Electron cloud in the CERN accelerator complex

G. Rumolo
on behalf of the **electron cloud/scrubbing ‘core team’** composed by H. Bartosik, E. Belli, G. Iadarola, K. Li, L. Mether, A. Romano, M. Schenk

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Electron cloud activities at CERN

Experimental studies (BE/ABP, BE/RF, BE/OP, TE/VSC, TE/CRG)

- Direct electron cloud measurements
- Monitoring of electron cloud observables
- Electron cloud effects on the beam and cures
- Scrubbing runs in SPS and LHC and strategies
- Laboratory measurements of SEY and scrubbing
- Coating and mitigation techniques (a-C, LESS, clearing electrodes)

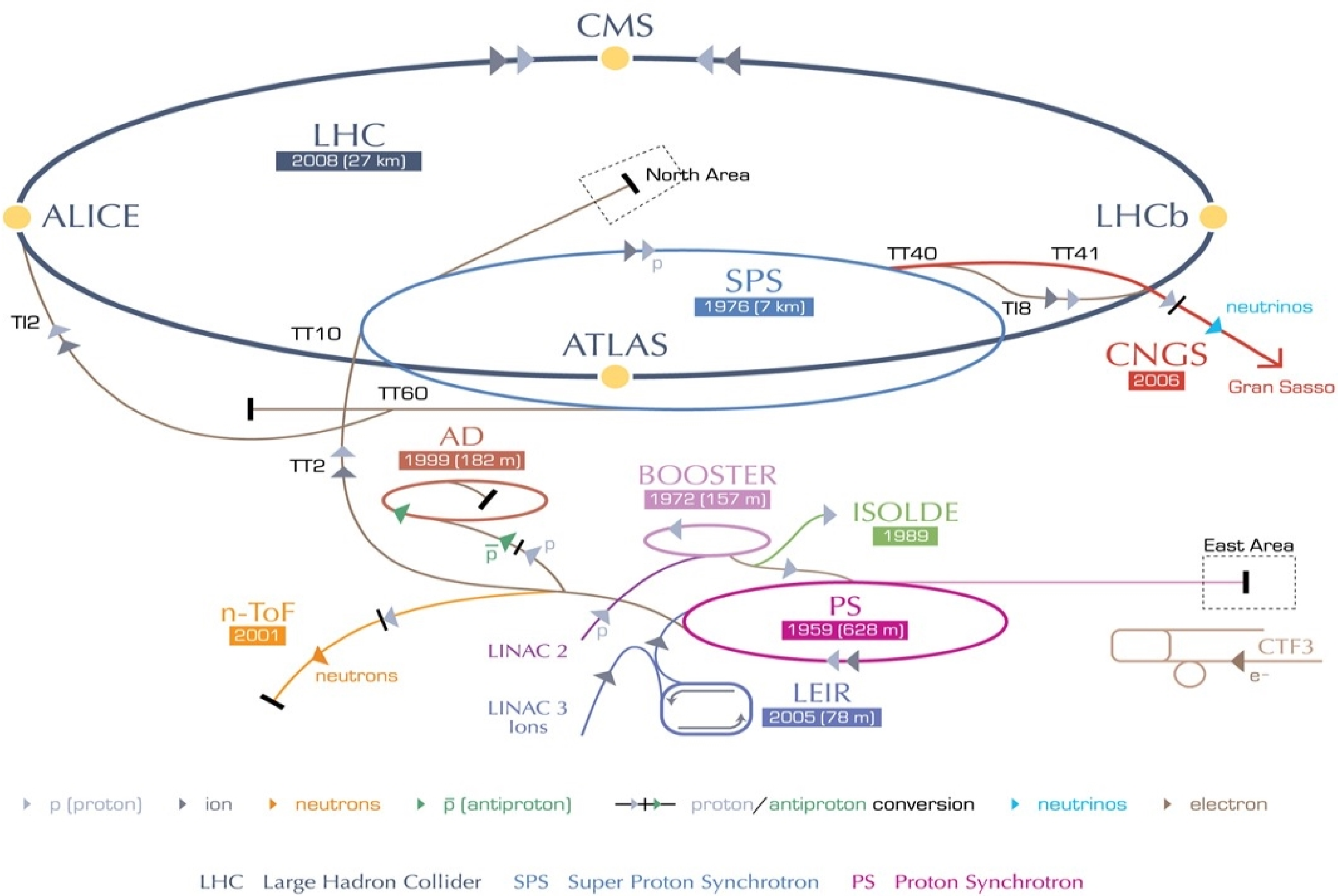
Numerical simulations (BE/ABP)

- Build up: PyECLOUD
- Beam dynamics: PyHEADTAIL
- Integration of build up and beam dynamics simulations into a single tool

Interpretation, planning, steering

Modeling, benchmarking, steering

CERN's accelerator complex



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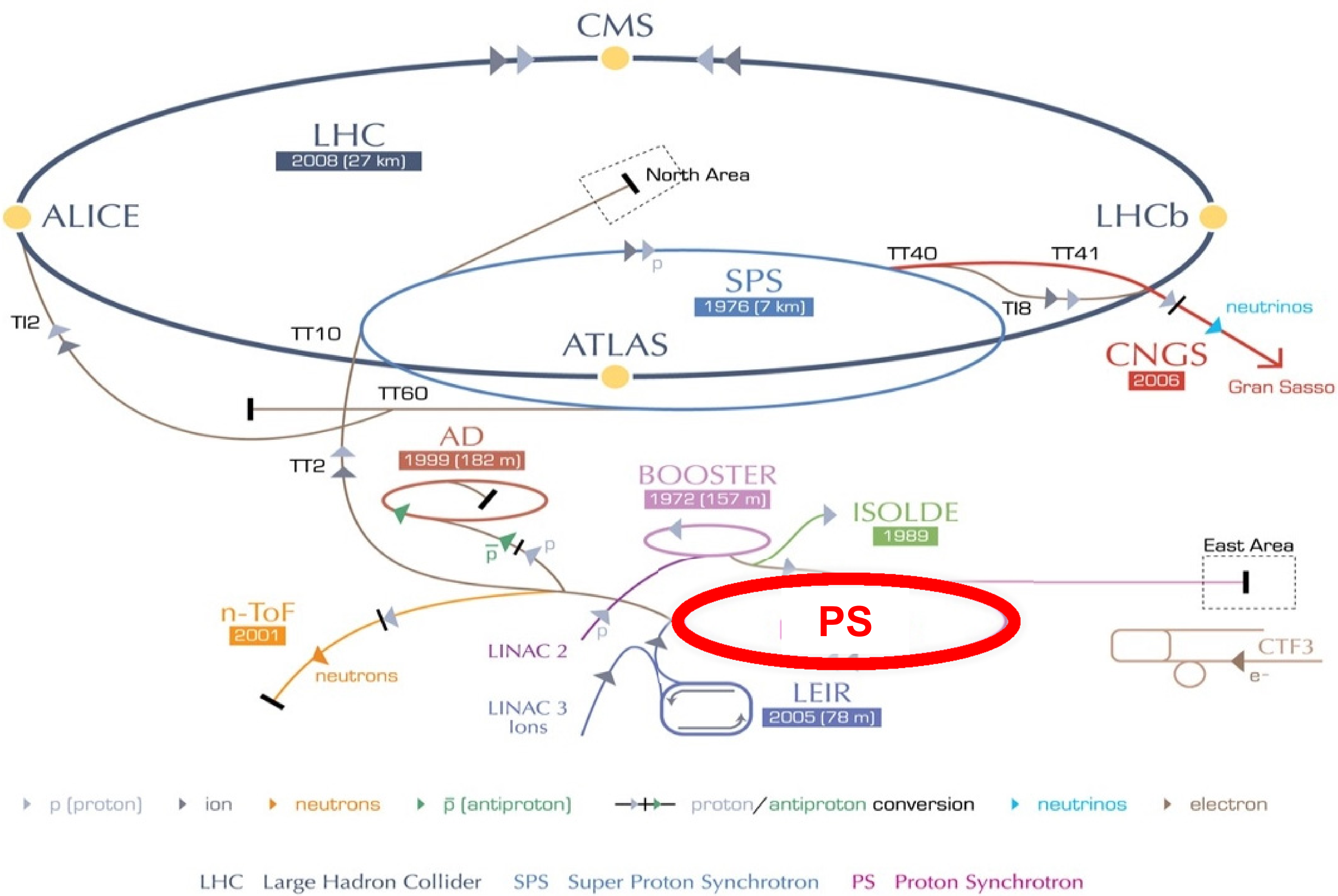
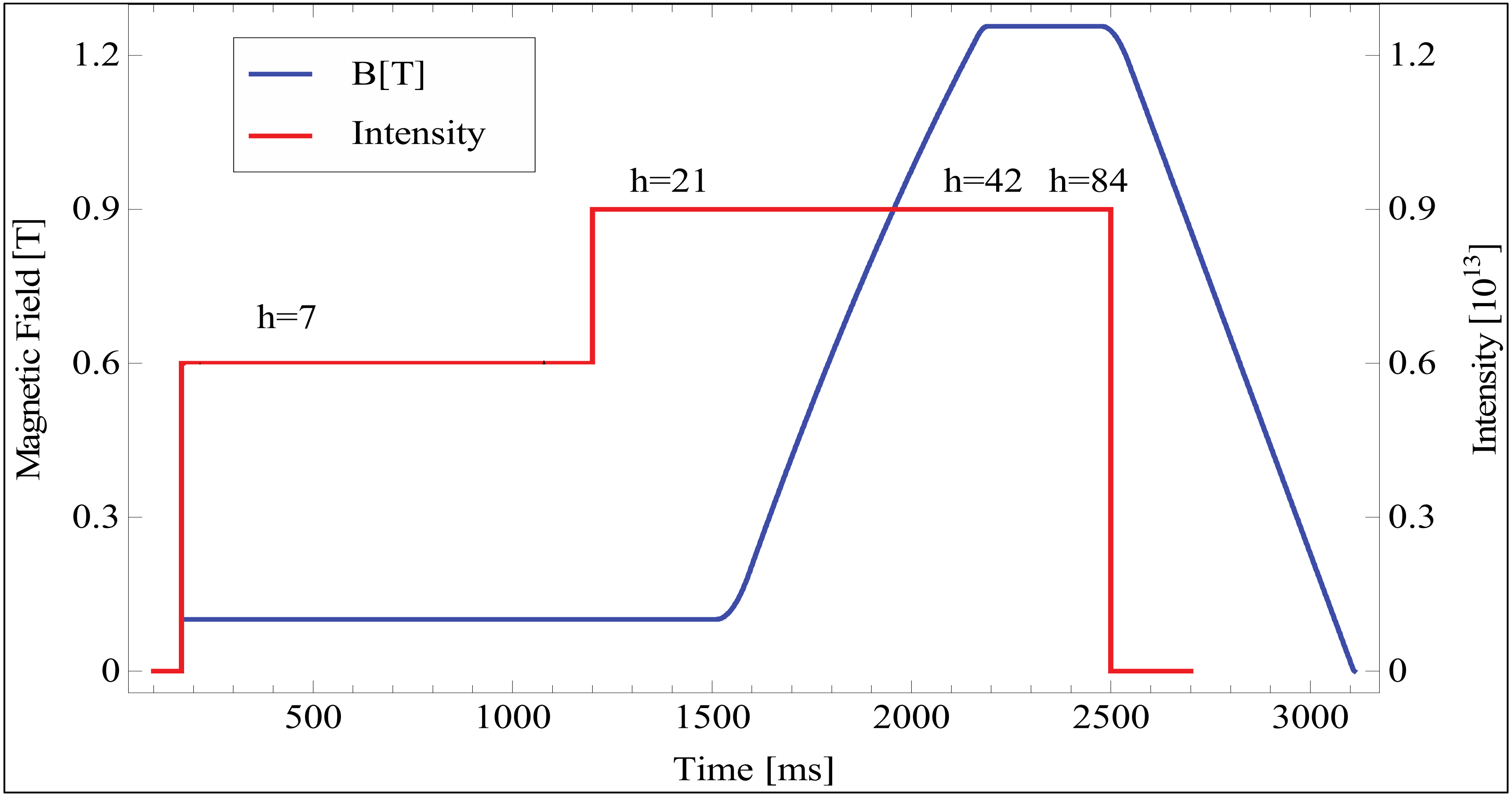


LHC beams in the PS



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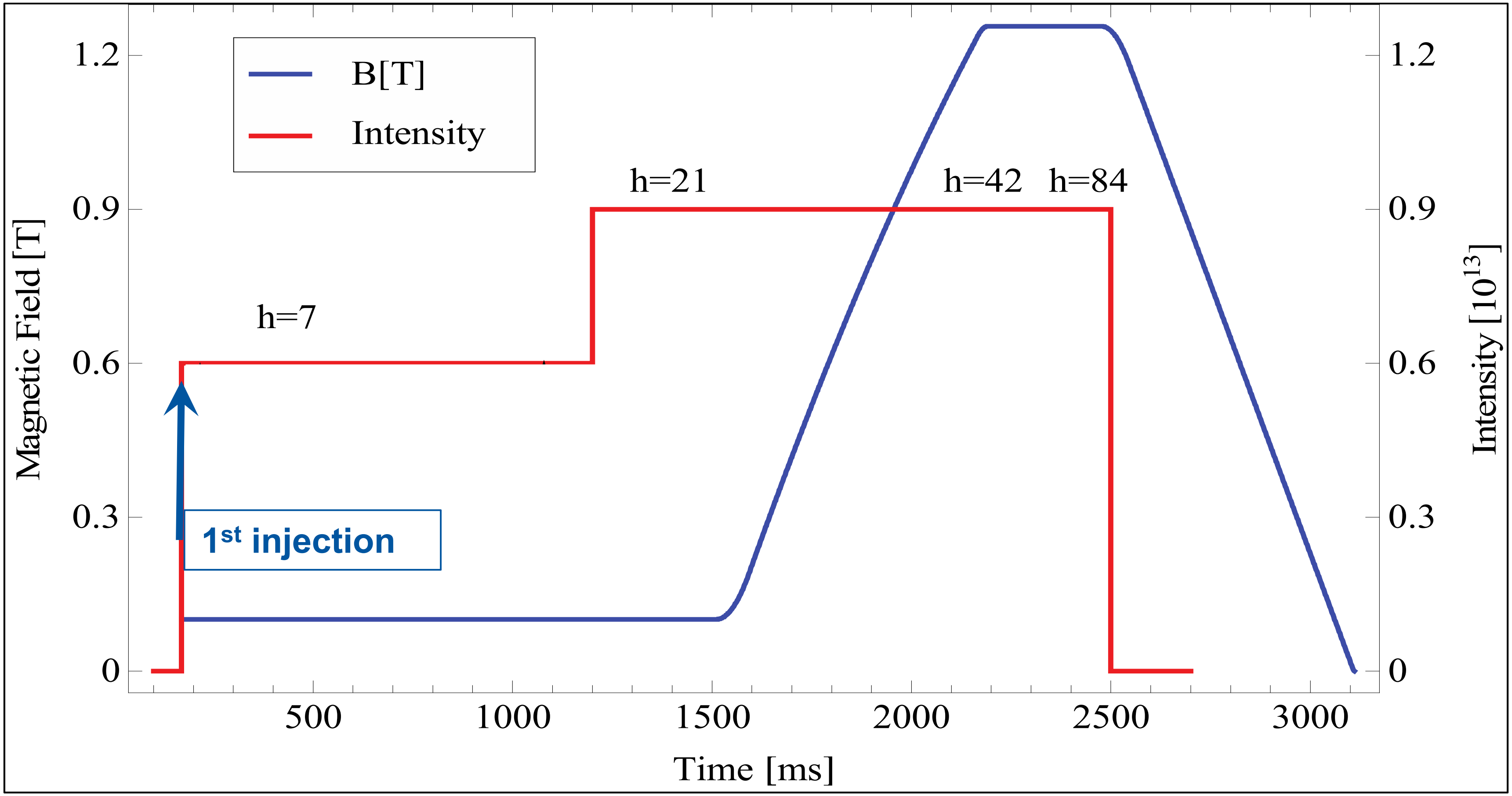

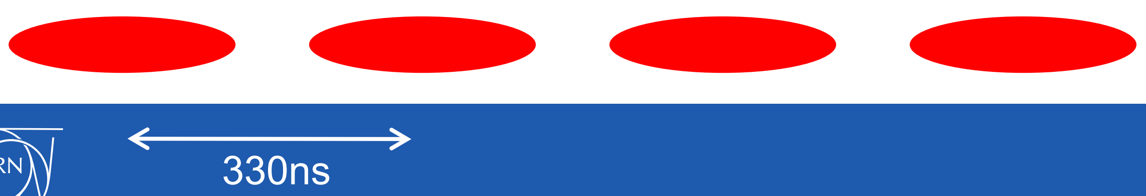

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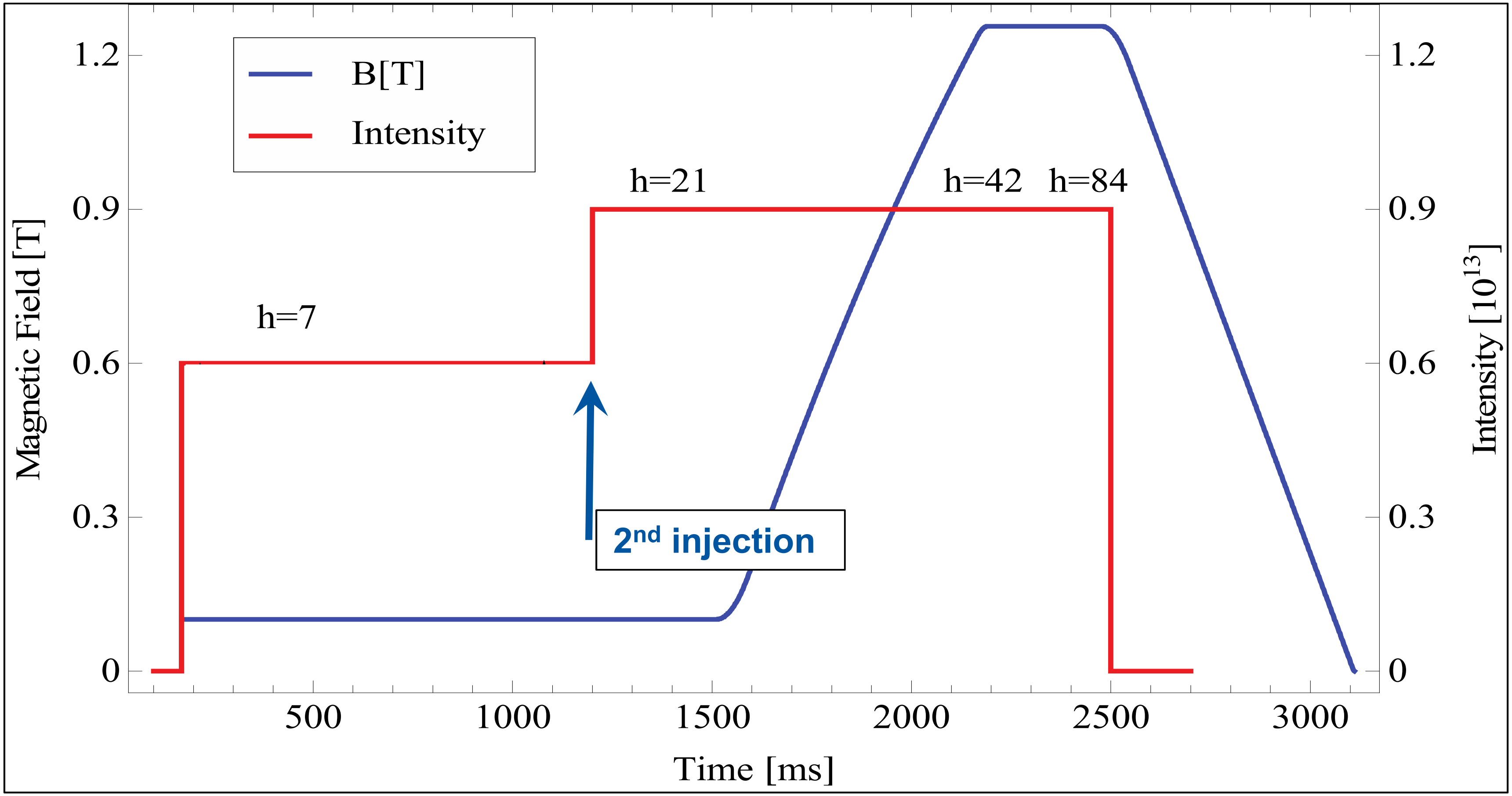

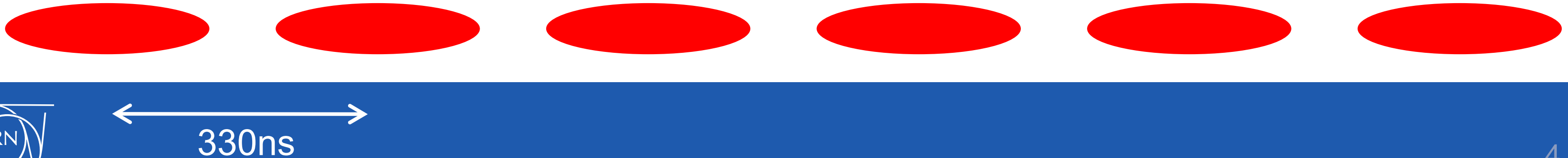

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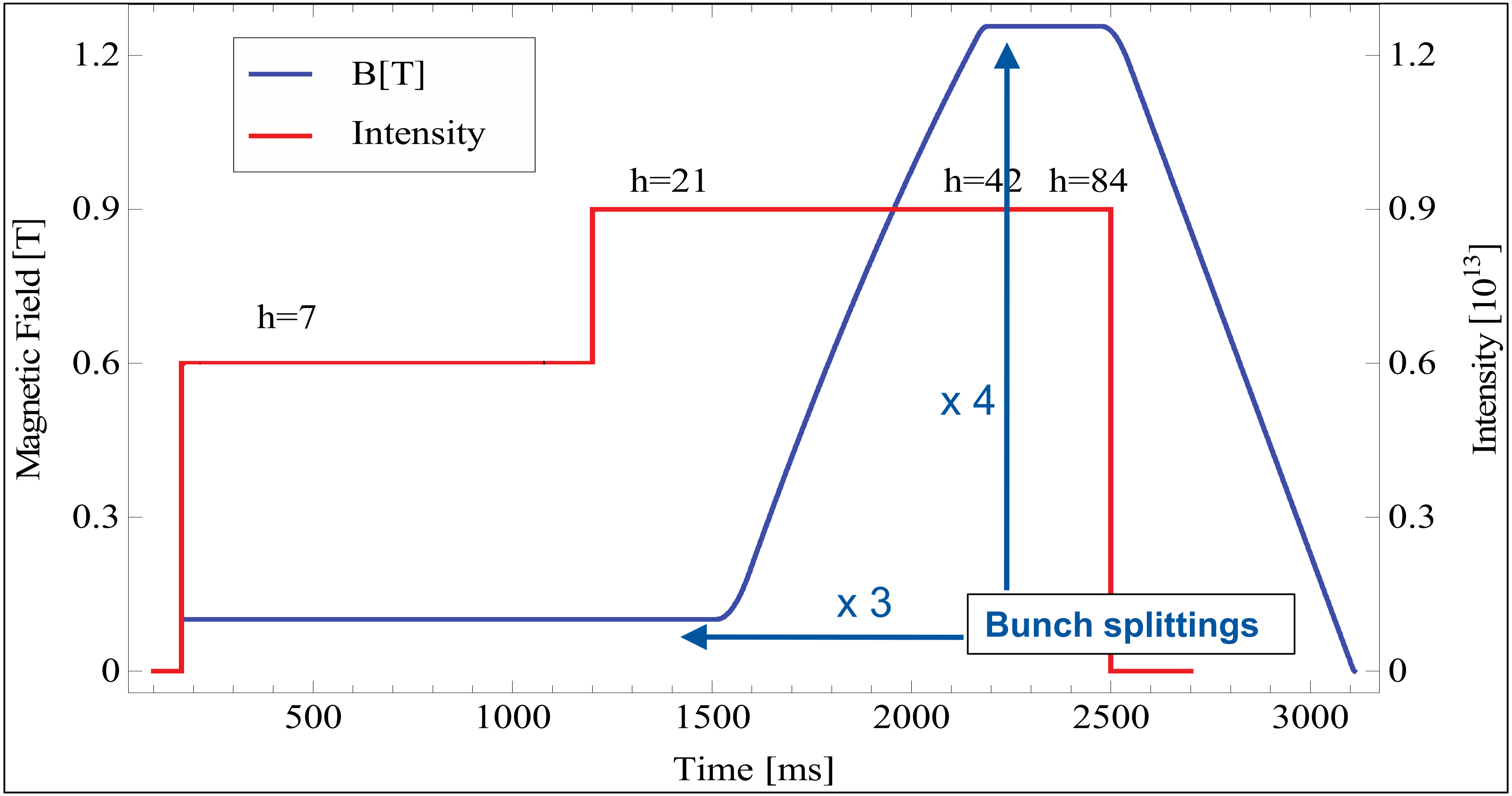

25ns bunch spacing

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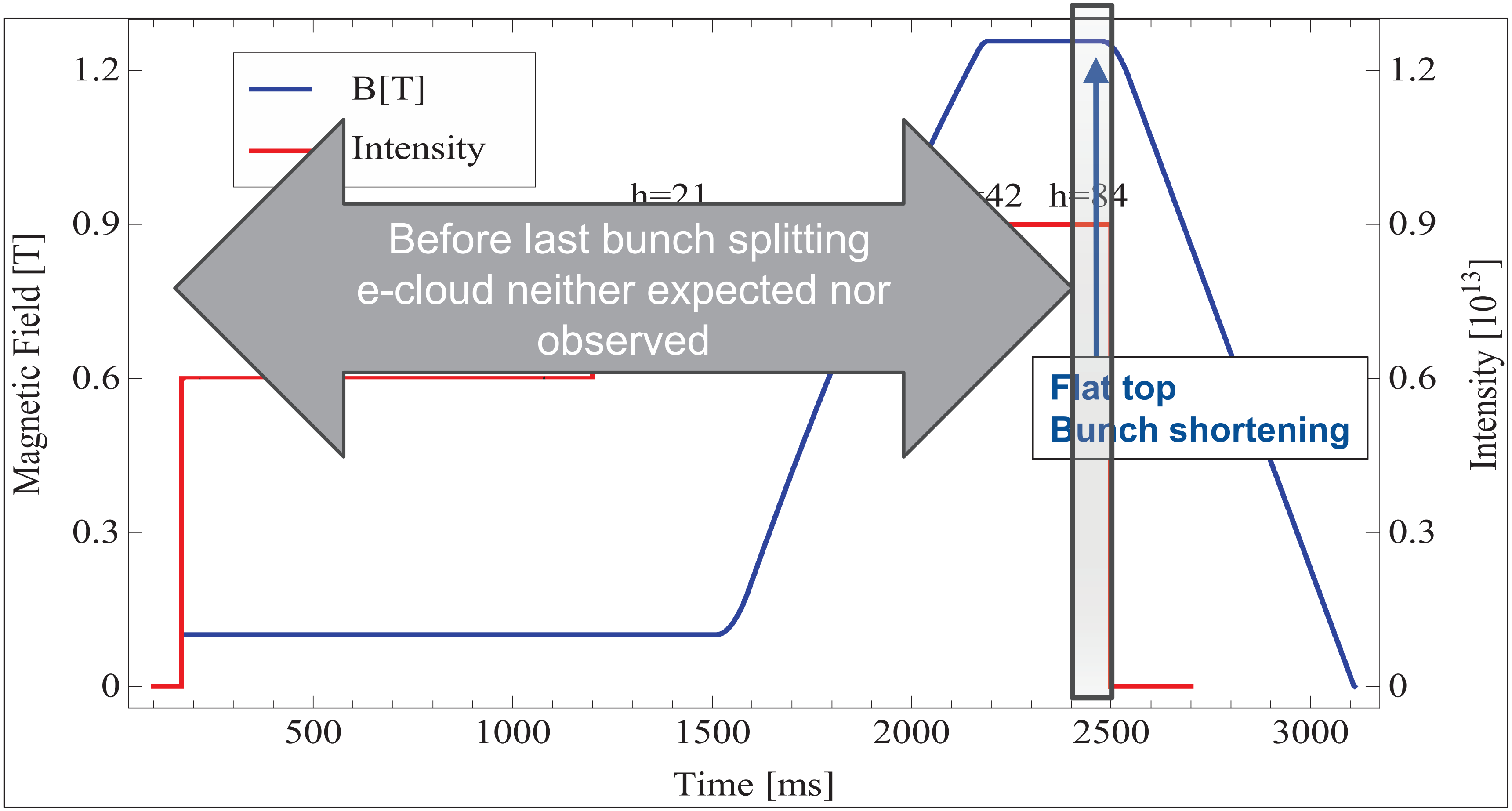

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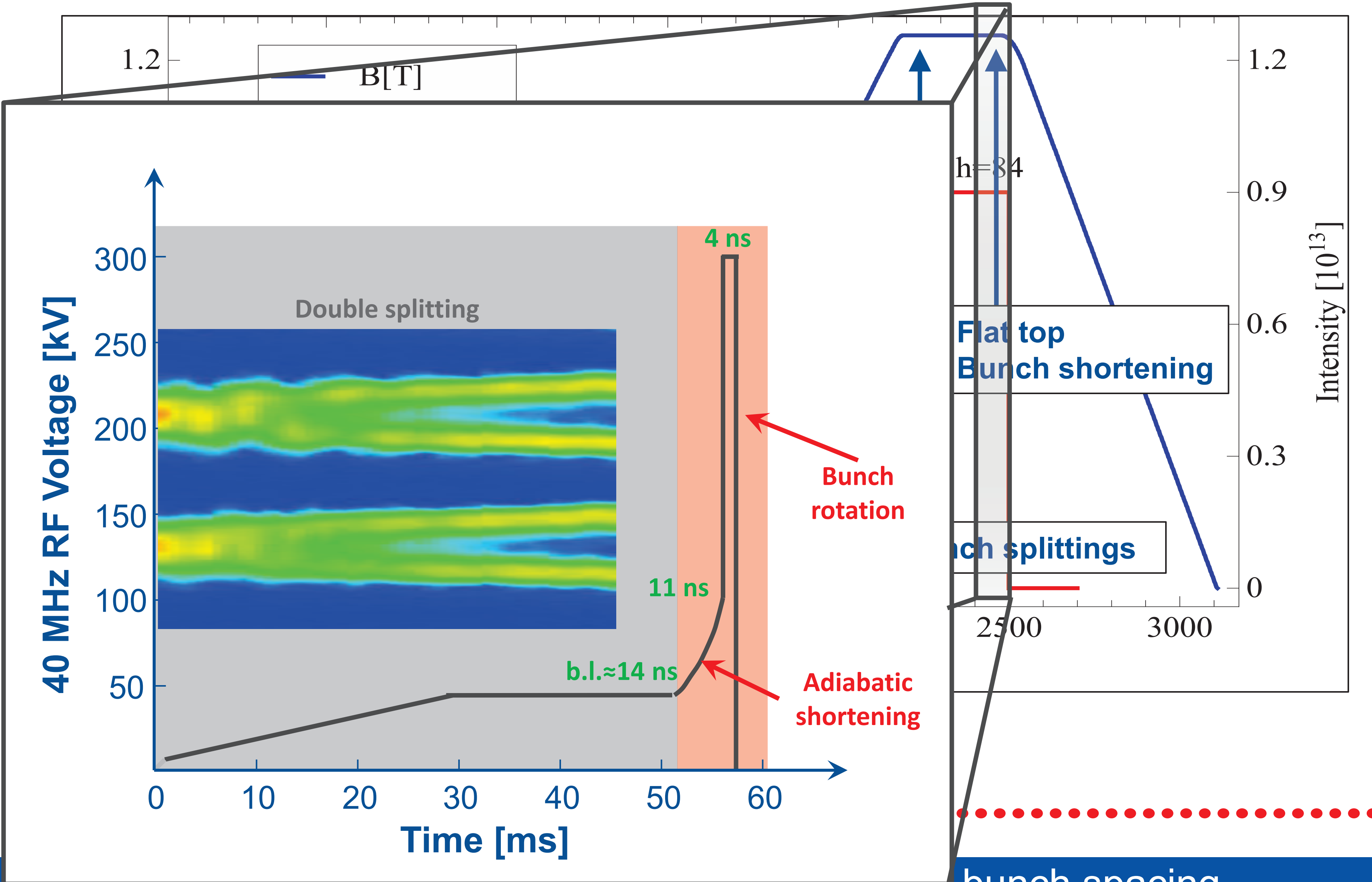

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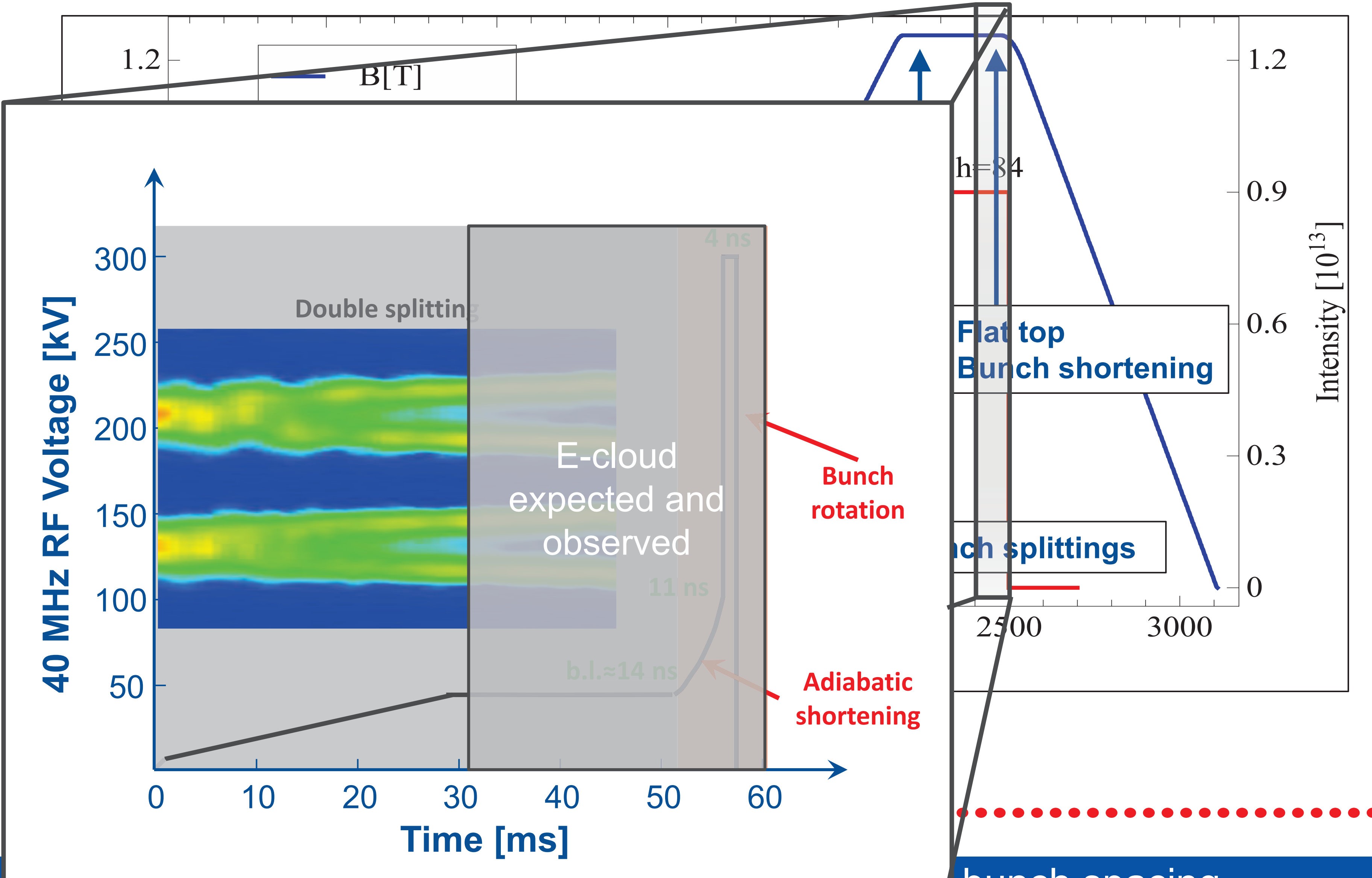

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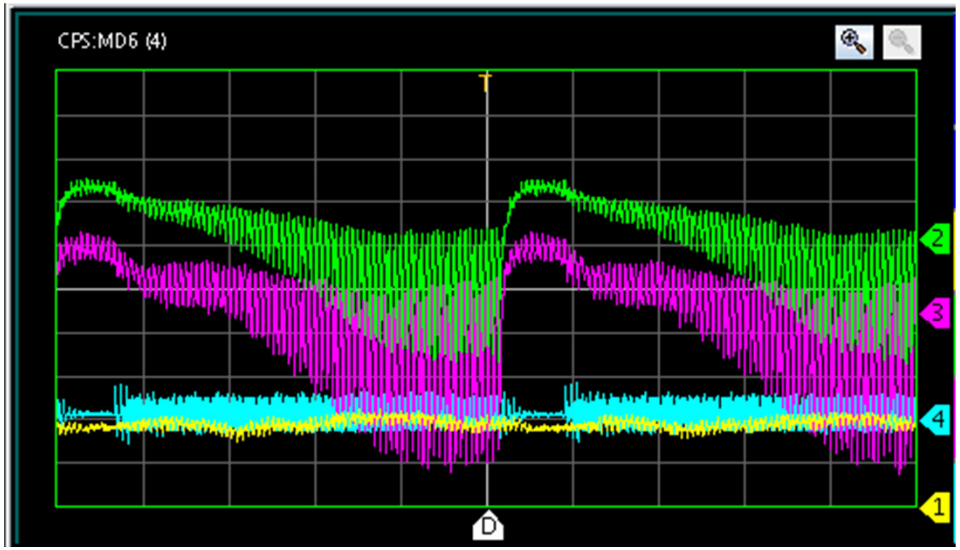

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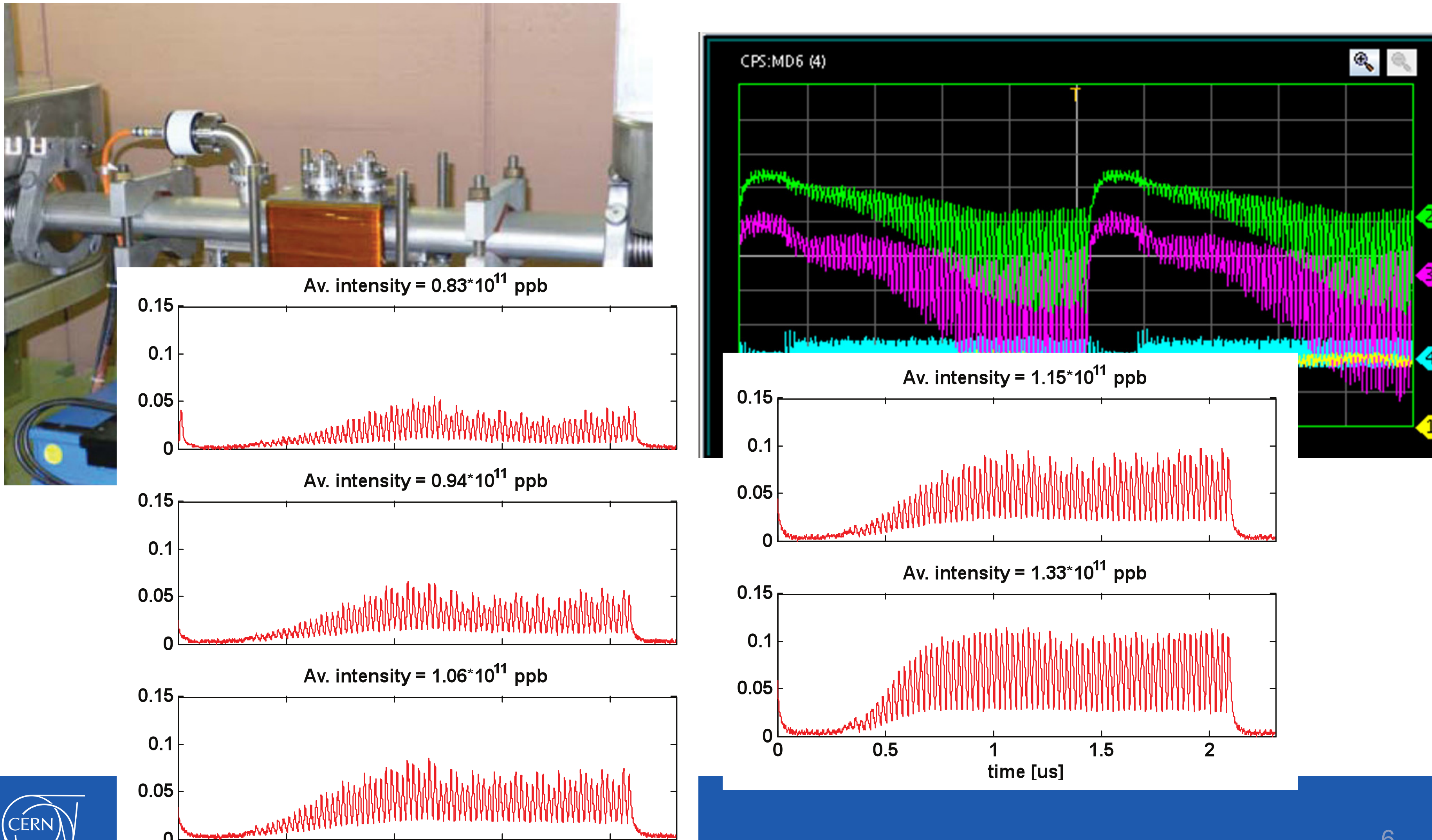

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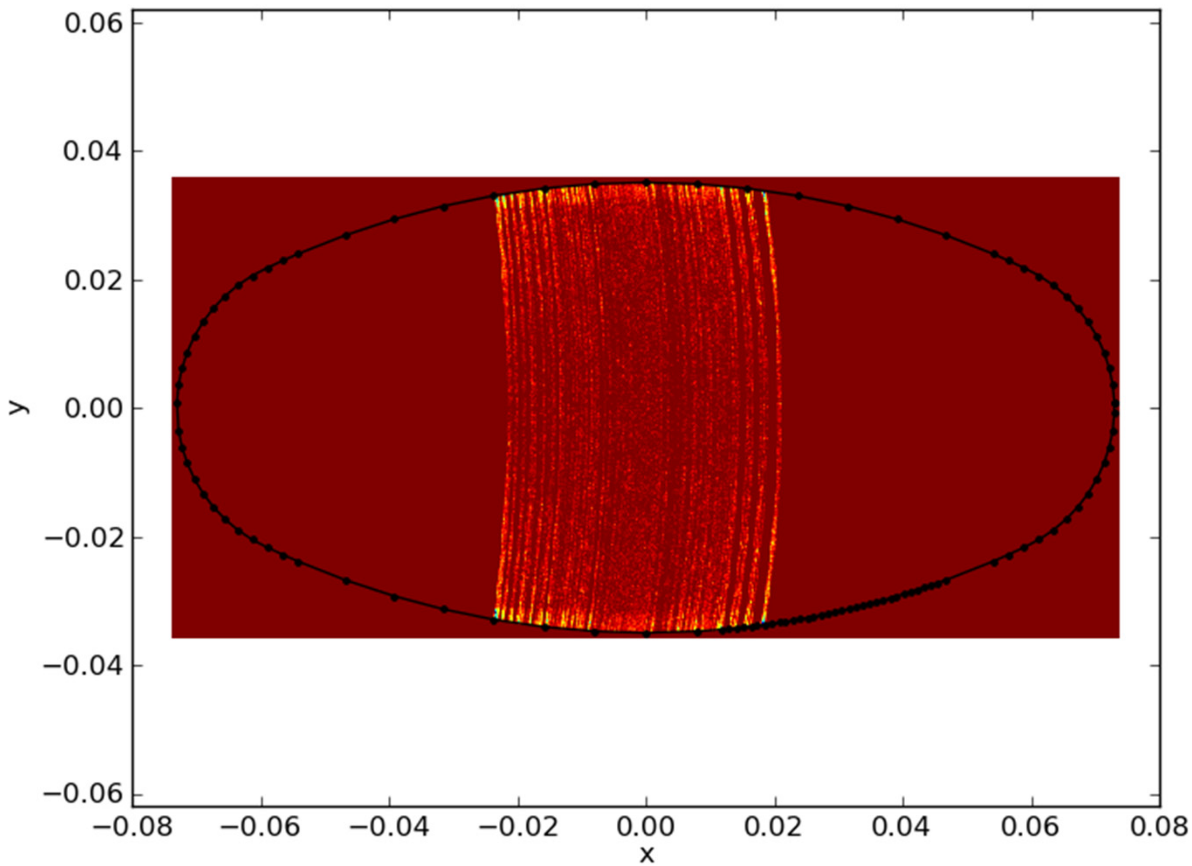

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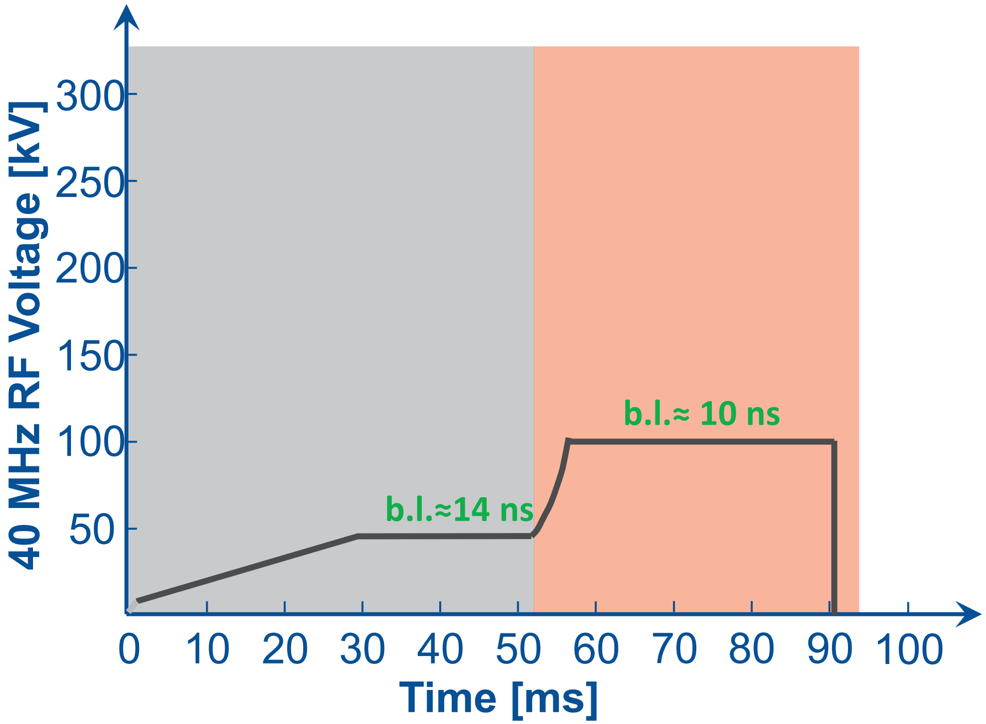
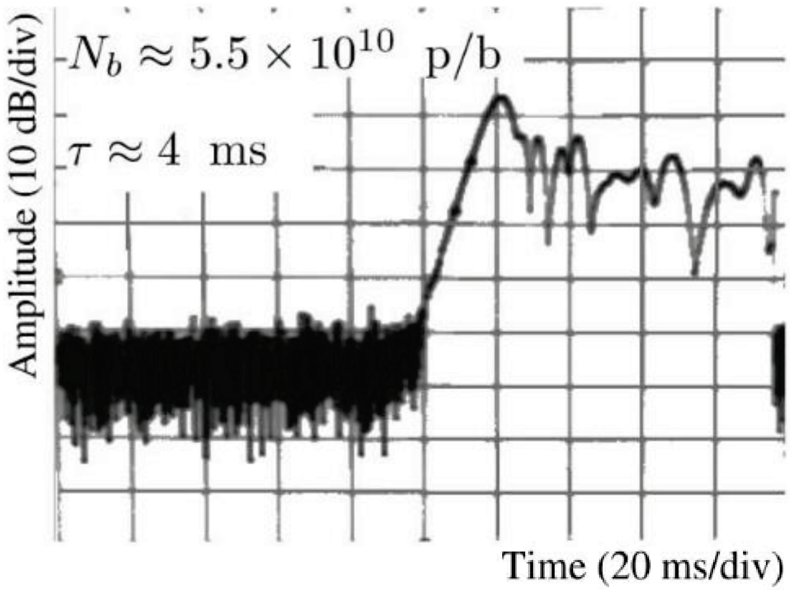


H pickup signal – 357 kHz component



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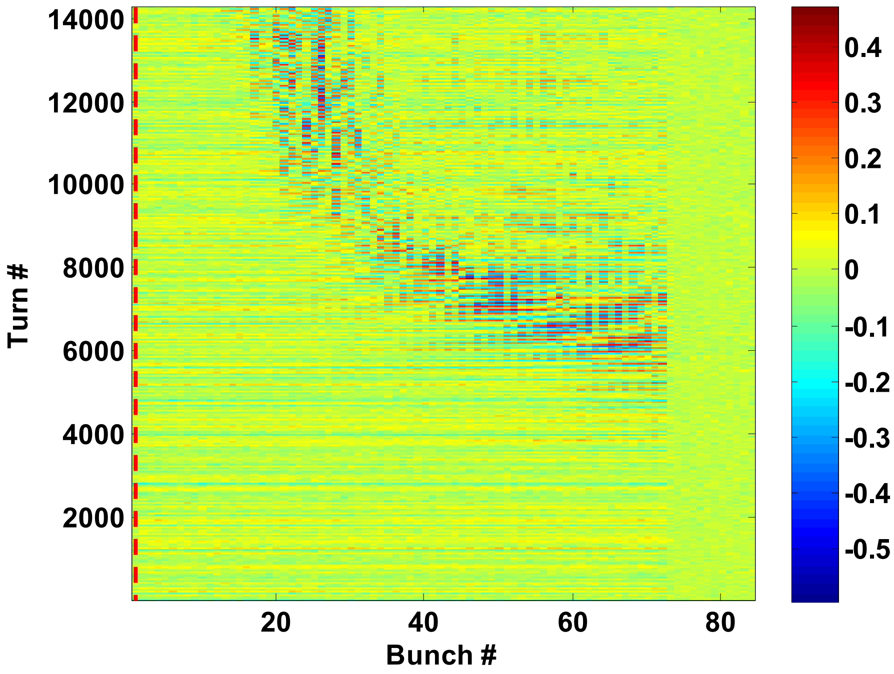

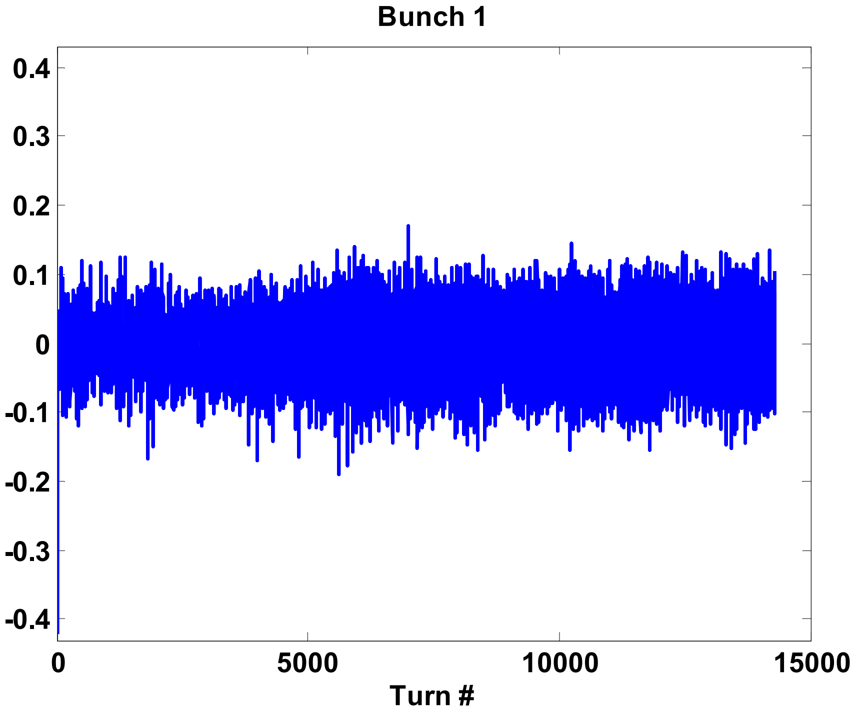

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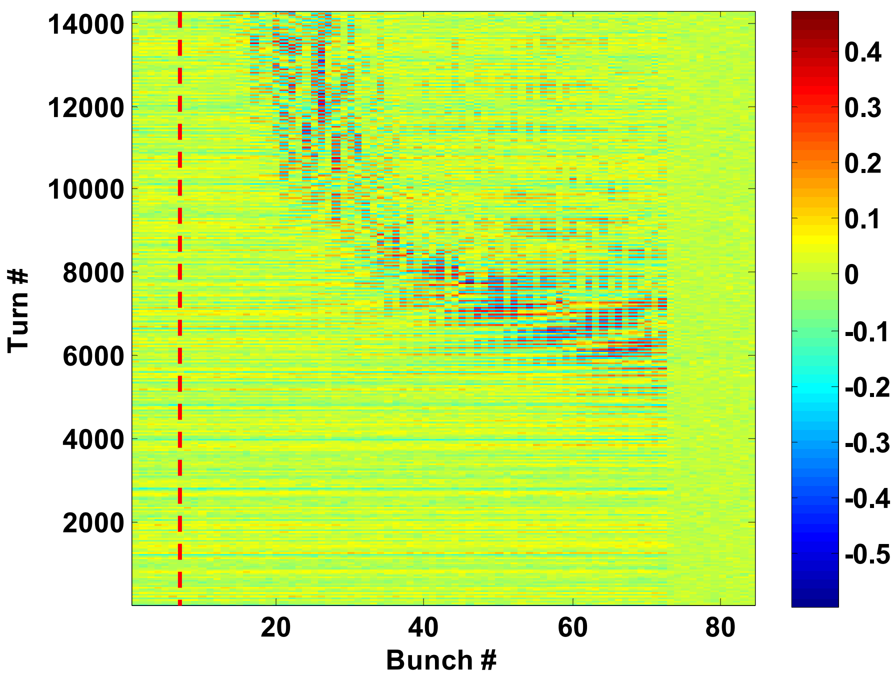

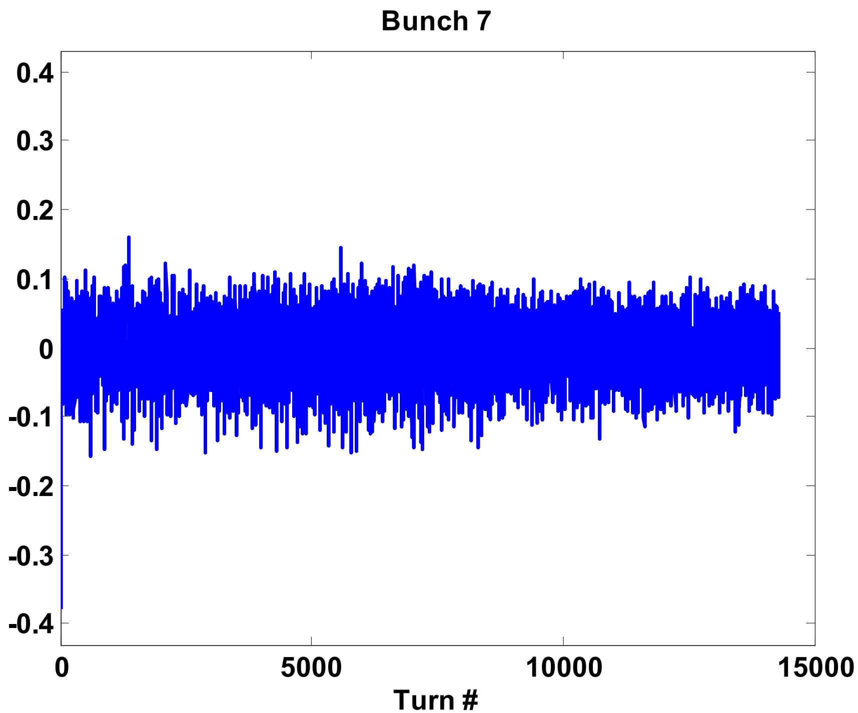

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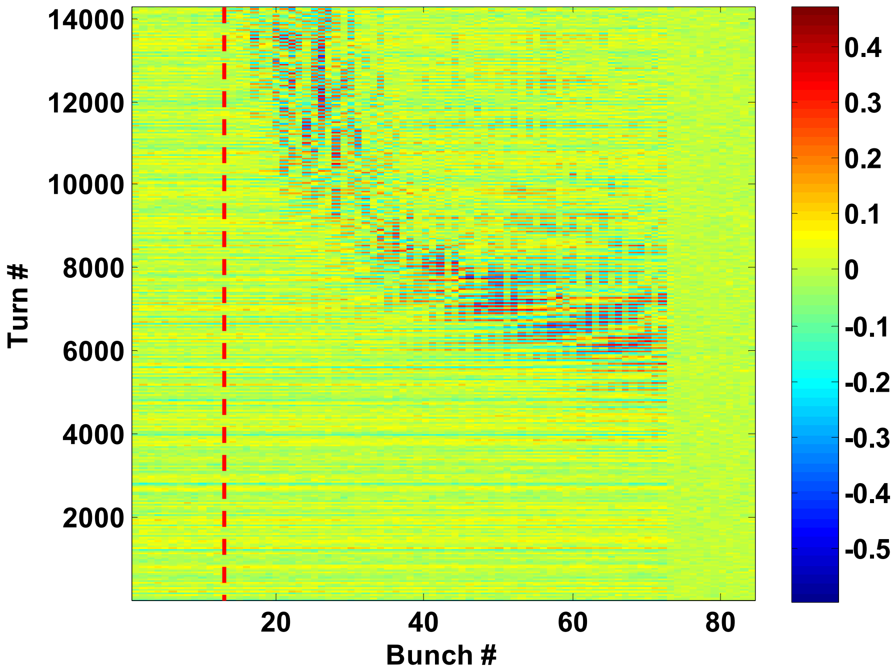

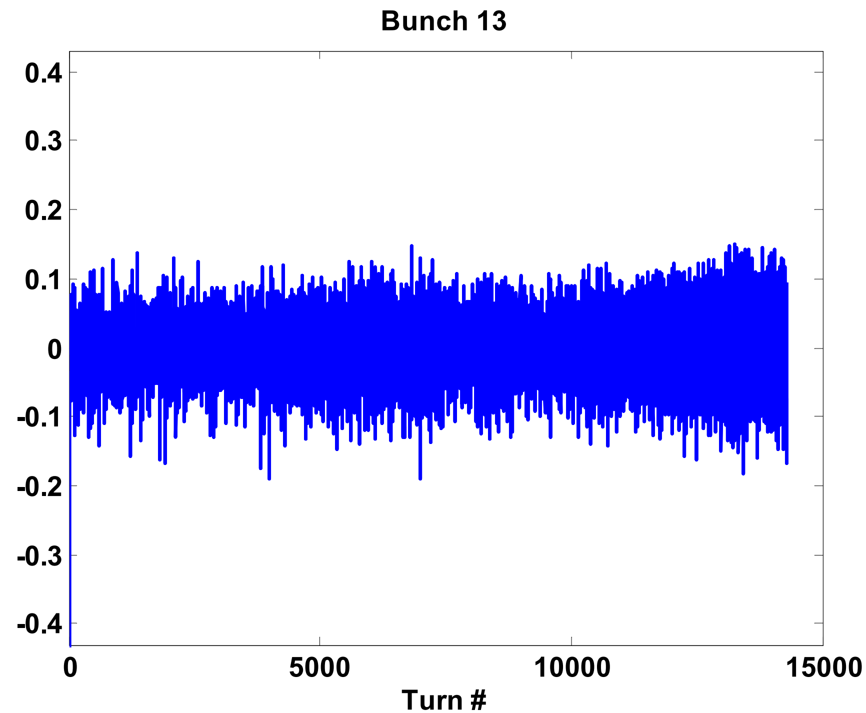

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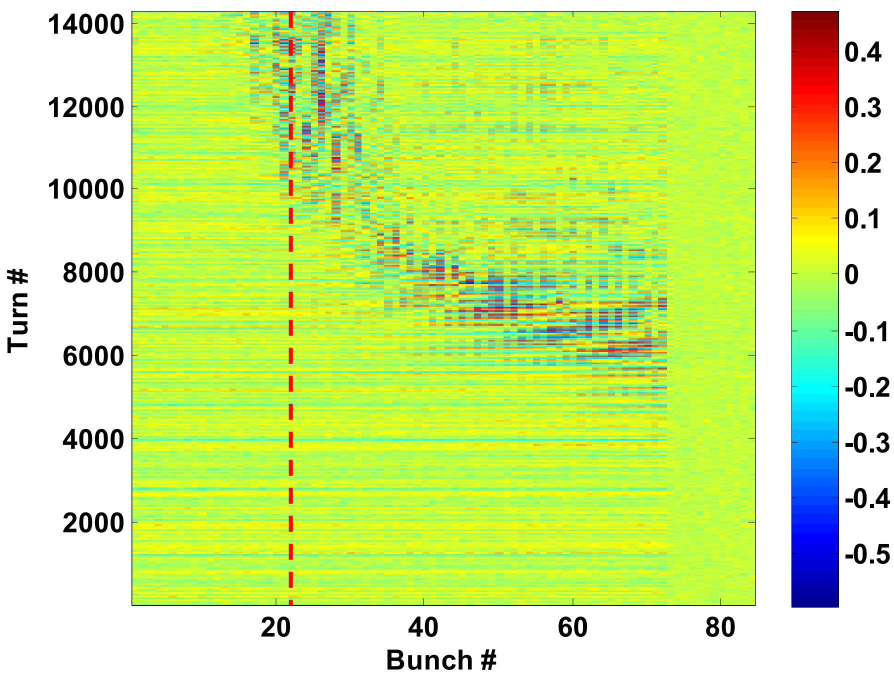

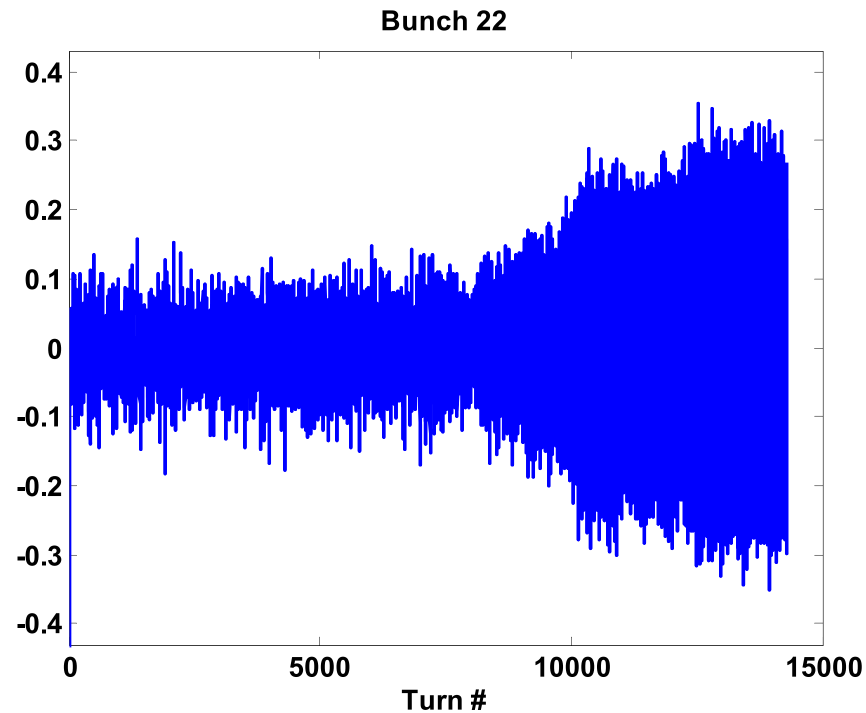

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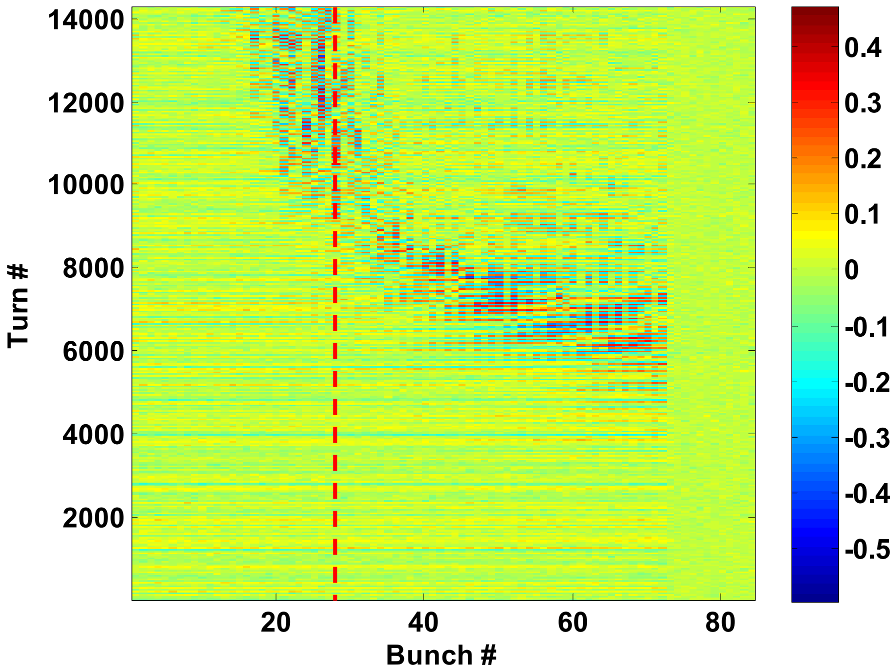

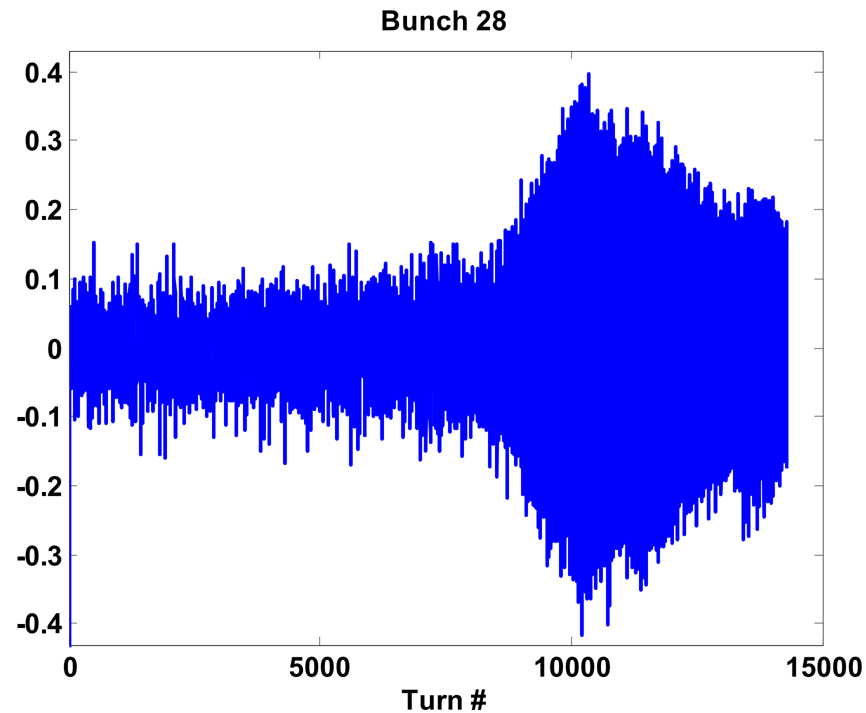

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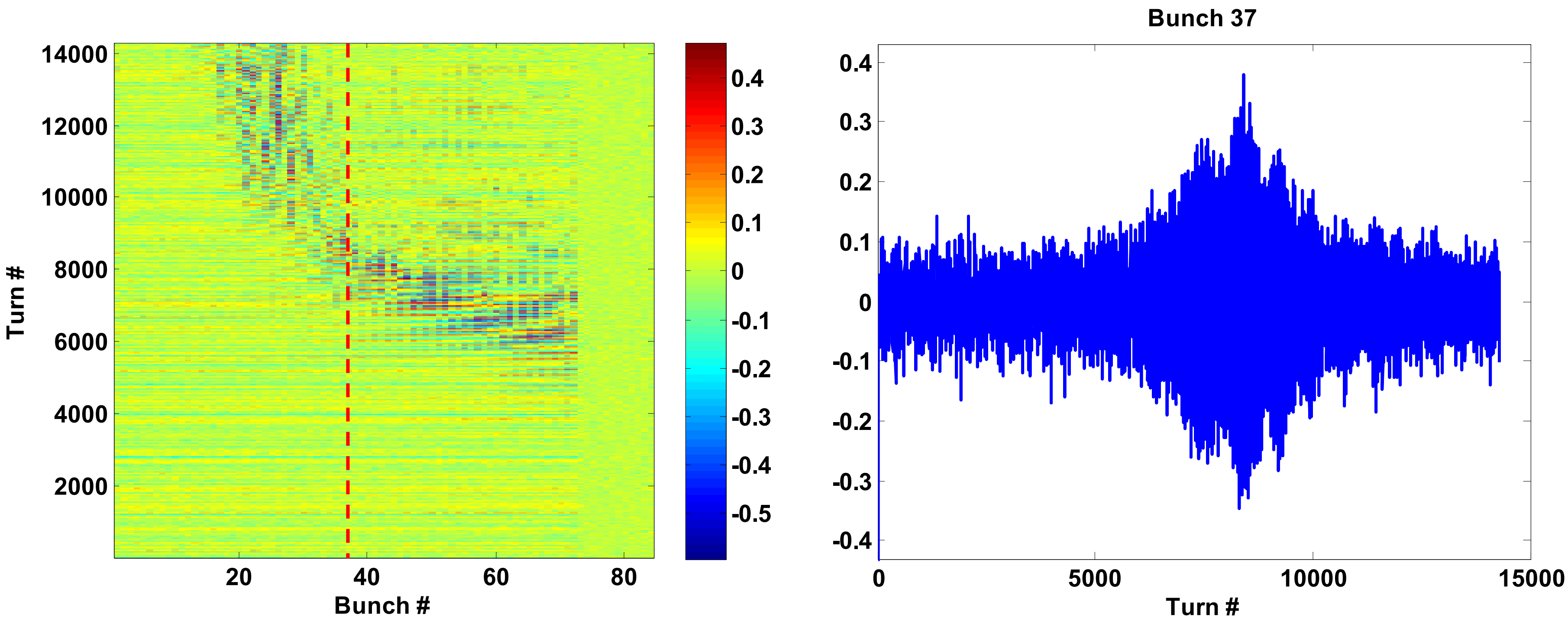

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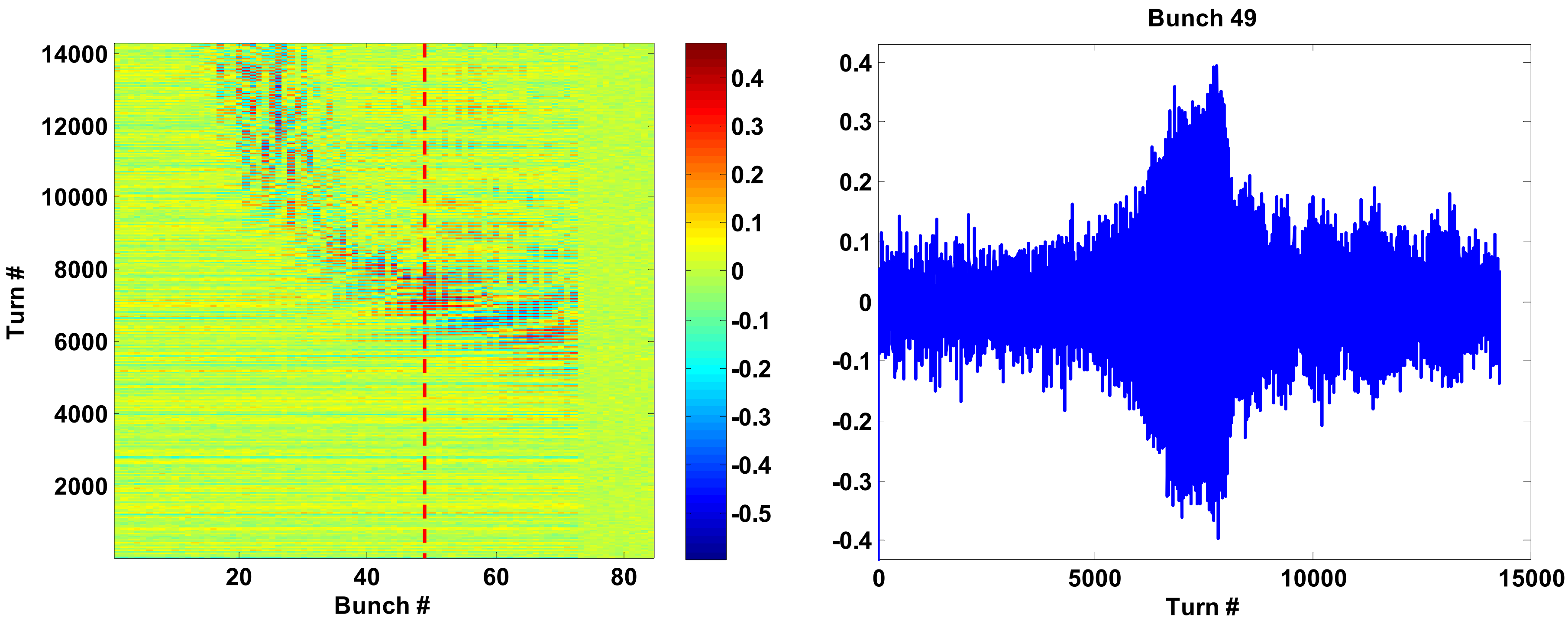

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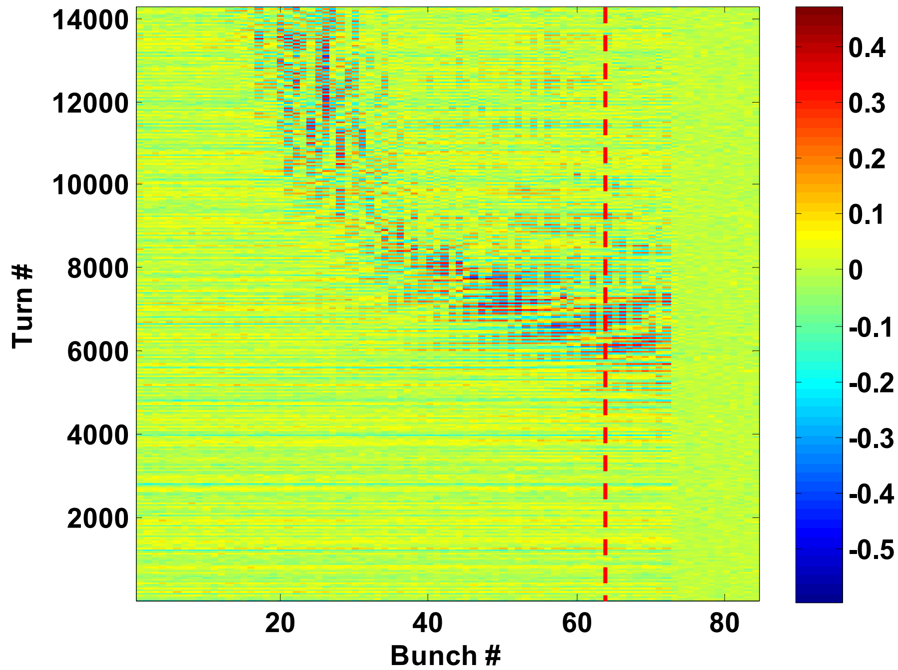

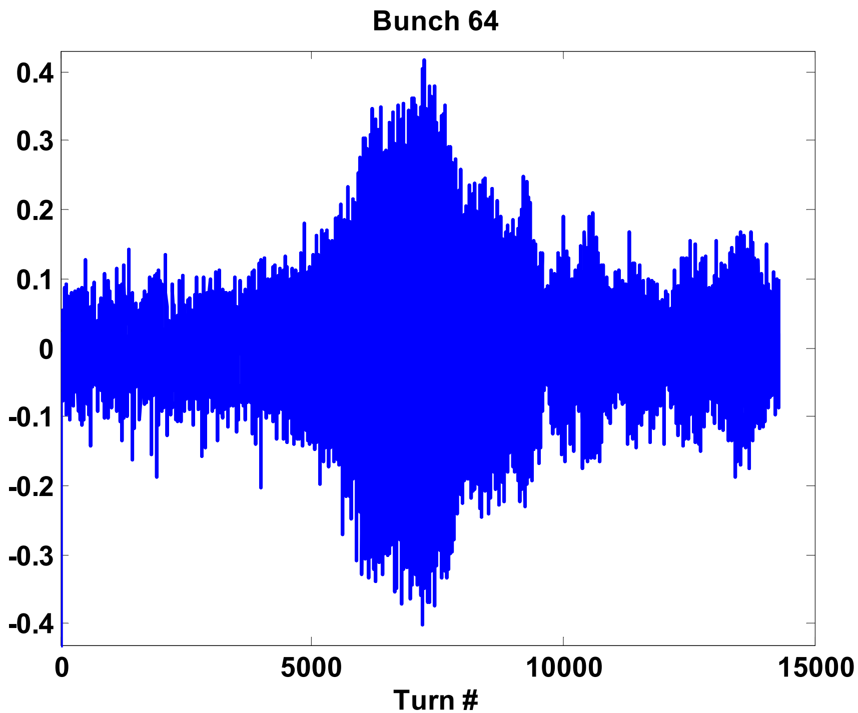

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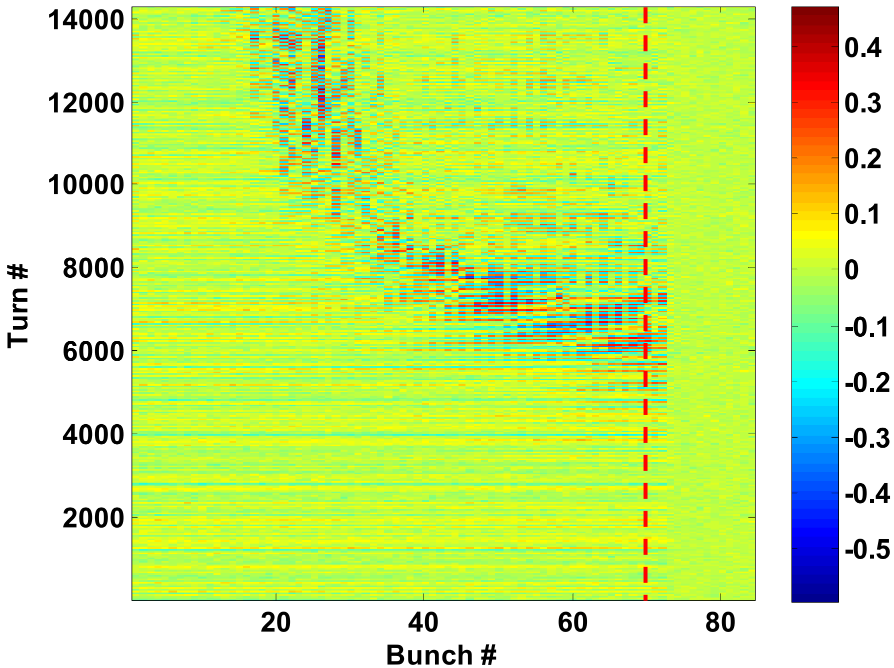

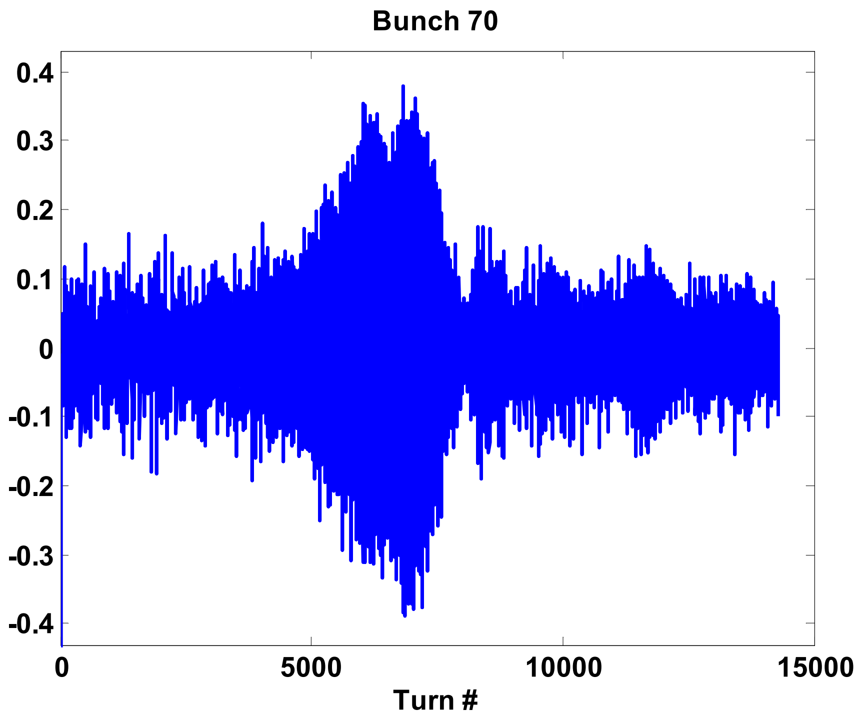

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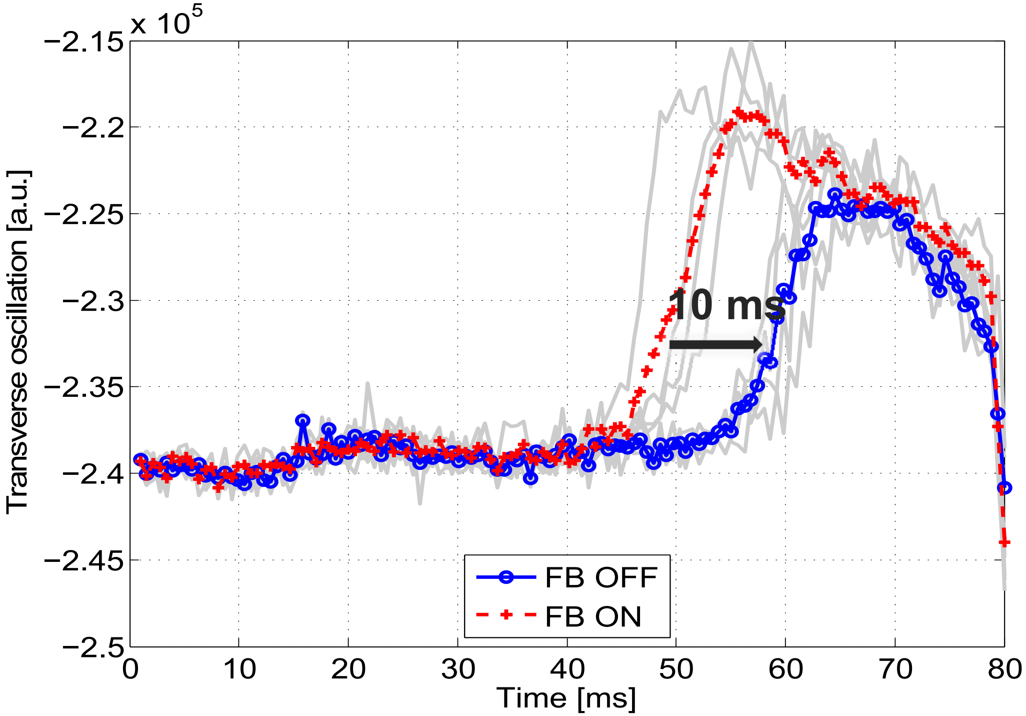
⇒ Instability onset can be efficiently delayed by means of transverse feedback system, which provides margin for future operation



Electron cloud in the PS: summary and outlook

⇒ The electron cloud with 25 ns beams makes a short appearance in the last few ms of the production cycle of these beams

☺ With the present beam parameters, not long enough to render beam unstable or let incoherent effects develop

☹ Very low electron doses on the chamber walls → scrubbing cannot be a solution for the PS!

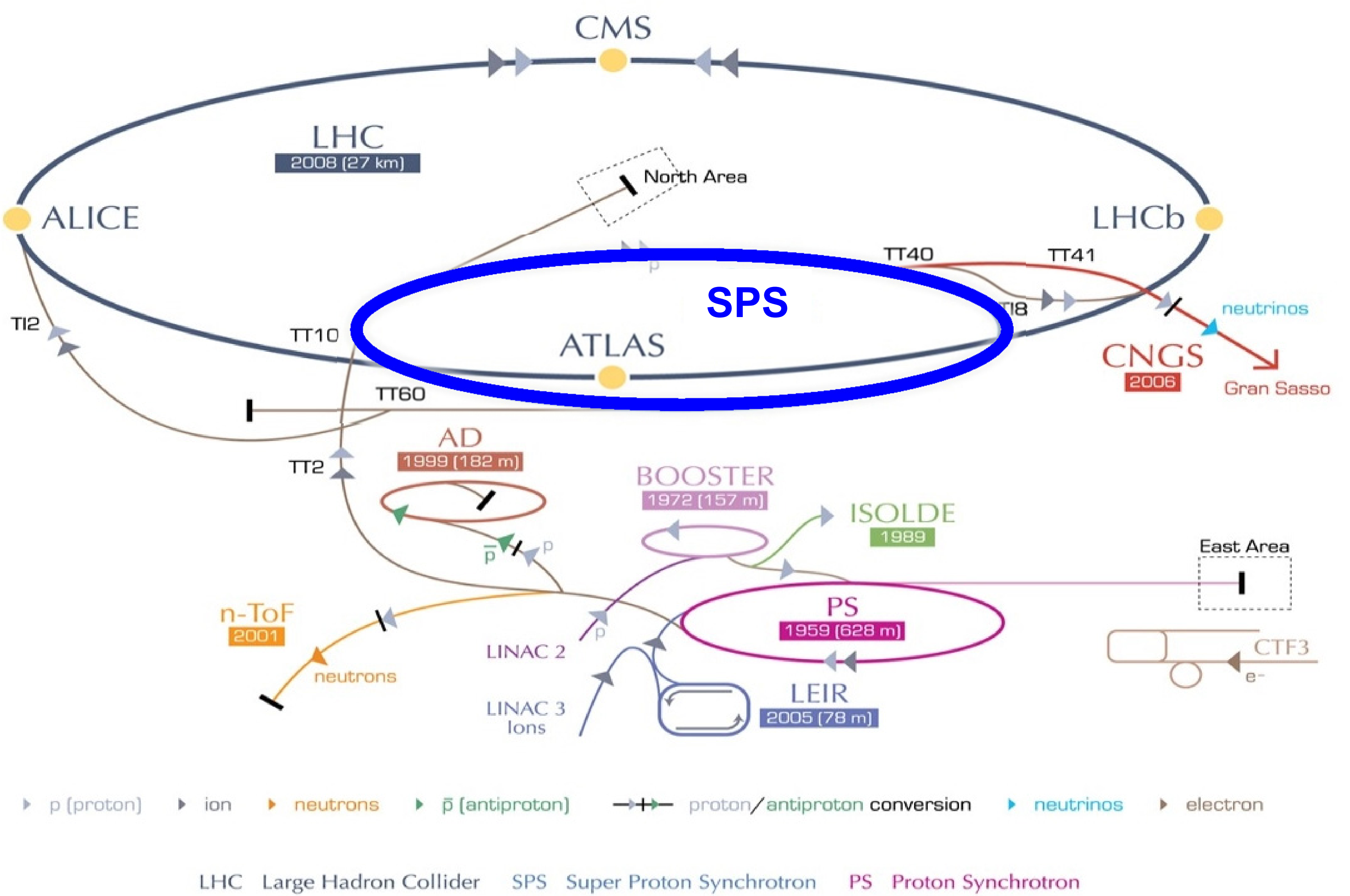
⇒ 25 ns beams with higher bunch charges and lower transverse emittances will be needed within the LHC Injectors Upgrade (LIU) project to serve HiLumi-LHC

→ Not expected to affect much the build up

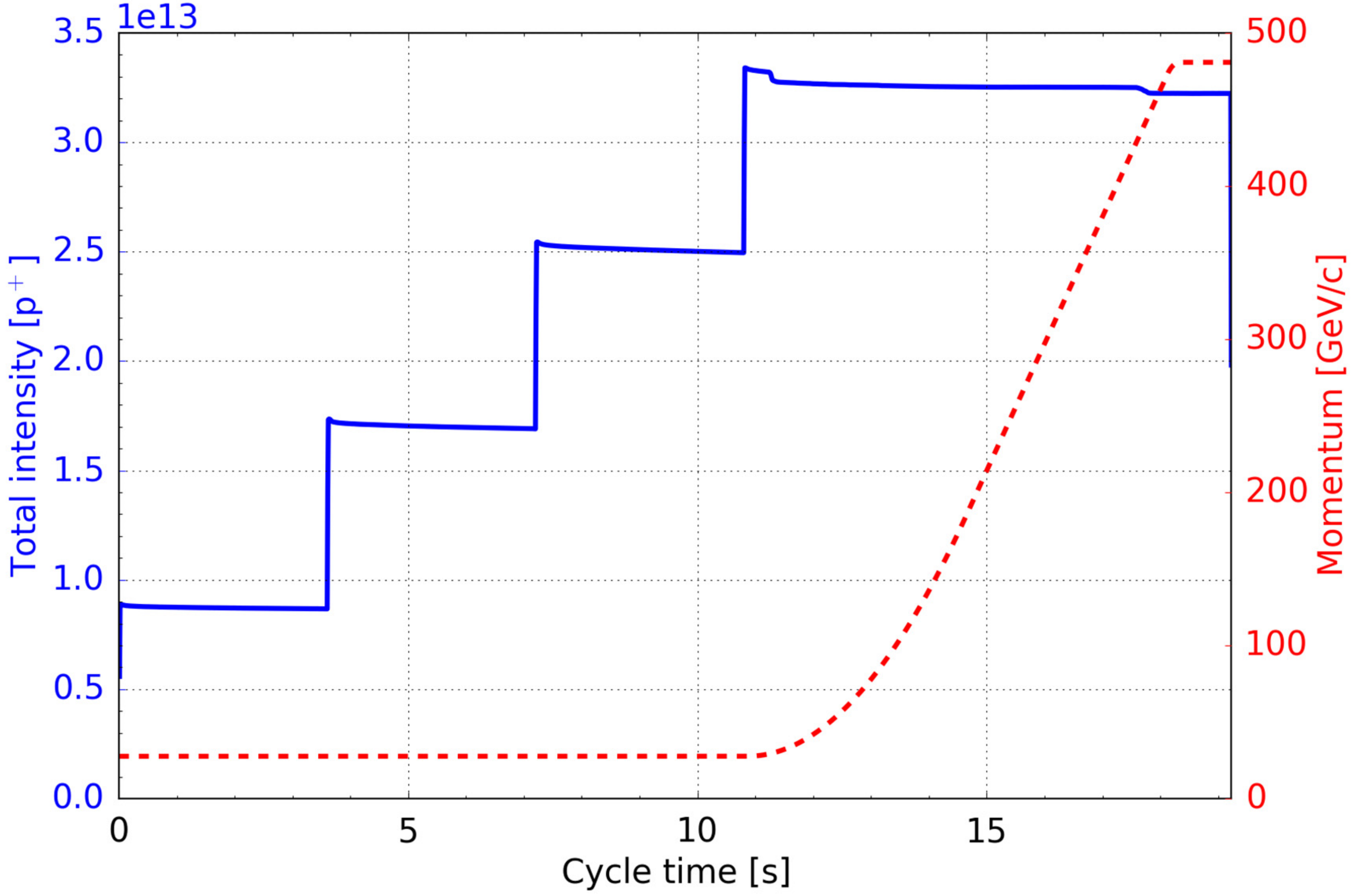
→ Beam certainly more prone to suffer from coherent instabilities, but margin for stabilization provided by transverse feedback system

→ Full simulation study relies on successfully coupling build-up and instability simulations → huge effort, currently underway

CERN's accelerator complex



LHC beams in the SPS



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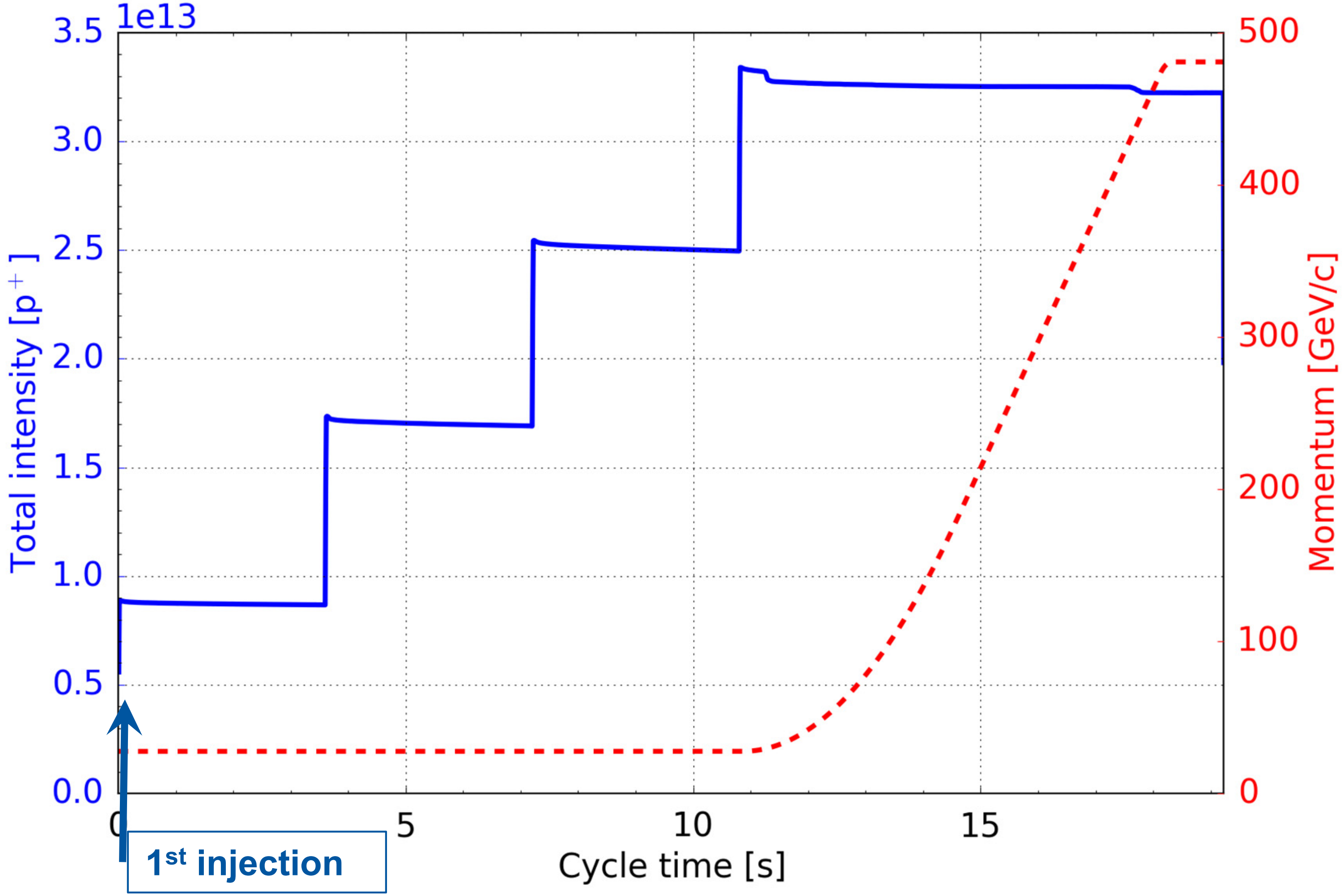

25ns bunch spacing

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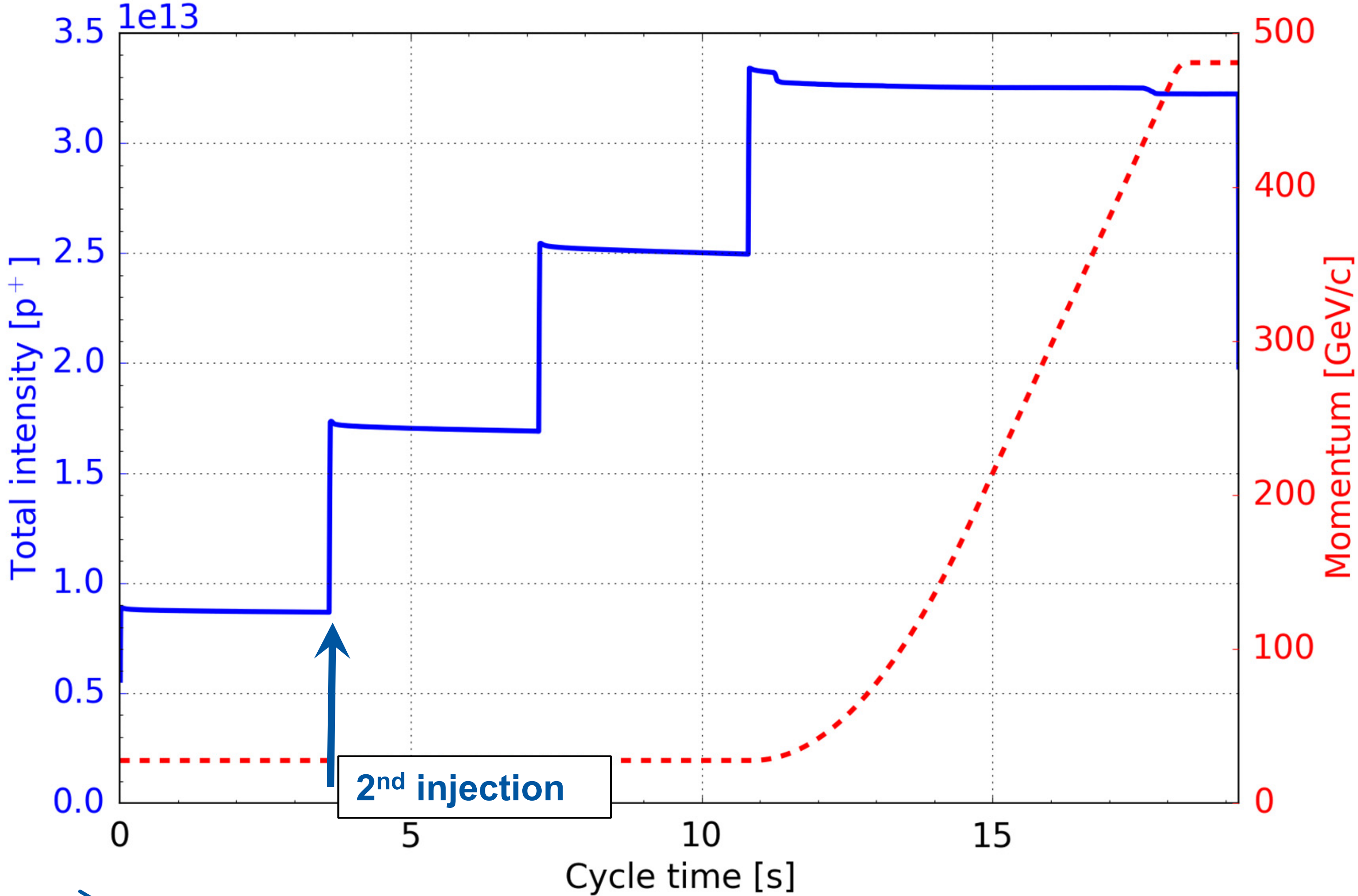

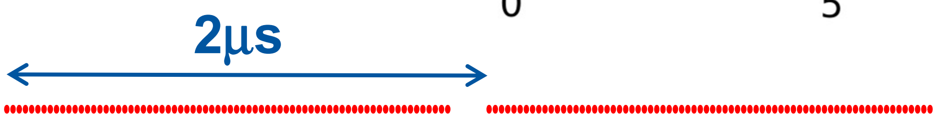

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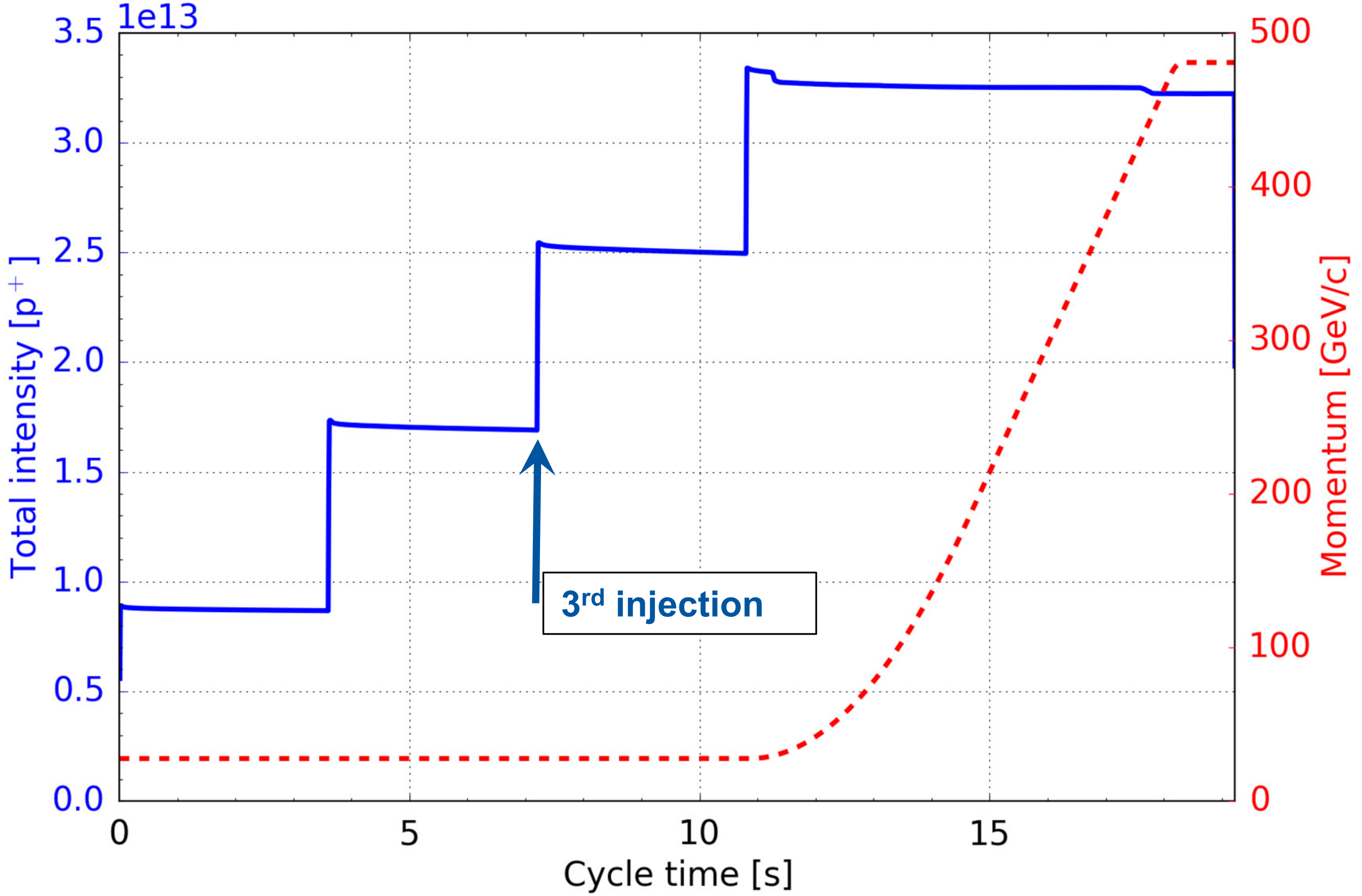

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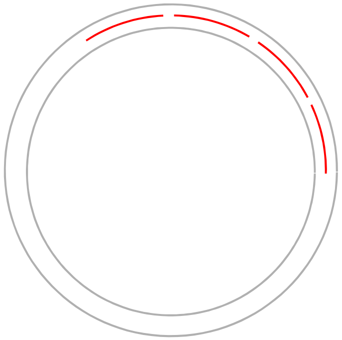

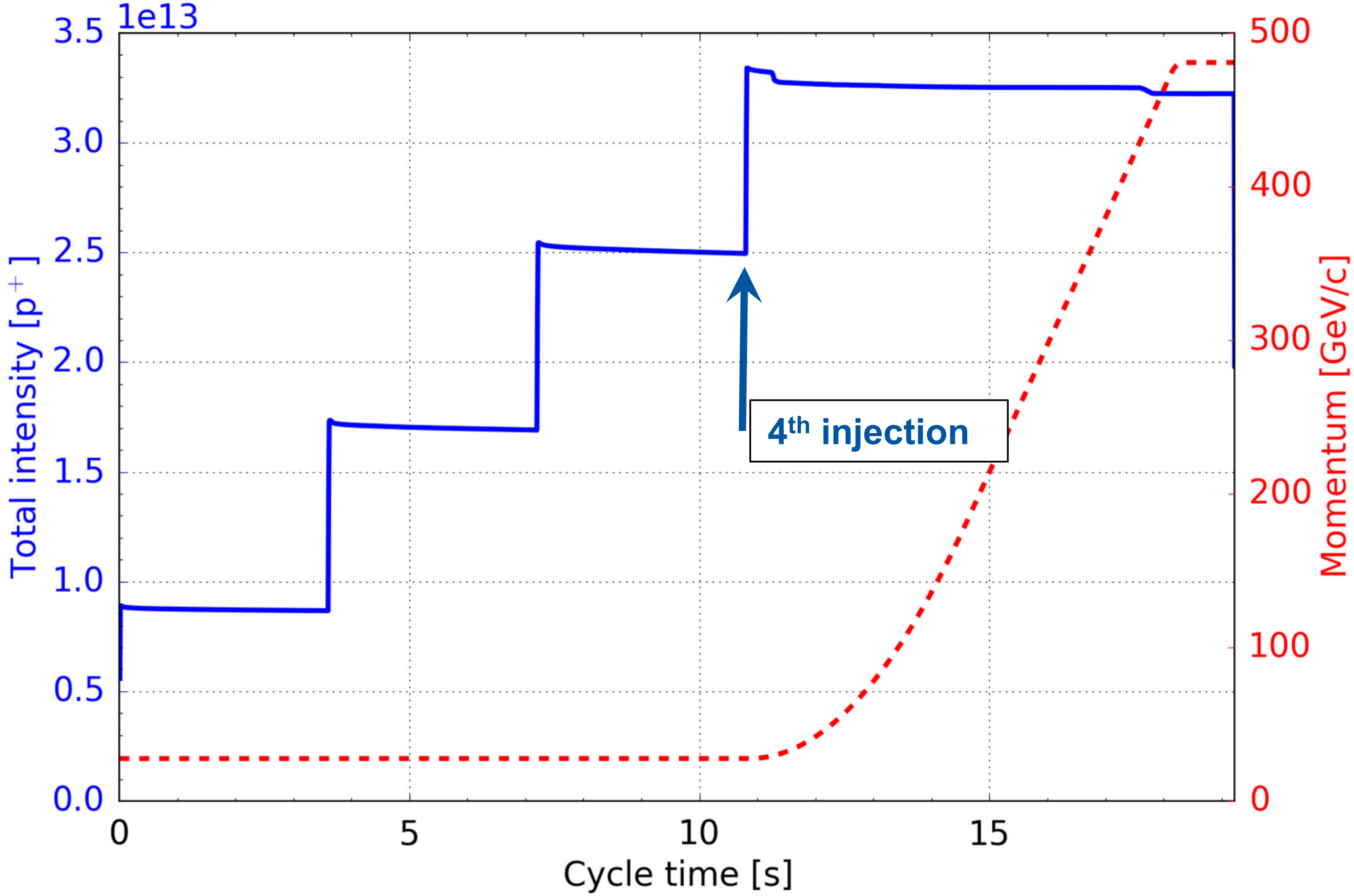

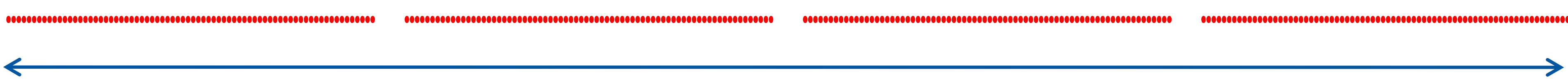

8µs (out of 23µs SPS circumference)

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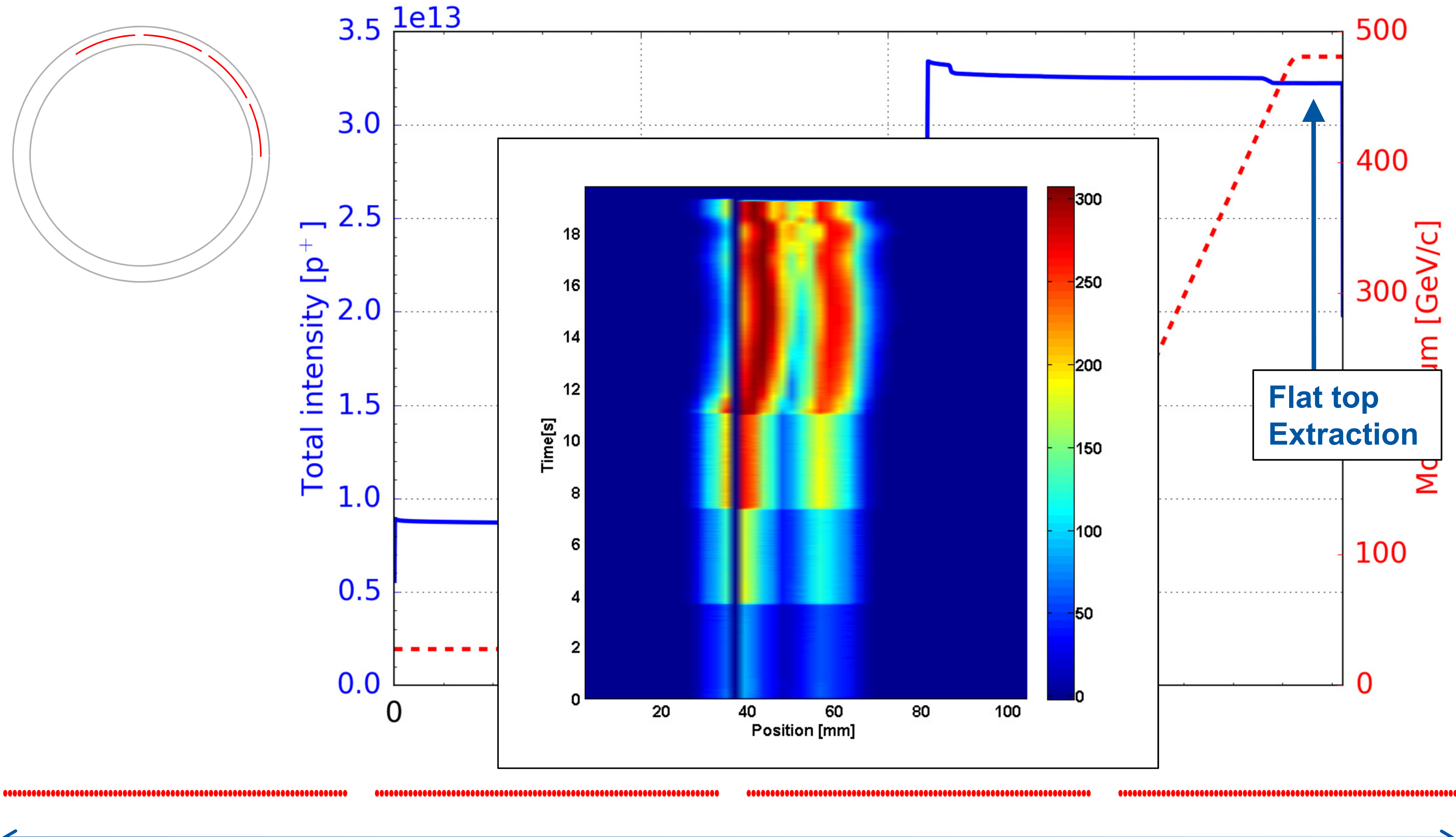

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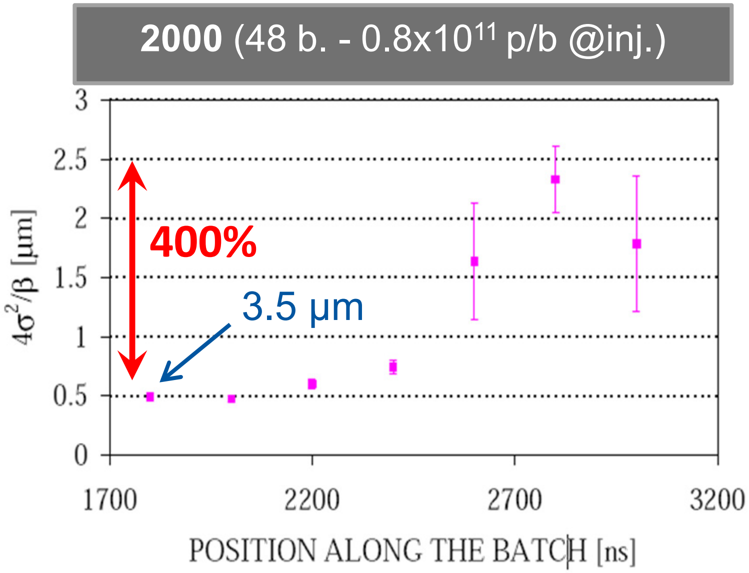
Electron cloud in the SPS

- Strong limitation due to e-cloud with 25 ns beams until ~2011
  - Instabilities at injection + incoherent effects: high chromaticity needed
  - Severe pressure rise around the machine
  - Strong emittance growth along bunch trains



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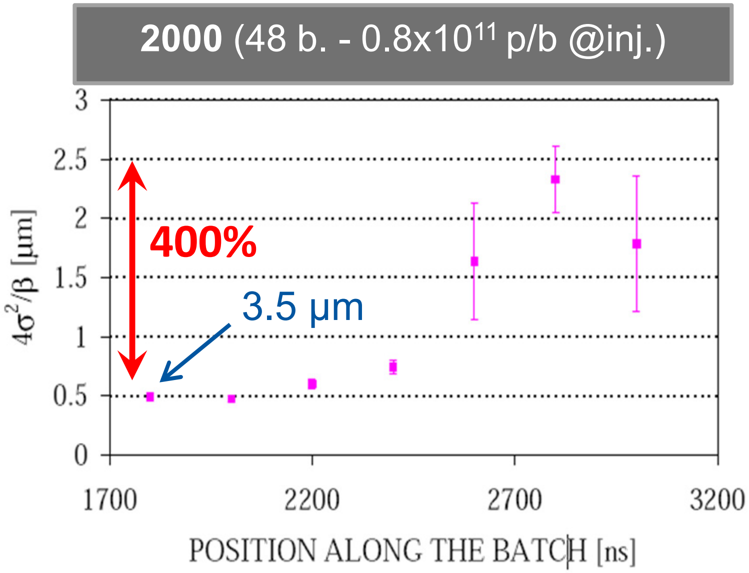

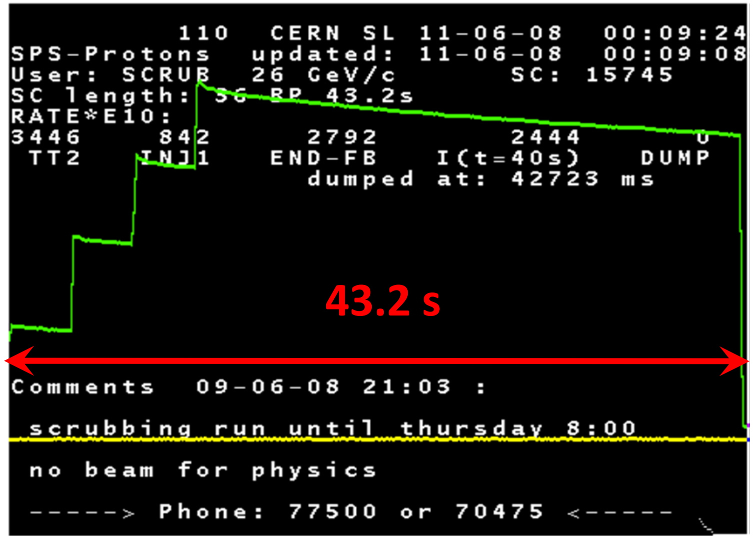

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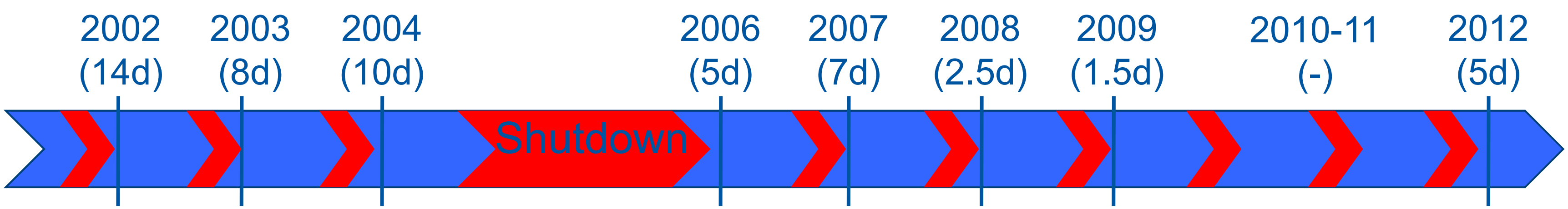

~1 month before 2005 long shutdown
16 days in 2006 – 2009

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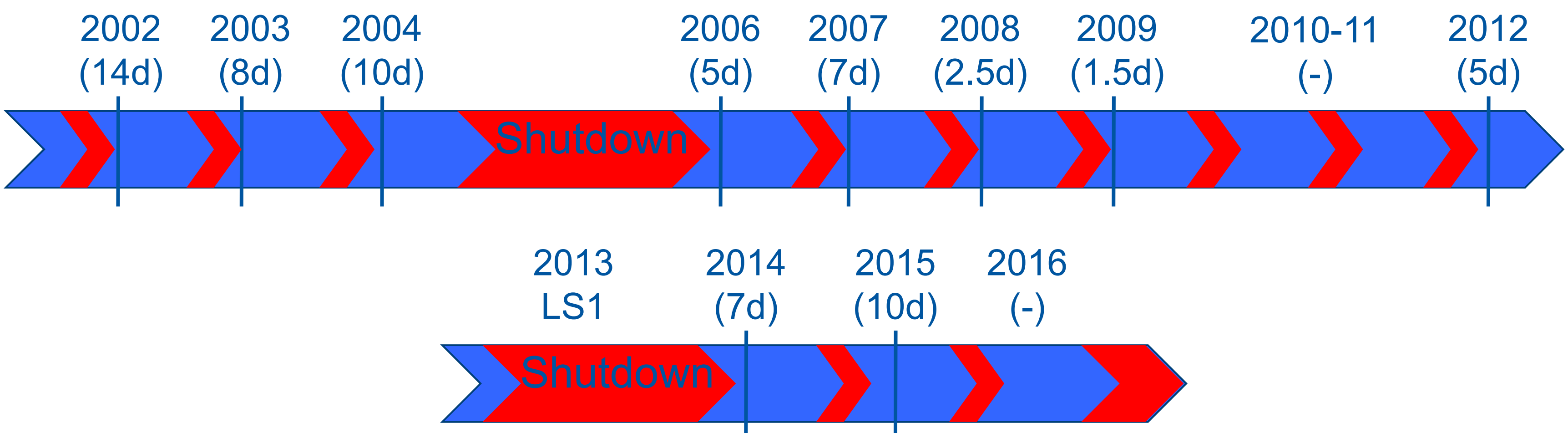
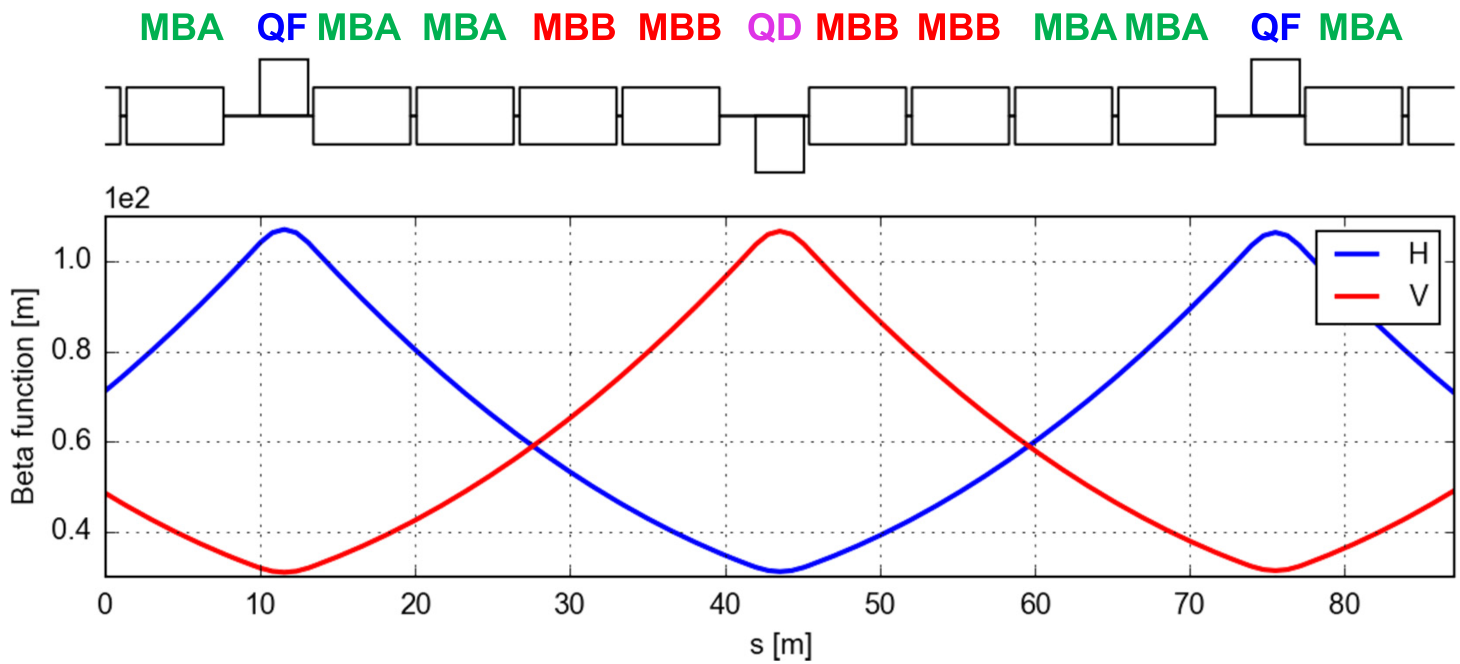
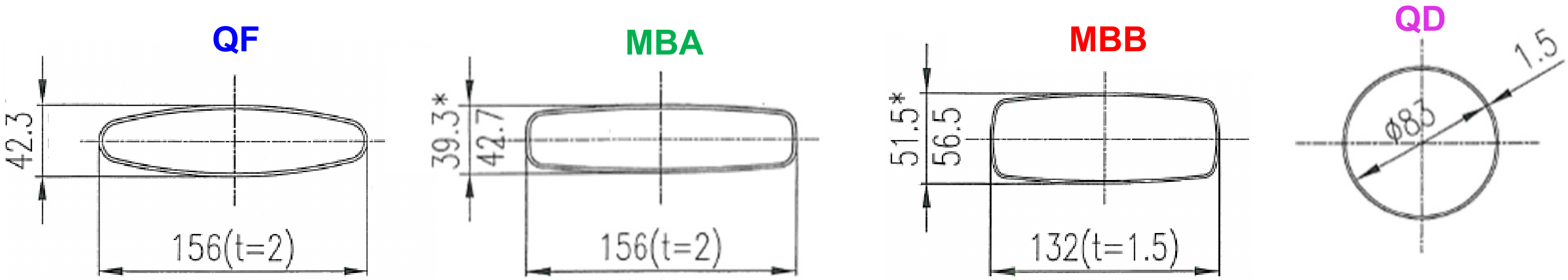
- Scrubbing runs in 2014-15 were mainly targeted to pre-LS1 performance recovery (5d) and qualification of scrubbing for future running conditions (12d)!



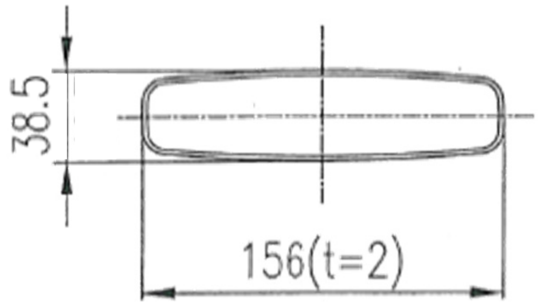
The SPS main magnets

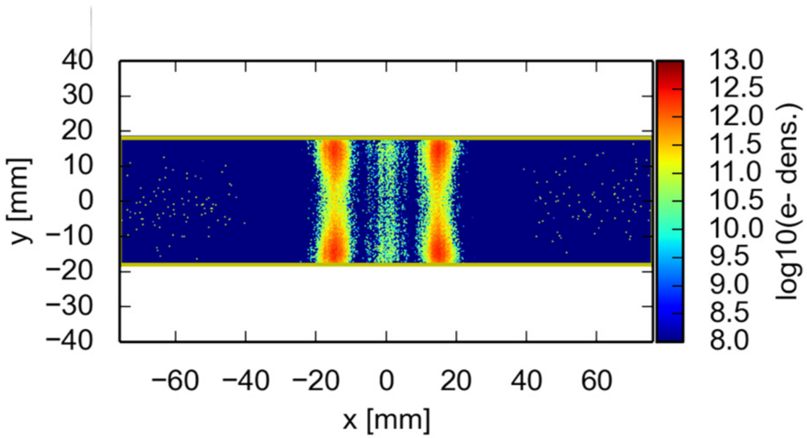
- Four types of main magnets and their chambers (following beam envelope)

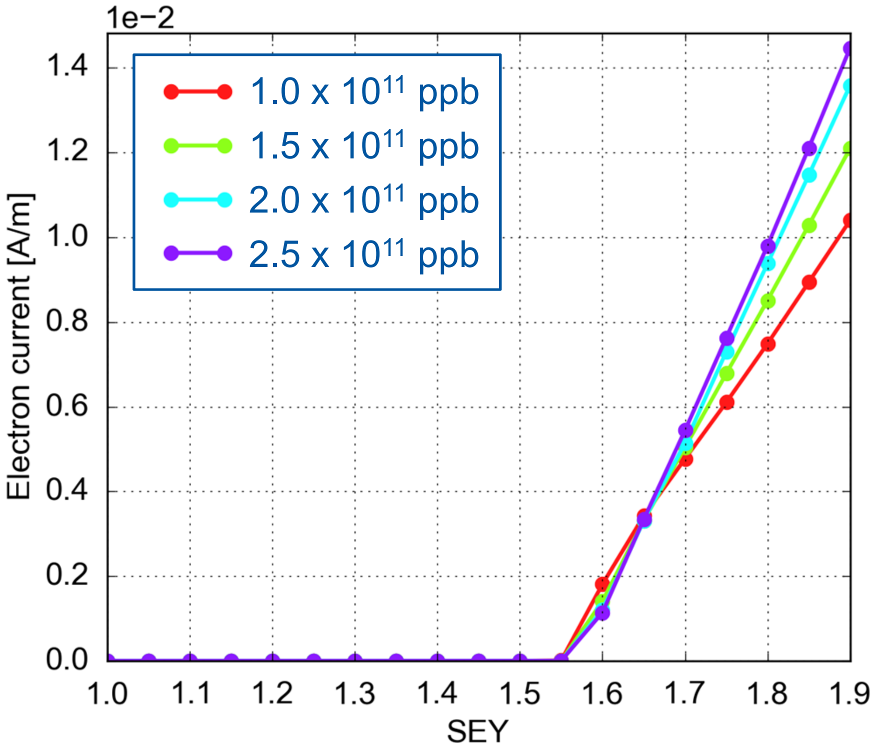




SPS MBA-type chambers

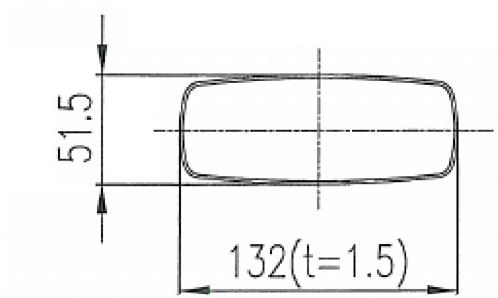


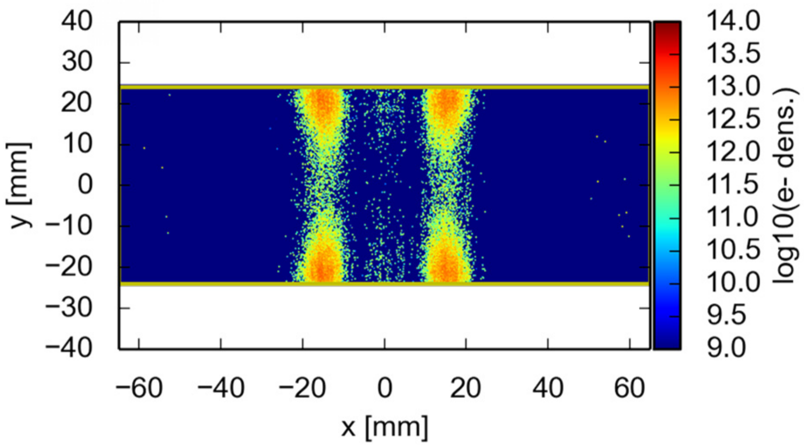


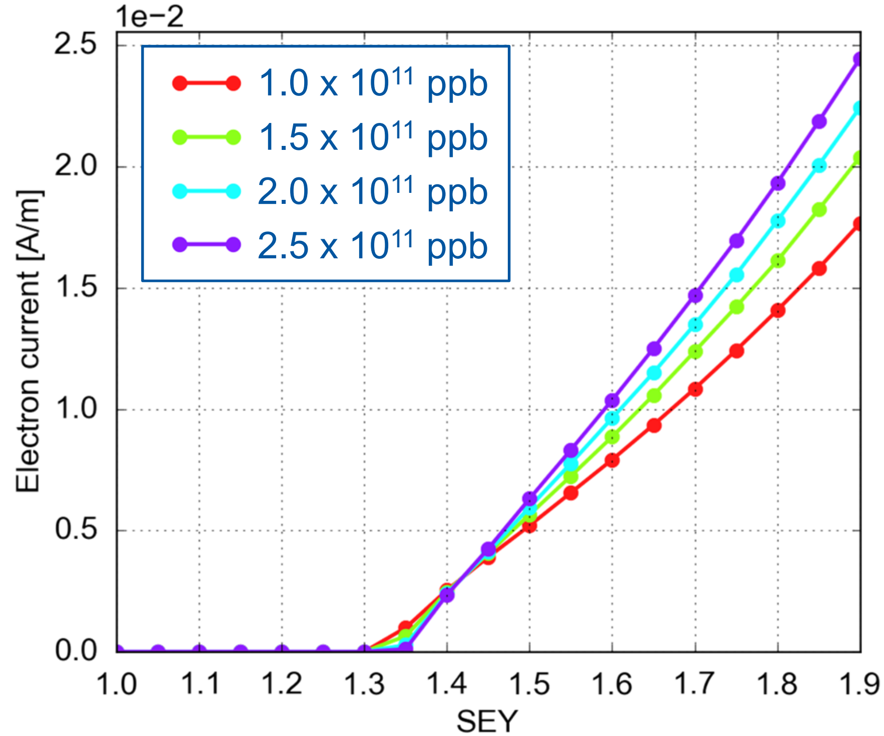


- Transverse distribution with two vertical stripes (typical of e-cloud in dipoles)
- Multipacting threshold at **SEY_{thr}=1.55**
- Dependence on bunch intensity is quite weak, but in reality increasing the intensity moves stripes to unscrubbed regions and may re-awaken e-cloud

SPS MBB-type chambers







- Transverse distribution with two vertical stripes (typical of e-cloud in dipoles)
- Multipacting threshold at **SEY_{thr}=1.3**
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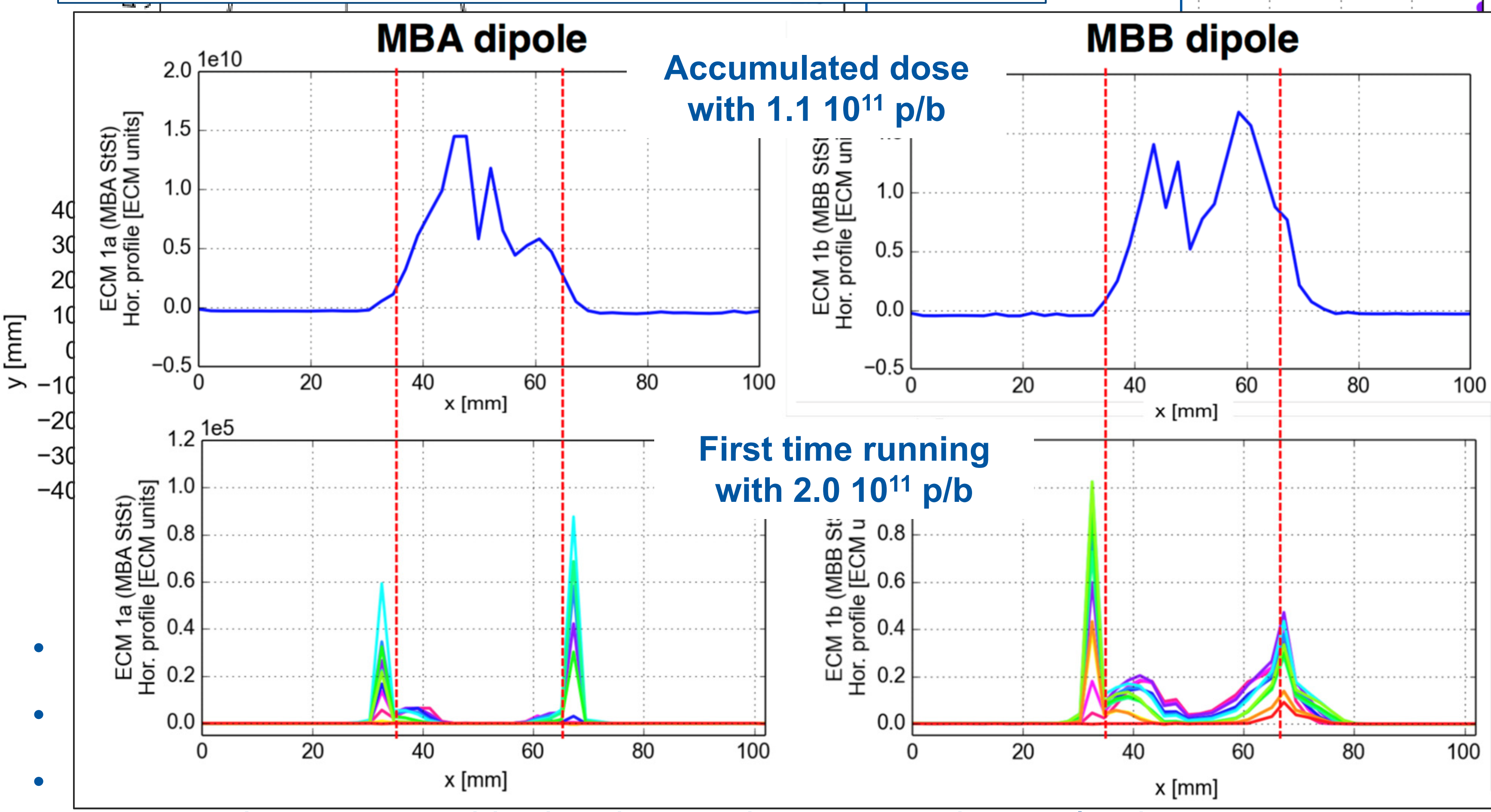
SPS MBB-type chambers

SPS measurements from e-cloud strip monitors



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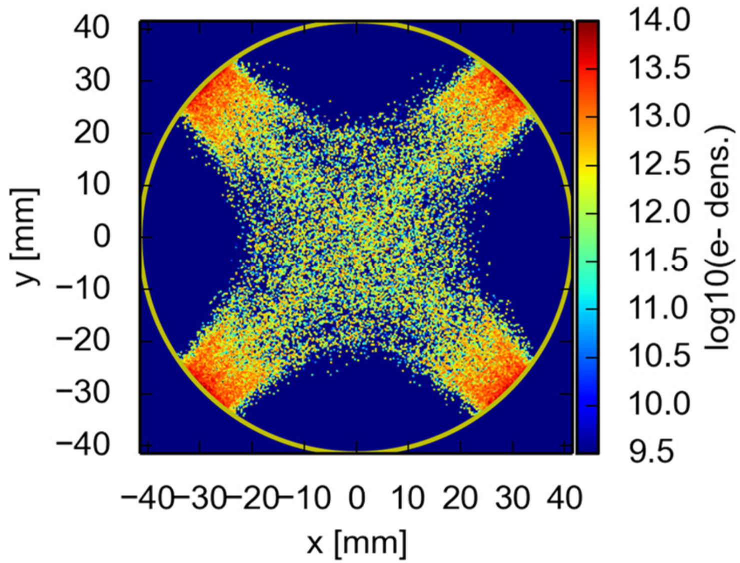
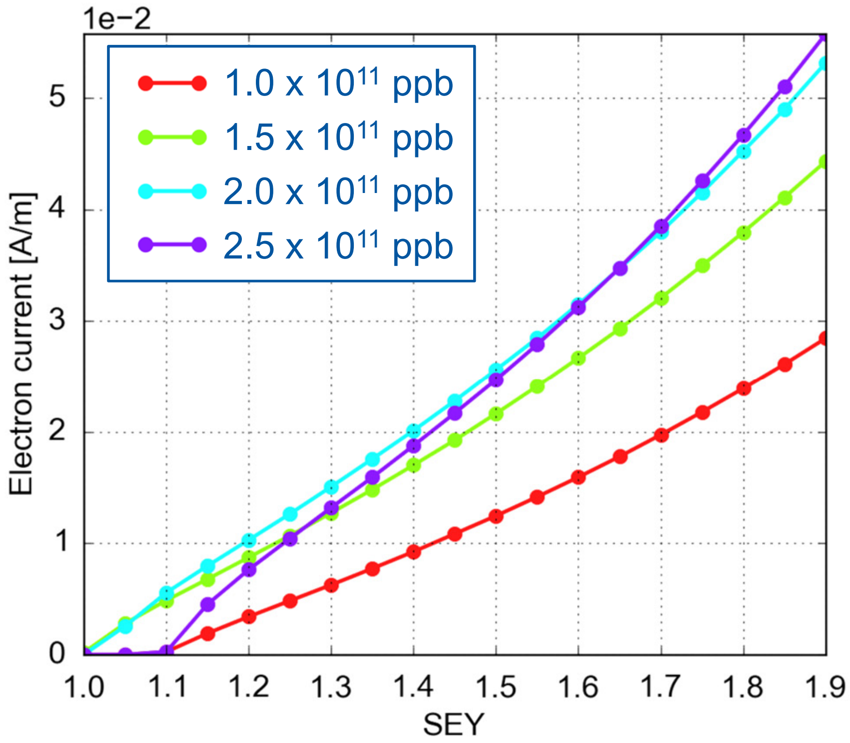
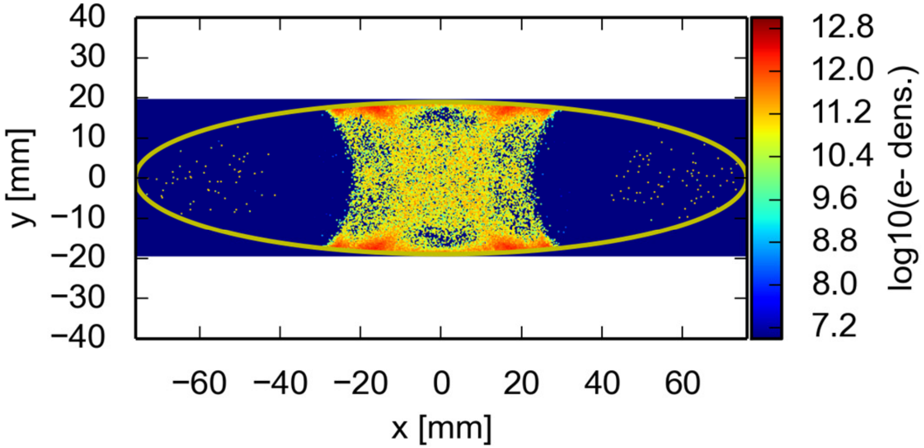
SPS QD-type chambers

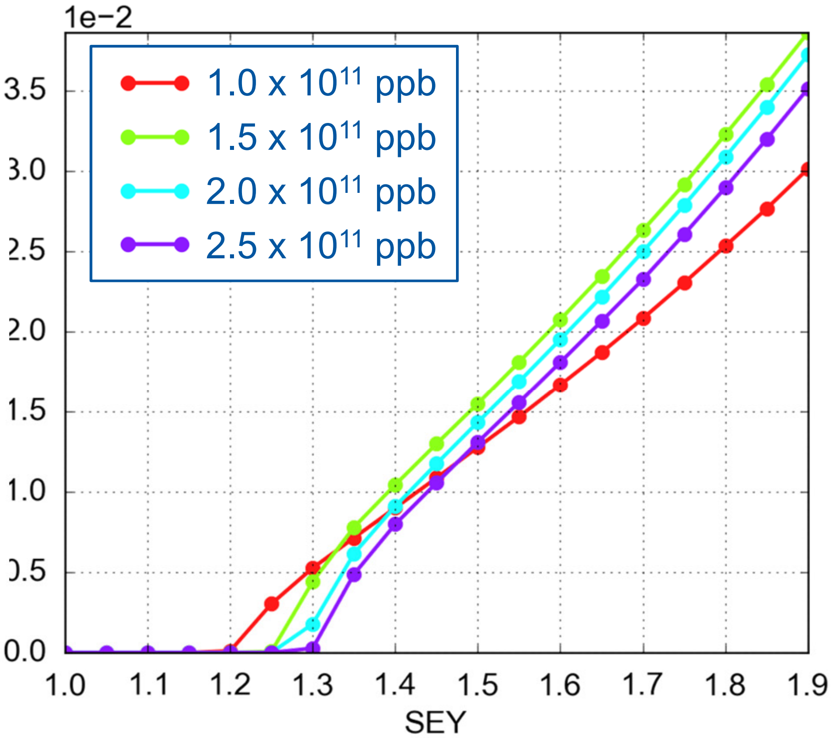




- Trapping of electrons along the field lines
- Very low multipacting threshold at **SEY_{thr}=1.0-1.1**
- Dependence on bunch intensity is quite weak and non-monotonic

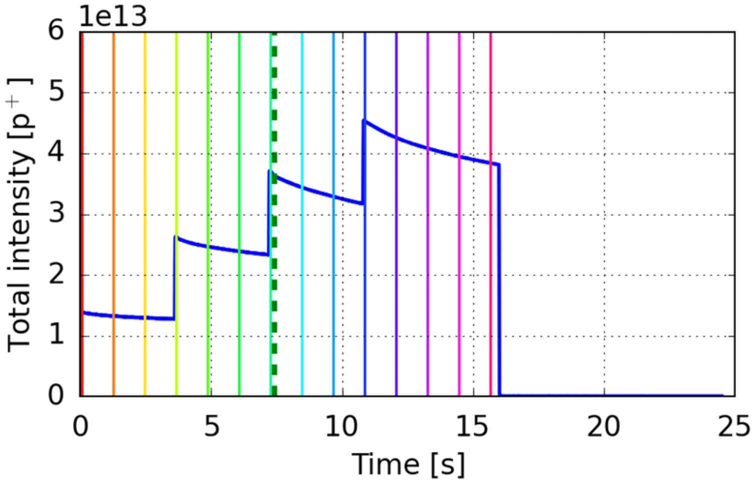
SPS QF-type chambers

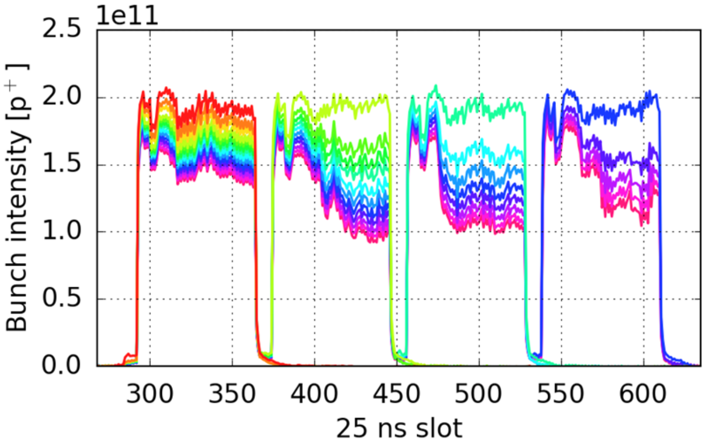


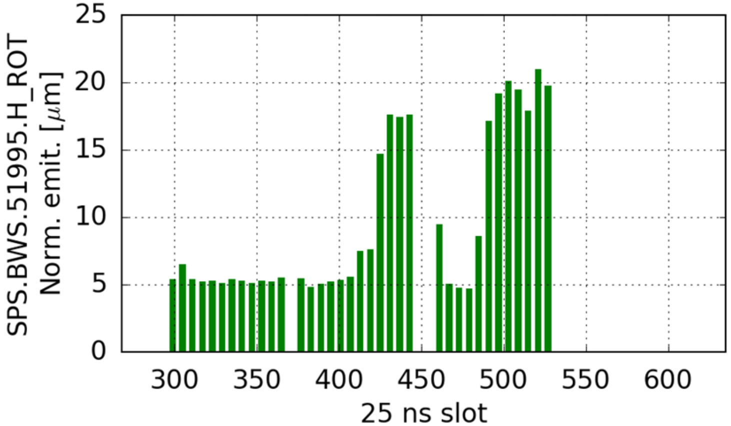


- Trapping of electrons along the field lines
- Multipacting threshold at **SEY_{thr}=1.2-1.3**
- “Inverse” dependence on bunch intensity (higher thresholds for higher currents)

High intensity LHC beams in the SPS







- LHC beams with 2e11 p/b exhibited transverse instability, emittance blow up and poor lifetime when it was first injected into the SPS

⇒ Beam quality improved with ~10 days scrubbing and tuning, but losses could not be decreased below 11% over 10 s (length of SPS injection plateau)

Electron cloud in the SPS: summary and outlook

⇒ Regular scrubbing runs with 25ns beams + several MD sessions with this type of beams
  - ✓ Performance with 25ns beams observed to be improving over the years → by 2011 the nominal LHC beam could be produced within specifications
  - ✓ Performance was quickly recovered in 2014 after Long Shutdown 1, scrubbing studies with high intensity (2e11 p/b) carried out in 2015

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⇒ The most critical parts of the SPS in terms of electron cloud are

- ✓ **MBB** chambers → low SEY threshold, large fraction of SPS
- ✓ **QD, large drift, QF** chambers → low SEY threshold

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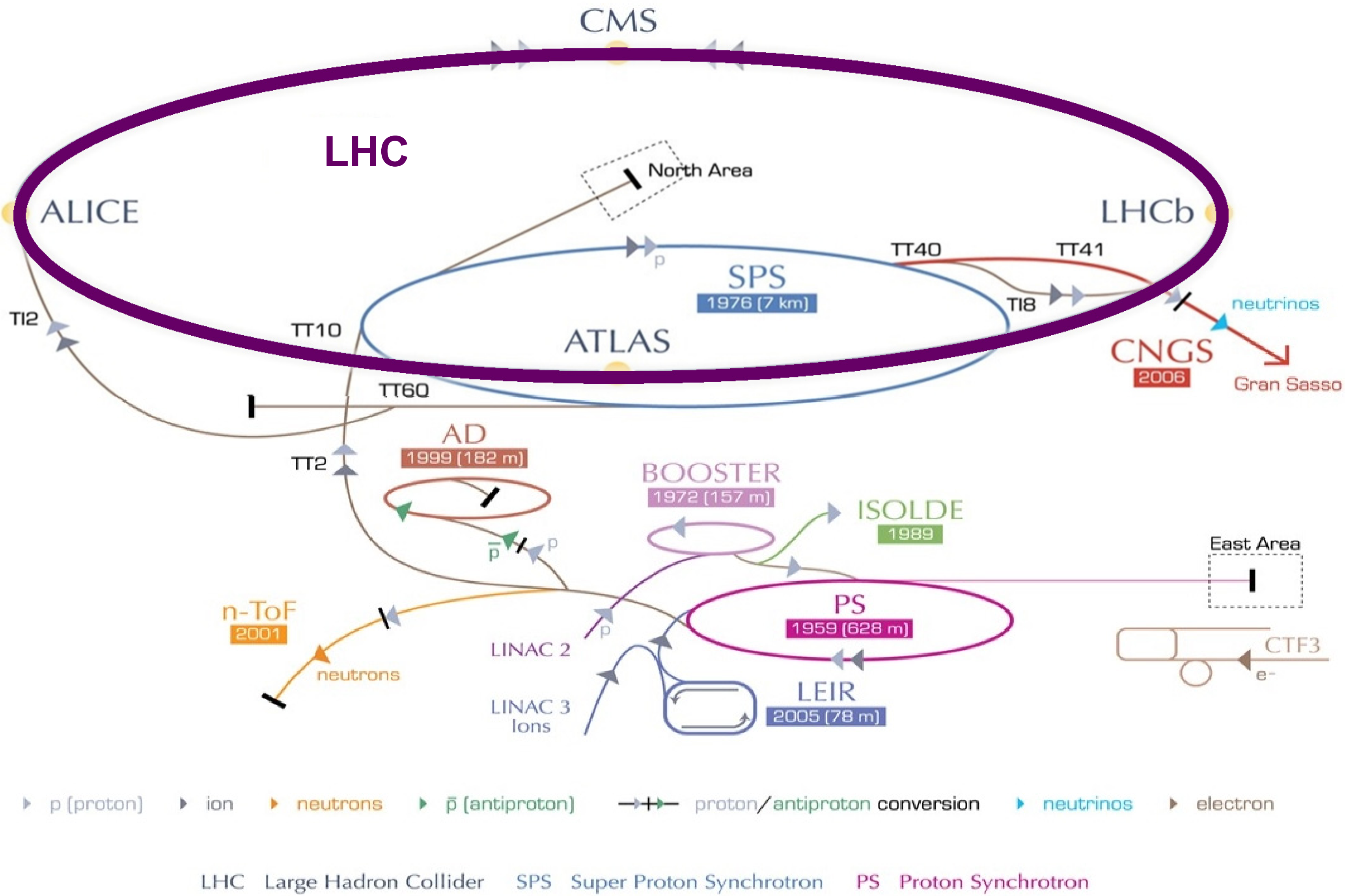
⇒ Post Long Shutdown 2 with high intensity (>2e11 p/b) will rely on

- ✓ Scrubbing
- ✓ a-C coating of QD, QF, large drift chambers + all MBBs in one full arc
- ✓ Full a-C coating to be carried out during Long Shutdown 3, if this turns out not to be enough (instabilities, high losses)

CERN's accelerator complex



Electron cloud in the LHC: historical (Run 1)

⇒ First evidence with 150 ns beam operation in 2010
  - Pressure rise in common chambers with both beams in the machine
  - Suppressed with solenoids at some locations
  ➢ **[1]** V. Baglin. G. Bregliozzi, M. Jimenez, G. Lanza, e.g. in IPAC'11

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⇒ Signs of strong electron cloud activity with 75 and 50 ns beams end 2010
  - Pressure rise in non-NEG coated straight sections
  - Heat load on the cold beam screen in the arcs
  - Instability and emittance growth along the trains
  - Energy loss measured from the shift of the synchronous RF phase
  - ➢ **[1] + [2]** G. Arduini, P. Baudrenghien, S. Claudet, J. Esteban-Müller, E. Métral, F. Roncarolo, GR, E. Shaposhnikova, L. Tavian, et al.

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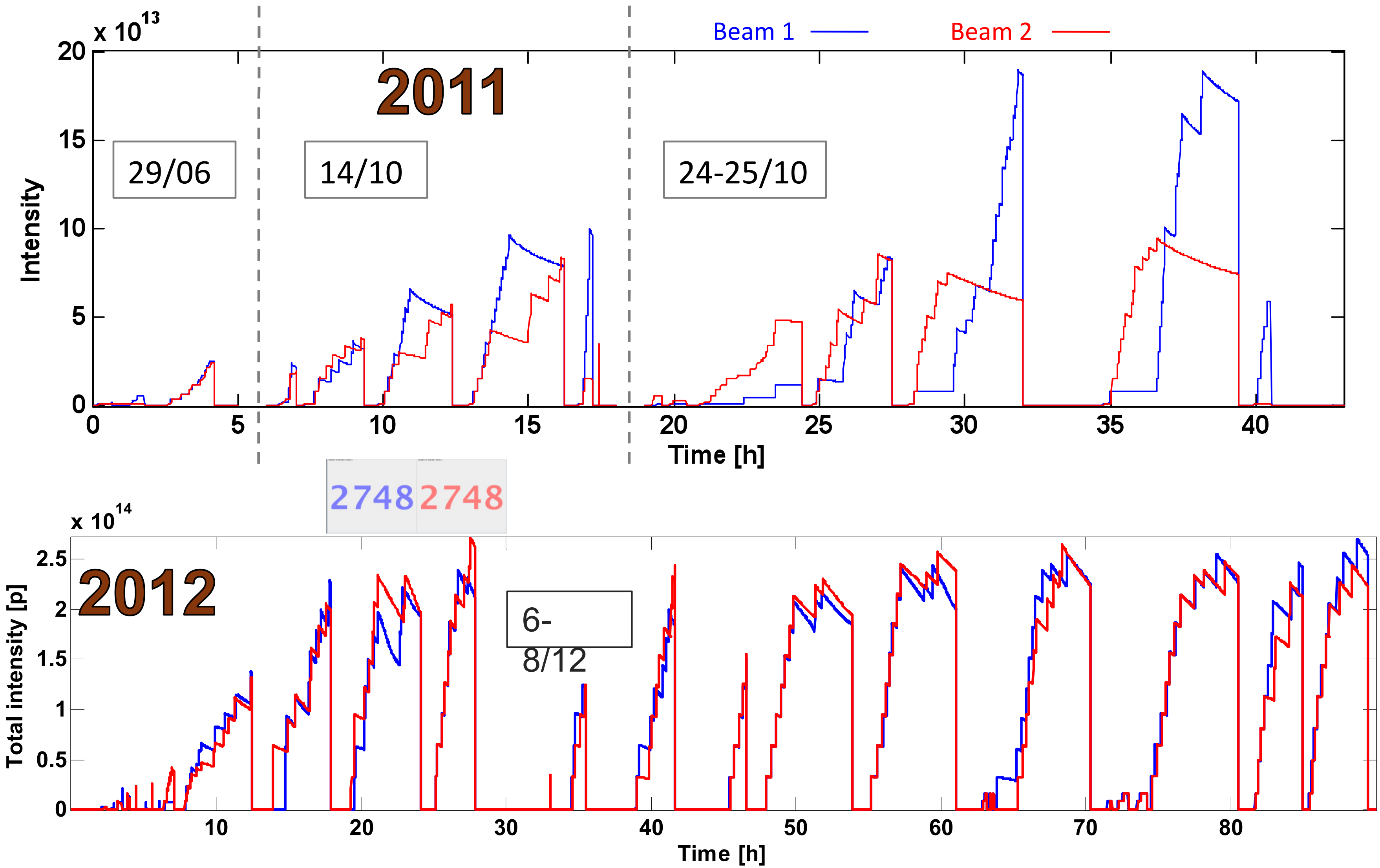
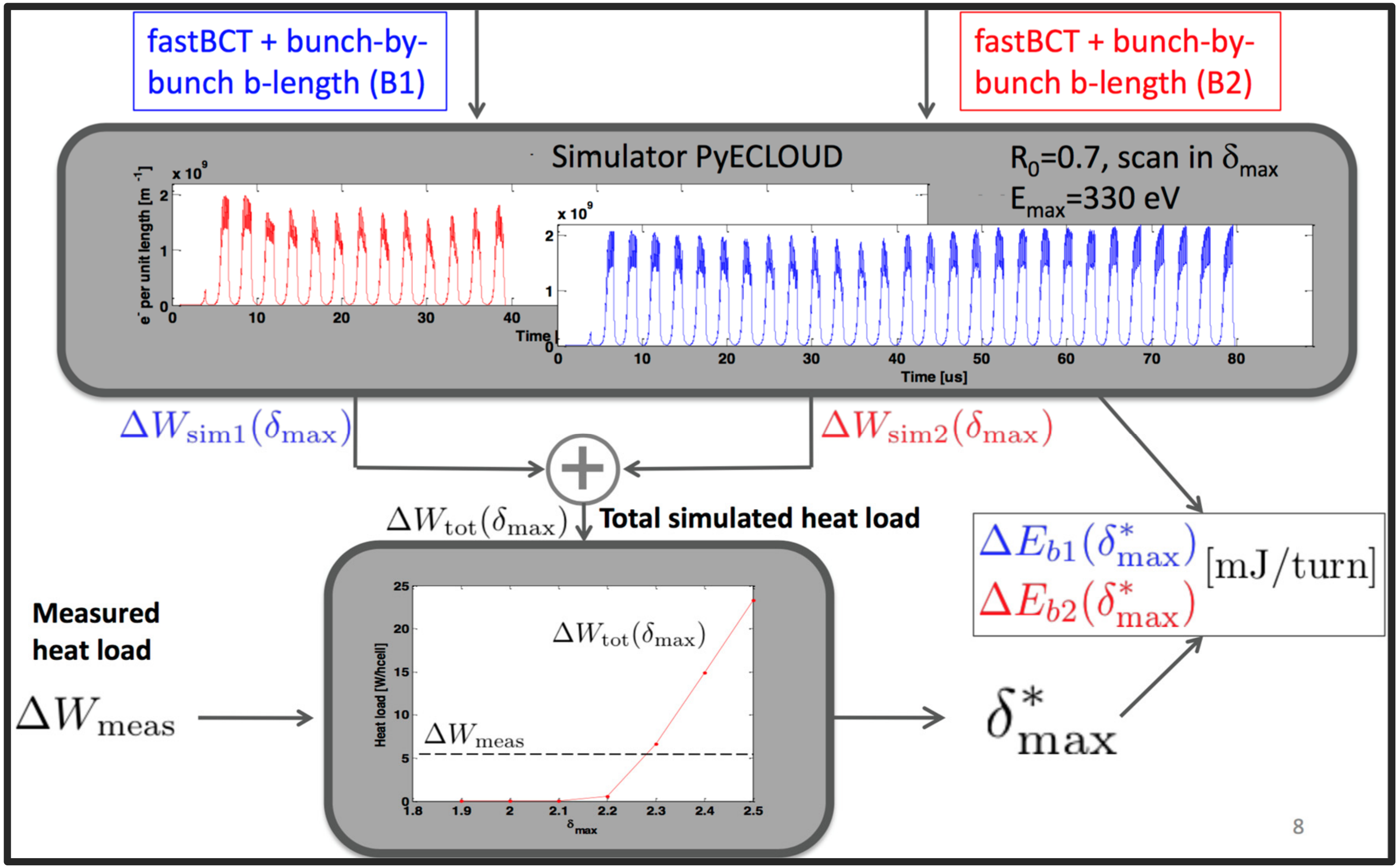
⇒ Smooth electron cloud free Run I (2011 – 2012) with 50 ns beams (3.5 and 4 TeV)
- Scrubbing run with 50 ns beams in April 2011 → no signs of e-cloud with 50 ns beams except in common regions (e.g. inner triplets)
- Tests with 25 ns beams in 2011 (stored more than 1000 bunches in trains of 72)
- Full scrubbing with 25 ns beams at the end of 2012 with trains of 288 bunches and acceleration + pilot physics run with low emittance variant of 25 ns beams (up to 800 bunches)
  - **[3]** G. Arduini, H. Bartosik, G. Iadarola, GR, et al. Evian OP Workshop 2011 and 2012, Chamonix Workshop 2012

Electron cloud in the LHC: 25 ns beams in 2011-12

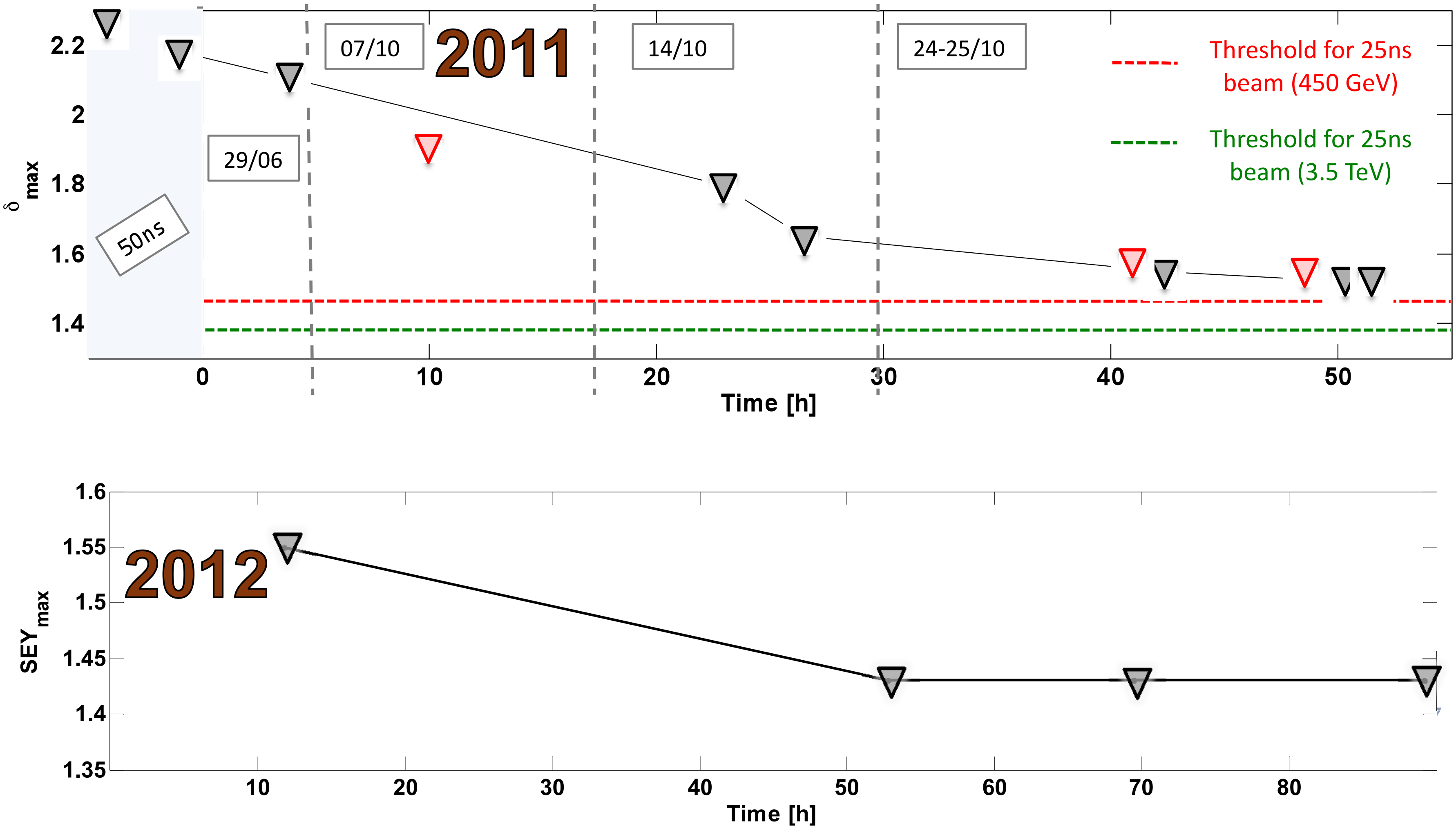


Electron cloud in the LHC: 25 ns beams in 2011-12

Calculation of beam screen SEY (δ_{max}) from heat load measurements



Electron cloud in the LHC: 25 ns beams in 2011-12



Electron cloud in the LHC: historical (Run 2)

⇒ Run II with 25 ns beams starting in 2015 (6.5 TeV)

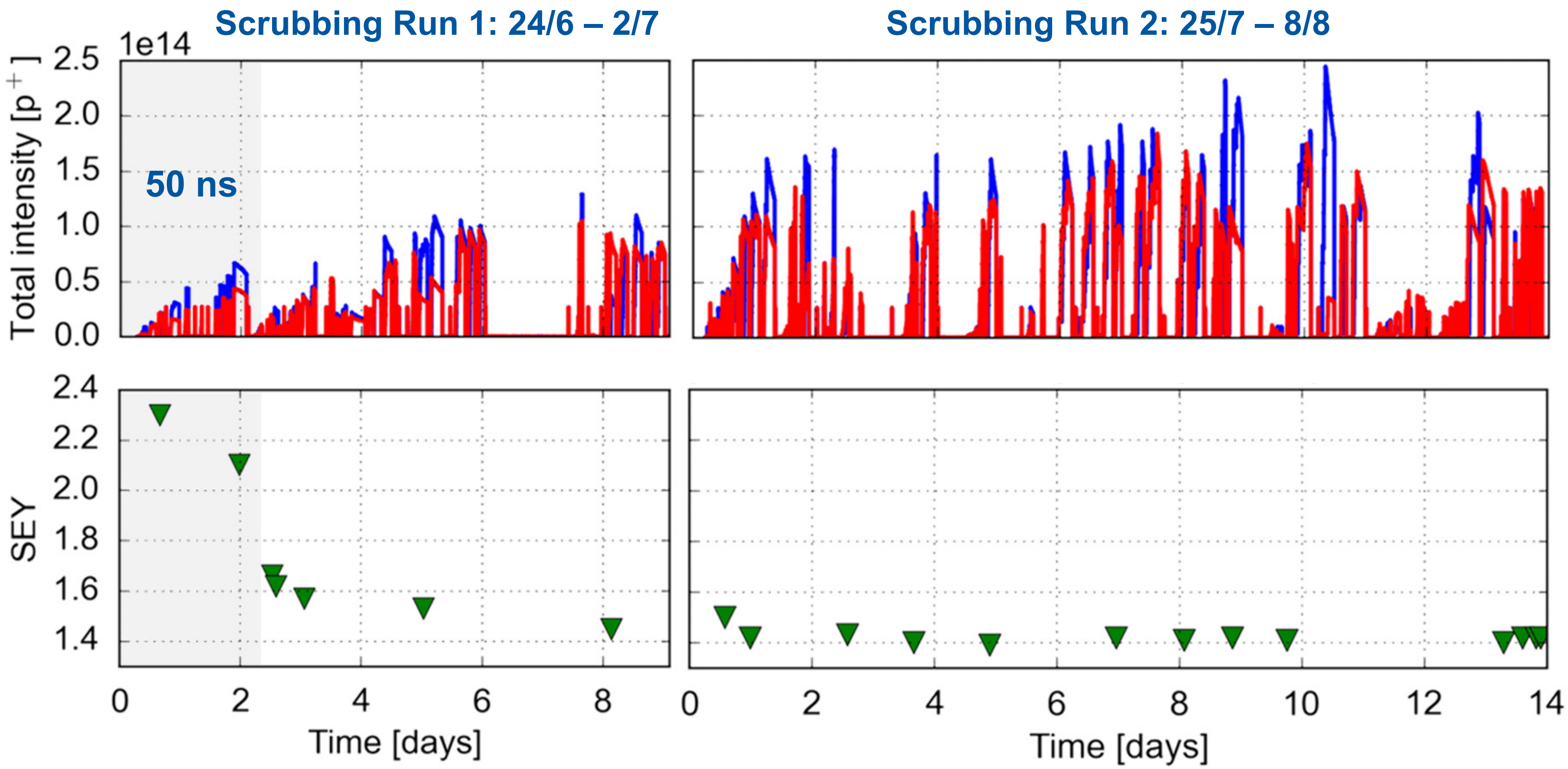
- Extended scrubbing runs to recover 2012 post-25ns conditioning (strong deconditioning)
- Slow process over ~4 weeks gradually increasing the length of the bunch trains (24 to 72 bunches in steps of 12, then 144 bunches)
- Intensity ramp-up up to 2240 bunches per ring in trains of decreasing length to comply with the limitations from the cryogenic system (144 → 72 → 36)
- Several cycles of conditioning-deconditioning observed
- Scrubbing with physics
- ➢ **[1]** Scrubbing team, Evian OP Workshop 2015, Chamonix Workshop 2016

⇒ Run II with 25 ns beams in 2016 (6.5 TeV)

- Short scrubbing (1.5d) to recover 2015 conditioning
- Intensity ramp-up with trains of 72 bunches (limited by SPS)
- Vertical instability at 6.5 TeV leading to emittance blow up at the tails of the trains → requires high chromaticity while colliding
- Scrubbing with physics, saturation of the process?
- ➢ **[2]** Scrubbing team, LMC meetings, electron cloud meetings, weekly updates

Electron cloud in the LHC during Run 2: scrubbing runs

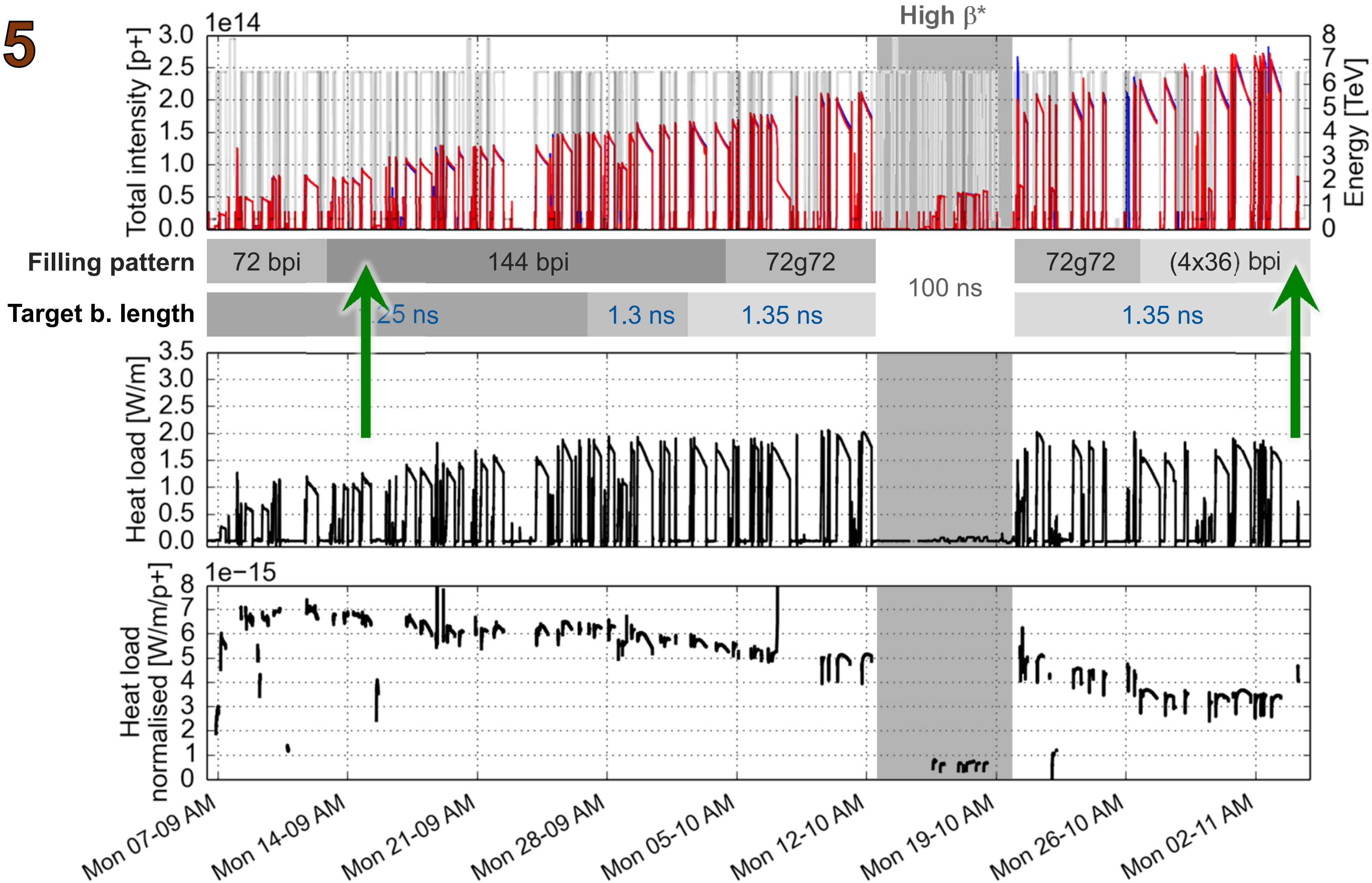
2015



- After Long Shutdown 1
  - SEY of beam screens reset to pre 25 ns values
  - Lots of limitations from instabilities, vacuum on sensitive equipment, cryogenic transients → defined machine settings also for physics run (tunes, chromaticities, octupoles, transverse feedback)
  - By end of scrubbing run, return to SEY values around 1.4 (beam quality improvement in last part)
  - → **Deconditioning evident – after initial SEY drop it took time to recondition**

Electron cloud in the LHC during Run 2: scrub with physics

2015

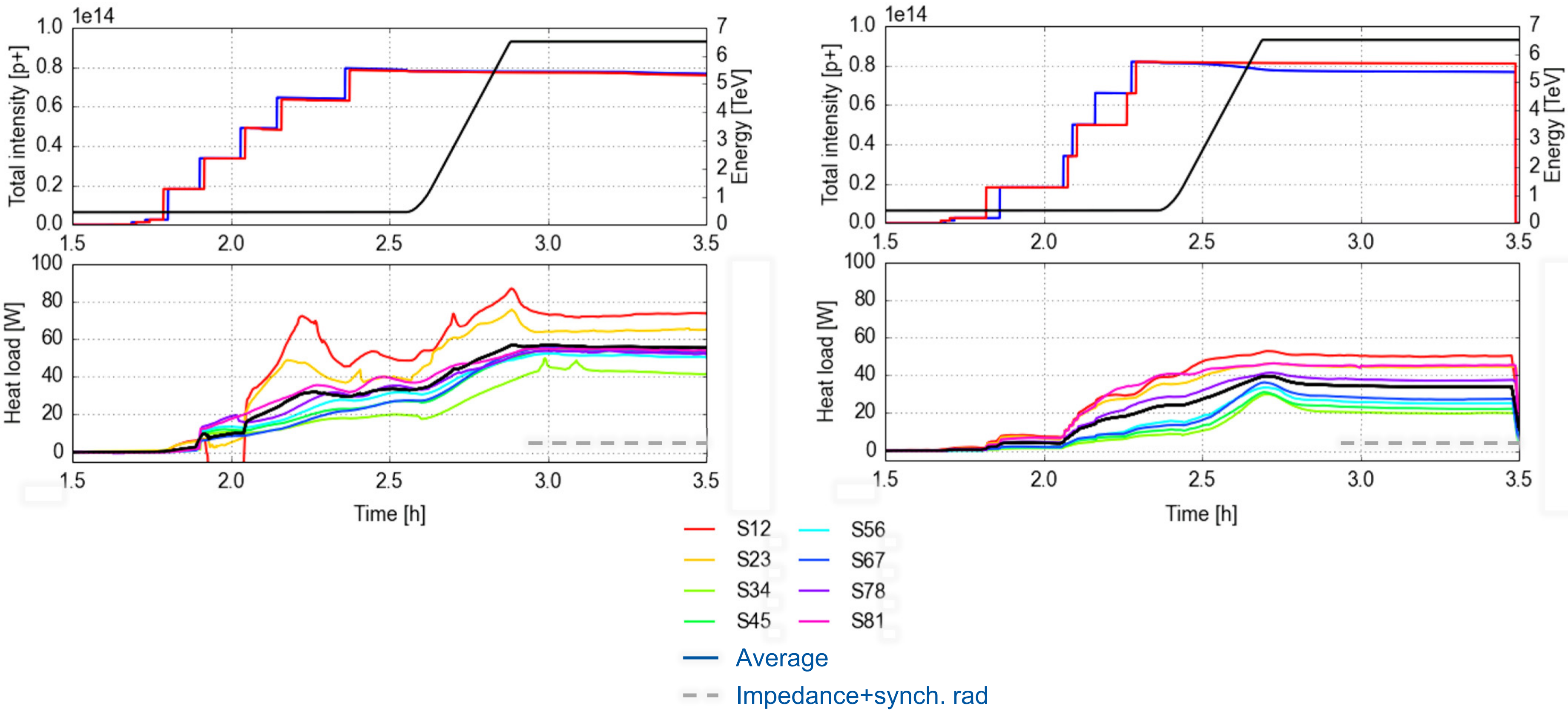


Electron cloud in the LHC during Run 2: scrub with physics

2015

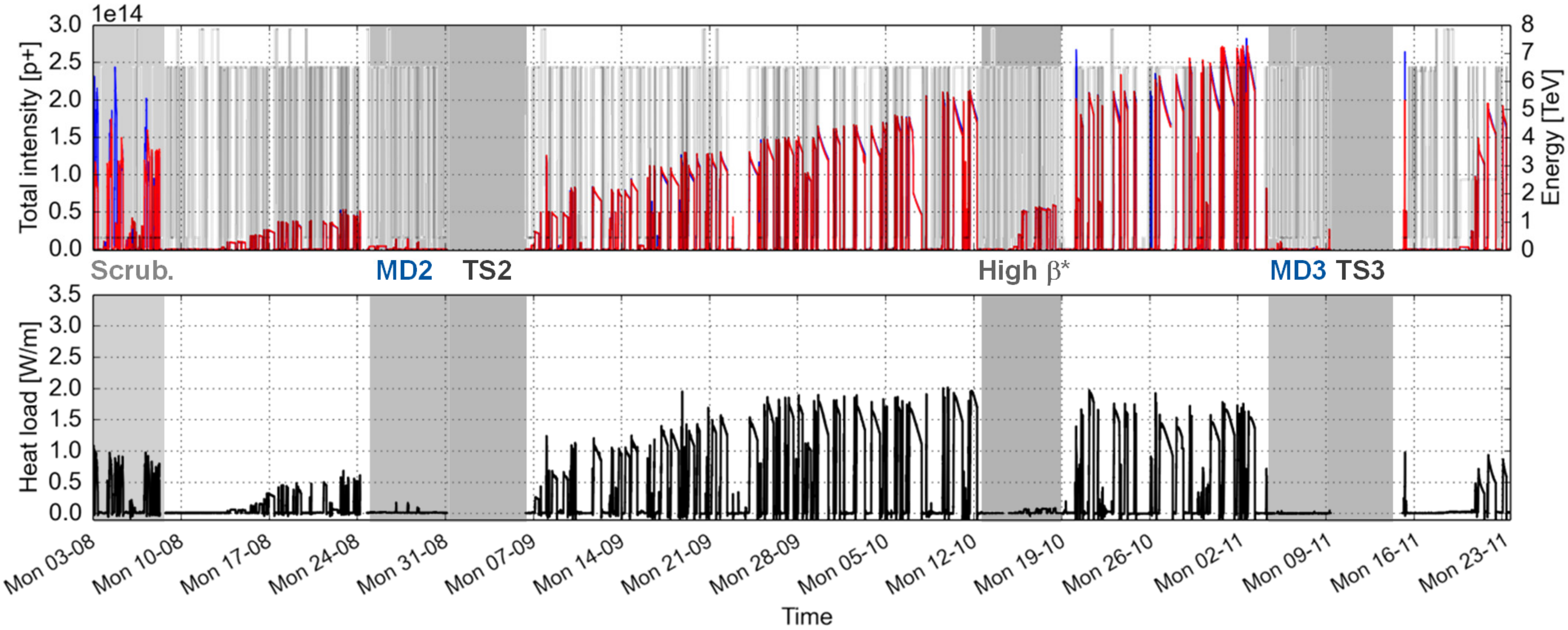
14 September – Average arc half cells

4 November – Average arc half cells



Electron cloud in the LHC during Run 2: deconditioning and reconditioning cycles

2015



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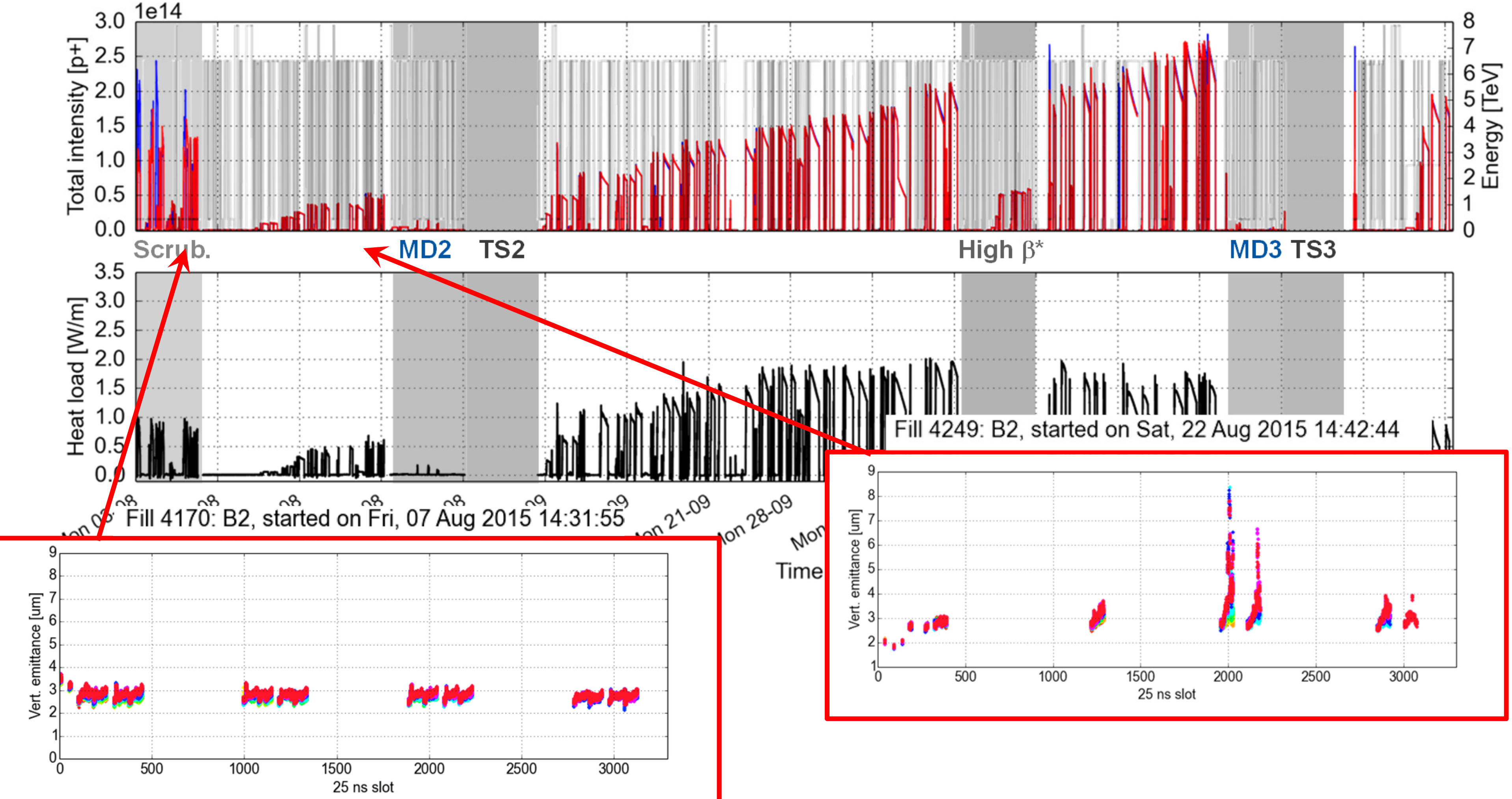

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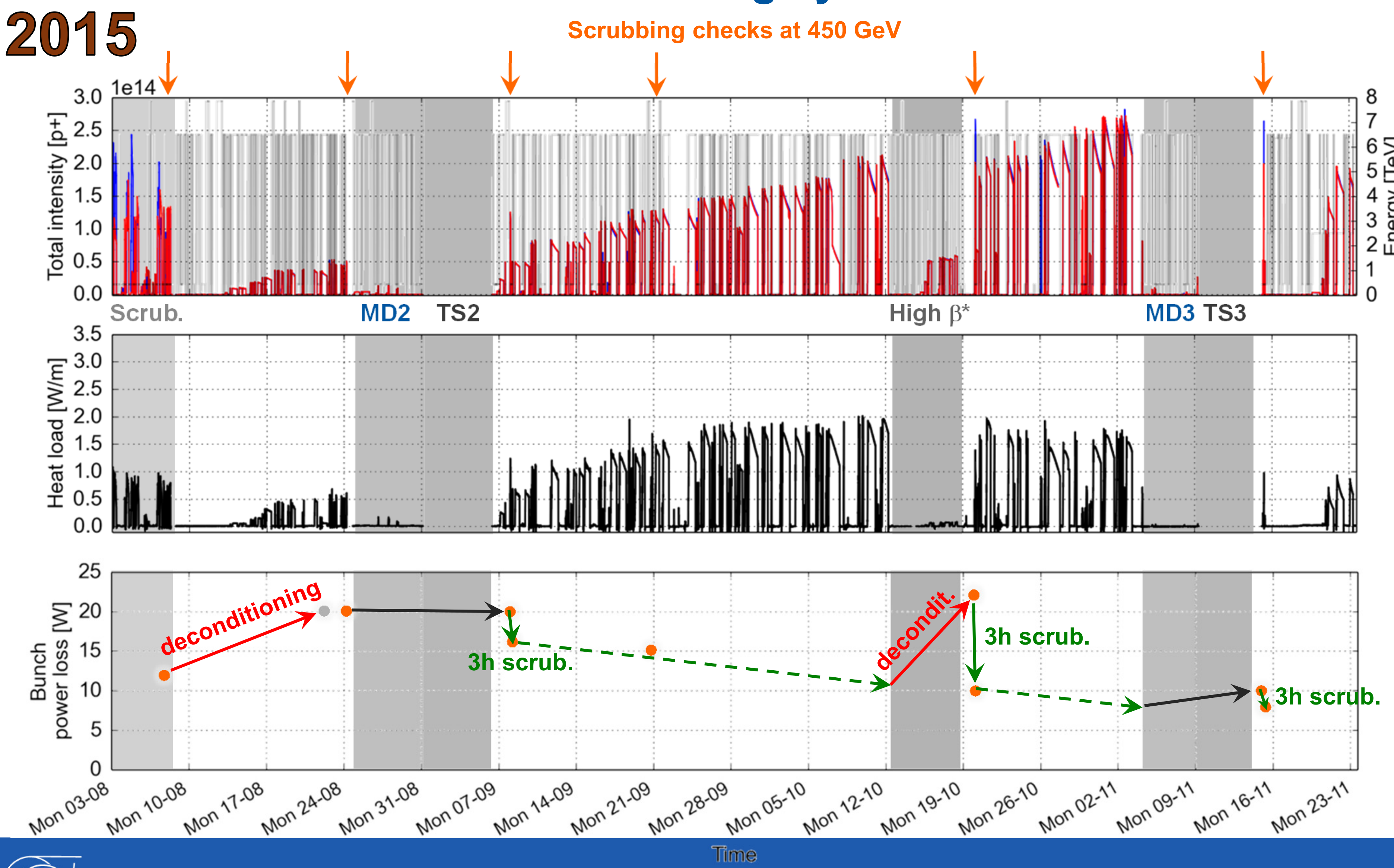
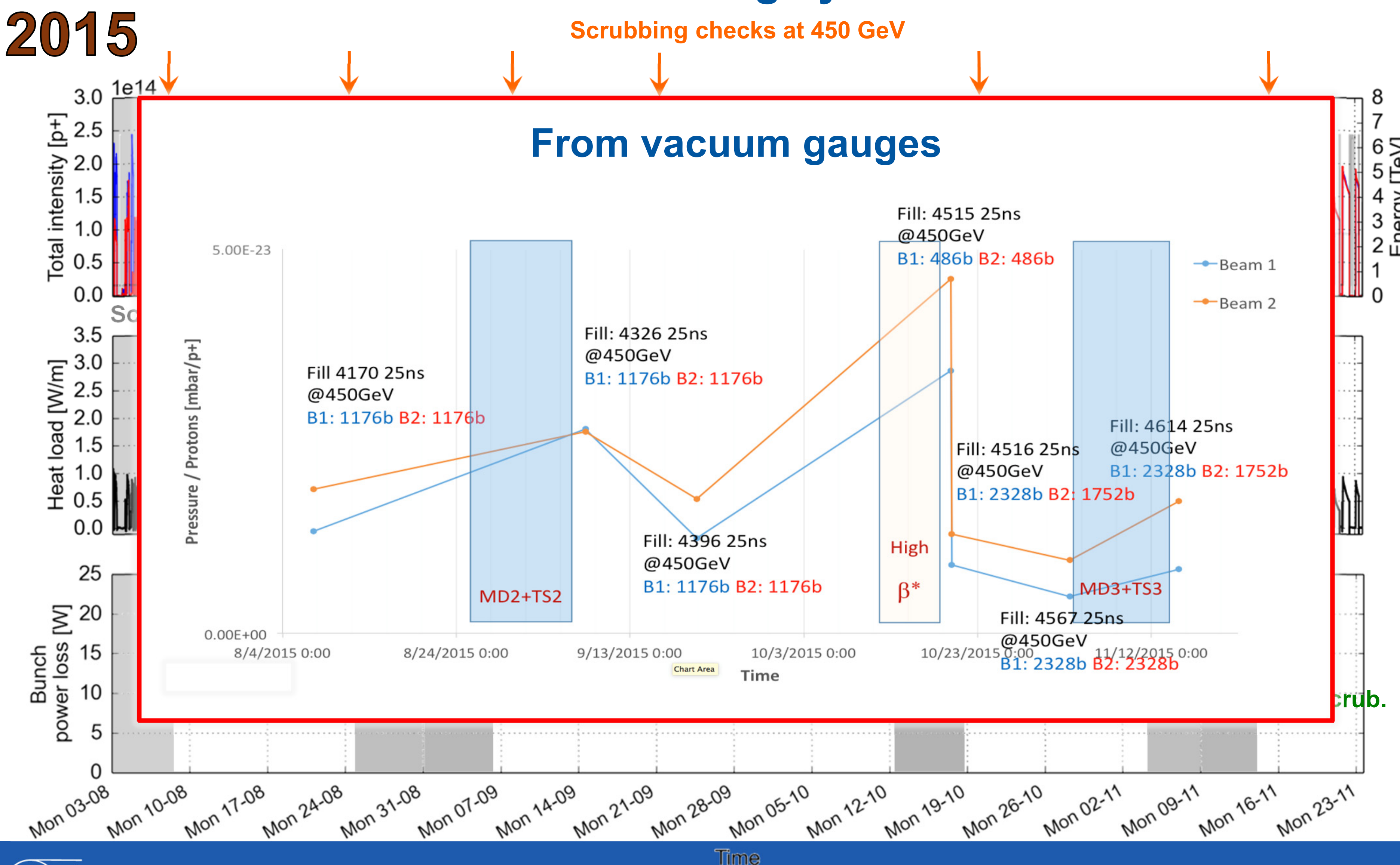


Electron cloud in the LHC during Run 2: deconditioning and reconditioning cycles



Electron cloud in the LHC during Run 2: deconditioning and reconditioning cycles

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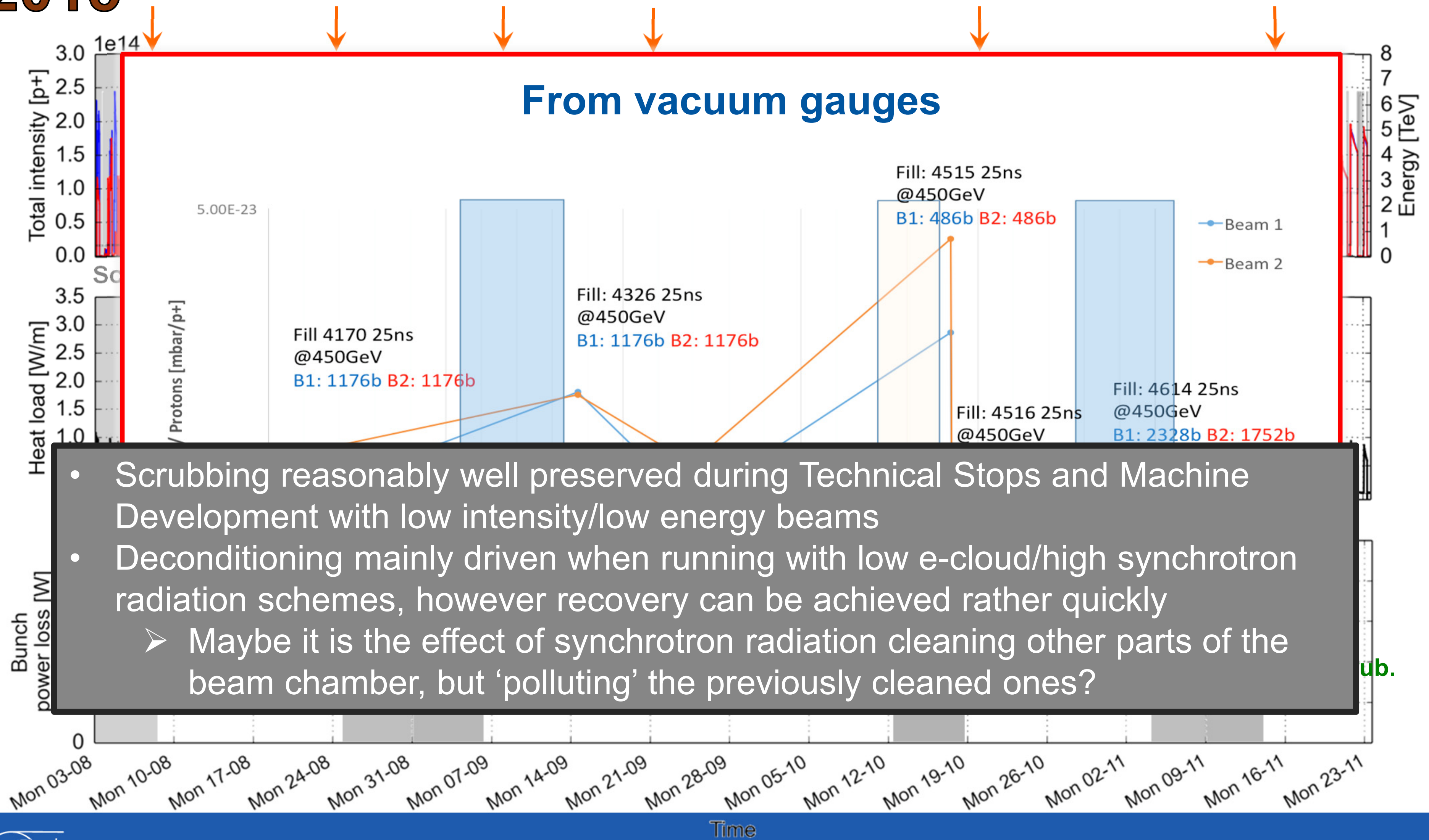
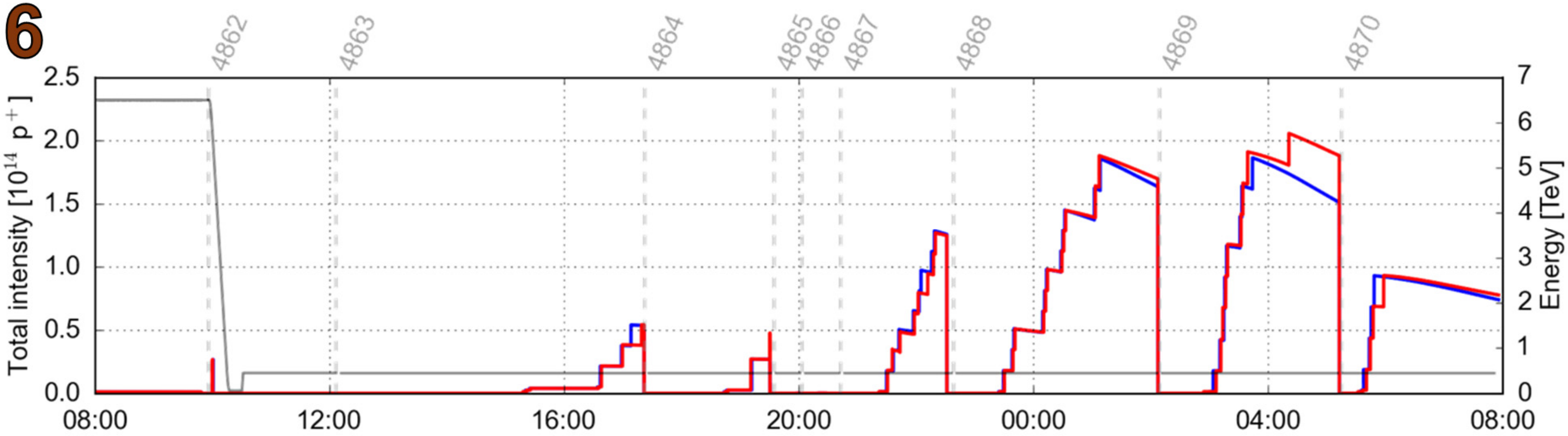


- Scrubbing reasonably well preserved during Technical Stops and Machine Development with low intensity/low energy beams
- Deconditioning mainly driven when running with low e-cloud/high synchrotron radiation schemes, however recovery can be achieved rather quickly
  - Maybe it is the effect of synchrotron radiation cleaning other parts of the beam chamber, but ‘polluting’ the previously cleaned ones?

Electron cloud in the LHC during Run 2: scrubbing run

2016

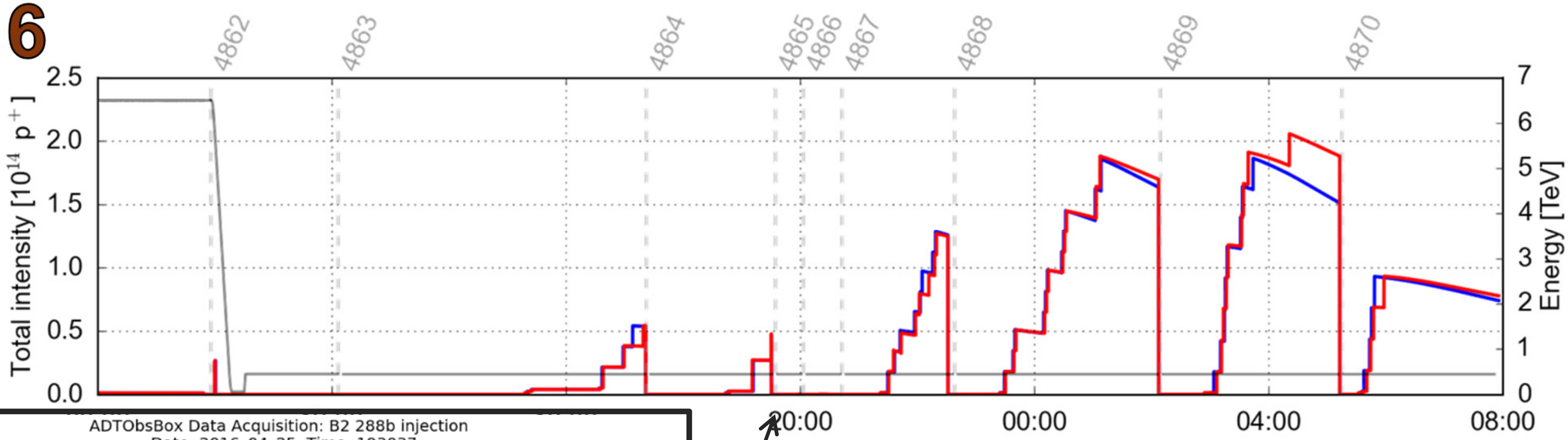


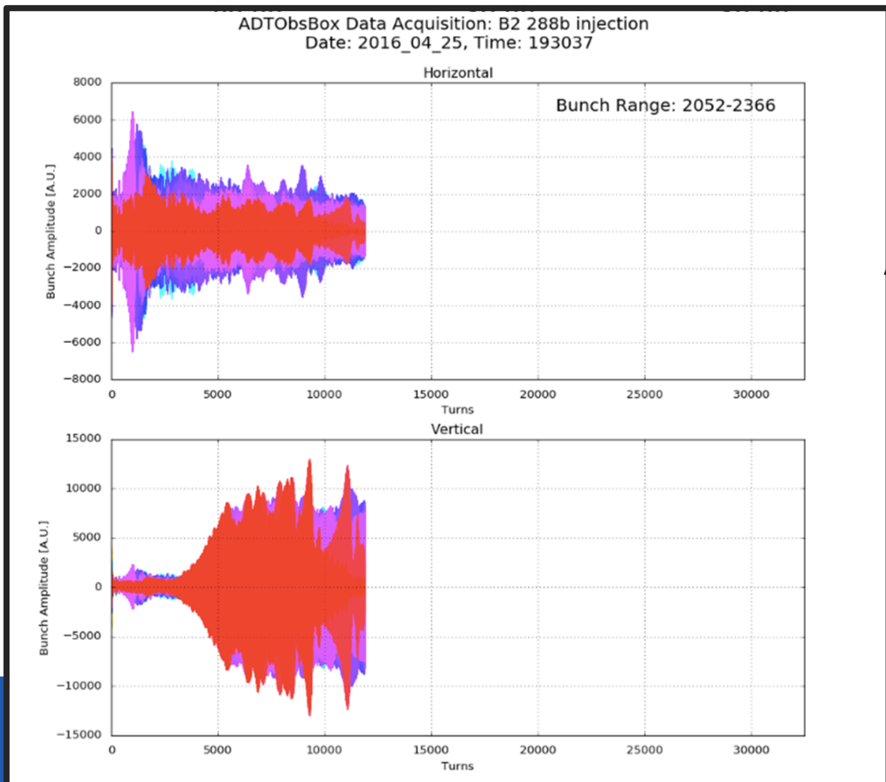
- Scrubbing run in 2016
  - Originally foreseen to last 4 days, reduced effectively to 18h due to different problems
  - E-cloud instability at injection observed with Q'<20 → Injections with Q'=20/20 needed to avoid fast blow-up
  - Up to injections of 144 and 216 bunches, only one attempt for injection of 288 bunches drove beams unstable

→ **Deconditioning could be seen from end 2015, fortunately quick recovery**

Electron cloud in the LHC during Run 2: scrubbing run

2016





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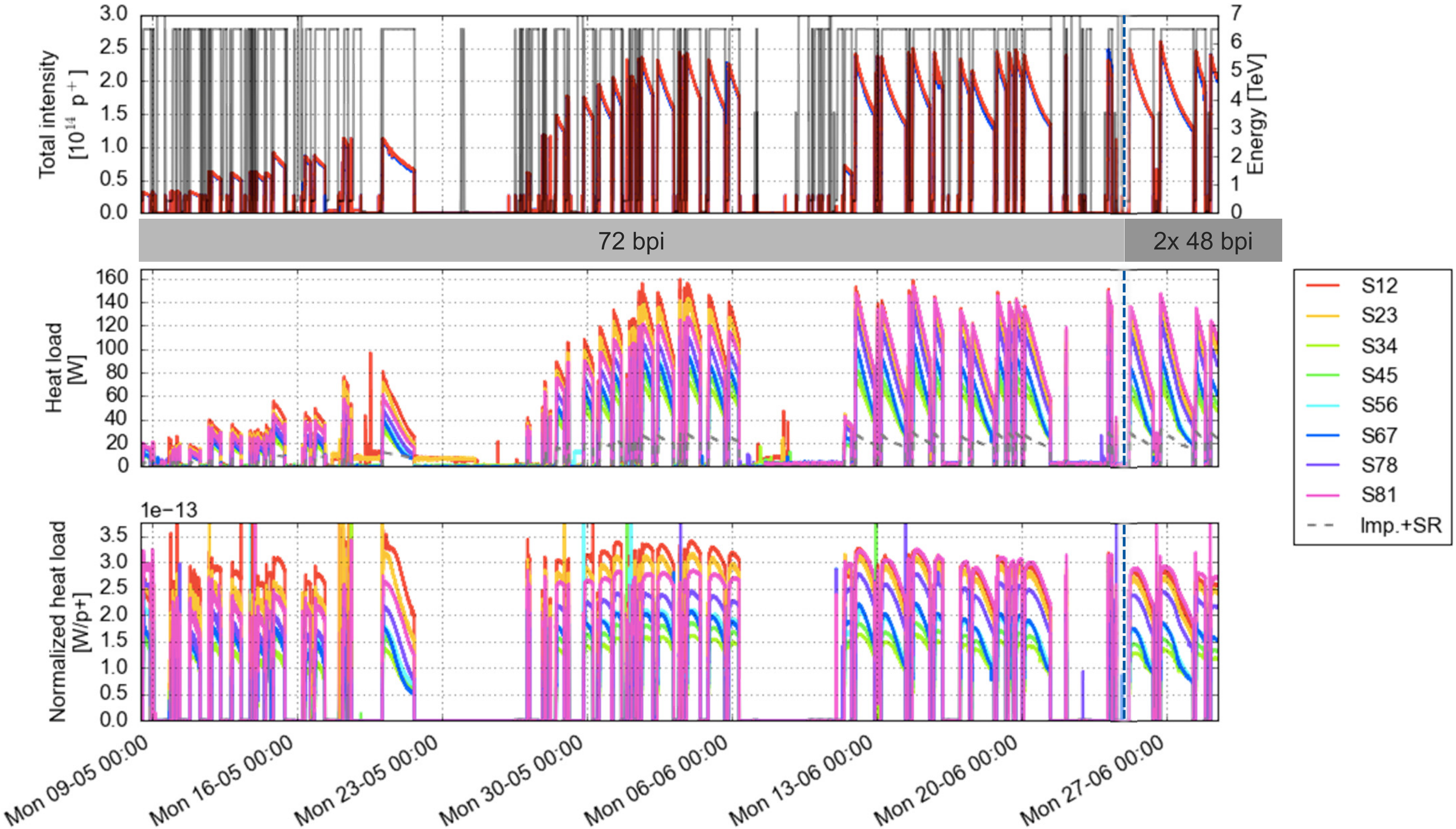
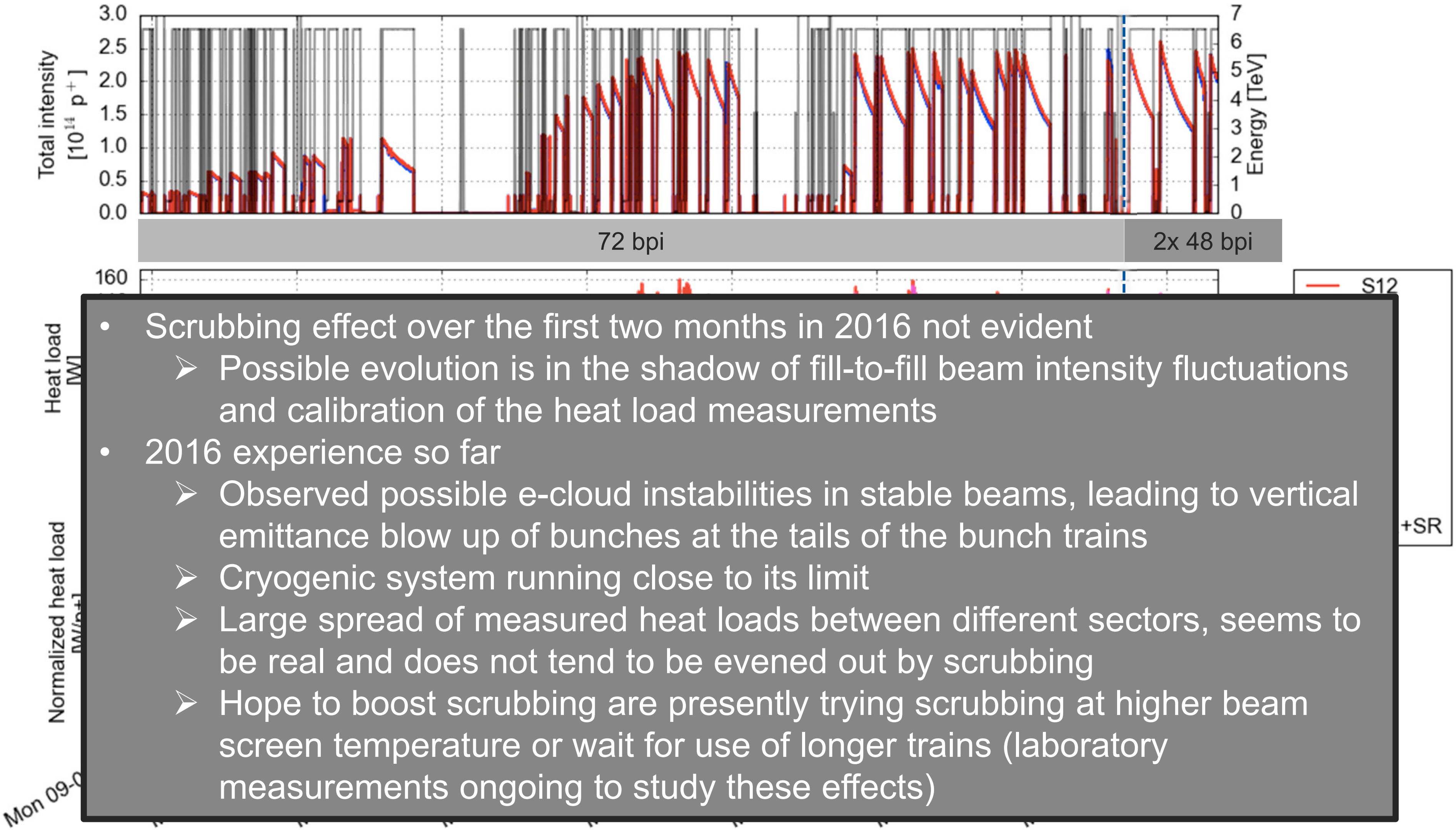
Scrubbing with physics?

2016



Scrubbing with physics?

2016



- Scrubbing effect over the first two months in 2016 not evident
  - ➢ Possible evolution is in the shadow of fill-to-fill beam intensity fluctuations and calibration of the heat load measurements
- 2016 experience so far
  - ➢ Observed possible e-cloud instabilities in stable beams, leading to vertical emittance blow up of bunches at the tails of the bunch trains
  - ➢ Cryogenic system running close to its limit
  - ➢ Large spread of measured heat loads between different sectors, seems to be real and does not tend to be evened out by scrubbing
  - ➢ Hope to boost scrubbing are presently trying scrubbing at higher beam screen temperature or wait for use of longer trains (laboratory measurements ongoing to study these effects)

Electron cloud in LHC: summary and outlook

- LHC has proven to run electron cloud free after relatively short scrubbing runs with bunch spacings of 50, 75 and 150 ns

- Operation with 25 ns beams, made possible only by extended scrubbing, is still hampered by electron cloud
  - Avoiding coherent instabilities requires high Q' from injection to collisions
  - High heat load in the arcs close to cryogenic limit for some of the sectors with 80% of the bunches
  - Point-like limitations come from outgassing of specific objects (kickers, collimators)
  - Losses in collisions exhibit e-cloud pattern once burn-off is removed

- Scrubbing seems to have significantly slowed down at the present stage, posing questions about future with higher intensity/brightness beams
  - Not easy to disentangle from fill-to-fill fluctuations (beam parameters, measurement calibrations)
  - Lab measurements suggest we may have hit the limit in SEY
  - Longer trains and higher screen temperatures will be used to attempt boosting the scrubbing process

Concluding remarks

⇒ Thanks to intensive measurements and highly empowered simulation tools, we have reached a deep knowledge of the electron cloud in the different CERN accelerators

- For the present beam parameters (25 ns beams)
  - PS and SPS can deliver the required beams well within original specs
  - LHC still suffers from electron cloud, but is now operating thanks to scrubbing with physics. The question is still open, up to which point?

- For future beam parameters (double intensity, double brightness)
  - PS is expected to deal with possible e-cloud instabilities at 26 GeV thanks to the transverse feedback system
  - SPS will rely on scrubbing and will prepare to full a-C coating of the most e-cloud prone chambers if that will not be enough during Run 3
  - HL-LHC will depend on the scrubbing evolution, experimental dependence of e-cloud on bunch intensity, a-C coating of the new triplet chambers – and may use e-cloud free filling patterns, if needed
  - Future projects should include anti-ecloud coatings in their baselines!

Thank you for your attention