LHC operation in 2015
and prospects for the future

Moriond Workshop – La Thuile

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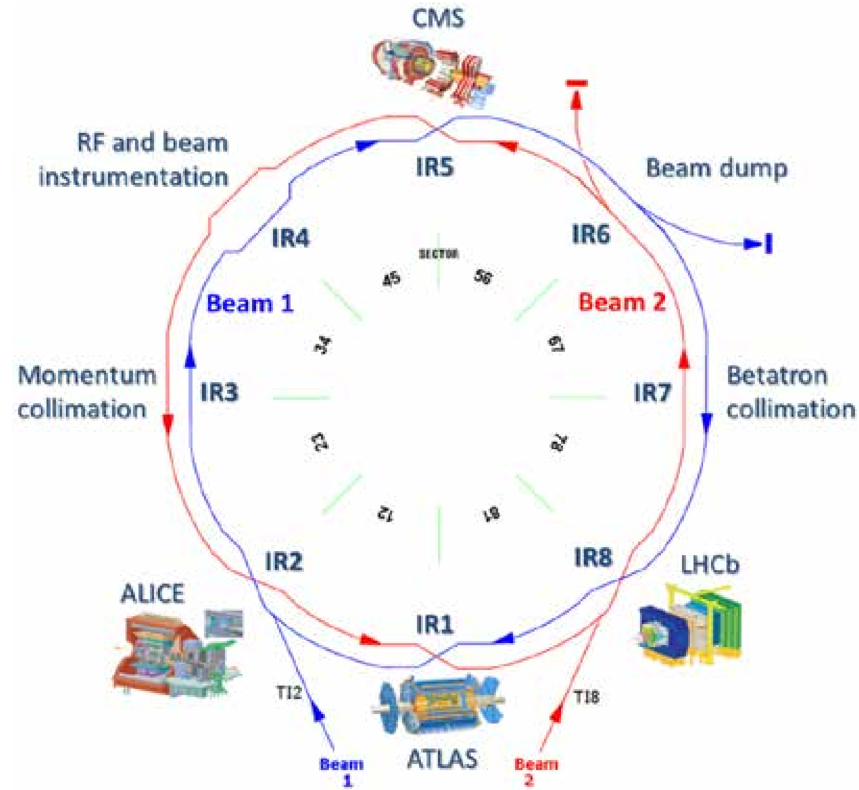
For the LHC commissioning and operation teams

Outline

Introduction

LHC operation in 2015

Outlook for 2016 and beyond



The Large Hadron Collider LHC

Installed in 26.7 km LEP tunnel

Depth of 70-140 m

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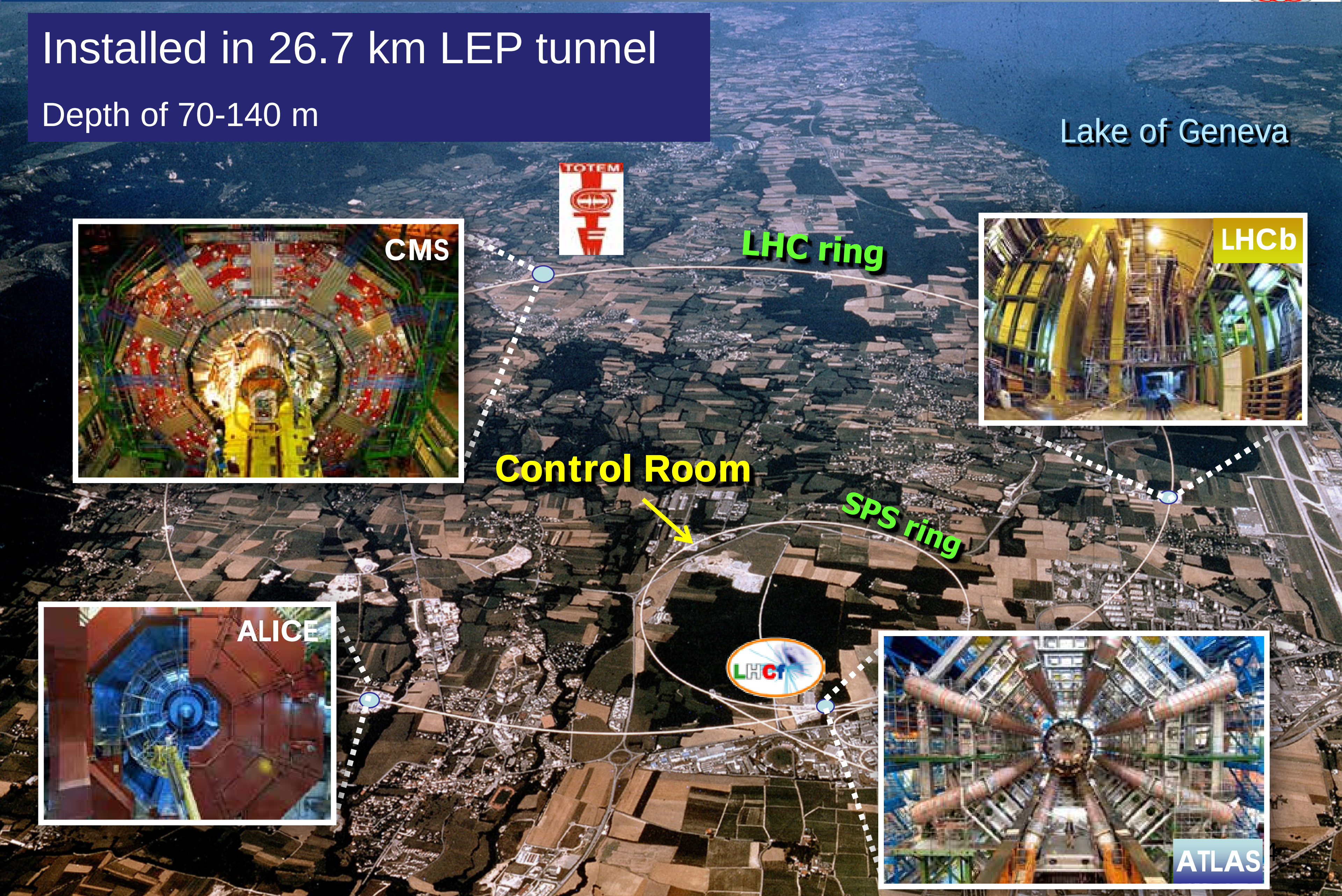
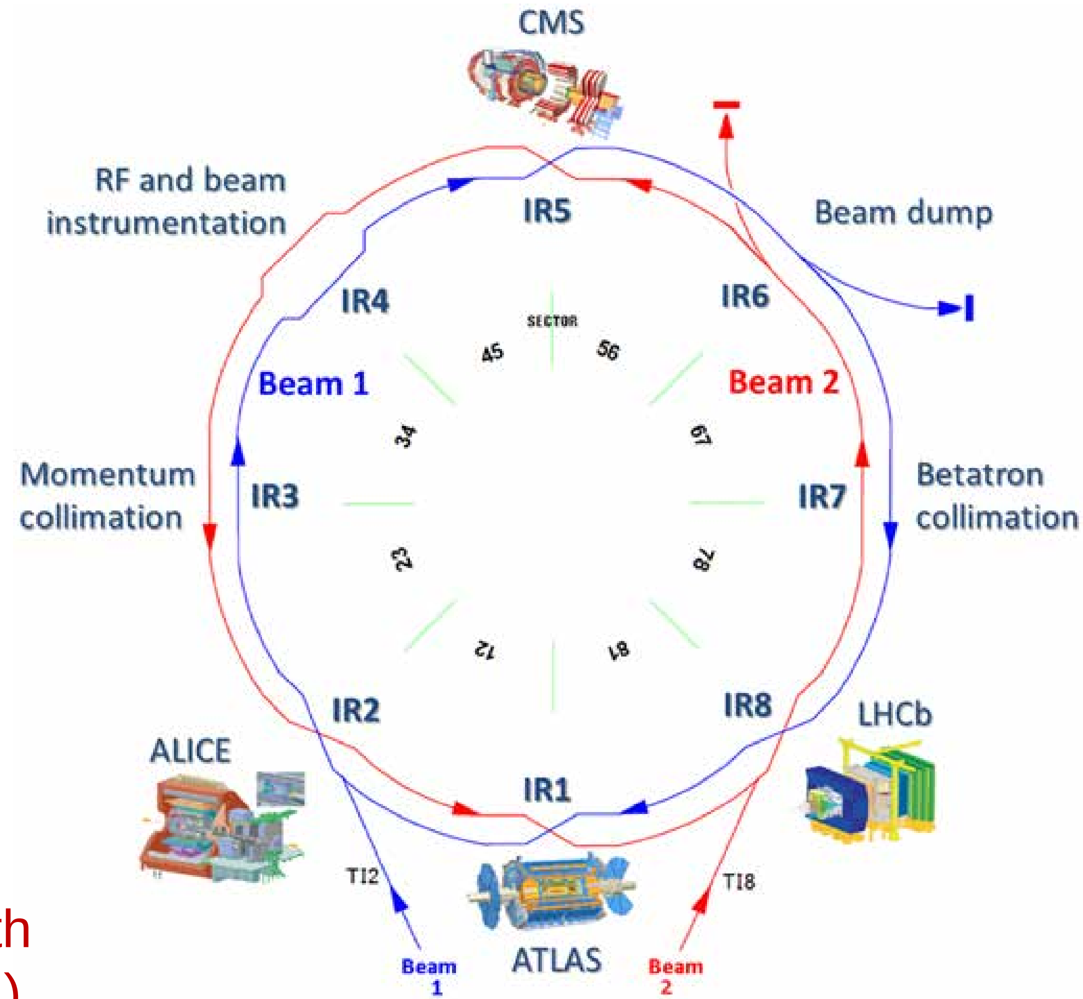


LHC ring layout

- Total length 26.66 km, in the former LEP tunnel.
- 8 arcs (sectors), ~3 km each.
- 8 straight sections of 700 m.
- Beams cross in 4 points.
- Design energy 7 TeV obtained with superconducting magnets operating at 8.3 T.

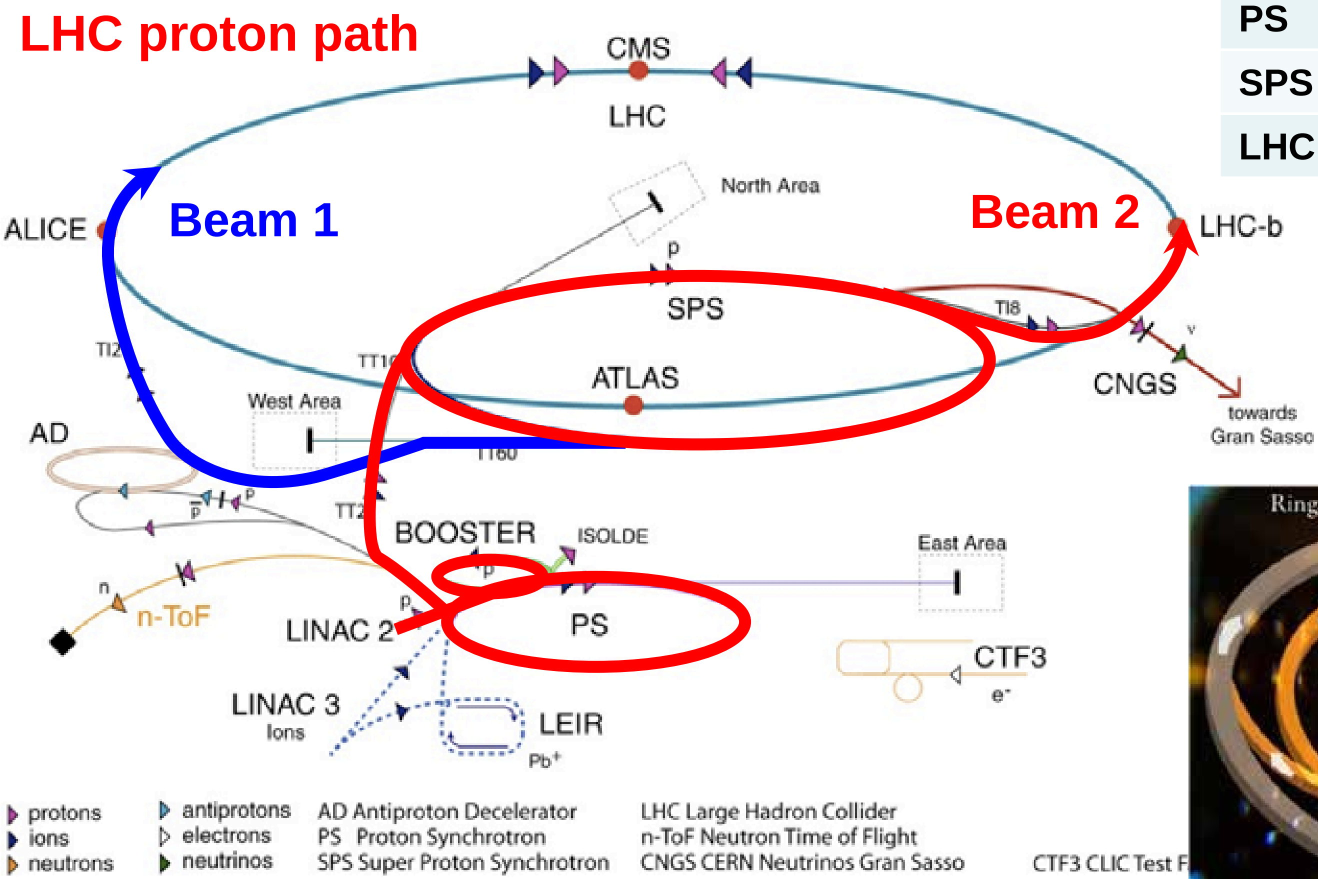
- 2-in-1 magnet design with separate vacuum chambers.
- **2 COUPLED rings**.

The LHC can be operated with protons and ions (so far Pb_{208}).



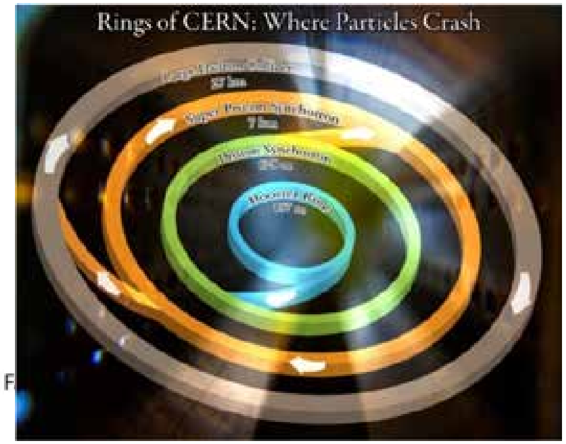
LHC accelerator complex

The proton journey from the source to injection into the LHC lasts ~7-24 seconds



	Max. P (GeV/c)	Length / Circ. (m)
LINAC2*	0.050	30
Booster*	1.4	157
PS	26	628
SPS	450	6'911
LHC	6'500	26'657

***: kinetic energy**

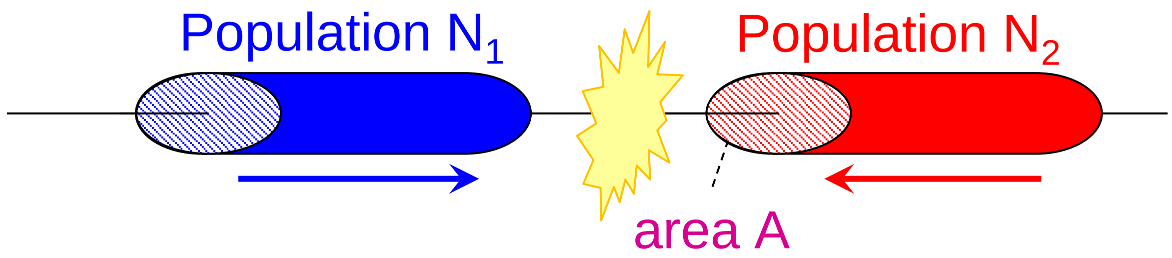


Collider luminosity

The key parameter for the experiments is the event rate dN/dt. For a physics process with *cross-section s* it is proprotional to the collider **Luminosity *L***:

$$dN / dt = L s$$

unit of L :
1/(surface × time)



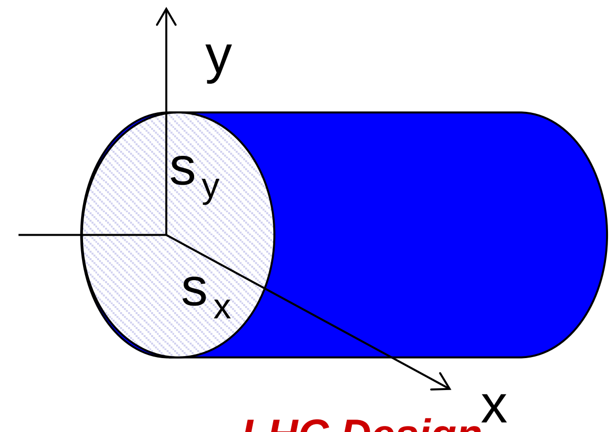
$$\text{Collision rate} \;\; \mu \;\; s \times \underbrace{\frac{N1 \times N2}{A} \times \text{encounters/second}}_{L}$$

To maximize L we have to squeeze as many particles as possible into the smallest possible volume !

Collider luminosity

Expression for the luminosity L (for equal particle populations, Gaussian profiles and round beams) :

$$L = \frac{k N^2 f}{4p\, s^*_x s^*_y} F = \frac{k N^2 f\, g}{4p\, b^* e} F$$



LHC Design

- ***k = 2808***
- ***N = 1.15×10^{11}***
- ***$s^*_x = s^*_y$ = 16 mm***
- ***L ~ 10^{34} cm^{-2}s^{-1}***

k, N, e: beam properties

b : property of the beam optics*

F : beam dynamics

- *s^*_x, s^*_y : transverse rms beam sizes - $(s^*)^2 = b^* e$*
- ***b**** *: betatron (beam envelope) function Û optics*
- ***e:*** *beam emittance (phase space volume)*
- ***k*** *: number of particle packets / bunches per beam.*
- ***N*** *: number of particles per bunch.*
- ***f*** *: revolution frequency = 11.25 kHz.*
- ***g*** *= E/m.*
- ***F*** *: geometric correction factor (crossing angles...).*

**** refers to the IP***

Beam parameters

q The intrinsic beam parameters are defined by the LHC injectors:

- Ø **Bunch spacing** *(à* **k***) : minimum (design) = 25 ns (Û 7.5 m),*
- Ø ***Bunch intensity* N***: up to ~ 2´10*^{11} *p/bunch,*
- Ø ***Bunch emittance e****: 1-3.5 mm mrad.*

$$L = \frac{kN^2 f \gamma}{4\pi \beta^* \epsilon} F$$

q For the design **bunch spacing of 25 ns**:

- ü *Bunch intensity* ***N*** *~1.2´10*^{11} *p / bunch,*
- ü *Bunch emittance* ***e*** *~ 3-3.5 mm mrad.*

Delivered in 2015 !

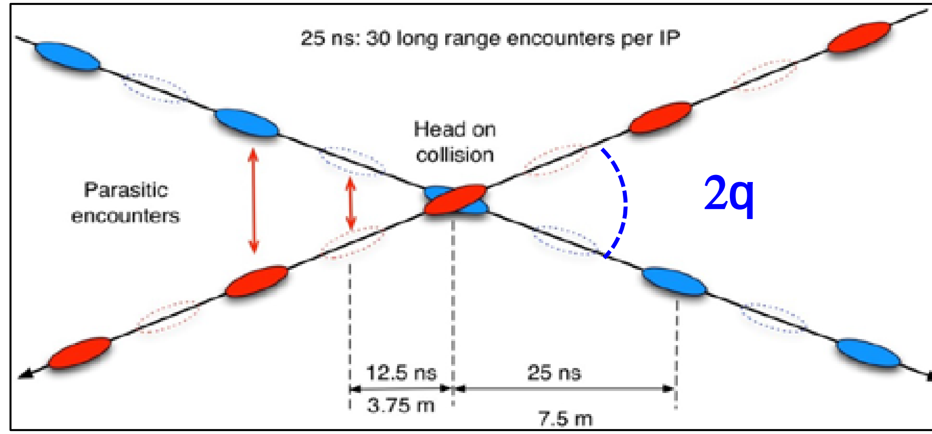
q To boost performance, it is sometimes useful to increase the bunch spacing: in 2011 and 2012 the LHC operated with **50 ns bunch spacing** due to e-cloud issues (à later).

- Ø *Bunch intensity* ***N*** *up to ~ 1.7´10*^{11} *p / bunch,*
- Ø *Bunch emittance* ***e****~2.0-2.5 mm mrad.*

à Provides ***higher luminosity per bunch collision*** *(factor ~3), but also higher event pile-up (overlap of events) à not favoured by the experiments !*

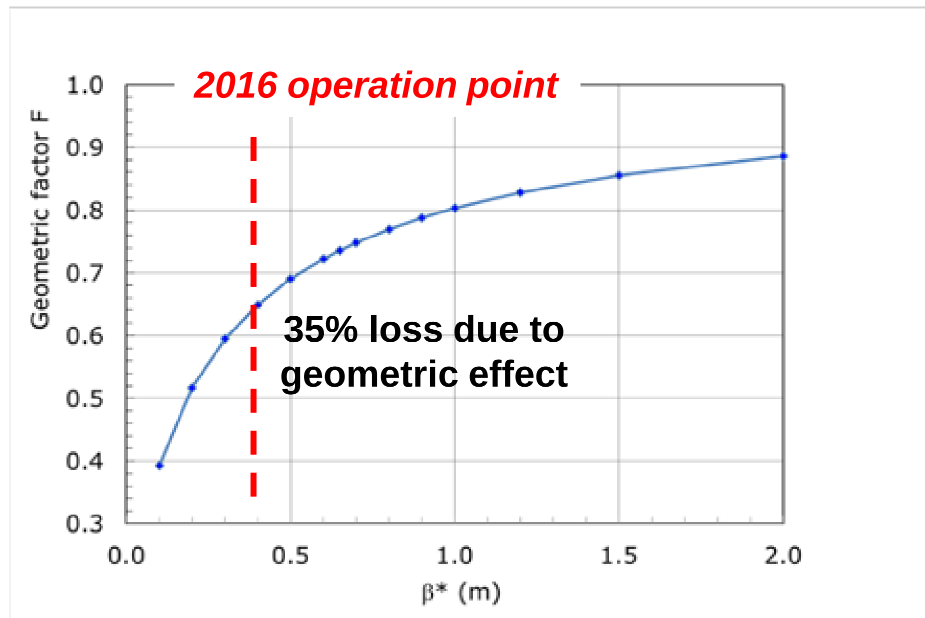
Collision point geometry

- A **crossing angle** between the beams is needed to minimize the electromagnetic interactions (***beam-beam*** effects) in the common vacuum chamber.
  - Min. separation ~10 beam sizes
  - 30 encounters per IP.



- Consequences of colliding at an angle:
  - Geometric luminosity reduction up to 40% depending on beam size and bunch length: **very steep function of the beam size** ($b^* e = s^{*2}$).
  - Reduction of the aperture.

$$L = \frac{kN^2 f g}{4p b^* e} F$$

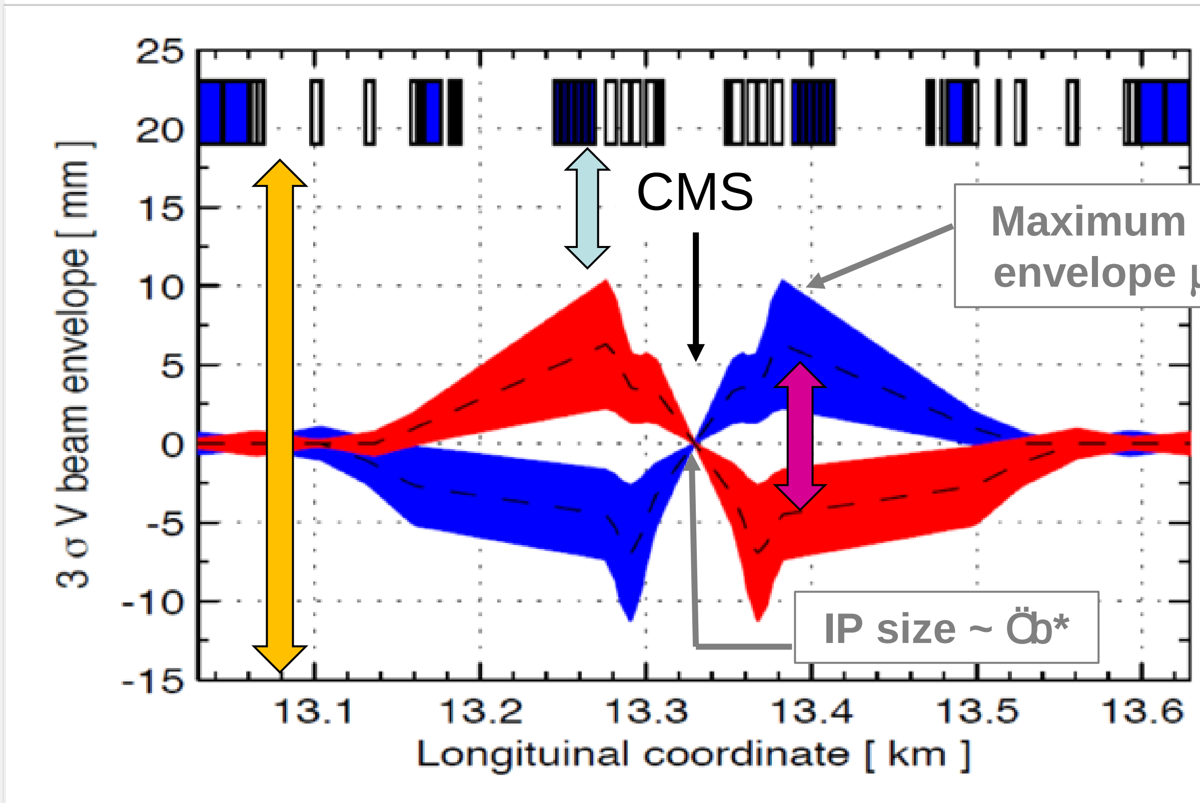


Collision point focusing

The maximum focusing (**minimum beam envelope b***) is determined by:

- *The mechanical aperture around the collision point,*
- *The crossing angle (q µ k, N, 1/Öb*),*
- *The margin to the aperture.*

$$L = \frac{kN^2 f g}{4p b^* e} F$$



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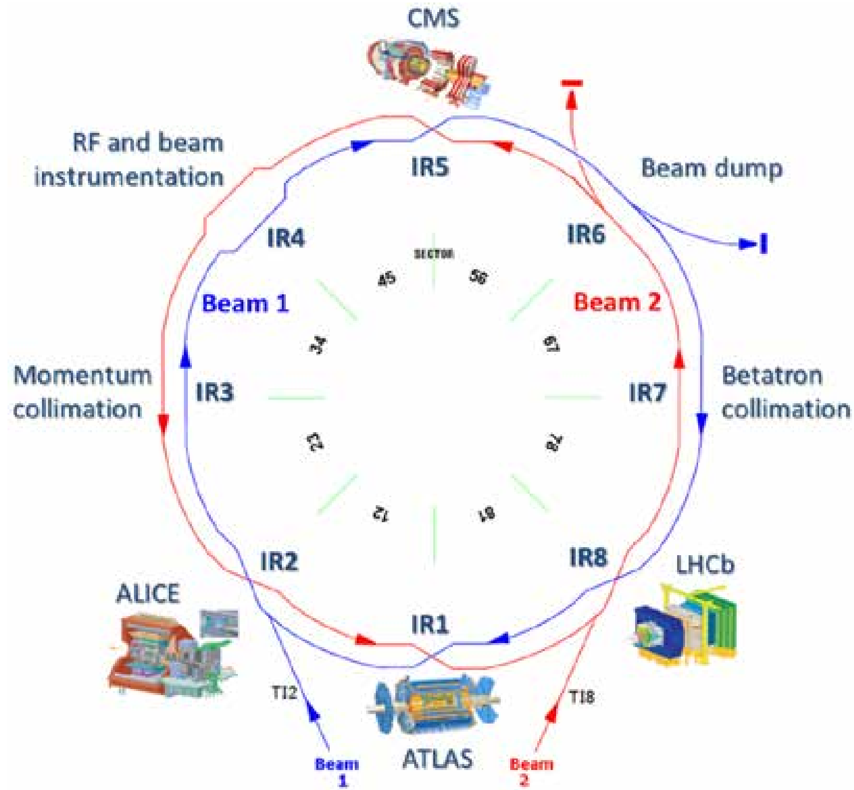


LHC Run 2 goals

q The LHC was operated in 2010-2013 at beam energies of 3.5 TeV and 4 TeV (‘Run 1’).

q Run 1 was followed by a ~2 year long shutdown to prepare the LHC for high energy operation.

Run 2 goals (2015-2018) :

ü Operate the LHC at 6.5 TeV (or higher).

ü Operate with a bunch spacing of 25 ns.

- *For Run 1 we operated with 50 ns spacing (e-cloud).*

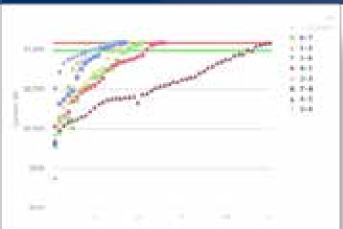
ü Deliver ≥ 100 fb^{-1} of integrated luminosity

Objectives for 2015 – learning year for Run 2:

q Stable & reliable operation at 6.5 TeV,

q High intensity beams with 25 ns bunch spacing.

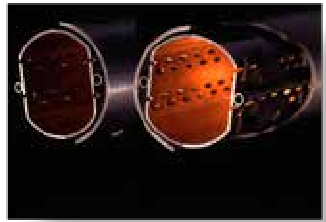
2015 operation



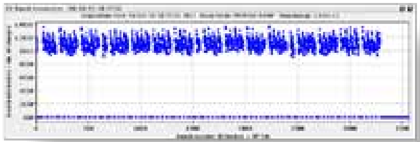
April 3,
End of powering tests – 150 quenches

April 10
First beam at

E: 6500 GeV



August 7,
Operation with 25 ns beam

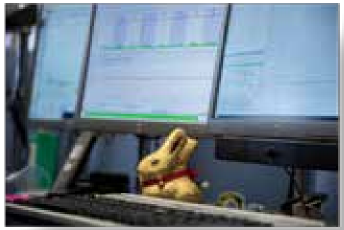


October 28,
Record no. bunches

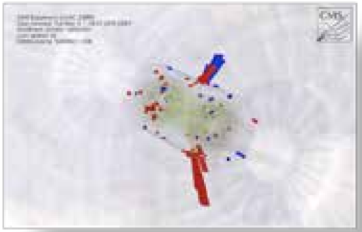
2244

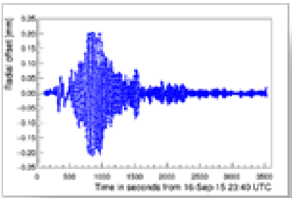
April | May | June | July | August | Sept | Oct | Nov | Dec

Easter,
Beam circulating



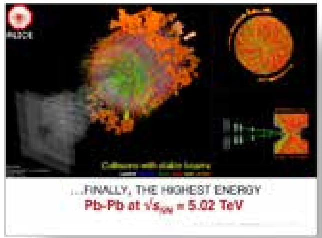
June 3,
Start of physics operation for run 2





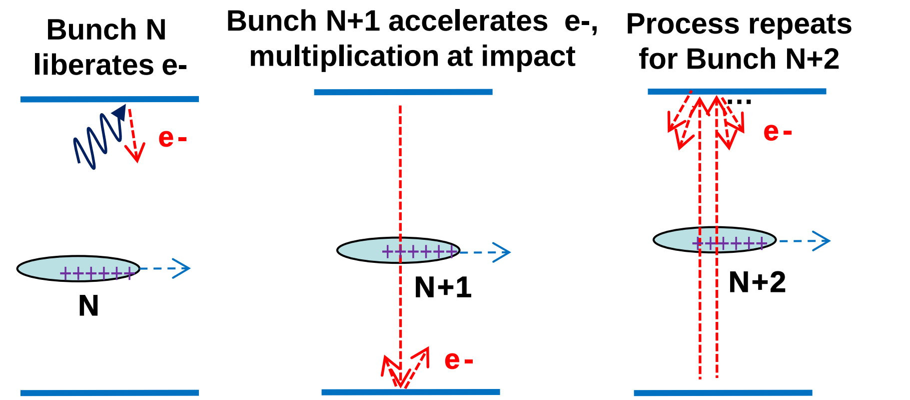
September 16,
Chili 8.3M earthquake shakes LHC rings

Nov-Dec,
Pb ion run

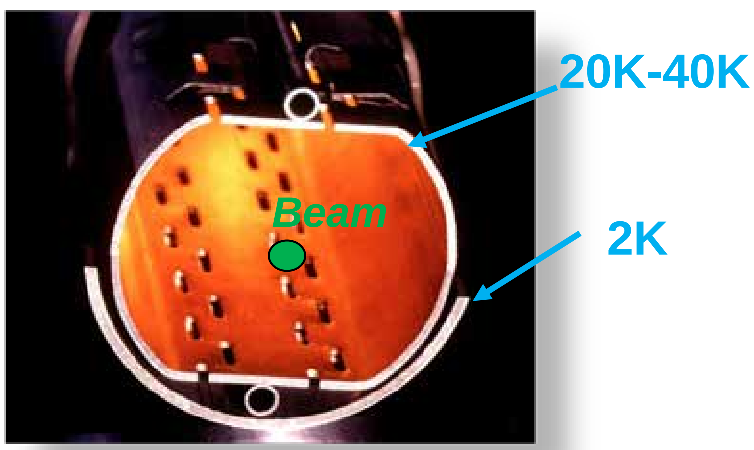


Electron clouds

- q **Electron cloud** effects:
  - – Vacuum pressure rise.
  - – Impact on beam quality (emittance growth, instabilities, particle losses).
  - – Excessive energy deposition on the vacuum chamber (~20K at LHC) → heat load on the cryogenic system.
- q Electron clouds affect all high intensity machines with **positive** bunch charge (e^+ Û B-factories).



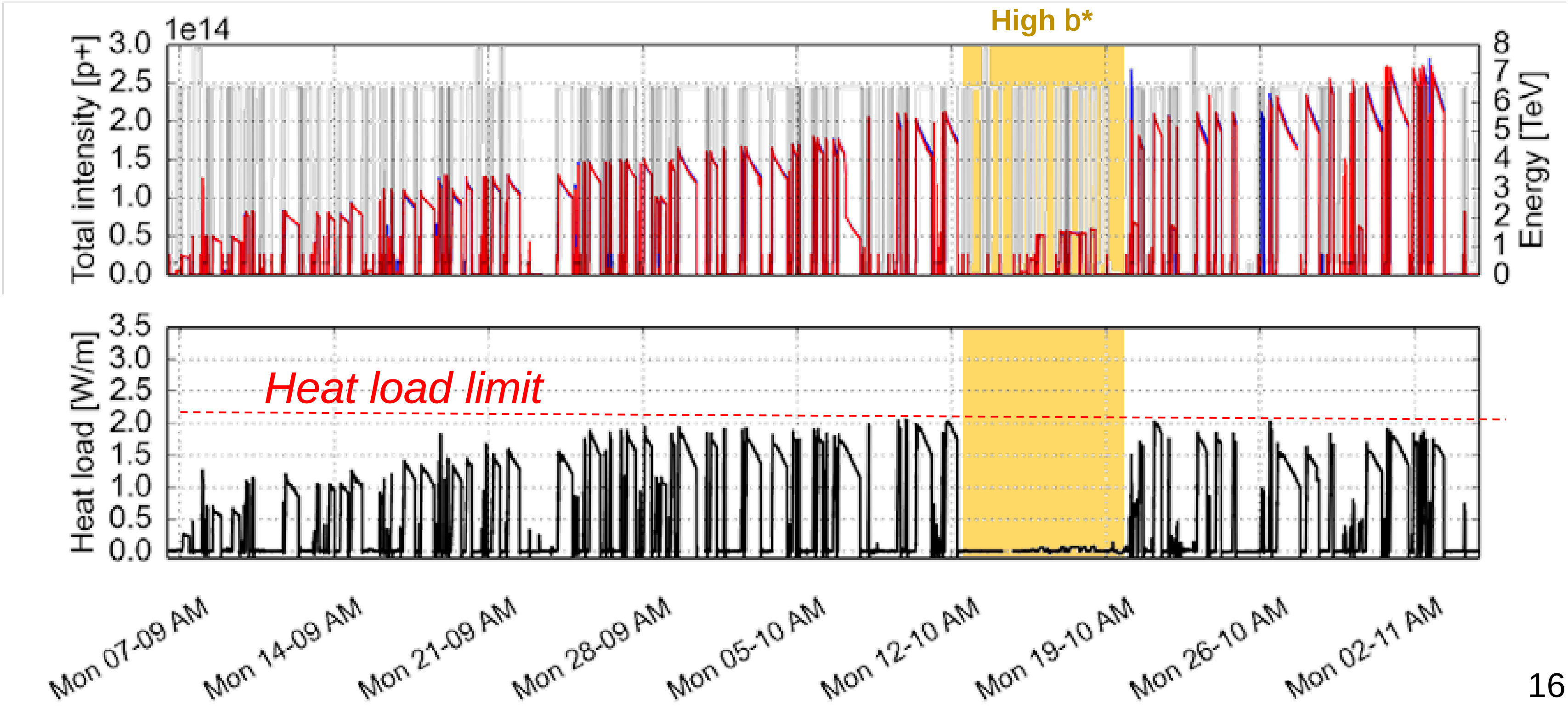
If the probably of emitting a secondary electron (Secondary emission yield [SEY]) above threshold $SEY>SEY_{th}$ è avalanche effect (multipacting)
SEY_{th} depends on bunch spacing and population



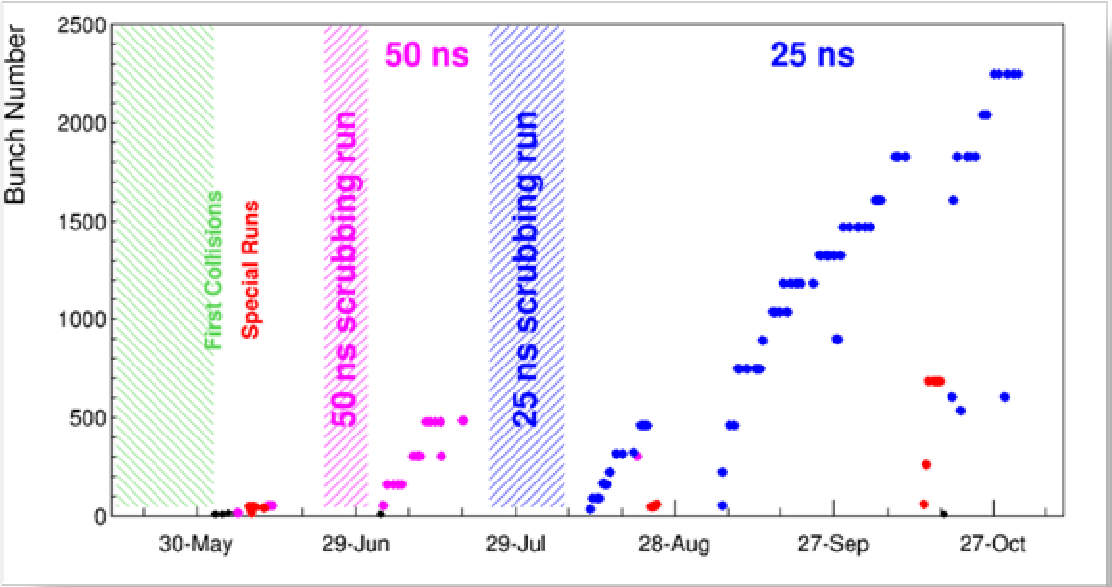
- q Remedy: conditioning by **beam-induced electron bombardment** (“**scrubbing**”) leading to a progressive reduction of SEY.

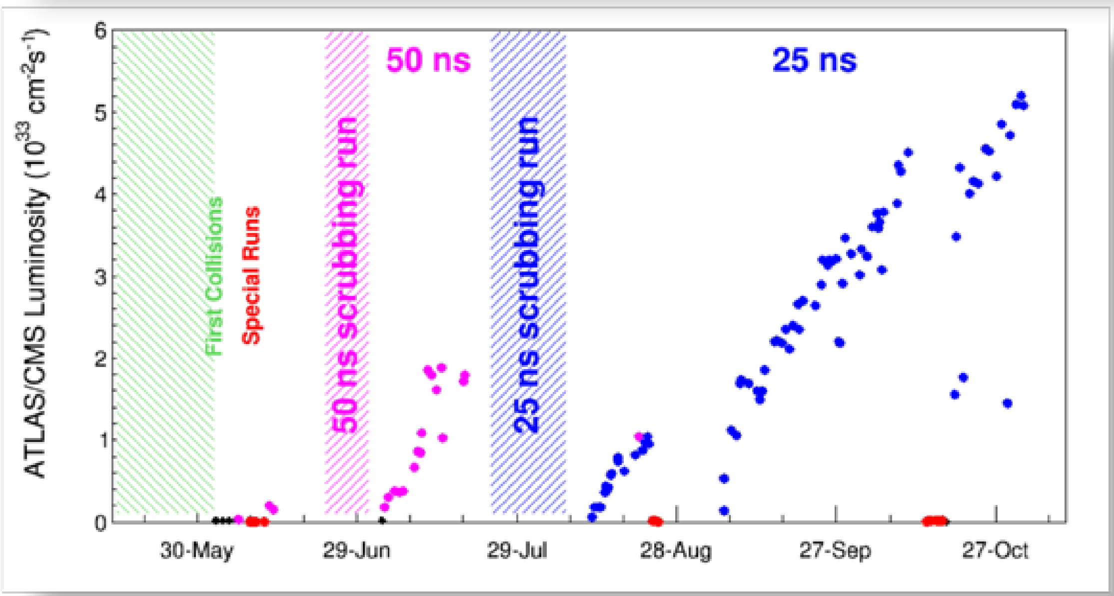
Electron cloud conditioning

- The SEY of the vacuum chamber is initially conditioned at injection energy until conditions are acceptable for physics operation at 6.5 TeV.
- The intensity at 6.5 TeV was *limited in 2015 by the heat load deposited on the vacuum chamber by the e-cloud* (cooling by cryogenic system !).
  - Operation at higher energy leads to a progressive reduction of SEY (conditioning during physics operation).
  - The beam intensity (number of bunches) is increased progressively.



LHC operation in 2015

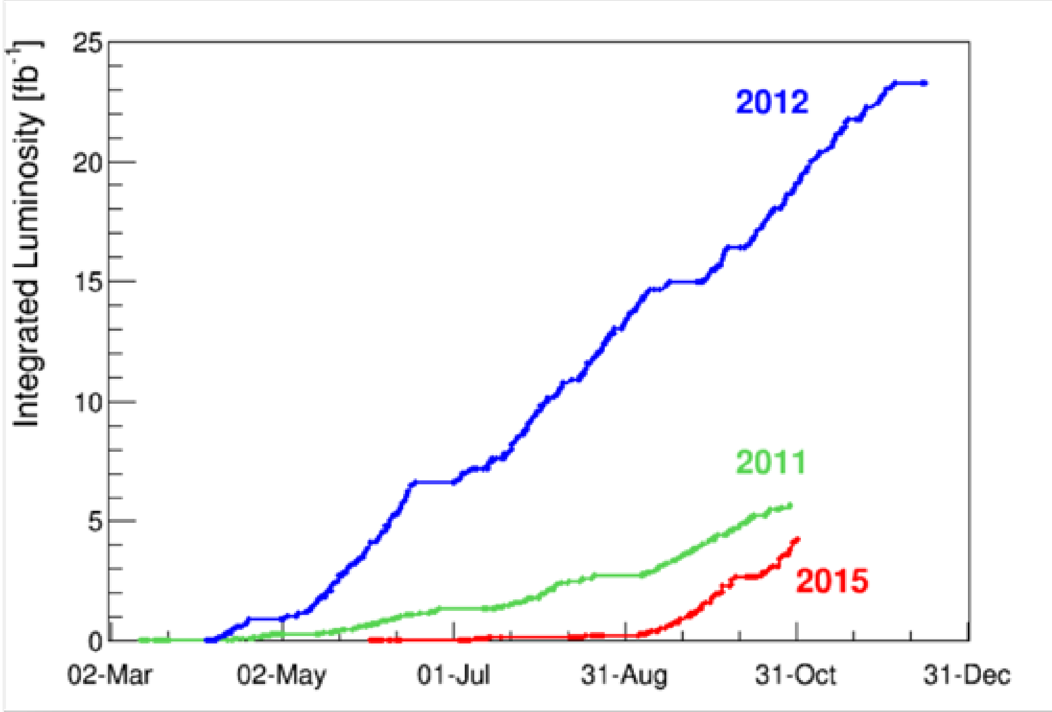




- Operation with 25 ns bunch spacing started mid-August, we reached **2244 bunches** per beam (nominal ~**2750** bunches – 82% filled) end of October.
  - ***Limited by cryogenics cooling power*** *(e-cloud heat load).*
  - *E-clouds are the main limitation, intensity follows conditioning.*

Integrated luminosity

- The initial projections of integrated luminosity for 2015 were ~5-15 fb^{-1}.
- We finally achieved ~ 4 fb^{-1}.
- The main reasons for the lower value:
  - Start-up delays (~6 weeks),
  - Availability issues,
  - Progress slowed down by electron cloud conditioning.



The production slope at the end of the year was almost as high as in 2012

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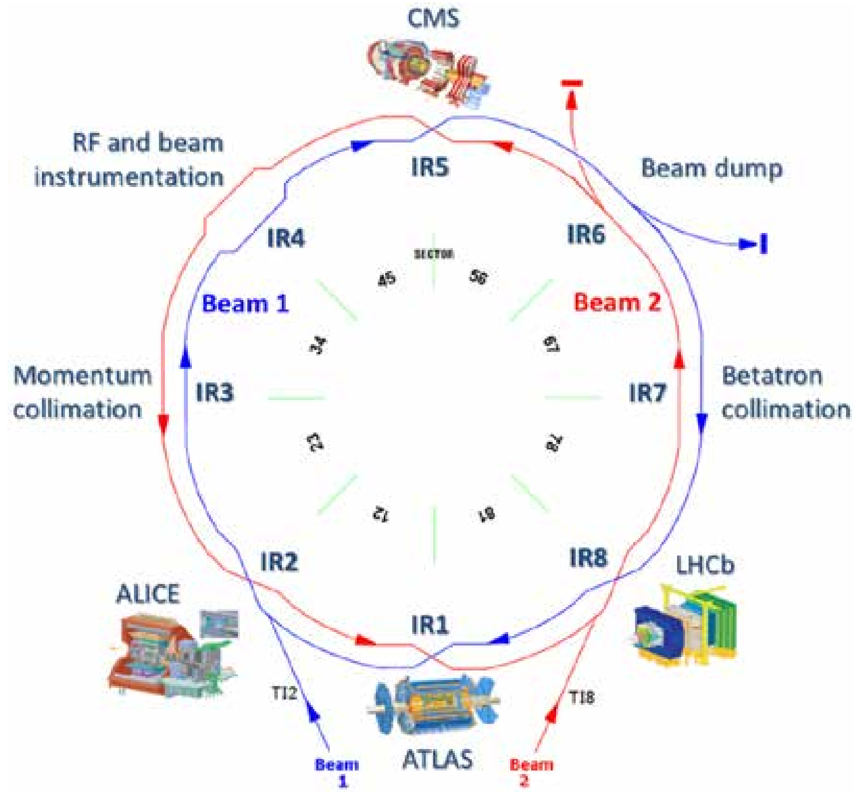


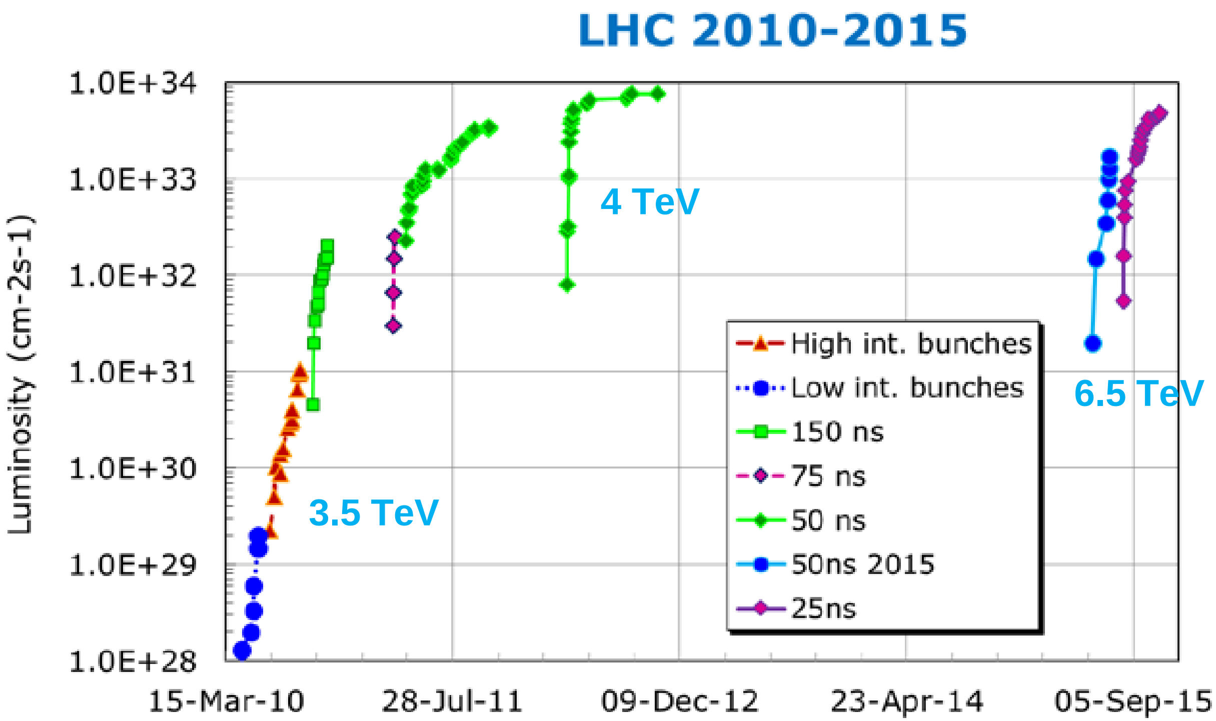
2016 performance estimate

- In 2016 we will push the IP focusing essentially to the limit (with round beams): b* lowered from **80 cm to 40 cm**.

- We should be able to hit the design luminosity this year !
  - *It will take ~6-8 weeks to ramp up the intensity.*

Parameter	2015	2016
Bunch intensity N_b (10^{11} p)	**~1.2**	**~1.2**
No. bunches k	**2244**	**2748**
Bunch emittance e (mm mrad)	**~3.5**	**~3.5**
Beam envelope b* (cm)	**80**	**40**
Beam size at IP s* (um)	**20**	**14**
Crossing angle (mrad)	**2 x 145**	**2 x 185**
F (bunch length 9 cm)	**0.84**	**0.65**
Peak luminosity (10^{34} $cm^{-2}s^{-1}$)	**0.51**	**1.0**
Integrated per 150 days (fb^{-1})	**--**	**~30**

Performance 2010-2015



Peak luminosity:

Run 1: 7.6´ 10^{33} $cm^{-2}s^{-1}$

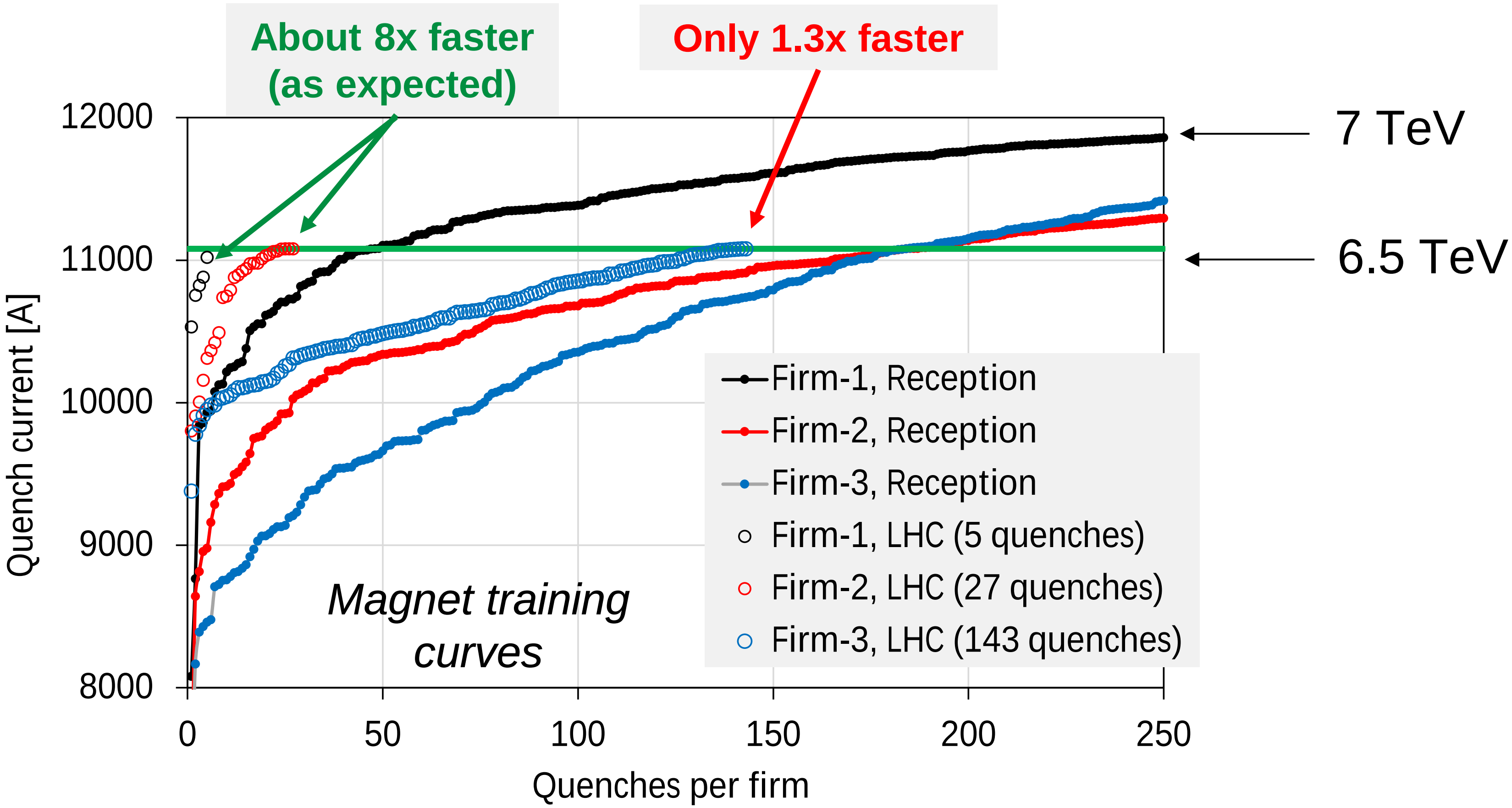
Run 2: 5.1´ 10^{33} $cm^{-2}s^{-1}$

Design & target 2016:

1´ 10^{34} $cm^{-2}s^{-1}$

With improved beam parameters from the injectors and a more *aggressive* setup (smaller crossing angle, reduced margins), the luminosity may be pushed further in 2017 and 2018.

- The 1232 main dipole magnets had to be trained for 6.5 TeV operation, 150 training quenches were required to bring the LHC to 6.5 + e TeV.
  - *Dominated by the magnets of firm 3.*
- With this new data, the **estimate for 7 TeV is ~300-400 additional quenches**.

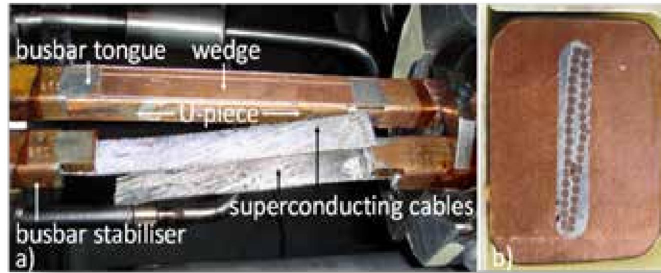


Outlook

- In 2015 operation was established **with 25 ns beams at 6.5 TeV**. Half of the design luminosity was reached with significant margin for improvements.
- We expect to reach **design luminosity in 2016**, with the potential for more improvements in the years to come.
  - *First beam injection around Easter.*
- With at least 30 fb^{-1} expected per year, the target of **100 fb^{-1} for Run 2** is well within reach.
- In 2016 LHC will operate at 6.5 TeV. Now that the 'quench cost' of operation at 7 TeV is better known, an energy increase can be considered in the coming years. To be agreed between machine and experiments.

Thank you for your attention!

LHC energy evolution



Energy (TeV)

7 TeV *Design*

5 TeV *Magnet de-training after installation*

Issues on Interconnection, incident

3.5 TeV

Consolidation delays

1.18 TeV

3.5 TeV

Energy increase Û no quench at 3.5 TeV

4 TeV

*Long Shutdown 1 (**LS1**)*

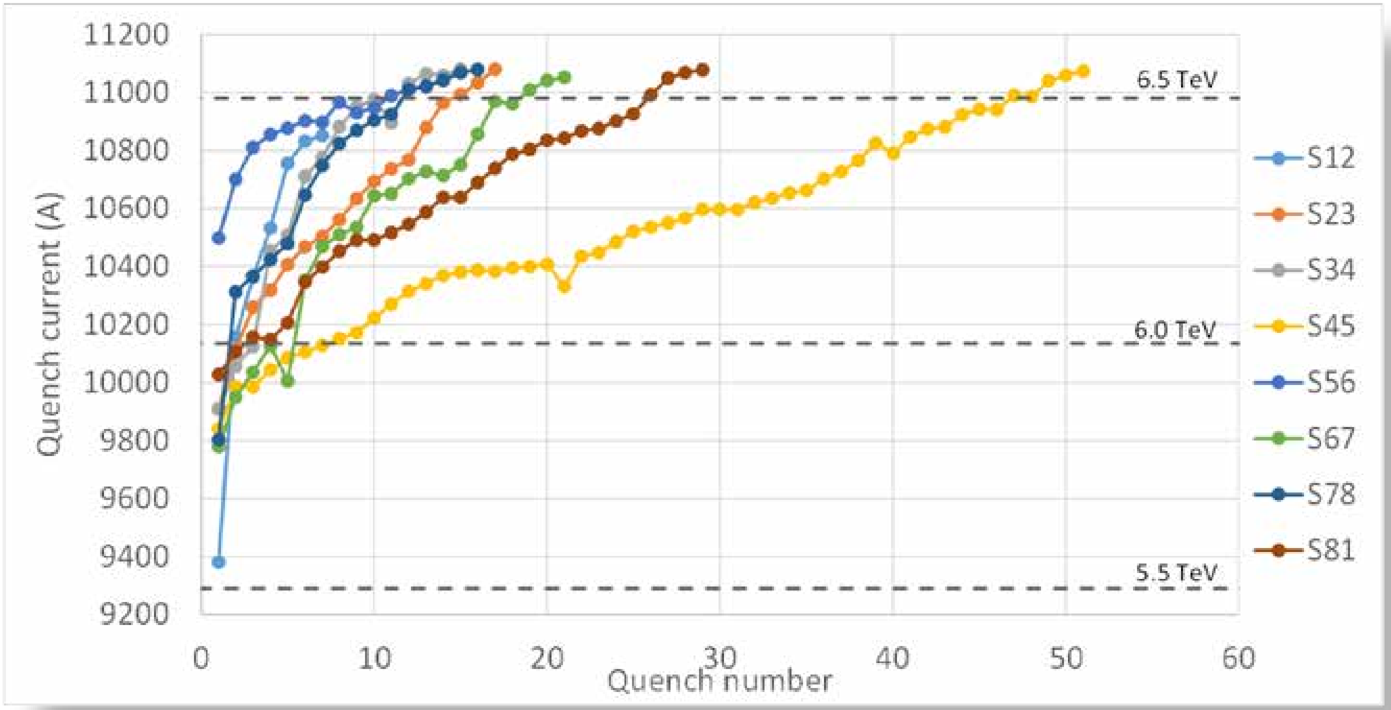
Consolidation of all interconnections

6.5 TeV

2007 2008 2009 2010 2011 2012 2013 2014 2015

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 over150 training quenches were required to bring the LHC to 6.5 + e TeV.
  - *The large spread in number of quenches between the eight sectors (arcs) is due to the mixture of magnets from the 3 producers.*
  - *3 spontaneous (no beam loss!) quenches occurred in operation at 6.5 TeV.*



The road to 7 TeV

- A new model for the quench behaviour was established from the 2015 quench campaign. The new estimates for the # quenches to reach 7 TeV :

~270 first quenches to go !

Best estimate for 7 TeV (first q. only)

sector	1000	2000	3000	total
12	3	19	7	28
23	3	12	30	44
34	2	16	22	40
45	2	9	62	73
56	1	8	63	73
67	3	7	46	56
78	3	24	46	72
81	3	5	50	58
LHC	20	100	325	445

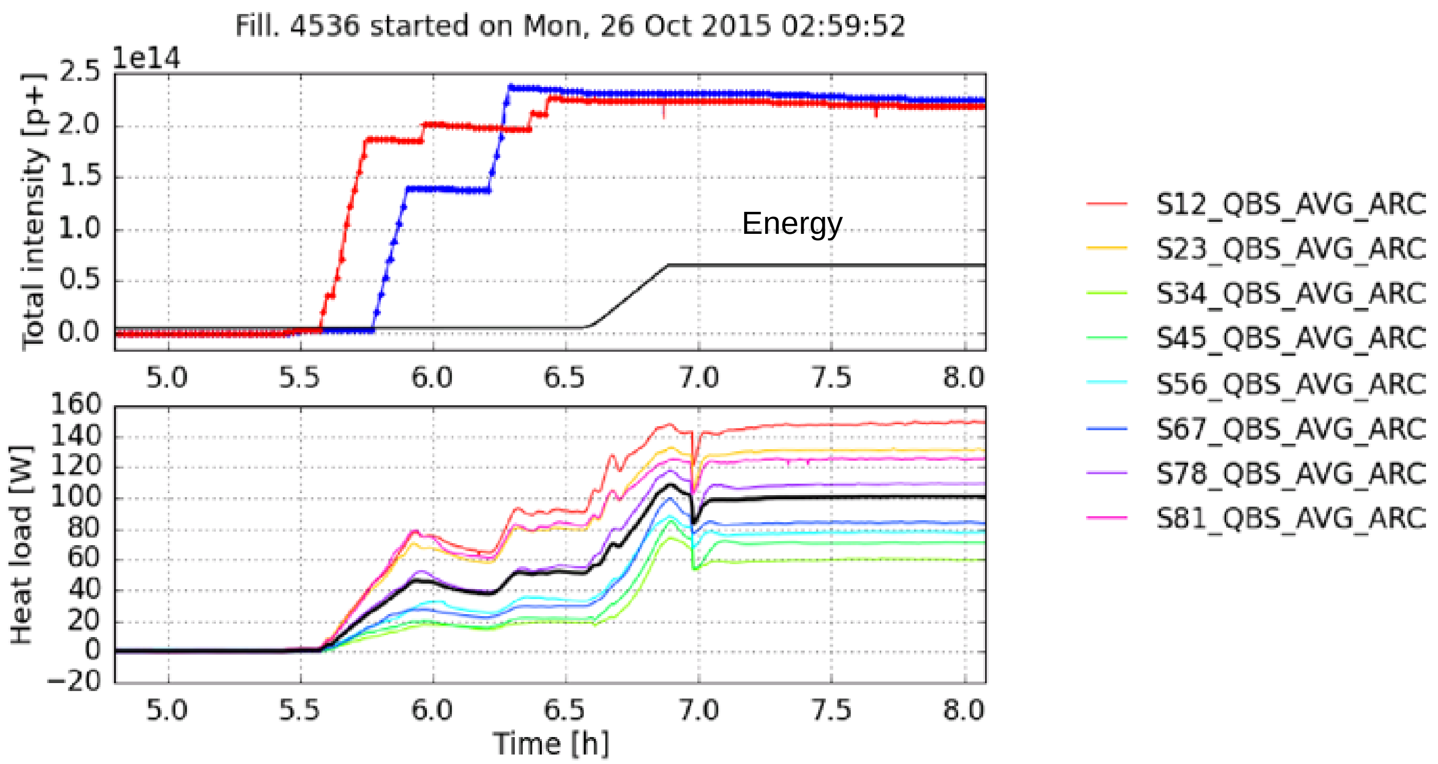
Done	to do
7	21
17	27
15	25
49	24
16	57
20	36
21	51
28	30
173	272

- The data are compatible with a scenario where after each warm-up we re-start in the same conditions than at the beginning of the previous campaign.
- We could probe the predictions by pushing ~2 sectors towards 7 TeV (future powering campaign).

Mera peak, 6.5 km high

Kun, 7 km high

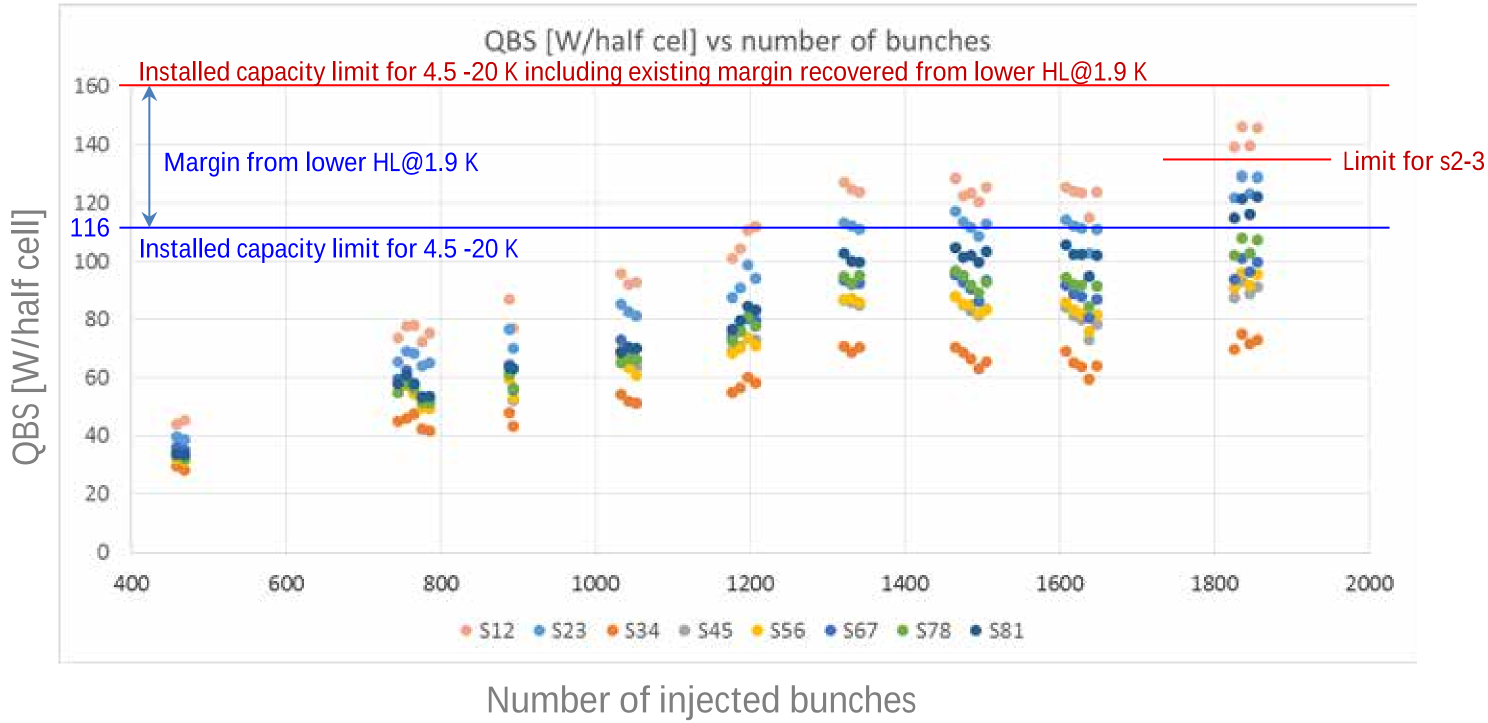
E-cloud diagnostics: heat load



- Example of heat load evolution during filling and ramp. During transient phases the heat load is not accurate (~10 mins delays).
- The large spread of heat load from one arc to the next is real and not understood ! **If all arcs would be at the level of the lowest one, we would have already reached design intensity**.

Heat load evolution

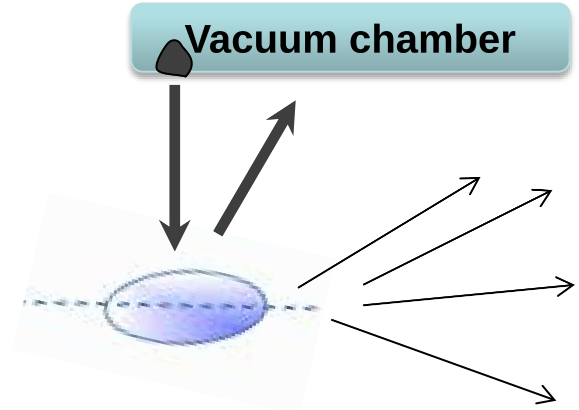
Courtesy K. Brodzinski



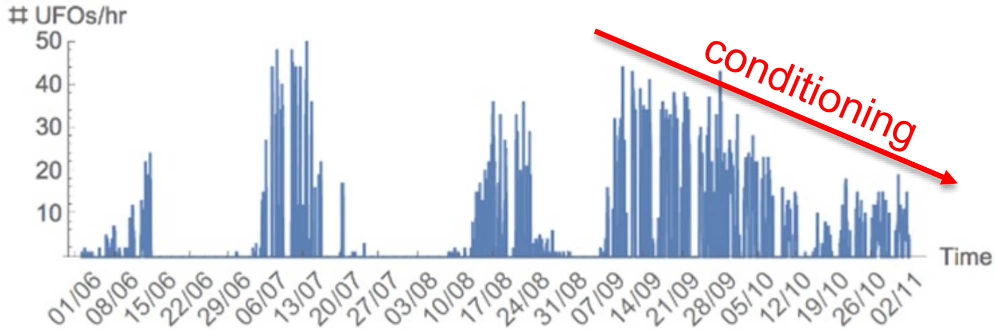
- As the number of bunches was increased the LHC was operated closer and closer to the heat load capacity of the cryogenic system.
- The intensity in the LHC is currently limited by the cryogenics, we can only step up intensity when we gain on the e-cloud front.

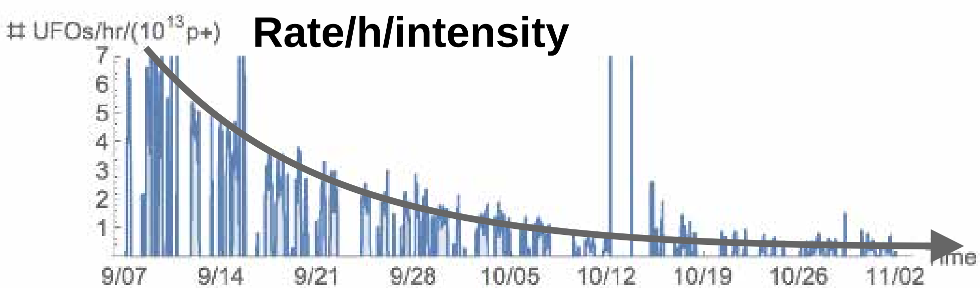
Unidentified Falling Objects - UFOs

- According to the most credible theory, the **Unidentified Falling Objects** are dust particles that fall into the beam and generate beam losses due to inelastic collisions with the beam. These losses can quench a superconducting magnet.
  - *Identified already in Run I*
  - *If the losses are too high, the beams are dumped to avoid a magnet quench (20 times / year in Run 1)*



Rate/h





- UFOs are also present at 6.5 TeV: **17 times beams were dumped by UFOs, and 2 magnet quenched.**
  - Loss monitor thresholds were adjusted to **balance the risk of spurious dumps and the need for quench prevention**
  - A clear conditioning has been observed along the year

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.

- The **object outline could be mapped accurately with our BLMs and BPMs**.
- The reference beam orbit was shifted upward and sideways to avoid the object.
- 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 !**