LHC commissioning and first operation at 6.5 TeV

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Acknowledgments to all my CERN colleagues for pictures and inspiration

Outline

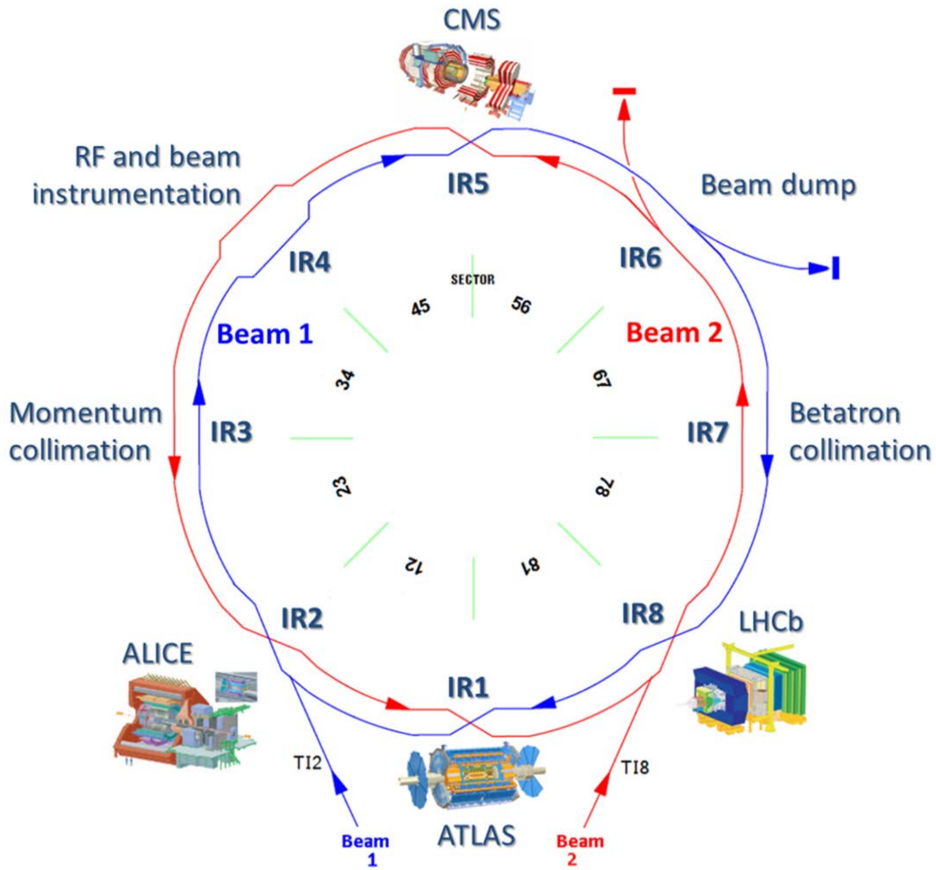
Long Shutdown 1 (LS1)

Re-commissioning of LHC

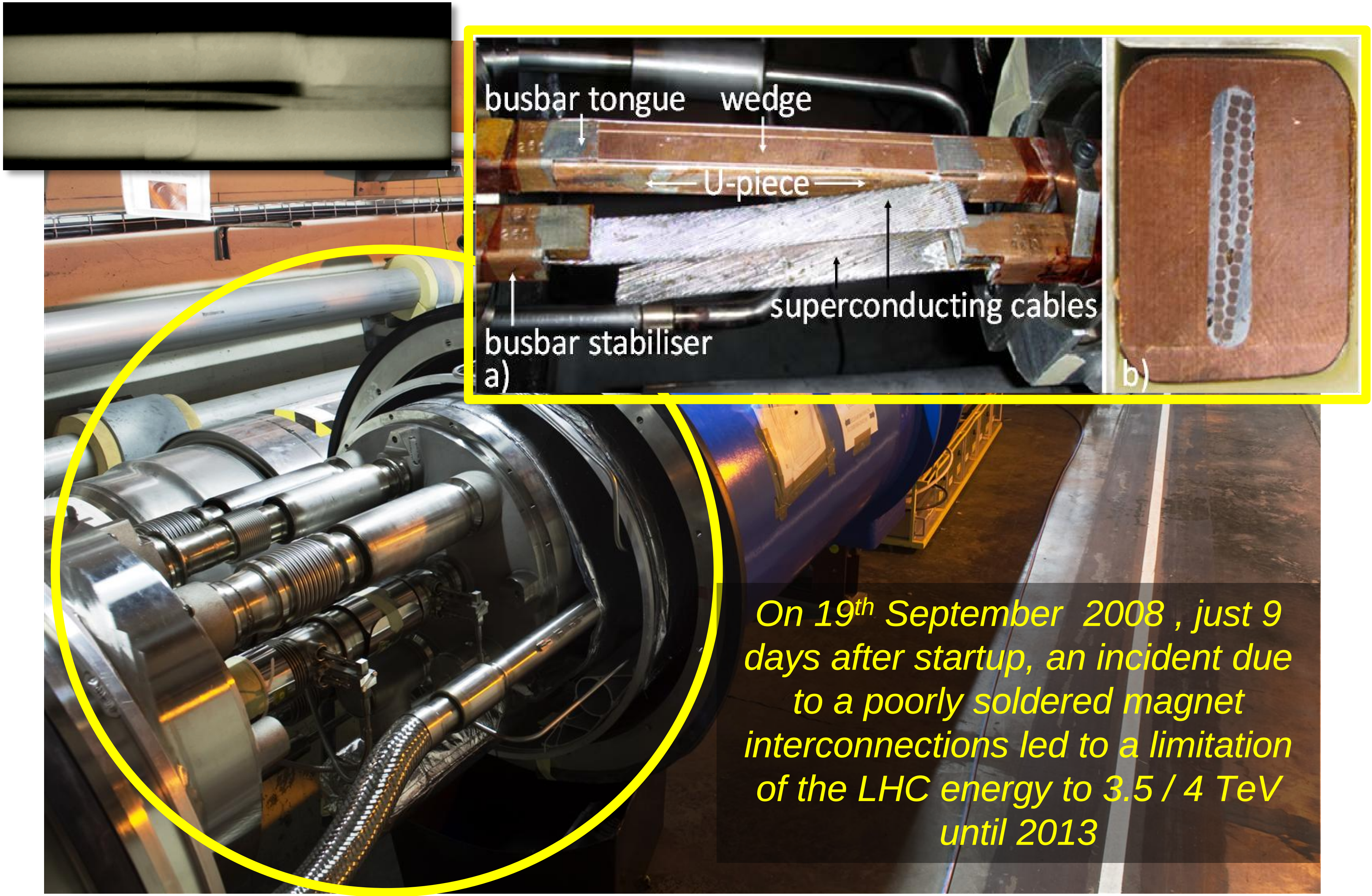
E-cloud ‘scrubbing’

First operational experience

Outlook



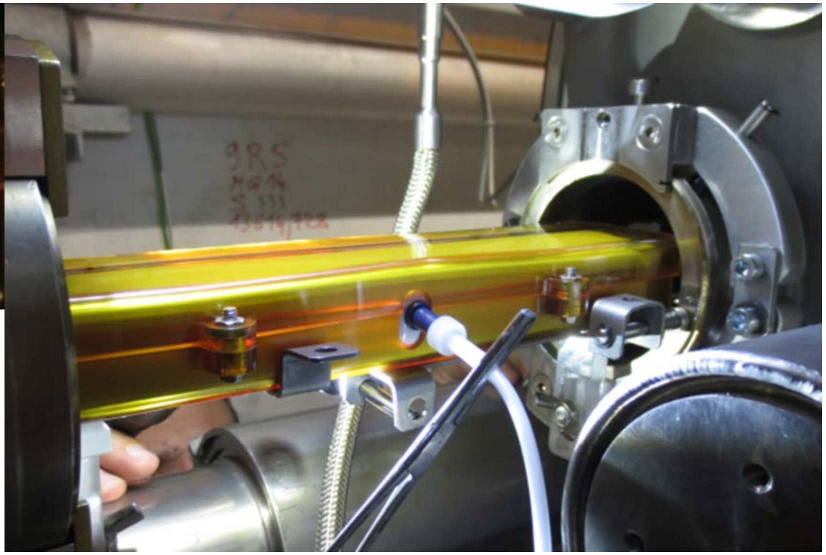
Long Shutdown 1 (LS1) driver



On 19th September 2008 , just 9 days after startup, an incident due to a poorly soldered magnet interconnections led to a limitation of the LHC energy to 3.5 / 4 TeV until 2013

Cable interconnection repair

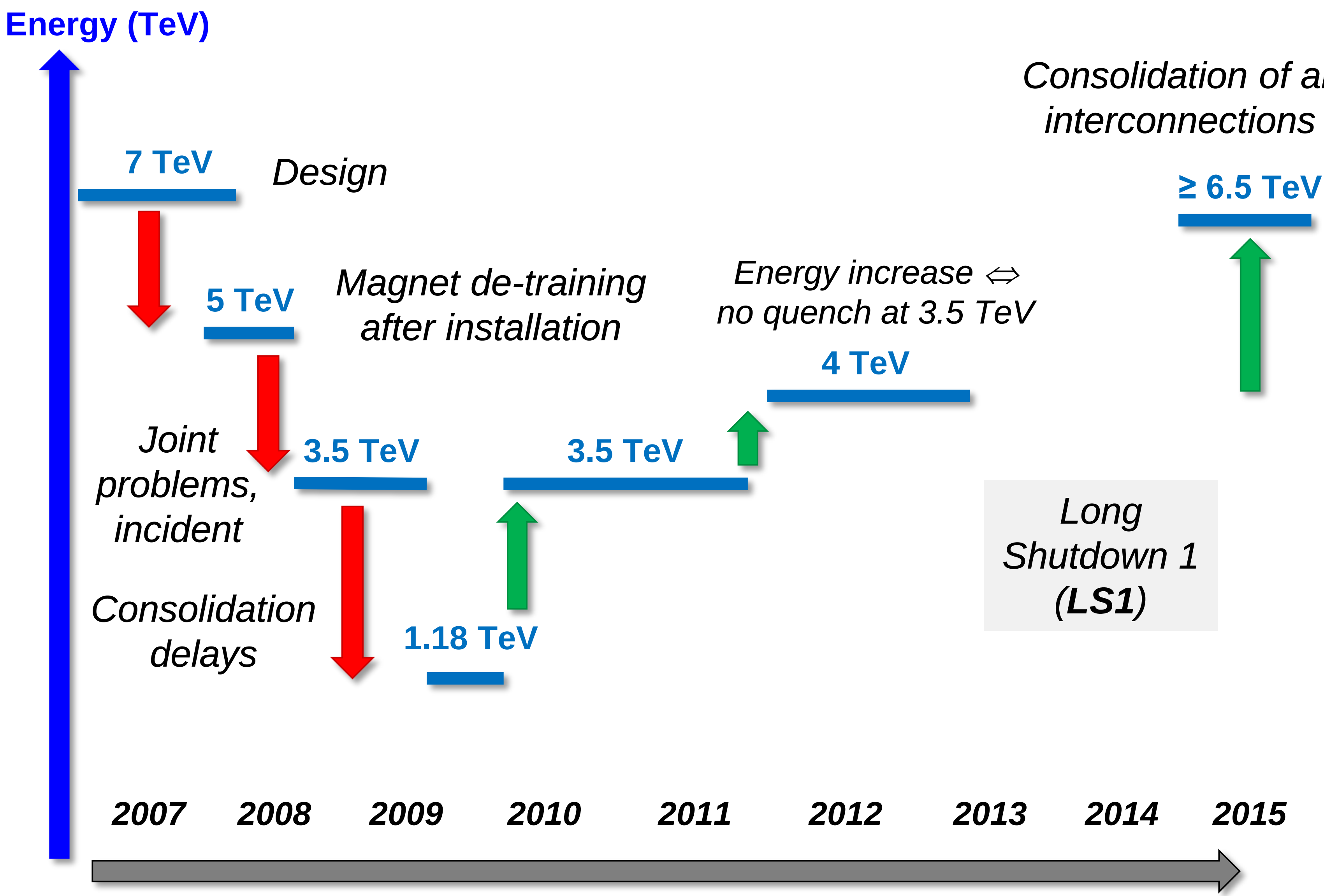
- Consolidation of the cable interconnections was the main driver of the LS1 Long Shutdown: restore conditions for operation at 13 kA nominal current.
- The electrical resistance of more than 10’000 high current interconnections was measured: 30% interconnections had to be de-soldered and redone.



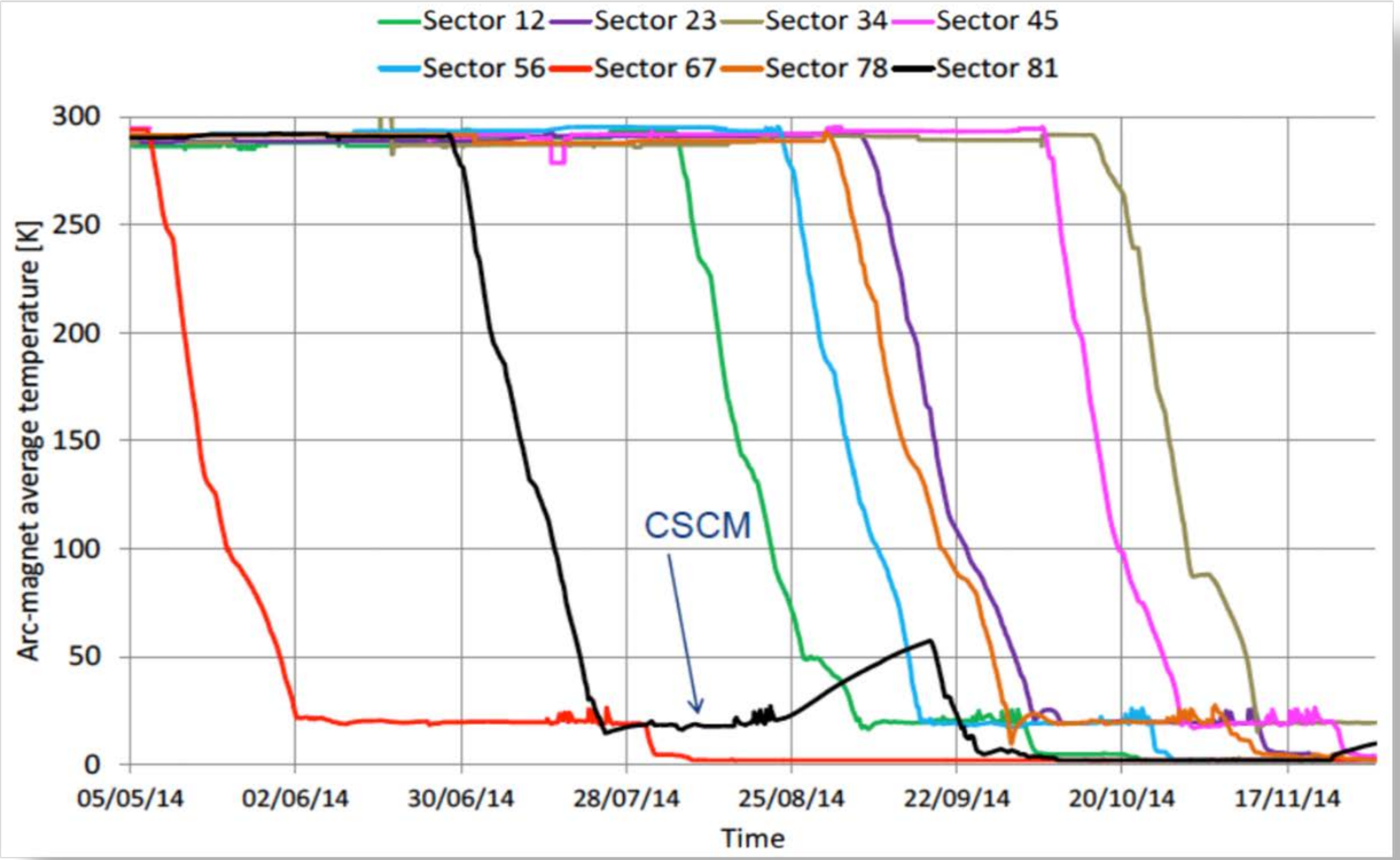
- Once electrical resistance and shape were in tolerance, the interconnections were surrounded by new mechanical stabilization and electrical insulation.

- In parallel to this activity all large industrial systems (cooling, cryogenics) performed major maintenance. Civil engineering work in many LHC points aimed to lower radiation effects to electronics.

LHC energy evolution



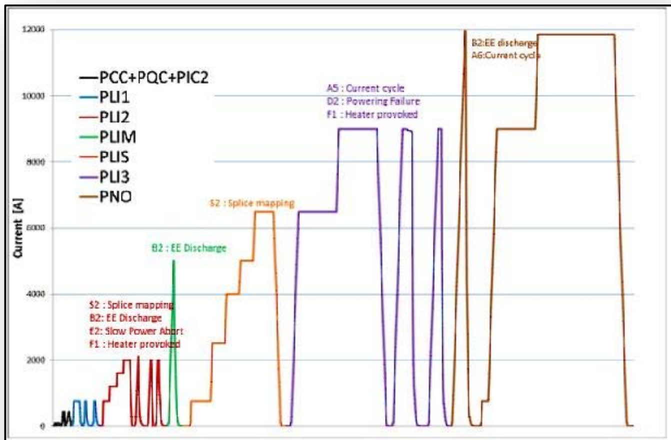
All LHC sectors cold in December 2014

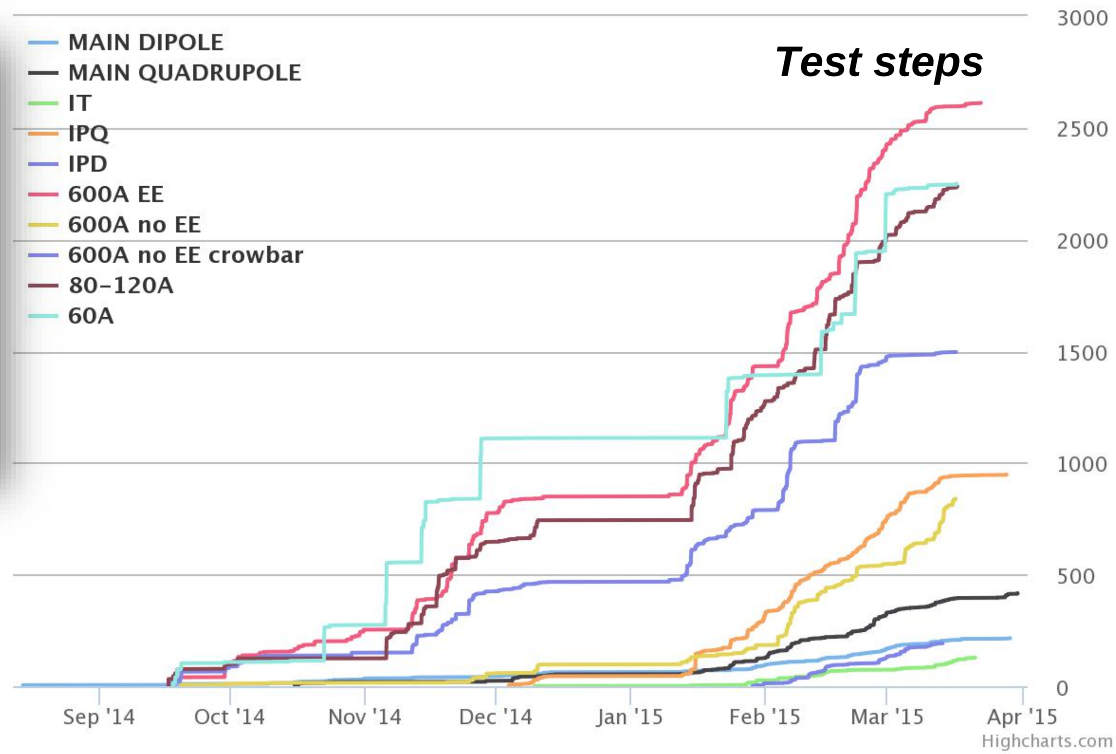


10,000 t of Nitrogen to pre-cool the machine, 130 t LHe inventory

Powering test campaign

From **September 2014** to **April 2015**: re-commissioning of the LHC magnet system with its 1600 electrical circuits

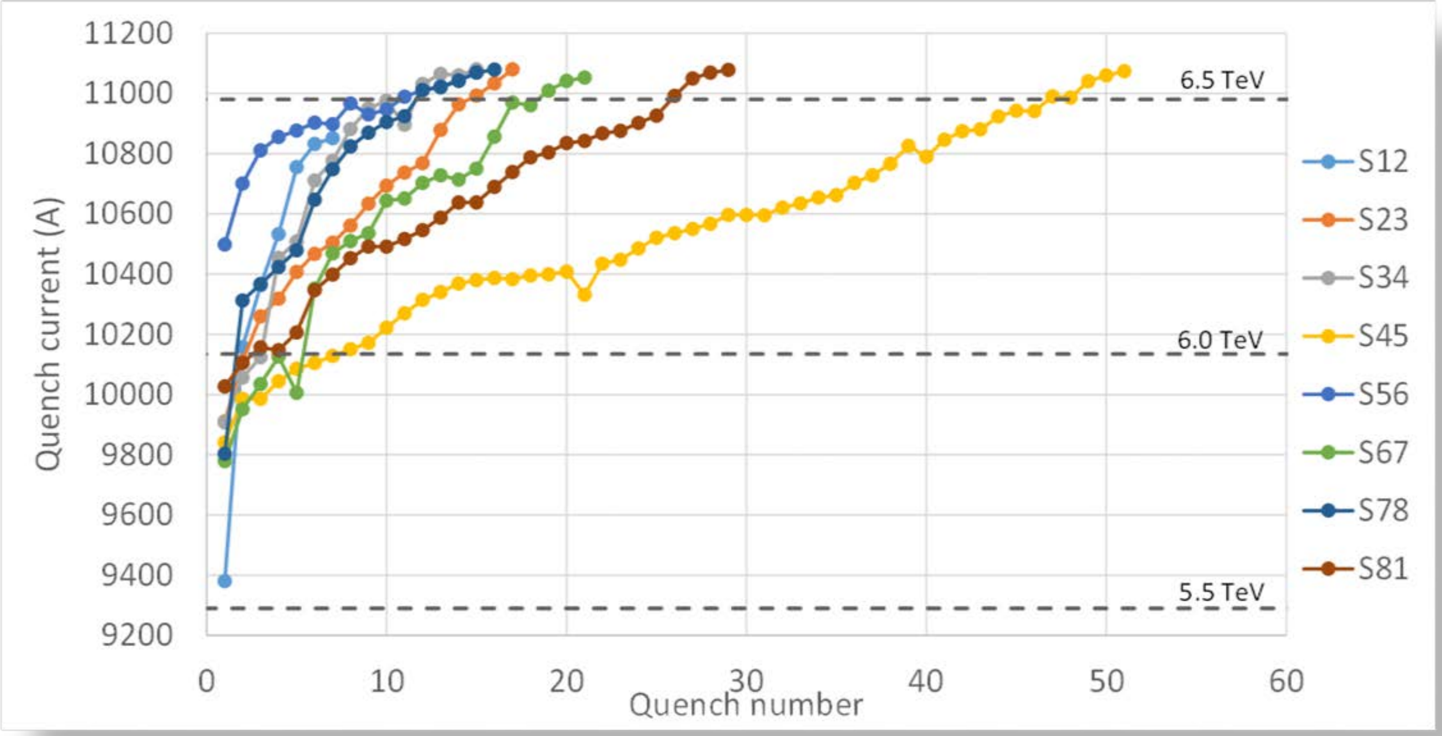




More than 6000 interlock tests & 11’000 commissioning steps

Dipole training campaign

- The 1232 main dipole magnets had to be trained for 6.5 TeV operation.
- 2-3 training quenches could be performed for each sector in 24 hours, limited by the recovery time of the cryogenic system.
- Just over 150 training quenches were required.
  - *The large spread in number of quenches between the eight sectors (arcs) is due to the mixture of magnets from the 3 producers.*
  - *Training quenches are due to frictional energy from coil movements.*



LHC Run 2 (2015 - 2018)

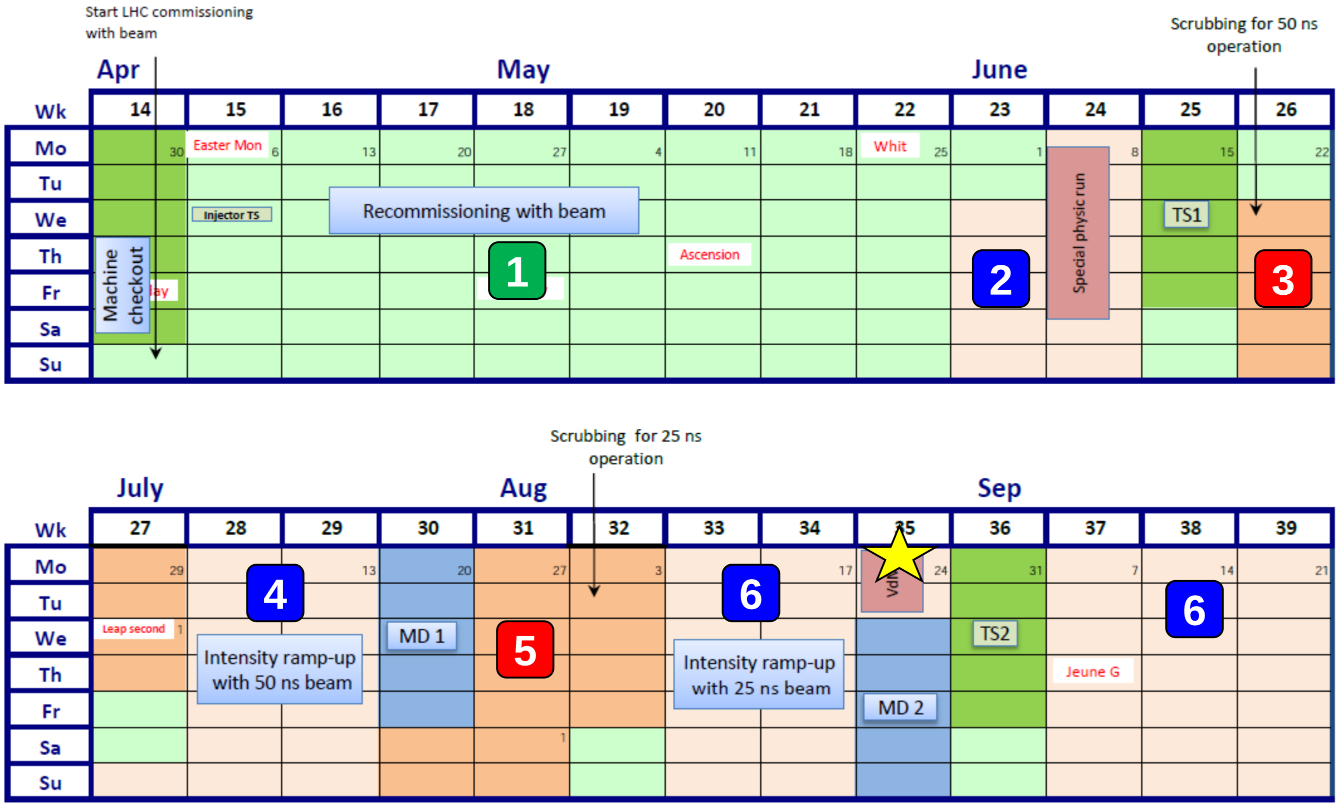
- ❑ Operate the LHC at 6.5 TeV (or higher).
- ❑ Operate with 25 ns bunch spacing.
  - o *50 ns spacing not favored due to event pile-up.*
- ❑ Maximize the integrated luminosity.
  - o *Small focusing – β* as small as possible.*
  - o *Highest possible efficiency.*

$$L = \frac{k\, f\, N_b^{\,2}}{4\pi\, \beta^* \varepsilon} F$$

Objectives for 2015:

- ❑ Learning year of Run 2 (6.5 TeV, 25 ns, availability etc),
- ❑ Top priority is to establish reliable operation with 25 ns spacing.
  - o *Focusing at the IP (β*) was relaxed to ease operation: β* = 80 cm was selected while 60-40 cm may be in reach (L ~ 1/β*).*

2015 commissioning strategy

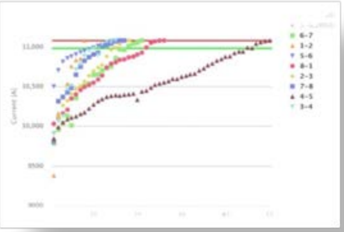


1. Low intensity commissioning – 8 weeks
2. First physics – low number of bunches, LHCf run
3. Electron cloud scrubbing for 50 ns (e-cloud)
4. Physics - intensity ramp-up with 50 ns

   Characterize high intensity operation (≈ repeat 4 TeV @ 6.5 TeV)

5. Electron cloud scrubbing for 25 ns (e-cloud)
6. Physics - ramp-up intensity for 25 ns operation

2015 beam commissioning

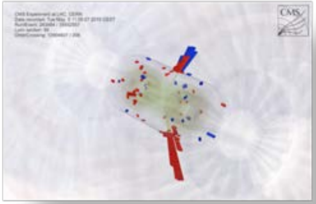


April 3,
End of
powering tests

April 10
First beam at 6.5 TeV

E: 6500 GeV

May 5,
Collisions at 450 GeV

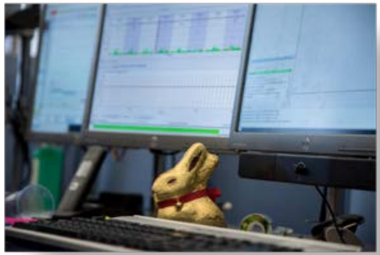


May 20,
First collisions (β^* 19 m)

June 3,
First stable beams,
start of physics for run 2

April | May | June

Easter,
Beam circulating



April 20,
Obstacle identified
in arc 81

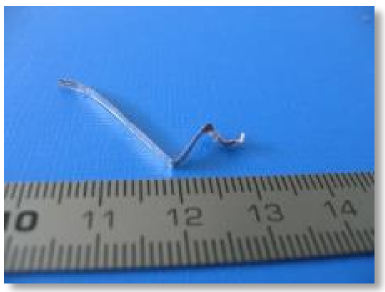
May 15,
Many bunches at
injection

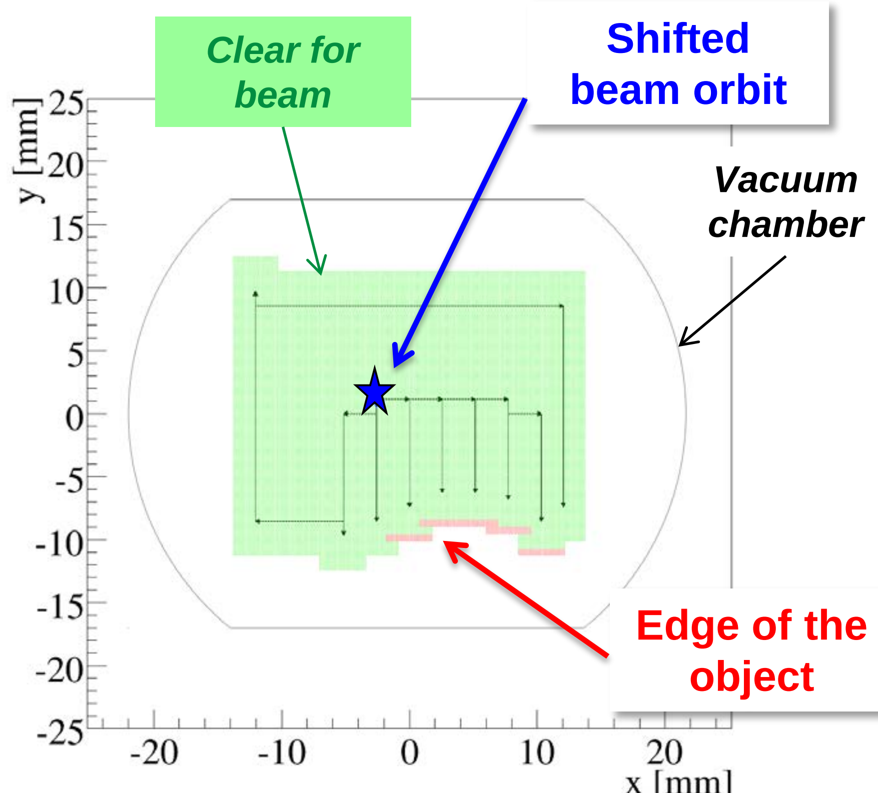
May 28,
First collisions at
low β^* (80 cm)

The only 'surprise' : aperture restriction

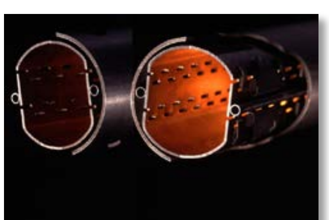
- A position with anomalous beam losses was located on beam 2 in the arc between LHCb and ATLAS only few days after commissioning.
- An aperture restriction due to an was found by scanning the beam position.

Objects found in the past in the LHC vacuum chambers



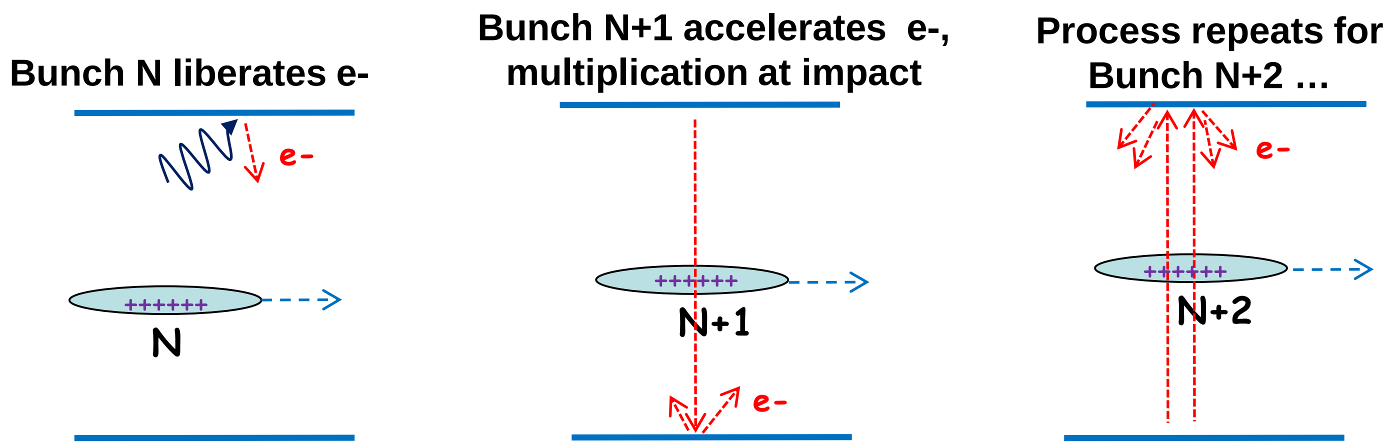


- The beam orbit was shifted upward and sideways to avoid the ULO.
- So far operation – even at high intensity – does not suffer from this object.
- **Opening the magnet to remove this object would take 2-3 months !**



Electron cloud challenge

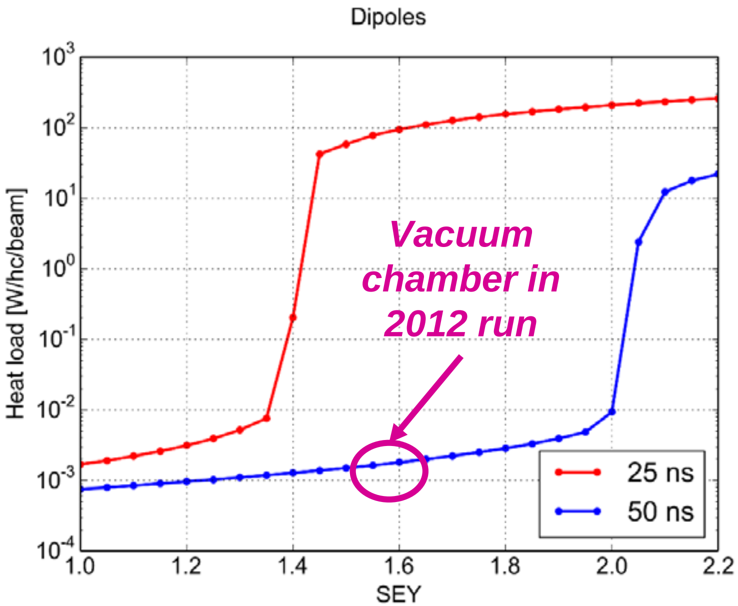
- In high intensity accelerators with positively charged beams and closely spaced bunches electrons liberated on vacuum chamber surface can multiply and build up a cloud of electrons.
- The key parameter for e-clouds is the **Secondary Emission Yield (SEY)** of electrons from the vacuum chamber surface.



- The cloud triggers *vacuum pressure increases* and *beam instabilities.* It may deposit excessive heat on the vacuum chamber walls → *cryogenic cooling capacity and stability.*
  - *Electron energies are in the 10 to few 100 eV range.*

Electron cloud mitigation

- There is a strong dependence of e-clouds on bunch spacing.



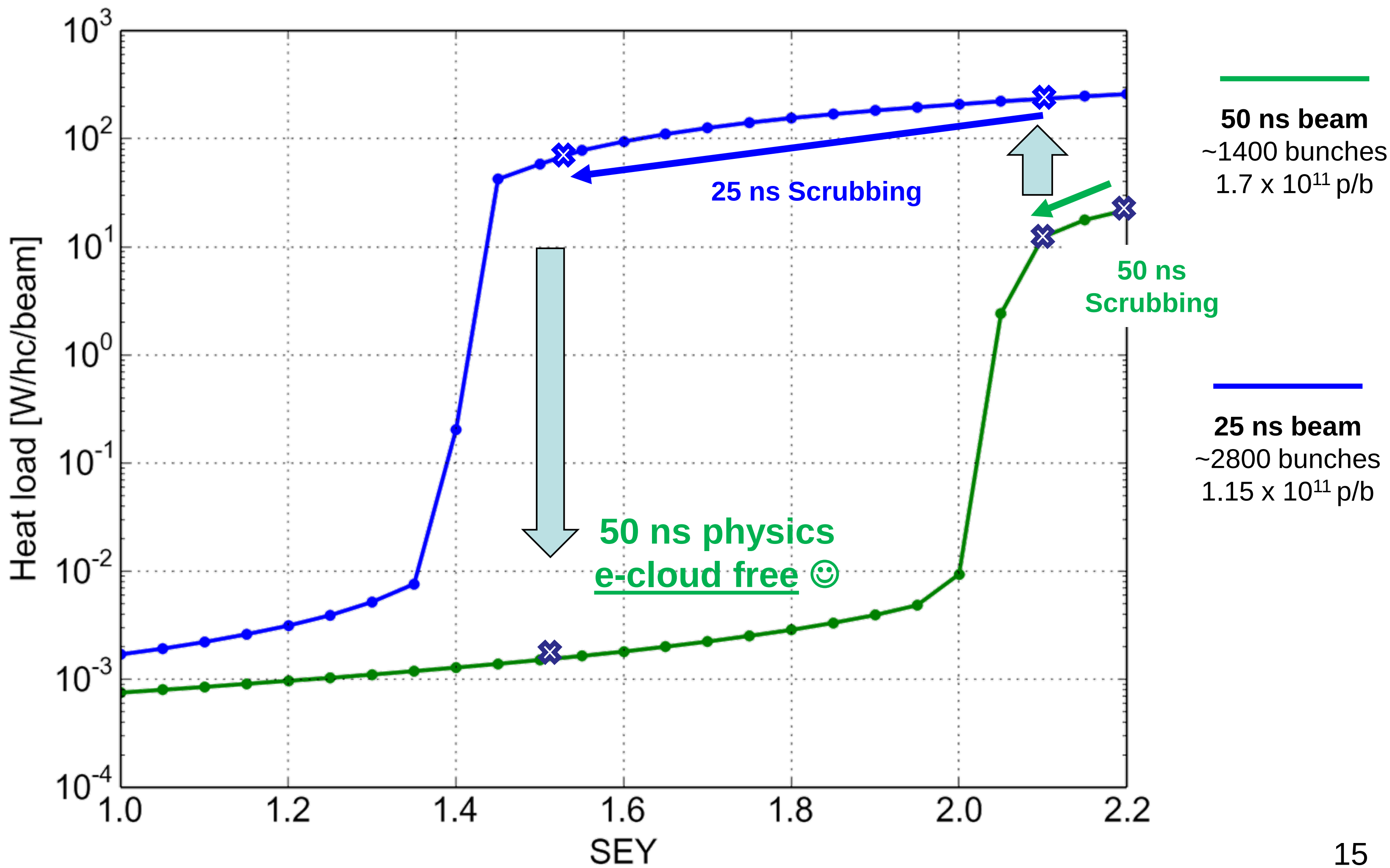
With 50 ns spacing e-clouds are much weaker than for 25 ns spacing !

→ To ease life during Run 1, the bunch spacing was reduced to 50 ns

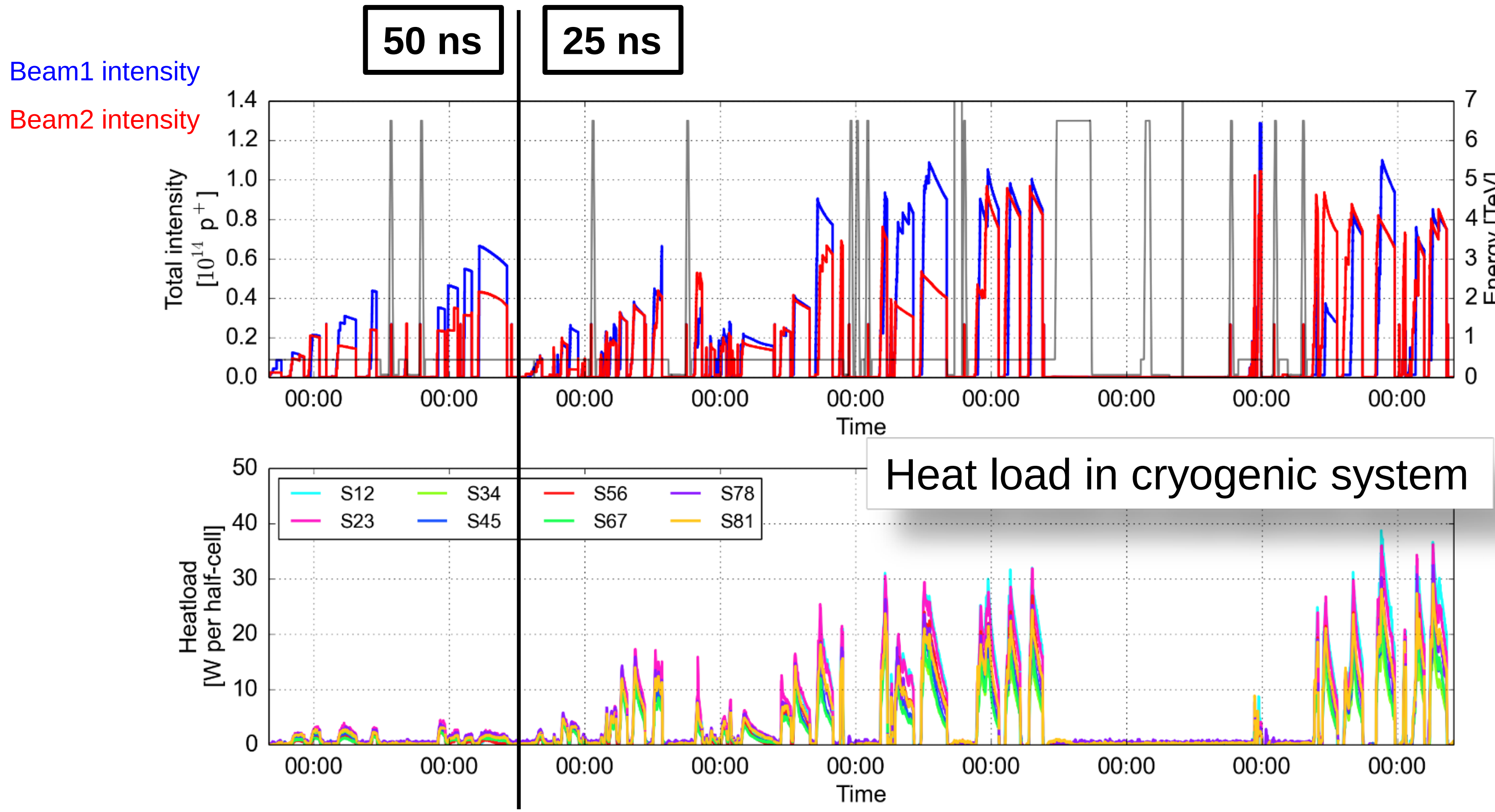
- Conditioning of the vacuum chamber by beam-induced electron bombardment ("**scrubbing**") leads to a **progressive reduction** of the **SEY**:
  - ***e-clouds are produced deliberately*** *with the beams to bombard the surface of the chamber to reduce the SEY until the cloud 'disappears' (self-destruction).*
  - *Conditioning is performed at 450 GeV where fresh beams can be injected easily.*
  - ***One must condition with a beam that is <u>more powerful</u>*** *(→ more electron could generation) that the beam one plans to use for operation.*

Scrubbing for 50 ns operation

During the first scrubbing run for 50 ns operation, a 25 ns beam is used to condition the vacuum chamber.



First 2015 scrubbing run

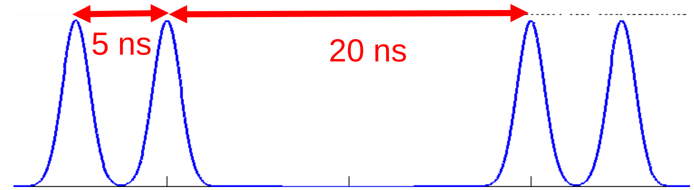


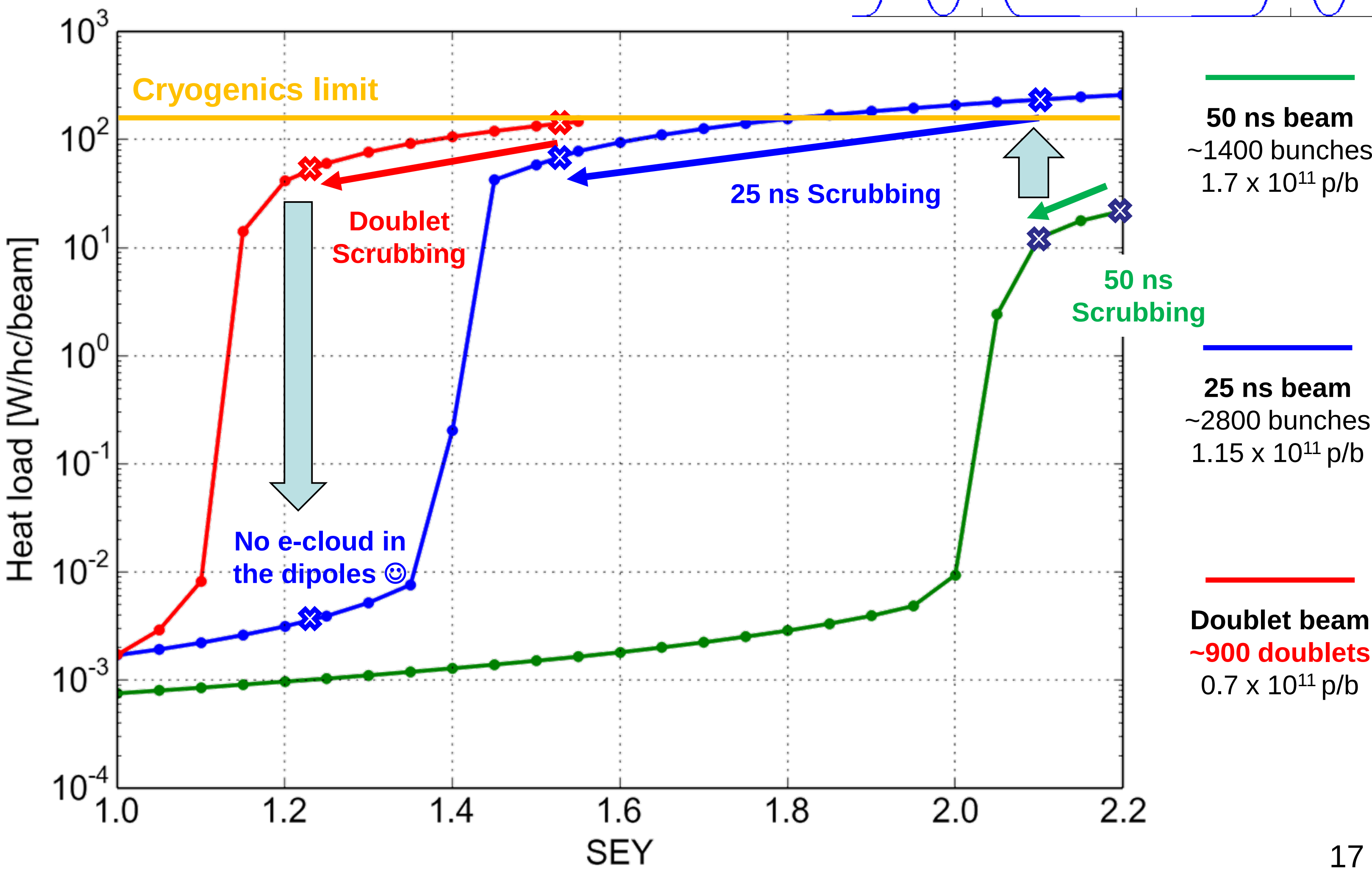
Note the large increase in heat load when switching from 50ns to 25ns beam scrubbing

At the end of the 8 day period: LHC is ready for high intensity 50ns operation

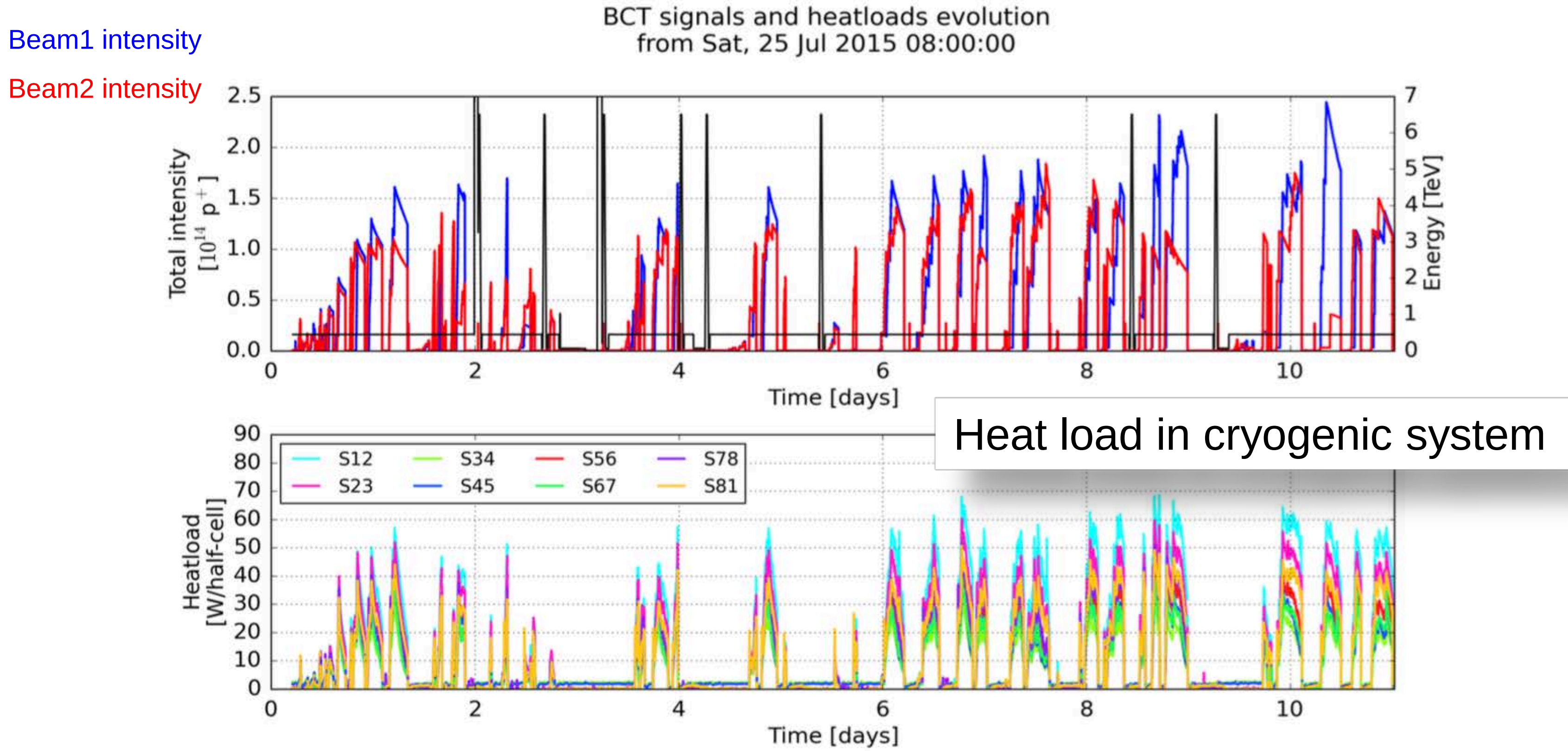
Scrubbing for 25 ns operation

To enhance scrubbing for 25 ns beam operation, a new ***doublet beam*** was prepared to enhance the e-cloud and speed up conditioning.





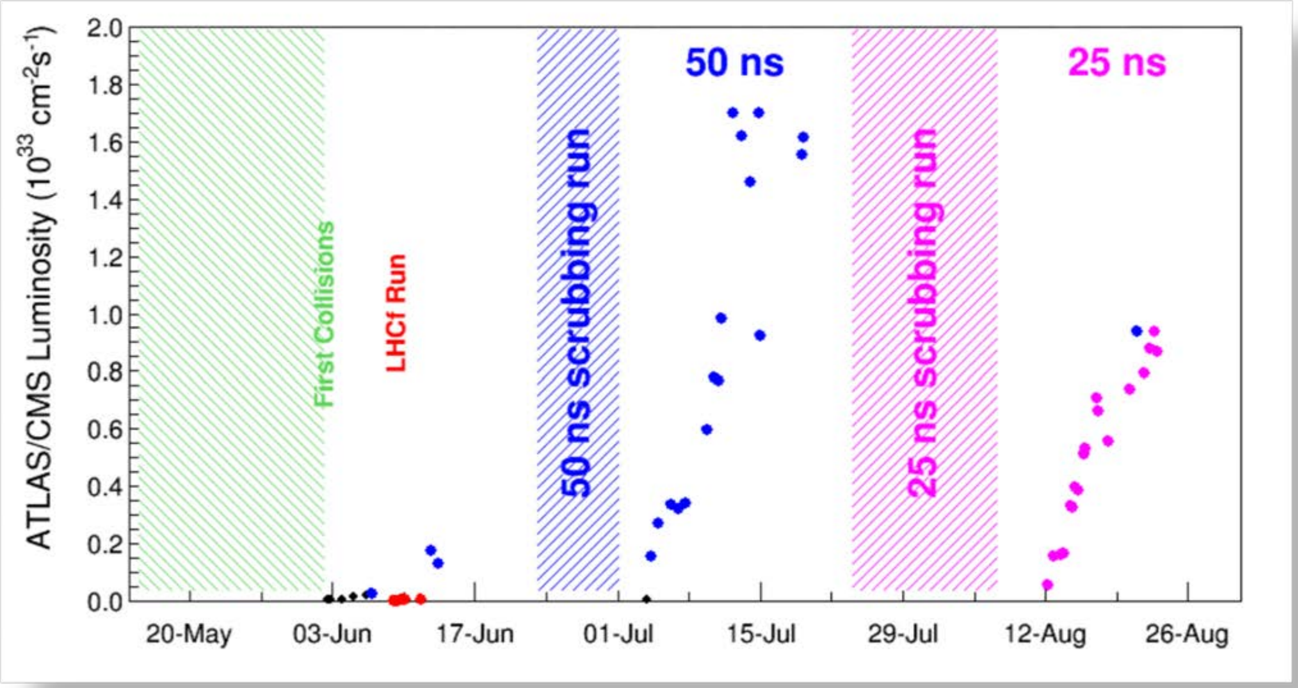
Second 2015 scrubbing run



- ❑ Scrubbing was performed with 25 ns beams, the doublet beam was injected but could not be used efficiently due to beam instabilities.
- ❑ At the end of the machine conditions were reasonable for ~**1200 b** operation (max. possible 2800). The number of bunches is currently limited by:
  - o *High vacuum pressures at injection on some absorbers,*
  - o *Cryogenic heat load at 6.5 TeV (→ need more scrubbing).*

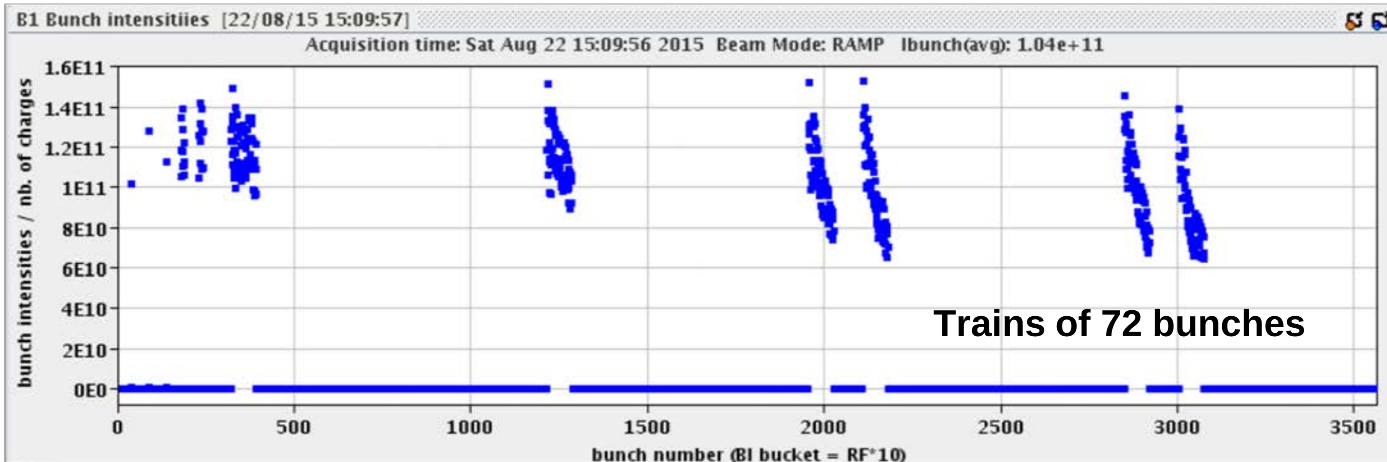
LHC operation evolution

- Operation started with a low luminosity run for the LHCf experiment.
- Due to delays the 50 ns operation period was shortened to 2 weeks.
  - *The intensity ramp up stopped at **480 bunches** (instead of 1300).*
- Operation with 25 ns beam spacing started 10 days ago, reached **460 bunches** per beam (nominal 2800 bunches).
  - *Operation of 25ns beams is delicate: beam stability and lifetime.*
- Only modest ~0.2 fm of integrated luminosity have been delivered.

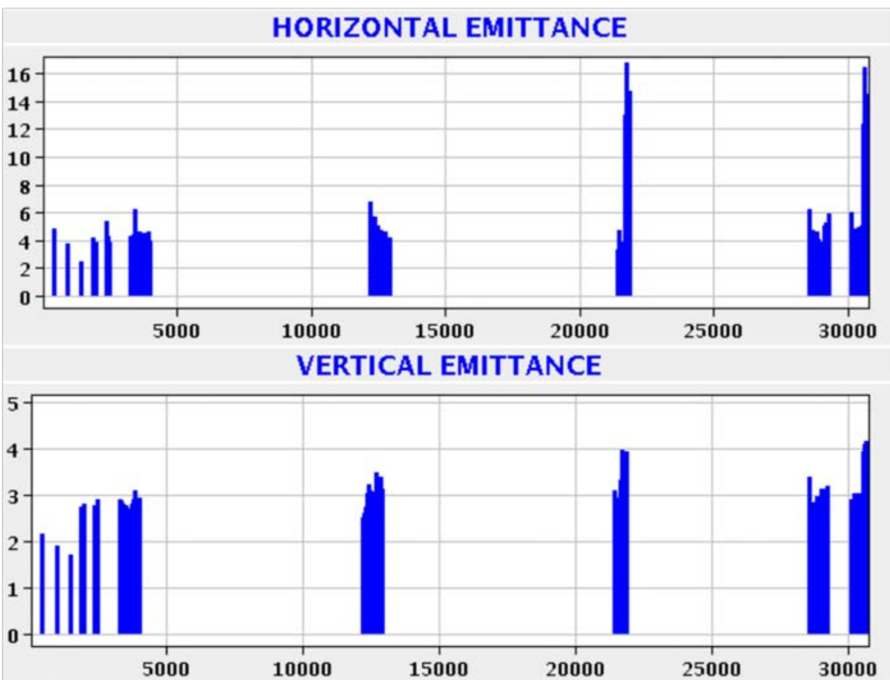


25 ns beam quality

Bunch intensity



Bunch emittance (μm)



The 25 ns beams are operated with trains of 48 or 72 bunches (nominal 288), the signature of electron clouds are visible:

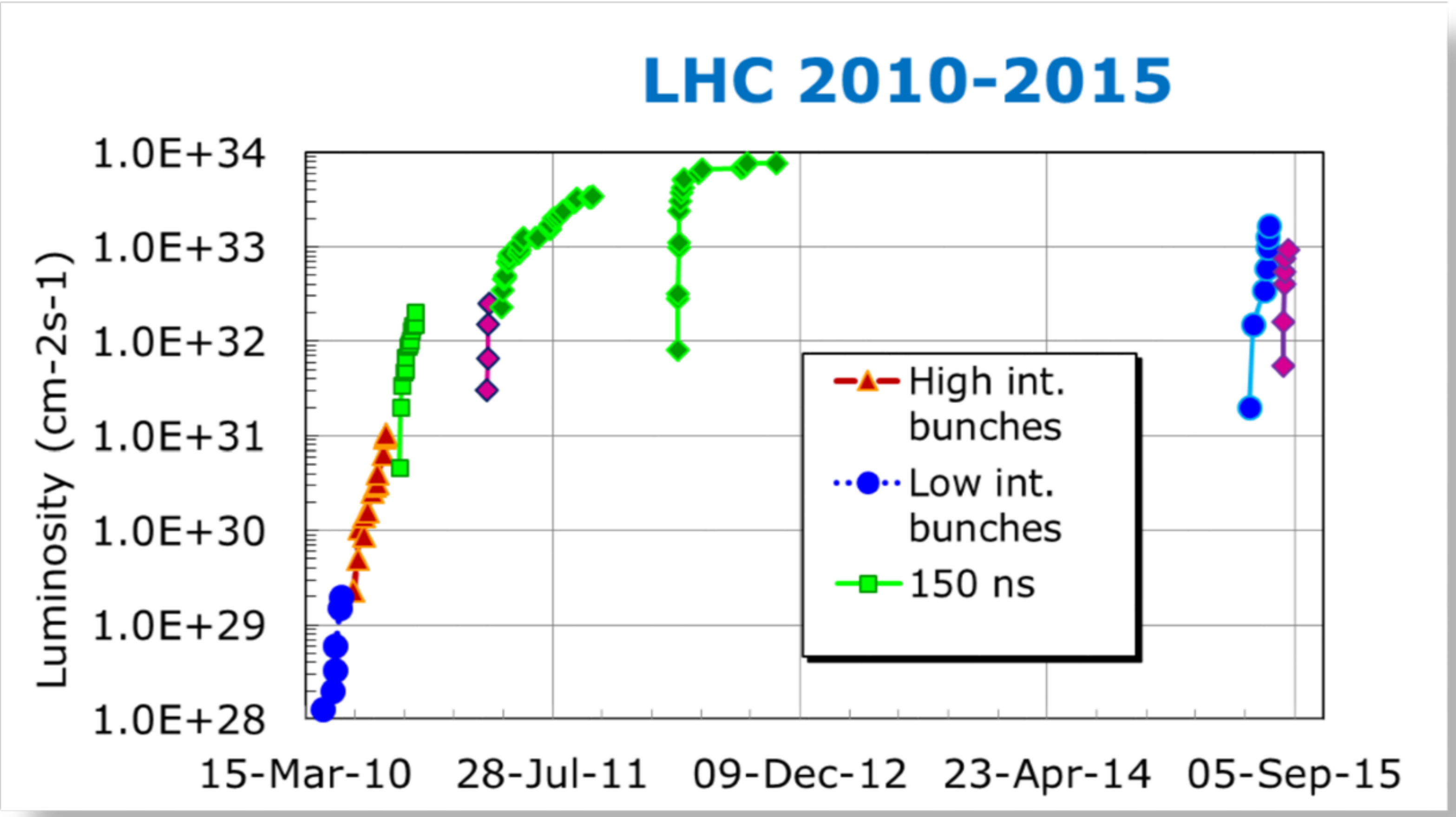
- *Intensity along the trains.*
- *Blown up bunches.*

Scrubbing has not completely removed e-clouds. The conditioning has to continue in parallel to physics operation.

Run 1 versus Run 2

The start-up of Run 2 was faster then for Run 1, but we are still far from the Run 1 performance. We are still in the learning phase for 25 ns.

Operation with 50ns beams is easier !

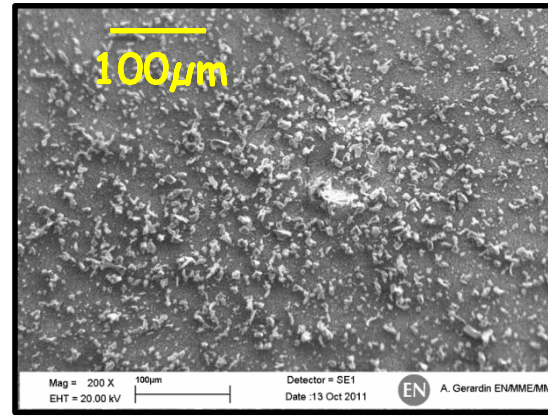


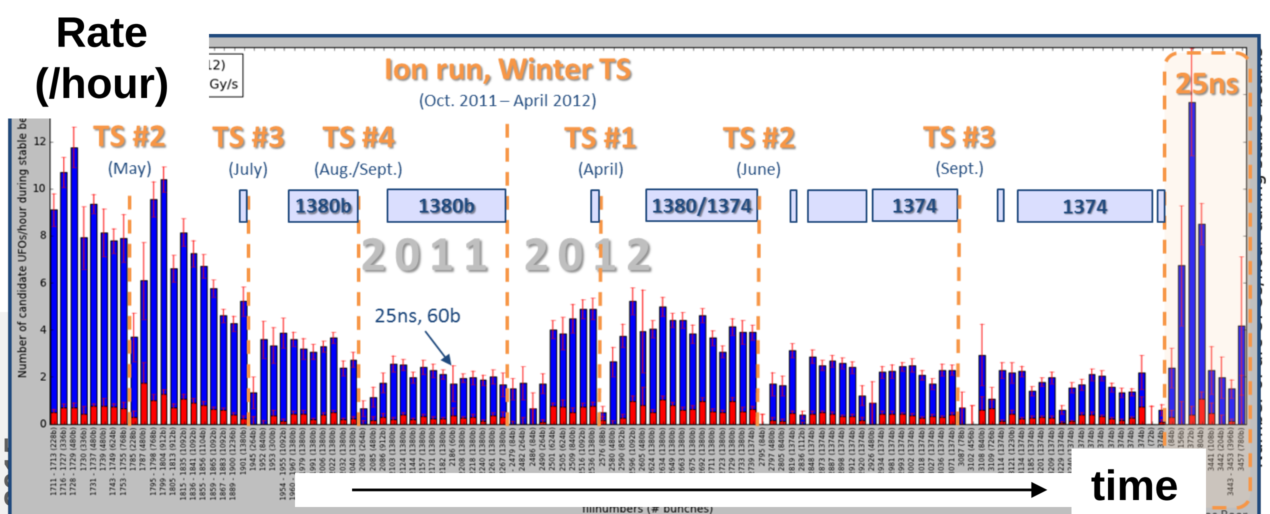
Issues and limitations

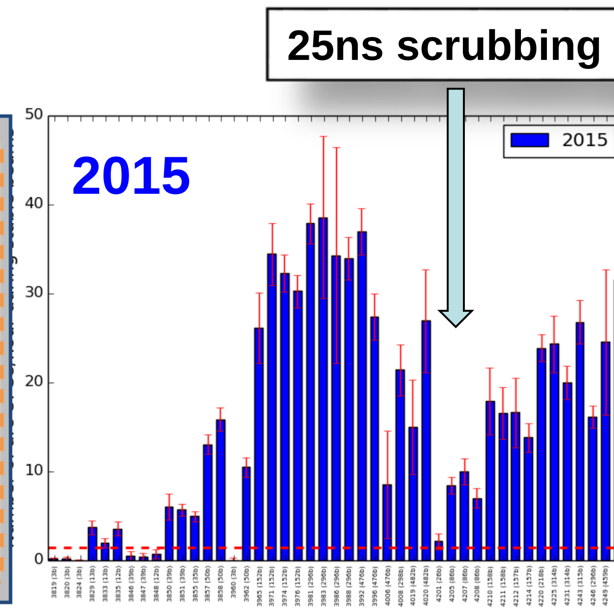
- **Radiation induced failures** on the Quench Protection System (component change) have limited the luminosity – 1400 boards will be exchanged during the upcoming technical stop.
- A protection device against injection failures (**TDI**) that must withstand the impact of a nominal beam injection is limited to due a weakness of the material (**Boron Nitrite**) – exchange planned during winter stop.
  - *One of the blocks also has a vacuum problem that slows down scrubbing with 25 ns beams.*
- **Transient earth faults** have been observed 3 times at high current on a dipole circuit – under observation.
- The overall equipment availability is not yet good enough !

Unidentified Falling Objects - UFOs

- **Dust particles falling into the beam** – '**UFOs**' – have interfered with operation in Run 1.
  - *If the induced losses are too high, the beams are dumped to avoid a magnet quench (20 times / year).*
- UFOs have already appeared at 6.5 TeV – 6 beams were dumped by UFOs and 2 magnets quenched.
- Fortunately the rate of such events goes down over time (conditioning), but we also observe a trend to increase with more 2 ns bunches.







Luminosity projections

Some scenarios @ 6.5 TeV

$$L = \frac{k\, f\, N_b^{\,2}}{4\pi\, \beta^{*} \varepsilon} F$$

Beam	k	N_b [10^{11} p]	ε [μm]	β* [m]	Peak L [10^{34} $cm^{-2}s^{-1}$]	Event pile-up	Int. L(*) [fb^{-1}]
25 ns – 2015	~1500	1.1	3.5	**0.8**	**0.31**	14	~2
25 ns – standard	~2700	1.2	3.0	**0.8**	**0.78**	21	~20
25 ns – pushed	~2500	1.2	2.0	**0.4**	**1.7**	51	~40-50
50 ns	1360	1.6	2.2	**0.4**	**1.65**	90	~30

Provided we manage to increase the efficiency and to collide more than 1000 bunches at 6.5 TeV, it is still possible to accumulate 2 fm^{-1} in 2015.

(*): per year

Outlook

- Beam commissioning with low intensity at 6.5 TeV was smooth, within 2 months the LHC was ready for operation.
- The preparation of 25 ns operation, in particular the scrubbing, is not finished and only ~1200 bunches can be stored with good quality at injection.
  - *Some limitations will be removed next winter.*
- We are now ramping up the intensity of the 25 ns beams at 6.5 TeV, but have to tackle beam stability and equipment reliability issues.

Thank you for your attention!