LHC Status

J. Wenninger – BE/OP/LHC

Acknowledgements: M. Solfaroli, M. Hostettler, S. Fartoukh, A. Lechner, G. Iadarola

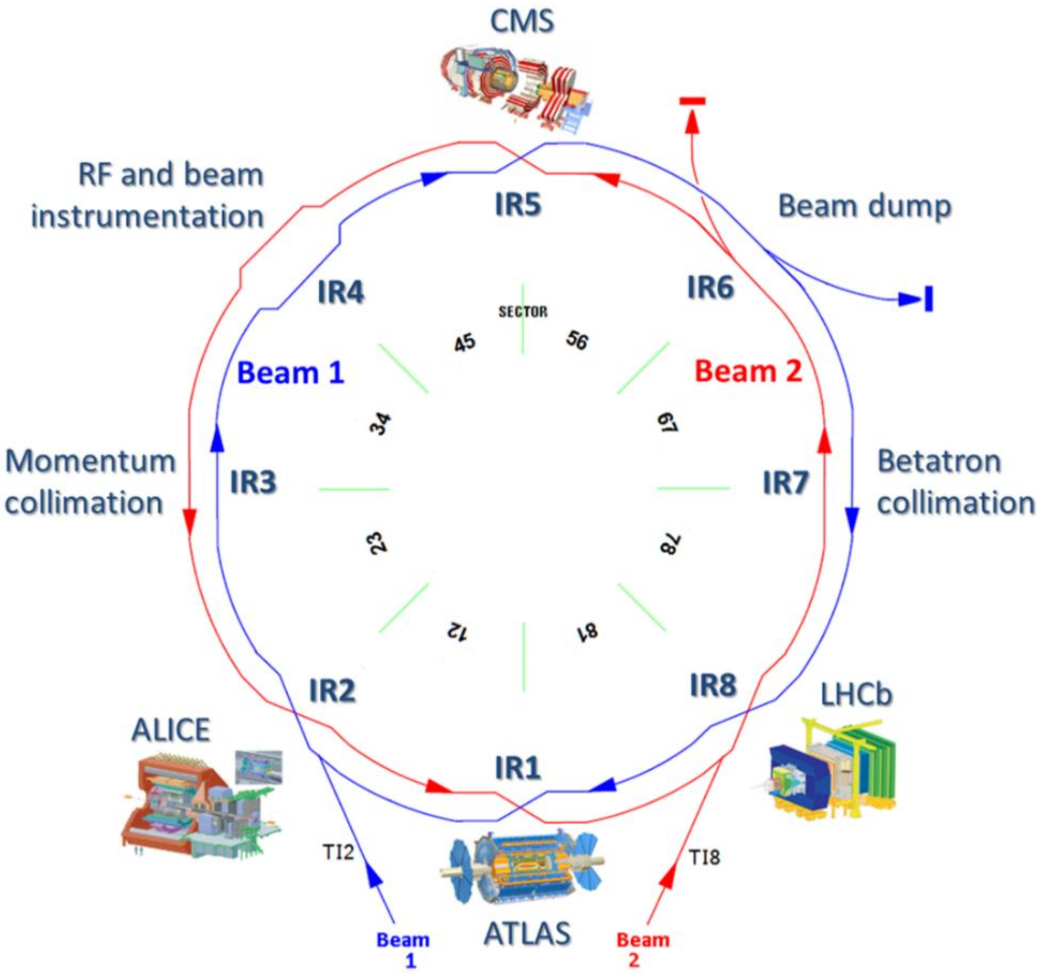
Outline

Introduction – LHC Run 3

Commissioning 2022

Performance limitations

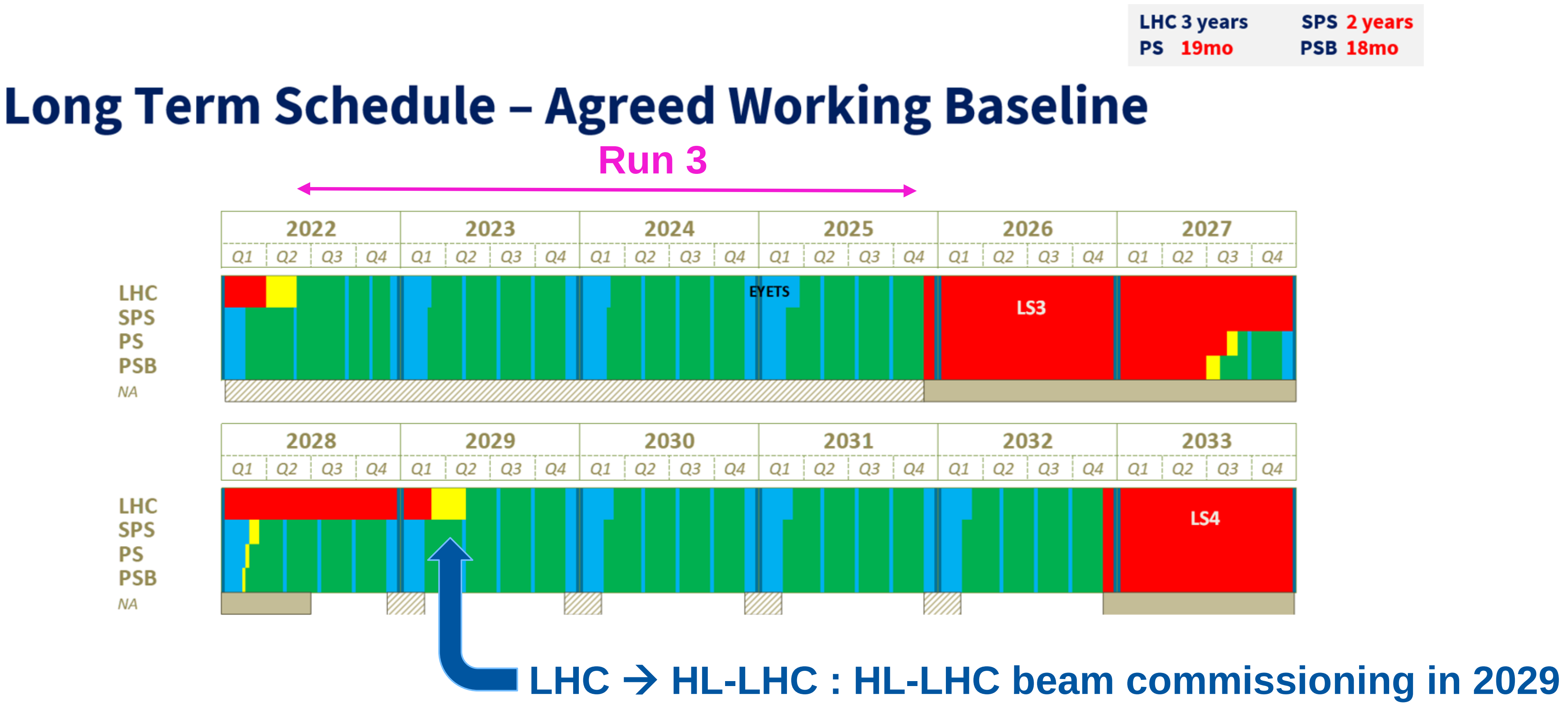
Conclusions



Long term CERN accelerator schedule

Long term operation plan of CERN – recent changes:

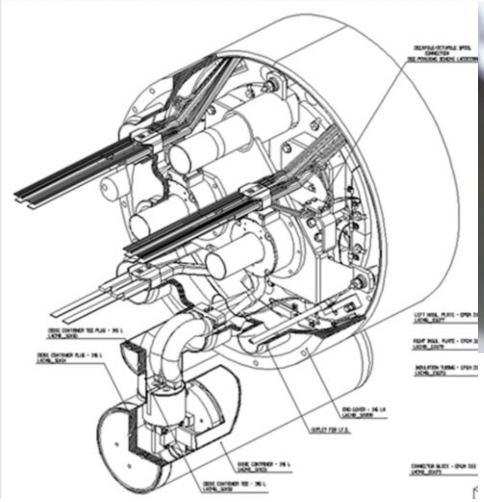
- **Extension of LHC Run 3 by one year** until the end of 2025.
- **Extension of Long Shutdown 3 (LS3) to 3 years** (for LHC).

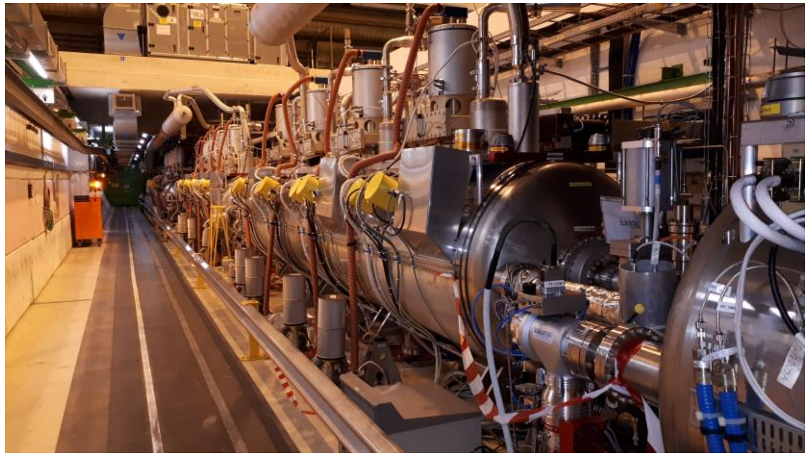


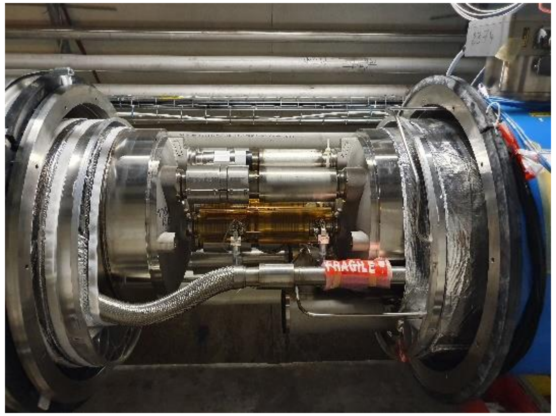
Long Shutdown 2 – 2019-2021

The main shutdown activities of LS2 :

- **Diode consolidation** for all dipole magnets
- Replacement of 24 **magnets with non-conformities**
- **RF module** replacement
- **Realignment** of the CMS beam line (~3mm shift)
- Consolidation of **LHC beam dumps**
- Maintenance of the major systems

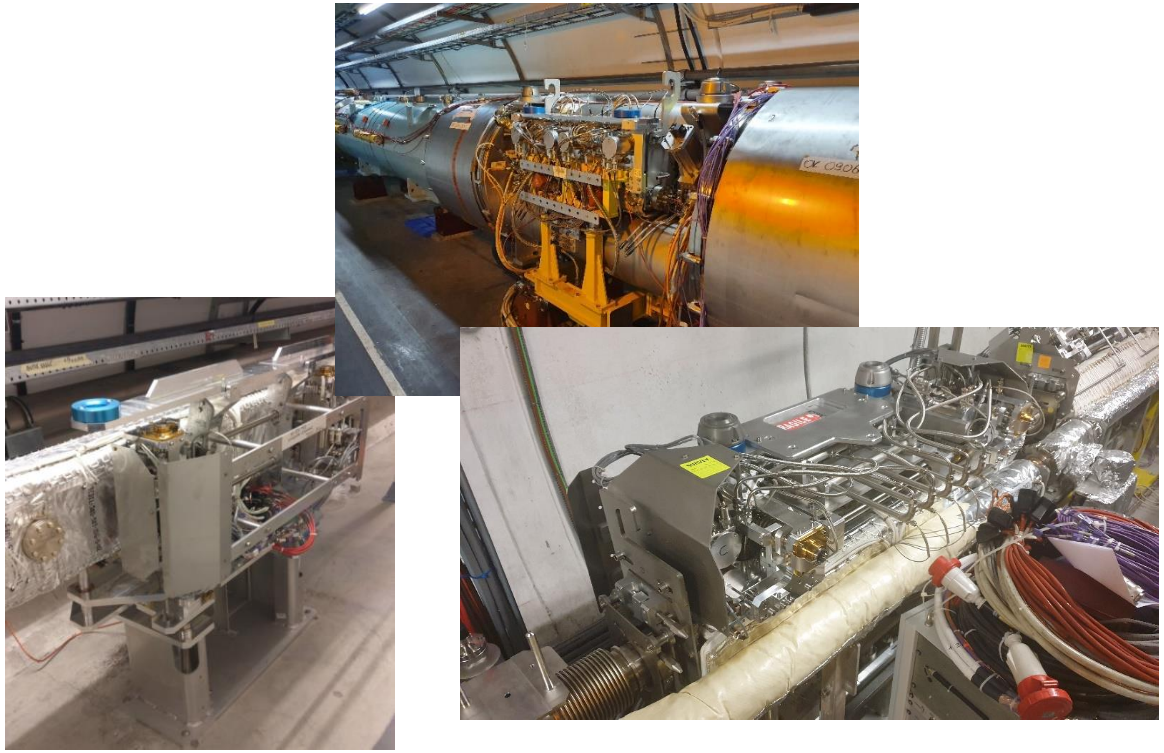


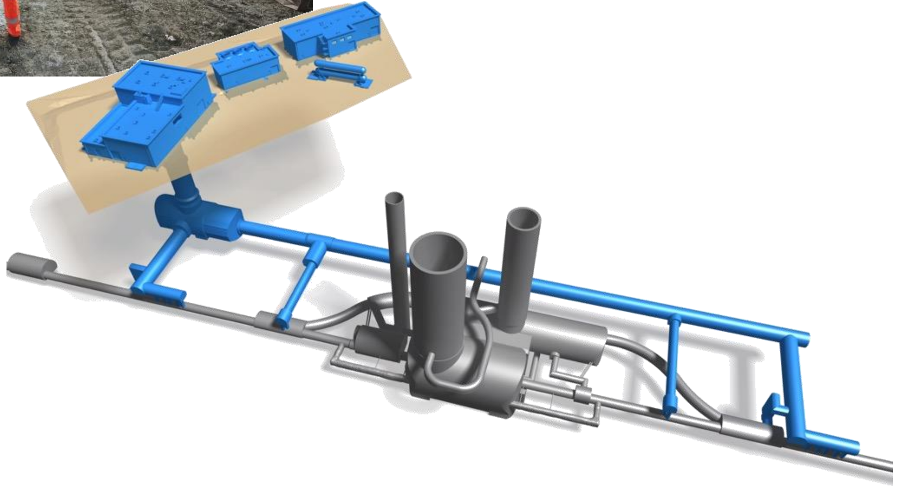




HL-LHC activities during Long Shutdown 2

- **Civil engineering** of new HL underground caverns and connection to the LHC tunnel.
- New **collimators and injection protection devices**.
- **No 11T dipole magnet installation**.





LHC Injectors Upgrade



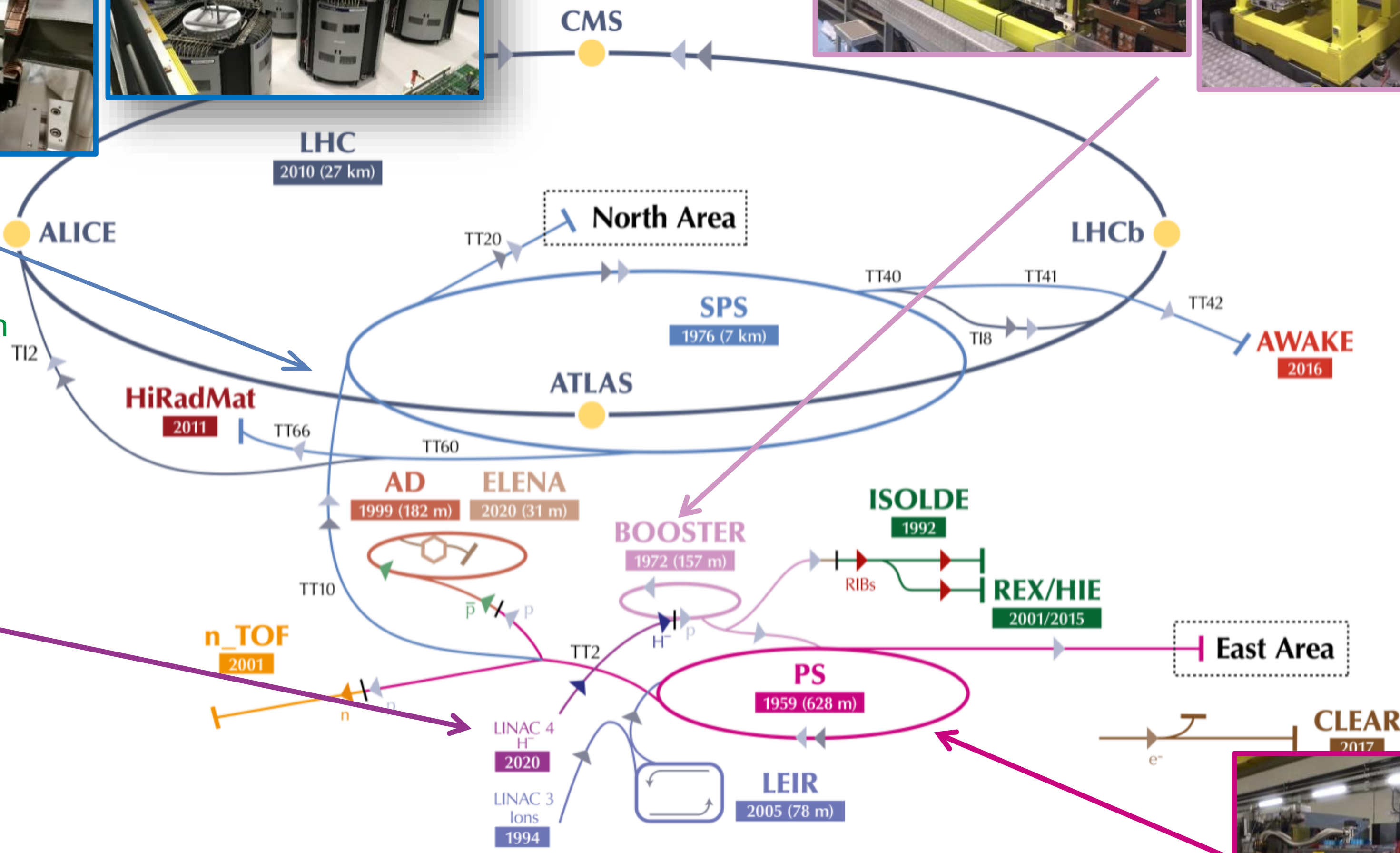
SPS

- **RF** system upgrade
- Longitudinal **impedance** reduction & partial a-C coating
- New **beam dump** and protection devices



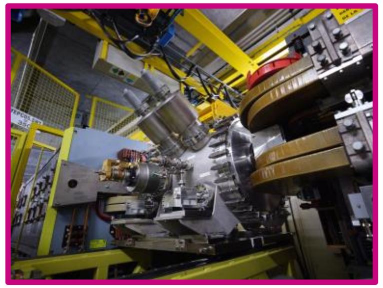
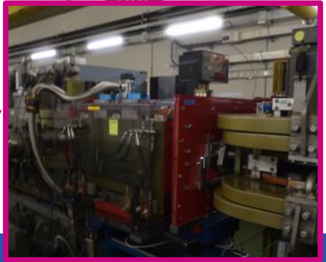
PSB

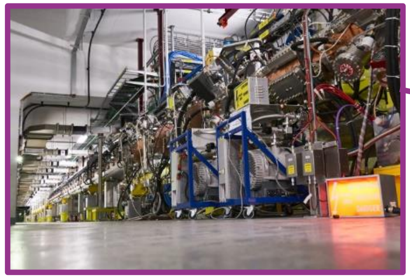
160 MeV H^- injection
Acceleration to 2 GeV



PS

2 GeV injection

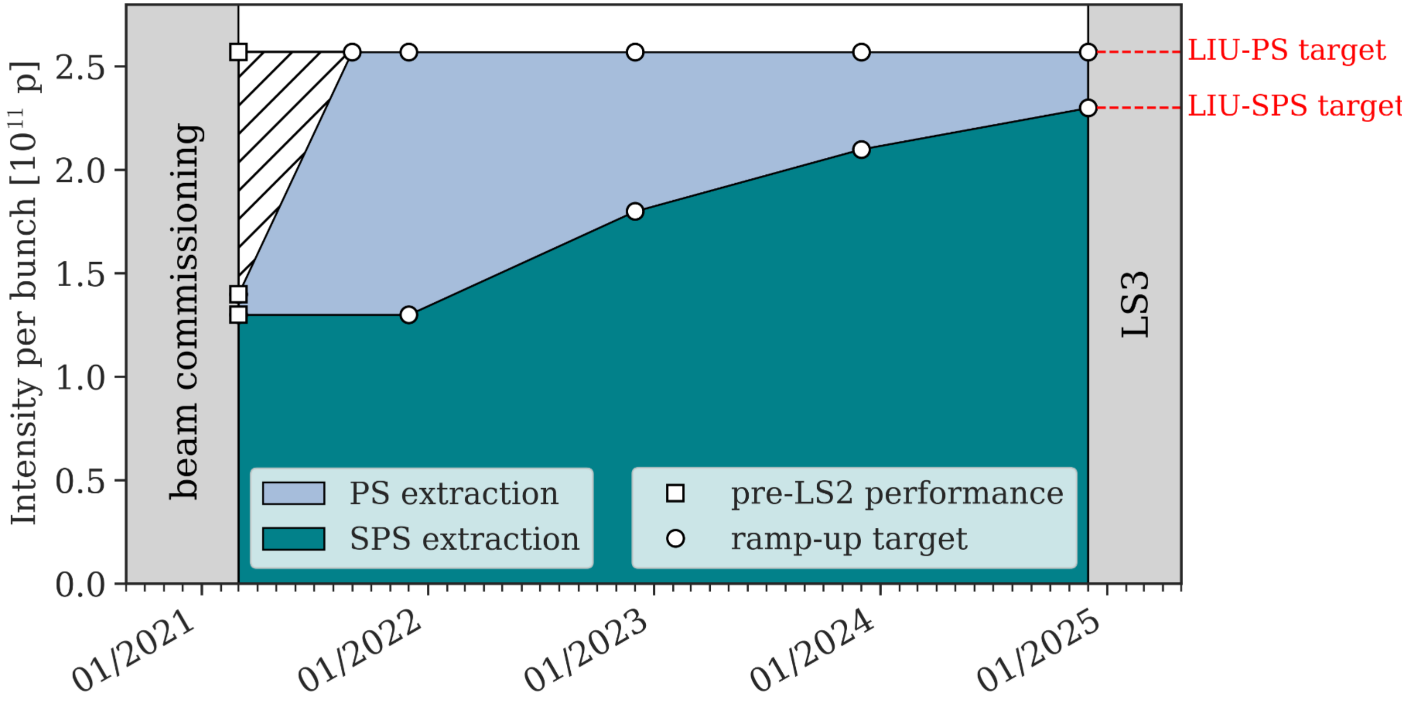
Linac4

Acceleration of H^- to 160 MeV

LHC injector intensity ramp up in Run 3

Year	Initial intensity [ppb]	Target intensity [ppb]
2022	1.4×10^{11}	**1.8×10^{11}**
2023	**1.8×10^{11}**	2.1×10^{11}

LHC baseline for 2023-2025



The target of 1.4×10^{11} has been achieved.

The injectors are on track to provide trains with **$1.8\text{x}10^{11}$ ppb at SPS extraction** for the **end of 2022**.

The injectors will push the intensity towards the **HL target of 2.2×10^{11} ppb** at extraction from the SPS in 2023-2025 – but the LHC cannot 'swallow' such beams in pp production in Run 3.

LHC Run 3 performance projections

The performance and configuration of LHC for Run 3 was studied and optimized during LS2*.

Performance estimate assumptions:

- **LHC peak luminosity limited to ≈2×10^{34} cm^{-2}s^{-1}.**
  - **Limited** by the **cryogenic cooling capacity** of the inner triplets quadrupoles.
- **Maximum bunch currents of 1.8×10^{11} ppb** for ~2750 bunches (BCMS beam), **limited by**:
  - the **RF system**,
  - the **beam dump core** integrity – **will be refined by observations during Run 3**,
  - the **beam dump protection absorber** integrity,
  - heating of the **injection kickers** (soft limit).

While the limit on peak luminosity is well established (within a few %), the limit on the bunch intensity carries more uncertainty as system as pushed to their limits.

(*): S. Fartoukh et al, LHC configuration and operational scenario for Run 3, CERN-ACC-2021-0007

Performance projections

For the available bunch intensities, the **luminosity in ATLAS/CMS** must be **levelled** at **2×10^{34} $m^{-2}s^{-1}$**.

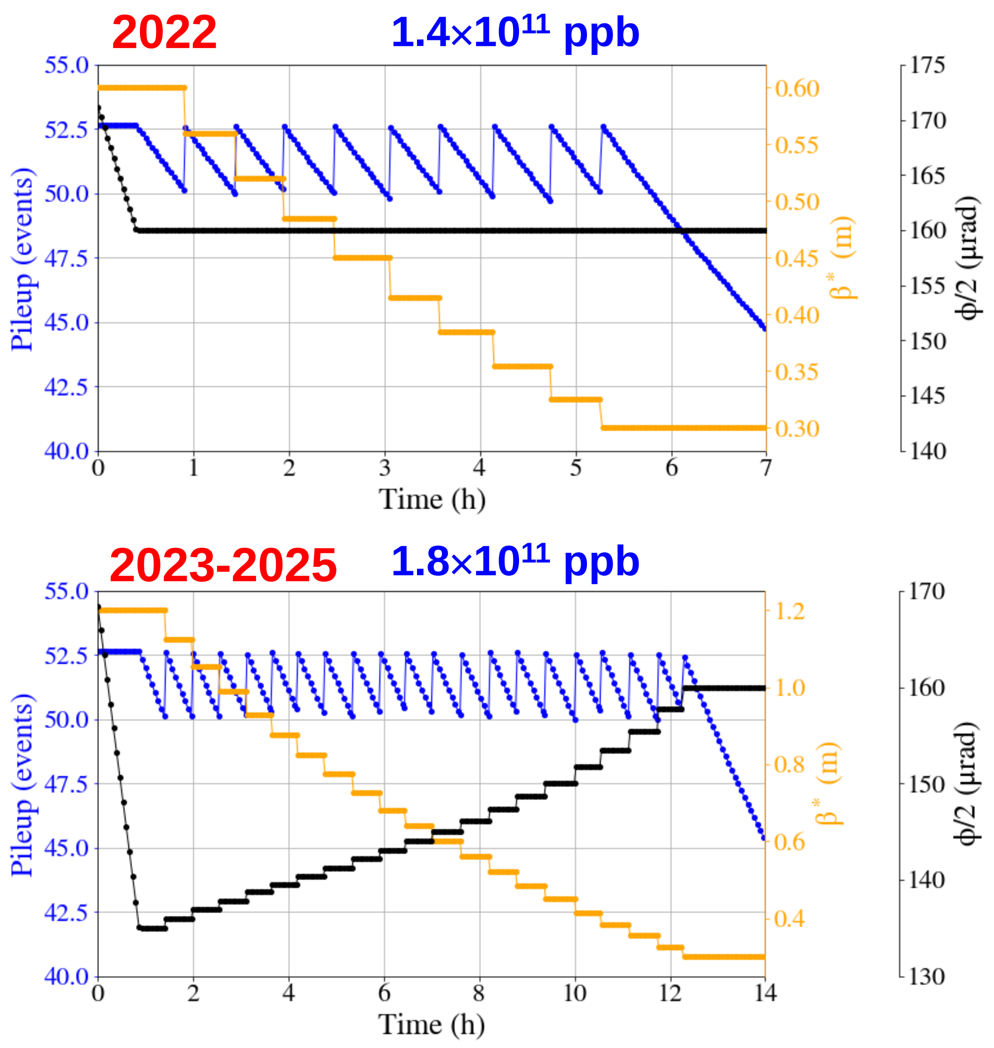
- Levelling times of 6 – 12 hours (1.4 – 1.8×10^{11} ppb) for good beam emittances, levelling by beam size (β* levelling).

Performance estimates:

Year	Efficiency* (%)	∫L (fb^{-1})
2022	**25%**	**≈30**
2023-25	**40%**	**85-90**

For a Run 2 efficiency of **49%**: ∫L ~100 fb^{-1}/year in 2023-25

Run 3 is expected to integrate **~300 fb^{-1}** until the end of 2025



2023-2025: indicative, details may vary !

(*): fraction of time spent in stable beams

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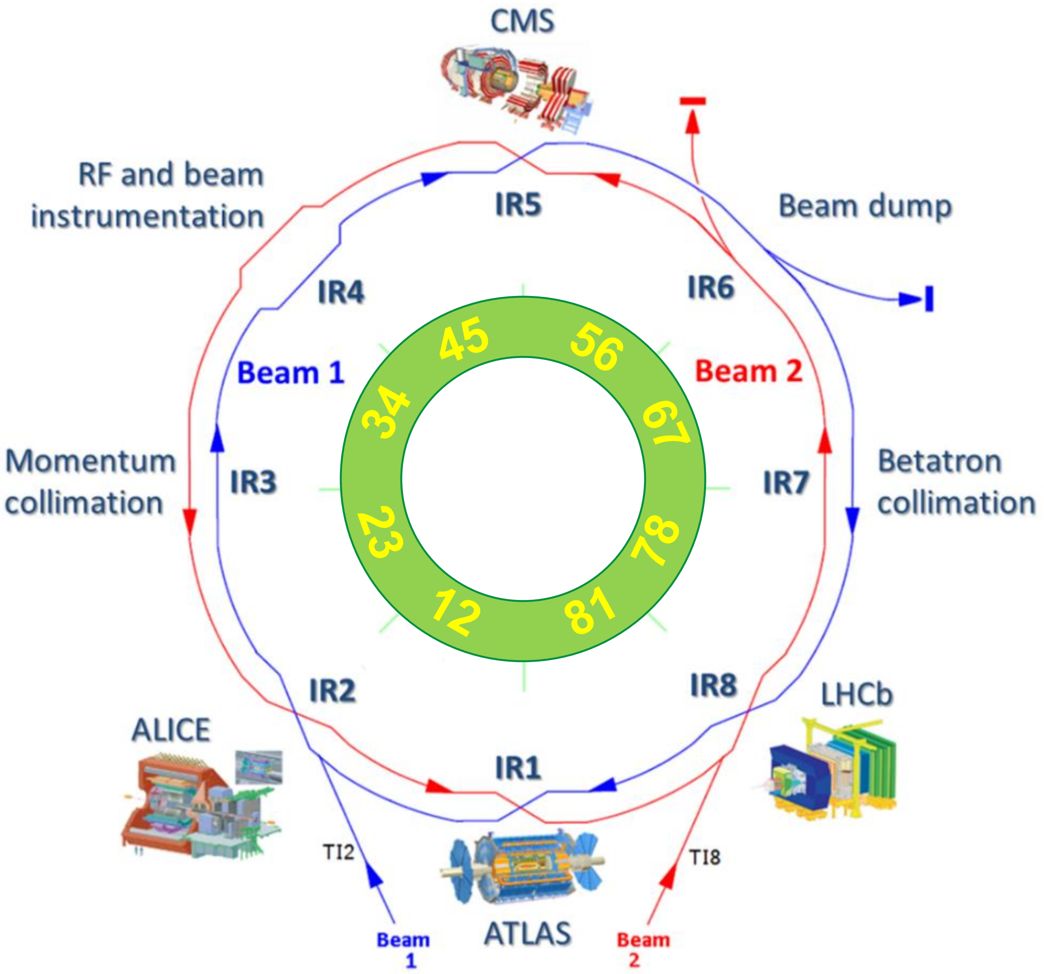


LHC cooldown

LHC cool downs started in 2020 to be ready for magnet powering tests in 2021.

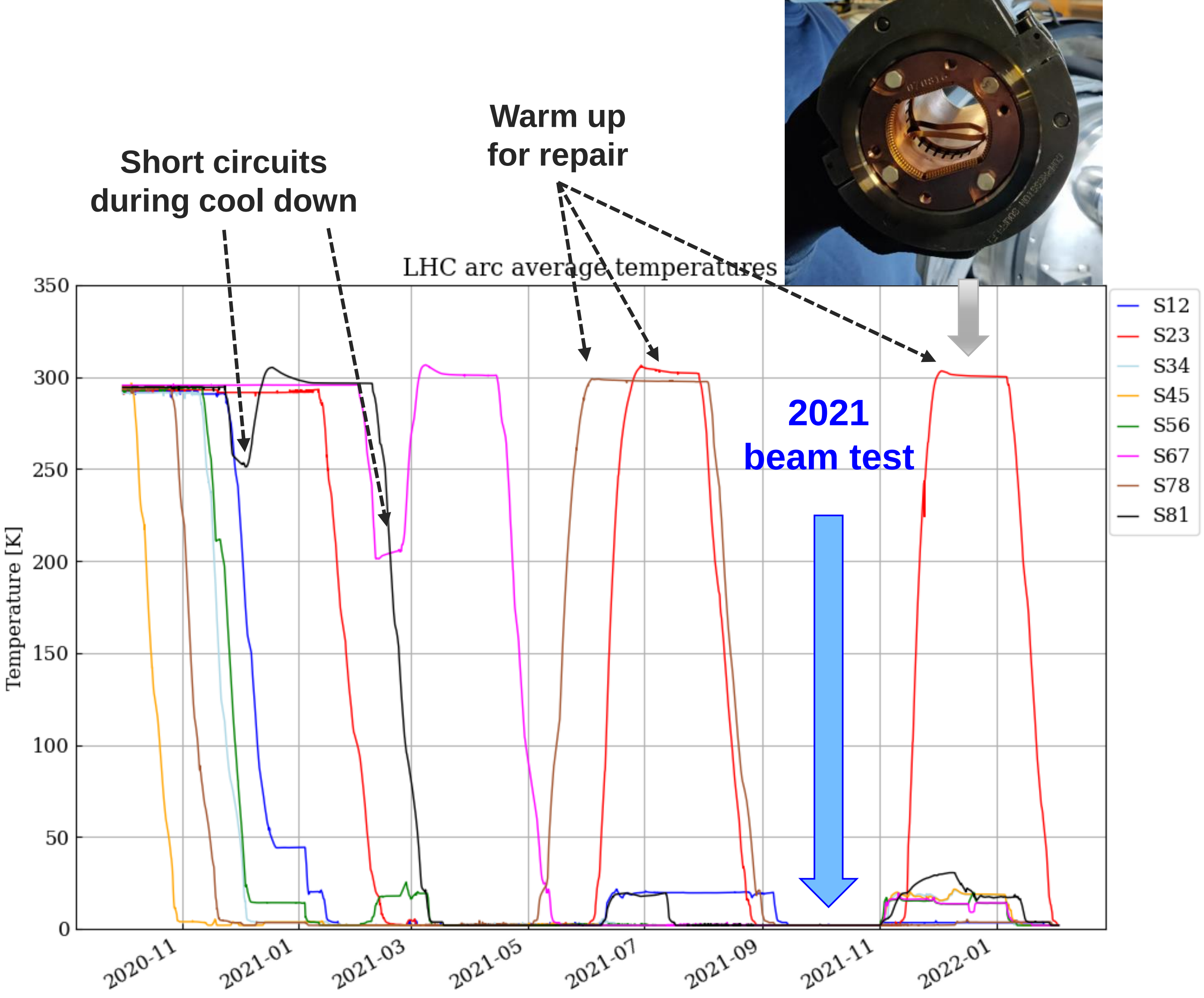
Two failures during **dipole magnet training to 7 TeV** required warm up cycles of sectors 23 and 78.

- This led to the decision to **reduce the target energy for Run 3 to 6.8 TeV**.

A third warm up cycle was required to repair a **buckled RF finger** in sector 23.

- Discovered during the beam test in Oct 2021.

The LHC was eventually ready at 1.9K in **February 2022**.



Dipole magnet training

During the magnet training campaign to **6.8 TeV** over **600 primary training quenches** were recorded on the dipole circuits.

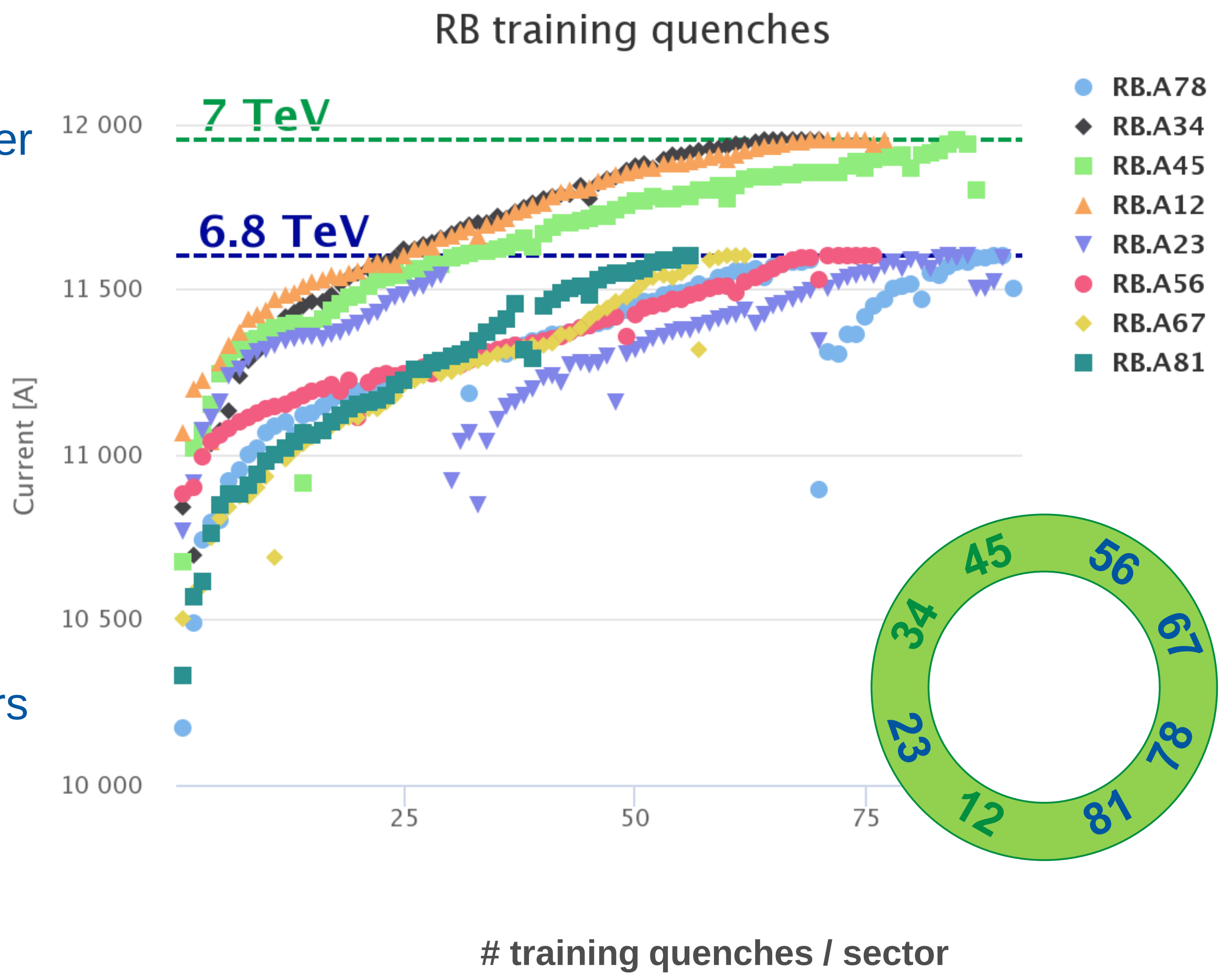
3 sectors were trained to **7.0 TeV.**

- completed before decision to lower target energy.

5 sectors were trained to **6.8 TeV.**

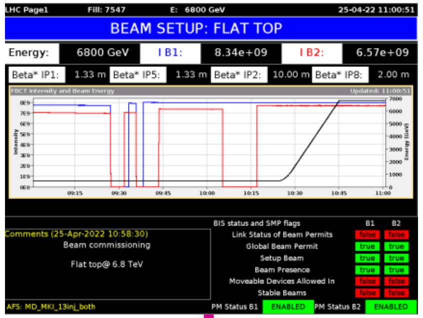
- sectors 23 and 78 had to be trained twice due to the warm up cycles.

Since the start of beam operation **12 spontaneous training quenches** have already occurred in sectors trained to **6.8 TeV** – **no training quenches** on dipoles were observed **at 6.5 TeV** during Run 2.

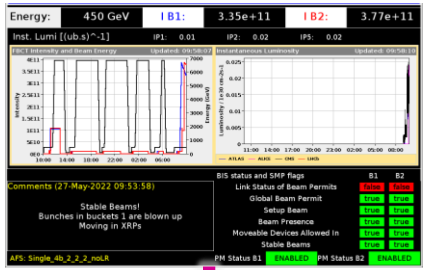


LHC restart in 2022

April 25th
First protons at 6.8 TeV



May 27th
Collisions at injection



July 5th
Start of Run 3 physics

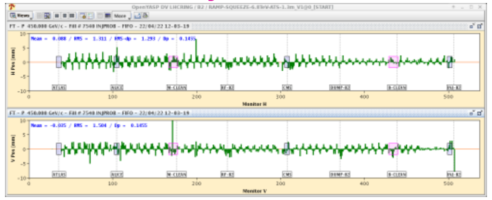
August 23rd

Accidental cooling tower stop leads to Helium release from RF cavities – warm up and conditioning of RF cavities required **– 4 week stop**

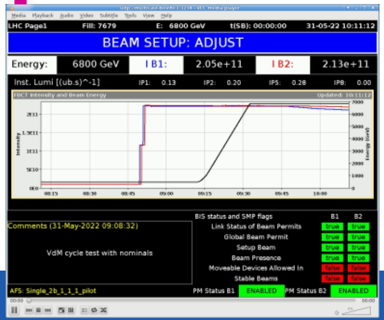
April | May | June | July | August | September

52 days devoted to beam commissioning

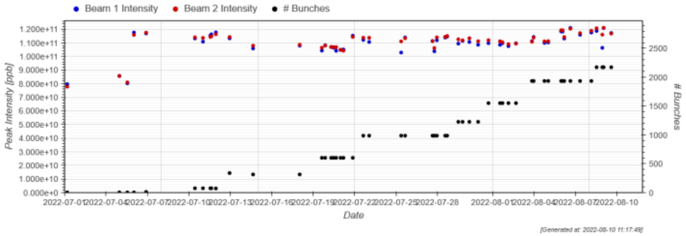
April 22nd
First beam injection



June 1st
Collisions at 6.8 TeV



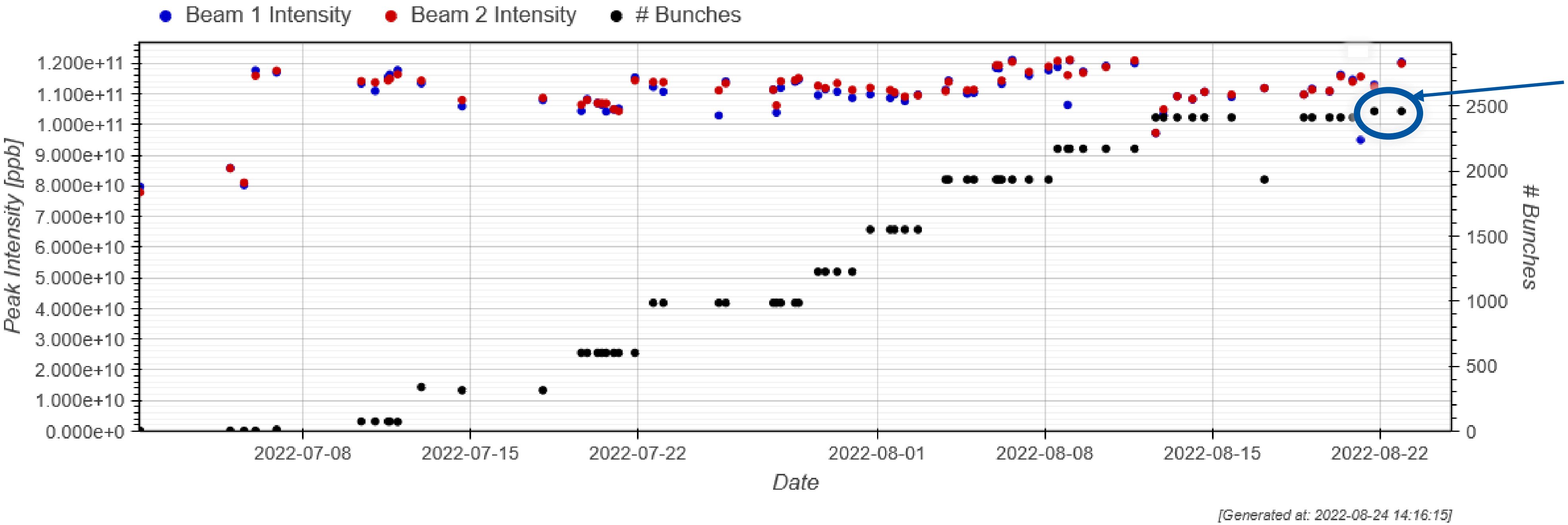
August 3rd
> 2000 bunches



Intensity ramp up

The beam intensity ramp up was initially performed with **trains of 48 bunches** at a bunch intensity of **~1.1 – 1.2x10^{11} ppb** – as planned.

Due **to electron cloud limitations** (see later), the train length was reduced to **36 bunches** just before the cooling tower incident interrupted the progress for 4 weeks.

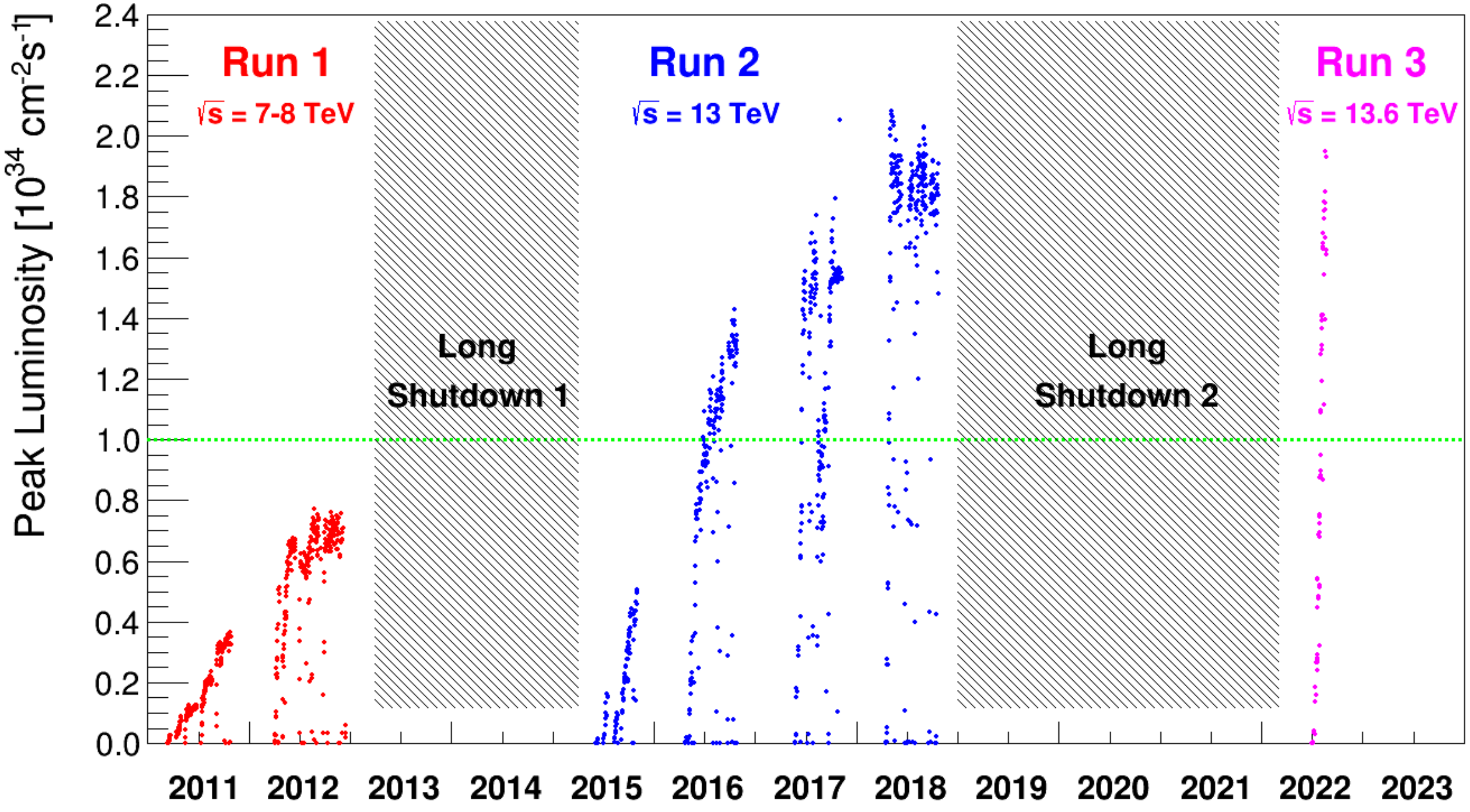


2461 bunches in trains of 36 bunches @ 1.2×10^{11} ppb

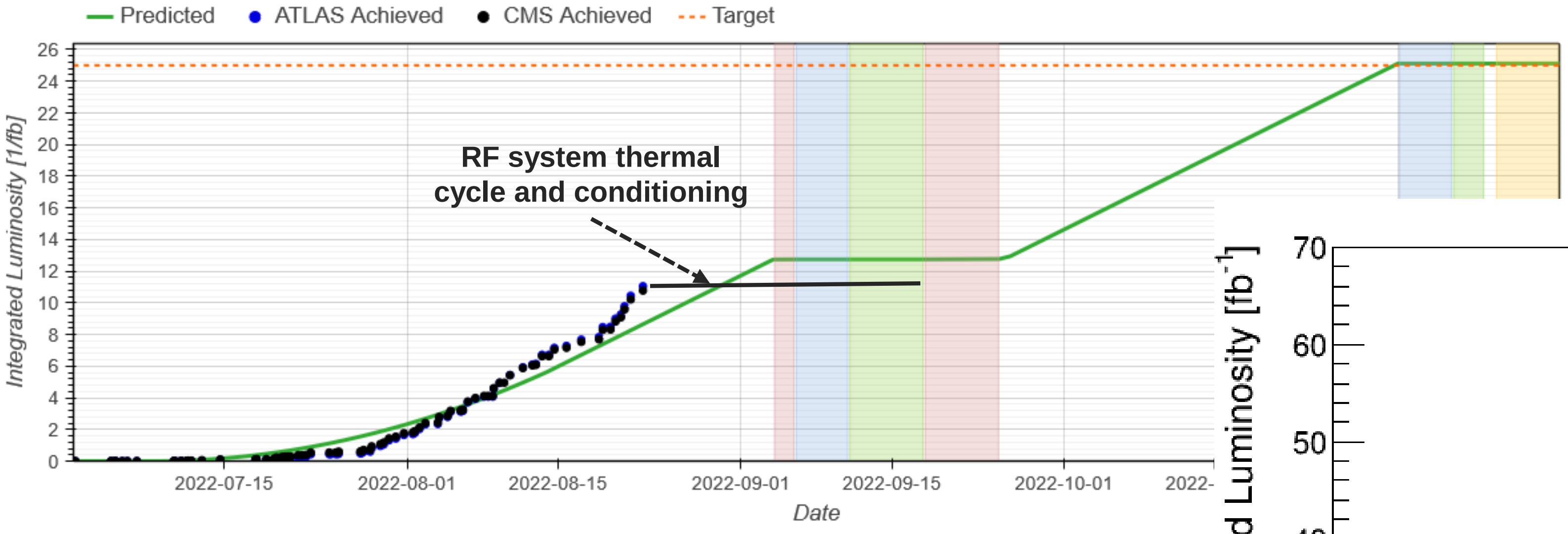
Performance 2022 status

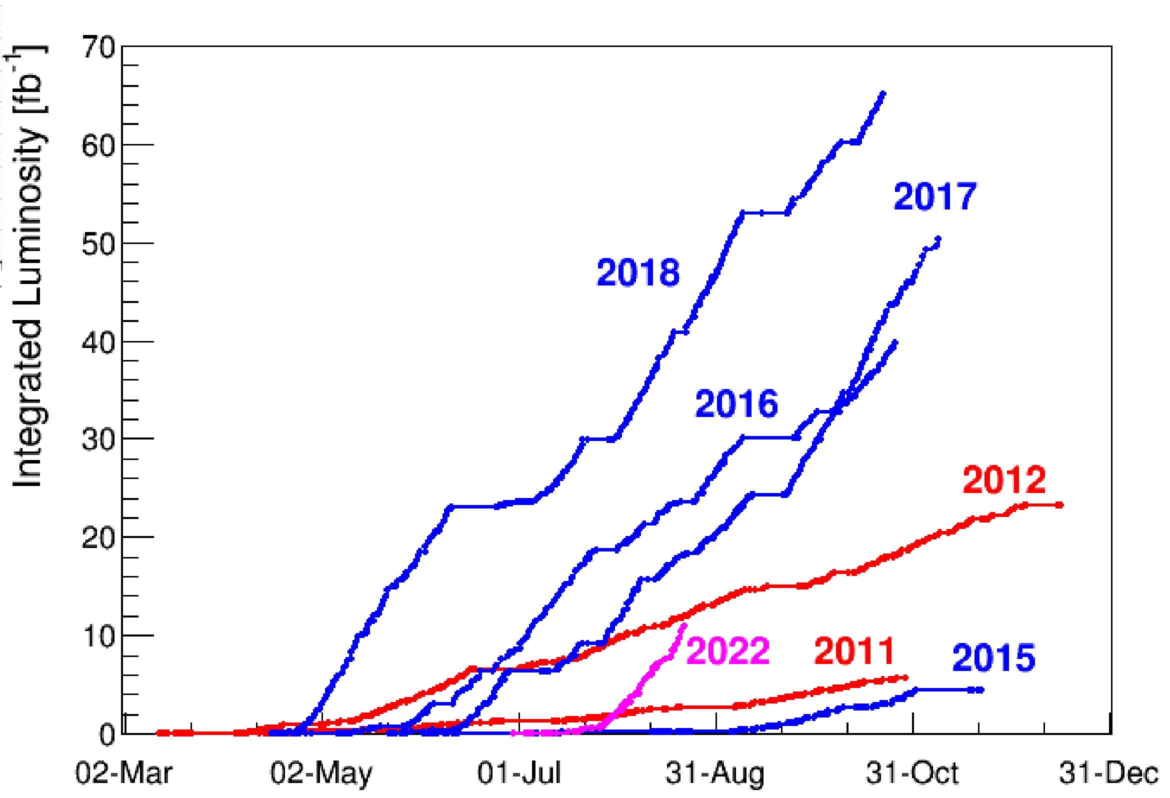
With the experience of the previous two runs, the increase of peak luminosity over such a short time was very steep.

- Reflects the excellent understanding of how to control and to operate LHC.
- **Peak luminosity almost within target.**



Performance 2022 status





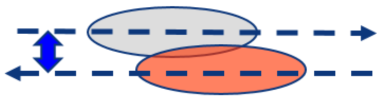
Luminosity Production started to exceed the (conservative) planning for this first run year before the beam stop.

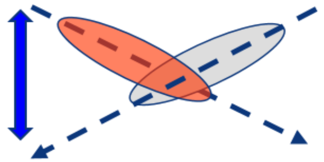
- Slope close to the best Run 2 periods.

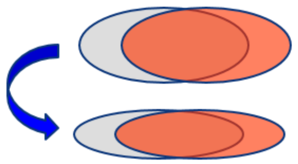
Luminosity levelling

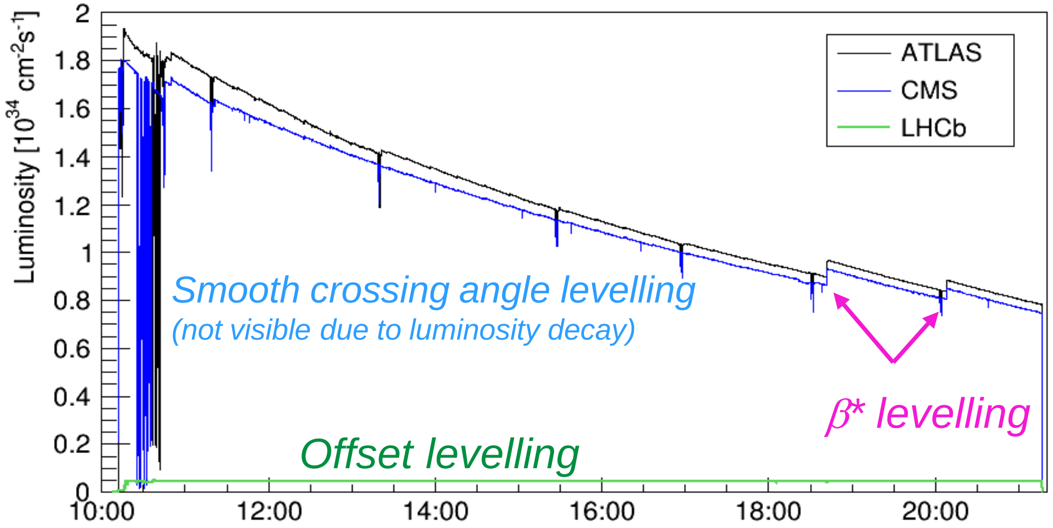
3 levelling techniques to control luminosity are used in **parallel** in Run 3:

- **Offset levelling** for **ALICE** and **LHCb.**
  - Local to one IP, well established since Run 1.
- **Crossing angle (up or down) levelling** for **ATLAS** and **CMS**.
  - Local to one IP, well established since Run 2.
- **β* levelling** for **ATLAS** and **CMS – beam size change at IP(s).**
  - Beneficial/essential for beam stability, tested at the end of Run 2.
  - **Key ingredient of Run 2 and HL-LHC operation**.









2018 fill with all levelling techniques in action in ATLAS, CMS and LHCb

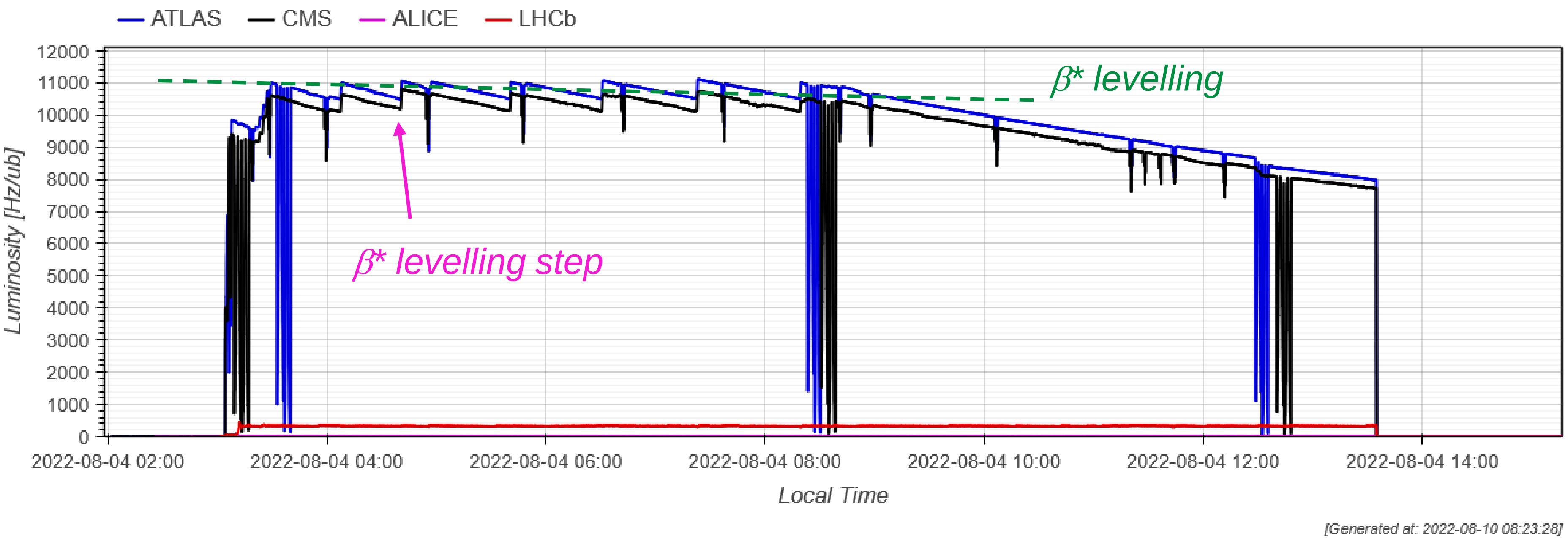
(ALICE luminosity not visible on this scale)

Beta* levelling in 2022

Luminosity levelling of ATLAS and CMS is performed in **10 steps in β* / beam size** to limit the luminosity jumps to ≤ ~ 5%.

- β* range of 60 cm to 30 cm.
- Already achieved fully **automated execution** based on target luminosity or pile-up.
- CMS & ATLAS are **fully coupled**, i.e. **β* changes occur at the same time at both IPs**.

Achieved a major milestone for LHC Run 2 and for HL-LHC !



Example of a 2022 fill

(ALICE luminosity not visible on this scale)

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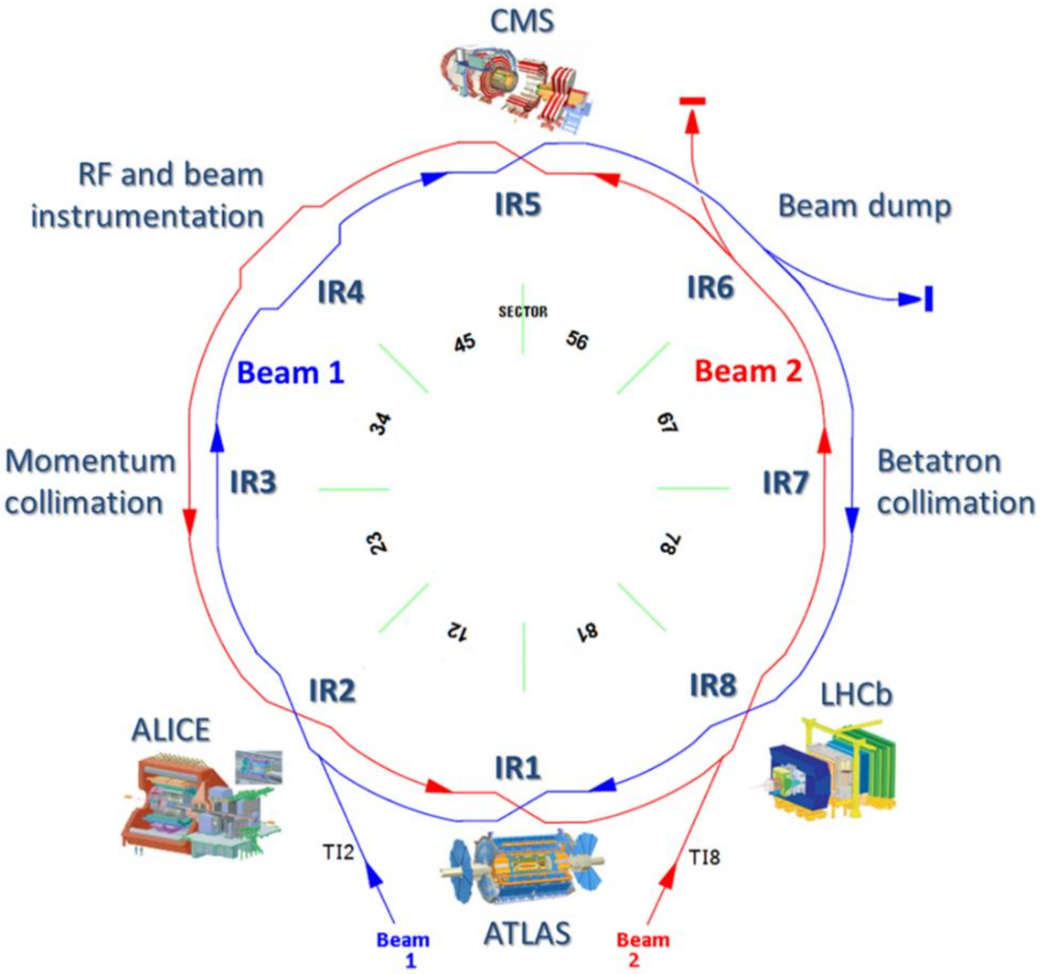
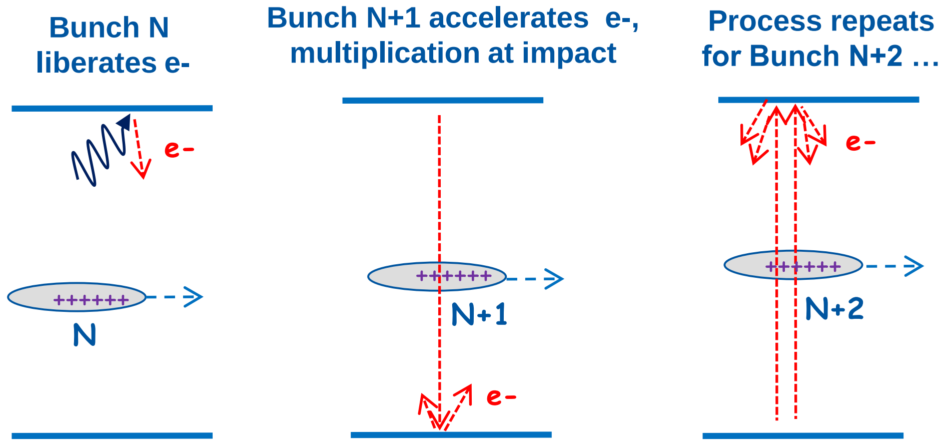


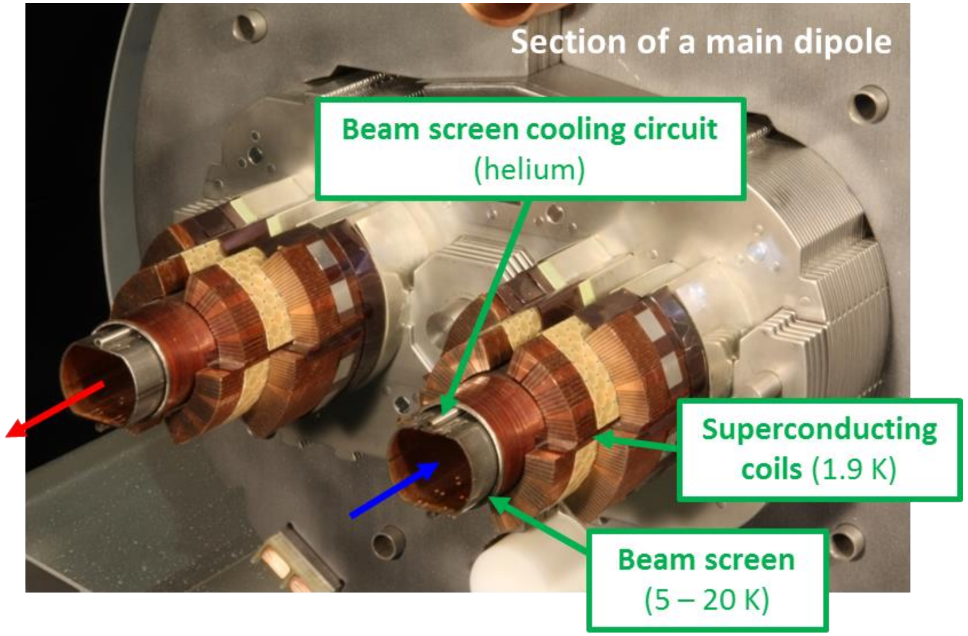
Electron clouds

Electron clouds can affect all accelerators with high currents of positive charge (p, ions, e+). **Impact** :

- **Vacuum pressure rise**.
- Degraded **beam quality** (emittance, instabilities, losses).
- **Energy deposition on the vacuum** chamber (~20K at LHC) → **heat load** for the cryogenic system.



*If the **probably of emitting a secondary electron (SEY)** is above threshold ➔ avalanche effect (multipacting) which depends on bunch spacing and population*



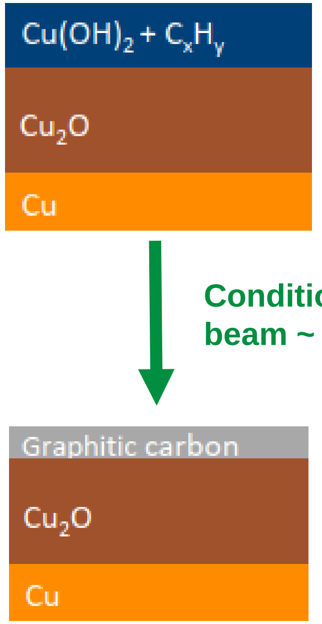
Remedies:

- Conditioning by **beam-induced electron bombardment** (“**scrubbing**”) leading to a progressive reduction of **SEY**.
- **Holes in bunch filling pattern** to break up cloud build-up → lower luminosity.
- Surface treatment of vacuum chamber (coatings..)

Electron cloud activity - Run 2

After **Long Shutdown 1** a **large increase in residual e-cloud activity** was observed.

- **Conditioning saturated**, e-cloud contributing to an **excess in heat load** for the cryogenic system.
- Strongly **sector dependent,** in “bad” sectors the heat load is a **factor ~2** higher than in good sectors.



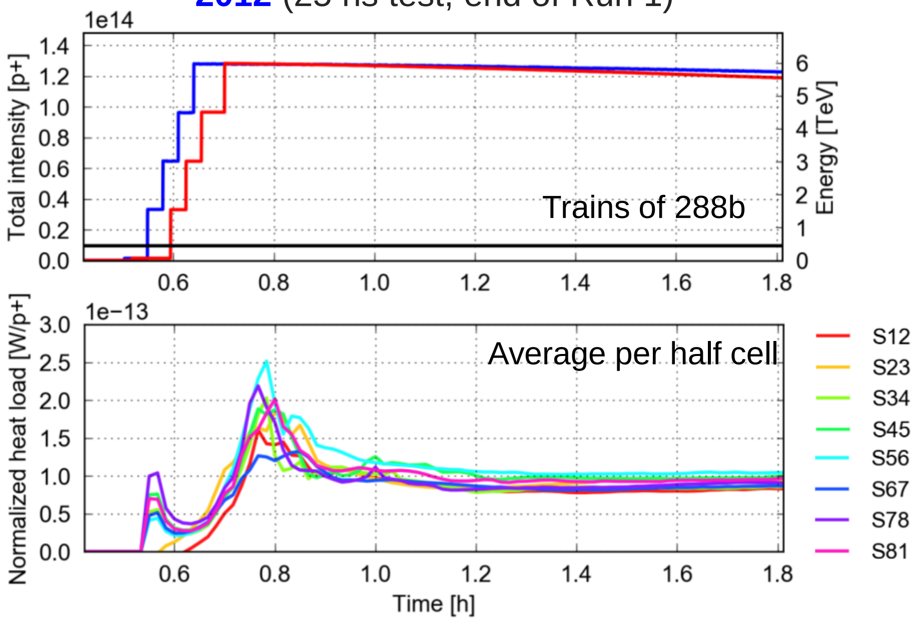
SEY ~ 2

Conditioning (scrubbing with beam ~ e- bombardment)

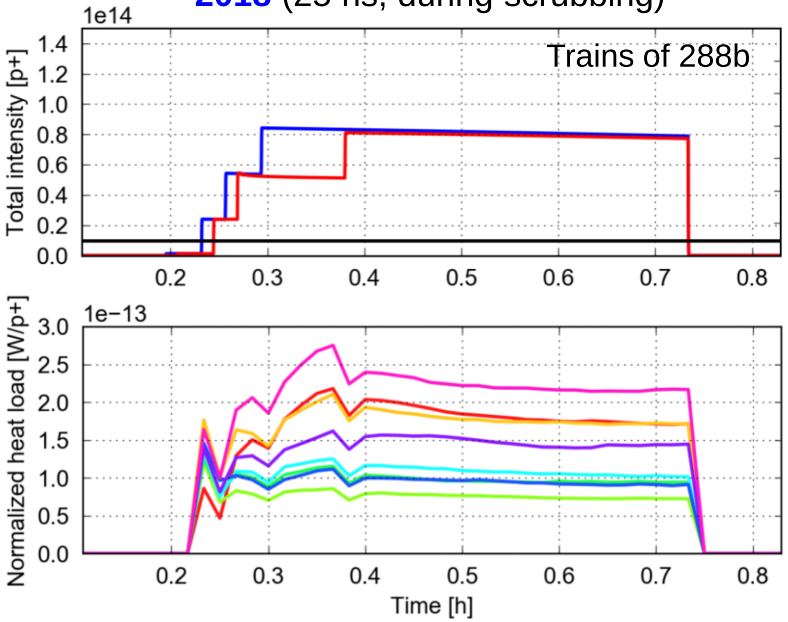
SEY ~ 1.1

Heat load by sector AFTER conditioning by e-cloud scrubbing

2012 (25 ns test, end of Run 1)



2018 (25 ns, during scrubbing)



Degradation

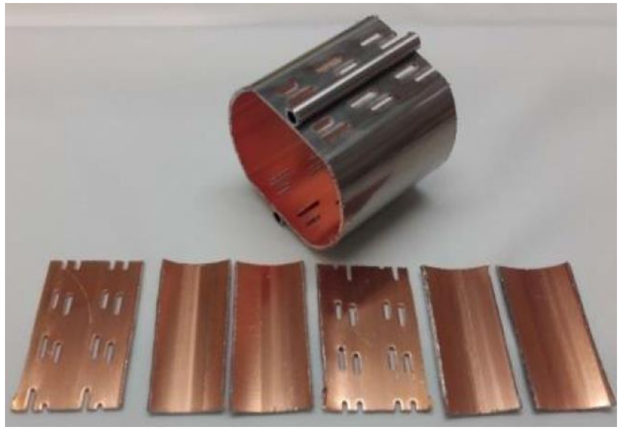
SEY = Secondary Emission Yield (of electrons)

Origin of high heat loads

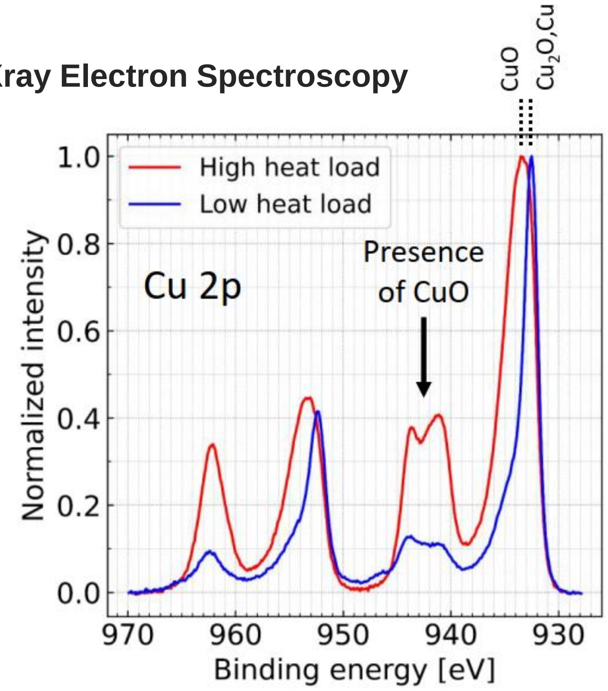
Vacuum chamber samples were analysed to identify **differences in surface properties** between high and low load magnets.

High heat load sector are characterized by:

- **Large** concentrations of **CuO**,
- **Low Carbon** content.



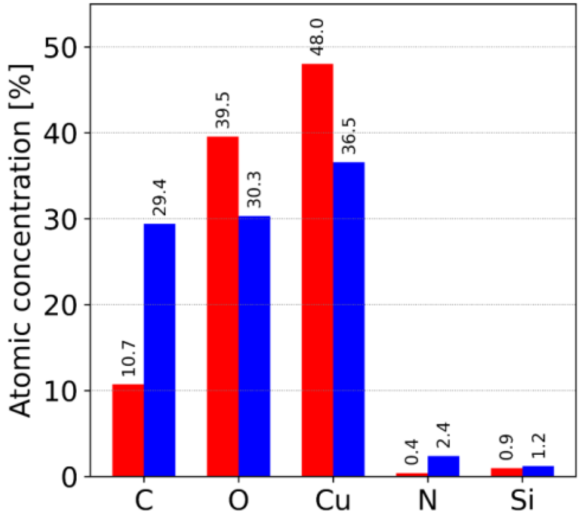
Xray Electron Spectroscopy



Laboratory tests show **much slower conditioning** of the high heat load surface samples under e- bombardment.

More work to understand the surface alteration in progress at a new cryogenic laboratory.

In-situ treatments of the vacuum chamber during a future long shutdown are **under evaluation**.



From Run 3 electron cloud forecast…

Simulations forecast a **mild increase** in heat load between **1.2×10^{11}** and **1.8×10^{11} ppb** for a **conditioned** machine.

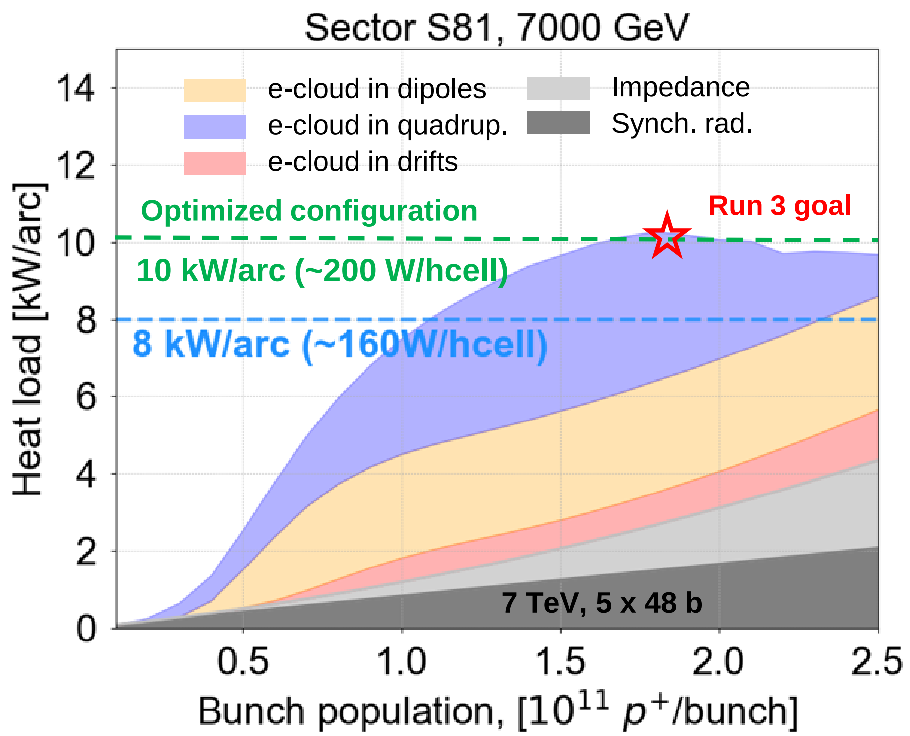
No performance limitations in Run 3 if:

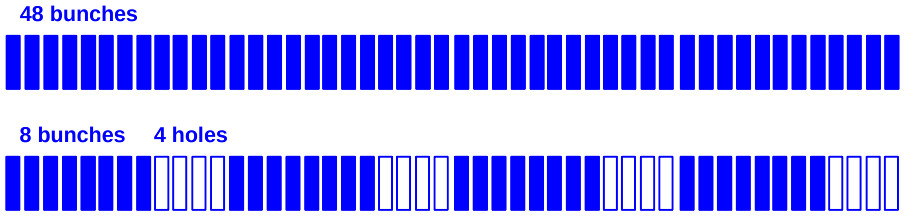
- **No further degradation** of the high-load sectors.
- The **surface model** used in simulations is **accurate** enough.

If **heat load limitations are encountered**, **mitigation measures** have to be applied, typically by **introducing empty bunches slots** in the bunch trains.

- Suppresses e-cloud growth along the bunch train.
- At the **cost** of **fewer bunches** !

Forecast for conditioned machine, bad sector





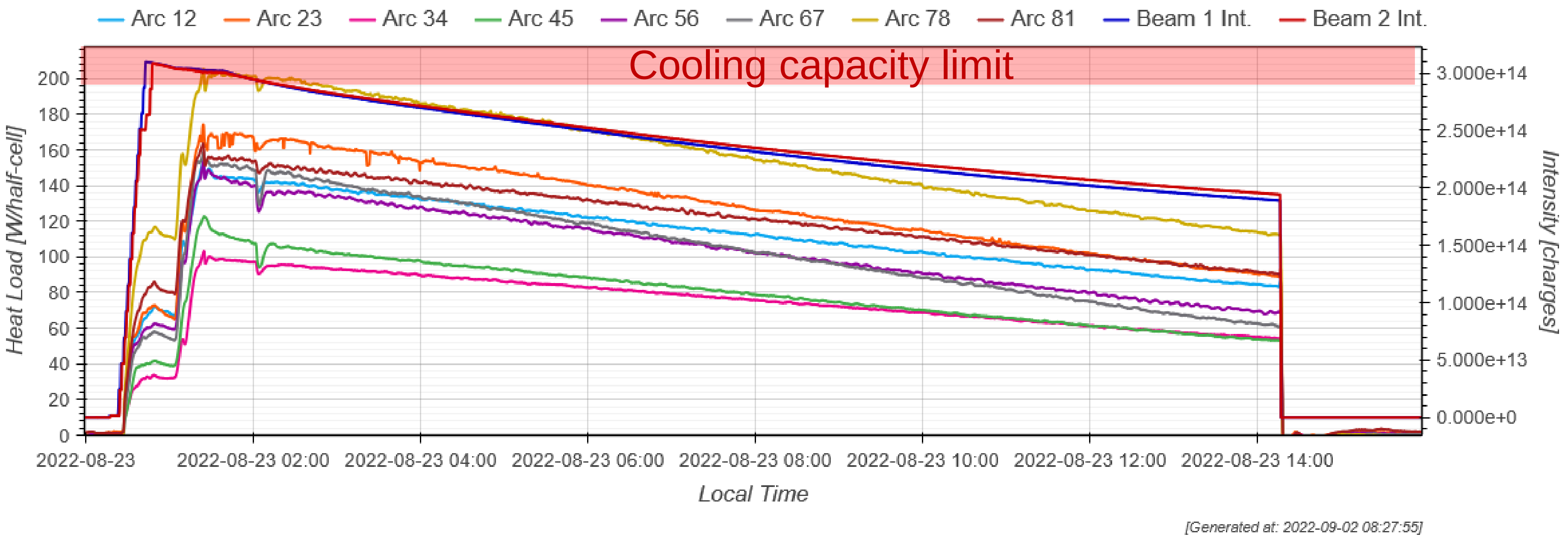
classical 48 bunch train

8b4e bunch train – same length

… to e-cloud observations in 2022

Unfortunately **the heat load of some sectors has degraded further**.

- The worst sector is no longer sector 81, but sector 78.
- LHC is currently **operating at the cryogenic cooling limit** of the vacuum chamber.
- **Conditioning seems to be saturating, or to be very slow** – more run time required for conformation.



The way forward

Options to push the beam intensity towards the Run 3 target:

- Operate with **8b4e bunch trains** only which limits the **number of bunches to ~1900** (compared to 2750 bunches forecast for Run 3).
  - **Secondary benefit**: **the electricity consumption** of the cryogenic system can be lowered by **~20%** - this may become important with rising electricity prices.
- **Mix 8b4e trains** with **classical trains** in the filling scheme and operate at the cooling limit.
  - The exact number of bunches will depend on the bunch intensity.

Work-around's are under discussion to push the beam intensity further in a few weeks.

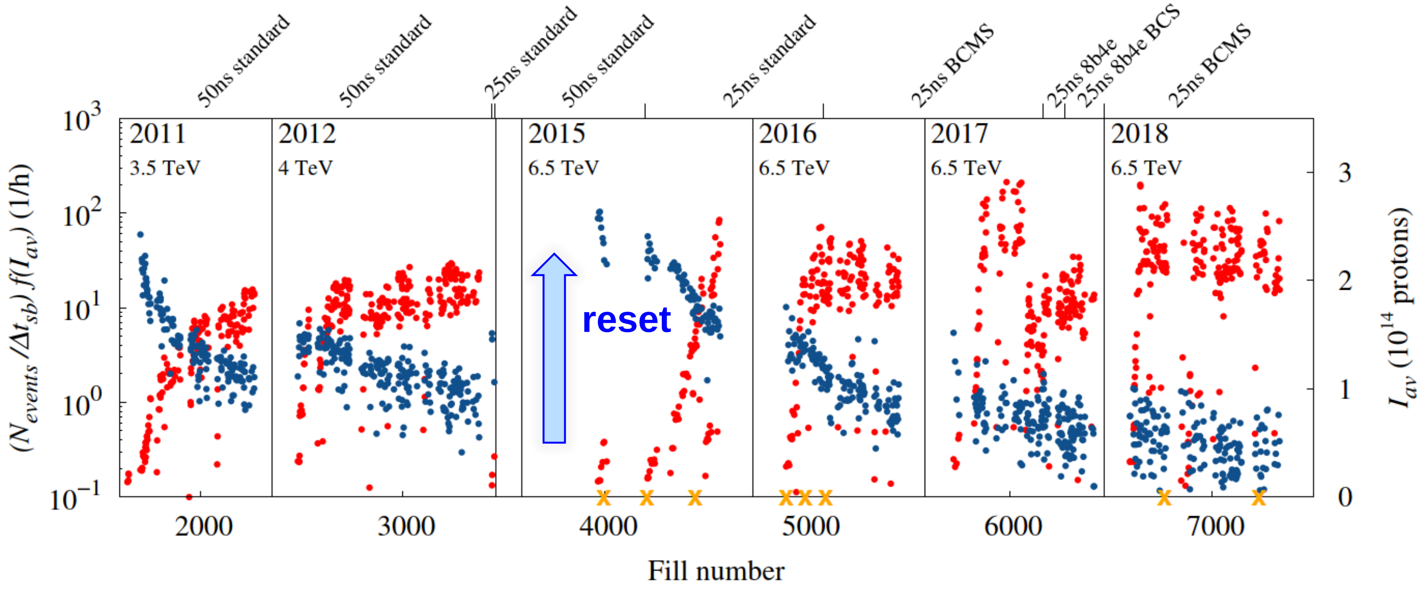
- Nota-bene: 8b4e beams have not yet been prepared in the injector chain.

Run 3 - UFOs

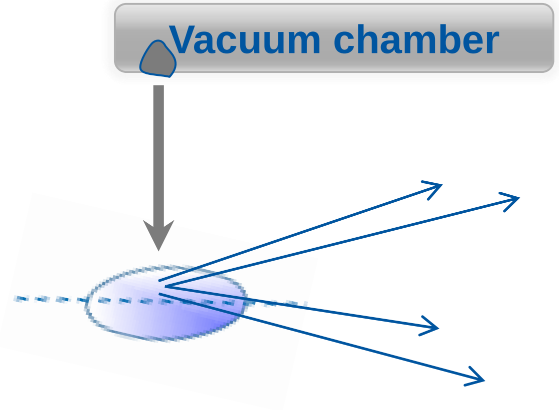
(Charged) **dust particles falling into the beam** – nicknamed **UFOs** – were expected to become **more critical at 6.8 TeV**: showers are more energetic and quench thresholds are reduced.

- Reduction of the margins by ~30% wrt 6.5 TeV.
- UFO events can **trigger beam dumps** when the interaction rates are to high (to high losses).

The UFO rates **condition** during runs, but a **rate reset** was observed **after long shutdown 1**.



Blue dots = UFO rate, red dots = fill-averaged intensity, orange crosses = quench

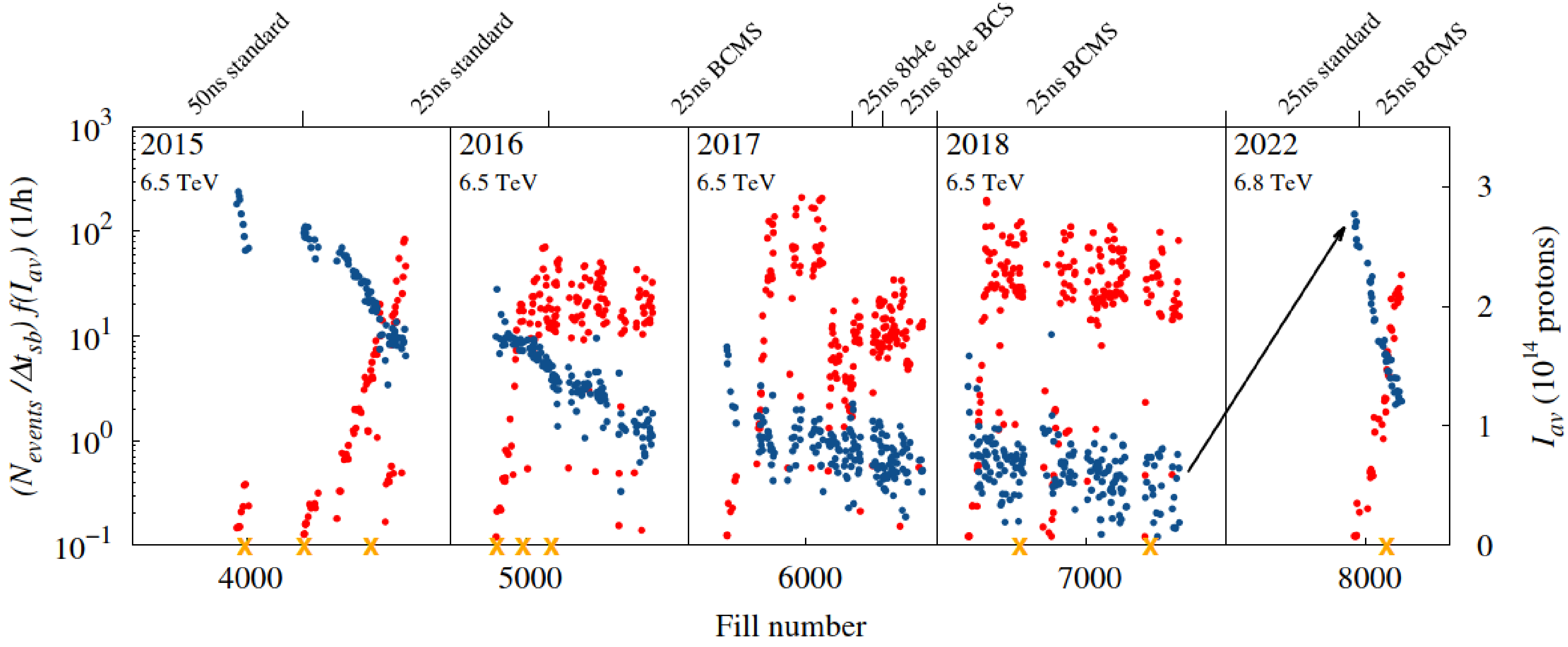


UFOs in 2022

This year we have observed a similar “reset”, with UFOs predominantly originating in **regions where magnets were exchanged during the shutdown**.

The rate drops rapidly, but **UFOs already triggered 23 beam dumps**.

- Important impact on availability this year, but **the worst should be over by the end of 2022** !



Blue dots = **UFO rate**, red dots = **fill-averaged intensity**, orange crosses = **quench**

Summary

The **LHC injector chain is in excellent shape**, good progress with the high intensity LHC beams for Run 3.

The LHC commissioning followed the planning, **Run 3 started on July 5th**.

Intensity and luminosity followed a steep curve despite the fight against UFOs and electron cloud.

The **complex luminosity levelling mix** of Run 3 (and HL-LHC) was implemented in a record time – now fully operational.

The **beam intensity** is currently **limited by electron cloud**, work-around's are under discussion, in particular bunch trains with holes (8b4e).