Approaching nominal performance at the LHC

THE 8th INTERNATIONAL PARTICLE ACCELERATOR CONFERENCE

Copenhagen, May 2017

Jörg Wenninger

CERN Beams Department

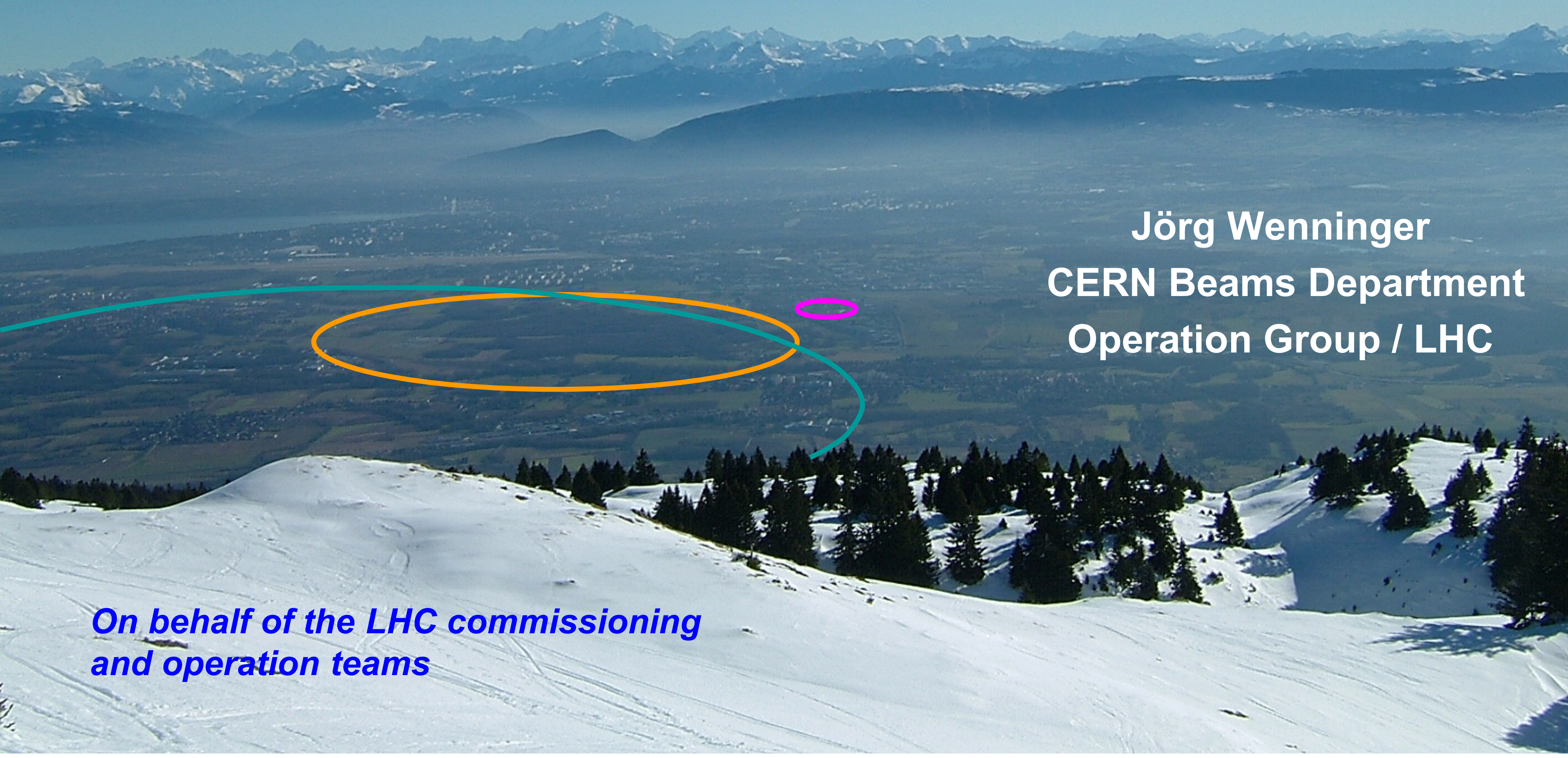
Operation Group / LHC

On behalf of the LHC commissioning and operation teams

Exceeding nominal performance at the LHC

THE 8th INTERNATIONAL PARTICLE ACCELERATOR CONFERENCE

Copenhagen, May 2017



Jörg Wenninger
CERN Beams Department
Operation Group / LHC

On behalf of the LHC commissioning and operation teams

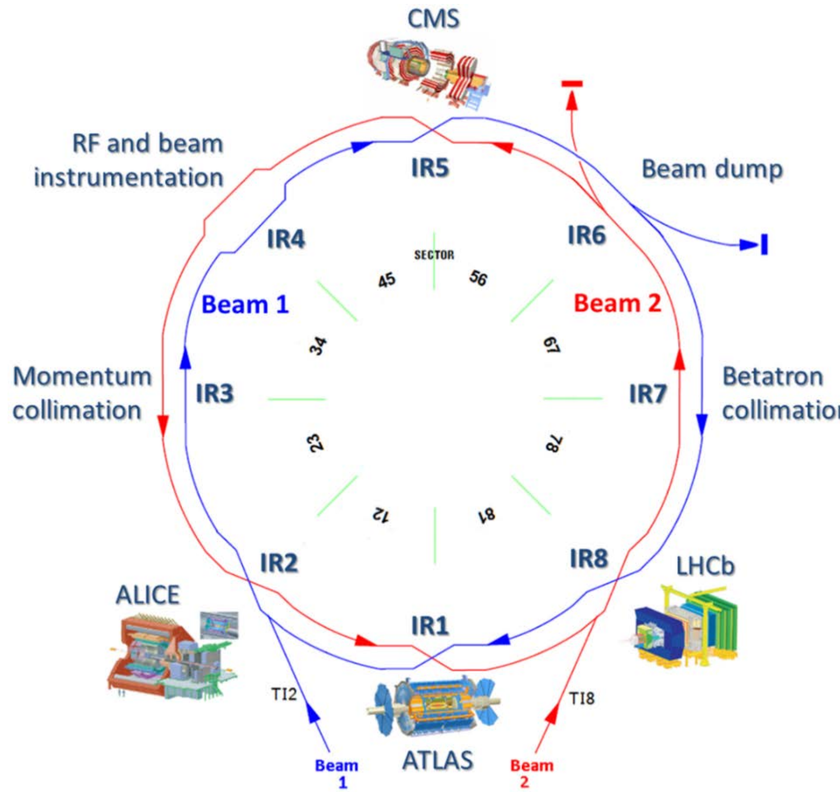
Outline

Introduction

LHC performance in 2016

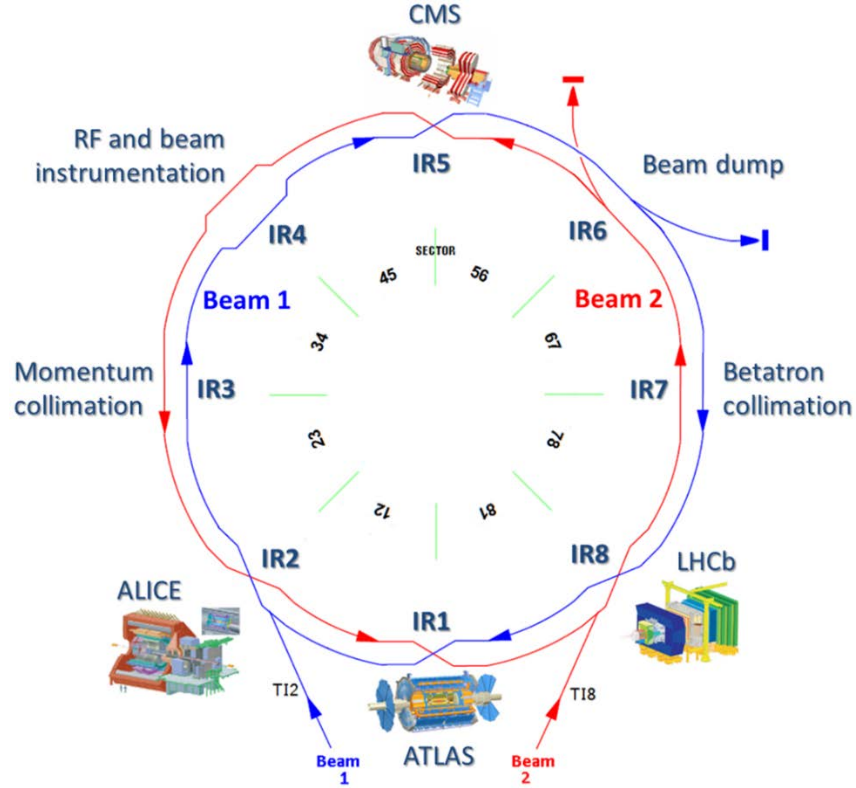
Operation and challenges

Outlook



The LHC experiments

- **ATLAS** and **CMS** are the two high luminosity experiments, **$L \sim 10^{34}$ cm^{-2}s^{-1}**.
  - *Most performance figures and parameters refer to those experiments (luminosity, β*).*
- **LHCb** is a medium luminosity experiment, **$L \sim 4\times10^{32}$ cm^{-2}s^{-1}**.
- **ALICE** is a low luminosity / 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.



LHC Run 2

- 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.*

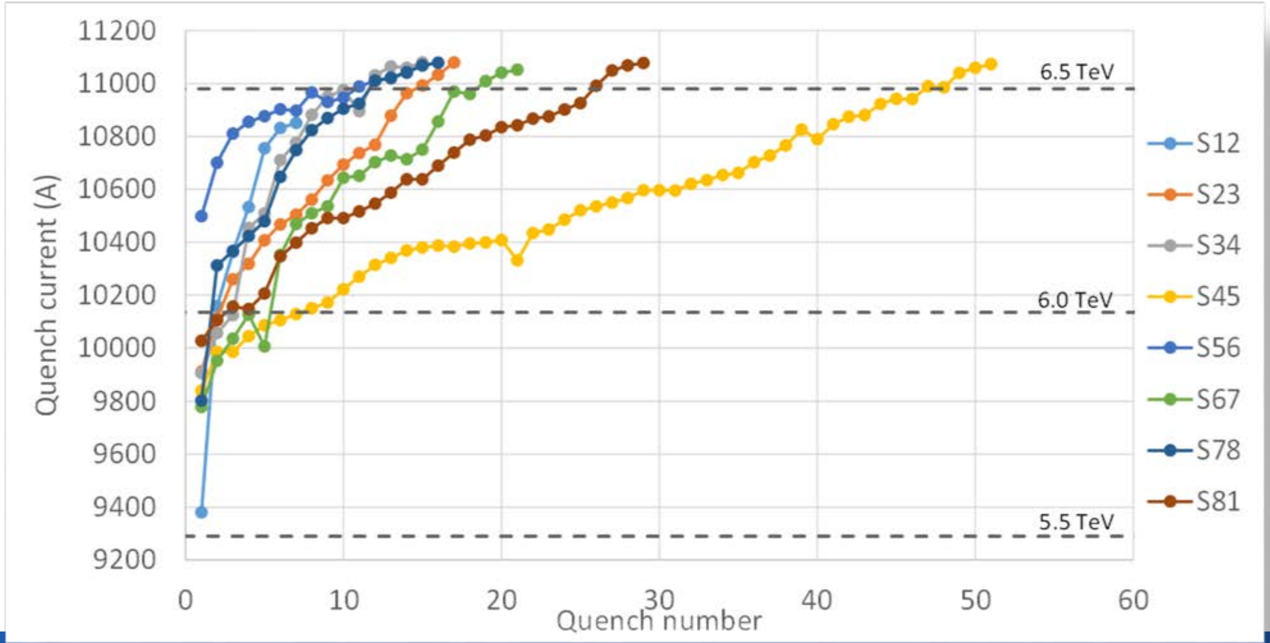
Goals of the 4 year long Run 2 that extends from 2015 to 2018:

- ✓ 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.

Dipole training and energy

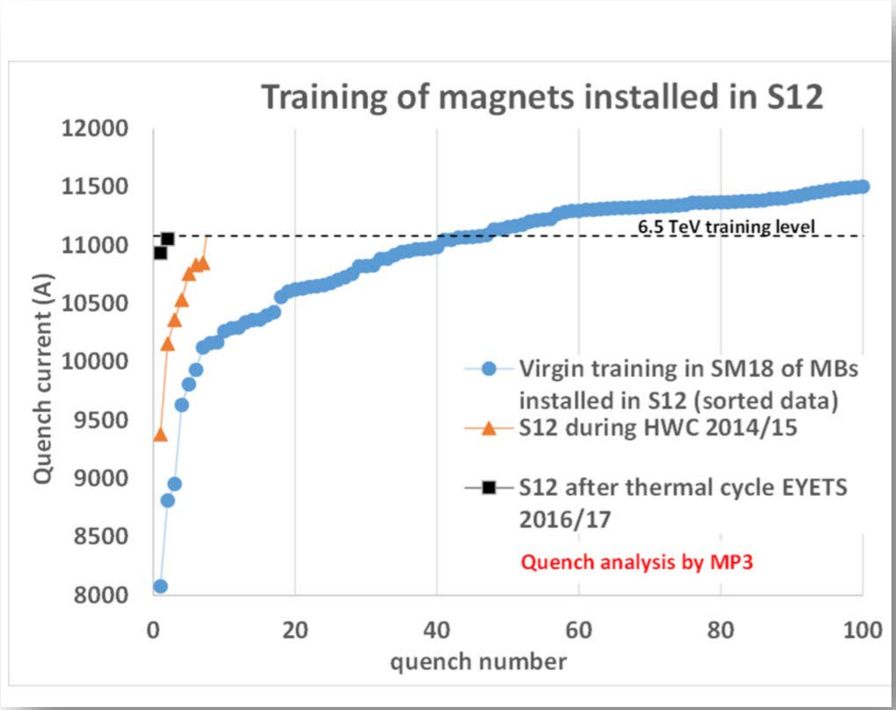
- The 1232 main dipole magnets were trained for 6.5 TeV operation in 2015.
- Just over 150 training quenches were required to reach 6.5 + ε TeV.
  - *The spread in number of quenches between the sectors (arcs) is due to the mixture of magnets from the 3 producers.*
  - *Two sectors were pushed to 6.75 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).



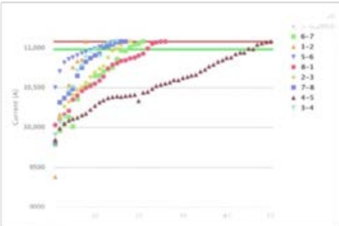
8 LHC sectors (~ arcs)

Dipole re-training

- During the winter shutdown 2016-2017 one sector (S12) was warmed up to room temperature to exchange a dipole magnet with a suspected intermitent short.
- The re-training after cooldown was very fast, with only 2 training quenches to reach 6.5 TeV.



Run 2 timeline



April 3,
End of powering tests – 150 quenches

April 10
First beam at

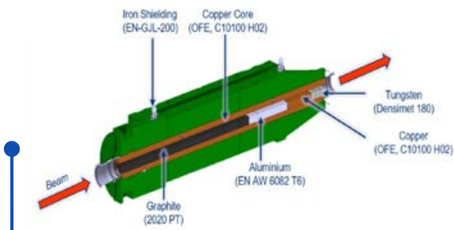
E: 6500 GeV

October 28,
Record no. bunches

2244

Easter again,
Beam back

April 25,
SPS dump vacuum leak
Limited train length to LHC

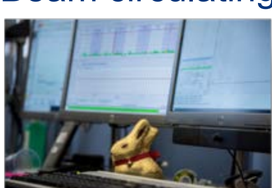


July,
Design luminosity

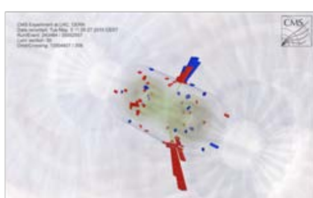
$\mathcal{L}$ >10^{34}cm^{-2}s^{-1}

2015 | **2016**

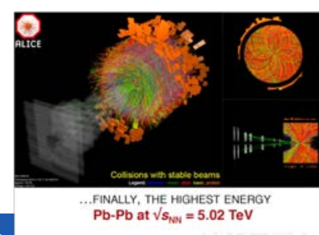
Easter,
Beam circulating



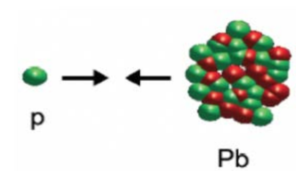
June 3,
Start of physics operation for run 2



Nov-Dec,
Pb ion run



Nov-Dec,
p – Pb run



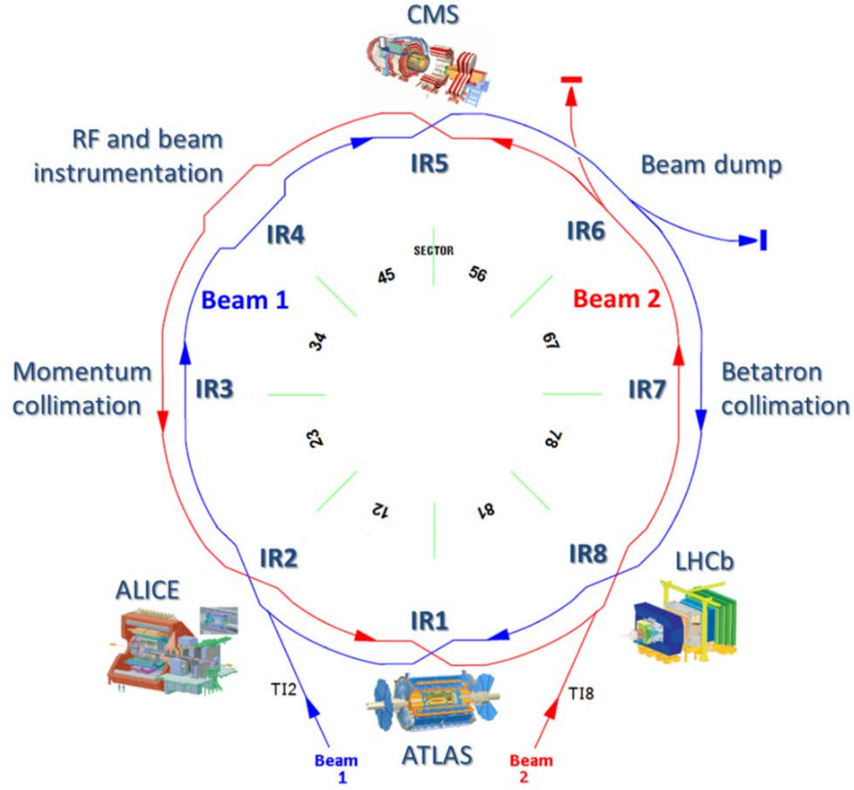
Outline

Introduction

LHC performance in 2016

Operation and challenges

Outlook



LHC parameters

- After the 2015 *training* run with a conservative configuration, β* was lowered from **80 cm to 40 cm** in 2016.
- Performance limitations encountered in 2016:

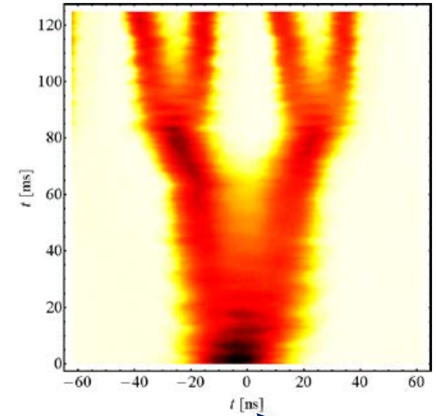
WEPVA110

  - *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**.*

WEPVA100

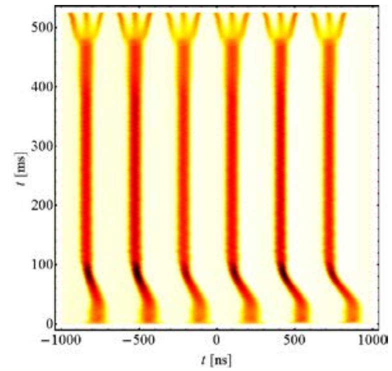
Parameter	Design	2015	2016	2017
Bunch population N_b (10^{11} p)	1.15	~1.2	~1.1	~1.2
No. bunches k	2780	2244	2220	~2550
Emittance ε (mm mrad)	3.5	~3.5	~2.2	~2.2
β* (cm)	55	80	40	40 (33)
Full crossing angle (μrad)	285	290	370 / 280	300 (340)
Peak luminosity (10^{34} $cm^{-2}s^{-1}$)	1.0	0.51	1.4	~1.7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

Injector beams

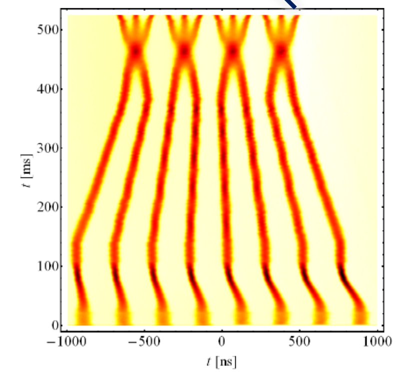


- The standard LHC beam with 25 ns bunch spacing is obtained in the Proton Synchrotron by splitting of 6 booster bunches into **72 bunches** at extraction.
  - *Triple splitting at low energy, 2x double splitting at high energy.*
  - ***Emittance at injection into LHC ~ 2.8 μm.***

- 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.***

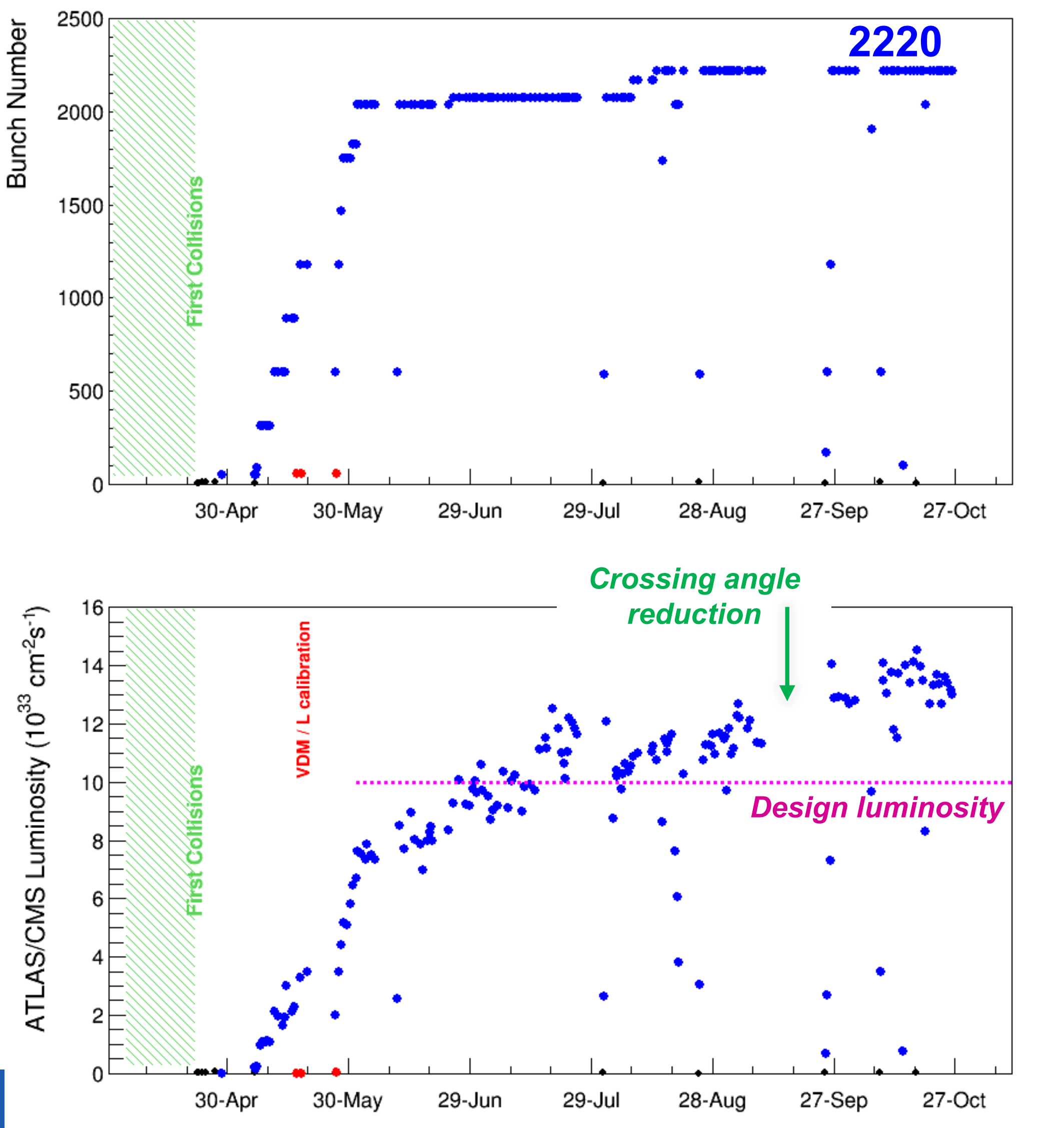


Standard (6 PSB b.)



BCMS (8 PSB b.)

Exceeding nominal performance in 2016

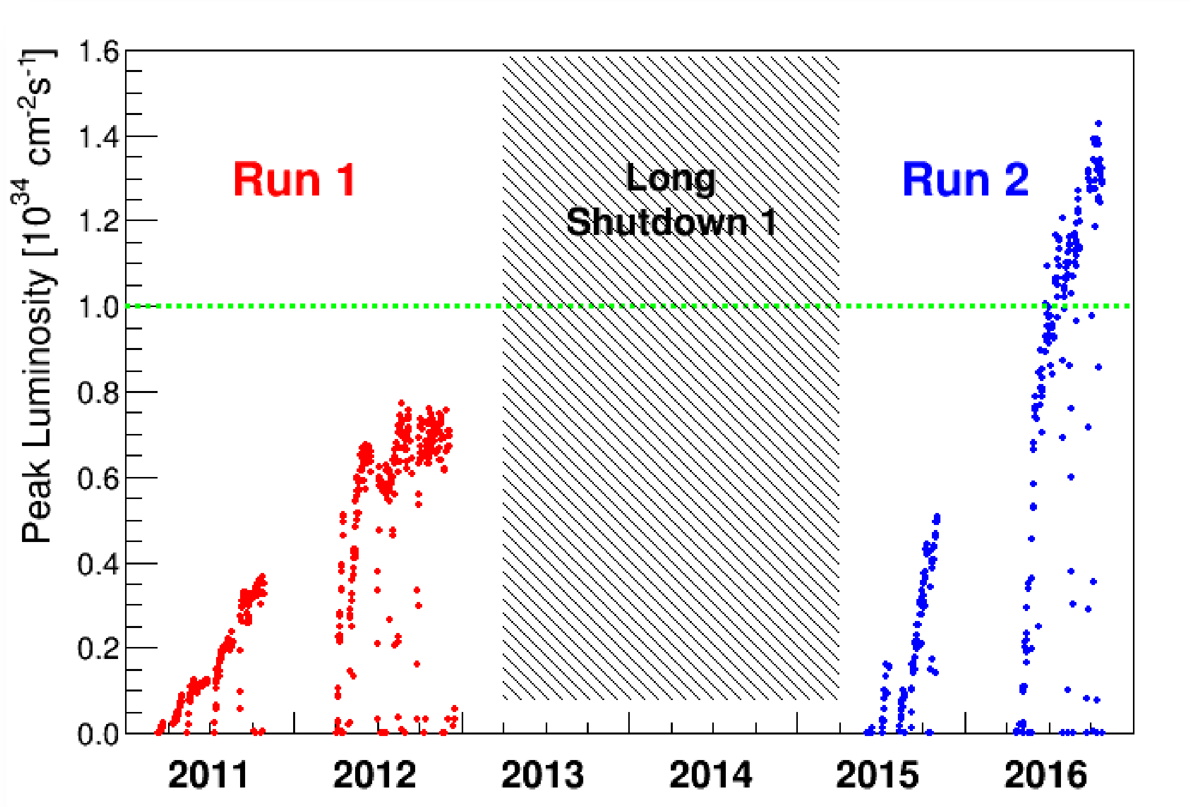


- Despite limitations on the injected intensity (SPS dump, LHC injection kicker vacuum), the *LHC exceeded its design luminosity by 40%.*
- The luminosity performance was achieved thanks to *low emittance beams* from the LHC injectors and to *smaller β^**.
- In September the half *crossing angle was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

TUPVA025

THPAB056

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}

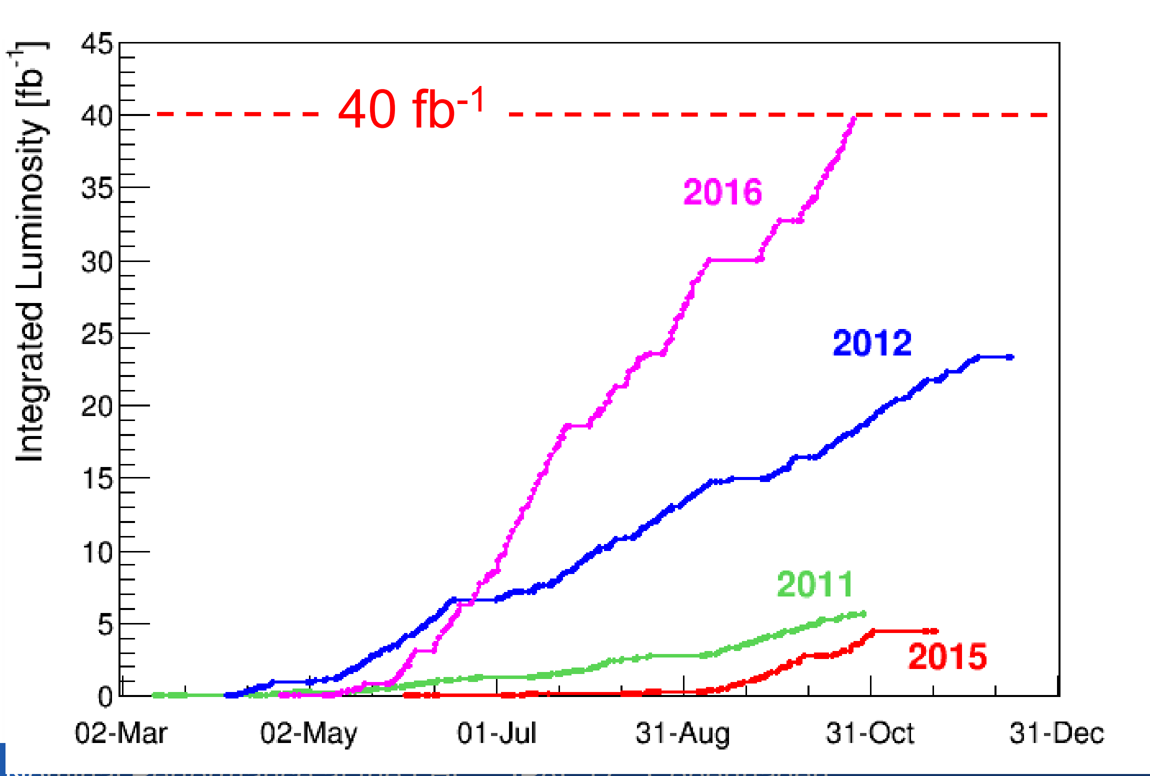
Design luminosity:

1×10^{34} cm^{-2}s^{-1}

Integrated luminosity 2016

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

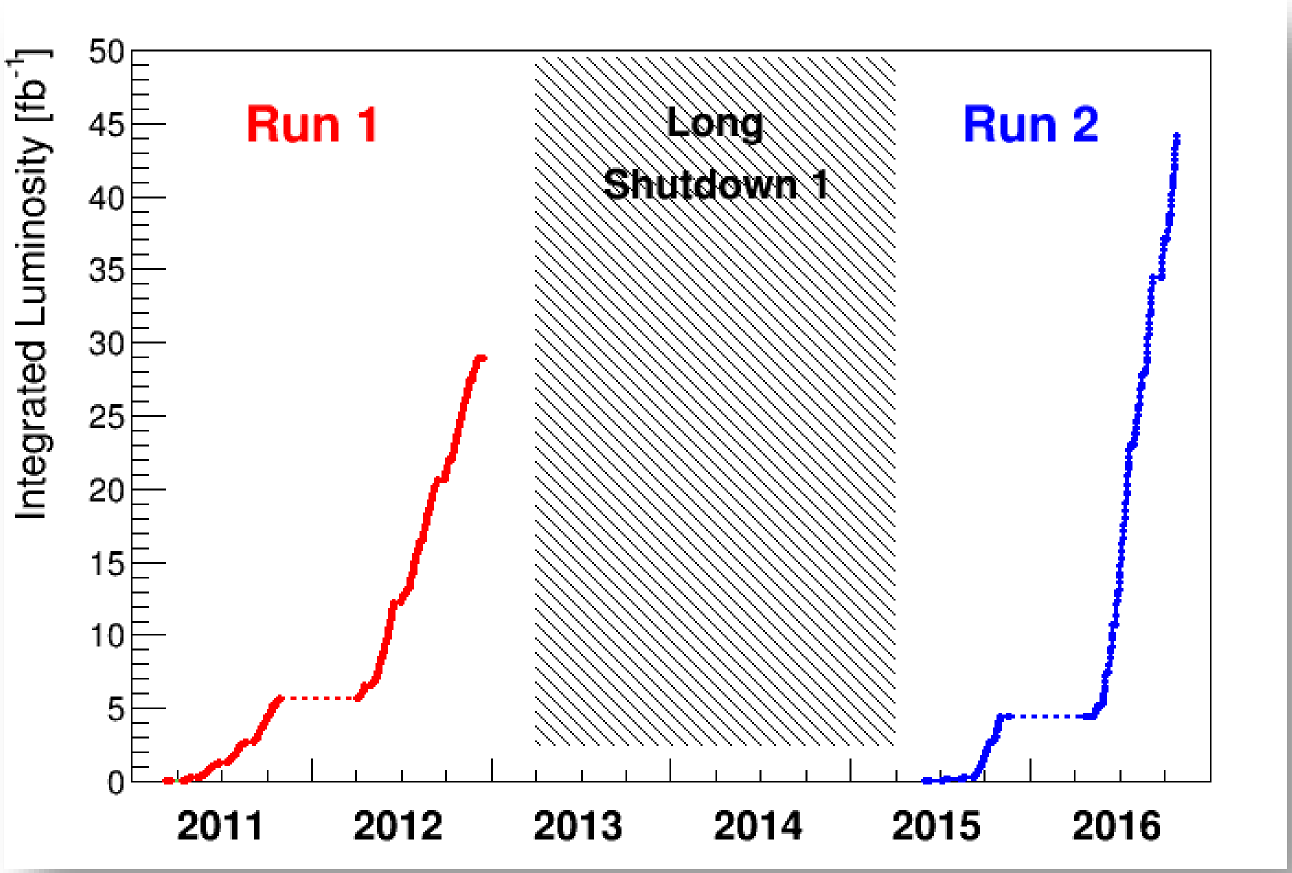
- ✓ ***Record peak luminosity***,
- ✓ ***Excellent machine reproducibility***,
- ✓ ***High availability***, *~ 50% better than in previous years.*



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.*



2016 LHC availability

TUPVA006

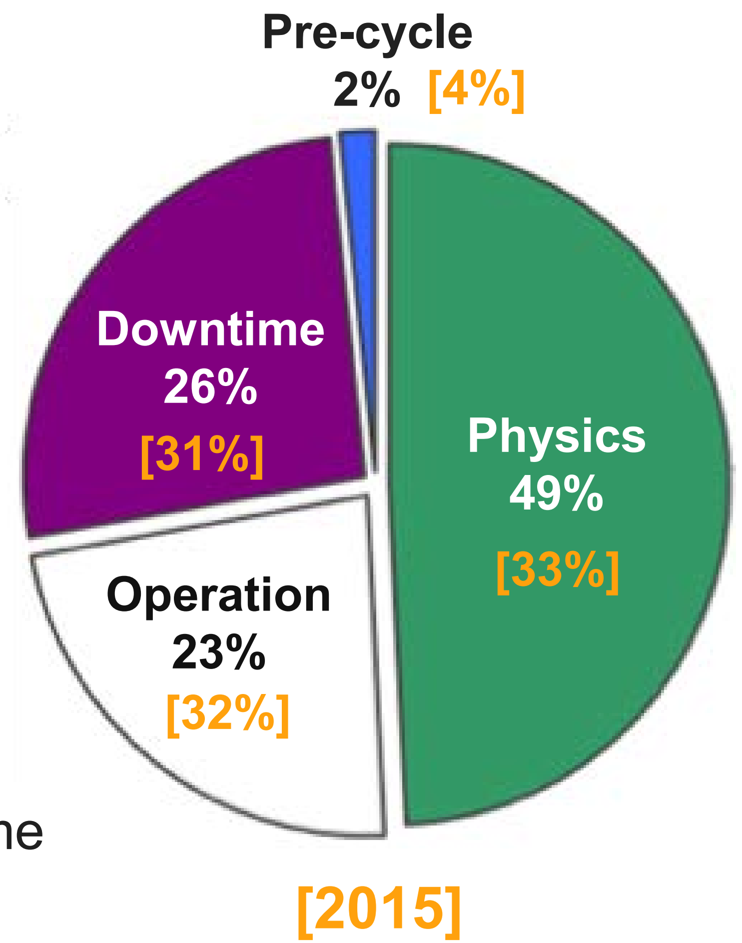
TUPAB007

Excellent improvement of availability in 2016:

- ✓ Increased operational efficiency
- ✓ Enhanced system availability
- ✓ New magnet cycling strategy

Availability for physics during the high luminosity production period reached **~56%**

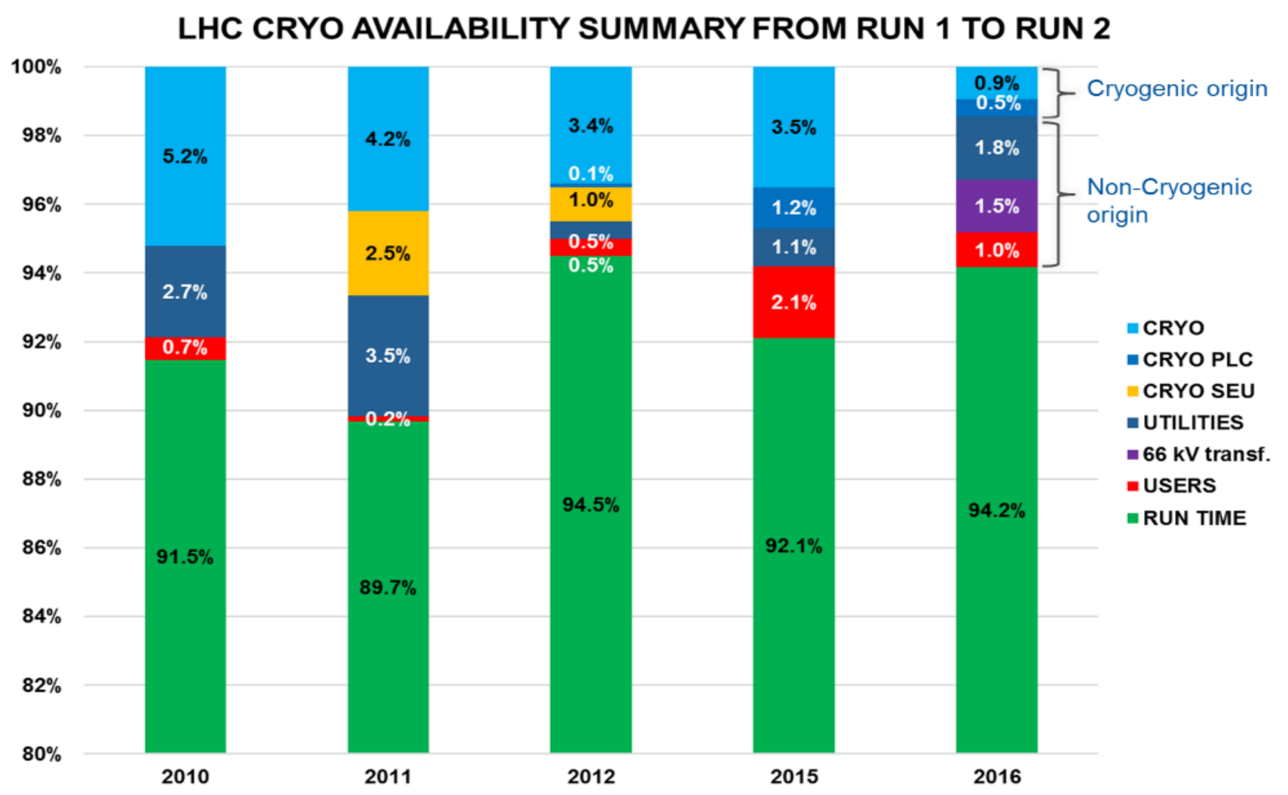
Non-availability of beams from the injector complex is the largest source of LHC downtime



Cryogenic system availability

The cryogenics system availability reached **98.6%**, **94%** when external failures – water, electricity… – are included.

✓ Feed-forward actions were essential in smoothing the thermal reactions related to electron cloud and the start of collisions.



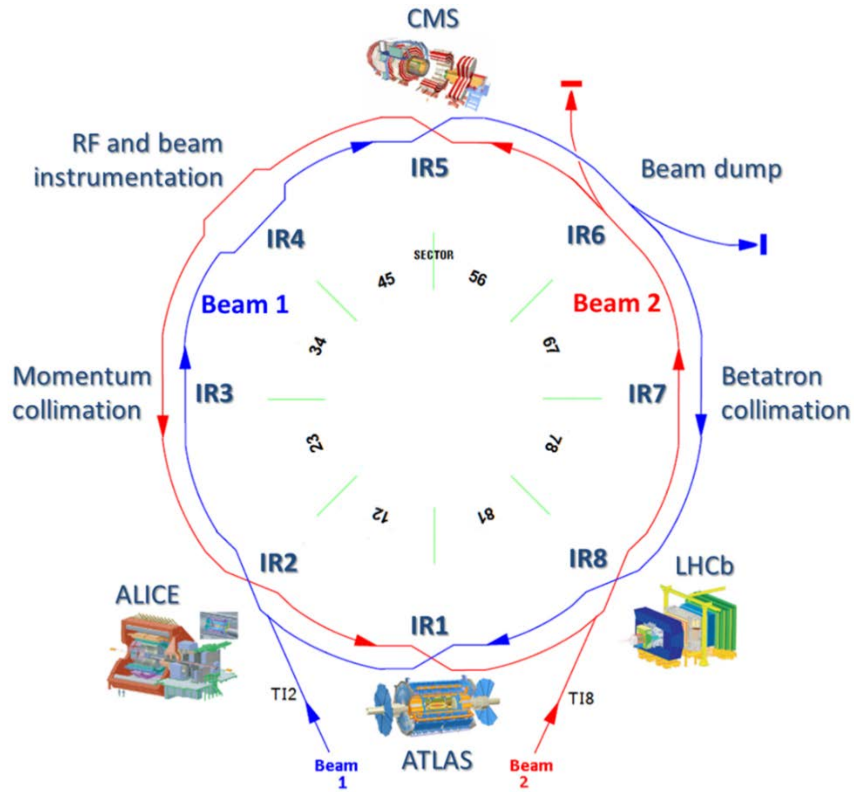
Outline

Introduction

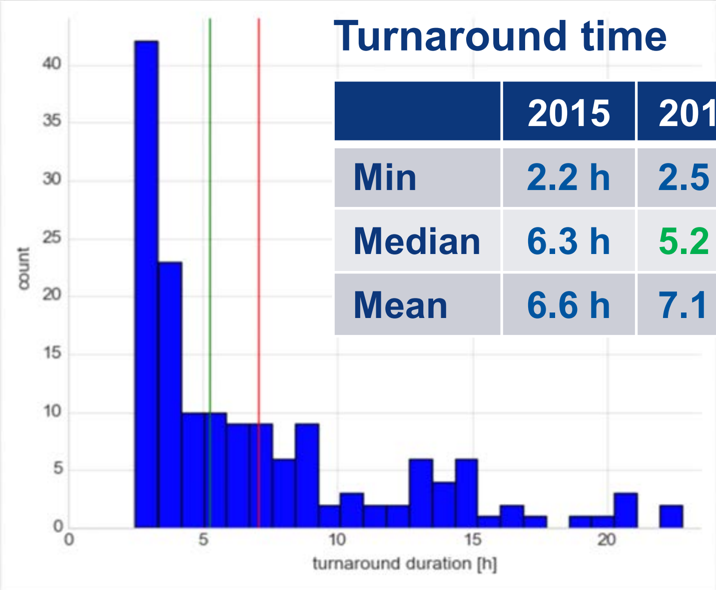
LHC performance in 2016

Operation and challenges

Outlook



LHC operation in 2016



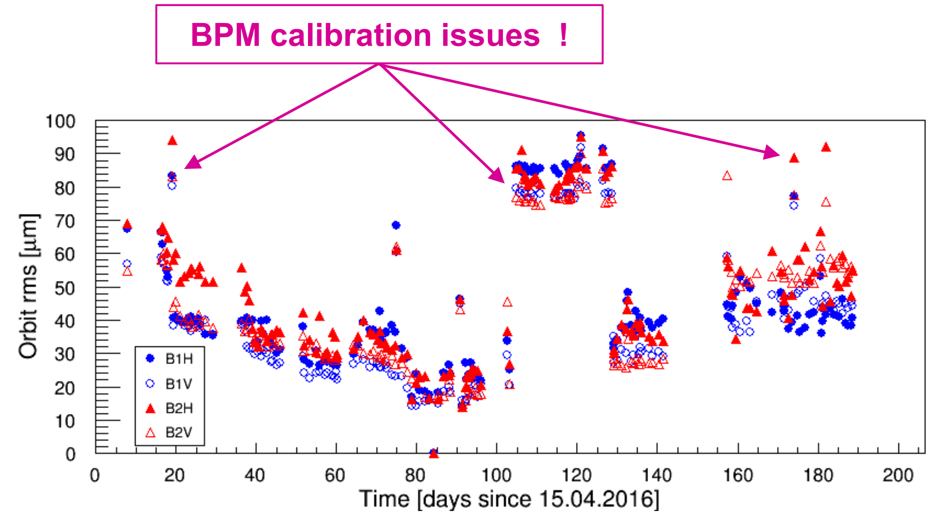
Turnaround time

	2015	2016
Min	2.2 h	2.5 h
Median	6.3 h	5.2 h
Mean	6.6 h	7.1 h

- The machine turn-around time is improving:
  - *Continuous cycle optimization (combining ramp and beta squeeze, rampdown etc) and automation.*
  - *Injection is the period were most time is 'lost'.*

TUPIK088

- At 6.5 TeV LHC is **very reproducible:**
  - **Q: ± 0.002**
  - **Q': ≤ ± 2**
  - **Coupling: ≤ ± 0.002**
  - **Arc orbit: ± 50 μm**



orbit RMS evolution wrt reference

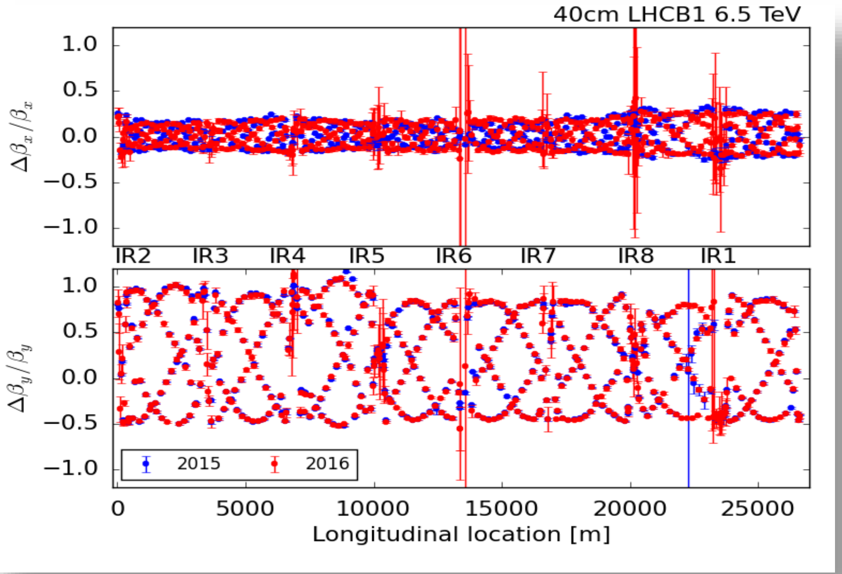
LHC optics

WEPIK092/93 **TUPVA042**

- The machine optics is reproducible from one year to the next and the beta-beating is corrected down to the % level at 6.5 TeV.
  - *K-modulation information from the low-beta quadrupoles was added in 2016 to the orbit correction to ensure a correct waist location.*

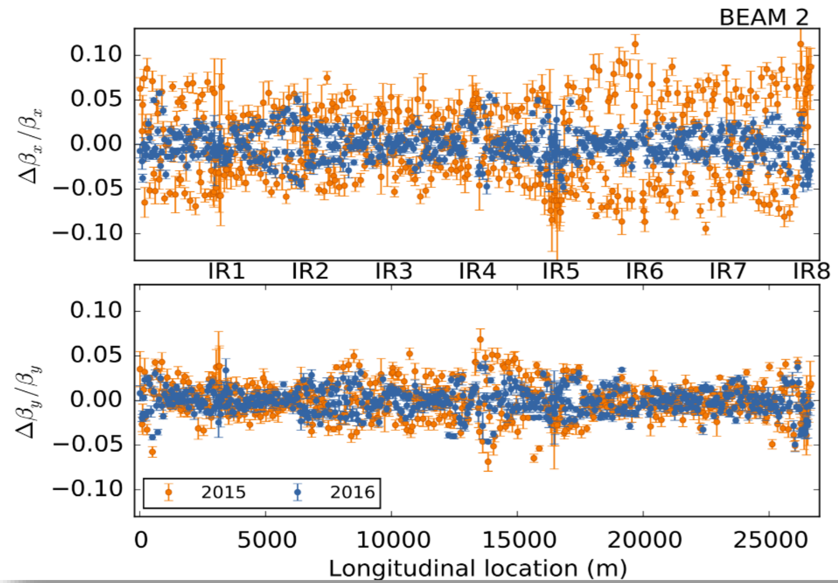
Virgin machine, β* = 40 cm

Beta-beating 50-100%



Corrected machine, β* = 40 cm

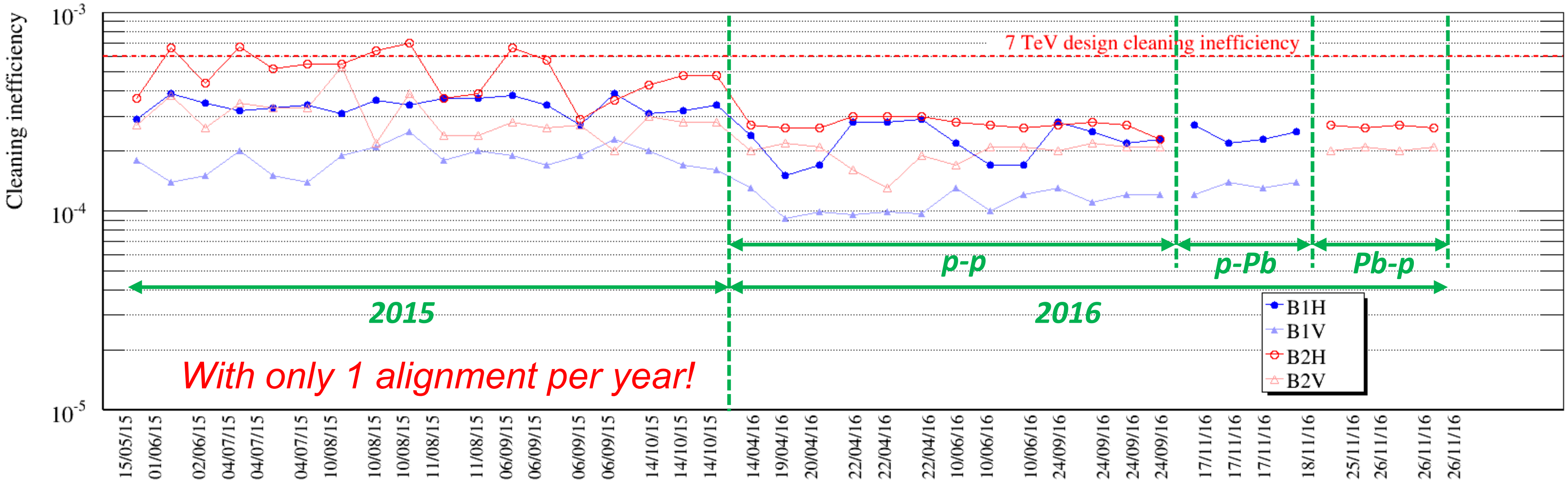
Beta-beating 2%



Collimation

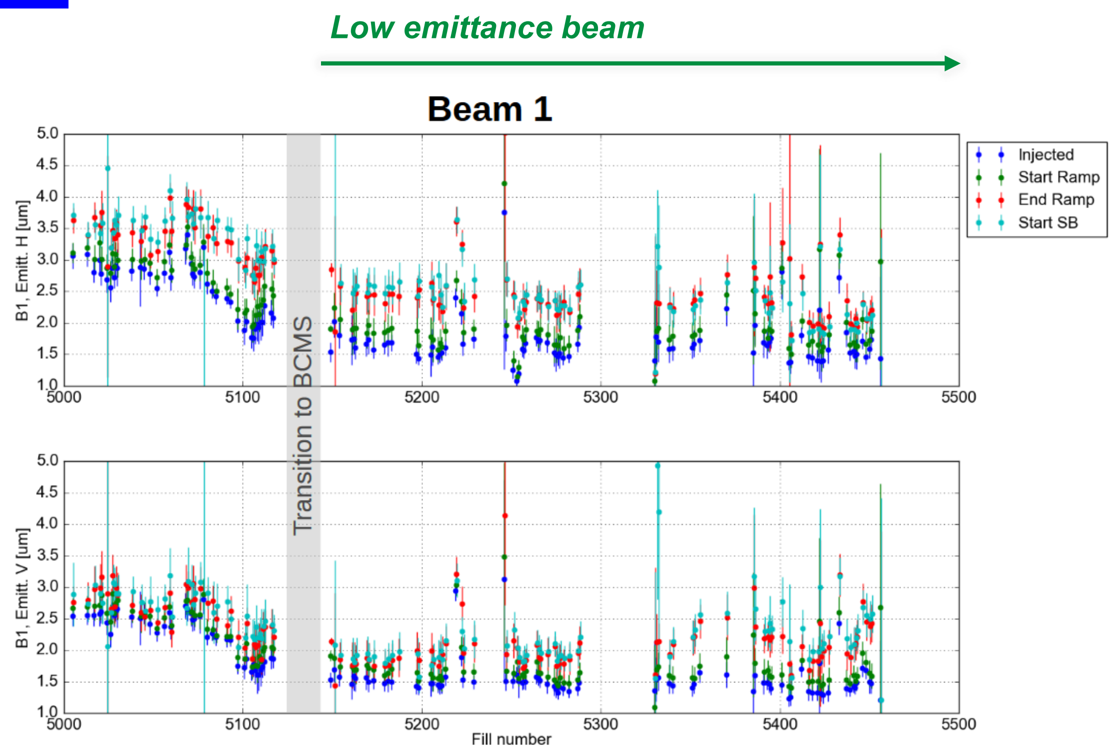
MOPAB009, MOPAB010

- 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.*
- **Tightening the collimation hierarchy** (reduced retractions between collimators) allowed to **lower β*** over time.



Emittance evolution

- **Emittance preservation** for the small emittance beams:
  - **Injected: ~1.5 μm**
  - **Start of collisions: ~2-2.5 μm**
- More blow-up in the horizontal plane, and largest blow-up observed during ramp.
- Additional blow-up **under investigation** – no apparent correlation with brightness.
  - *With collisions additional blow up of ~0.05 μm/h.*



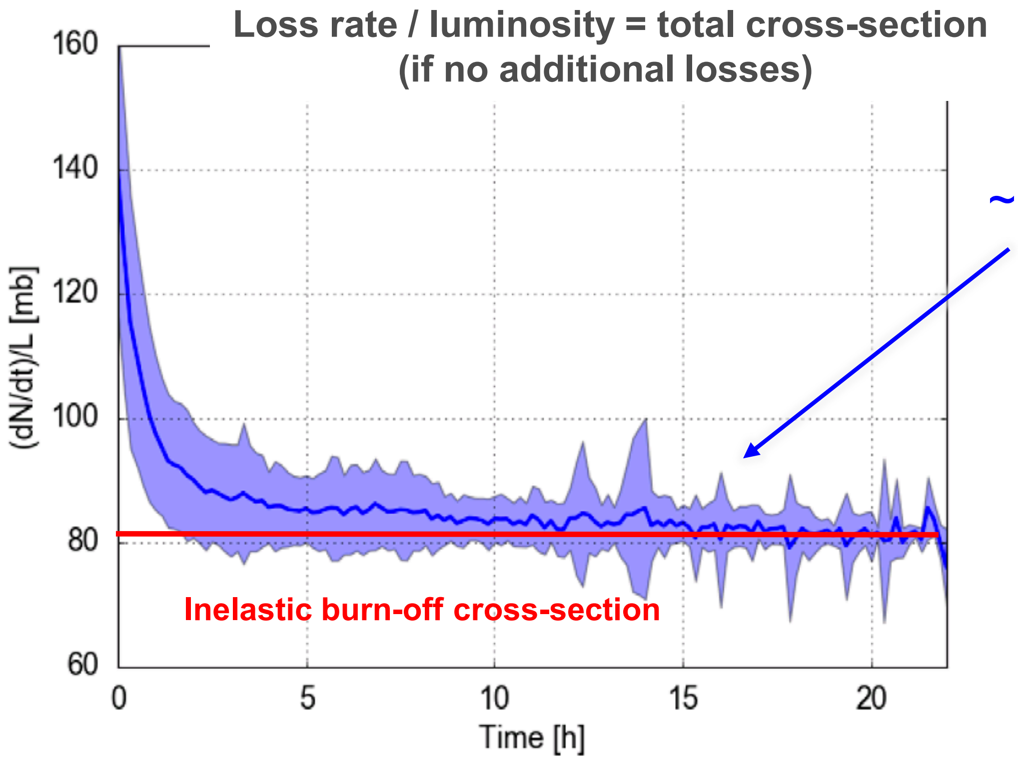
	Emittance blow up		
	Injection	Ramp	6.5 TeV
Horizontal	0.1 - 0.12 μm	0.35 - 0.5 μm	≈ 0.05 μm
Vertical	0.1 - 0.14 μm	≈ 0.25 μm	≤ 0.05 μm

MOPAB110

MOPAB130

Beam losses in collision

- During the first 2-3 hours after colliding the beams, additional losses are observed due to dynamic aperture (with head-on beam-beam).
  - *Ongoing effort to mitigate the lifetime drops (tune working points, machine non-linearities etc).*
  - *Integrated luminosity loss corresponds to a few %.*

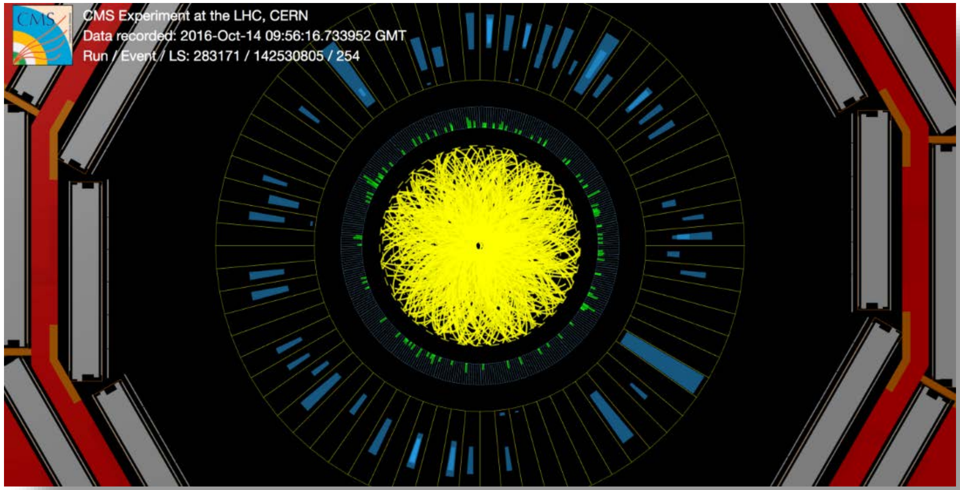


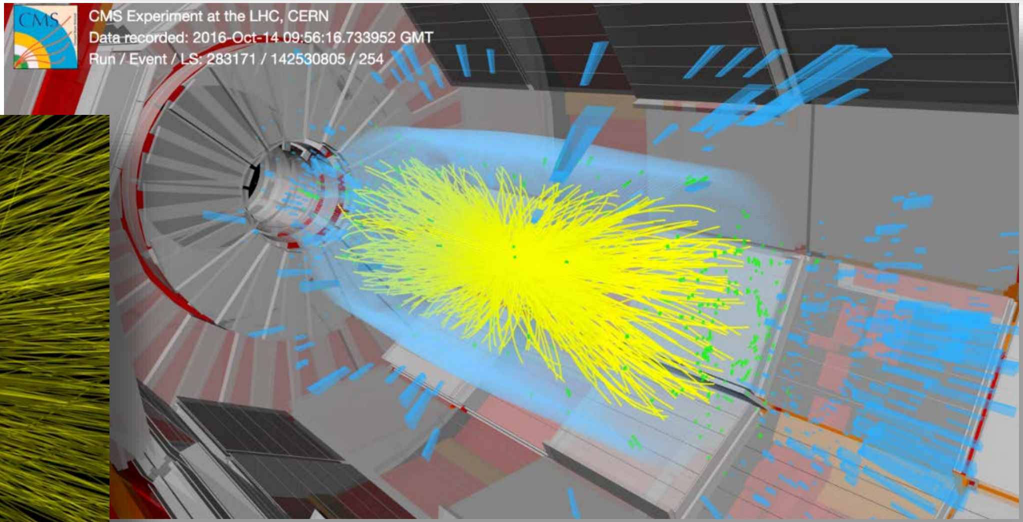
~ all particles are burned off by collisions !

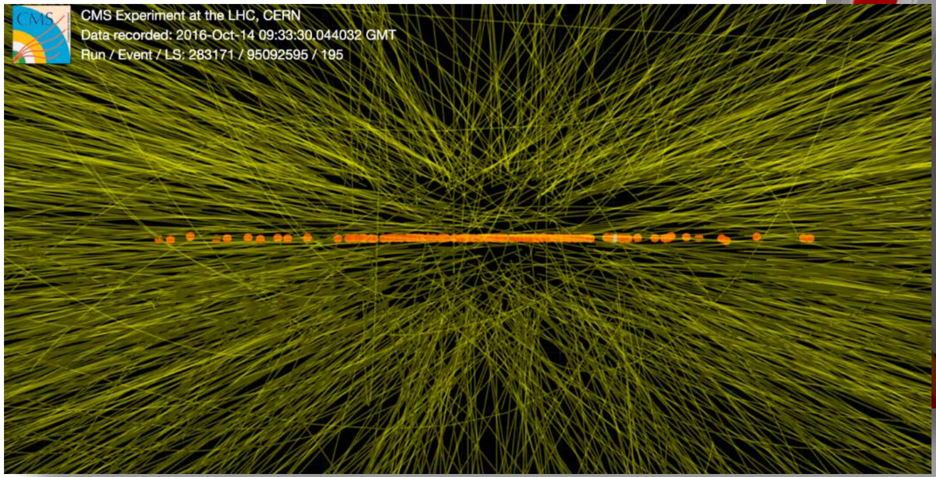
THPAB048 **MOPAB008**

Event pileup

- In 2016 the peak event pile-up reached **~50 events / crossing** at the start of fills.
  - *Design ~ 25 event/crossing*
- Special high pile-up tests were organized as preview for HL-LHC upgrade. Here an example event with **pile up of ~90 in the CMS detector**.

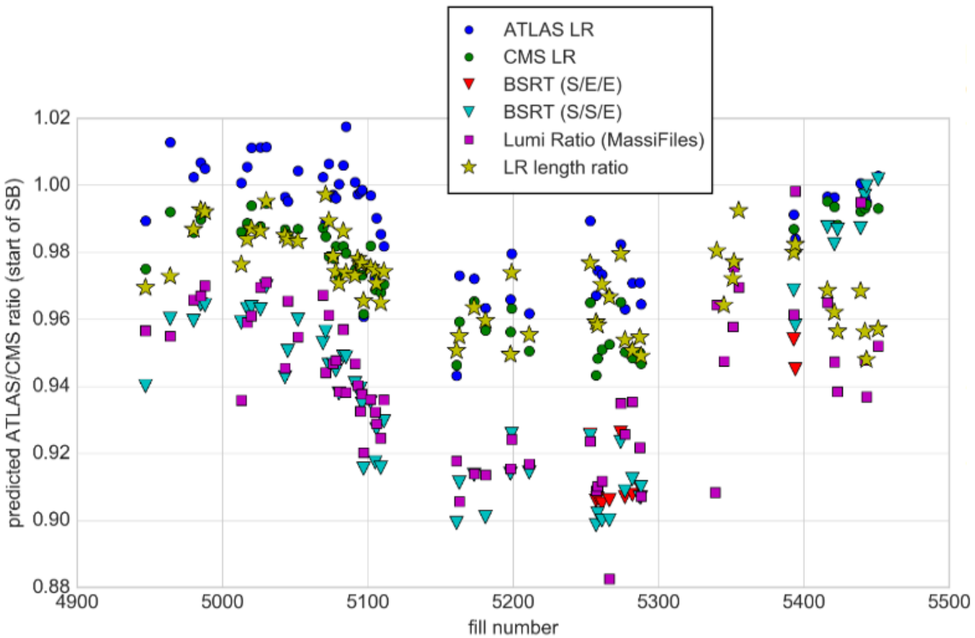






Luminosity imbalances

- Luminosity imbalances between the ATLAS and CMS experiments were present during the 2016 run. A large effort was invested to understand the sources:
  - ***Machine / beam effects and/or luminosity measurement errors?***
- The imbalance of the H-V emittances coupled with the different crossing planes (V in ATLAS, H in CMS) explains part of the imbalance.



TUPVA005

LR = luminous region

BSRT = synchrotron light monitor

Luminosity ratio

Electron clouds

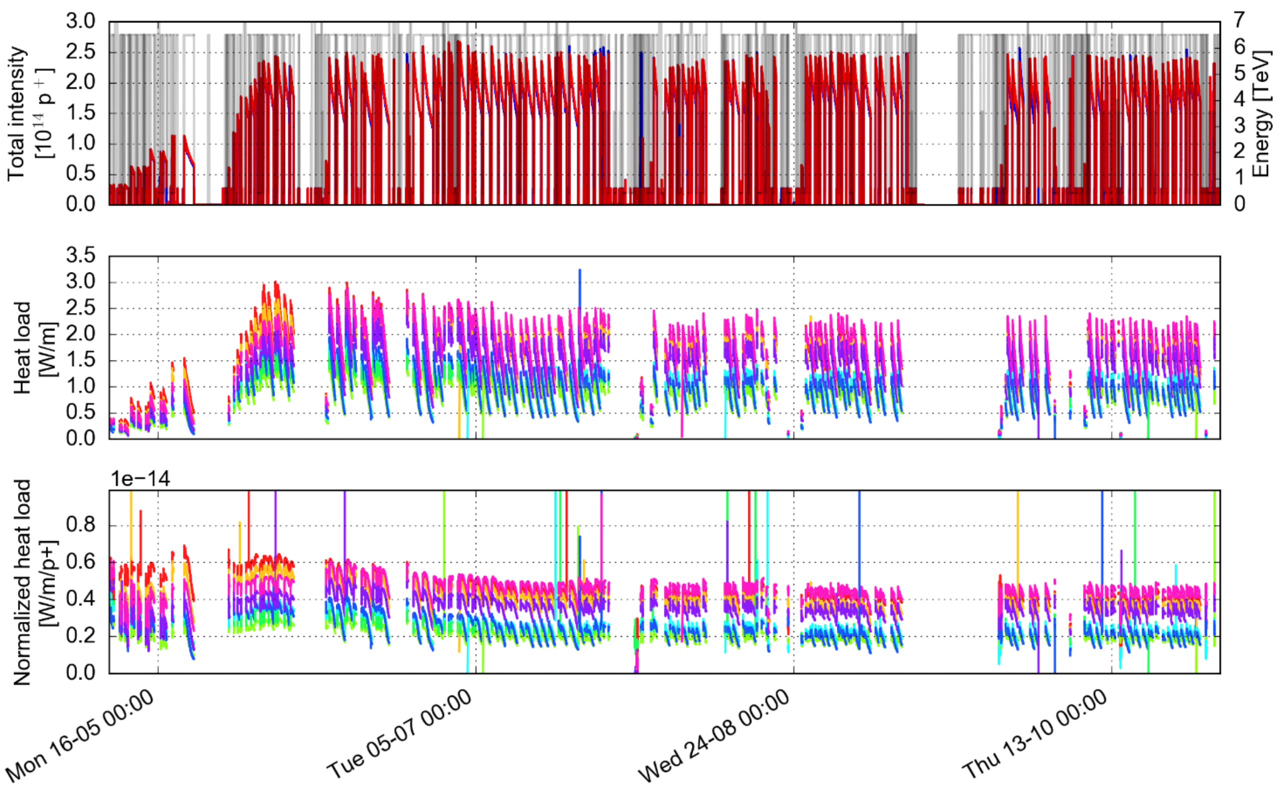
Oral MOZA1 by G. Rumolo

- At high intensity the LHC is operated in the **presence of electron clouds**.
- There is a slightly decreasing trend of electron cloud heat-loads in 2016 with **~20% gained** over the year (gain of 2015 40%).
  - *Most electron could 'scrubbing' is performed parasitically to physics operation.*
  - *The beams are stabilized with a transverse feedback, octupoles and head-on beam-beam (Landau damping).*

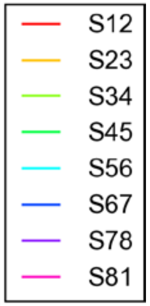
Beam intensity

Heat load (W/m)

Heat load per proton (W/m/p)

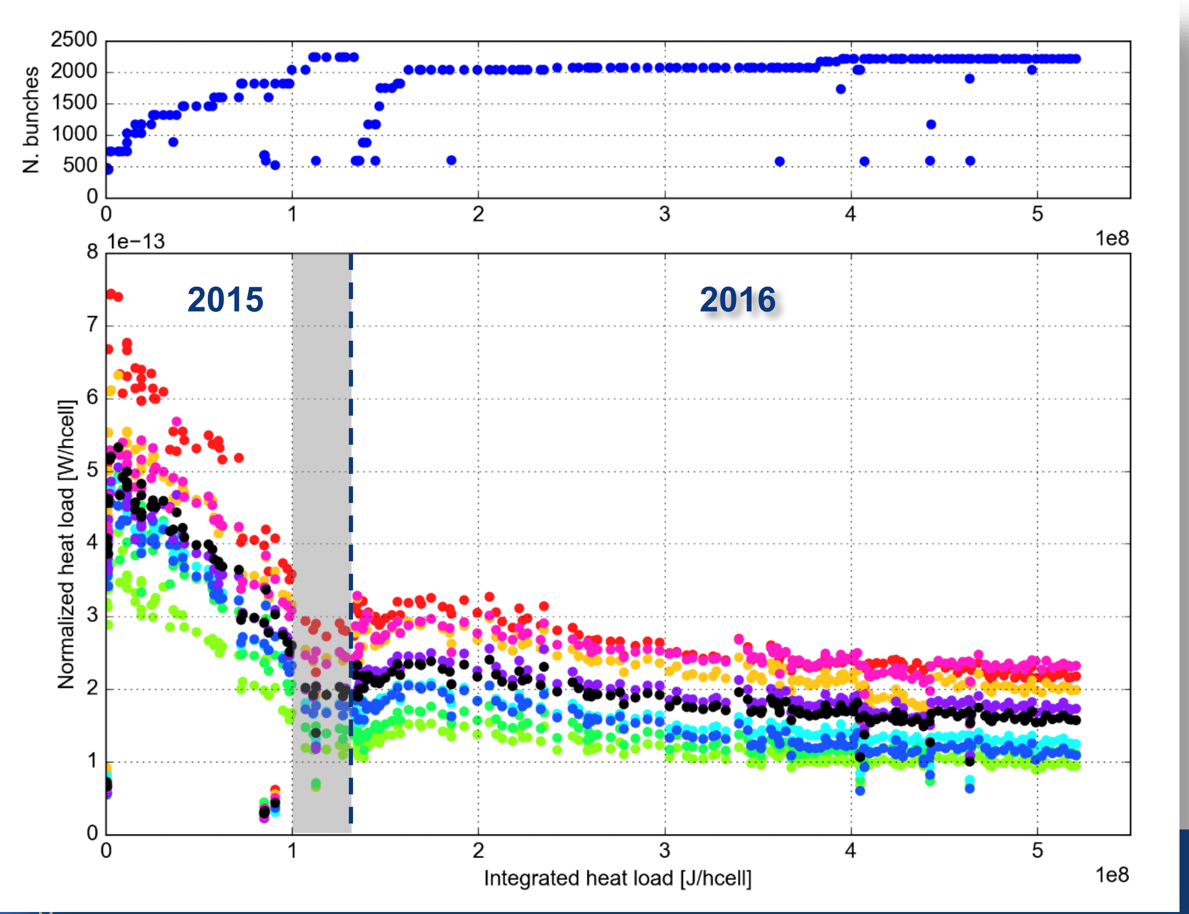


The 8 sectors (arcs) behave differently



Electron clouds

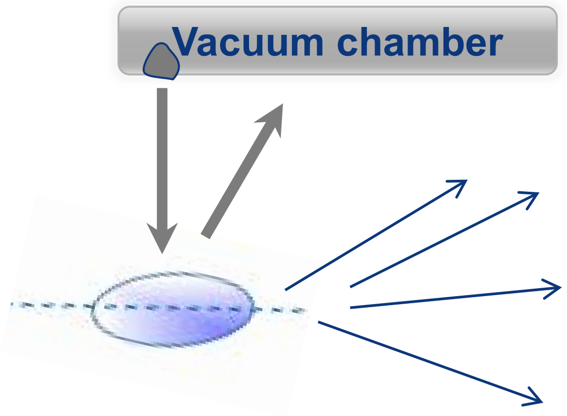
- Evolution from the heat load normalized by the total beam intensity:
  - *Conditioning observed in 2015 continued over the first two months of 2016,*
  - *Very little change in the following months,*
  - *No correlation of this evolution with changes of settings and beam configuration.*



Oral MOZA1

Unidentified Falling Objects - UFOs

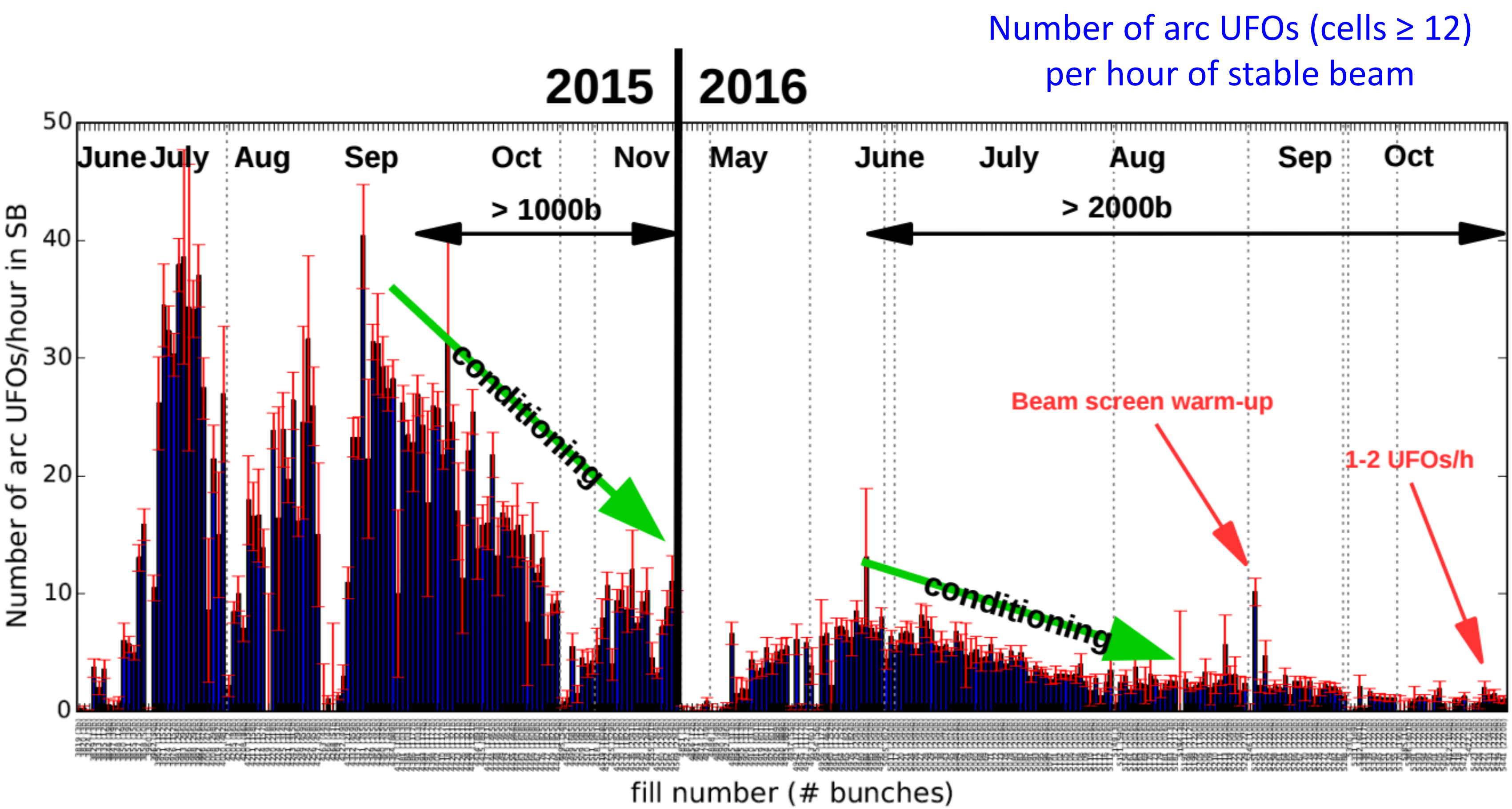
- According to the most credible theory, the **Unidentified Falling Objects** observed at the LHC are dust particles that fall into the beam and generate beam losses due to inelastic collisions with the beam. These losses can quench a superconducting magnet.
  - *Already Identified during Run 1.*
  -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



- UFOs induced **17 beams dumps and quenched 2 magnets** in 2016**.**
  - *Loss monitor thresholds were adjusted to **balance the risk of spurious dumps and the need for quench prevention** in 2015 and 2016 – still ongoing.*
  - *A clear **conditioning** has been observed along the year*

UFO conditioning

A steady conditioning is observed on the UFO rate.



Ion runs

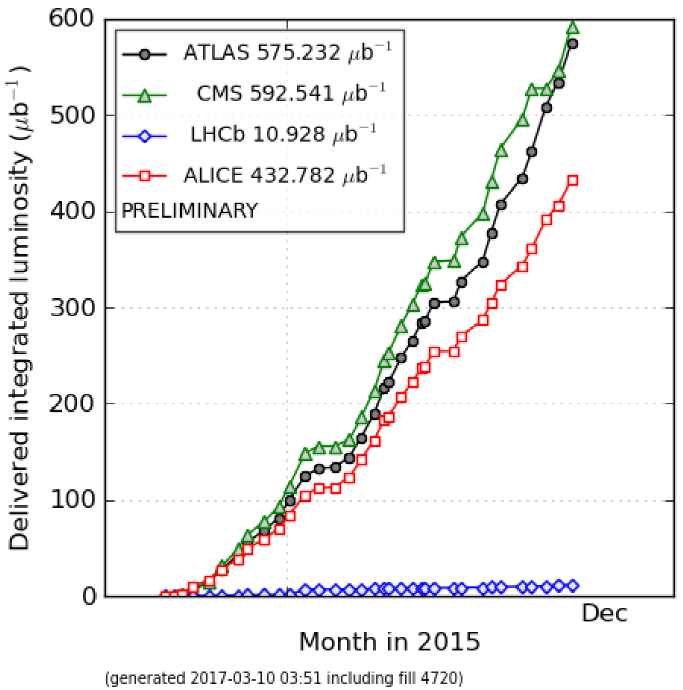
- Successful lead-lead (2015) and proton-lead (2016) runs took place after each proton run before going into winter shutdown.
- Peak luminosities:

TUPVA014

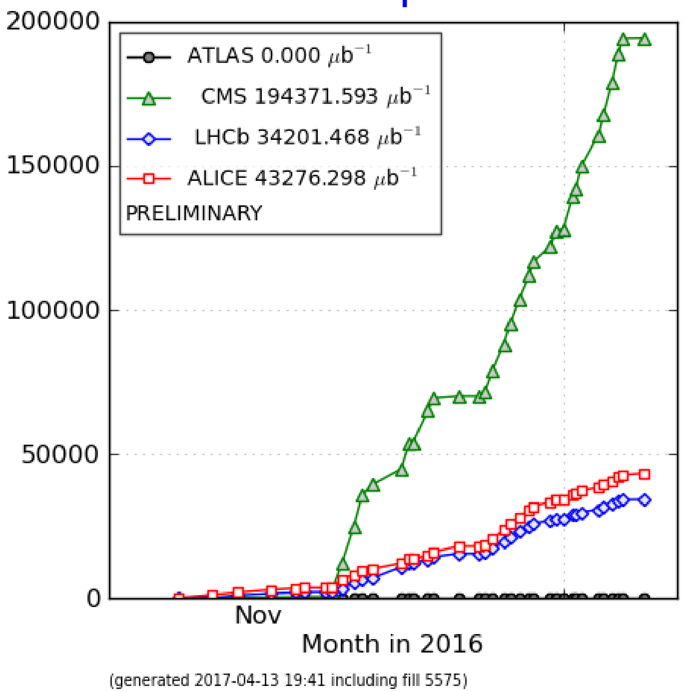
Pb-Pb : 3×10^{27} cm^{-2}s^{-1}

p-Pb : 8×10^{29} cm^{-2}s^{-1}

2015 Pb-Pb



2016 p-Pb



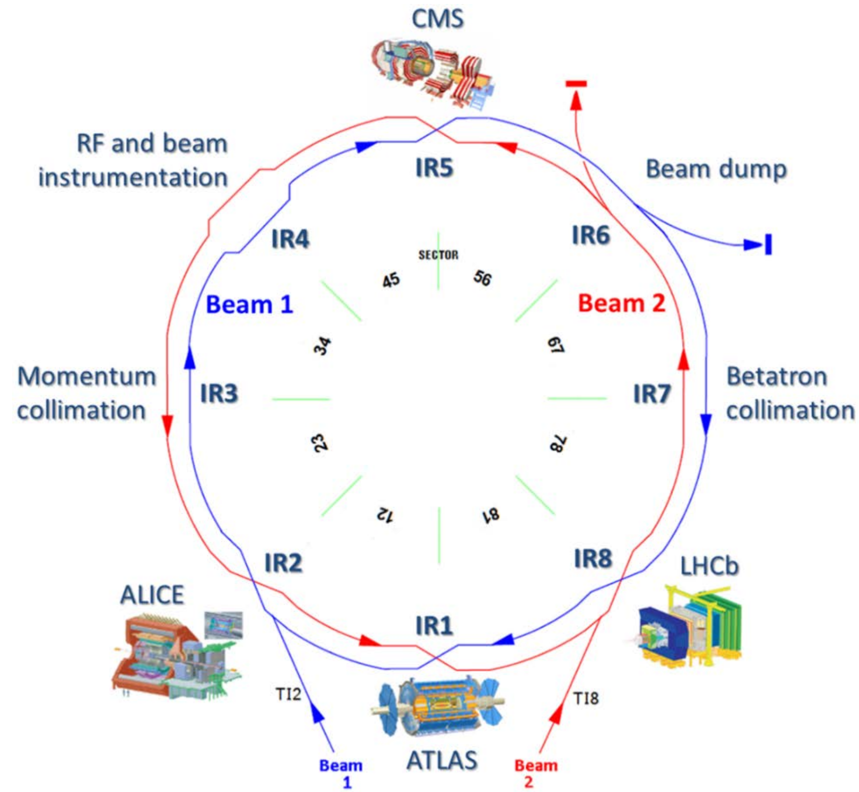
Outline

Introduction

LHC performance in 2016

Operation and challenges

Outlook



LHC in 2017

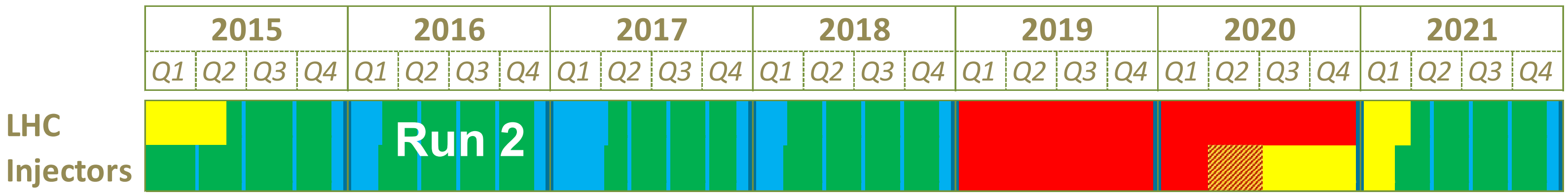
- The 2017 LHC run is in the beam commissioning phase, the machine should be **ready for physics before the end of May**.
- The optics has been changed to be compatible with an **Achromatic Telescope Squeeze (ATS)** that is the baseline optics for HL-LHC.

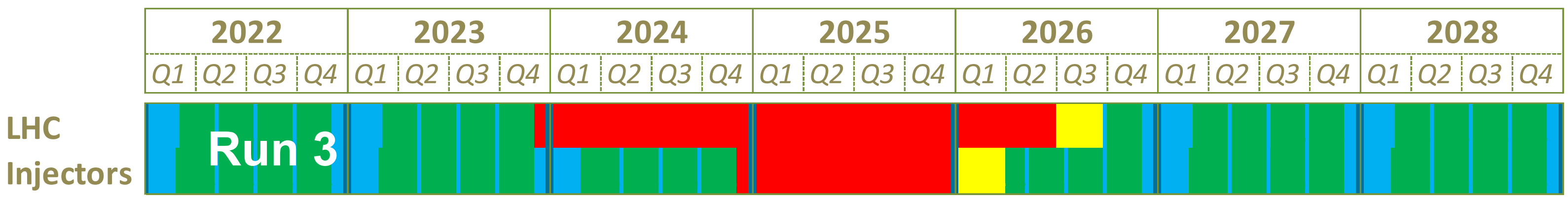
  WEPIK030

  - *The initial β^* remains at 40 cm, with the option to move to 33 cm later in the year.*
- The intensity limitations at injection should be 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 (at constant dynamic aperture).

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 $\geq$ 6.5 TeV by the end of 2023.
- Between 2024-2026 the HL-LHC upgrade will deploy its changes across the LHC for Run4.





Thank you for your attention