



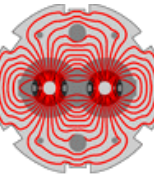
# Obtaining a record luminosity production in the Large Hadron Collider in 2025

J. Wenninger / CERN

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# Introduction – LHC



**ATLAS & CMS:** high luminosity experiments,  $L \sim 2.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ .

► Most performance parameters refer to those experiments.

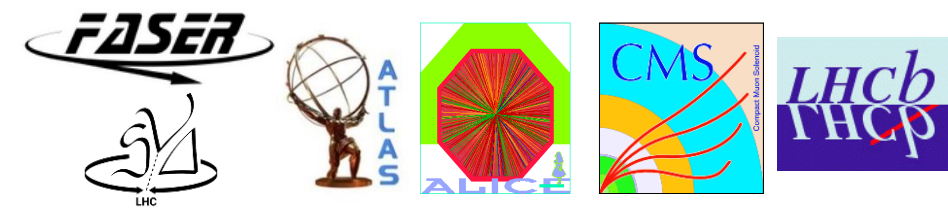
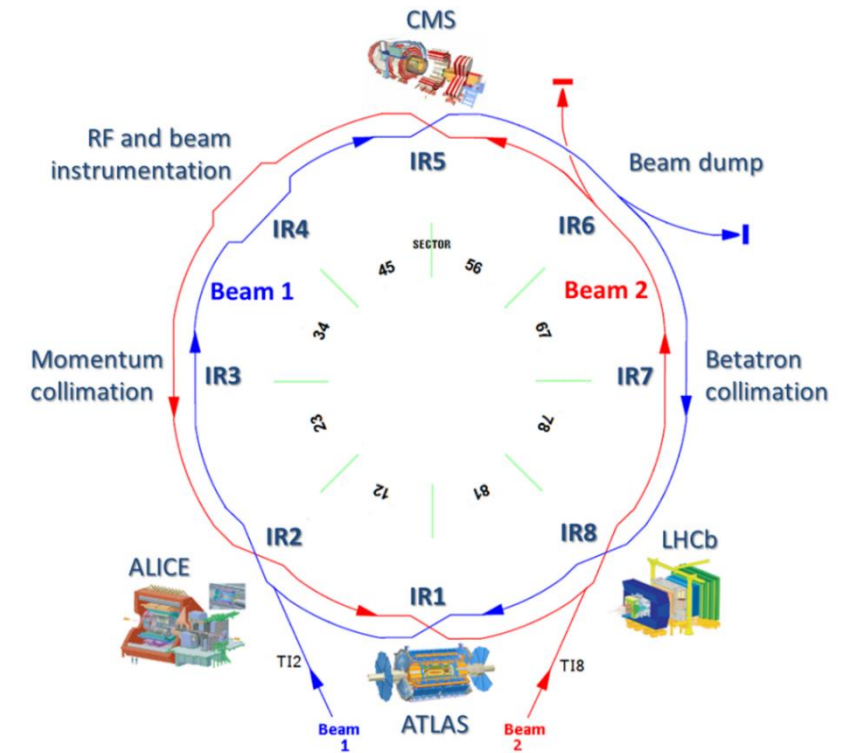
**LHCb:** medium luminosity experiment,  $L \sim 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ .

**ALICE:** low luminosity / ion experiment,  $L \sim 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ .

**SND and FASER:** Beyond Standard Model and neutrino physics experiments located  $\sim 500 \text{ m}$  downstream of the ATLAS IP.

LHC is operating the **3<sup>rd</sup> long run** (Run 3) which began in 2022 and which will **end in June 2026**.

**Long shutdown 3** (LS3) will begin in July 2026 and will last 4 years to install the **High Luminosity LHC (HL-LHC) upgrade**.



# Optics and radiation (1)

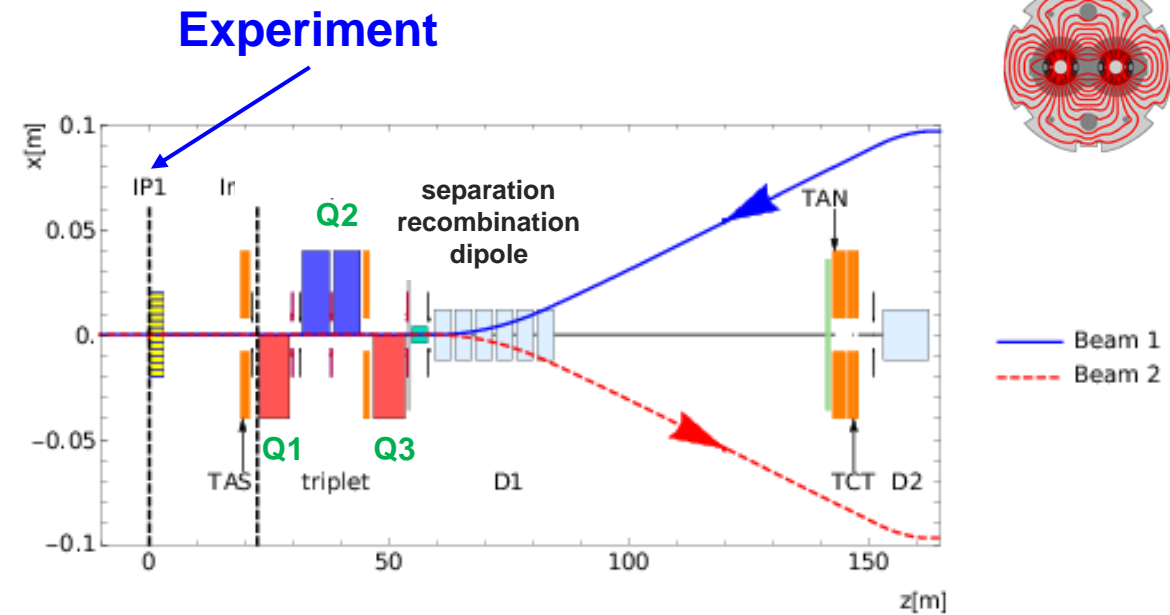
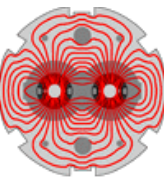
The low-beta (inner triplet) magnets have accumulated **high radiation doses due to collision debris** (low-angle collisions).

Estimated lower **dose limits**:

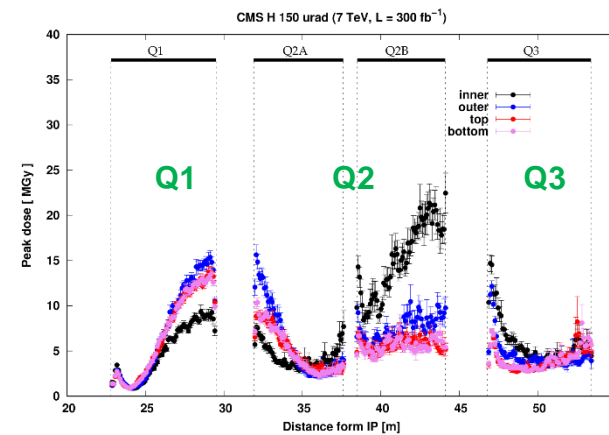
- ▶ Quadrupoles: **30 MGy**
- ▶ Corrector magnets: **7 MGy**
- ▶ Normal conducting separation dipole: **75 MGy**

Peak doses can be mitigated by modifying the **distribution in space** of the radiation in the magnets.

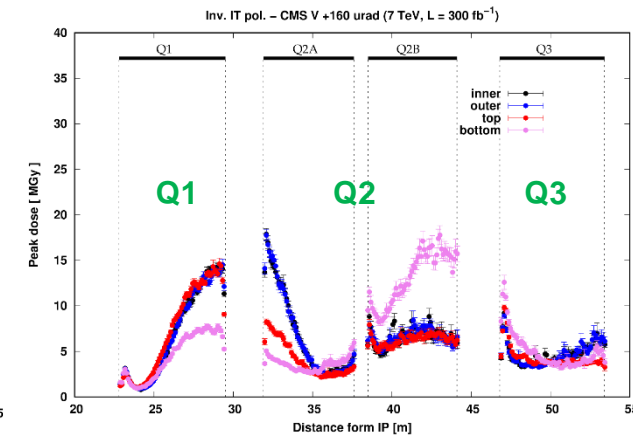
- ▶ In some magnets the radiation dose is very **localized**.
- ▶ The dose limit is already exceeded in many corrector magnets !



**CMS – horizontal crossing**



**CMS – inverted polarity and vertical crossing**



# Optics and radiation (2)

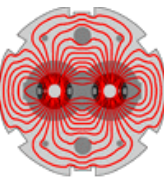
Peak doses can be mitigated by modifying the **distribution** in space of the radiation in the magnets:

- ▶ Modifying the triplet optics by inverting the quadrupole polarities.
- ▶ Exchanging the beam crossing between vertical and horizontal planes: ATLAS:  $V \rightarrow H$ , CMS :  $H \rightarrow V$

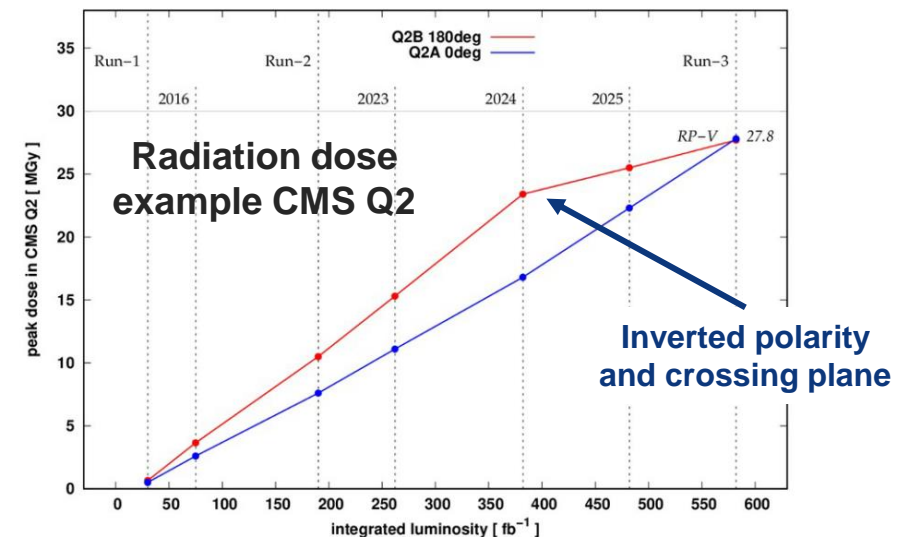
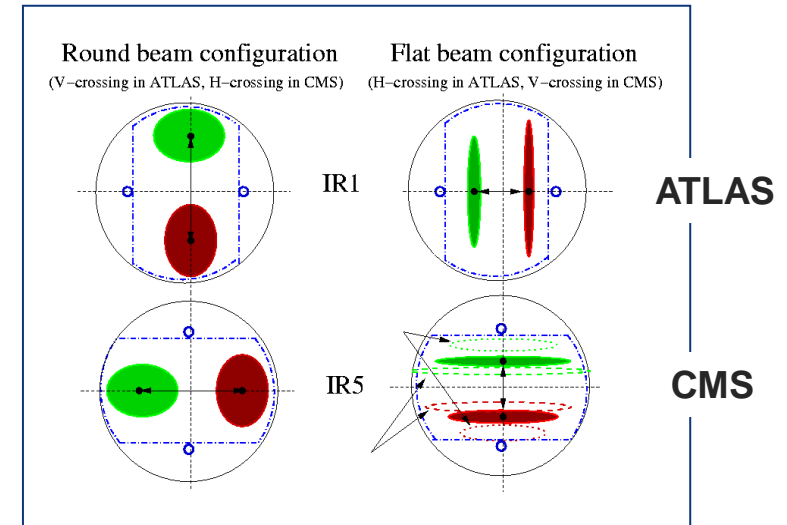
To switch the beam crossing planes, a **flat optics** had to be introduced to accommodate the beams in the IT quadrupoles due the **shape of the beam screen**, with larger  $\beta^*$  in the beam crossing plane.

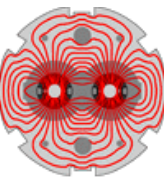
- ▶ **Round optics**  $\leq 2024$ :  $\min \beta_x^*/\beta_y^* = 30 \text{ cm}/30 \text{ cm}$
- ▶ **Flat optics**  $\geq 2025$ :  $\min \beta_x^*/\beta_y^* = 60 \text{ cm}/18 \text{ cm}$

The crossing planes are flipped at high energy during the machine cycle: injection is not possible with flipped planes.



## Beam profiles in the IT quadrupoles



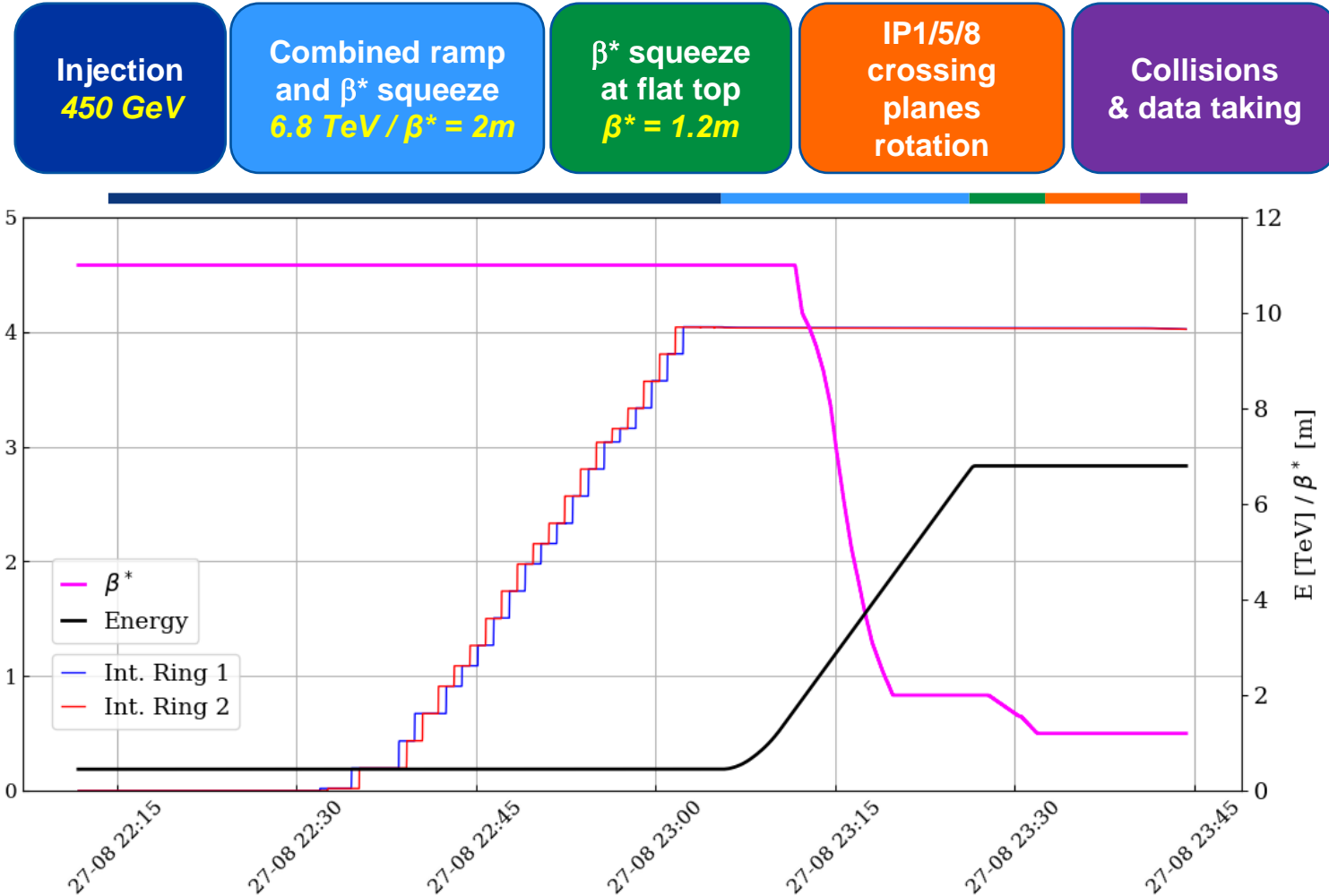


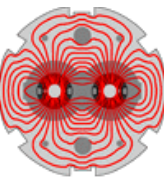
# LHC machine cycle

Beam commissioning and machine cycle have been optimized over many years.

- ▶  $\beta^*$  squeeze partially incorporated into the 20 min long ramp (in 2026: entirely incorporated).
- ▶ End of  $\beta^*$  squeeze and crossing planes rotation on 6.8 TeV flat top.

The minimum time from beam dump to the following start of data taking is 1.8 hours.





# Intensity limitations (1)

The **bunch intensity** is limited during Run 3 to  $1.8 \times 10^{11}$  p due to:

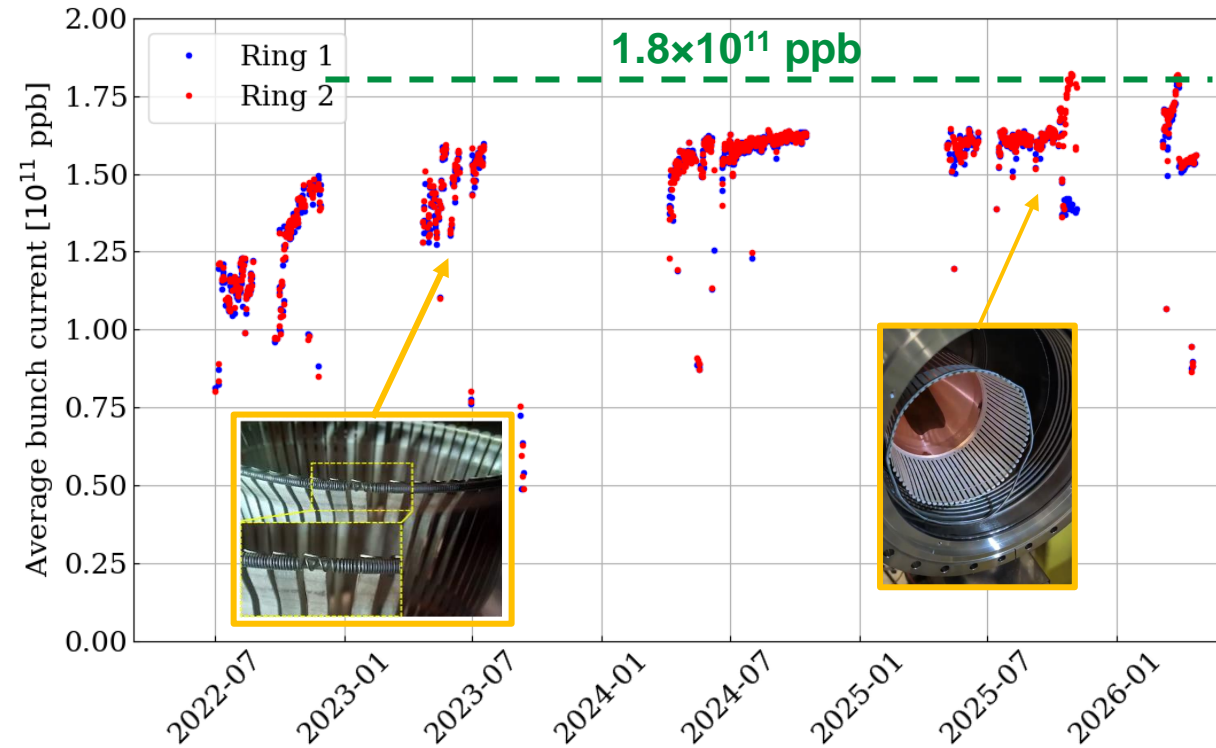
- ▶ Beam dump protection devices damage limits.
- ▶ Electron cloud heat-load to the cryogenic system.

Following the **failure of a vacuum interconnection** in 2003, **impedance driven beam heating** became a new limitation.

- ▶ Damage to vacuum interconnection modules due to mechanical non-conformities.

The **bunch intensity of  $1.8 \times 10^{11}$  p** was finally reached in **2025 for ring 2**, for **both beams in 2026**.

- ▶ After replacement of ~100 vacuum system components.
- ▶ Another ring 1 component failure in 2025.



# Intensity limitations (2)

The intensity limitations in Run 3 are related to non-conformities of **vacuum interconnection modules**.

The main limitation – **2023 failure** - was related to a 212 mm diameter interconnection module.

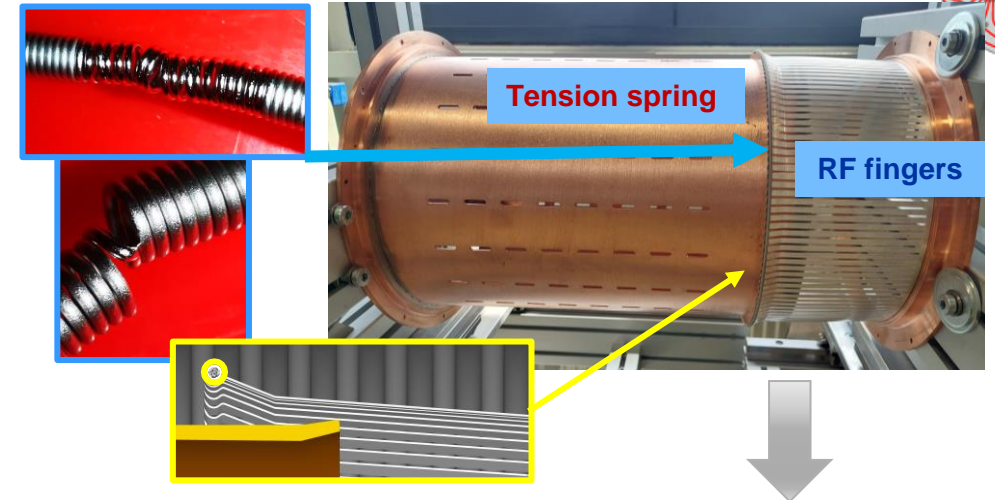
- ▶ **Non-conform positioning** and **holding** of ‘**RF fingers**’ can lead to thermal run-away and damage.

**~100 modules were exchanged** with a new design between 2023 and 2025 to lift this limitations.

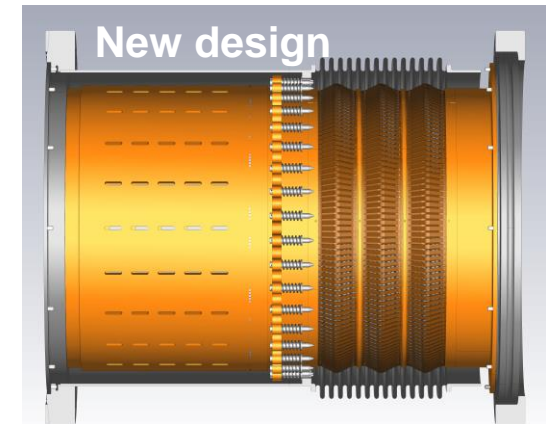
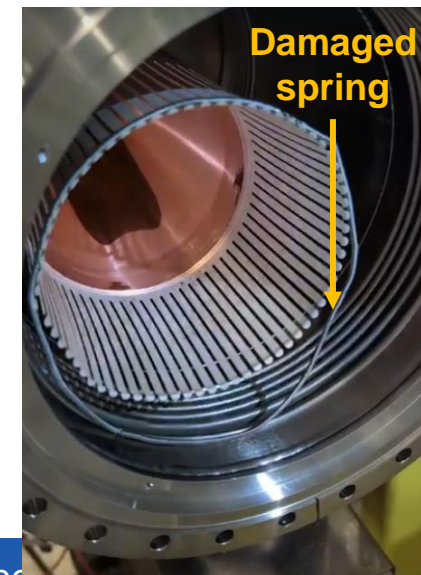
In **2025** a different **specialized module** installed in the injection region of ring 1 failed.

- ▶ Again, tension spring issue.
- ▶ Exchanged during the 2025-2026 winter shutdown with a modified design.

2023 issue



2025 issue



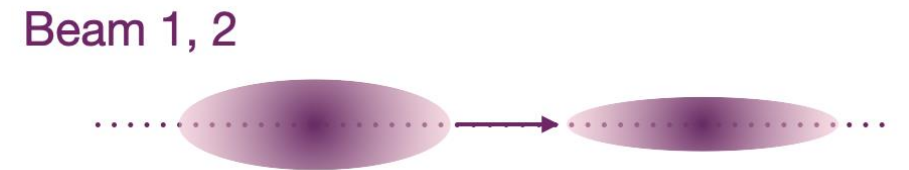
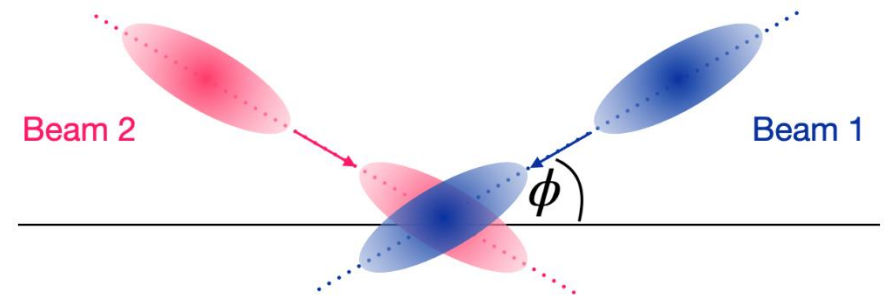
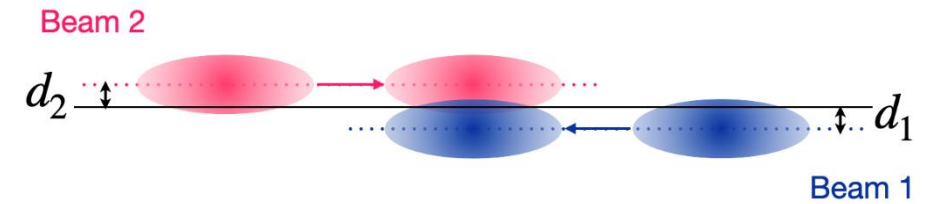
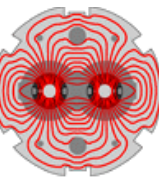
# Luminosity levelling

The LHC peak luminosity is limited to  $L \sim 2.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  by the **local cryogenic cooling capacity**.

**Luminosity leveling** is applied at the LHC for all experiments either due to **detector limitations** (ALICE, LHCb) or due to the **cooling capacity** (ATLAS/CMS).

Leveling techniques:

- ▶ **Transverse beam offset**
  - ▶ Very simple, individual to any IP – used for LHCb and ALICE.
  - ▶ If applied in all IPs bunches may become unstable due to loss of Landau damping.
- ▶ **Crossing angle.**
  - ▶ Limited in range.
- ▶ **Beam size** ( $\beta^*$  squeeze).
  - ▶ Beams remain head-on, provides Landau damping from head-on beam-beam tune spread.

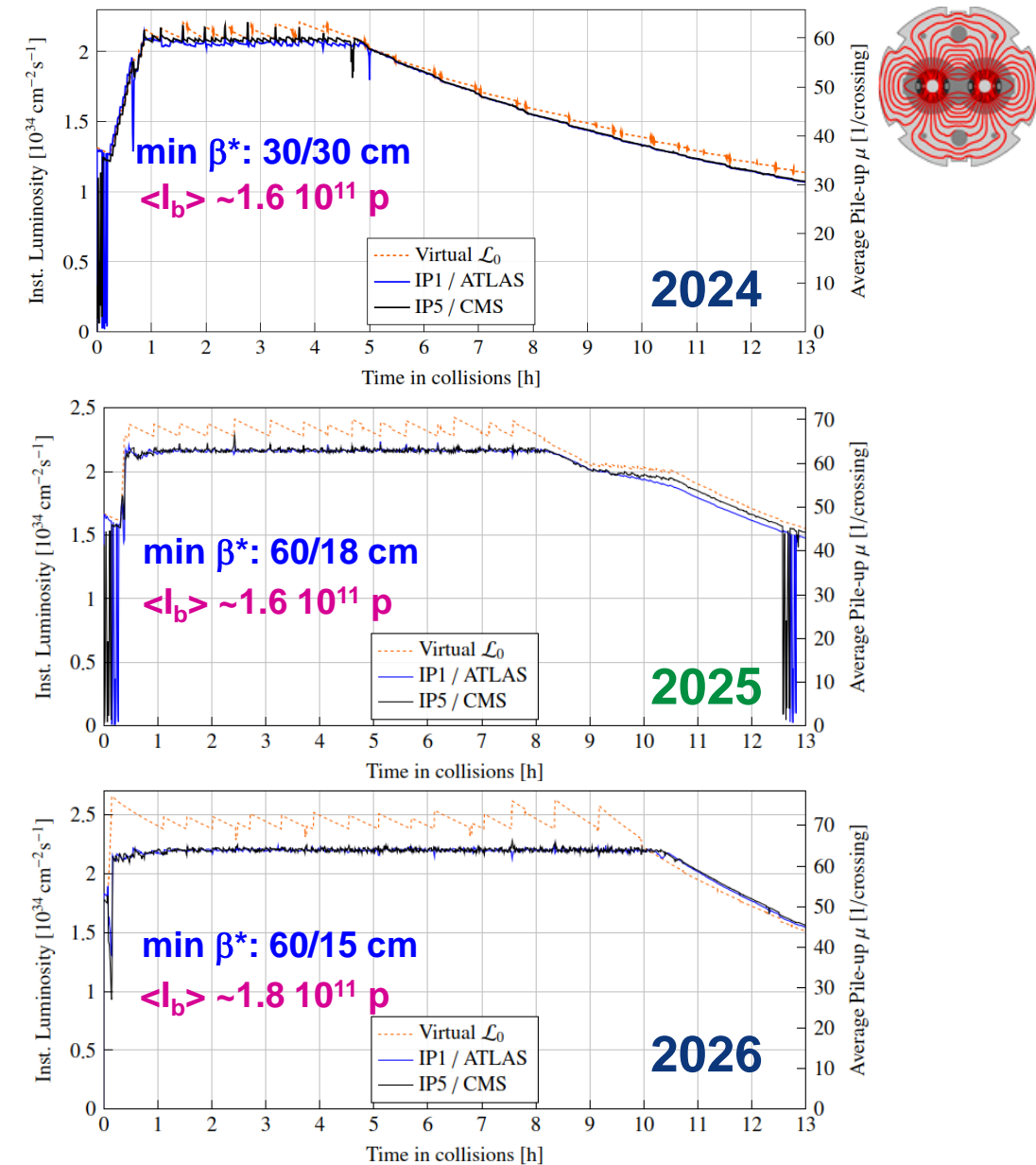


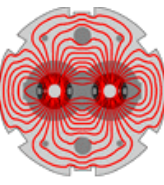
# LHC production fills

Once beams collide at 6.8 TeV,  $\beta^*$  is squeezed until the **target luminosity is reached**, followed by a period of **levelling at constant luminosity**.

- ▶ **Primary levelling** for high luminosity experiments by beam size ( $\beta^*$  **levelling**).
- ▶ Beam separation levelling is added on top to provide a smoother luminosity evolution.

The length of the period at constant peak luminosity was steadily increased with changes to the **optics** and to the **maximum bunch intensities**.



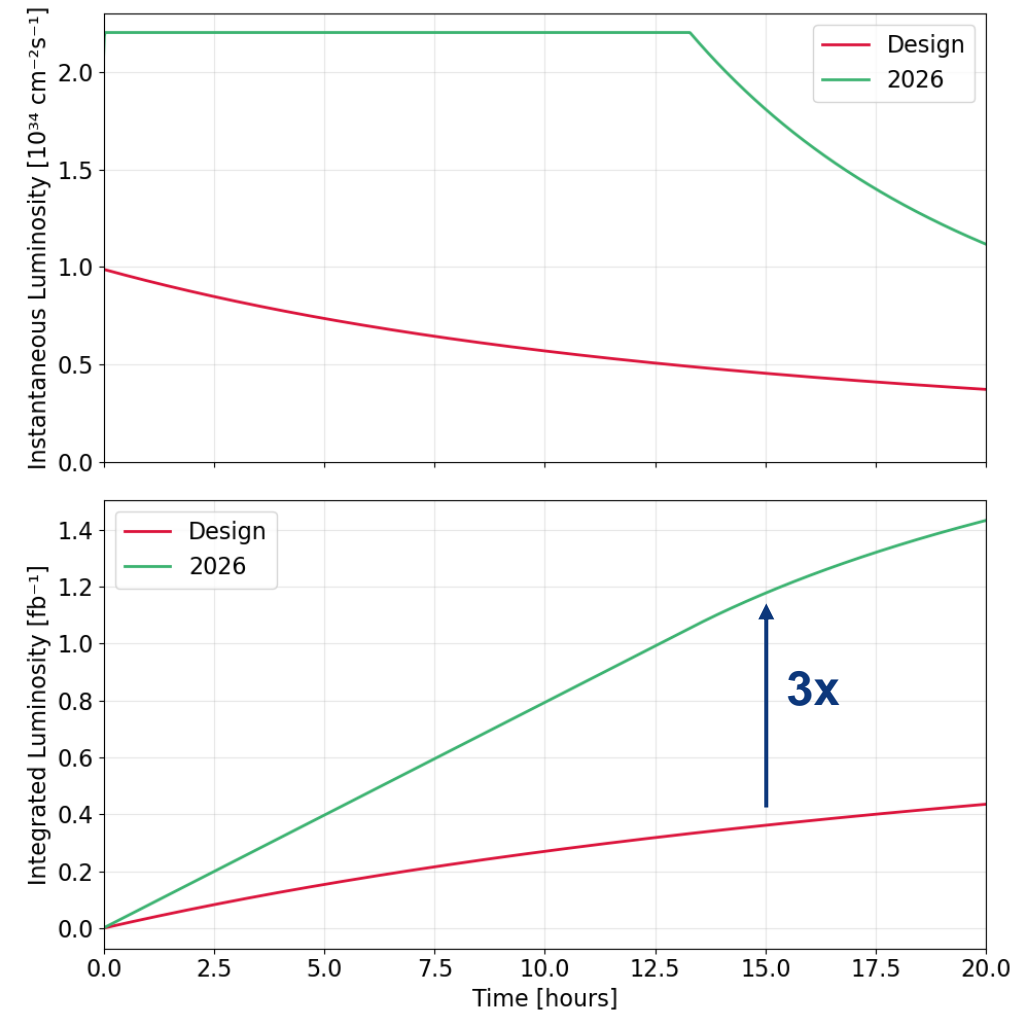


# Design versus 2025

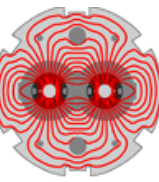
A comparison of the luminosity evolution of a **LHC design fill** with the current performance highlights the important **improvements that took place over 3 LHC runs** on the LHC and on its **injectors**.

- ▶ **Reduction in  $\beta^*$ .**
- ▶ **Higher bunch currents  $\rightarrow$  injectors upgrade**
- ▶ **Smaller emittances  $\rightarrow$  injectors upgrade**

Parameter	Design	2025	2026
Minimum $\beta^*$ (cm)	55/55	60/18	60/15
Bunch current ( $10^{11}$ p)	1.15	1.6-1.8	1.8
Norm. emittance ( $\mu\text{m}$ )	3.5	$\sim 2$	$\sim 2$

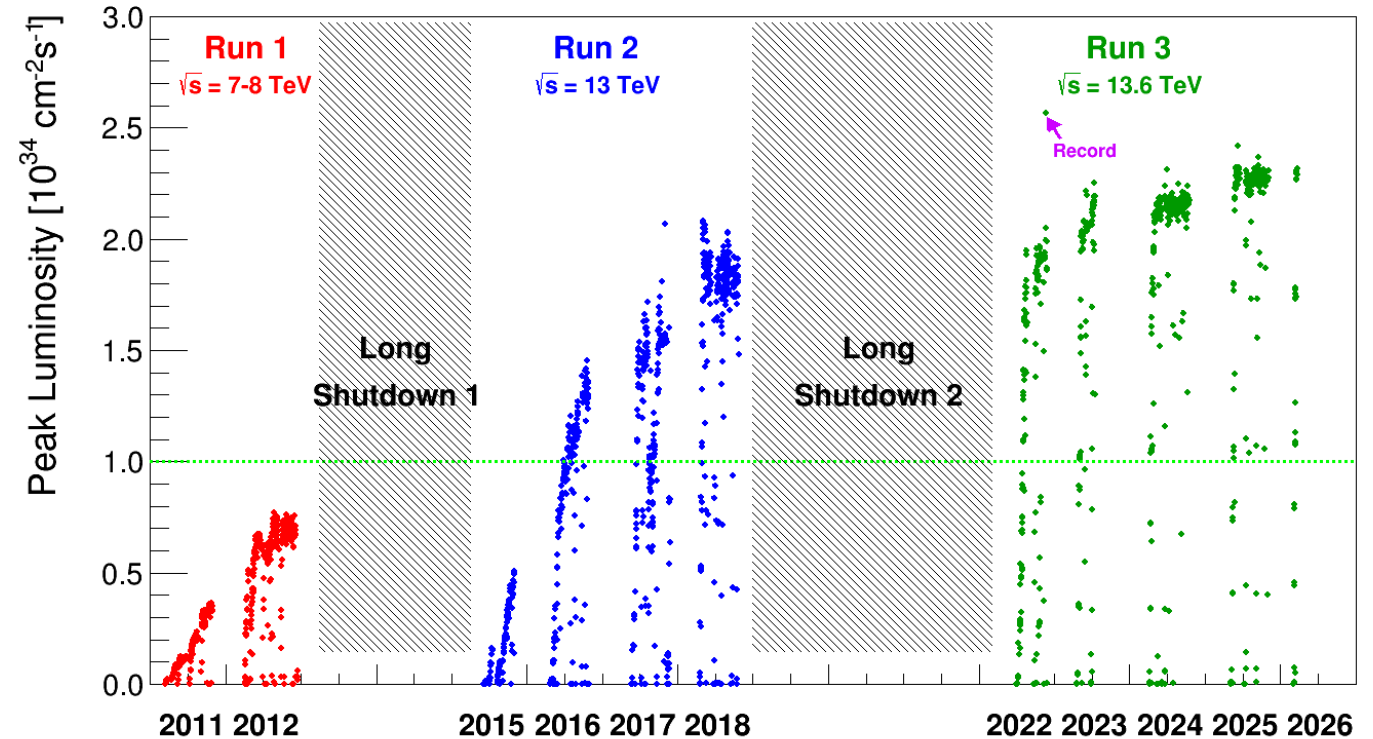


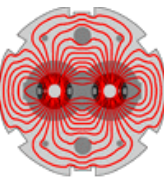
# Peak luminosity



The LHC peak luminosity exceeds the LHC design target of  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$  since 2016.

It has since been pushed up to the limit compatible with the cryogenic cooling capacity of the low-beta quadrupole triplet.

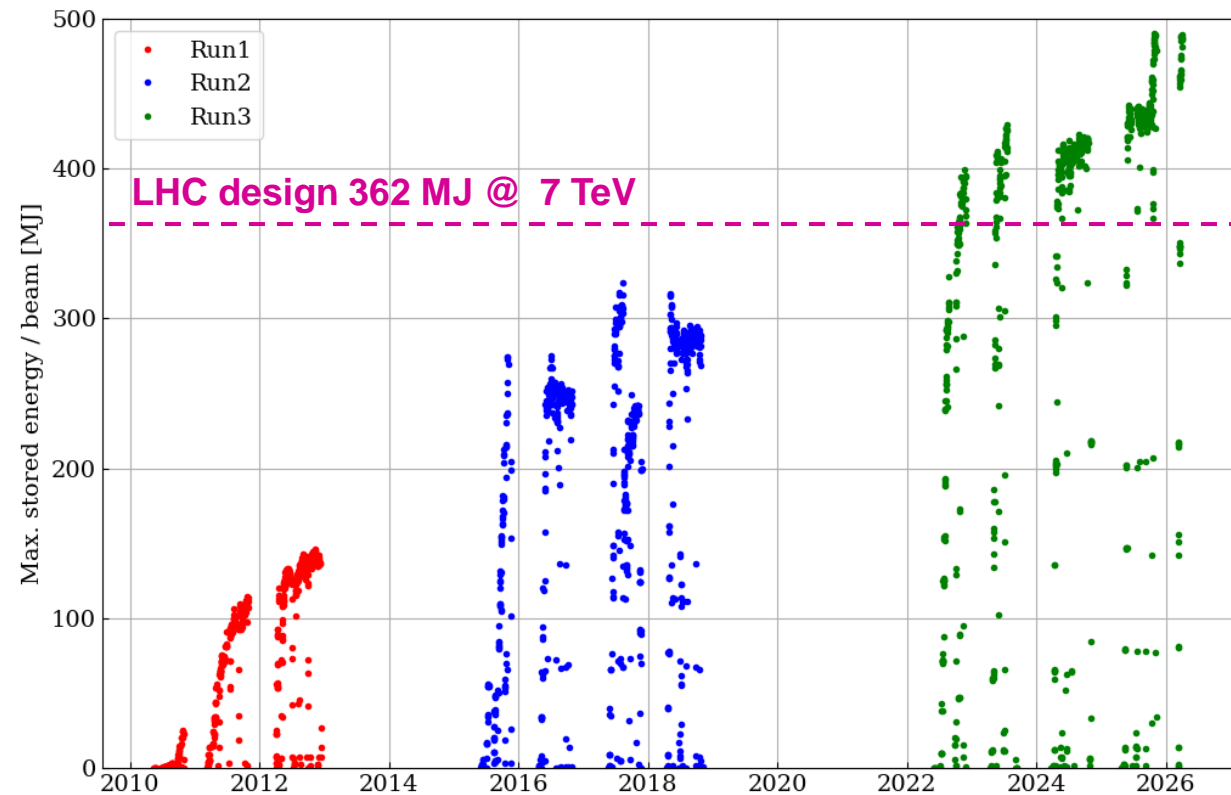




# Stored beam energy

In parallel to the peak luminosity, the energy stored also increased over time thanks to the excellent performance of the **beam cleaning** and **machine protection** systems.

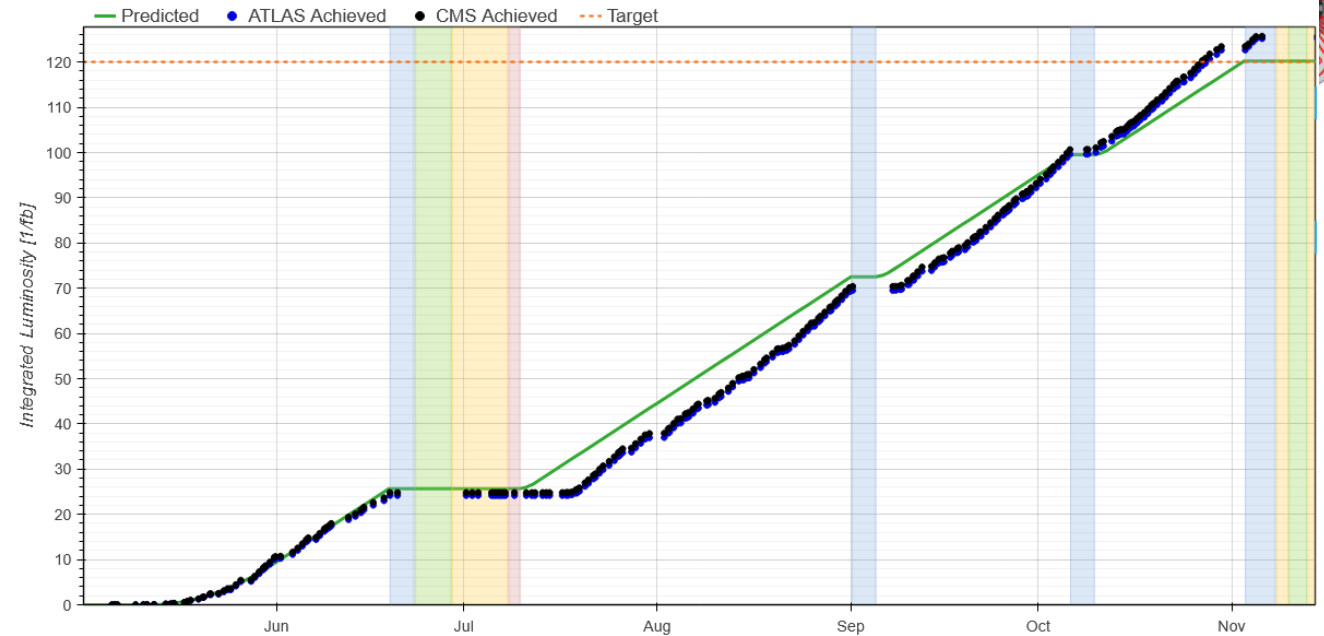
Parameter	Design	2025
No. bunches	2808	2640
Bunch current ( $10^{11}$ p)	1.15	1.8
Beam energy (TeV)	7	6.8
Stored energy (MJ)	362	490



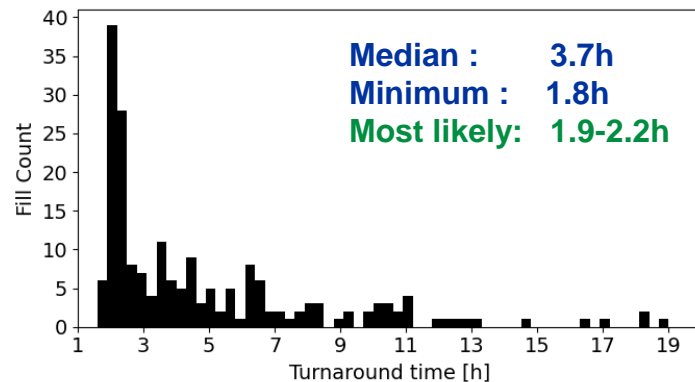
# 2025 performance

The performance target for 2025 was set to **120 fb<sup>-1</sup>** delivered to both ATLAS and CMS. Despite some time lost in the early summer, the target was exceeding, **2025** became the **best LHC production year**.

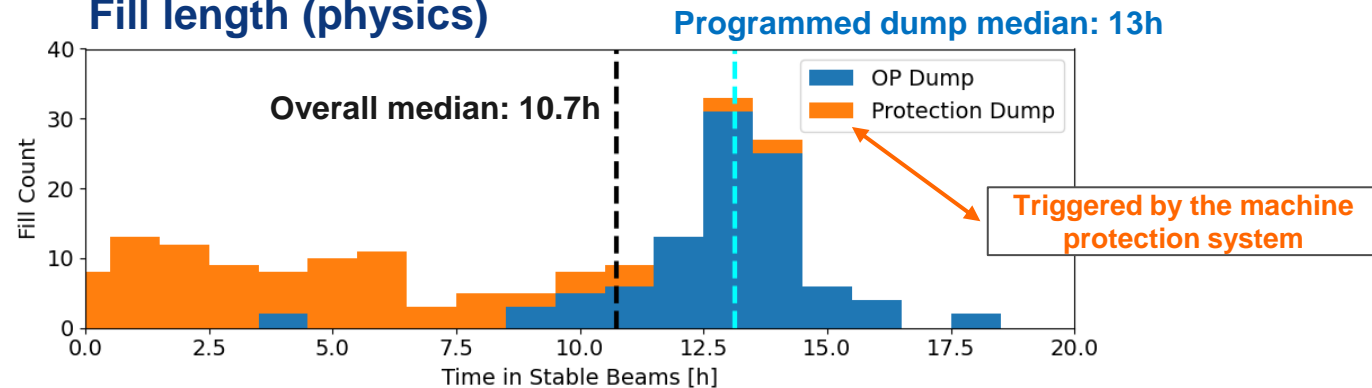
- ▶ Machine availability: 70%
- ▶ Availability for physics data taking: 54%



## Turn-around time

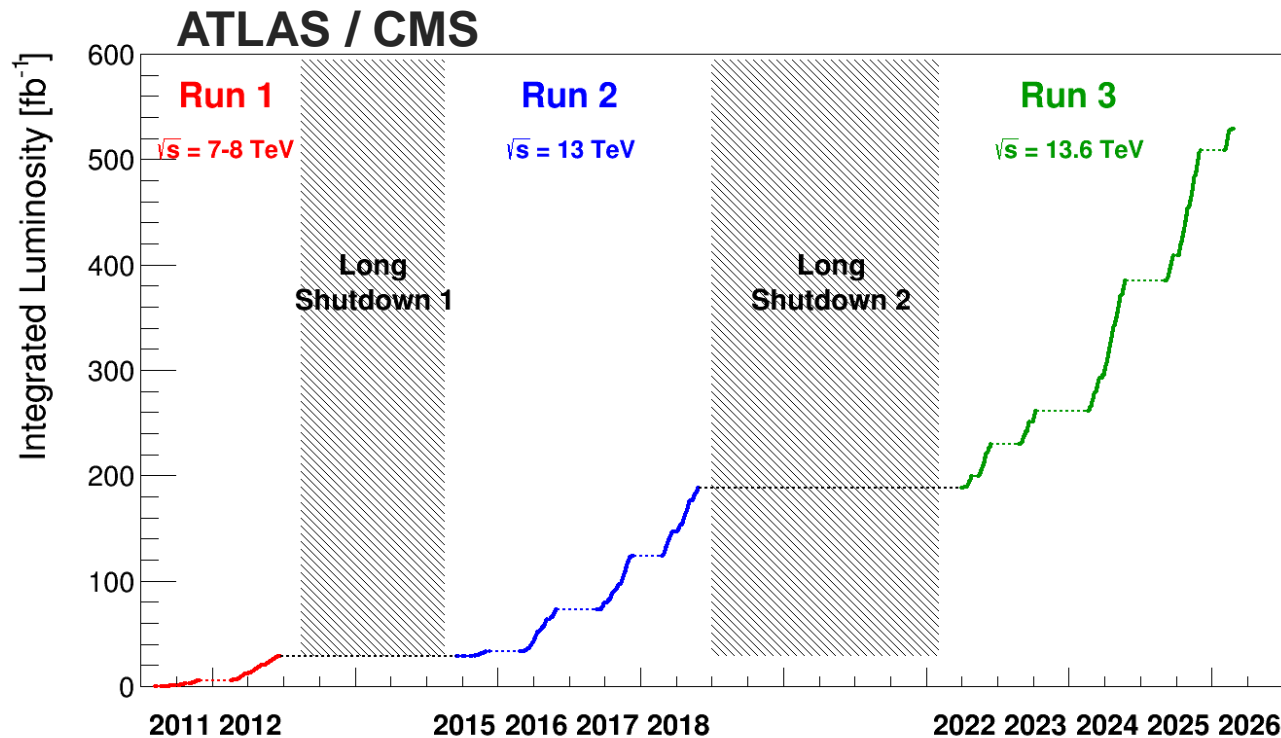


## Fill length (physics)

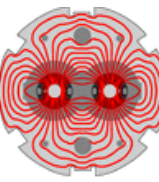
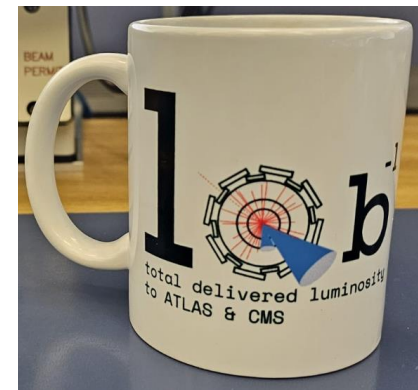


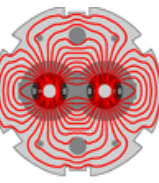
# The atto-barn area

LHC delivered more than **1 ab<sup>-1</sup> of integrated luminosity** to the ATLAS and CMS experiments (combined).



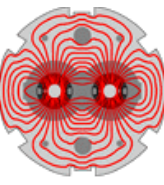
← 530 fb<sup>-1</sup>

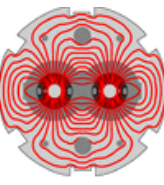




# Summary and outlook

- ▶ The LHC achieved **record performance in 2025**, following a long **evolution and improvement process**:
  - ▶ Refining beam control and beam commissioning for efficient operation.
  - ▶ Pushing the beam intensity with the support of excellent injector performances.
  - ▶ Storing close to 500 MJ of energy per beam in a superconducting machine.
  - ▶ Mastering luminosity levelling for optimal performance.
- ▶ **LHC operation will end in June 2026**, the machine will **restart as HL-LHC in 2030** after a 4 year long shutdown.
- ▶ The **beam intensity** has reached **~70% of the HL-LHC target**.
- ▶ In June 2026, as last test before the shutdown, we aim to store HL-LHC intensity beams.





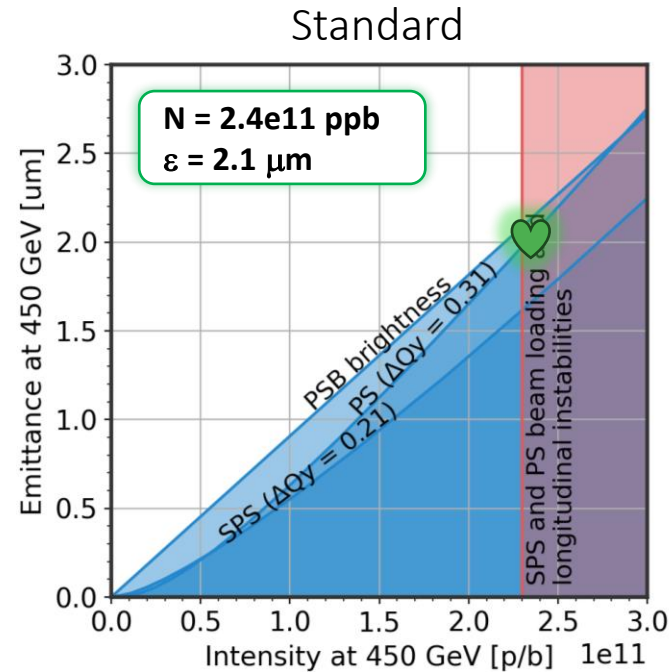
# Injector beams

Nominal HL-LHC beam intensities and emittances have been reached in the LHC injectors in 2026.

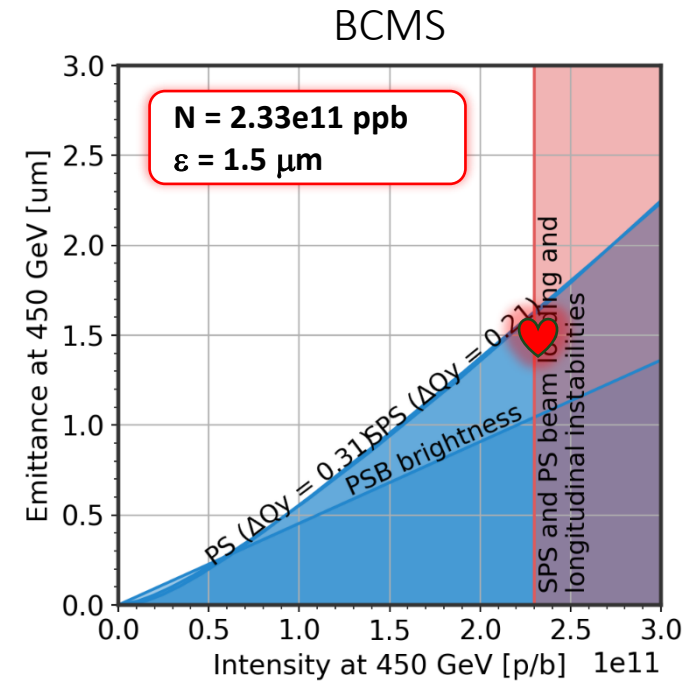
- ▶ Bunch intensity:  $2.3 \times 10^{11}$  proton/bunch.
- ▶ 4 x 72 bunch trains ('nominal beam').
- ▶ 5 x 48 bunch trains ('low emittance beam').

In 2026 the LHC injector chain will perform a 'reliability run'.

- ▶ Preparation of the HL-LHC beams for LHC injection will be exercised a few times per week when the LHC is not requesting beam.



Trains: 4x72b



Trains: 5x48b  
(low emittance variant)