CERN Summer School 2017
Introduction to Accelerator Physics

Part V

by
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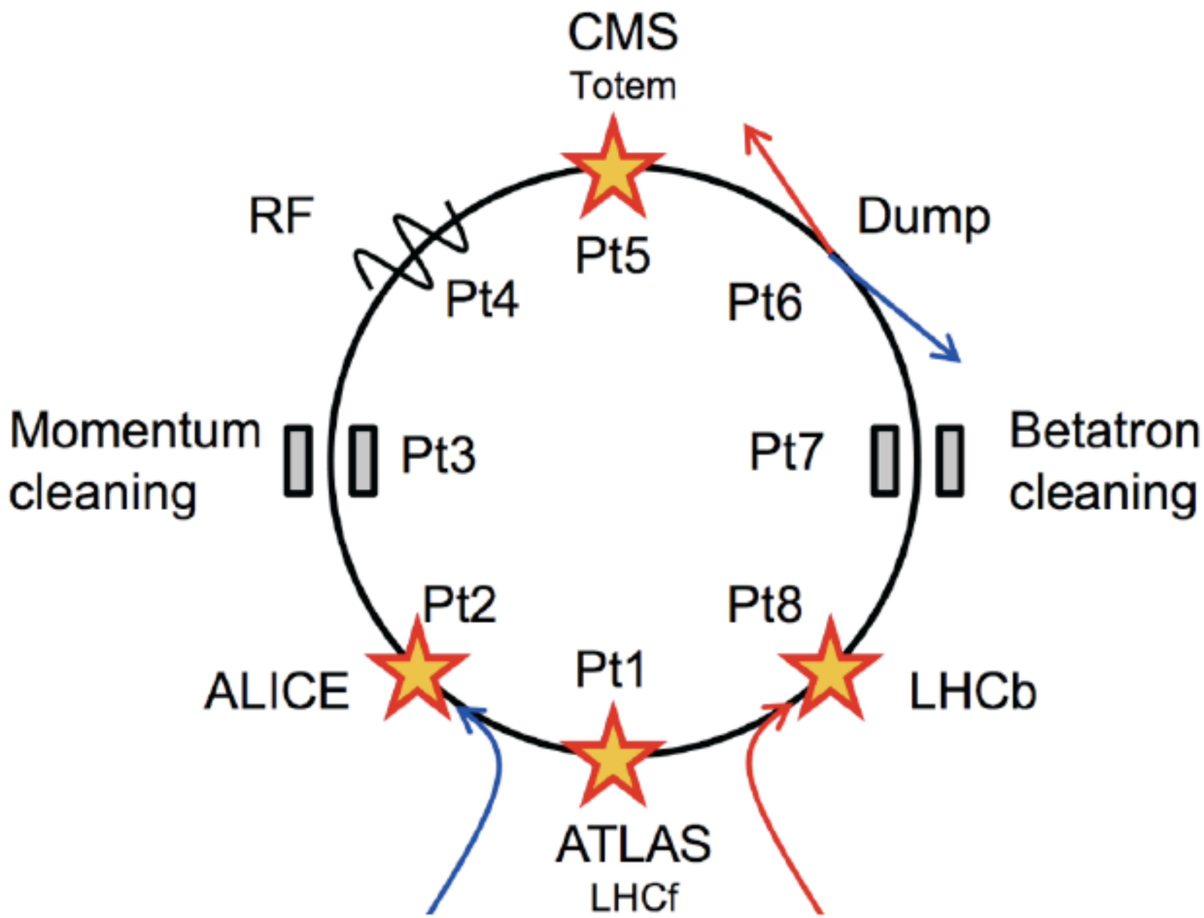
Many thanks to J. Wenninger for material

What's next?


Installed in 26.7 km LEP tunnel
Depth of 70-140 m
Lake of Geneva
The LHC

The Large Hadron Collider

- Total length 26.66 km, in the former LEP tunnel.
- 8 arcs (sectors), ~3 km each with FODO lattice
- 8 straight sections
- beams cross in 4 points.



- 2-in-1 magnet design with separate vacuum chambers.
- Designed for acceleration to 7 TeV/c beam

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

LHC Design Goals as Proton-Proton Collider

Basically....

As high an energy as possible

$$p = 7\ \mathrm{TeV/c}$$ in existing LEP tunnel with 27 km circumference

$$\frac{p}{e} = B\rho \quad \rightarrow B = 8.3\ \mathrm{T}$$

➔ Superconducting magnets

As high a collision rate as possible in the experiments

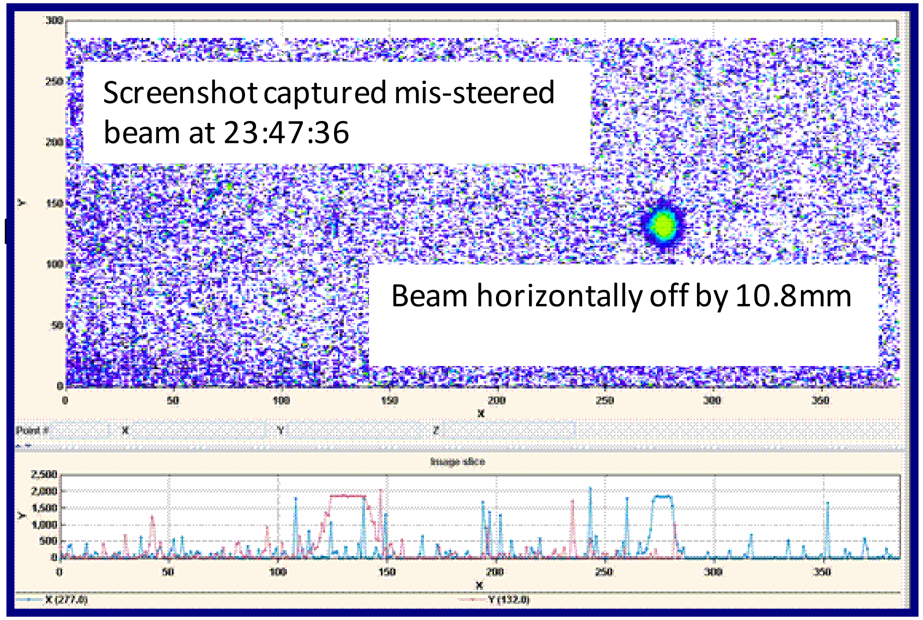
2808 proton bunches with 1.15×10^{11} p^{+} per bunch
spaced by 25 ns

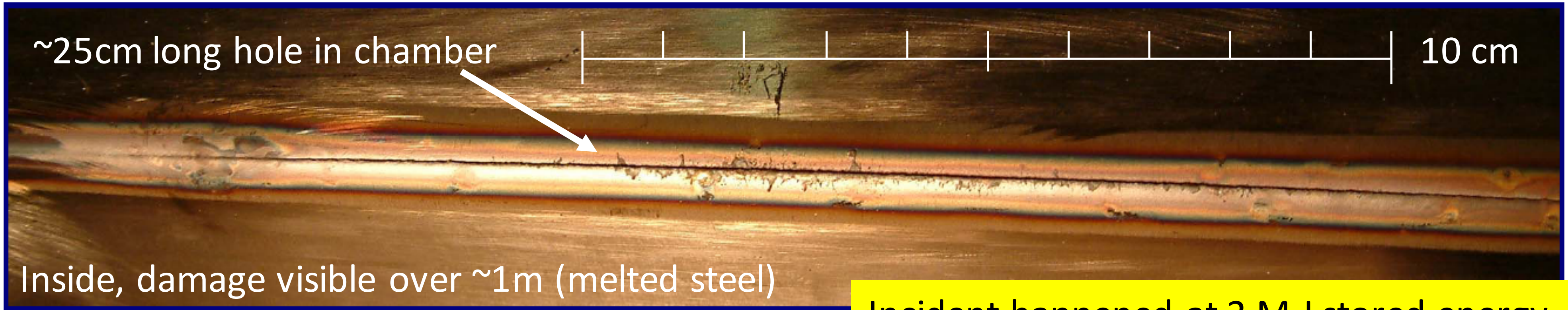
$$\rightarrow 360\ \mathrm{MJ}$$

stored in beam at 7 TeV

Already at injection energy beam loss can damage

- Failure in SPS during setting-up of LHC beam (25/10/04)
- Extraction septum supply tripped due to EMC from the beam
- In 11ms the field dropped 5%
- 3.4×10^{13} p+ @ 450GeV were wrongly extracted onto aperture
- Chamber and quadrupole magnet were damaged and had to be replaced

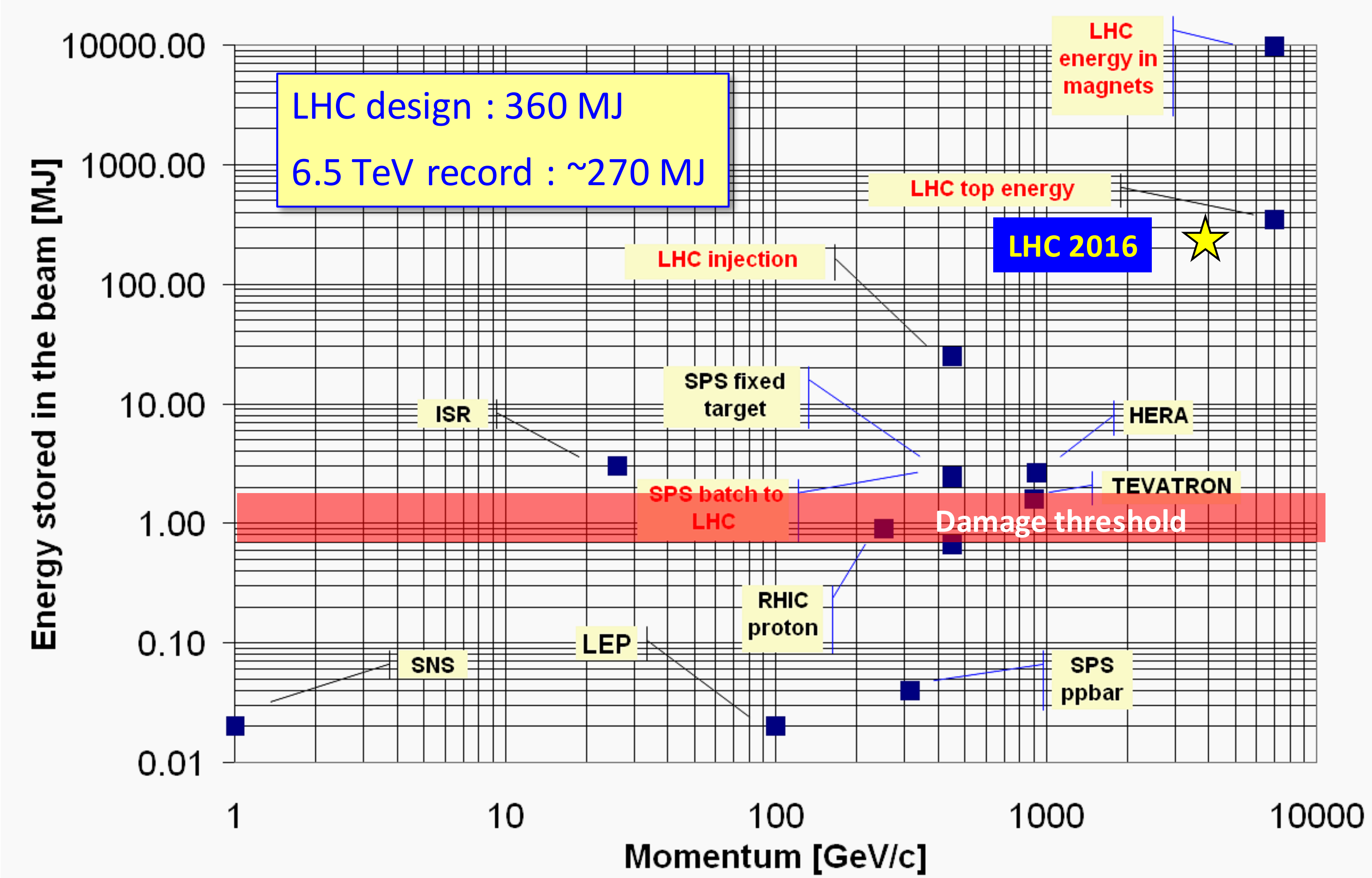




Incident happened at 2 M J stored energy

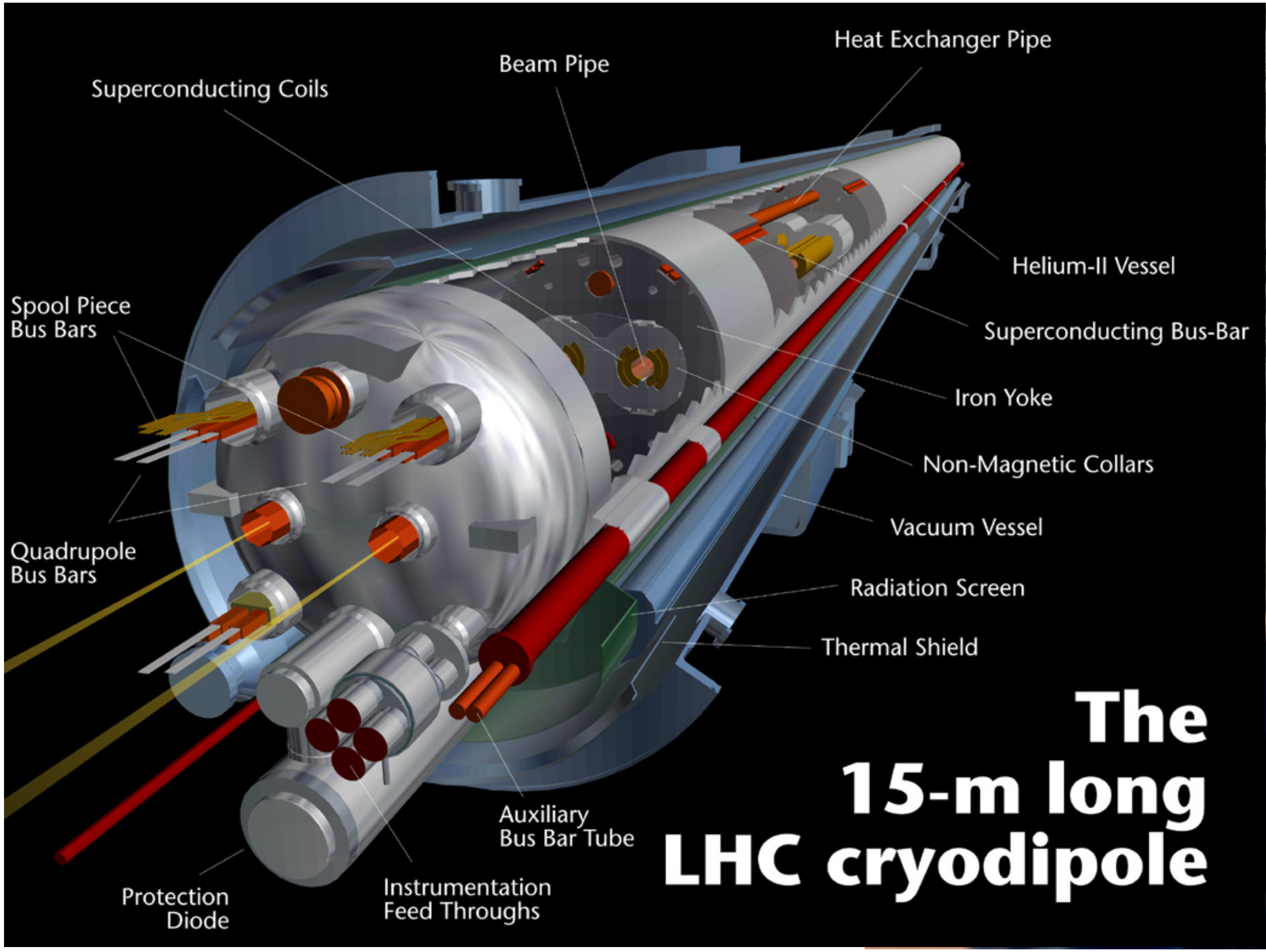
Stored Energy

The stored energy in beam and magnets is orders of magnitude above damage threshold: LHC key system ➔ **Machine Protection System**



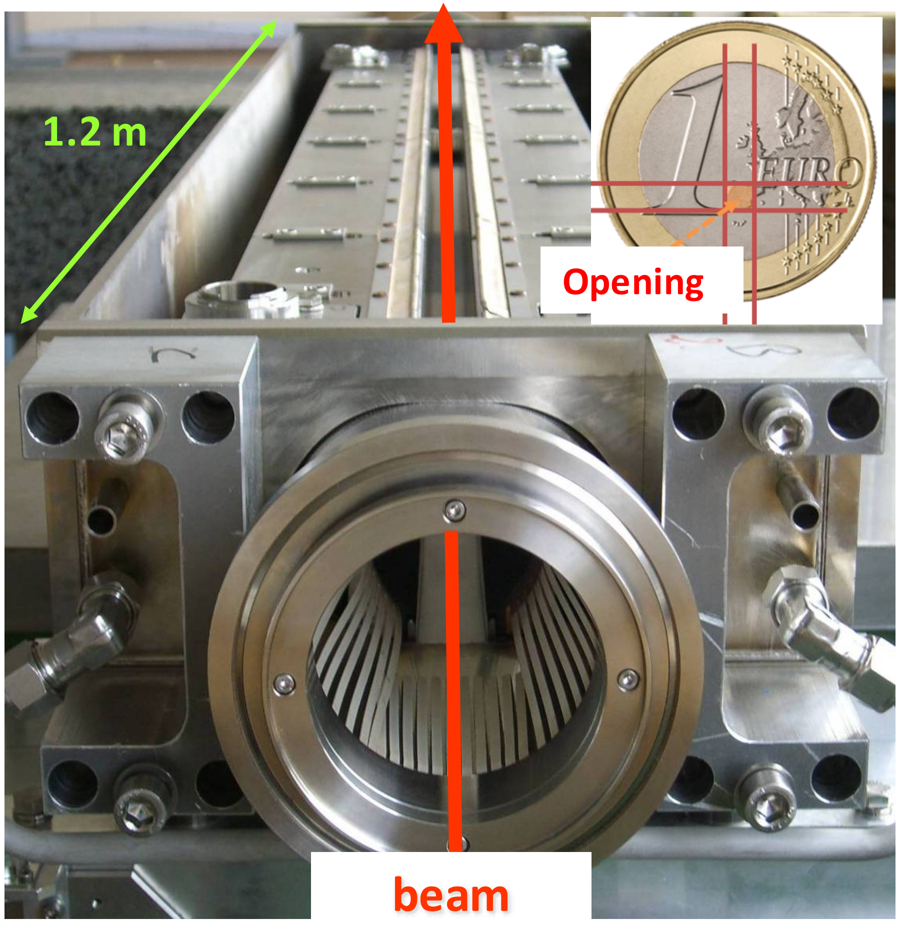
The LHC 2-in-1 Main Dipoles

- **1232** NbTi superconducting dipole magnets – each 15 m long
- Magnetic field of 8.3 T (current of 11.8 kA) @ 1.9 K (super-fluid Helium).
  - *But they do not like beam loss – quench with few mJ/cm^3.*



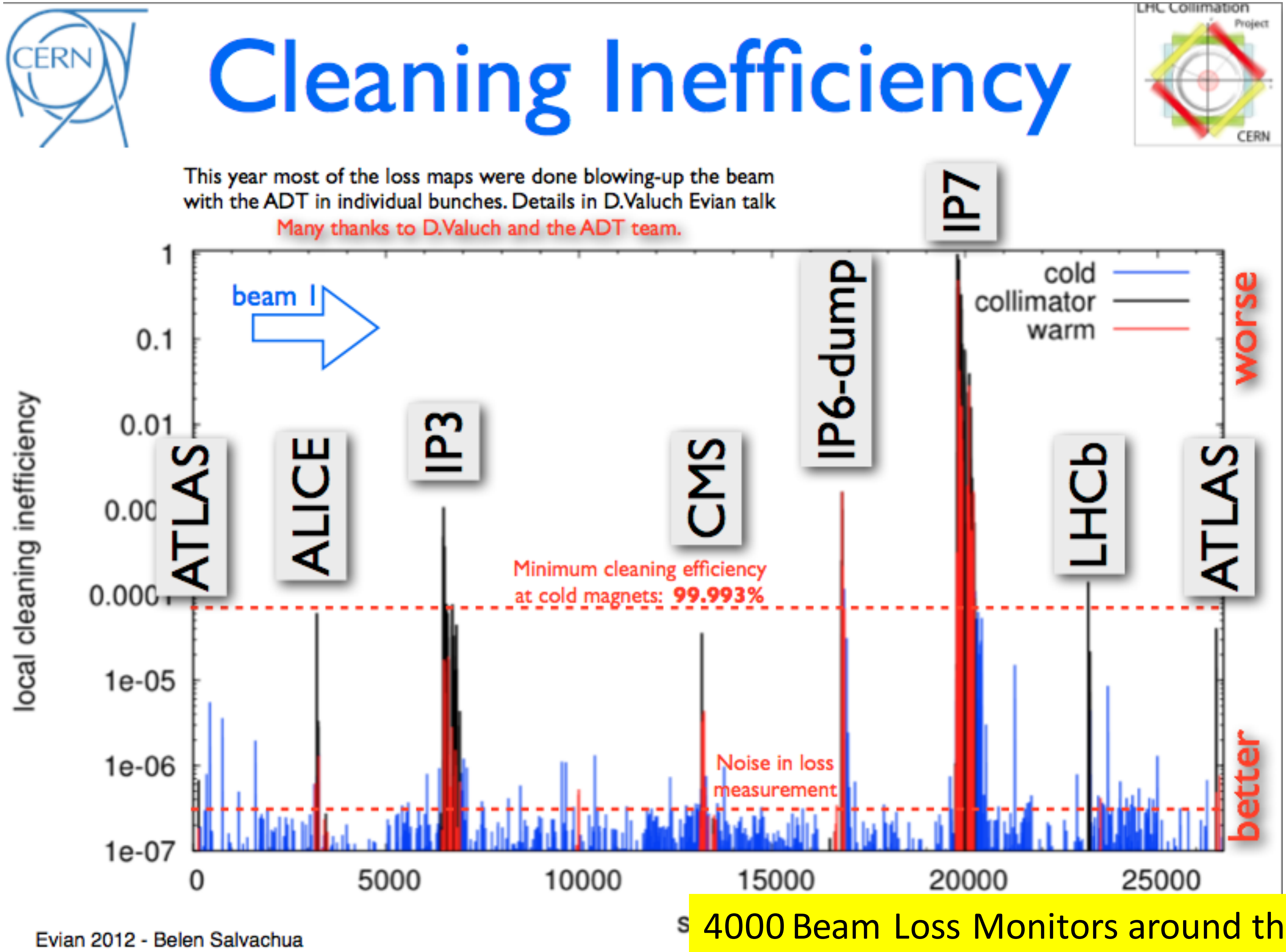
Beam Collimation

- 2 dedicated beam collimation insertions in the LHC. "All" particles should be lost on the beam cleaning collimators and not on the superconducting magnets.
- The different collimators have to be aligned with beam, 1-by-1. Their settings have to follow the collimation hierarchy and the energy ramp.



- Almost ***100 collimators*** *and* ***absorbers***, with a typical length of ~1 m.
- The collimation performance is excellent and very stable, in 2016 the inefficiencies were ≤ 0.03% for a stored energy of 270 MJ/beam.
  - ***No beam induced quench from collimation losses in operation.***
  - *A single setup per year is sufficient ⇔ machine reproducibility.*
  - *The time for alignment was reduced by a factor 10 over 6 years to ~ 6 hours.*

Collimator beam loss cleaning inefficiency



4000 Beam Loss Monitors around the ring

LHC Run II

- The LHC was operated between 2010 and 2013 at beam energies of 3.5 TeV and 4 TeV: **Run 1**.
  - *Run 1 was followed by a ~2 year long shutdown to prepare the LHC for high energy operation.*

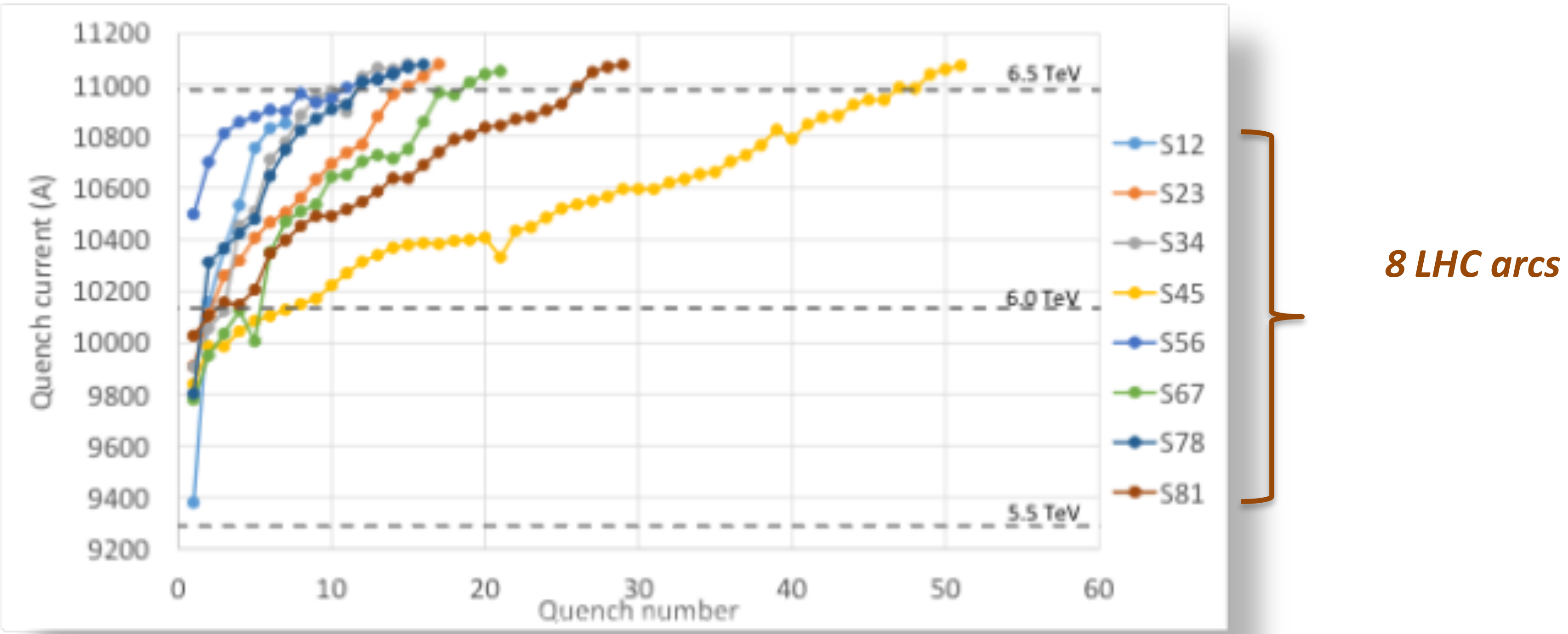
Goals of the 4 year long Run 2 that extends from 2015 to 2018:

- ✓ Operate the LHC at 6.5 TeV.
- ✓ Operate with a bunch spacing of 25 ns.
  - *During Run 1 LHC was operated with 50 ns spacing (e-cloud).*
- ✓ Deliver ≥ 100 fb^{-1} of integrated luminosity.

- After a recovery and learning year in 2015, the goal of the 2016 run was to push the machine towards design performance.

Why not running @ 7 TeV? Dipole training

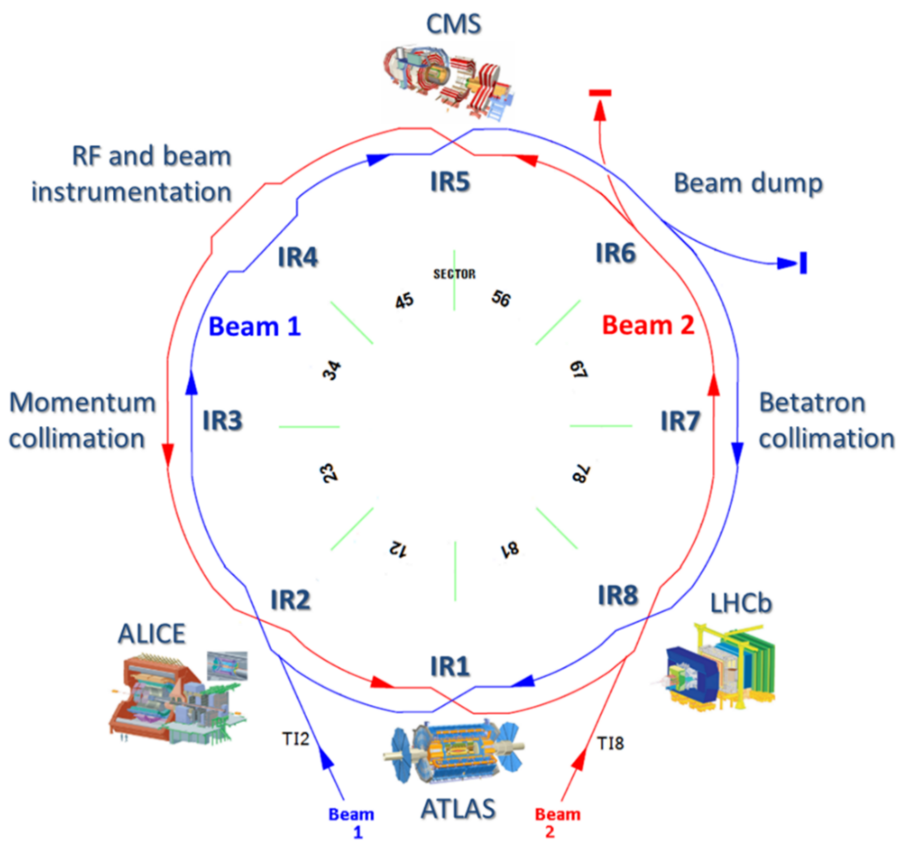
- The 1232 main dipole magnets were trained for 6.5 TeV operation in 2015.
- Just over 150 training quenches were required to reach 6.5 + ε TeV.
  - *The spread in number of quenches between the sectors (arcs) is due to the mixture of magnets from the 3 producers.*
  - *Two sectors were pushed to 6.75 TeV in December 2016.*
    - The training was stopped due to risk of short-circuits in the bypass diodes (metallic debris displaced by gaseous helium waves).



LUMINOSITY

The LHC Experiments

- **ATLAS** and **CMS** are the two <u>high luminosity</u> experiments, **$L \sim 10^{34}\ cm^{-2}s^{-1}$**.
  - — *Most performance figures and parameters refer to those experiments (luminosity, β*).*
- **LHCb** is a <u>medium luminosity</u> experiment, **$L \sim 4\times10^{32}\ cm^{-2}s^{-1}$**.
- **ALICE** is a <u>low luminosity</u> / ion experiment, **$L \sim 10^{31}\ cm^{-2}s^{-1}$**.
- LHCb and ALICE are **luminosity levelled** by beam separation.
  - — *At β* of 10 m (ALICE) and 3 m (LHCb).*
- **TOTEM**, **ALFA** and **AFP** are forward physics experiments.

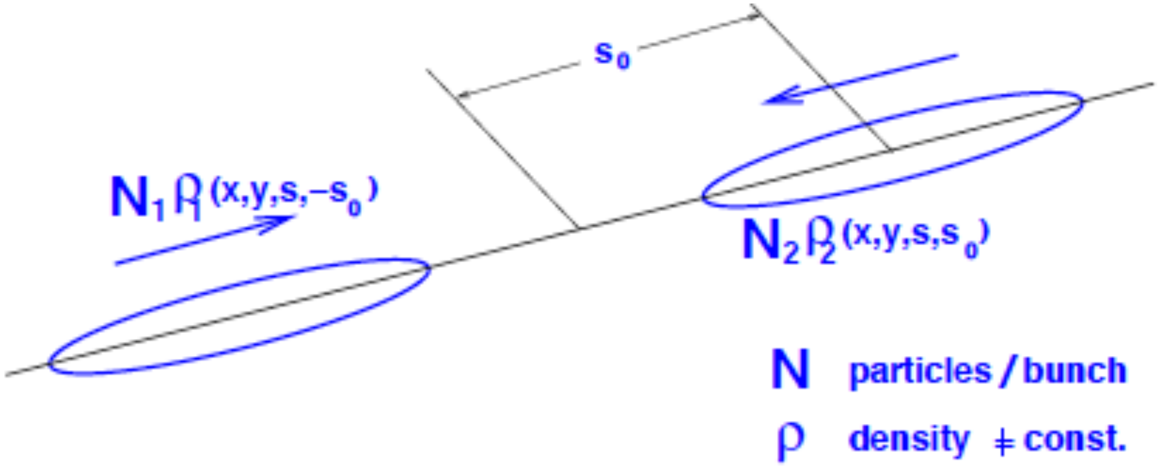


Collider Luminosity

Experiments are interested in maximum number of interactions per second dR/dt:

Luminosity is the proportionality factor between cross section and number of interactions per second:

$$\frac{dR}{dt} = \mathcal{L} \times \sigma_p$$



$$\mathcal{L} \propto K \cdot N_1 \cdot N_2 \int\int\int\int_{-\infty}^{+\infty} \rho_1(x,y,s,-s_0)\rho_2(x,y,s,s_0)dx,dy,ds,ds_0$$

$$s_0 = c \cdot t \qquad K = \sqrt{[(\vec{v}_1 - \vec{v}_2)^2 - (\vec{v}_1 \times \vec{v}_2)]/c^2}$$

Collider Luminosity

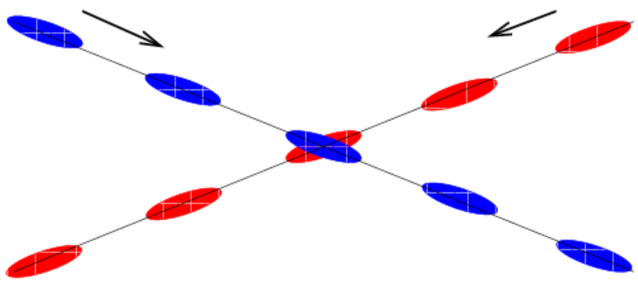
Assume Gaussian particle distributions $$\rho(x) = \frac{1}{\sigma_x \sqrt{2\pi}} \exp(-\frac{x^2}{2\sigma_x^2})$$

And assume: $$\sigma_{1x} = \sigma_{2x}, \sigma_{1y} = \sigma_{2y}, \sigma_{1s} = \sigma_{2s}$$

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi \sigma_x \sigma_y} \cdot S \cdot H$$

Correction factors S and H.

If colliding with many bunches, need collision with crossing angle to avoid unwanted collisions.



The larger the crossing angle, the smaller S.

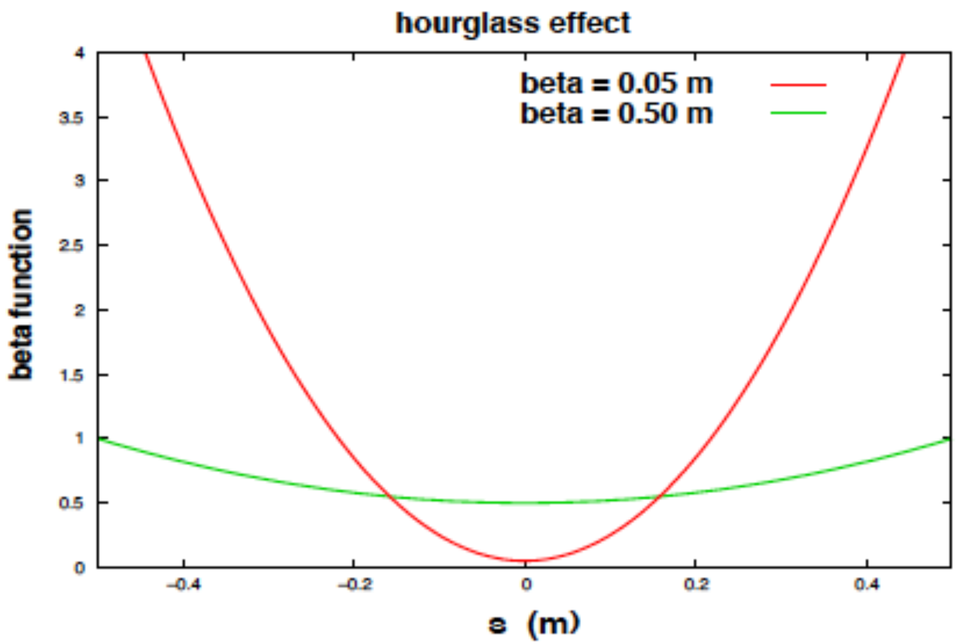
Collider Luminosity

Correction factor H: Hour glass effect

$$\sigma_{x,y} = \sqrt{\beta^*_{x,y} \cdot \varepsilon}$$

β depends on s $$\beta(s) = \beta^* \cdot (1 + (\frac{s}{\beta^*})^2)$$

Beam size depends on s. The longer the bunch the larger the effect.



LHC Design Luminosity

Design parameters for 7 TeV/c per beam operation:

- $N_1 = N_2 = 1.15 \times 10^{11}$ protons per bunch
- $n_b = 2808$ bunches per beam ➔ bunch spacing = 25 ns
- $f_{rev} = 11.2455$ kHz
- crossing angle $\phi = 285$ μrad
- $\beta^*_x = \beta^*_y = 0.55$ m
- $\sigma^*_x = \sigma^*_y = 16.6$ μm (3.5 μm normalized emittance), $\sigma_s = 7.7$ cm

LHC Design Luminosity

Without crossing angle and hour glass effect:

$$\mathcal{L} = 1.2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

Effect of crossing angle:

$$\mathcal{L} = 0.973 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

Effect of crossing angle & hour glass:

$$\mathcal{L} = 0.969 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

Integrated luminosity

What counts for the ATLAS, CMS, LHCb and ALICE is not peak performance but total accumulated number of events

$$\underbrace{\sigma_p}\cdot\underbrace{\mathcal{L}_{int}} = \sigma_p \cdot \int_0^T \mathcal{L} dt$$

unit "barn" = 10^{-24} cm^2

unit " inverse barn" = 10^{24} cm^{-2}

1 fbarn^{-1} = 10^{39} cm^{-2}

For example:

For 1 fbarn^{-1}: requires 10^7 s at $\mathcal{L} = 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

One year has 3.1536×10^7 s.

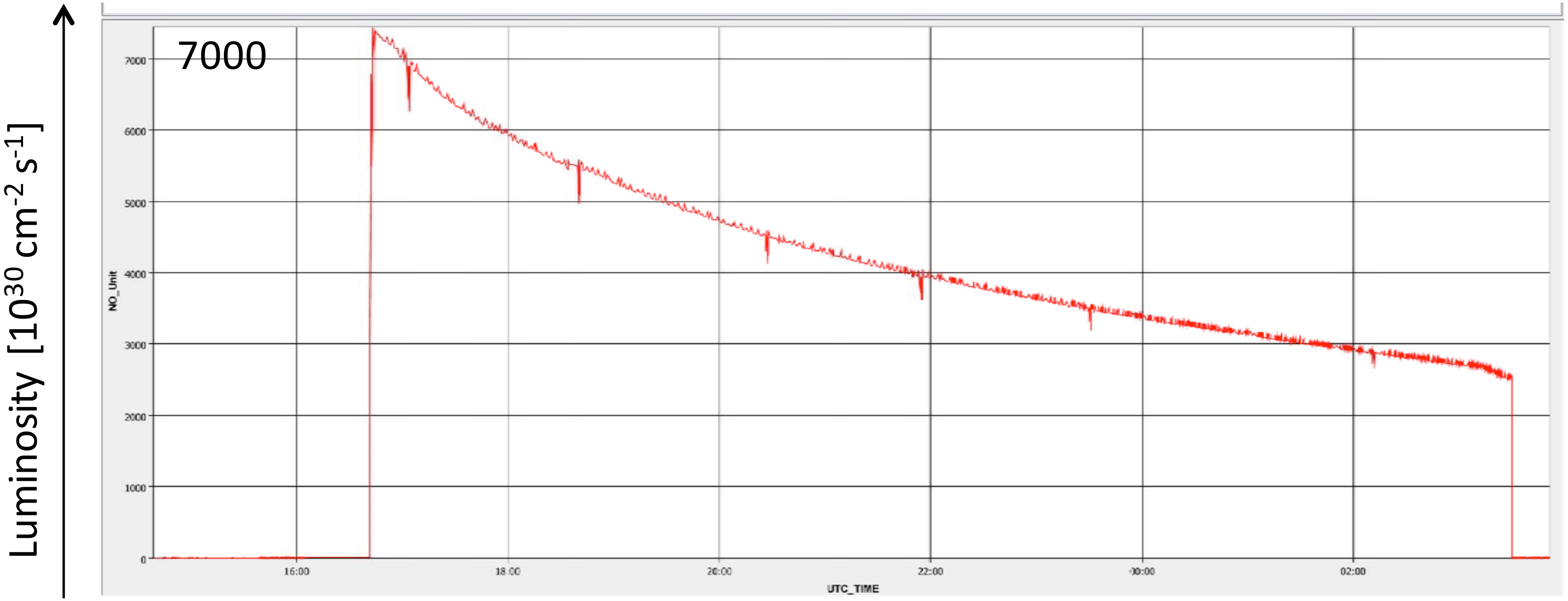
Luminosity during Fill

LHC fill = one full operational cycle: injection + energy ramp …collision + data taking + beam abort

Luminosity decays during fill after beams have been put into collision:

- intensity burn-off (for nominal parameters about 20 interactions per crossing)
- Emittance growth

$$\mathcal{L}(t) = \mathcal{L}_0 \exp(-\frac{t}{\tau})$$



Optimizing Luminosity

Luminosity is higher for

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma^2} = \frac{N_1 N_2 f n_b}{4\pi\beta^* \varepsilon}$$

- High number of bunches
- High number of particles per bunch $\propto N^2$
- Small emittance
- Small β^*
- Small crossing angle, short bunches

Unfortunately cannot arbitrarily play with these parameters:
"Collective effects" cause beam instabilities for too high bunch intensities, too small bunch spacing, too "bright" beams

β^* together with crossing angle are linked to the available aperture in the triplet quadrupole magnets.

β^* and the Squeeze

Remember: mini-beta insertions

Beta around the waist:

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

Unfortunately the detectors are large

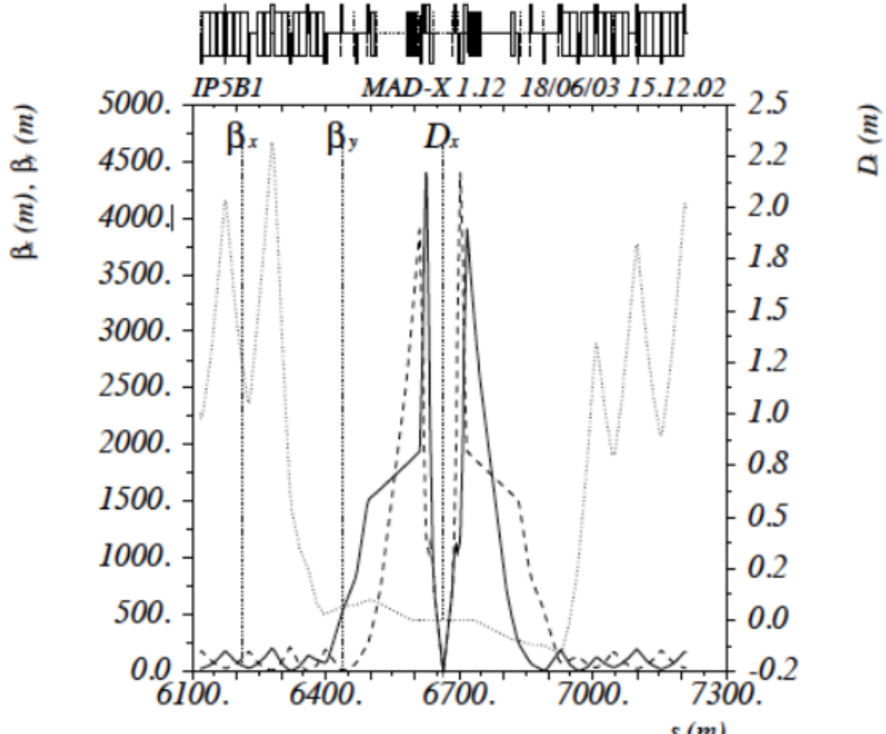
$$\beta_{max} = 4.5\text{km} \qquad \sigma = 1.5\text{mm}$$

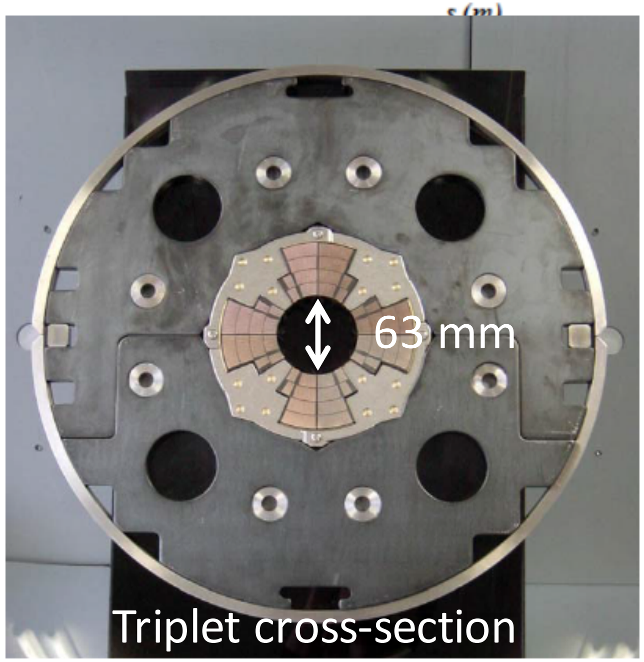
... @ 7 TeV

@ 450 GeV: 5.7 mm!!!

➔ Can only go to small β^* at top energy.

➔ Inject with β^* = 11 m. Max $\beta_{triplet}$ ~ 240 m





Triplet cross-section

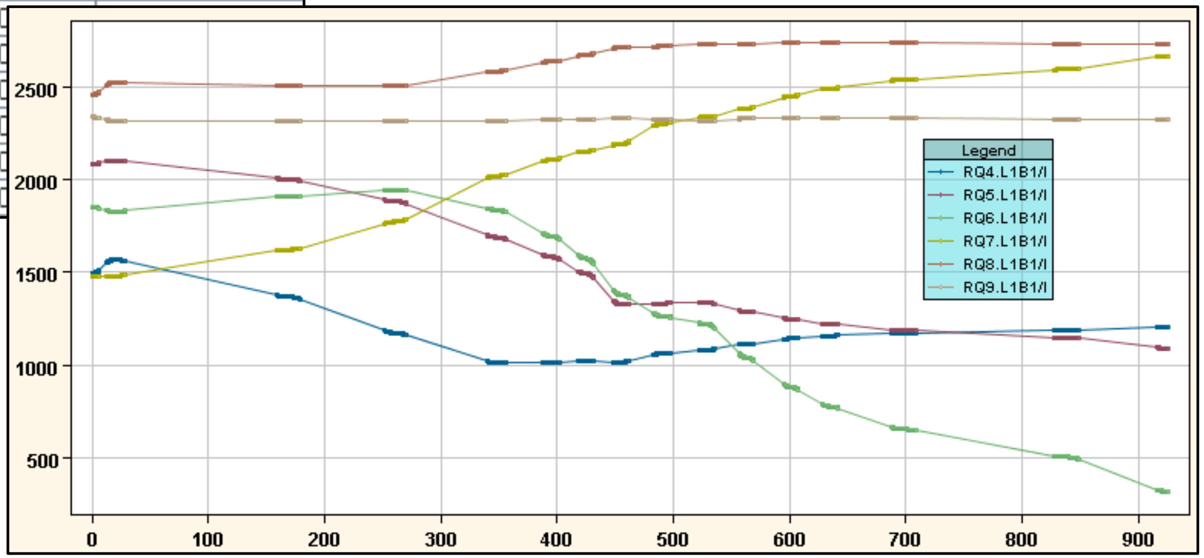
The Squeeze

During the squeeze the optics is changed locally. Everywhere else the beta functions are kept constant.

Go through a set of different optics. Can stop at each point and correct.

Optic Name	Energy	Time
A1100C1100A1000L1000_INJ_2012	4000.0	0
A1100C1100A1000L1000_2012	4000.0	19
A900C900A900_0.00915L750_0.00932_2012	4000.0	169
A700C700A750_0.00897L600_0.00909_2012	4000.0	262
A400C400A600_0.00889L500_0.00900_2012	4000.0	348
A300C300A500_0.00889L375_0.00888_2012	4000.0	396
A250C250A450_0.00889L350_0.00882_2012	4000.0	425
A200C200A400_0.00889L325_0.00878_2012	4000.0	455
A160C160A350_0.00889L300_0.00875_2012	4000.0	491
A150C150A300_0.00889L300_0.00875_2012	4000.0	529
A120C120A300_0.00889L300_0.00875_2012	400	
A100C100A300_0.00889L300_0.00875_2012	400	
A90C90A300_0.00889L300_0.00875_2012	400	
A80C80A300_0.00889L300_0.00875_2012	400	
A70C70A300_0.00889L300_0.00875_2012	400	
A60C60A300_0.00889L300_0.00875_2012	400	

The different optics played during the 2012 squeeze.

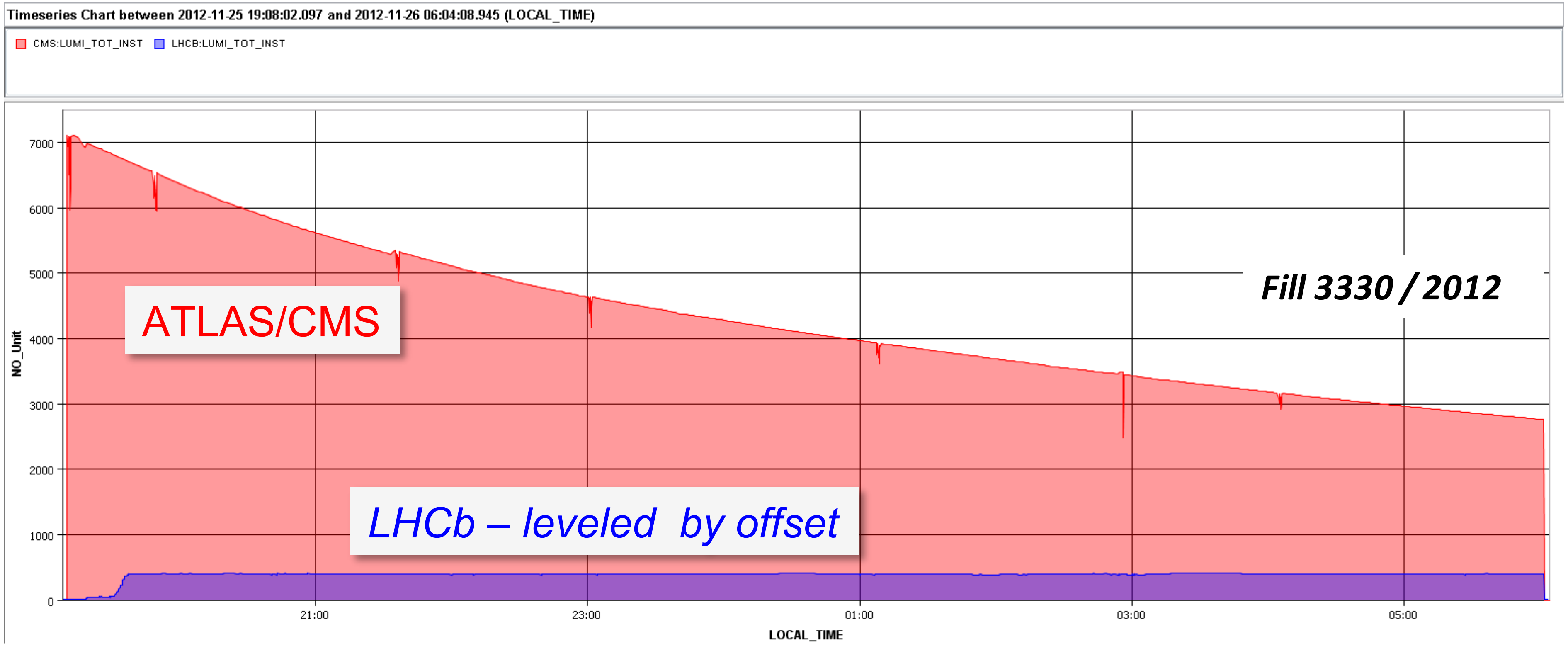


The current functions of some of the involved quadrupoles in point 1.

Luminosity Leveling

Reduce the peak luminosity on purpose by

- Offset leveling
- β^* leveling



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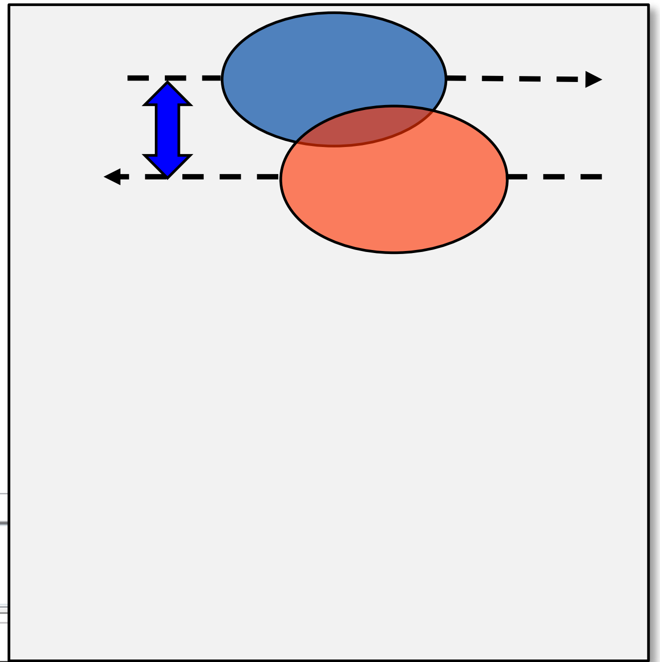

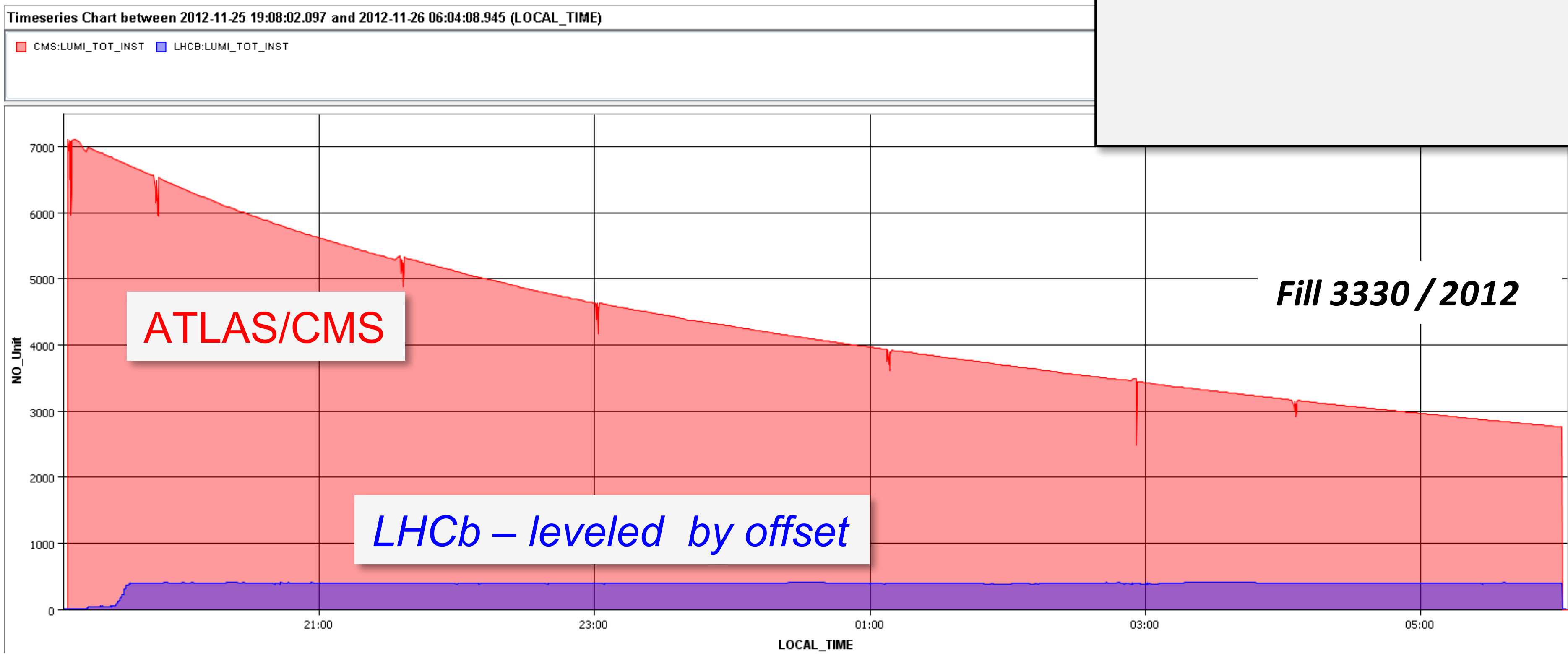

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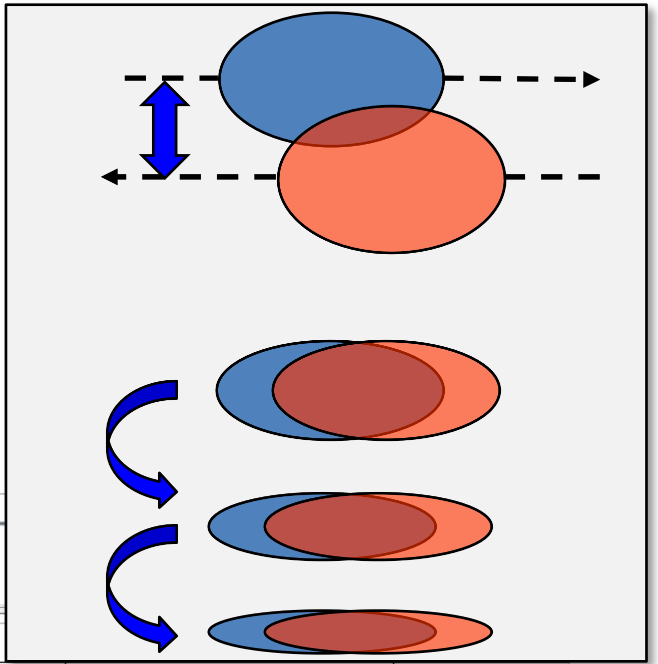
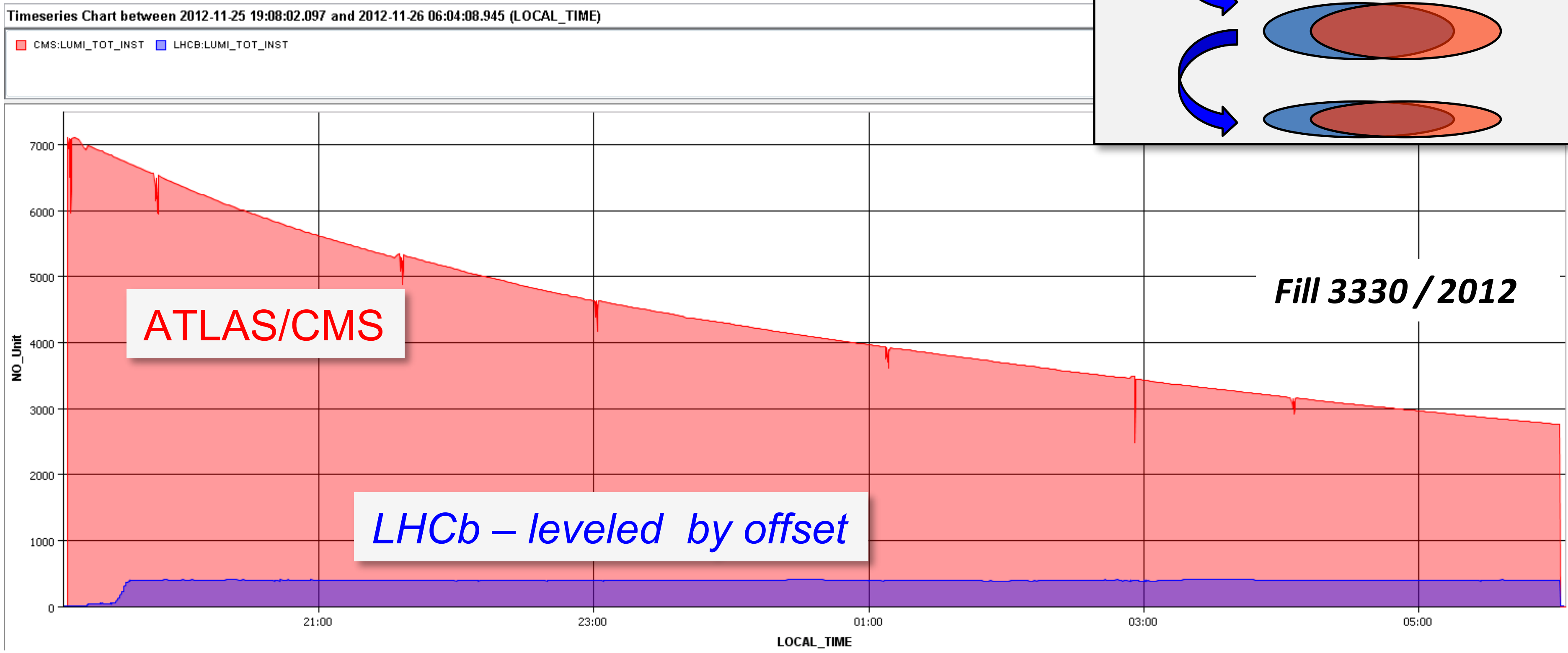
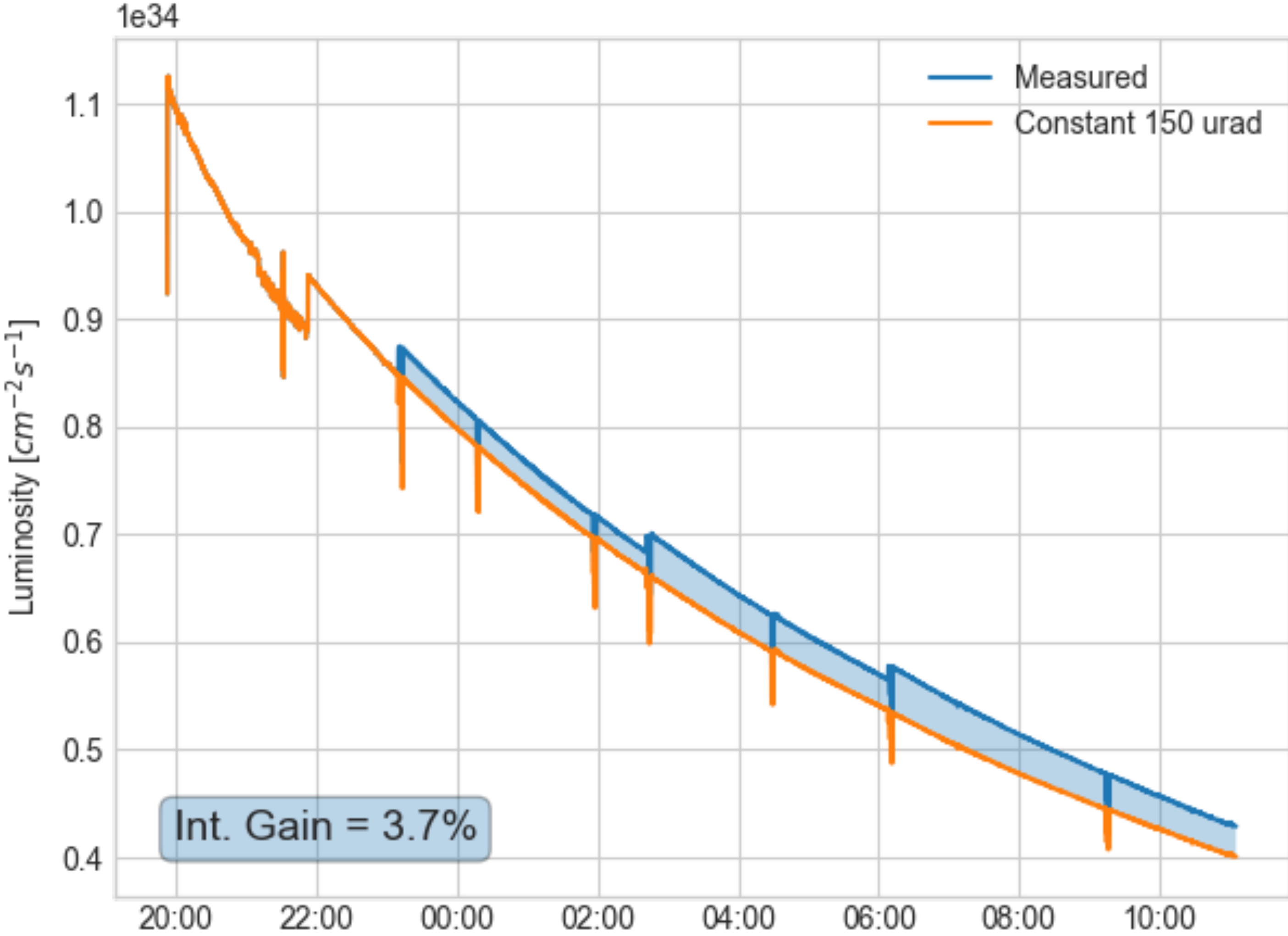




Crossing angle "leveling"

LHC 2017 operation



Courtesy M. Hofstettler

Luminosity: The Event Pile-up Issue

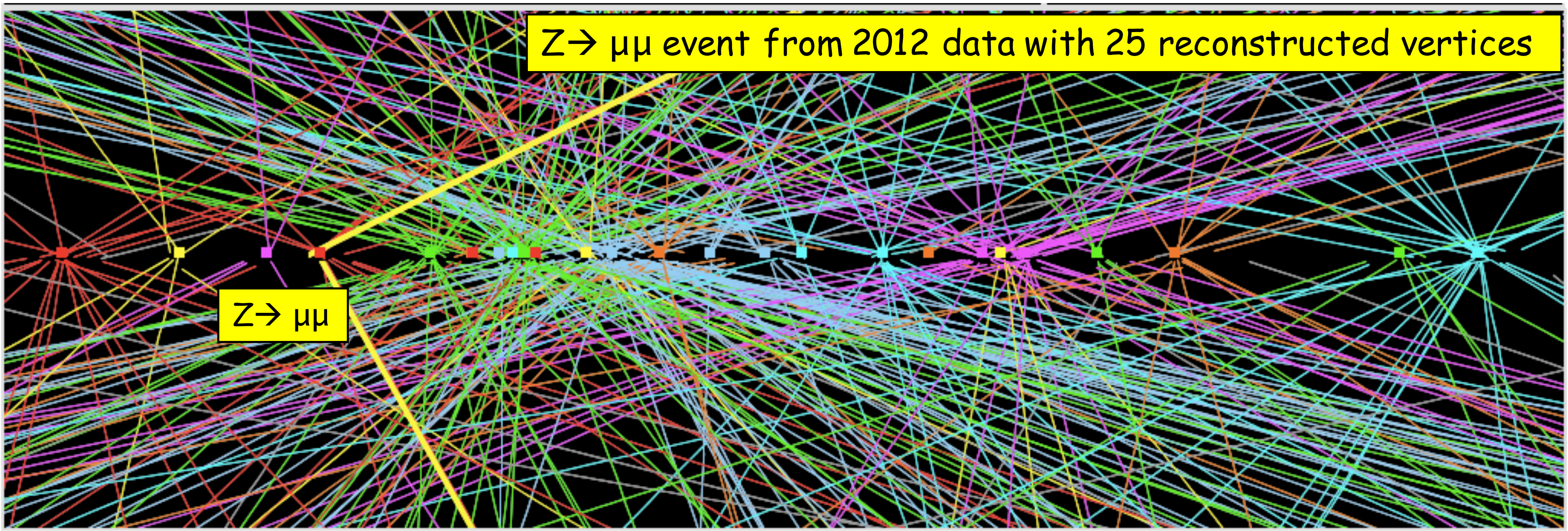
Excellent performance during LHC run I due to very "bright" 50 ns beams from injectors.

Brightness: $\frac{N}{\varepsilon}$

50 ns 2012: 1.7×10^{11} p+/bunch, 1.5 μm normalized emittance

The price to pay (apart from instabilities):

High luminosity with fewer collisions: high pile-up. 2012 up to 35 events per crossing



The Event Pile-up μ Issue

➔ Run 2 energy ≥ 6.5 TeV

Scaling $\mathcal{L} = 7.7 \times 10^{33}$ cm^{-2} s^{-1} to 7 TeV: ~ 2 × 10^{34} cm^{-2} s^{-1} with 50 ns

➔ Pile-up of ~ 100

The pile-up limit for the experiments in 2015: μ ~ 50

Run 2:

- Make 25 ns bunch spacing work:
    - For the same total luminosity: less luminosity per bunch

LHC Run II Parameters

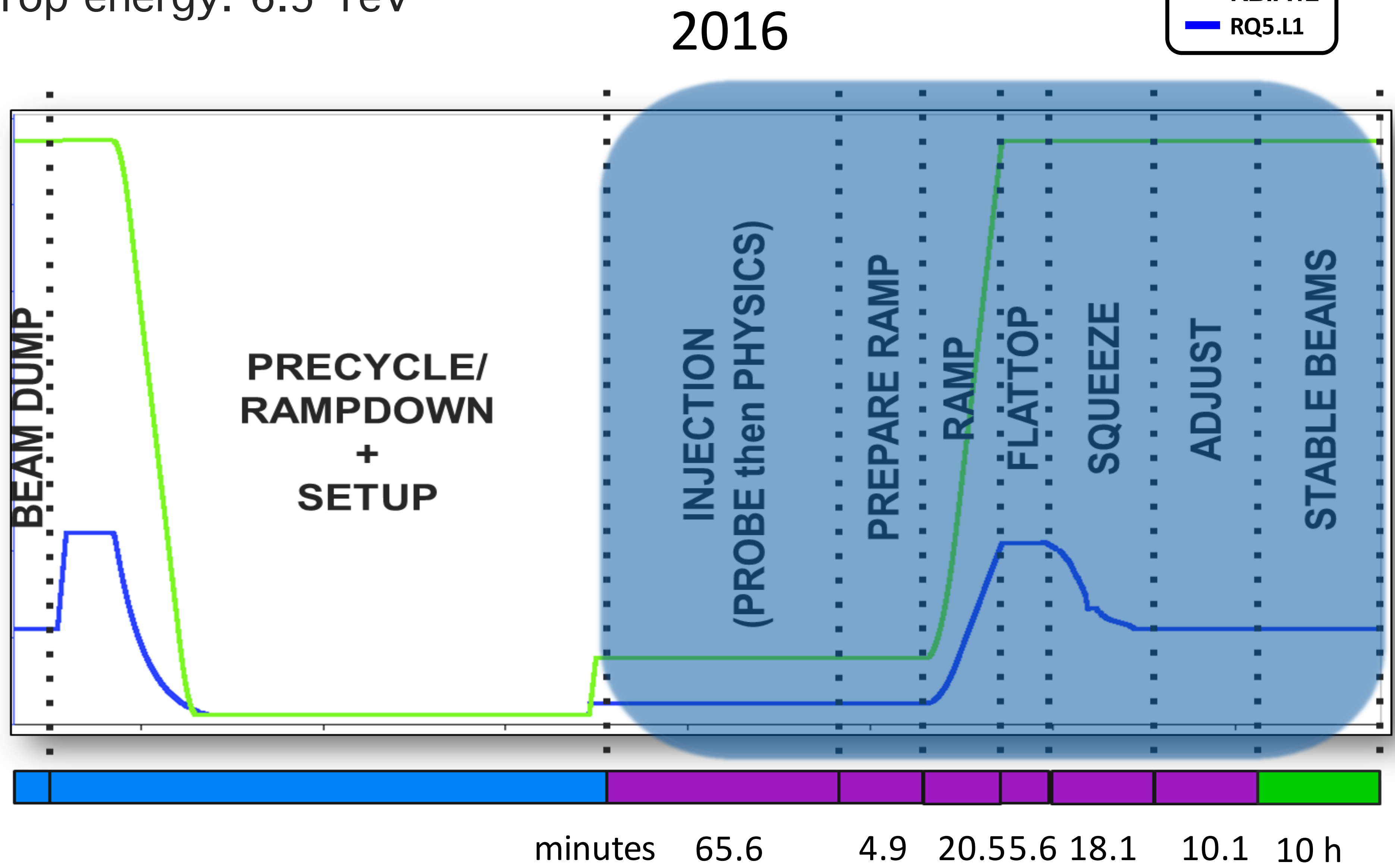
- After the 2015 *training* run with a conservative configuration, β* was lowered from **80 cm to 40 cm** in 2016.
- The injector performance was key!
- Performance limitations encountered in 2016:
  - *A vacuum leak in the SPS (injector) beam dump limited the train length to 144 bunches (instead of 288) → **limit on bunch number** in the LHC.*
  - *Electron cloud induced vacuum pressure rise around the LHC injection kickers **limited the bunch intensity**.*

Parameter	Design	2015	2016	2017
Bunch population N_b (10^{11} p)	1.15	~1.2	~1.1	~1.2
No. bunches k	2780	2244	2220	~2550
Emittance ε (mm mrad)	3.5	~3.5	~2.2	~2.2
β* (cm)	55	80	40	40 (33)
Full crossing angle (μrad)	285	290	370 / 280	300 (340)
Peak luminosity (10^{34} $cm^{-2}s^{-1}$)	1.0	0.51	1.4	~1.7 (1.9)

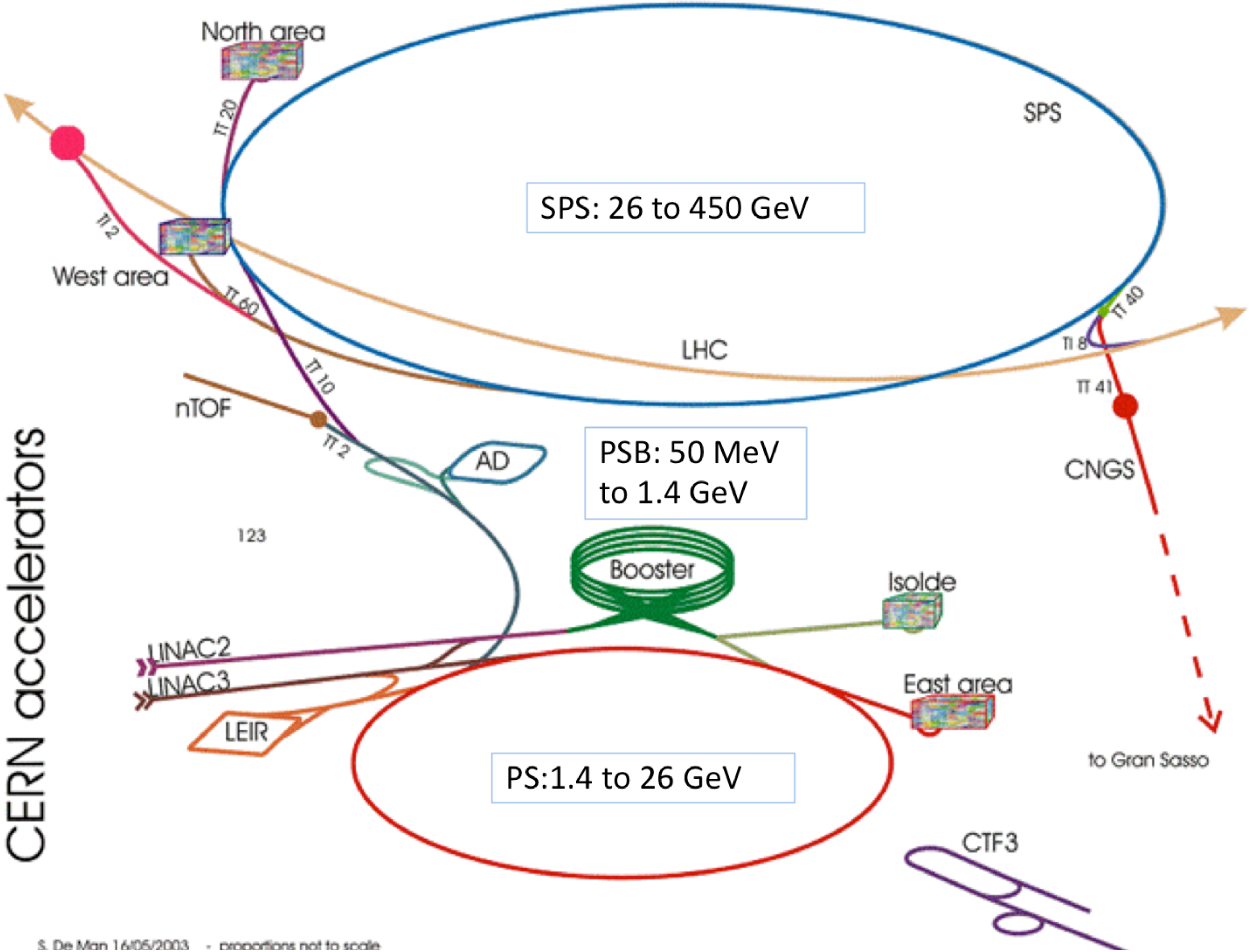
LHC Operational Cycle Run II

Injection energy: 450 GeV

Top energy: 6.5 TeV

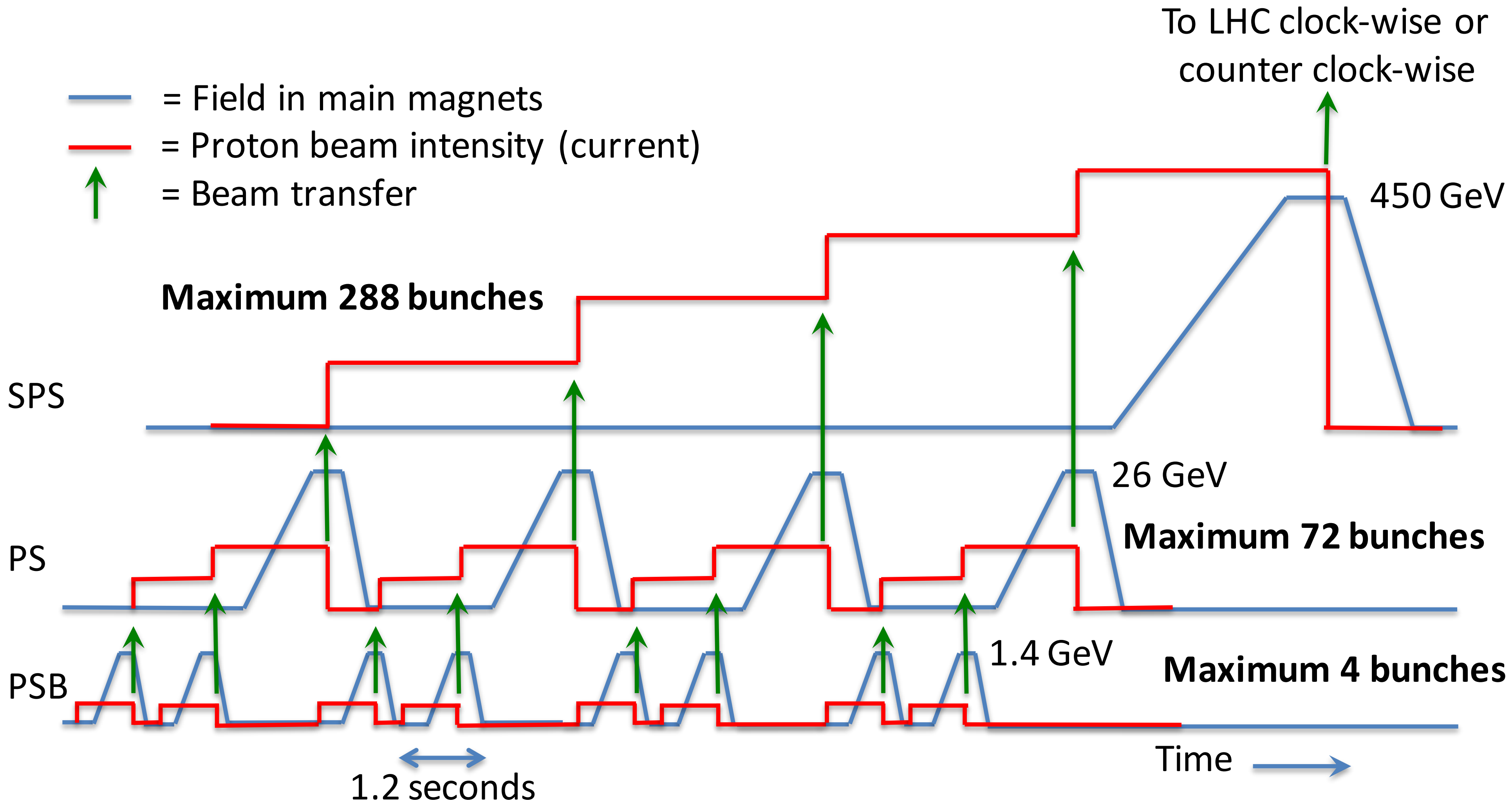


LHC Filling from the LHC Injector Chain



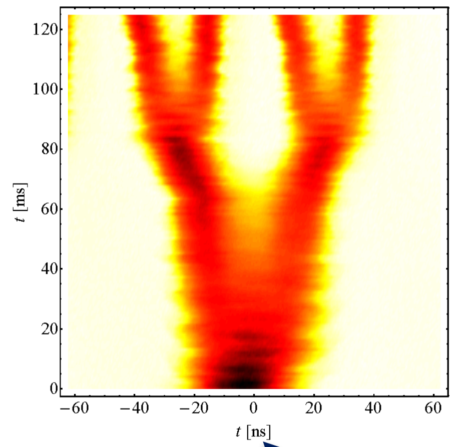
The LHC Injector Cycling

LHC needs ~ 12 injections per ring from the SPS.

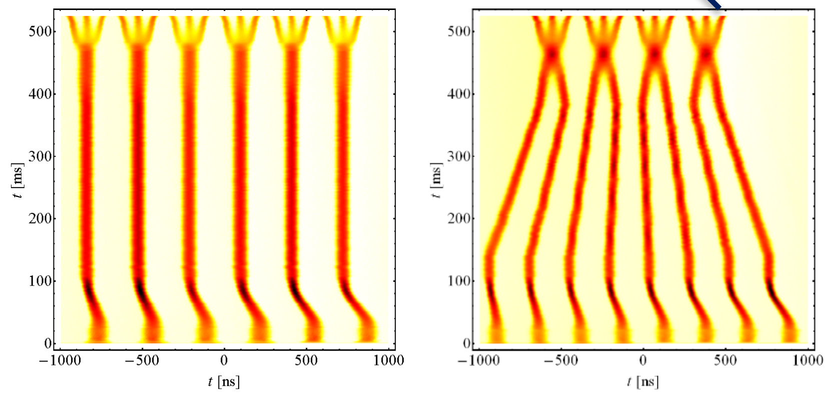


Injector Beams

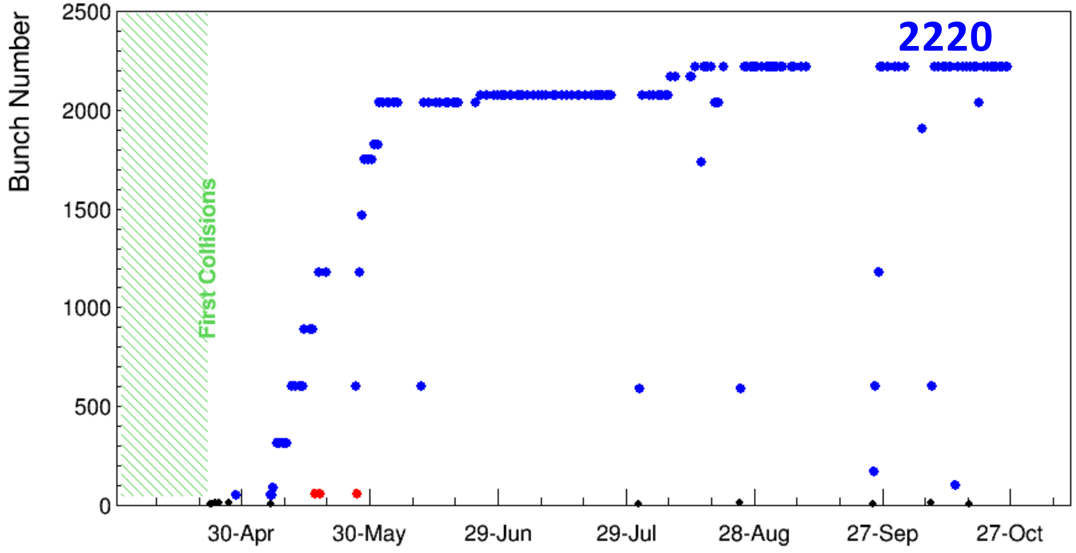
- The standard LHC beam with 25 ns bunch spacing is obtained in the Proton Synchrotron by splitting of 6 booster bunches into **72 bunches** at extraction.
  - *Triple splitting at low energy, 2x double splitting at high energy.*
  - ***Emittance at injection into LHC ~ 2.8 μm.***

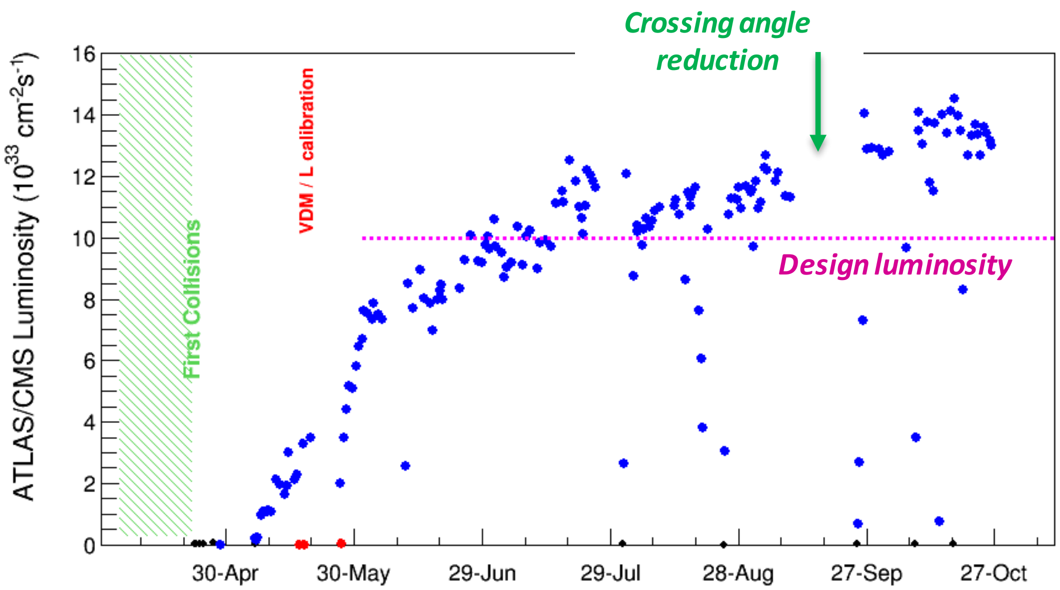


- A lower emittance variant is obtained from 8 booster bunches that are first compressed and merged longitudinally into 4 bunches (Batch Compression Merging and Splitting, BCMS), followed by splitting into **48 bunches** at extraction.
  - ***Emittance at injection into LHC ~ 1.5 μm.***



Exceeding nominal performance in 2016

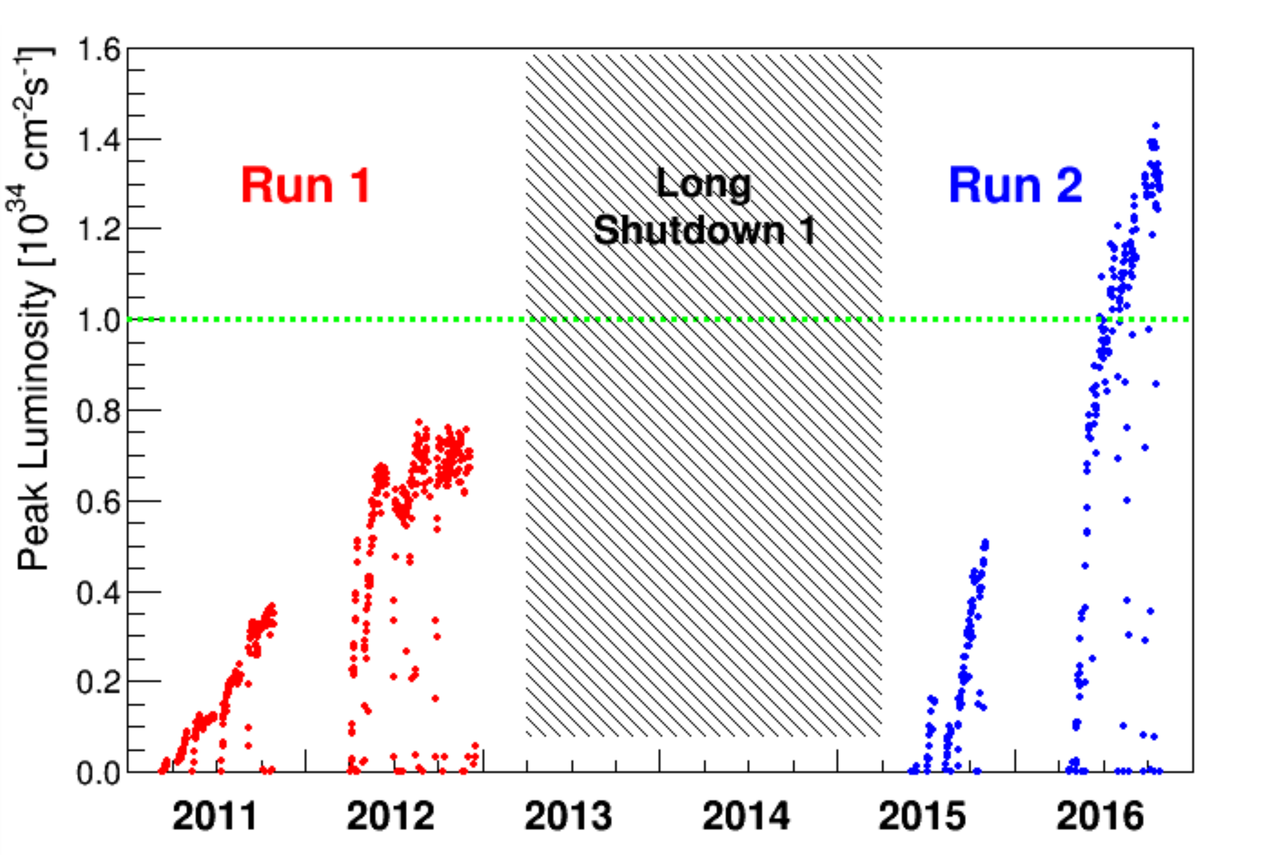




- Despite limitations on the injected intensity (SPS dump, LHC injection kicker vacuum), the *LHC exceeded its design luminosity by 40%.*
- The luminosity performance was achieved thanks to *low emittance beams* from the LHC injectors and to *smaller β**.
- In September the half *crossing angle was reduced from 370 to 280 μrad*, providing an additional luminosity gain of ~25%.

Courtesy J. Wenninger

Peak performance 2011-2016



Peak luminosity:

Run 1: 7.6×10^{33} cm^{-2}s^{-1}

Run 2: 1.4×10^{34} cm^{-2}s^{-1}

Design luminosity:

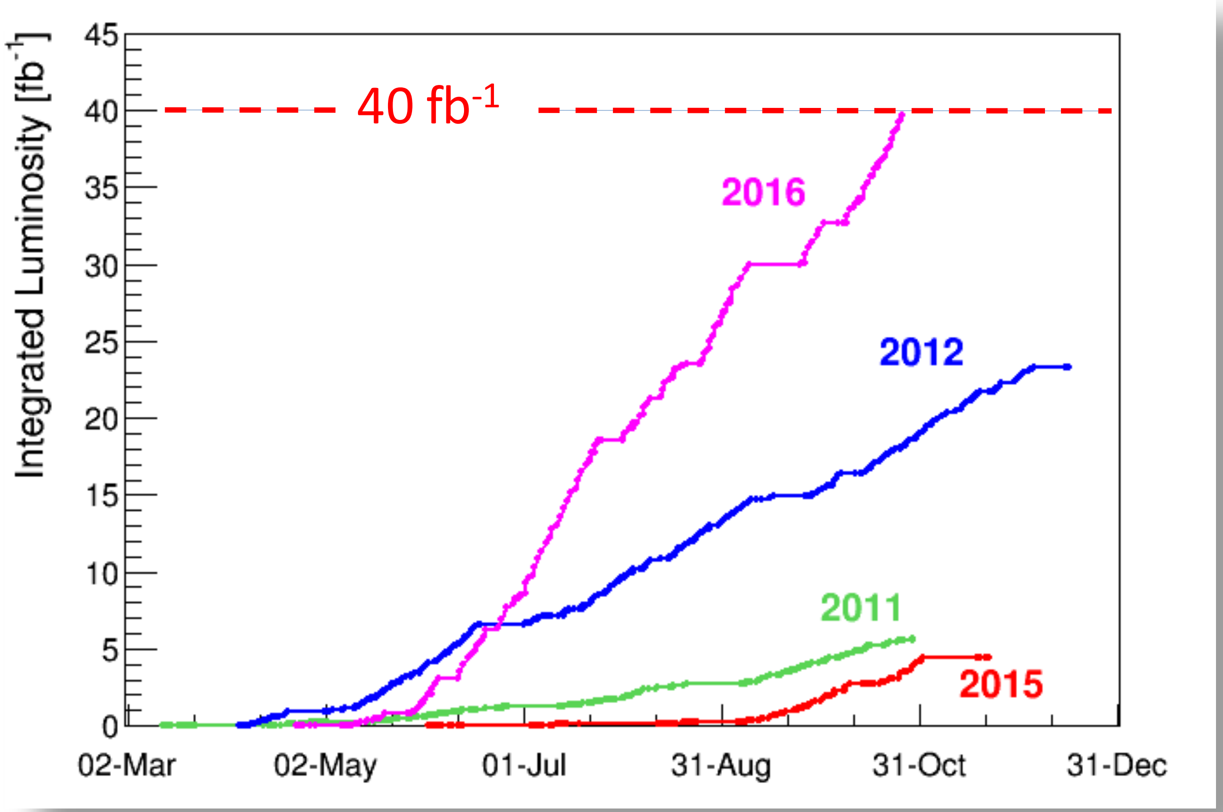
1×10^{34} cm^{-2}s^{-1}

Courtesy J. Wenninger

Integrated luminosity 2016

The integrated luminosity reached 40 fb^{-1}, well above the 25 fb^{-1} target:

- ✓ ***Record peak luminosity,***
- ✓ ***Excellent machine reproducibility,***
- ✓ ***High availability,*** *~ 50% better than in previous years.*

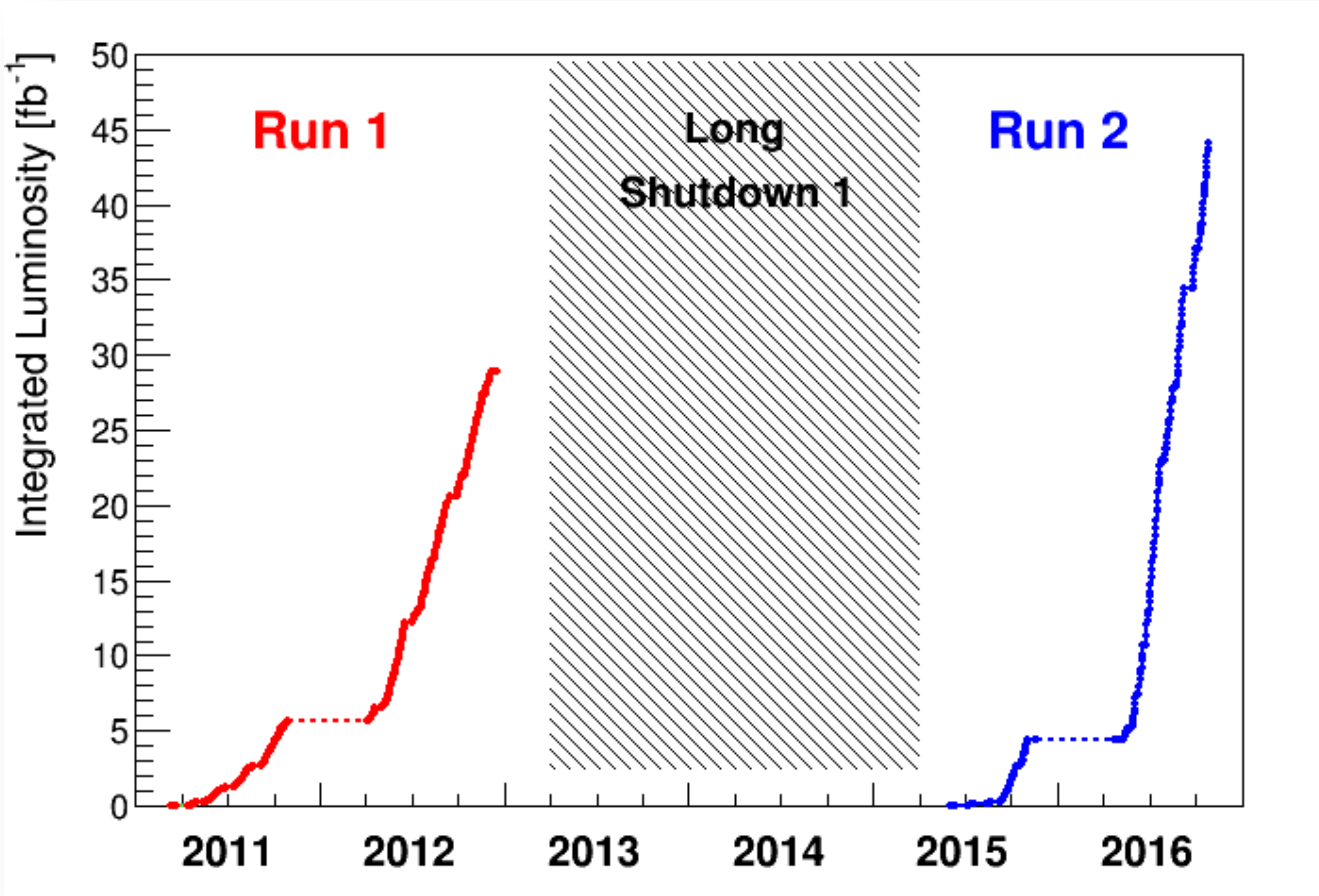


Courtesy J. Wenninger

Integrated performance 2011 - 2016

Total integrated luminosity:

- ✓ ***30 fb^{-1}*** *at 3.5 TeV & 4 TeV – Run 1,*
- ✓ ***45 fb^{-1}*** *at 6.5 TeV – Run 2.*



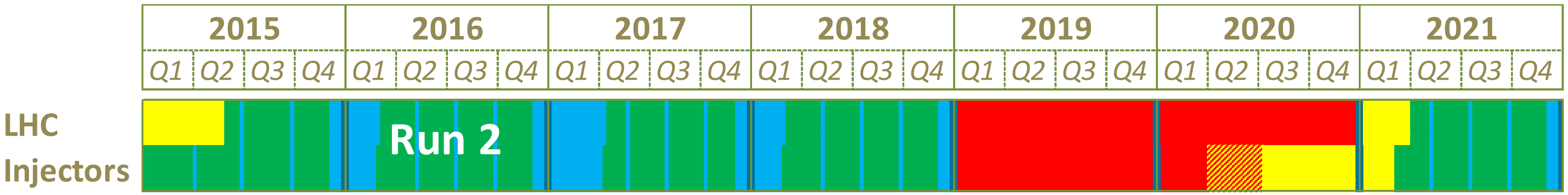
Courtesy J. Wenninger

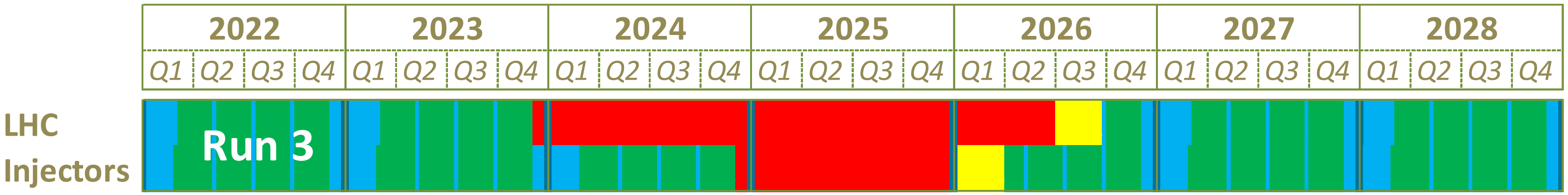
LHC in 2017

- The LHC is in physics s**ince end of May.**
- The optics has been changed to be compatible with an Achromatic Telescope Squeeze (ATS) that is the baseline optics for HL-LHC.
  - *The initial β^* remains at 40 cm, with the option to move to 33 cm later in the year.*
- The intensity limitations at injection are lifted and the peak luminosity may reach (or exceed) 1.7×10^{34} cm^{-2}s^{-1}.
  - *The cryogenic cooling capacity of the low-beta quadrupoles is estimated to be around 1.75×10^{34} cm^{-2}s^{-1}.*
- **In addition to luminosity levelling by offset** (to lower the luminosity) **levelling by crossing angle** will be attempted for the first time to increase the luminosity by reducing the crossing angle during fills.

Outlook for LHC Run 2

- With the **LHC operating beyond design luminosity**, pushing the experiments improve their capacity to handle high pile-up, the prospects to reach and exceed the **Run 2 target of 100 fb^{-1}** are very good.
- A major upgrade of the **LHC injectors** is foreseen during Long Shutdown 2 (2019-2020) to reach the HL-LHC beam parameter targets.
- During Run 3 (2021-2023) the LHC may operate at 7 TeV and the integrated luminosity should reach 300 fb^{-1} at energies ≥ 6.5 TeV by the end of 2023.
- Between 2024-2026 the HL-LHC upgrade will deploy its changes across the LHC for Run4.





THE END