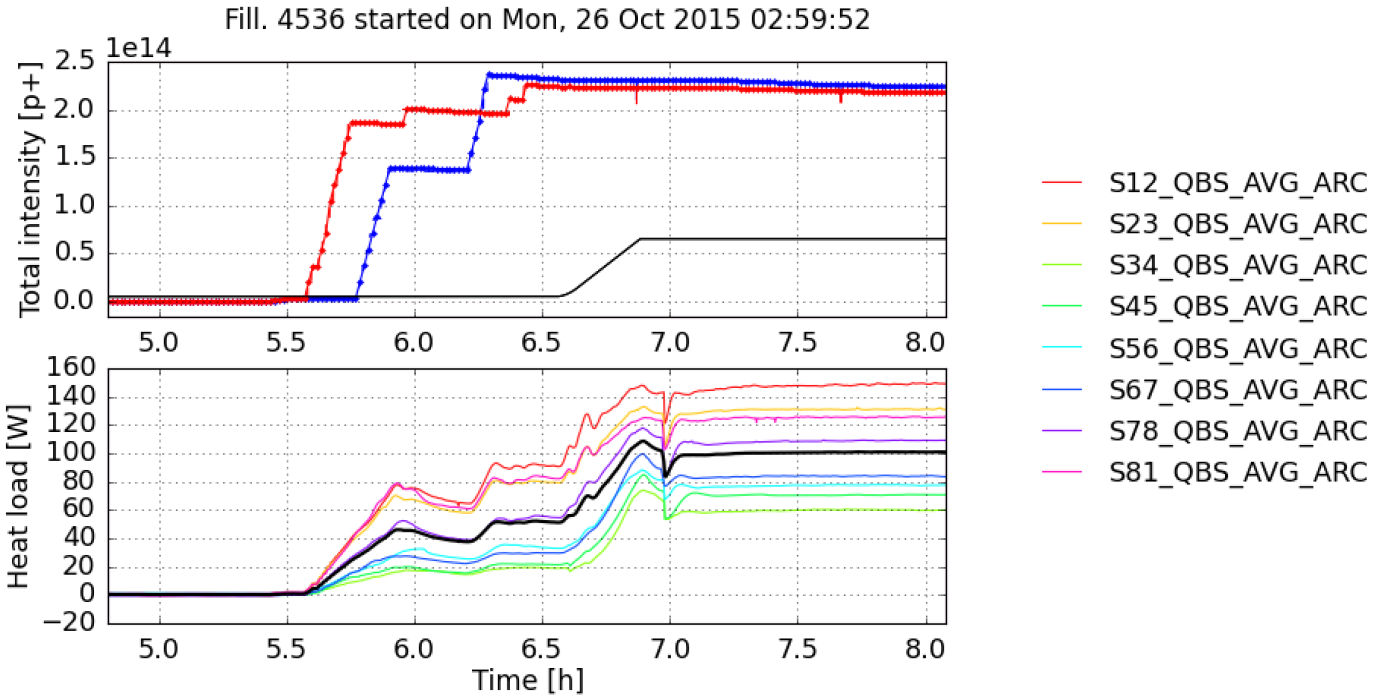
Intensity ramp-up with 25 ns beams: heat loads

- Even with relatively low number of bunches, **strong transients of the beam screen temperatures were observed**, leading to loss of cryo-conditions (during injection, ramp and at the beam dump):
  - 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
  - After careful analysis, it was decided to **modify the interlock rules in order to allow for larger temperature excursion** → since then practically no loss of cryo-conditions during injection and ramp



Intensity ramp-up with 25 ns beams: heat loads

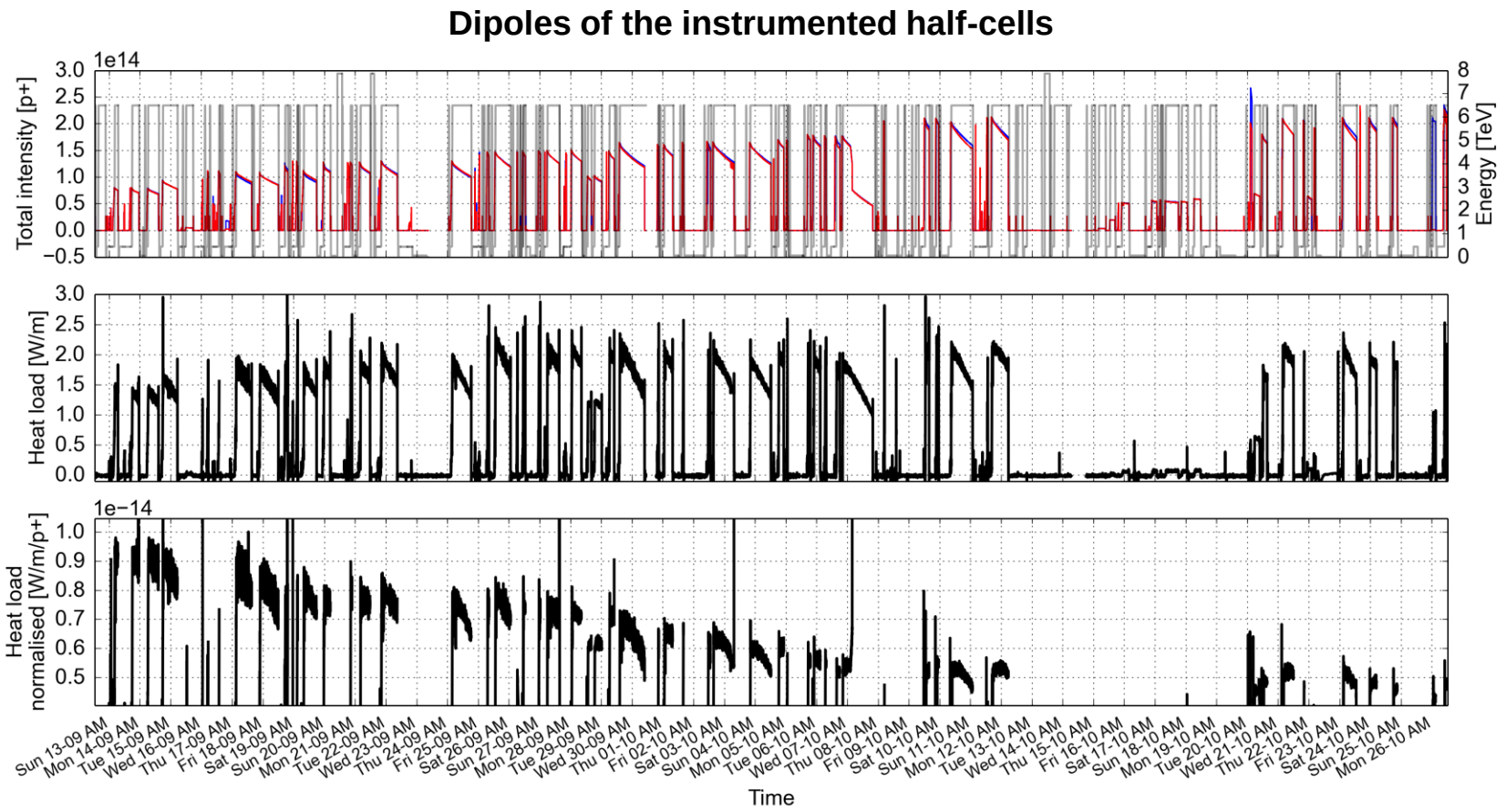
- Around ~1450b. we started approaching the **limit of the available cooling capacity** on the arc beams screens
  - → Increased **longitudinal emittance blow-up** on the ramp (bunch length target from 1.2 ns to 1.35 ns) and **optimized filling scheme** to gain additional margin
- Since last Monday running with **2041b. per ring**:
  - → **Sector 12 and 23 close to the margin** of available cryo cooling capacity (some margin still available for the others - important to understand this difference)



Intensity ramp-up with 25 ns beams: heat loads

Scrubbing observed with physics fills at 6.5 TeV

- Hopefully gaining margin to further increase the number of bunches
- **Scrubbing "memory" kept** while running with 25 ns beams



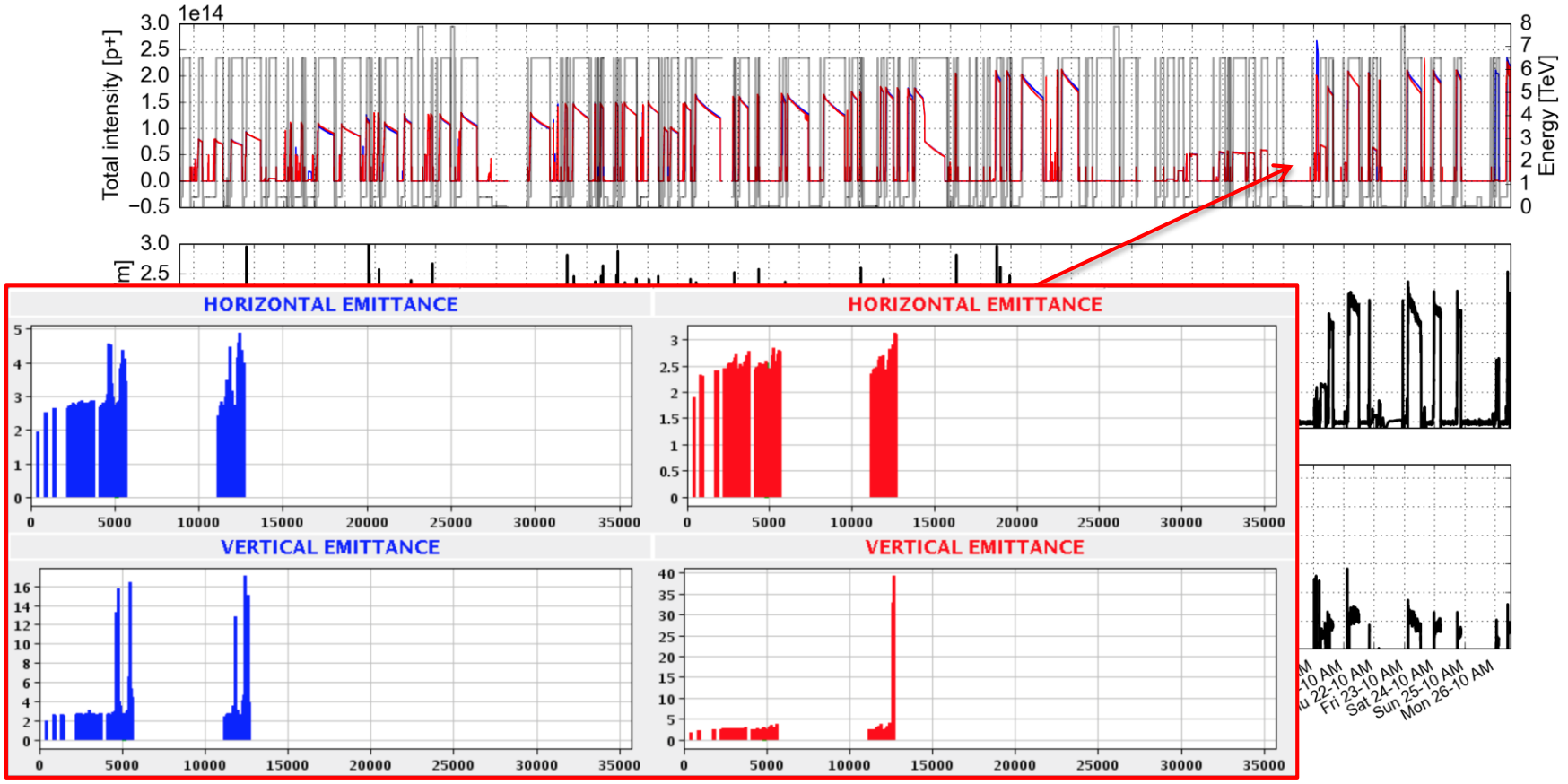
Intensity ramp-up with 25 ns beams: heat loads

Scrubbing observed with physics fills at 6.5 TeV

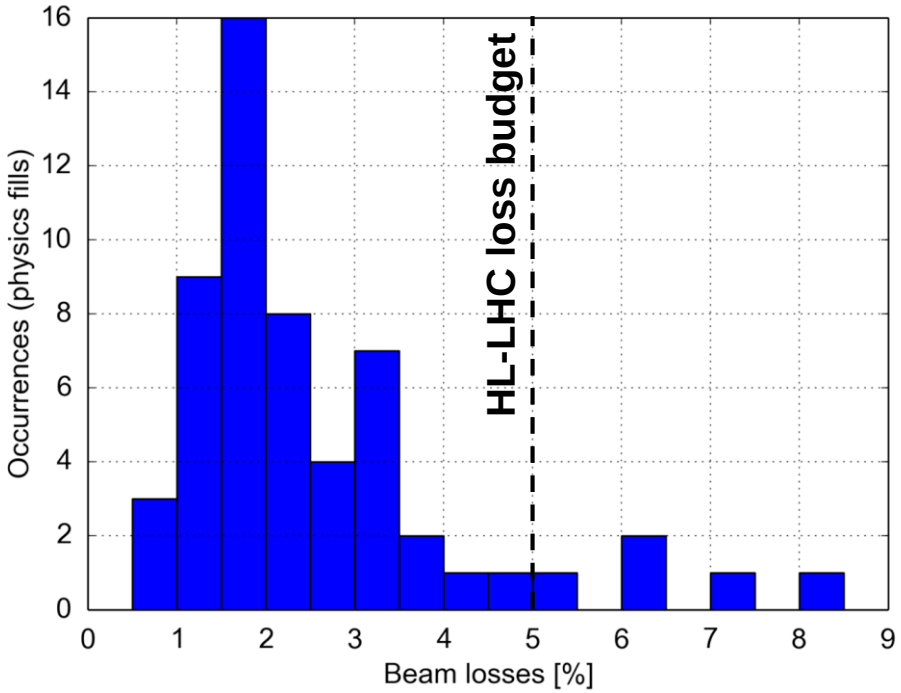
- Hopefully gaining margin to further increase the number of bunches
- **Scrubbing "memory" kept** while running with 25 ns beams
- **Deconditioning** observed after periods of low e-cloud **configurations**

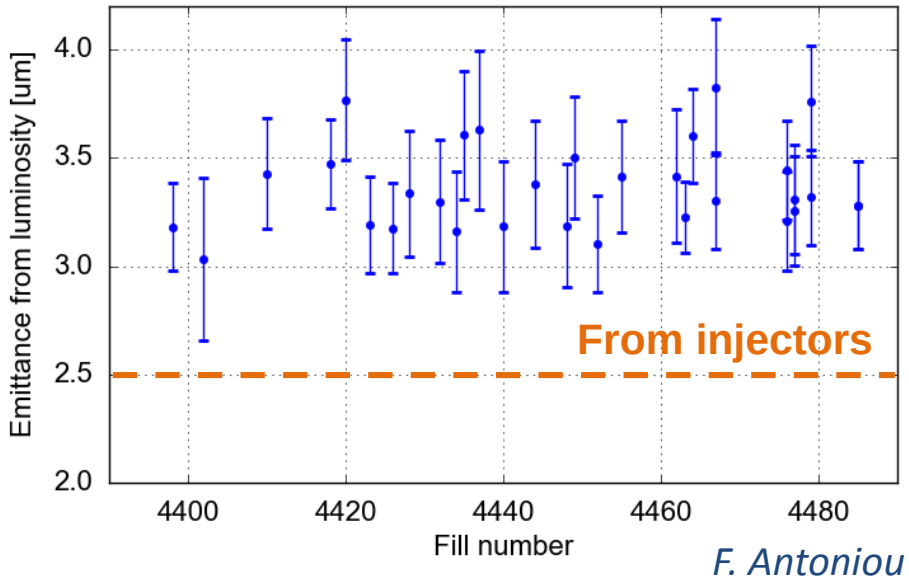
→ **Could be** recovered with ~2h scrubbing at 450GeV

Dipoles of the instrumented half-cells



Intensity and emittance preservation (injection to collisions)





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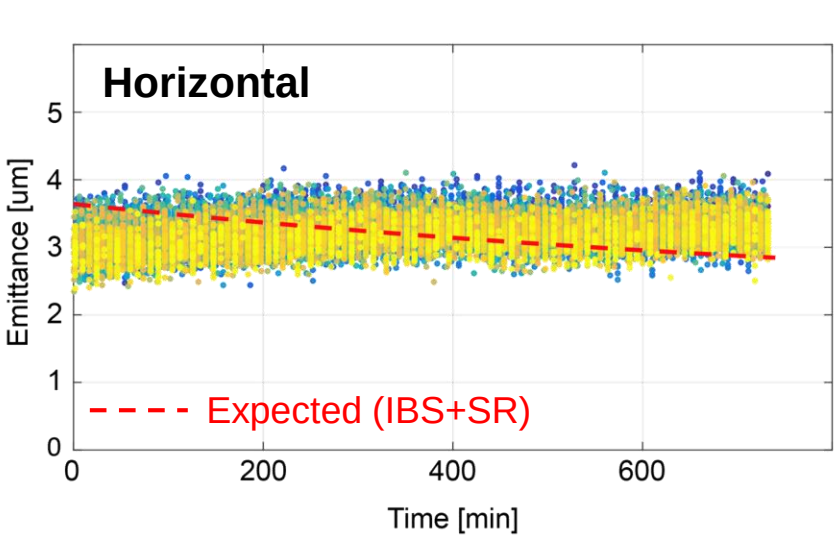
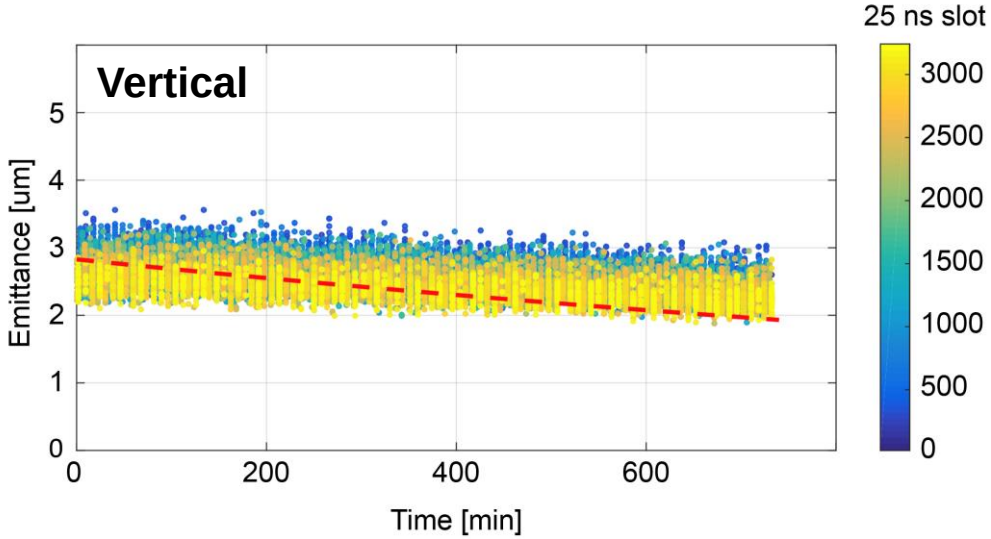
- **Excellent transmission** along the cycle (also thanks to the new working point)
- **3-3.5 um** convoluted emittances at beginning of collisions (similar values in H and V)
  - **Injected emittances** of the order to **2.5 um**
  - **Much less blow-up observed with single bunches**

    → Possible culprits: e-cloud, high Q' and octupoles, ADT noise (to be further investigated)

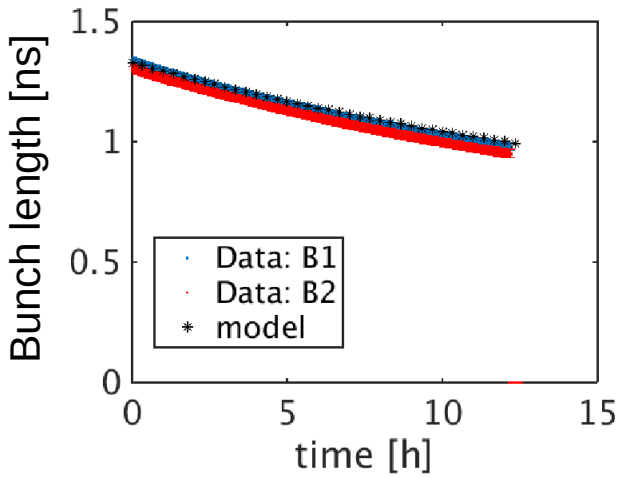
Beam evolution in “stable beams”

- Overall **good emittance preservation in “stable beams”**
  - → Slow **damping** observed in the **vertical** plane
  - → **Some additional blow** up w.r.t. expectations from IBS + Synchrotron Radiation (SR)

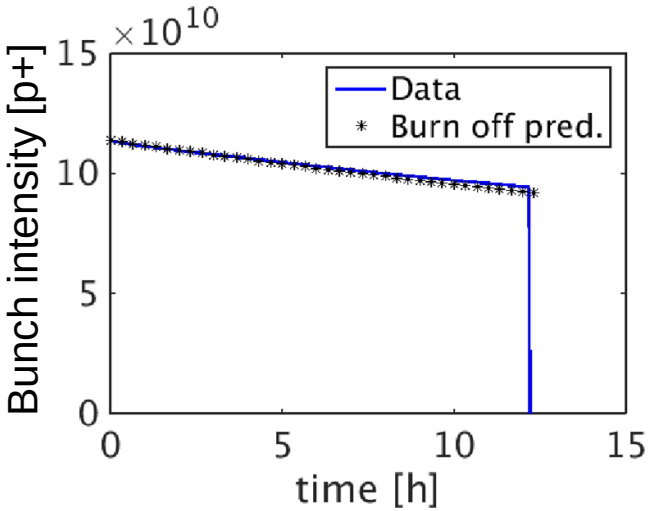




→ **Strong damping in longitudinal**



→ **Burn-off consistent with model**



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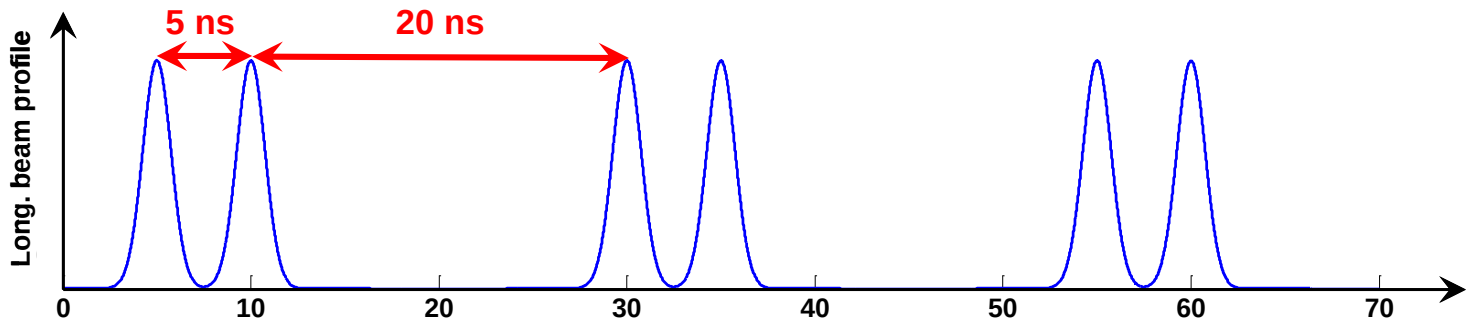
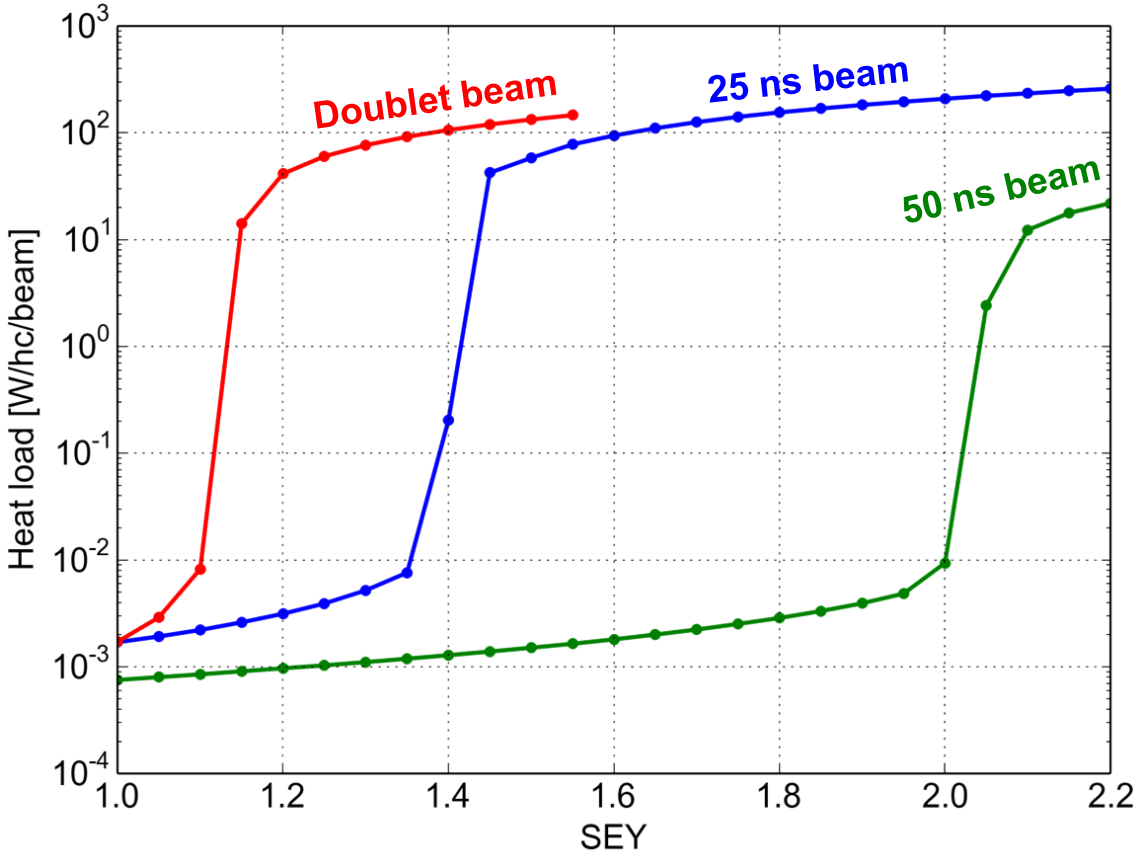
Filling pattern for e-cloud enhancement: the “doublet” beam

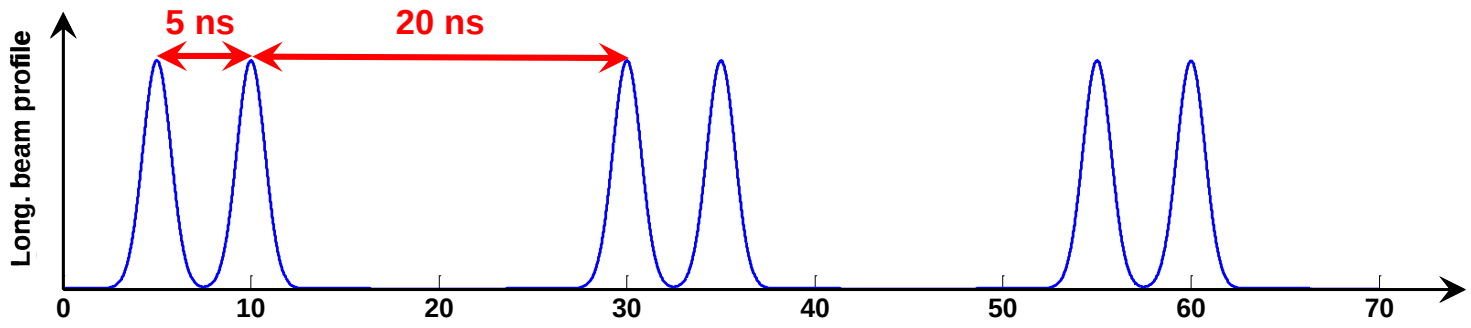




Lower multipacting threshold w.r.t. 25ns

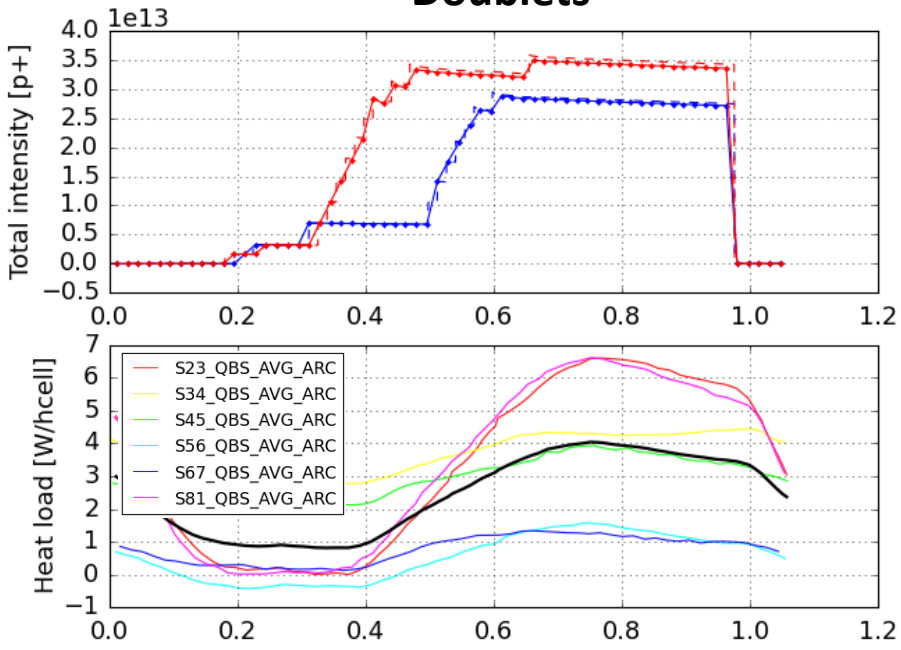
→ well suited for scrubbing

Filling pattern for e-cloud enhancement: the “doublet” beam

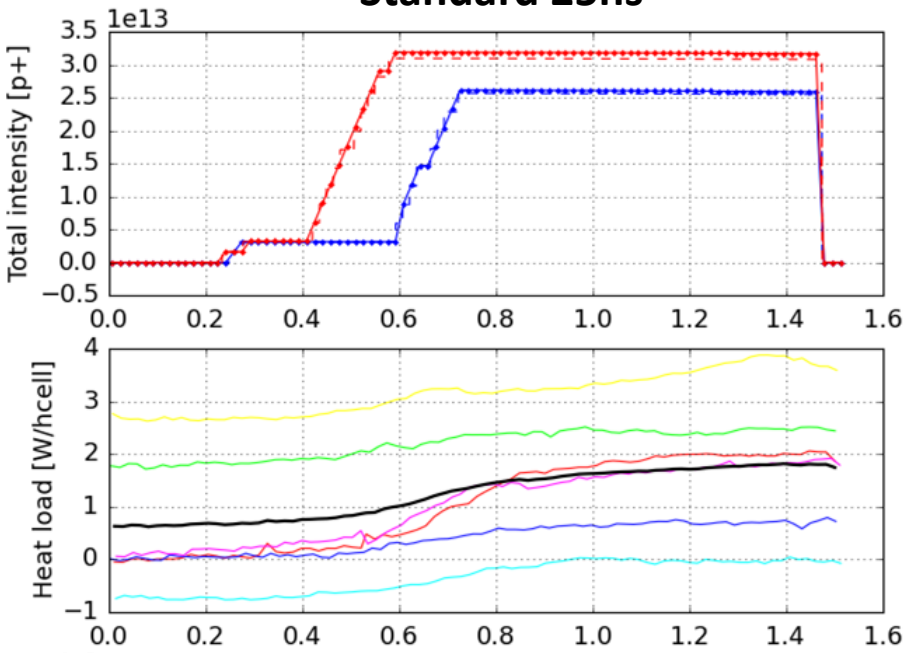


- Tested in the LHC in August 2015: electron cloud **enhancement demonstrated experimentally**

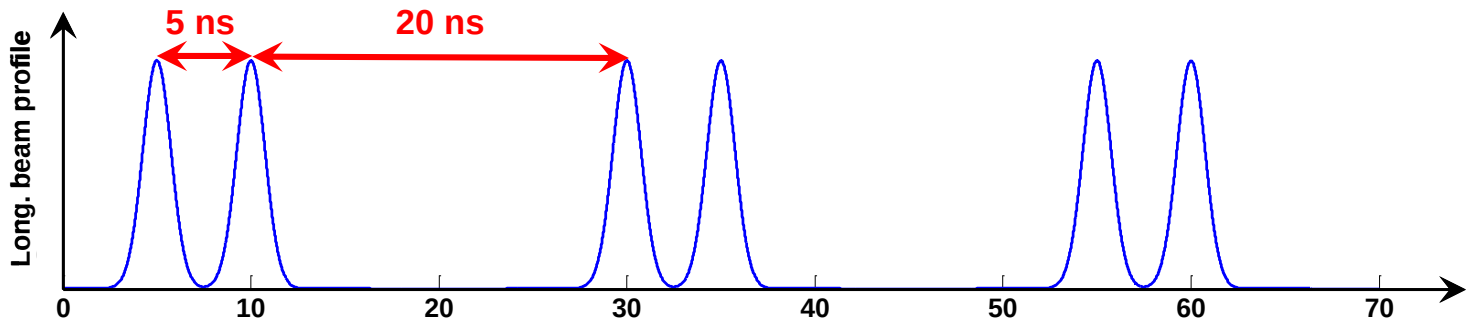
Doublets



Standard 25ns

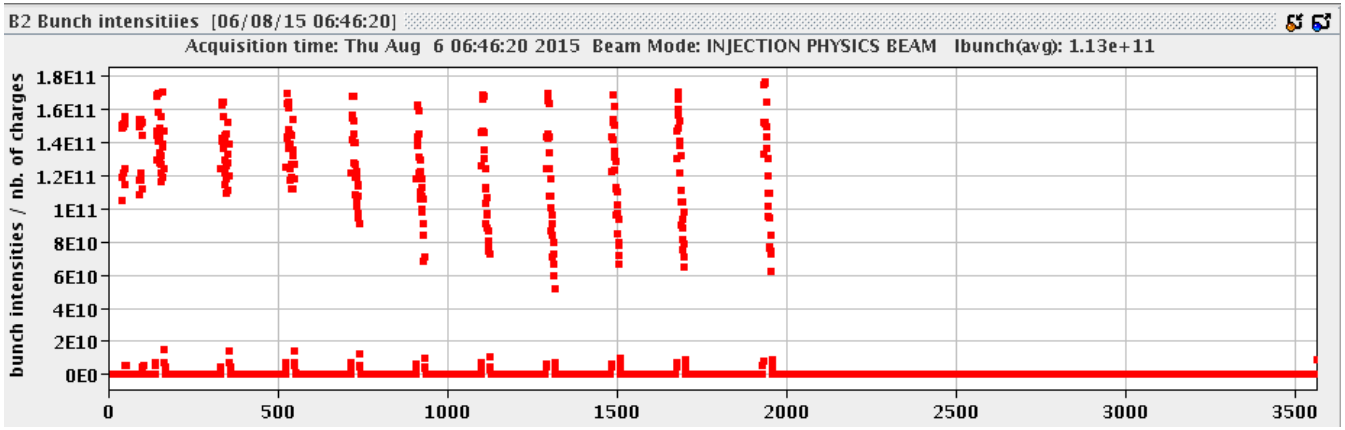


Filling pattern for e-cloud enhancement: the “doublet” beam



Tested in the LHC in August 2015:

- At that point SEY still high
  - → very **strong e-cloud instabilities** and **beam degradation**
  - → **Impossible to accumulate enough beam** for efficient scrubbing
  - → To be tested again after accumulating more scrubbing with 25 ns beam

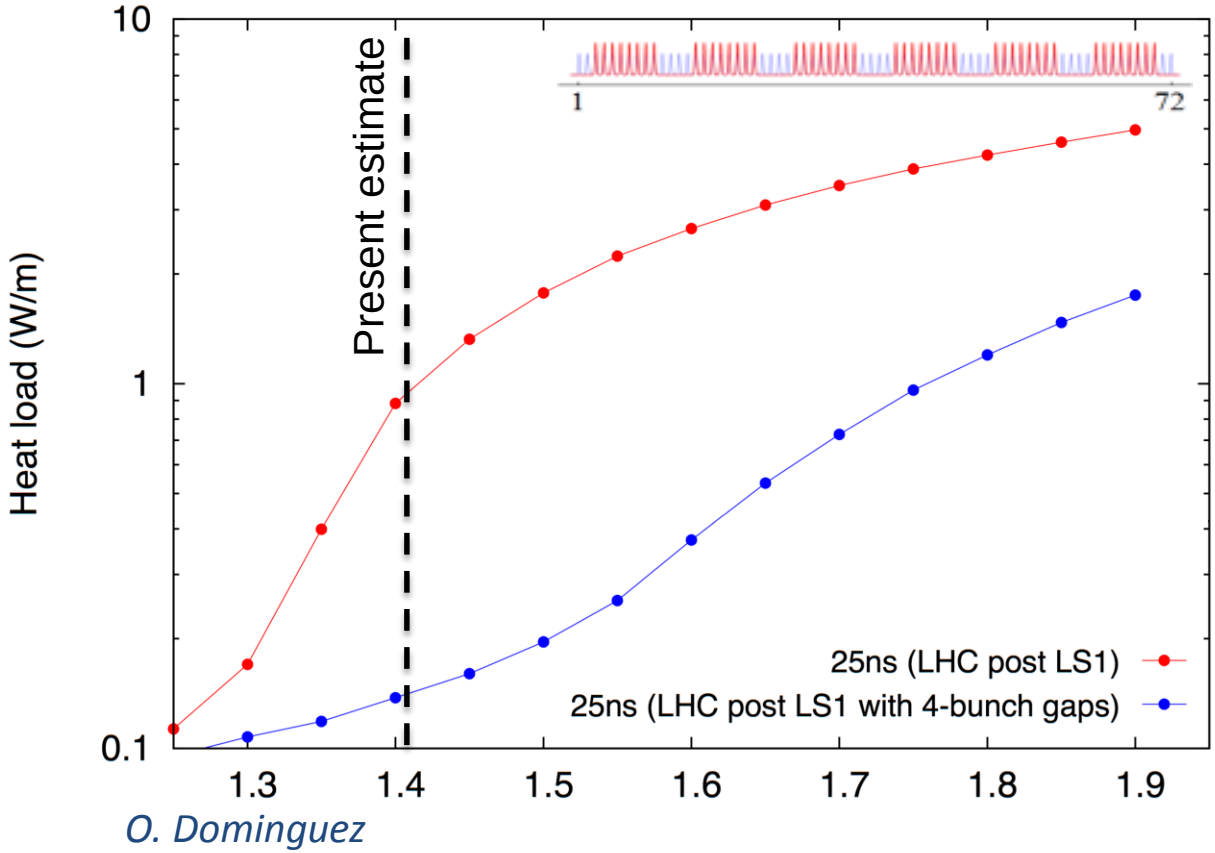


Filling pattern for e-cloud suppression: the “8b+4e” beam

Micro-trains of 8 bunches spaced by 4 empty slots (~30% less bunches w.r.t. nominal)

→ Simulations predict a **larger multipacting thresold** compared to the standard 25 ns

→ For the present SEY value in the LHC beam screens (dipoles), e-cloud suppression should be achieved



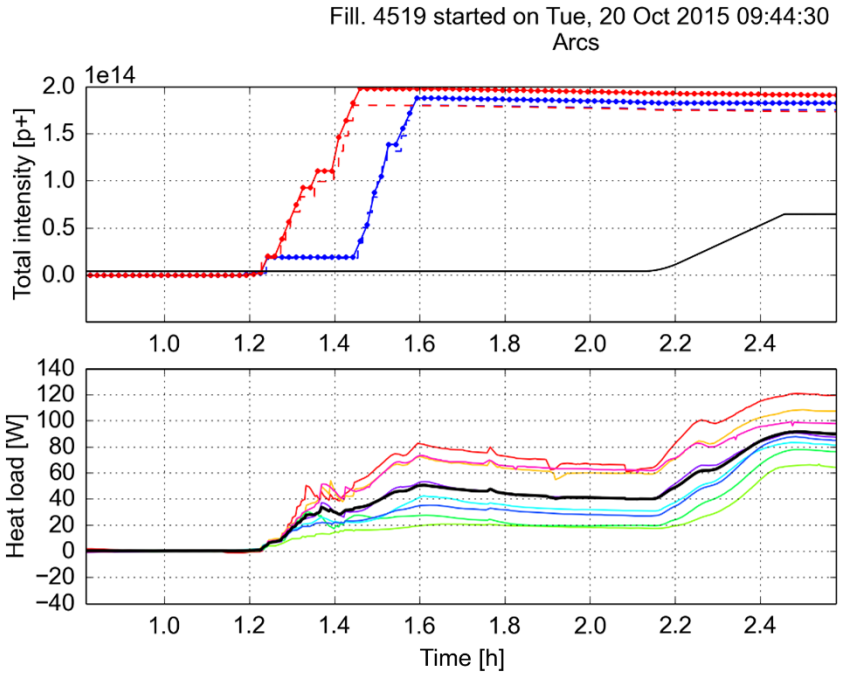
O. Dominguez

Filling pattern for e-cloud suppression: the “8b+4e” beam

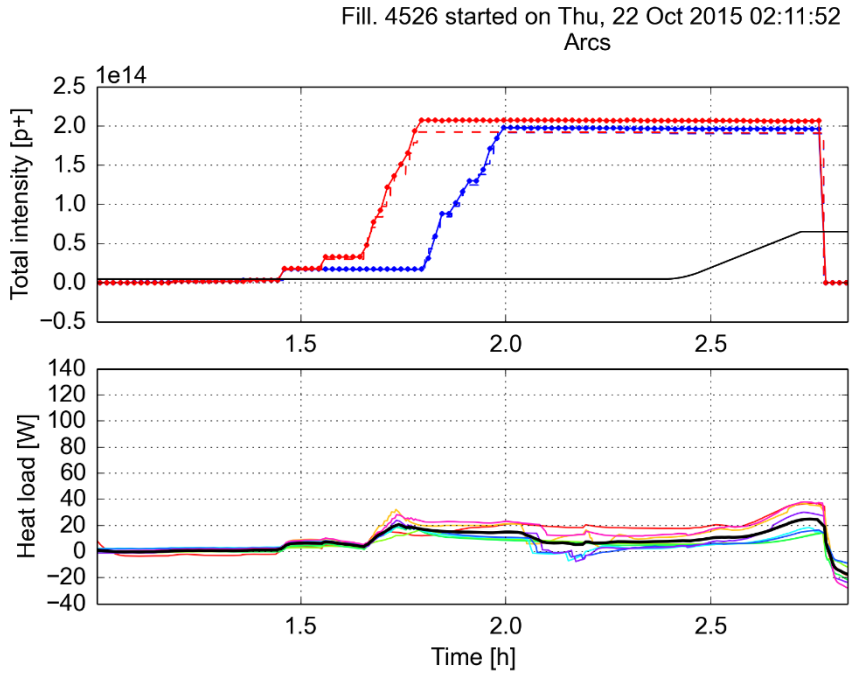
Tested in LHC last Thursday:

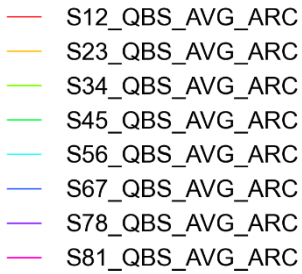
→ **e-cloud reduction visible on heat loads** measured by cryogenics

Standard 25 ns



8b+4e



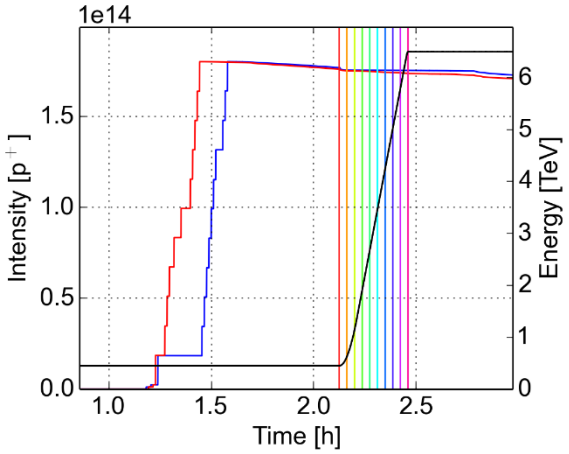


Filling pattern for e-cloud suppression: the “8b+4e” beam

Tested in LHC last Thursday:

→ **e-cloud reduction visible on stable phase shifts**

Standard 25 ns



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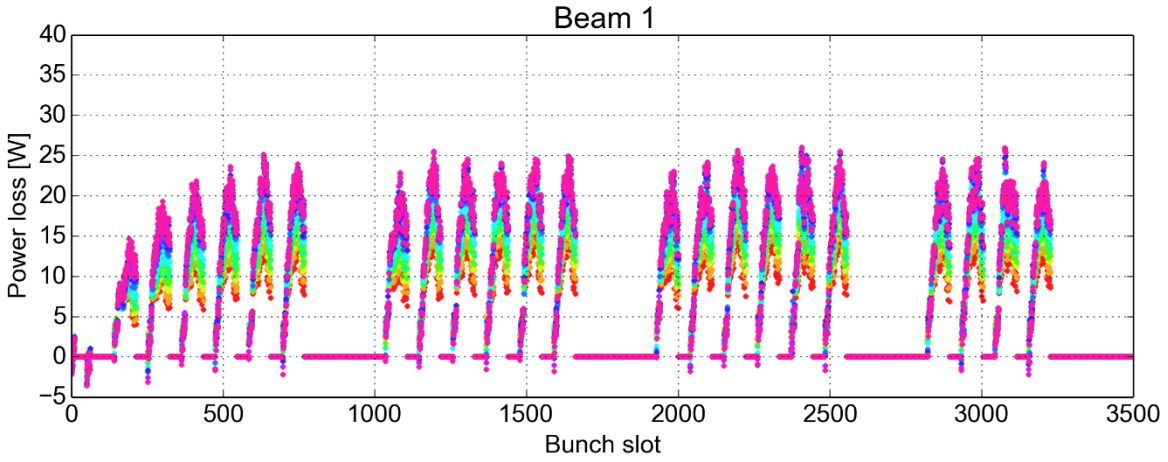
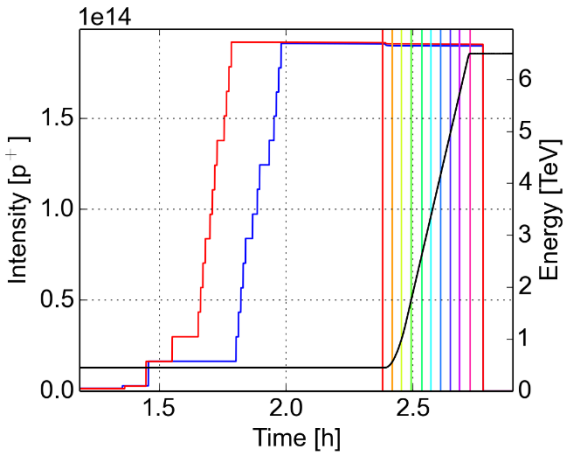


8b+4e



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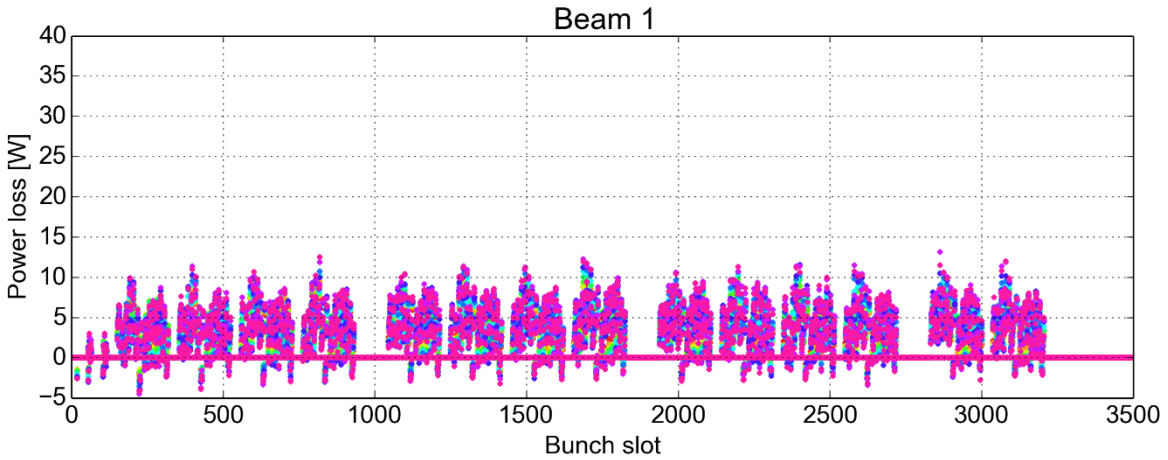

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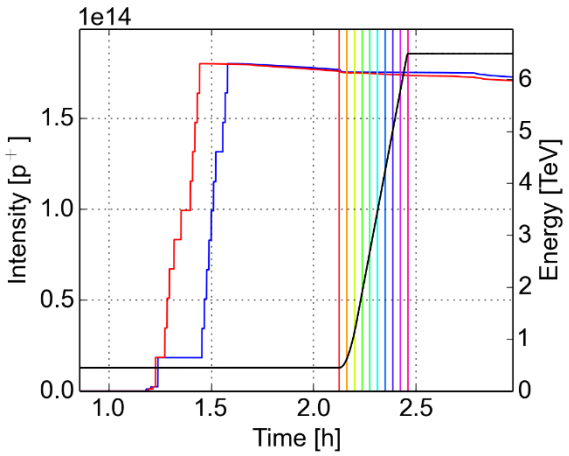
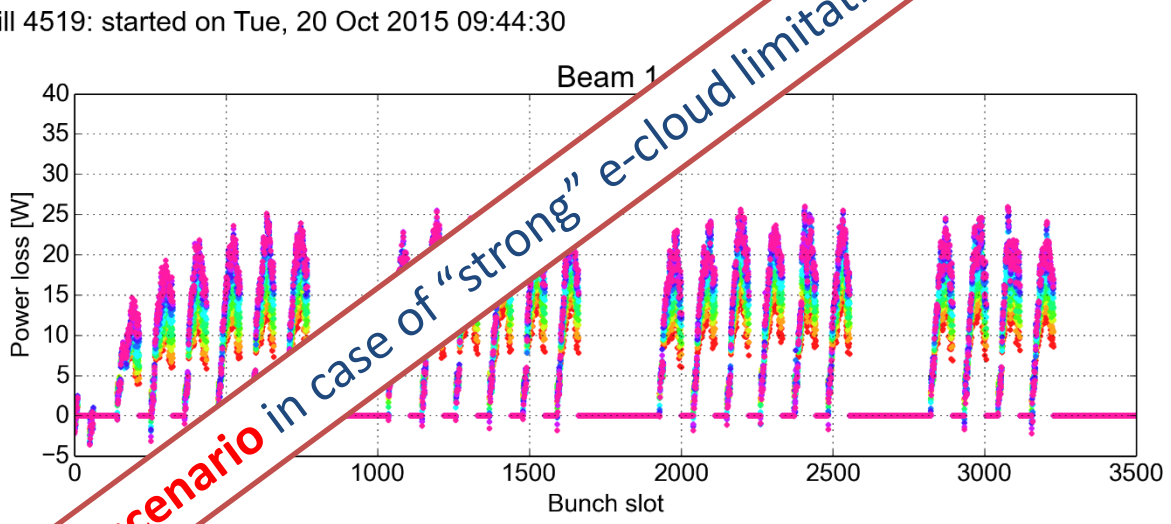
Filling pattern for e-cloud suppression: the “8b+4e” beam

Tested in LHC last Thursday:

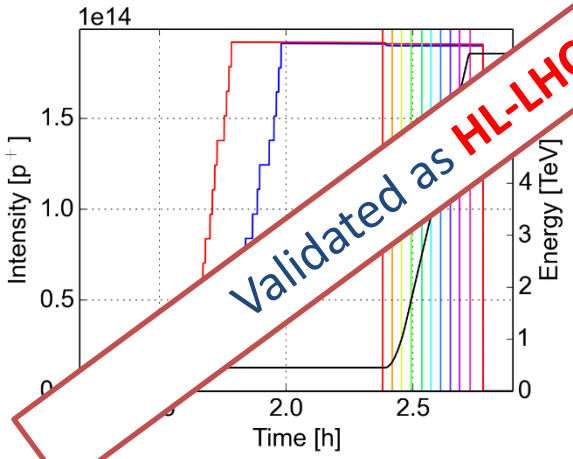
→ **e-cloud reduction visible on stable phase shifts**

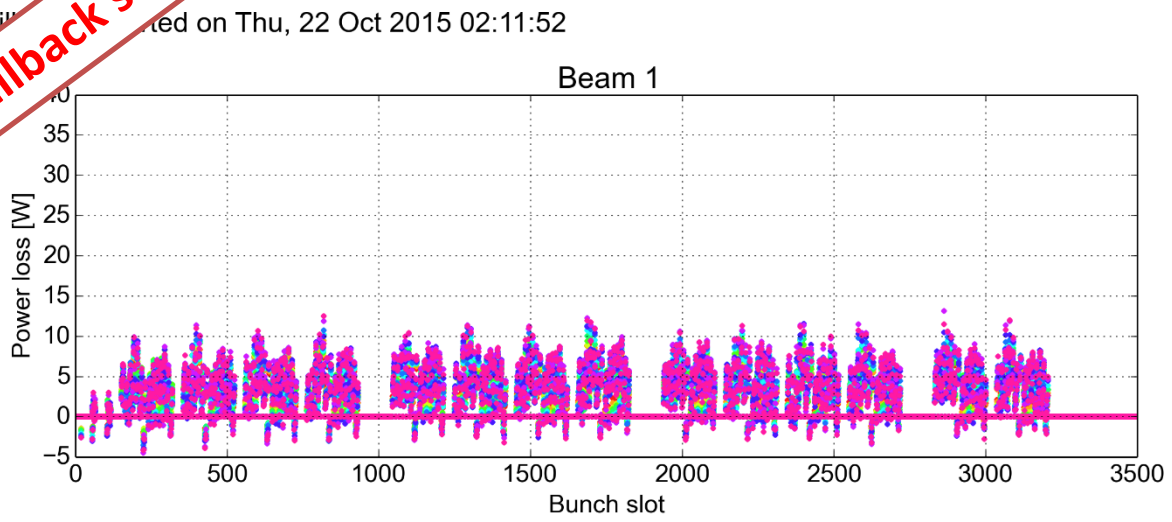
Standard 25 ns





8b+4e





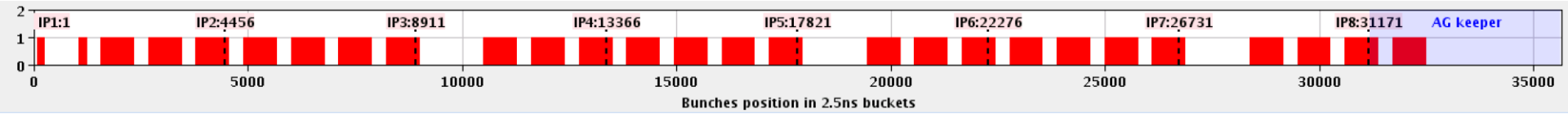
Validated as HL-LHC fallback scenario in case of “strong” e-cloud limitations

J. Esteban Muller

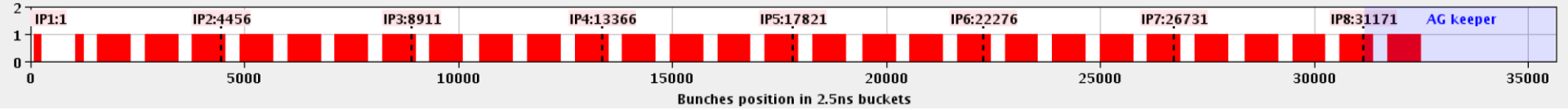
Filling schemes “tailored” for given heat load

At the moment we are **exploiting the flexibility on the filling scheme** to **maximize the number of bunches** within the heat load **limits of the cryogenics (160 W/hc)**

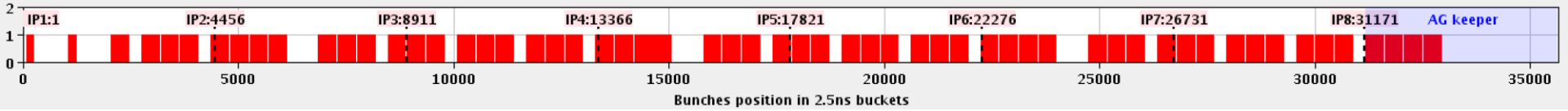
25ns_1825b_1813_1495_1536_144bpi16inj_sp: **HL_{12}= 140 W/hc** - **1825b.** in trains of 72b.



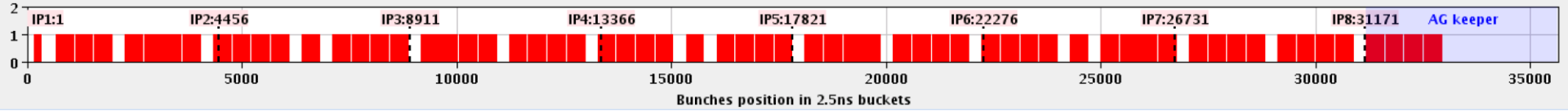
25ns_2041b_2029_1666_1710_144bpi17inj_sp: **HL_{12}= 157 W/hc** - **2041b.** in trains of 72b.



25ns_2041b_2029_1561_1678_144bpi20inj_36: **HL_{12}= 134 W/hc** - **2041b.** in trains of 36b.

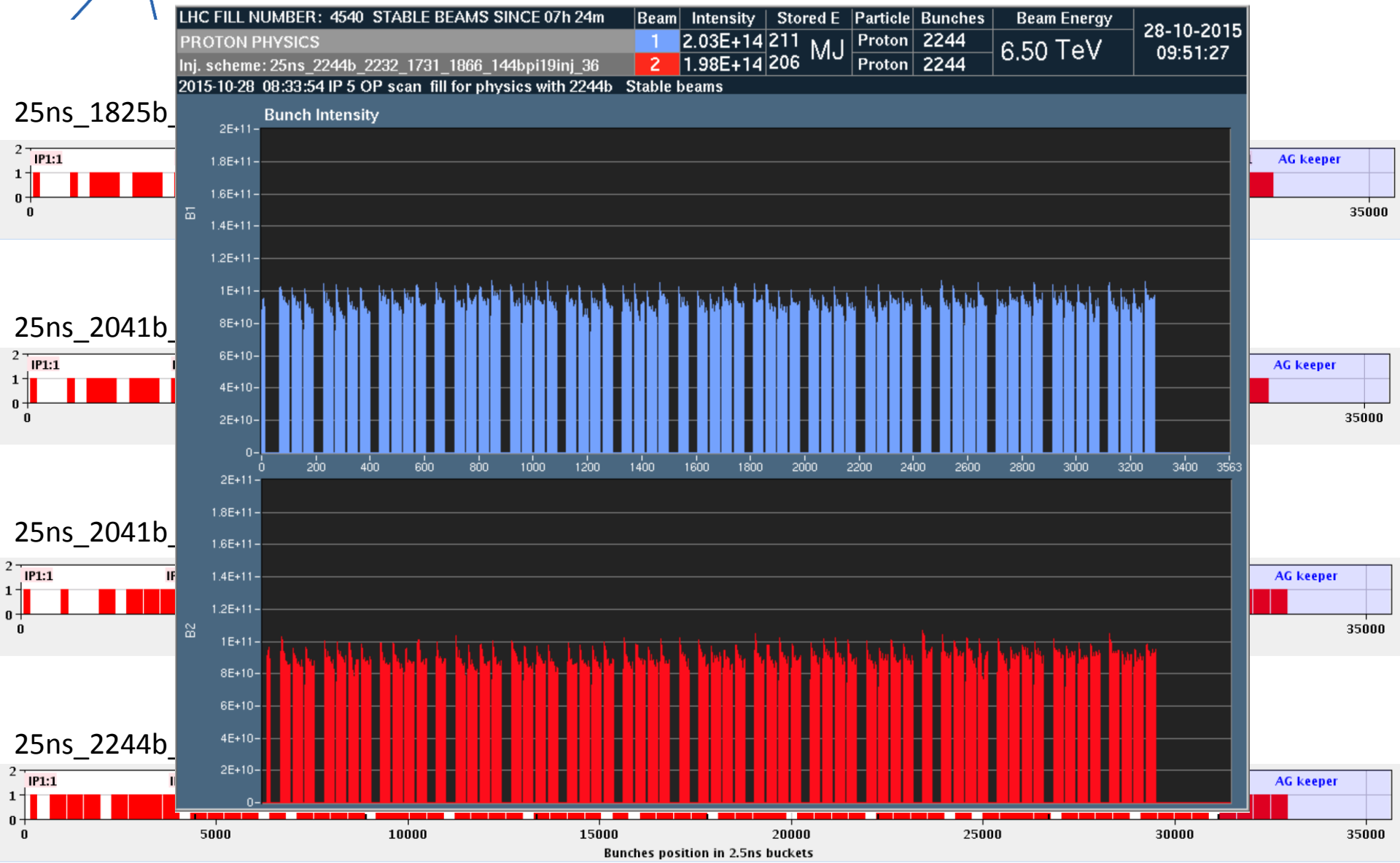


25ns_2244b_2232_1731_1866_144bpi19inj_36: **HL_{12}= 150 W/hc** - **2244b.** in trains of 36b.



Optimized filling schemes for given heat load

At the moment we are **exploiting the flexibility on the filling scheme** to **maximize the**

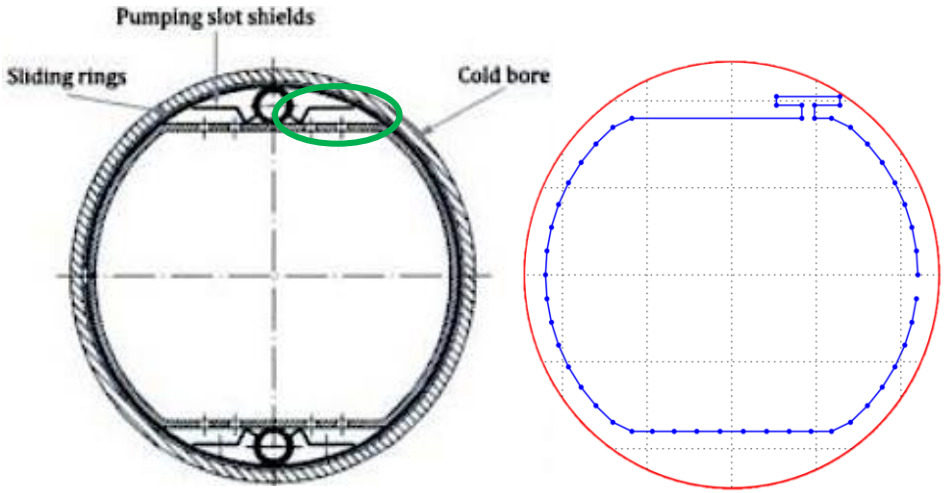


Outline

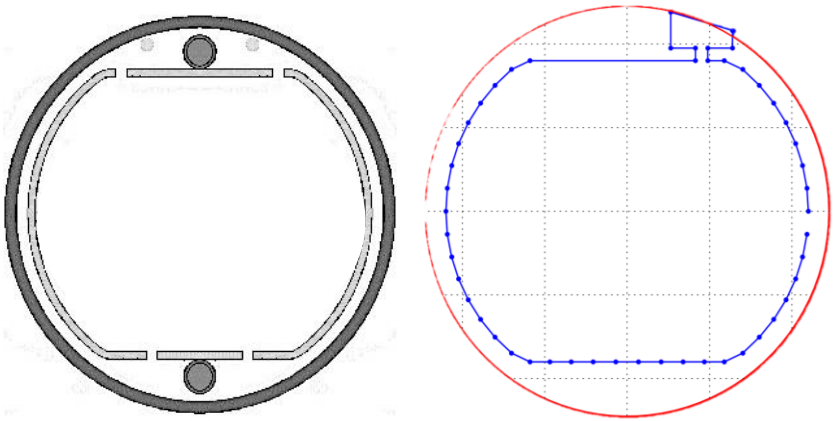
- **Introduction**
- **Scrubbing runs in 2015**
  - Main limitations
  - Beam observations
  - Evolution of the Secondary Electron Yield (SEY)
- **Intensity ramp-up in physics**
  - Optimal working point at 450 GeV
  - Dealing with high heat load on the cryogenic system
  - Losses and emittance preservation
- **Experience with different beam variants**
  - “Doublet” beam
  - 8b+4e scheme
  - “Tailored” filling schemes
- **Simulation study on impact of baffle plates**
- **Summary**

e-cloud buildup with/without shielding baffle plates

LHC beam screen with baffle plate



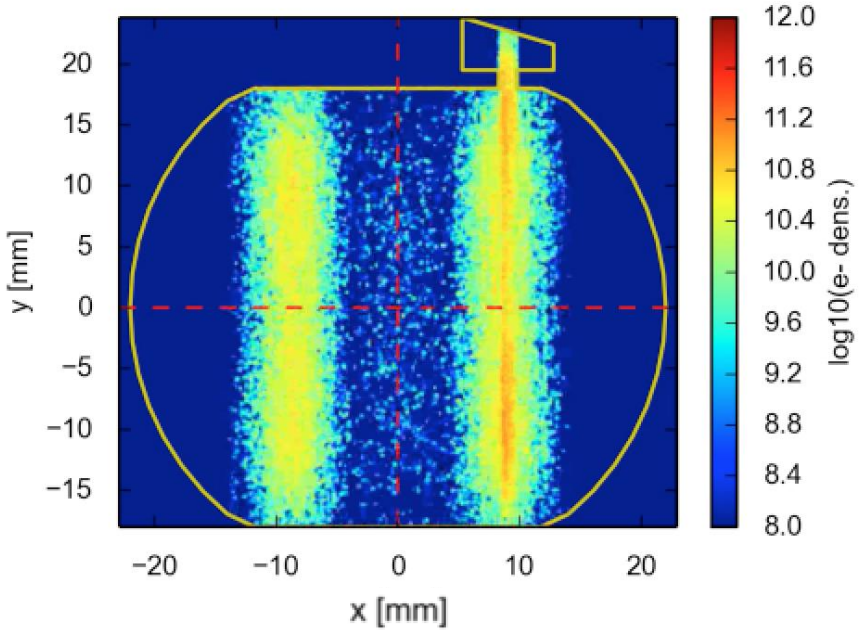
LHC beam screen without baffle plate



- **We wanted** check the need to shield the pumping holes to avoid multipacting with the cold bore
  - In particular, check whether electric shielding provided by the beam screen is already sufficient to suppress multipacting
- **PyECLOUD had to be modified** in order to handle non convex boundaries:
  - Electron impact detection and handling
  - Boundary condition in the PyPIC space charge module (to continue using Shortley-Weller refined boundary)

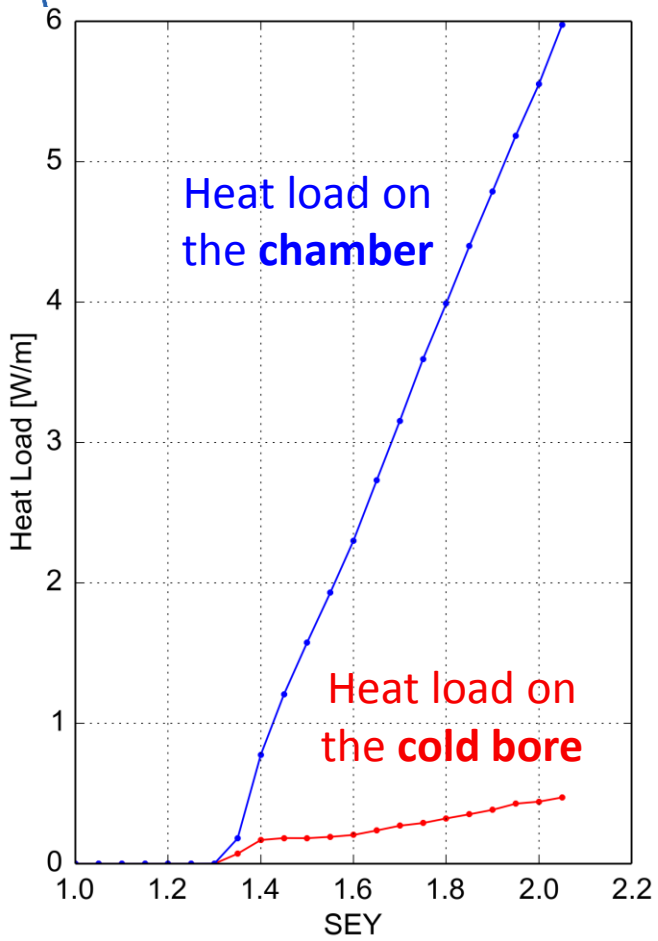
e-cloud buildup with/without shielding baffle plates

- Already at 450GeV (B=0.53 T) the e^- cyclotron radius does not exceed few micrometers
  - → Practically electrons **move only in vertical**
- The **kinetic energy** of secondary electrons is **not larger than 30 eV**
  - → It is enough for them to make **few mm per ns**
  - → Electrons can make it to **go back into the chamber before the following bunch passage** even without being accelerated by the beam

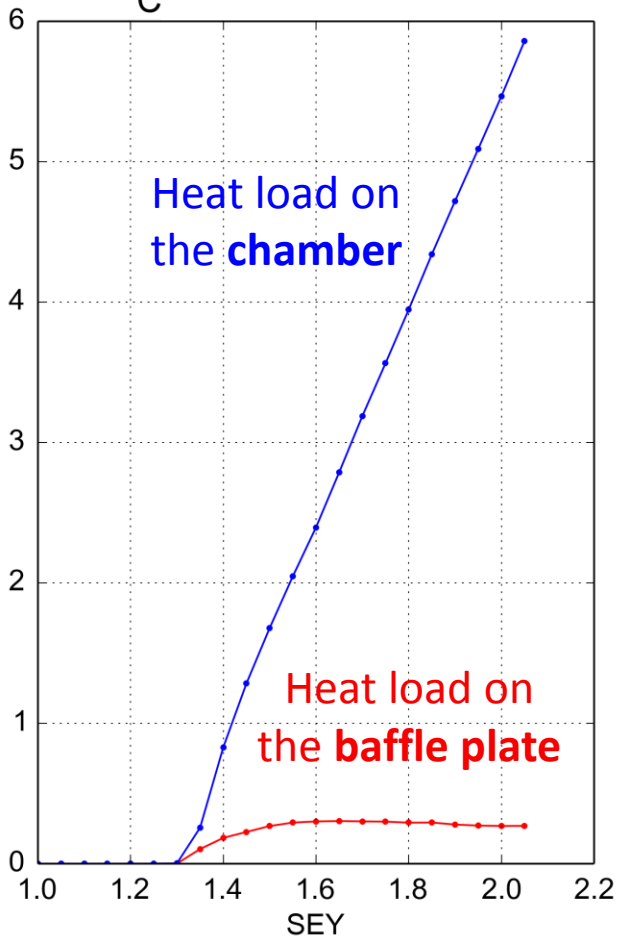


e-cloud buildup with/without shielding baffle plates

Without baffle



With baffle



Arc dipole - 450GeV
Single aperture with a single indefinite slot

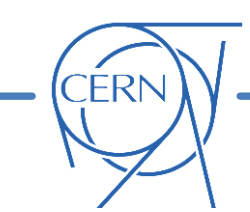
- Assuming the **SEY equal to 1.4**, the heat load deposited is **almost 0.15 W/m** for both cases

  → **baffles protect the cold bore from a non regligible heat load**

  → **to be taken into account** innthe design of the **beam screens for the new HL-LHC elements**

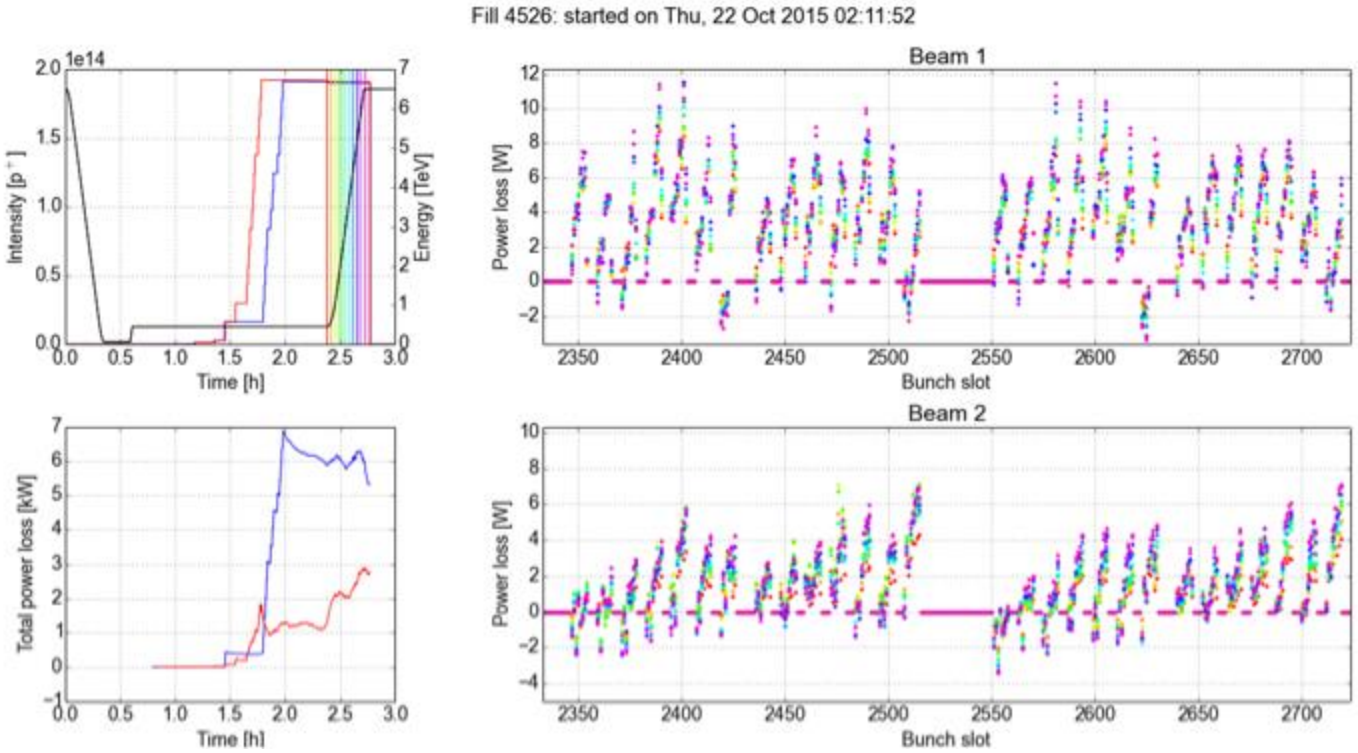
Summary

- SEY in the arcs was found **reset to beginning of Run 1**
- **~3 weeks of scrubbing with 25 ns beams** provided sufficient mitigation against beam degradation at 450 GeV but **full suppression of the e-cloud was not achieved**
- Intensity **ramp-up dominated by impact of e-cloud effects**:
  - **Beam degradation under control** with strong Q', octupoles, and high damper gain
    → Running on **different working point at injection** to get better lifetime
  - **Cryogenics had to learn how to deal with high heat loads**
  - Heat load in Sector 12 presently **limits to ~2000 bunches/ring** but **scrubbing is progressing** with the physics fills
  - **Losses and emittance growth** along the fill **are under control**
- Different **beam variants** tested in the LHC **behaved as predicted by simulations:**
  - **"Doublet"** beam proved to enhance the e-cloud; at the moment of the test beam degradation too severe to allow its usage for scrubbing
  - **"8b+4e"** scheme showed practically full e-cloud suppression in the arcs → important validation as HL-LHC fall-back schme in case of strong limitations from e-cloud effects
  - The **filling scheme is a powerful handle** to control heat loads in case of cryo limitations
- Simulation studies confirmed the **importance of baffle plates** to avoid non negligible heat load on the cold bore of the cold magnets

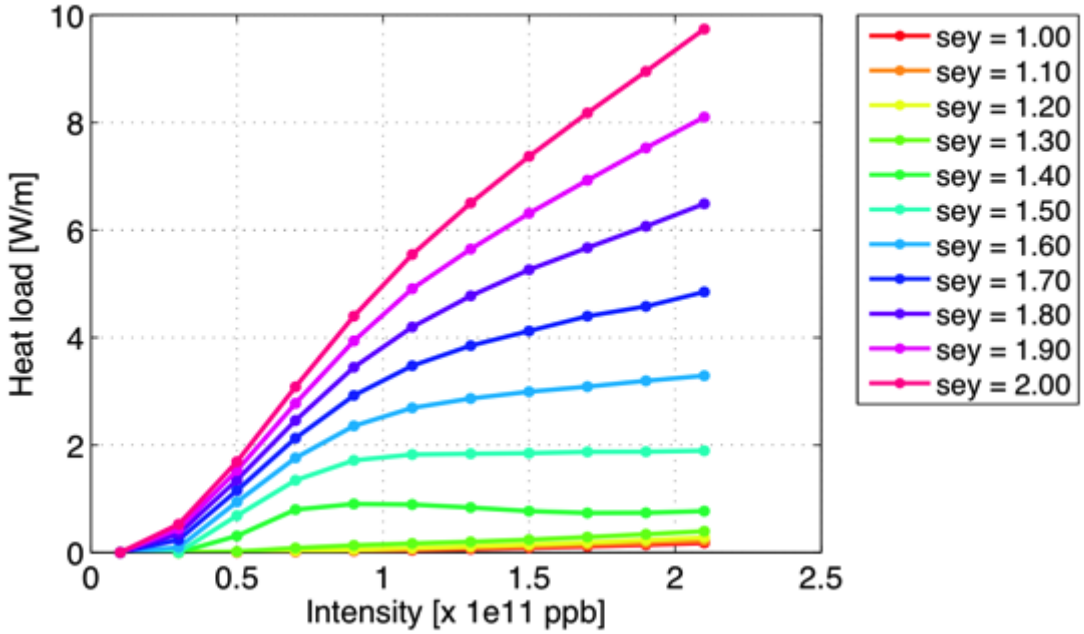


Thanks for your attention!

Zoom

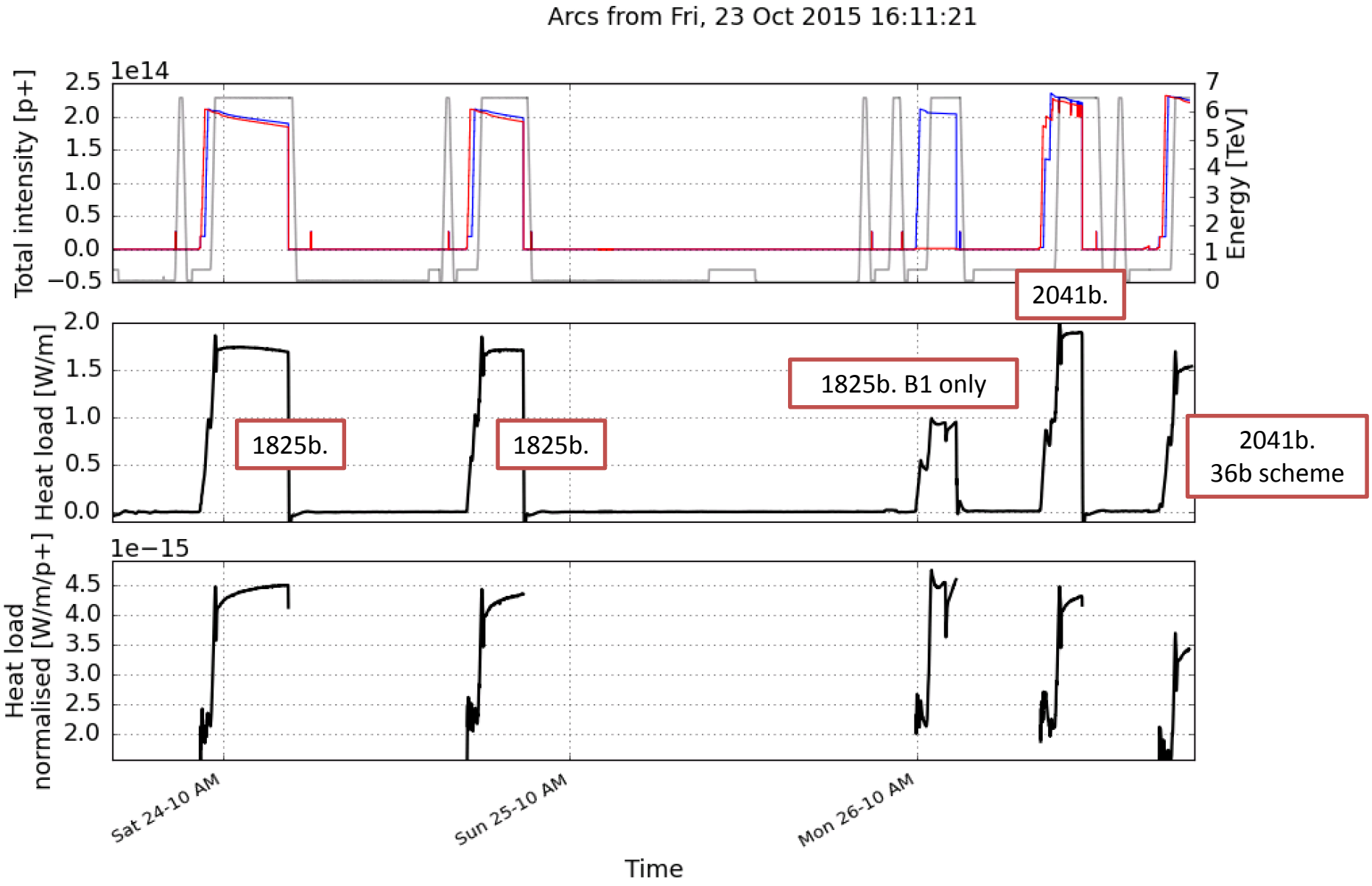

Fill 4526: started on Thu, 22 Oct 2015 02:11:52
1e14
Intensity [p+]
Energy [TeV]
Time [h]
Beam 1
Power loss [W]
Bunch slot
Total power loss [kW]
Time [h]
Beam 2
Power loss [W]
Bunch slot

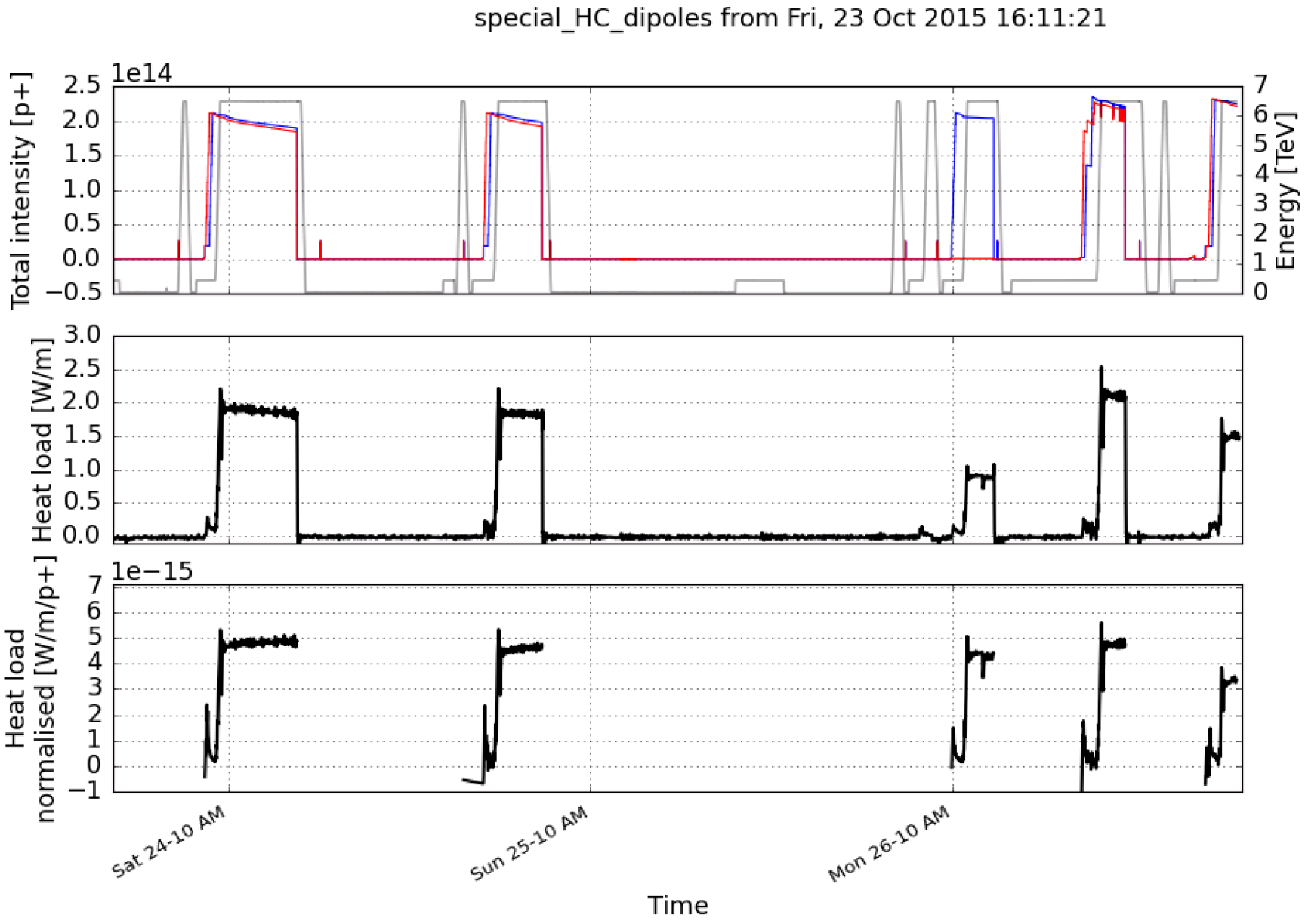
Scrubbing in the HL-LHC era…



Dependence on bunch intensity is **quite steep for high values of the SEY** and flattens down when approaching the threshold:

→ cooling capacity important to minimize required scrubbing time


Arcs from Fri, 23 Oct 2015 16:11:21
1e14
Total intensity [p+]
Energy [TeV]
2041b.
Heat load [W/m]
1825b.
1825b.
1825b. B1 only
2041b.
36b scheme
1e−15
Heat load
normalised [W/m/p+]
Sat 24-10 AM
Sun 25-10 AM
Mon 26-10 AM
Time


special_HC_dipoles from Fri, 23 Oct 2015 16:11:21
1e14
Total intensity [p+]
Energy [TeV]
Heat load [W/m]
1e−15
Heat load normalised [W/m/p+]
Sat 24-10 AM
Sun 25-10 AM
Mon 26-10 AM
Time