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

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Introduction – LHC

ATLAS & **CMS**: high luminosity experiments, **L ~ 2.2×10^{34} cm^{-2}s^{-1}**.

- Most performance parameters refer to those experiments.

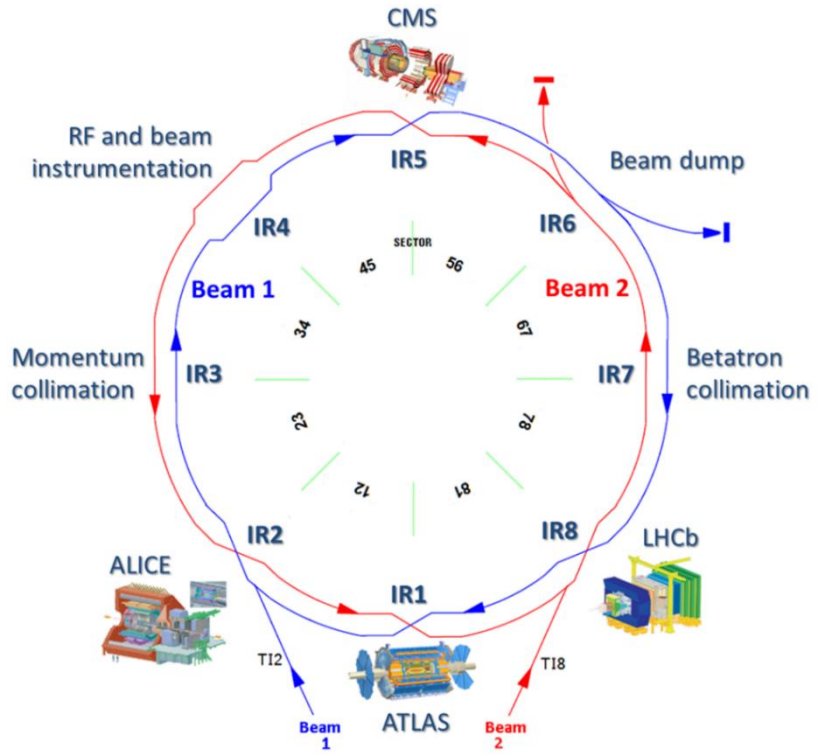
LHCb: medium luminosity experiment, **L ~ 2×10^{33} cm^{-2}s^{-1}**.

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

SND and **FASER:** Beyond Standard Model and neutrino physics experiments located ~500 m downstream of the ATLAS IP.

LHC is operating the **3rd 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)

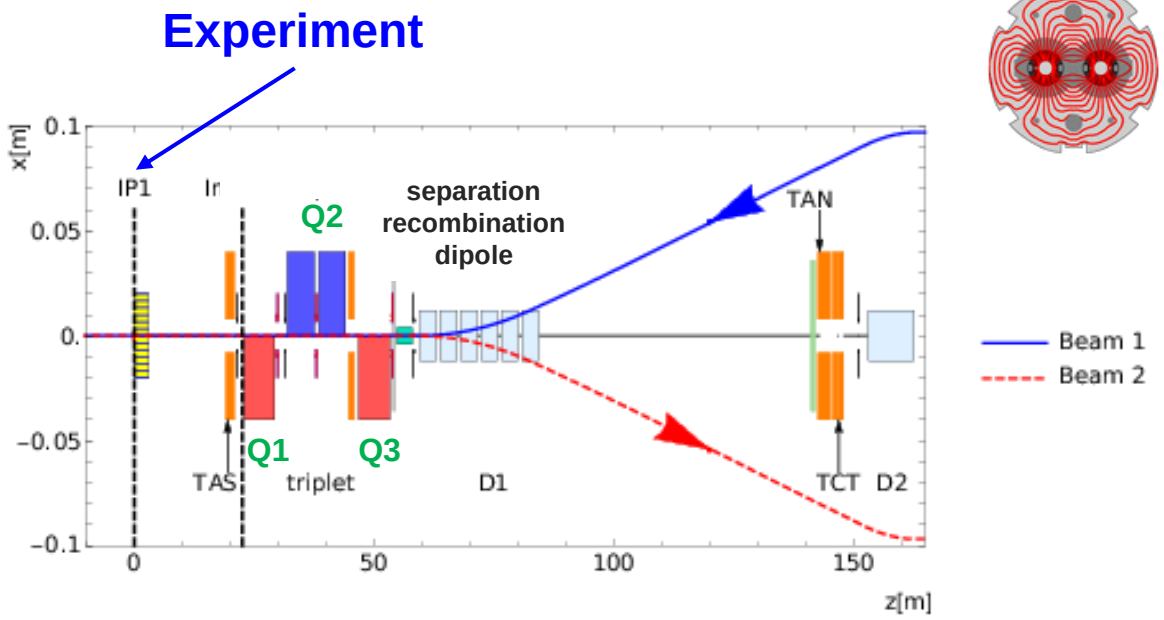
The low-beta (inner triplet) magnets have accumulated **high radiation doses due to collision debris** (low-angle collisions).

Estimated lower **dose limits**:

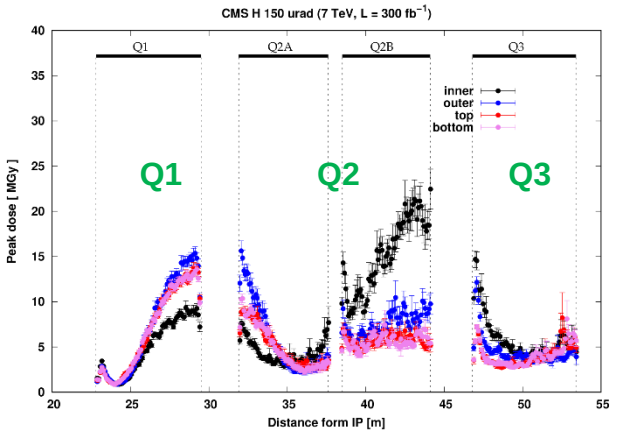
- Quadrupoles: **30 MGy**
- Corrector magnets: **7 MGy**
- Normal conducting separation dipole: **75 MGy**

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

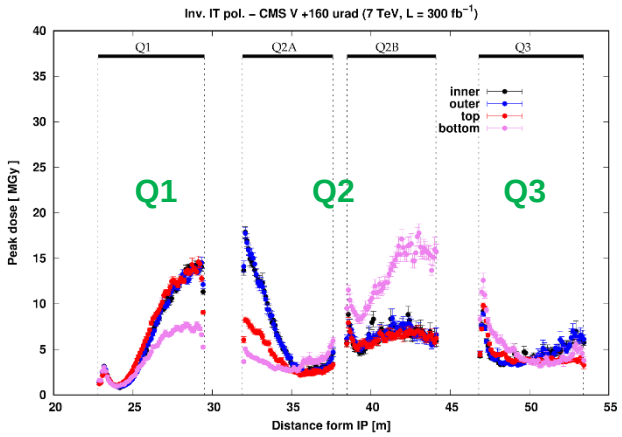
- In some magnets the radiation dose is very **localized**.
- The dose limit is already exceeded in many corrector magnets !



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:

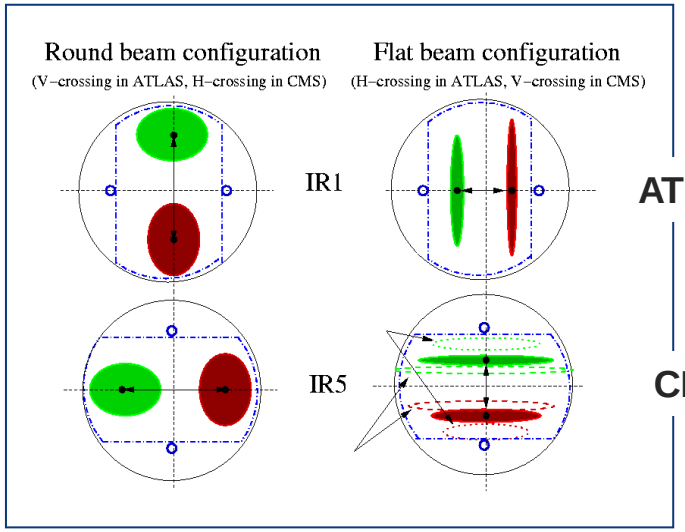
- Modifying the triplet optics by inverting the quadrupole polarities.
- Exchanging the beam crossing between vertical and horizontal planes: ATLAS: V → H, CMS : H → V

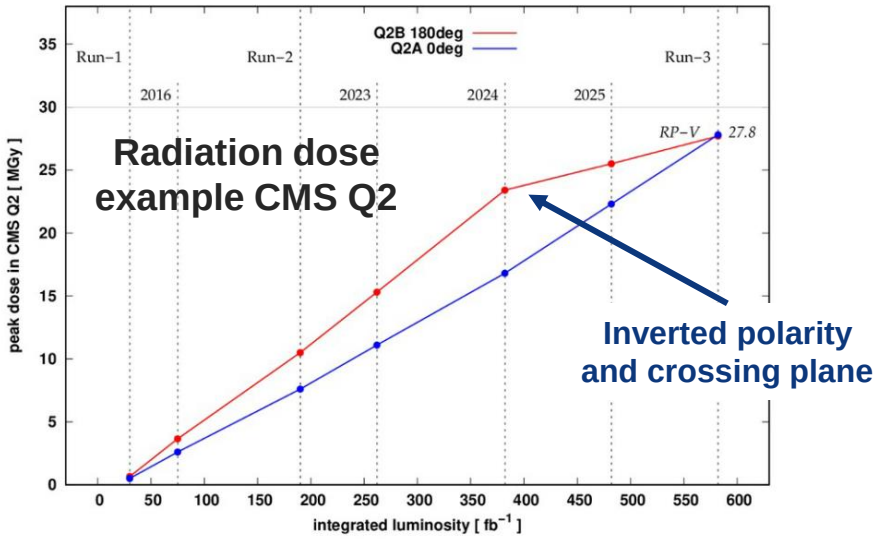
To switch the beam crossing planes, a **flat optics** had to be introduced to accommodate the beams in the IT quadrupoles due the **shape of the beam screen**, with larger β* in the beam crossing plane.

- **Round** optics ≤ 2024: min β^*_x/β^*_y = **30 cm/30 cm**
- **Flat** optics ≥ 2025: min β^*_x/β^*_y = **60 cm/18 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



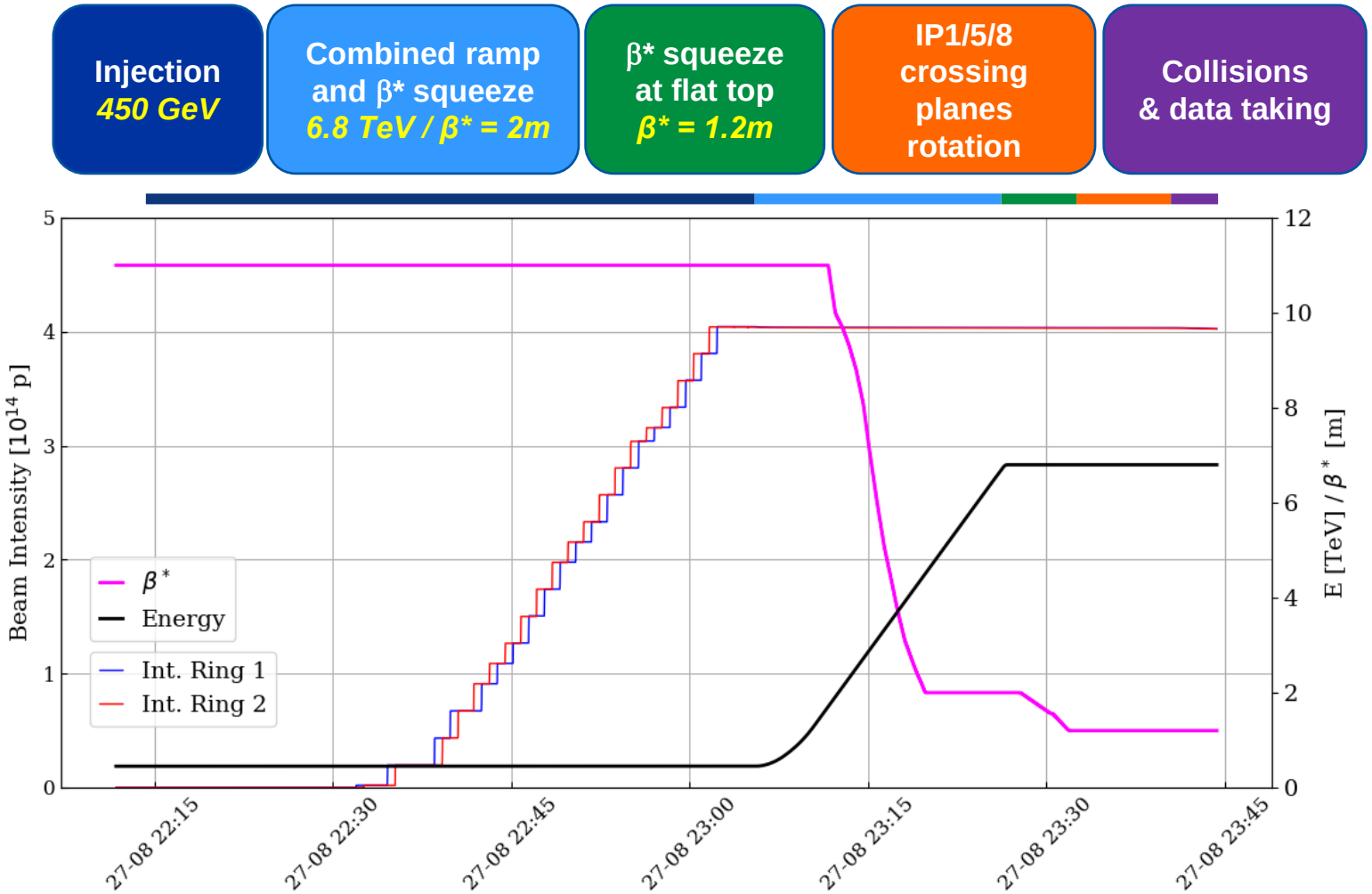


LHC machine cycle

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

- β* squeeze partially incorporated into the 20 min long ramp (in 2026: entirely incorporated).
- End of β* 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 **1.8×10^{11} p** due to:

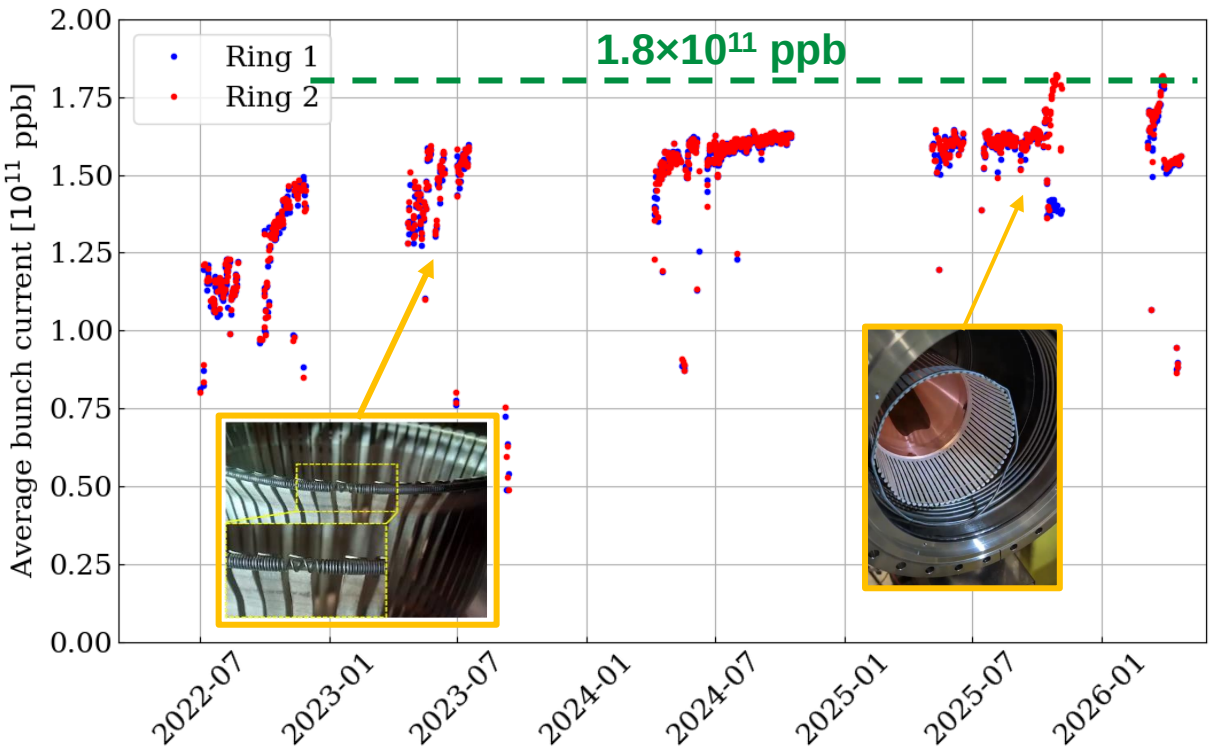
- Beam dump protection devices damage limits.
- Electron cloud heat-load to the cryogenic system.

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 1.8×10^{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.

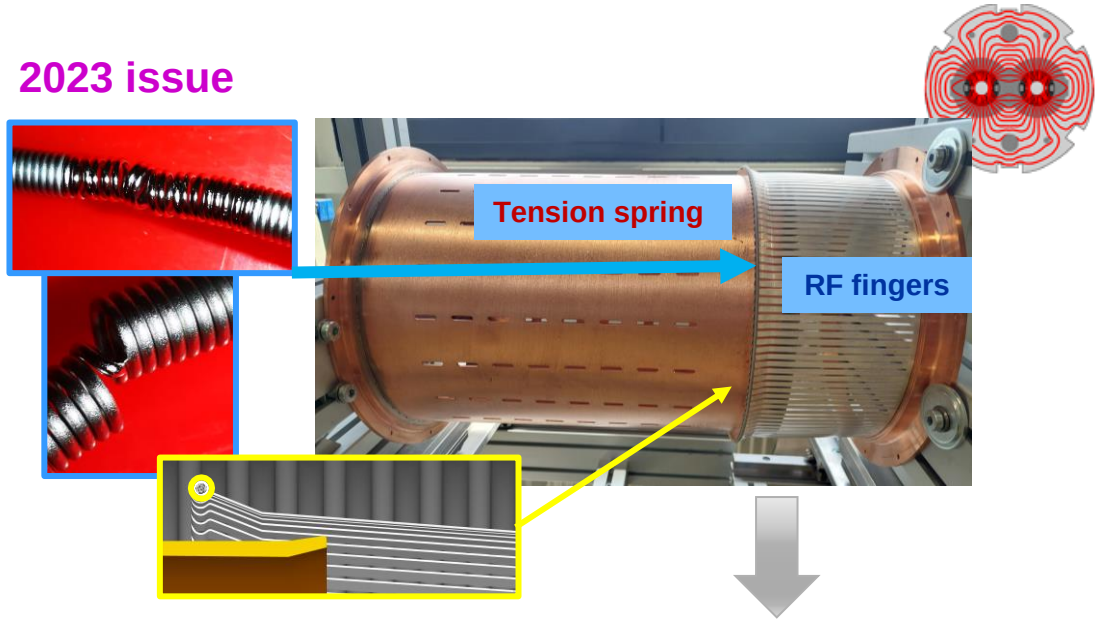
- **Non-conform positioning** and **holding** of '**RF fingers**' can lead to thermal run-away and damage.

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

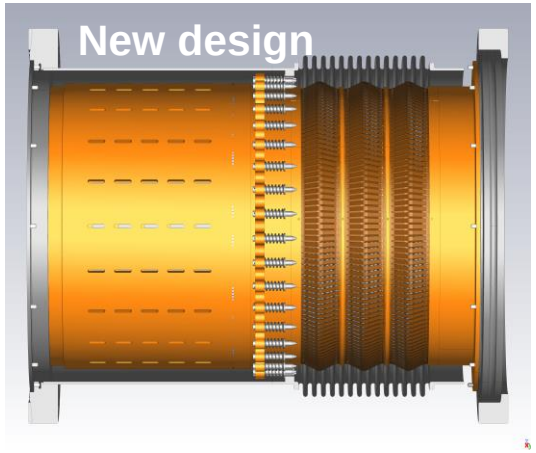
In **2025** a different **specialized module** installed in the injection region of ring 1 failed.

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

2023 issue



2025 issue



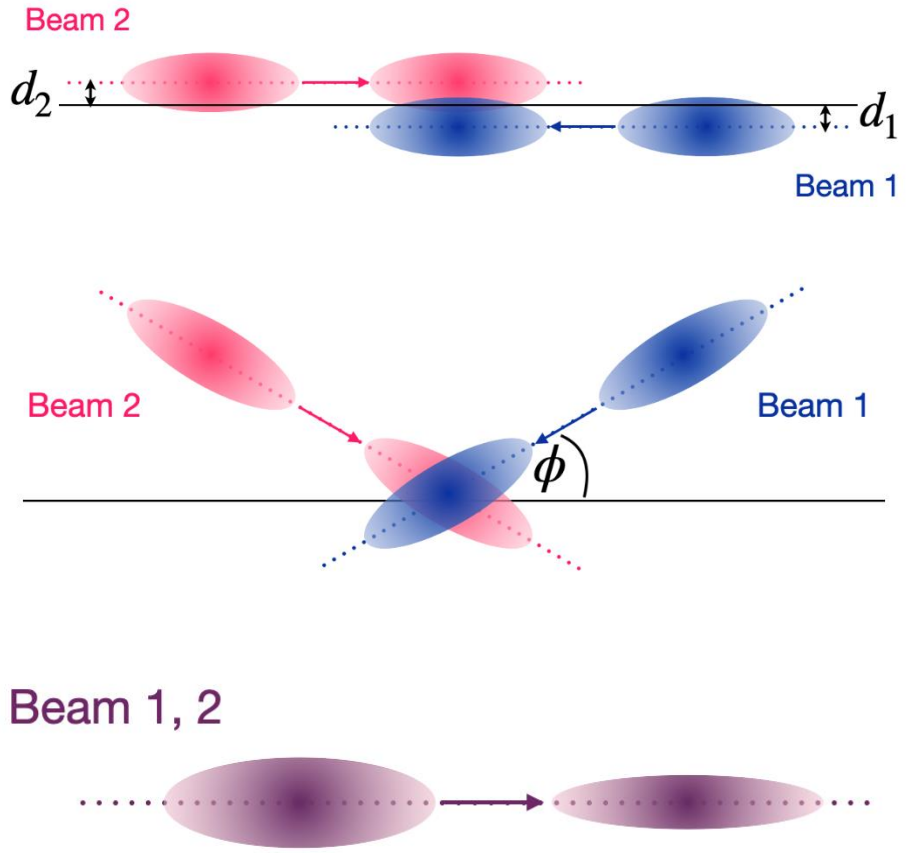
Luminosity levelling

The LHC peak luminosity is limited to **L ~ 2.2×10^{34} cm^{-2}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** (β* squeeze).
  - Beams remain head-on, provides Landau damping from head-on beam-beam tune spread.

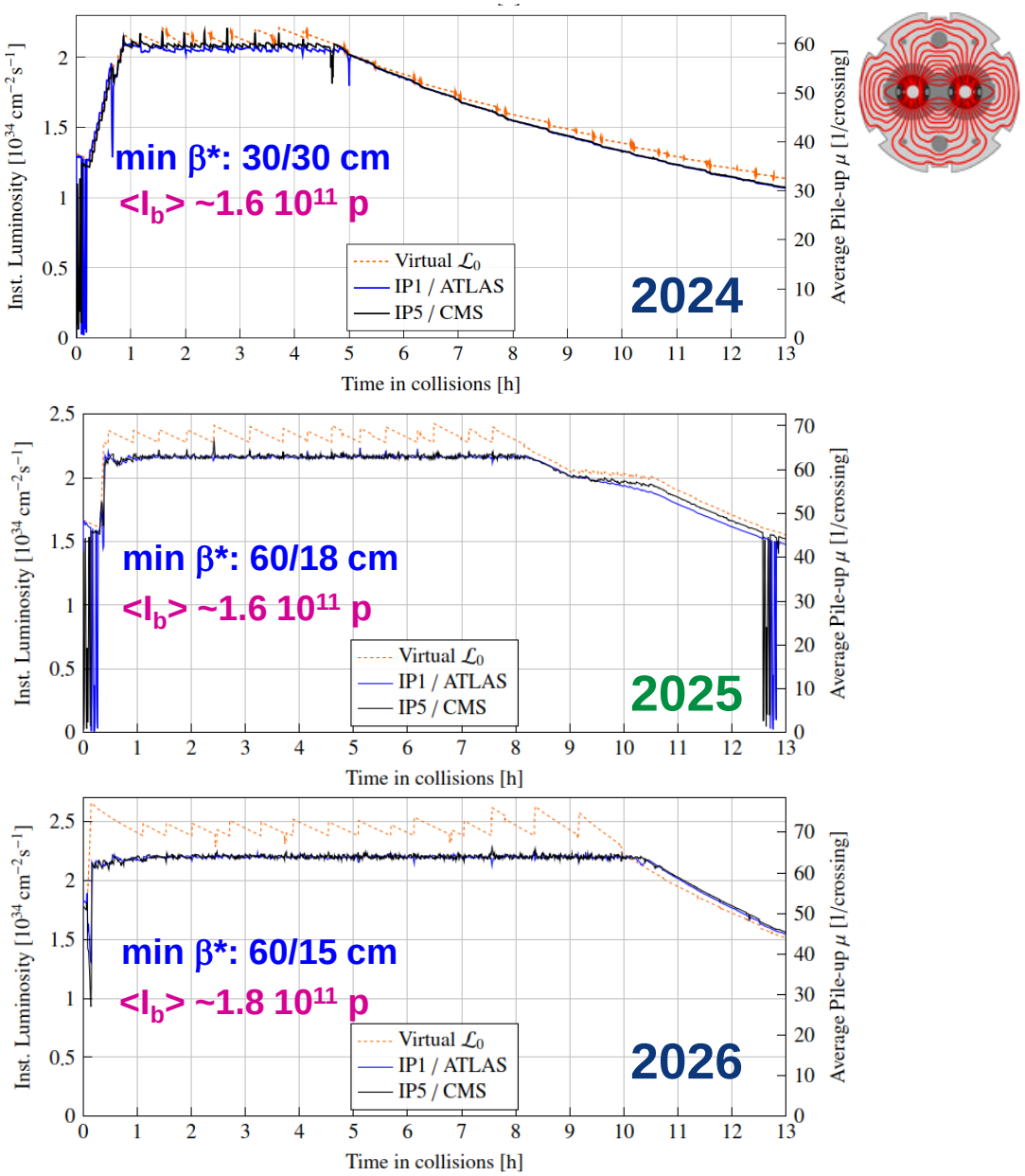


LHC production fills

Once beams collide at 6.8 TeV, β* 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 (**β* 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**.

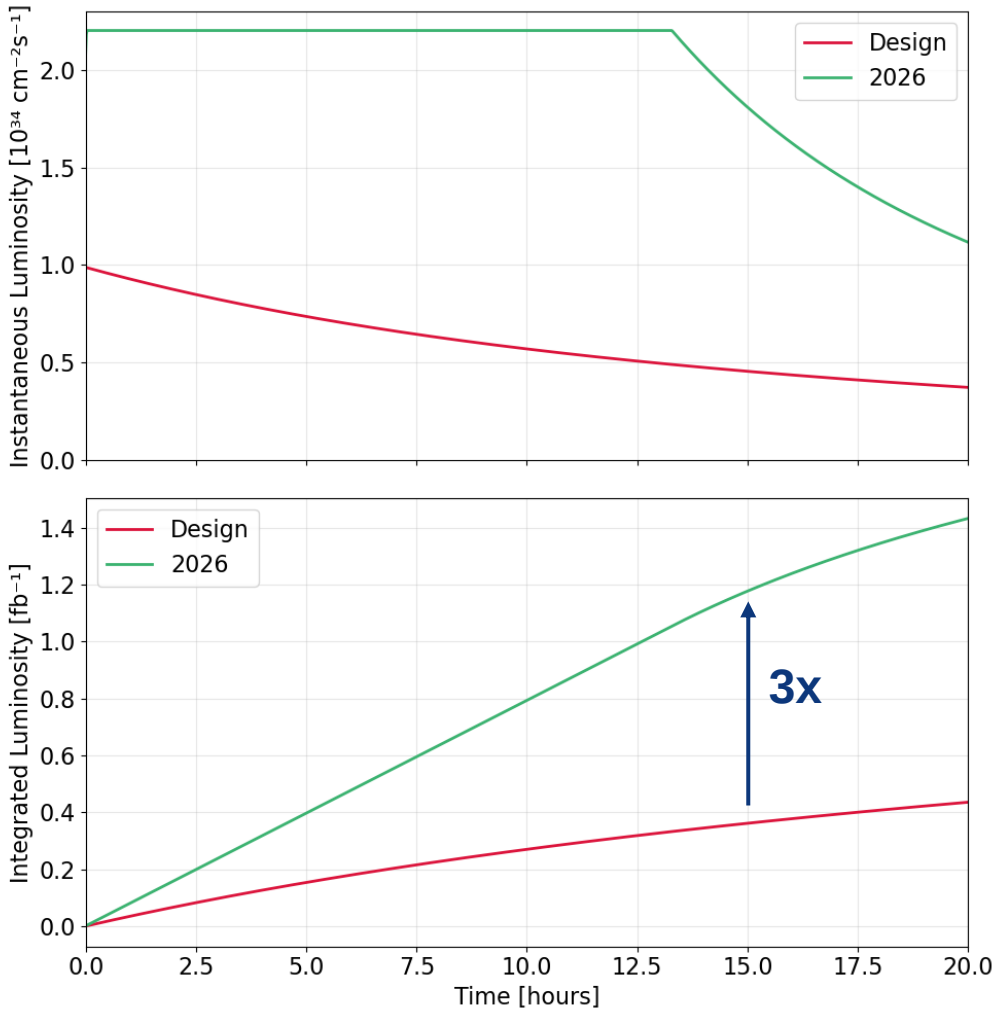


Design versus 2025

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 β*.**
- **Higher bunch currents → injectors upgrade**
- **Smaller emittances → injectors upgrade**

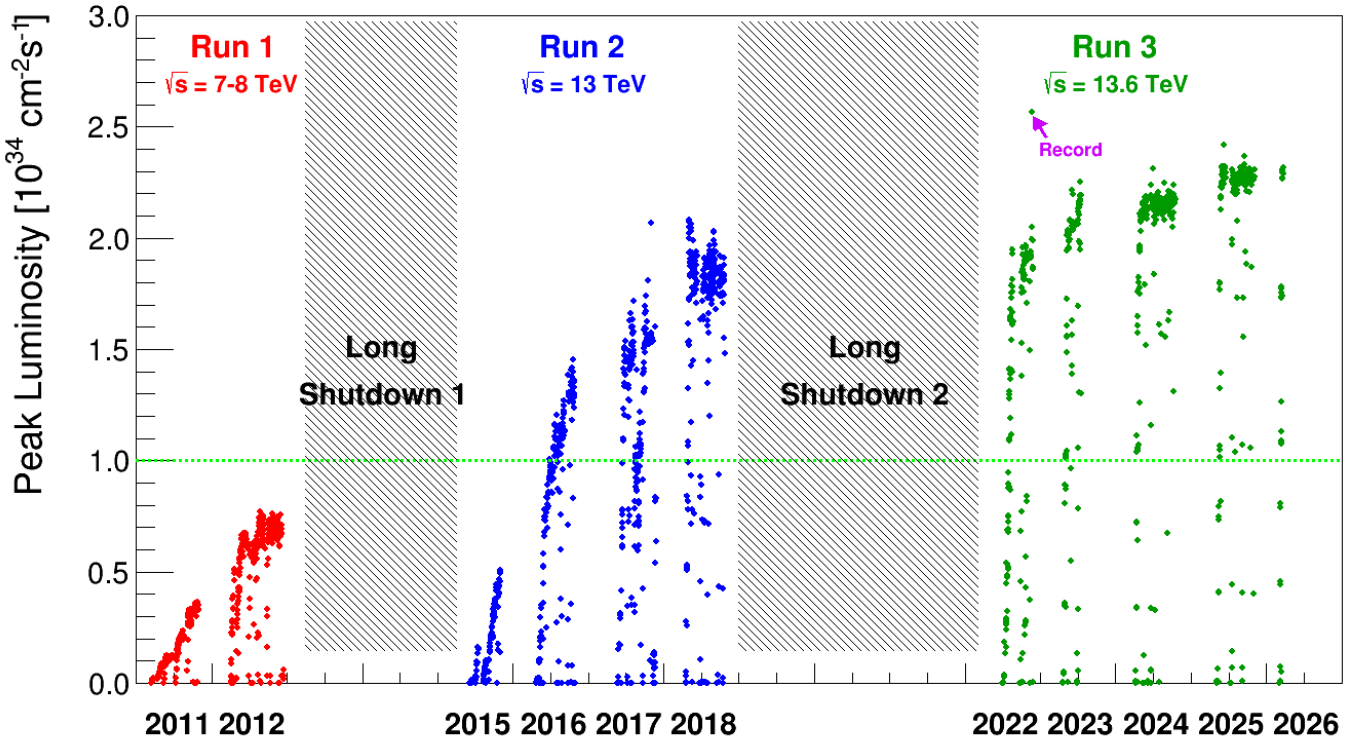
Parameter	Design	2025	2026
Minimum β* (cm)	55/55	60/18	60/15
Bunch current (10^{11} p)	1.15	1.6-1.8	1.8
Norm. emittance (μm)	3.5	~2	~2



Peak luminosity

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

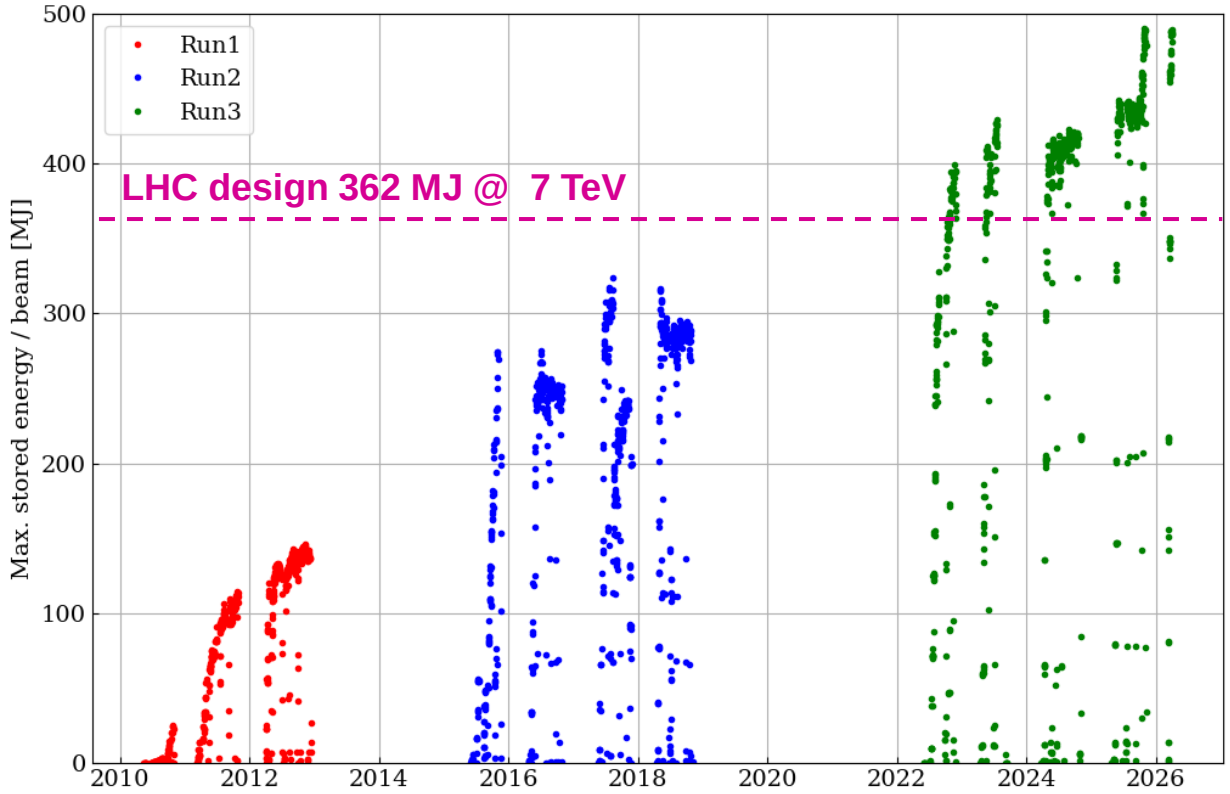
It has since been pushed up to the limit compatible with the **cryogenic cooling capacity** of the low-beta quadrupole triplet.



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

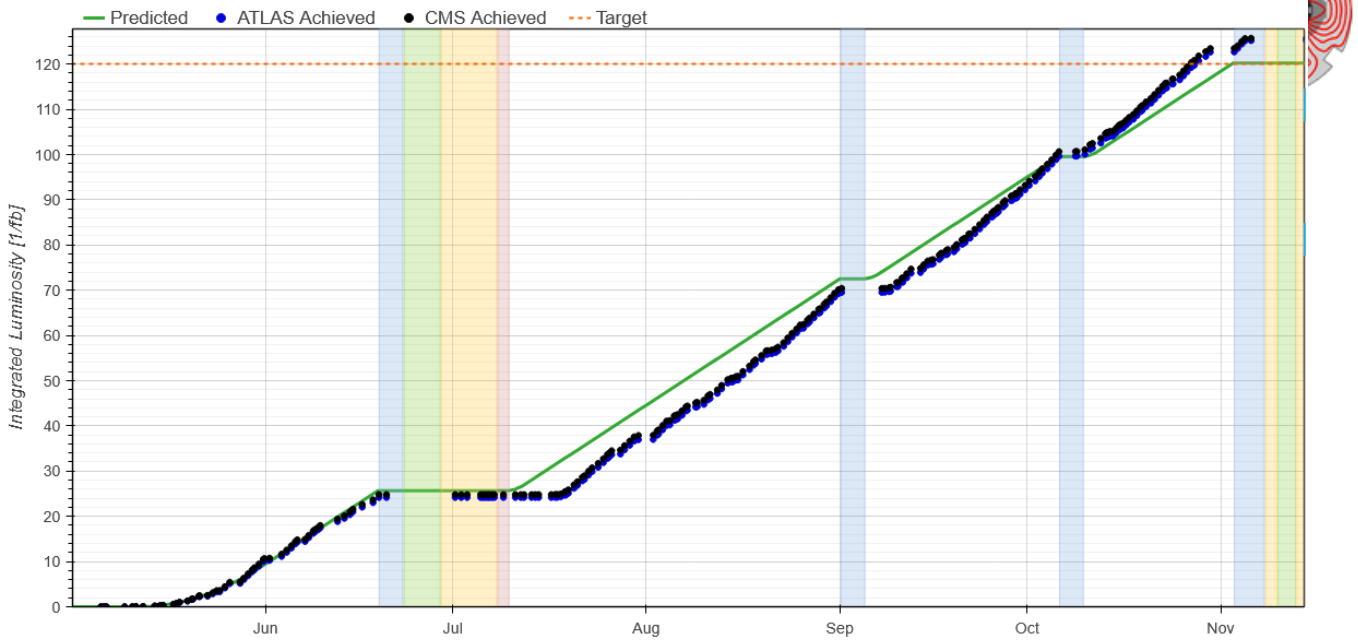


2025 performance

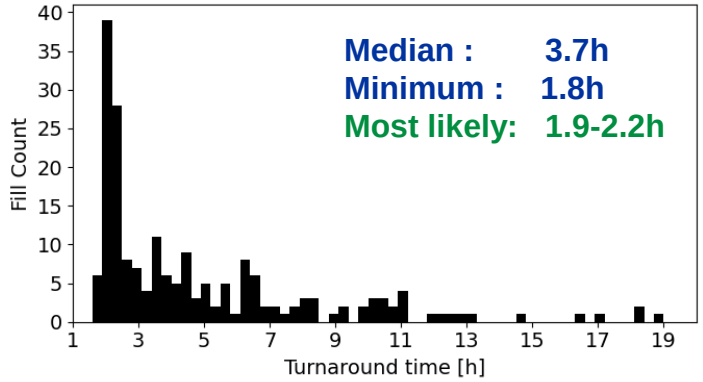
The performance target for 2025 was set to **120 fb^{-1}** delivered to both ATLAS and CMS.

Despite some time lost in the early summer, the target was exceeding, **2025** became the **best LHC production year**.

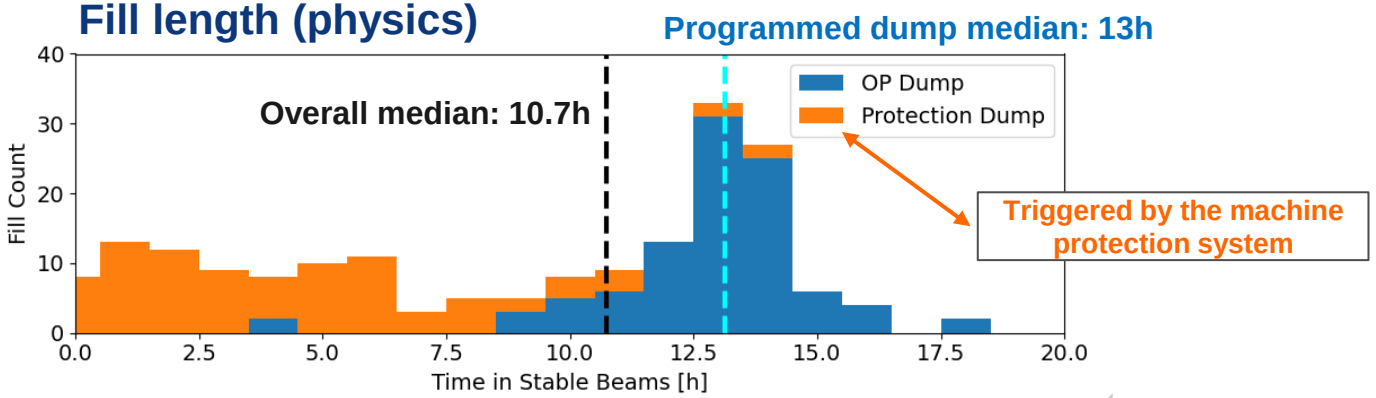
- **Machine availability: 70%**
- **Availability for physics data taking: 54%**



Turn-around time



Fill length (physics)



The atto-barn area

LHC delivered more than **1 ab^{-1} of integrated luminosity** to the ATLAS and CMS experiments (combined).

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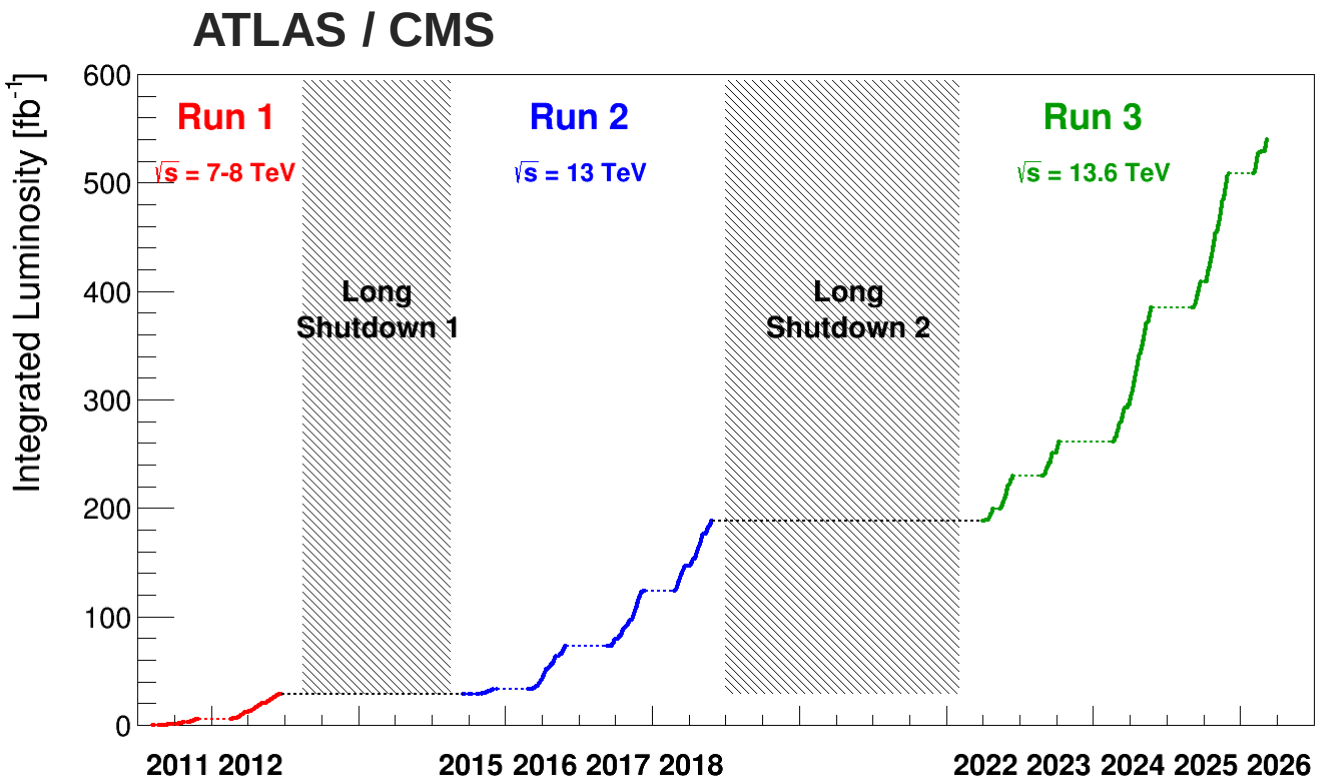
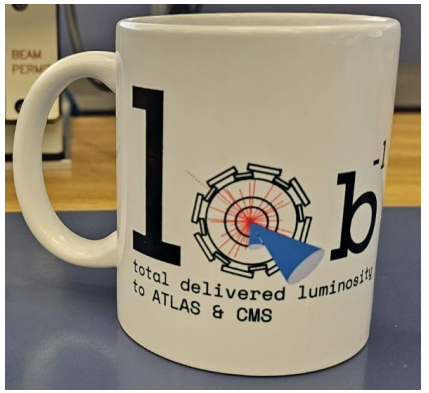
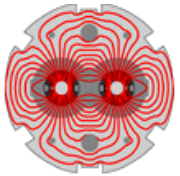


540 fb-1



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

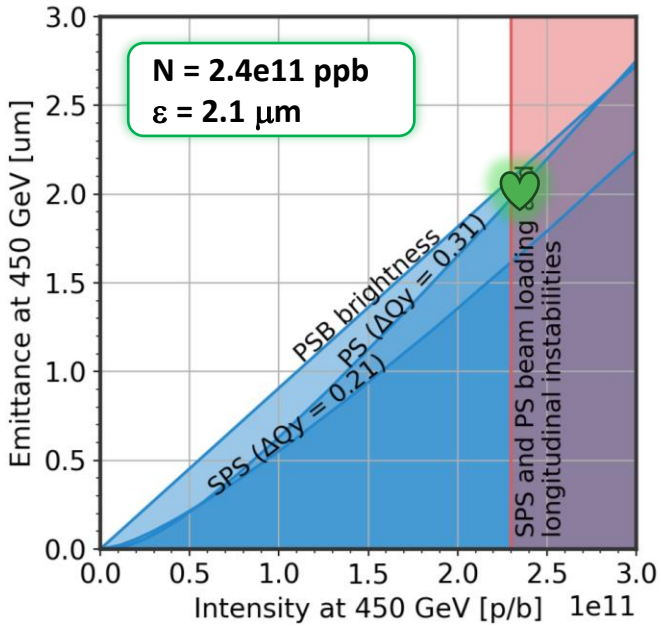
Nominal HL-LHC beam intensities and emittances have been reached in the LHC injectors in 2026.

- Bunch intensity: 2.3×10^{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**’.

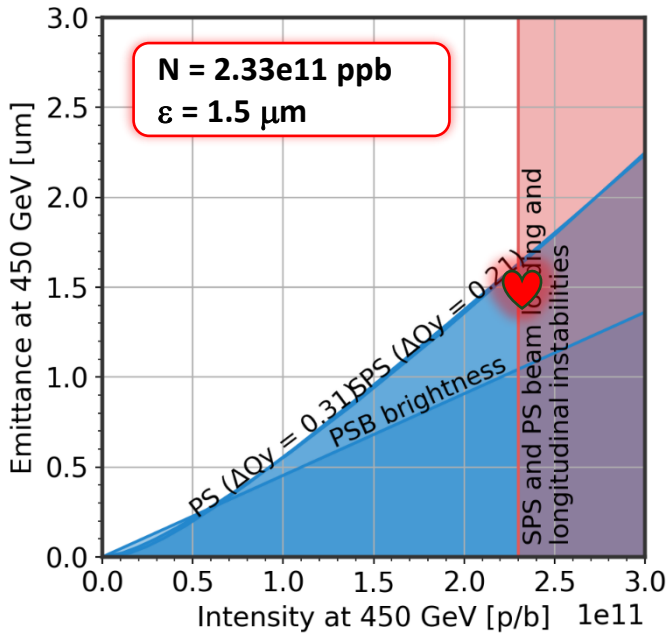
- Preparation of the HL-LHC beams for LHC injection will be exercised a few times per week when the LHC is not requesting beam.

Standard



Trains: 4x72b

BCMS



Trains: 5x48b
(low emittance variant)