LHC Machine Status

Gianluigi Arduini – CERN – Beams Department

With input from: J. Wenninger, A. Apollonio, C. Bracco, R. Bruce, O. Bruening, S. Fartoukh, S. Redaelli, M. Solfaroli, J.Ph. Tock, A. Verweij

TOP2021 - 13/09/2021

Outlook

- Long Shutdown 2
- Cool-down and training campaign
- Run 3
- HL-LHC

Long Shutdown 2

Injector upgrades

$$L = \frac{kN_b^2 f\gamma}{4\pi\beta^* \varepsilon^*}F$$

Goal of the Injector Upgrade: boost nominal LHC beam parameters

$N_b = 1.15\times10^{11}$ protons/bunch → $N_b = 2.3\times10^{11}$ protons/bunch

$\varepsilon^* = 3.5\ \mu m$ → $\varepsilon^* = 2.1\ \mu m$

Main modifications of the LHC Injector Upgrade (LIU) project:

LINAC4/PSB
- Connection of **Linac4**
- **H- injection at 160 MeV** and increased **top energy of 2 GeV** (instead of 1.4 GeV)

PS
- **Injection at 2 GeV**
- RF upgrades
- New transverse feedback system

SPS
- **RF upgrades**
- Impedance reduction
- New beam dump and protection devices

In addition SPS to LHC transfer line collimator upgrade to lift the limitation on the max. number of high brightness bunches that can be transferred safely

LHC Long Shutdown 2

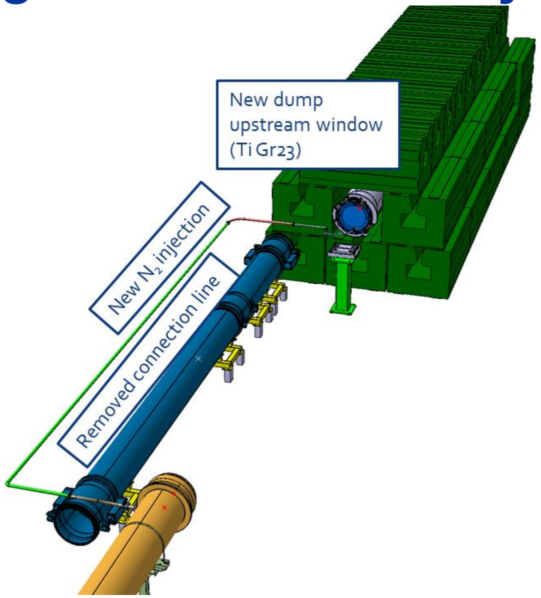
Main activities in the LHC driven by consolidation / removal of known limitations / initial HL-LHC Upgrades to favour intensity ramp-up during Run 3:

- Consolidation of all 1232 dipole bypass diodes and replacement of ~20 superconducting magnets
- Removal of limitations observed in Run 2 (ULO, 16L2)
- Installation of low-impedance collimators and crystals
- Injection protection upgrades
- Beam dump consolidation
- HL-LHC civil engineering

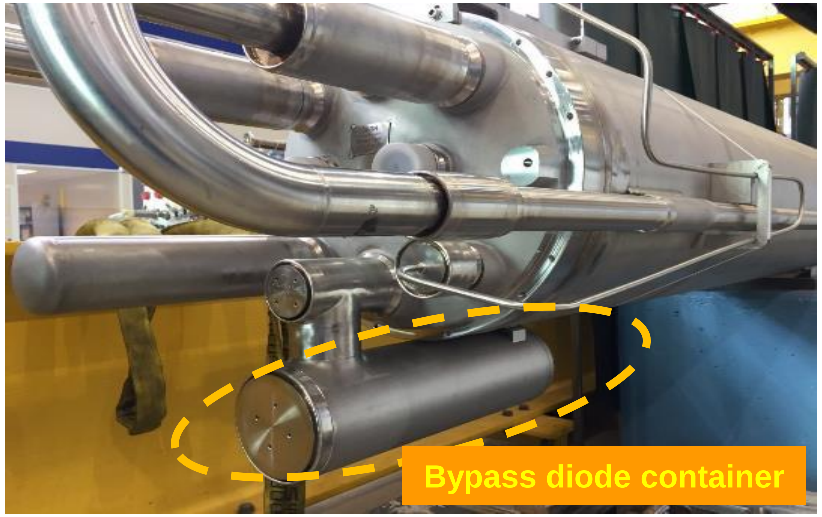
LS2 activities: LHC consolidation

The **by-pass diodes** of all LHC dipoles were consolidated (DISMAC project) to protect them against metallic debris and avoid short circuits to ground – in view of training the magnets to 7 TeV.

The LHC **beam dump** was consolidated to cope with higher beam intensity and beam density in Run 3.



LHC beam dump blocks

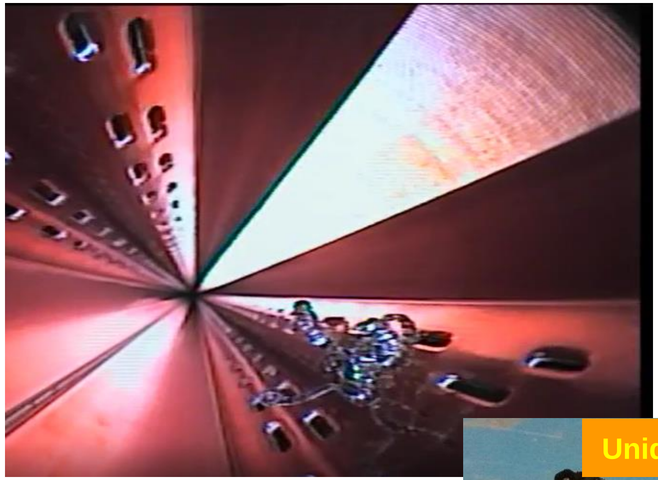


Bypass diode container

Metallic debris found in diode boxes

LS2 activities: Removal of limitations

Removal of aperture restriction in 15R8 (ULO)



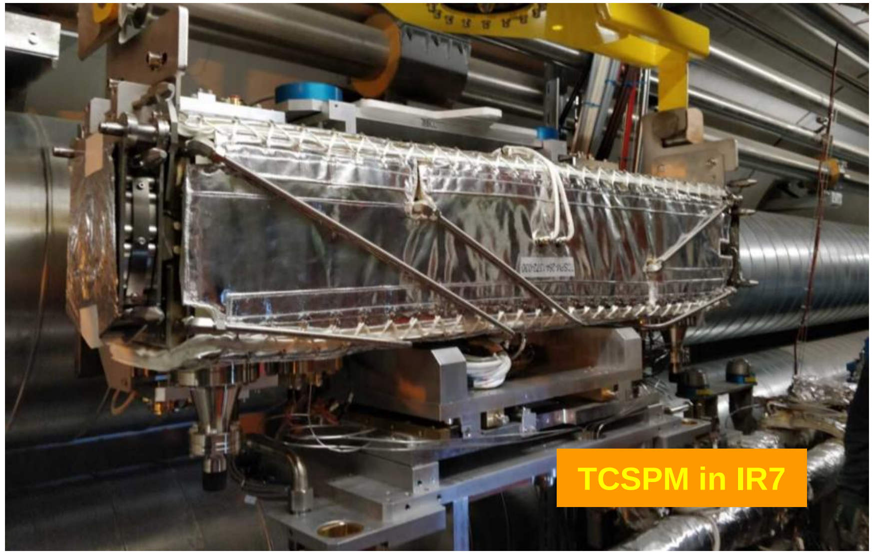
Replacement of beams screens Q16L2 and C16L2 following accidental air in-leak during YETS 2016-2017

LS2 activities: HL-LHC Collimation

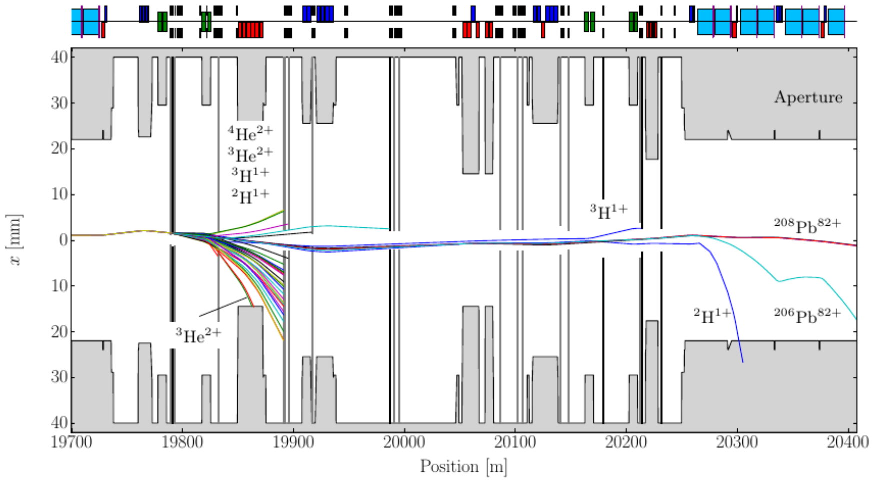
First phase of HL-LHC collimation upgrade

- Low-impedance primary and secondary (coated) collimators in IR7 ➔ Higher proton intensities possible during Run 3
- Dispersion suppressor collimators (TCLD) in IR2 (ALICE) ➔ prevent collisional losses from EM processes on SC elements during ion operation ➔ Higher ion luminosities possible for ALICE during Run 3

22 new collimators built!

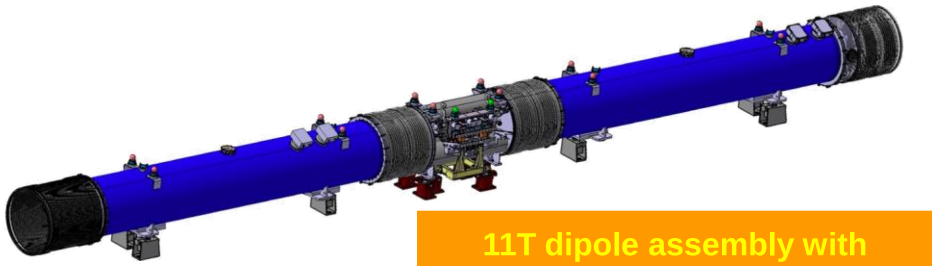


LS2 - HL-LHC activities



Ions interacting with collimators have a high chance of fragmenting and of being lost in the beginning of the downstream SC arcs ➔ risk of quench. Two countermeasures identified:

- 11T dipoles with TCLD collimator in IR7
- Back-up: crystal collimators (ions channeling between atomic planes in bent Si crystals ➔ suppression of fragmentation process)



11T dipole assembly with collimator in the centre

The 11T dipoles could not be installed:

- Observed limitation and degradation in performance not fully understood

Crash programme for replacement of 2 existing crystal goniometers progressing well at CERN

Bent crystals

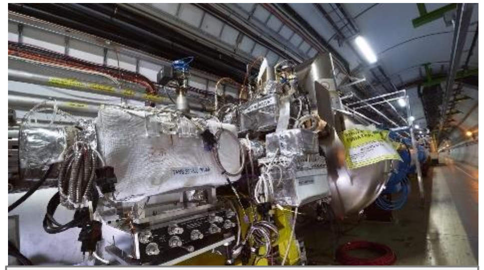
LS2 – HL-LHC activities


WP14: TDIS @ P2 and @ P8

Several additional upgrades implemented:

- Injection Dumps (TDIS)
- Neutral absorber for IR8 in view of higher luminosity operation of LHCb (TANB)
- Upgraded cryogenics plant in Point 4
- New beam instrumentation for Halo Monitoring
- In-situ amorphous Carbon coating for electron cloud suppression as test bed for the coating of IR2 and IR8 triplets during LS3

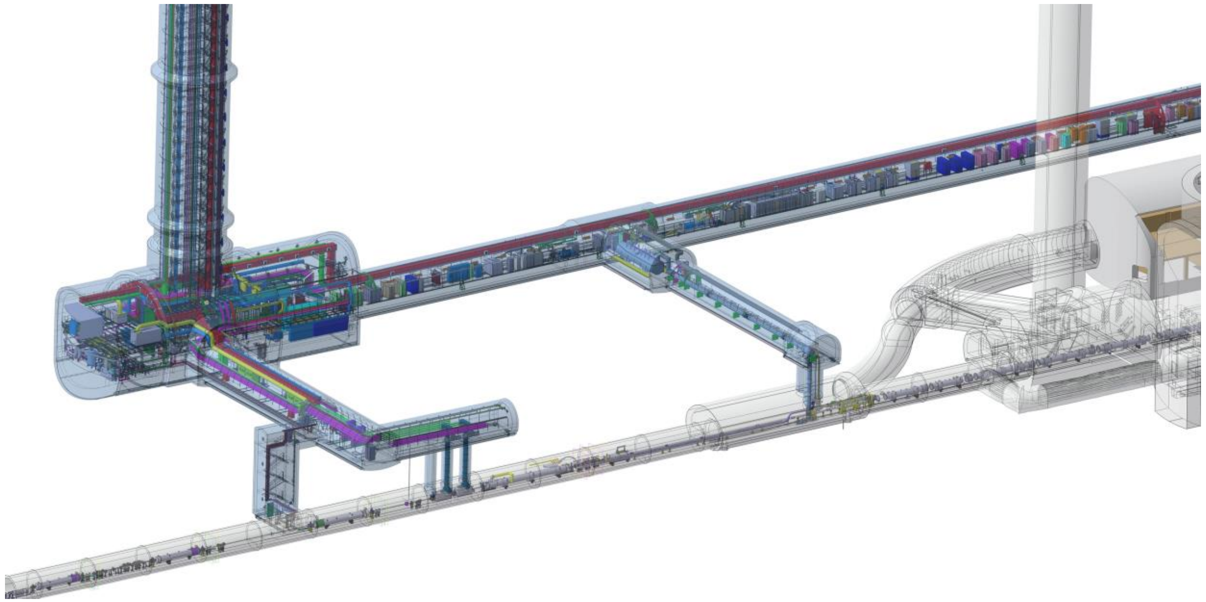

WP9: Cold box @ P4

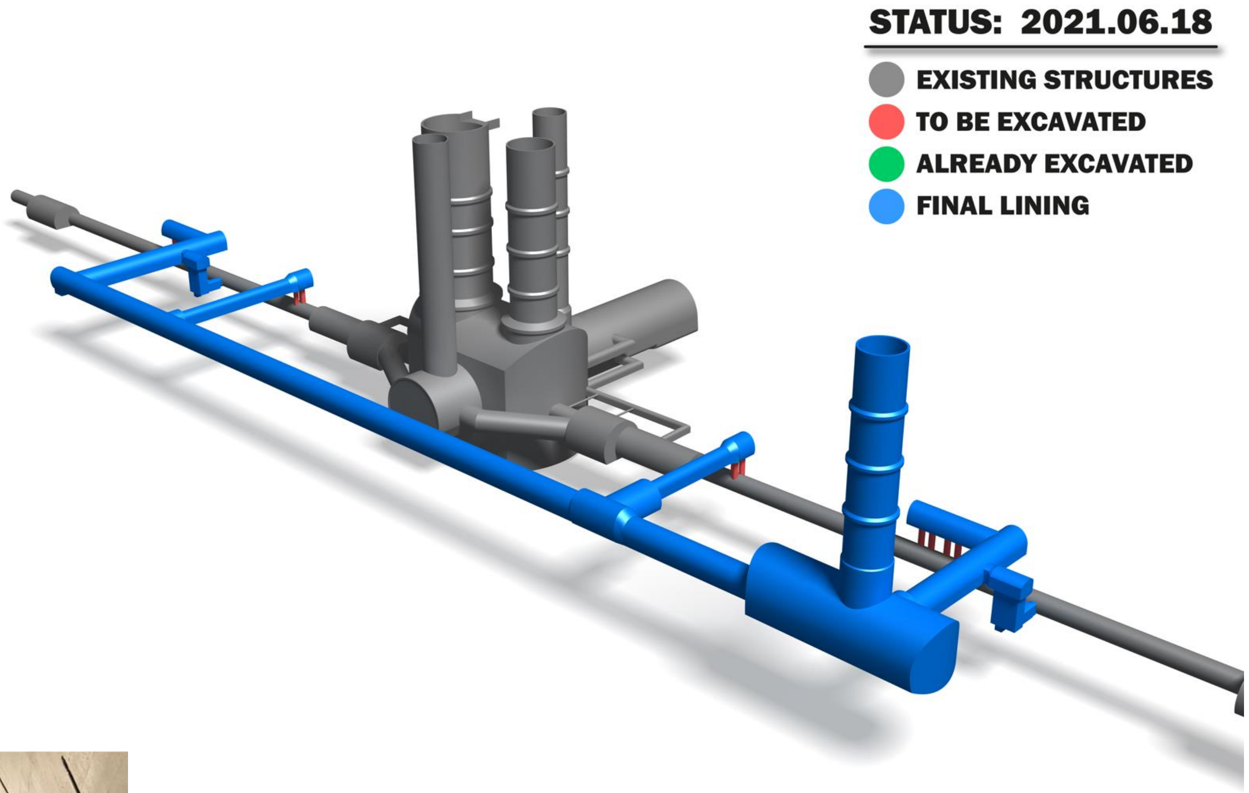

WP8: TANB @ P8


WP13: BSRT halo monitoring @P4


WP12: In-situ a-C coating Q5L8 @ P8

LS2: HL-LHC activities





IR1 Excavation = 100% excl. vertical cores
IR1 Final lining = 100% excl. trench covers, etc.

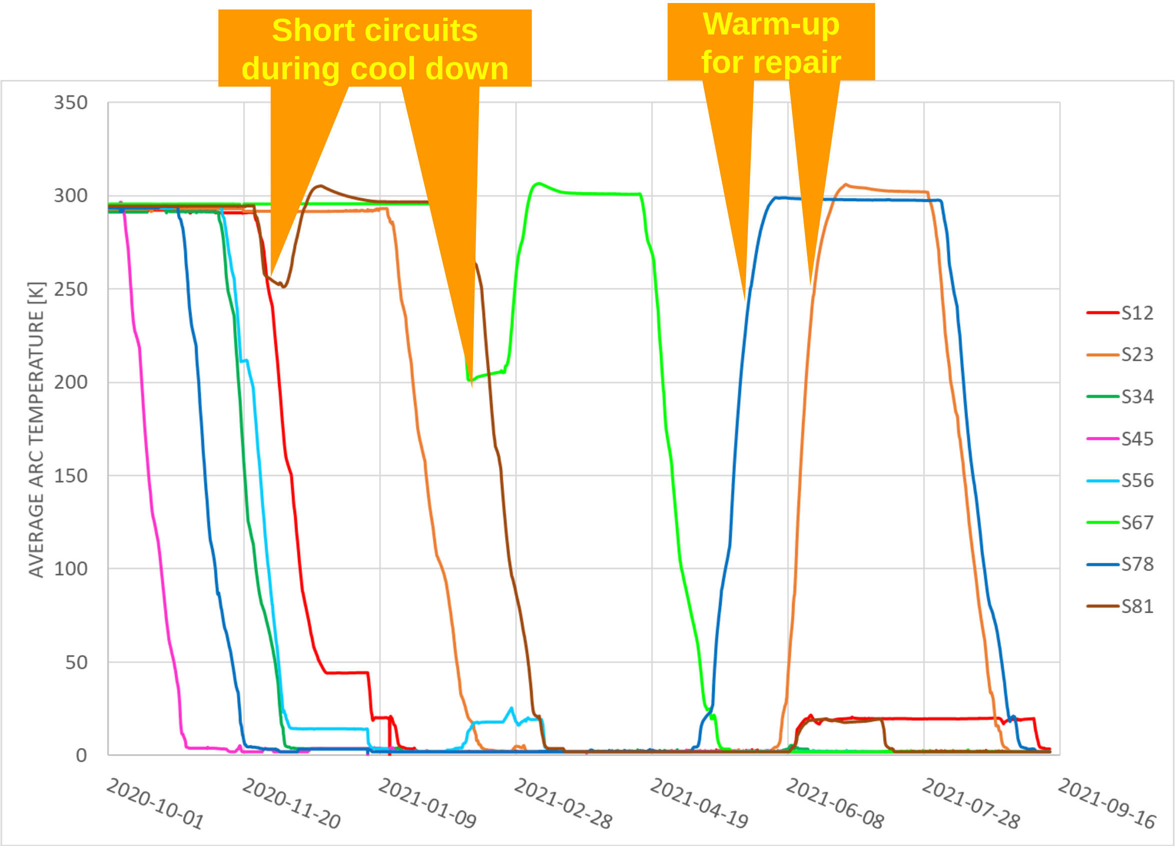
Cool-down and training campaign

LHC cool down after LS2

Cool down started in October 2020

Delayed in 2 sectors by the appearance of short circuits between 200K - 270K.

- Back to room temperature for repair



Failures on 2 sectors (67 & 81) during the training campaign, requiring warm up to room temperature for repair:

- Diode damage on a dipole in sector 23
- Short circuit in a dipole of sector 78

repairs finished, cool down completed

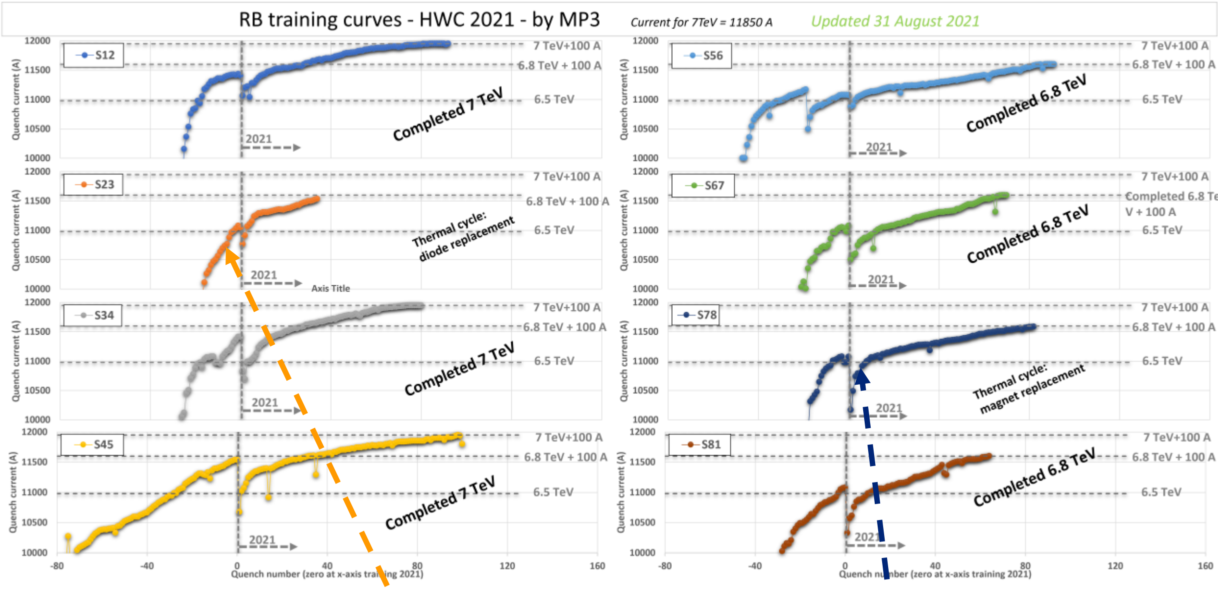
Training to 7 TeV

Part of the preparation the LHC for 7 TeV operation

Target energy lowered to 6.8 TeV following the failures during training

Training status – 6 oo 8 sectors ready for 6.8 TeV:

- 3 sectors ready at 7 TeV – 12/34/45
- 3 sectors ready at 6.8 TeV – 56/67/81
- 600 training quenches so far



Training of sectors 23 and 78 interrupted for repairs

Risk analysis of training to 6.8 TeV vs. 7 TeV being finalized for decision on energy

Schedule update

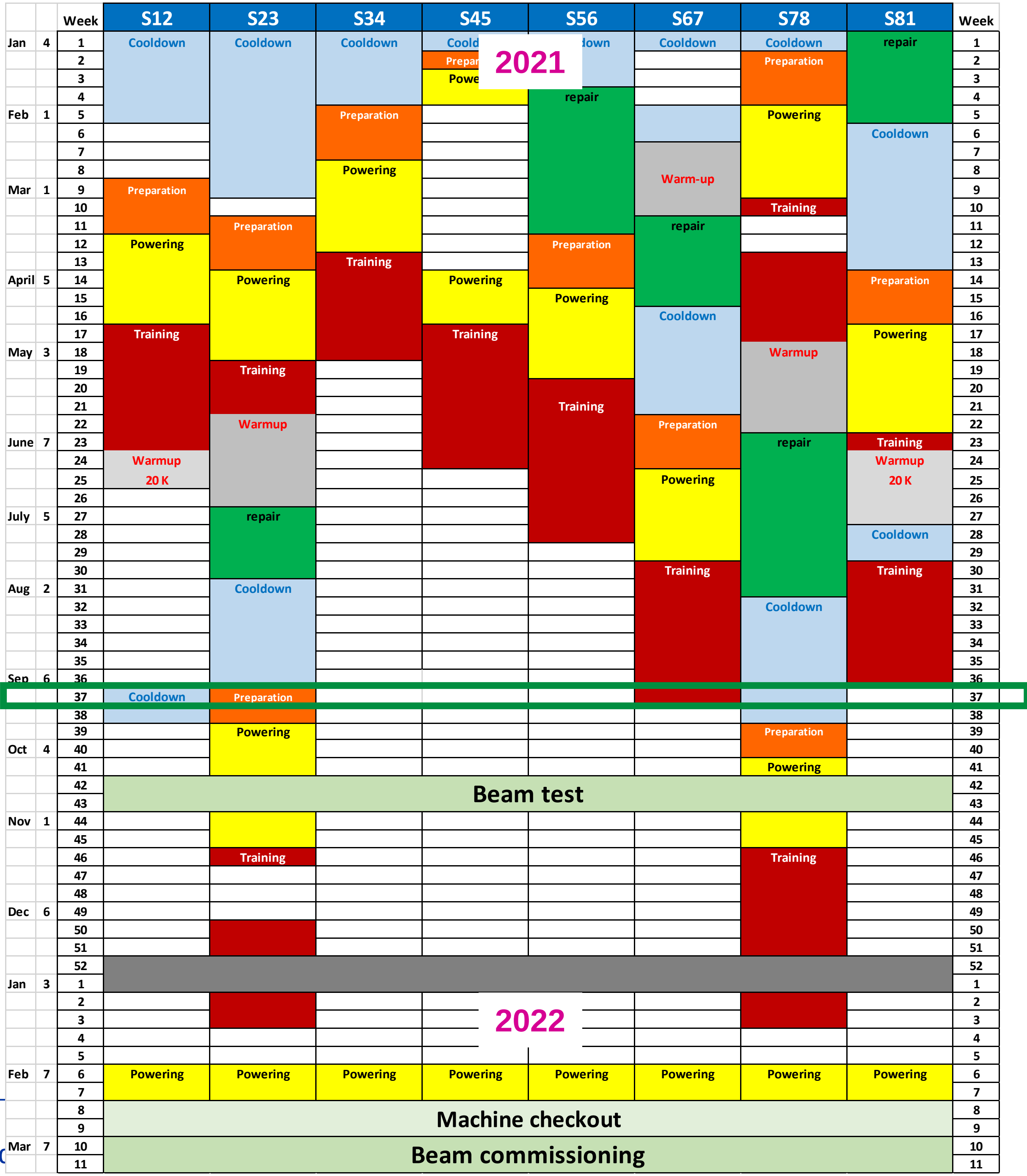
Due to the repair of sectors 23 and 78, magnet training will only be completed around Dec 2021 – Jan 2022

- Final confirmation of beam energy only at end of the year taking into account risk analysis

2 week beam test at injection energy in October 2021

- Verification of machine aperture, pre-commission of key systems ahead of 2022 run.
- Collisions for all experiments (injection energy).

The start of Run 3 beam commissioning is scheduled for March 7th 2022



Run 3

Injector beam evolution

Expected injector beam intensity ramp up during Run 3
Being revised based on commissioning experience

Year	Initial bunch population [ppb]	Target bunch population [ppb]
2021	1.1×10^{11}	1.4×10^{11}
2022	1.4×10^{11}	**1.8×10^{11}**
2023	**1.8×10^{11}**	2.1×10^{11}

The maximum bunch population in the LHC is estimated to be $\approx1.7\text{-}1.8\times10^{11}$ ppb due to limitations from beam stability, beam dump system, beam induced heating

With such bunch intensities the LHC can *virtually* achieve luminosities more than twice the cryogenic cooling limit at the triplet of 2×10^{34} $cm^{-2}s^{-1}$ at 7 TeV

- Opens the door for long luminosity levelling fills at the limiting luminosity.

Operation in Run 3 - 2022

$$L = \frac{kN_b^2 f\gamma}{4\pi\beta^* \varepsilon^*} F$$

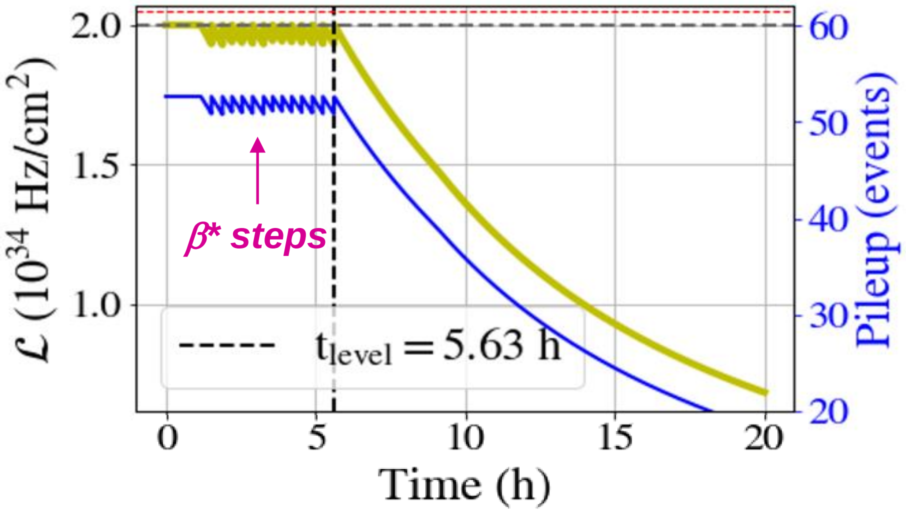
The 2022 physics run includes a 10-12 weeks long recommissioning after LS2

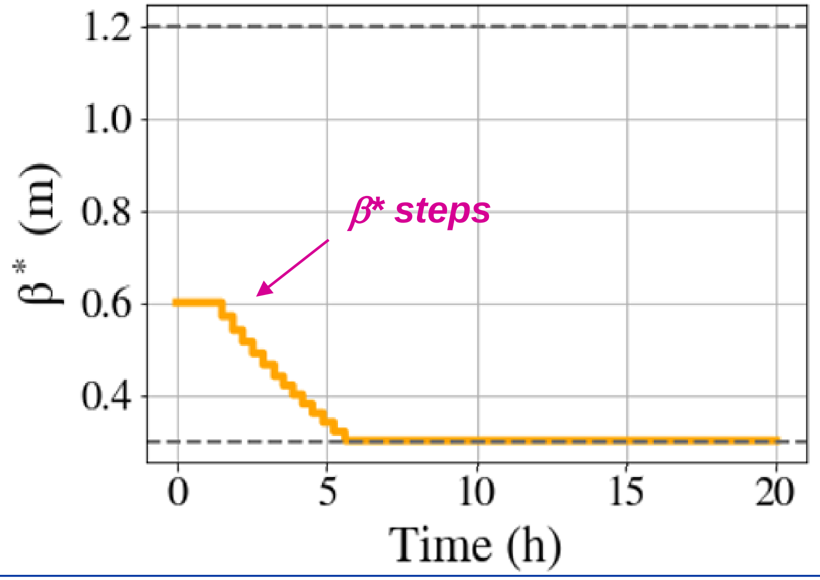
- Full intensity only expected during the summer.

For bunch populations of 1.4×10^{11} ppb, it should be possible to level the luminosity at 2×10^{34} $cm^{-2}s^{-1}$ over 5-6 hours.

- Levelling by β* for ATLAS and CMS
- Discrete steps of β* with ~5-7% luminosity change/step.

Due to reduced length of the 2022 run, an integrated performance of 30-40 fb^{-1} is expected in 2022





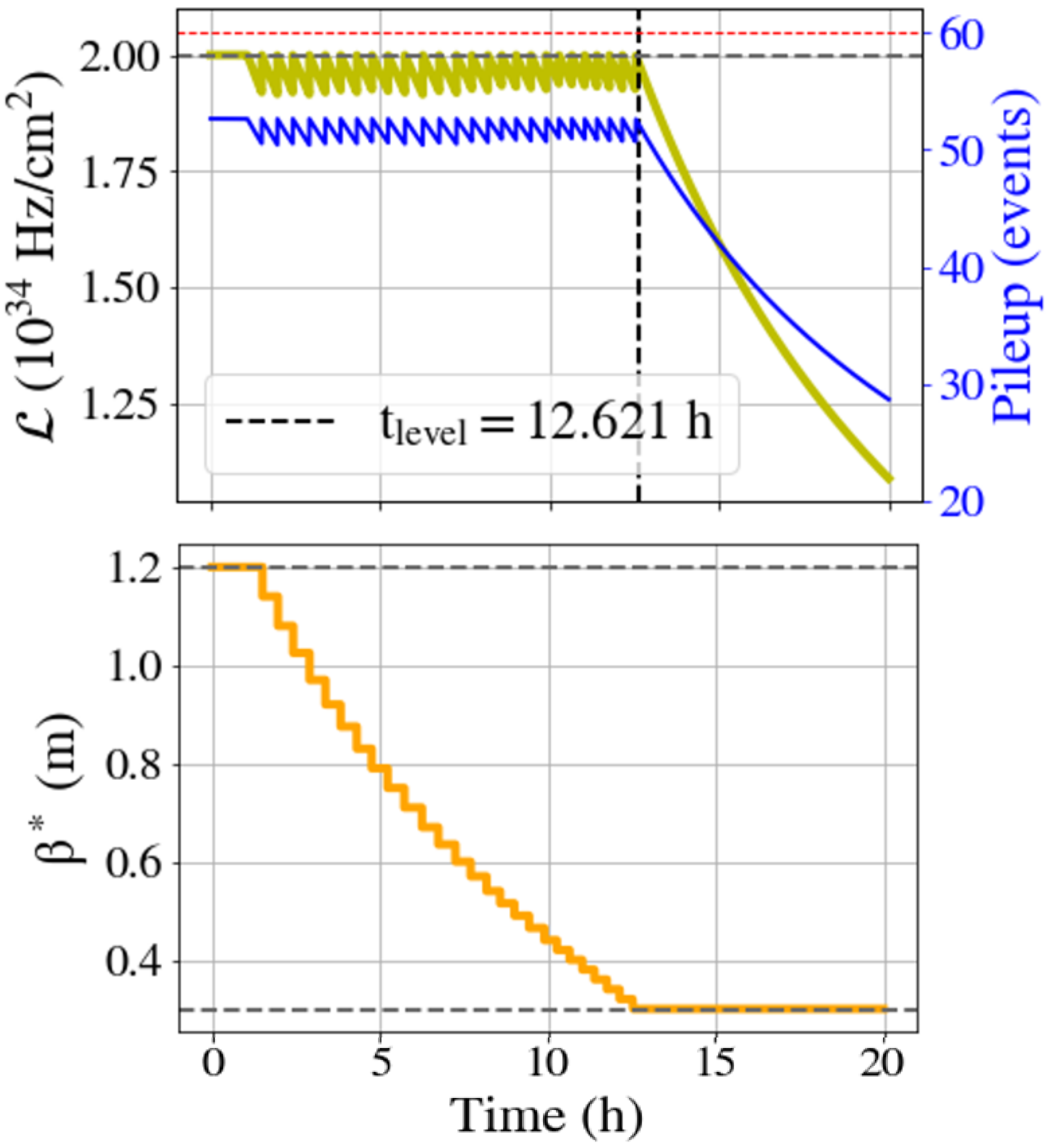
Operation in Run 3 – 2023-24

For the maximum bunch population of 1.8×10^{11} ppb the levelling time may reach ~ 12 hours

In 2023 and 2024 the integrated luminosities are expected to reach 70-80 fb^{-1}

The current estimate for the integrated luminosity over Run3 is ≈ 160-200 fb^{-1}

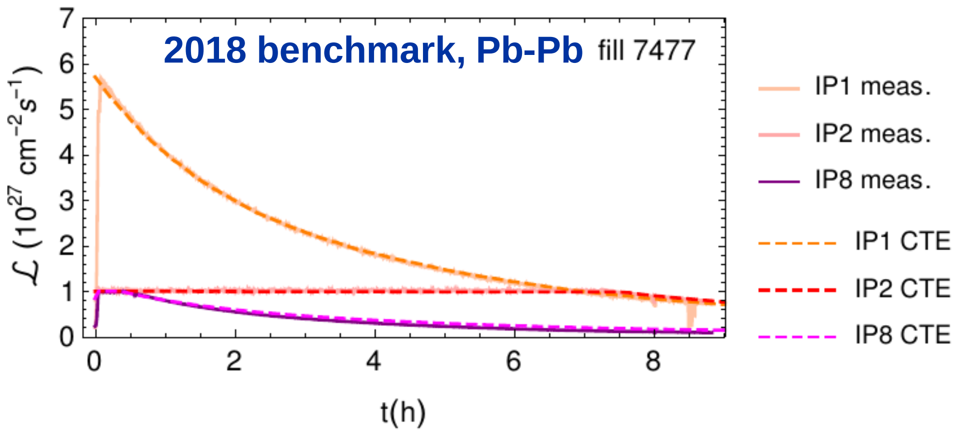
Doubling the Run 1 + Run 2 data set!



Ion operation in Run 3

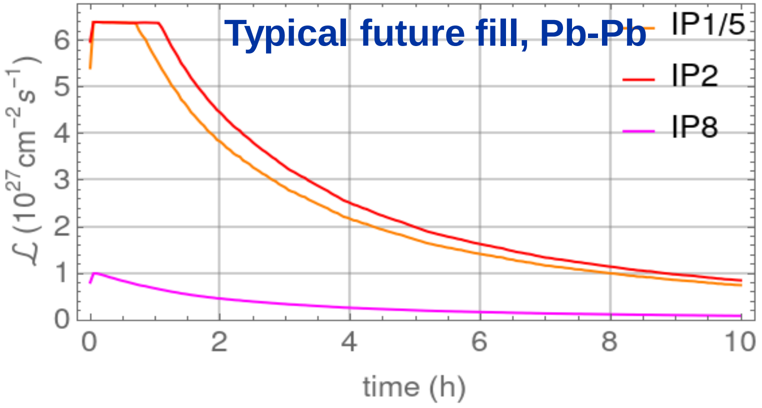
HL-LHC Pb-Pb luminosity was demonstrated in ATLAS and CMS, *L* ~6×10^{27} cm^{-2}s^{-1} (design x 6)

- This will be possible also in ALICE during Run 3 (TCLD collimators installed)



Pb bunch spacing will be reduced from 75 ns to 50 ns (~740 → ~1240 bunches) thanks to SPS RF upgrades during LS2

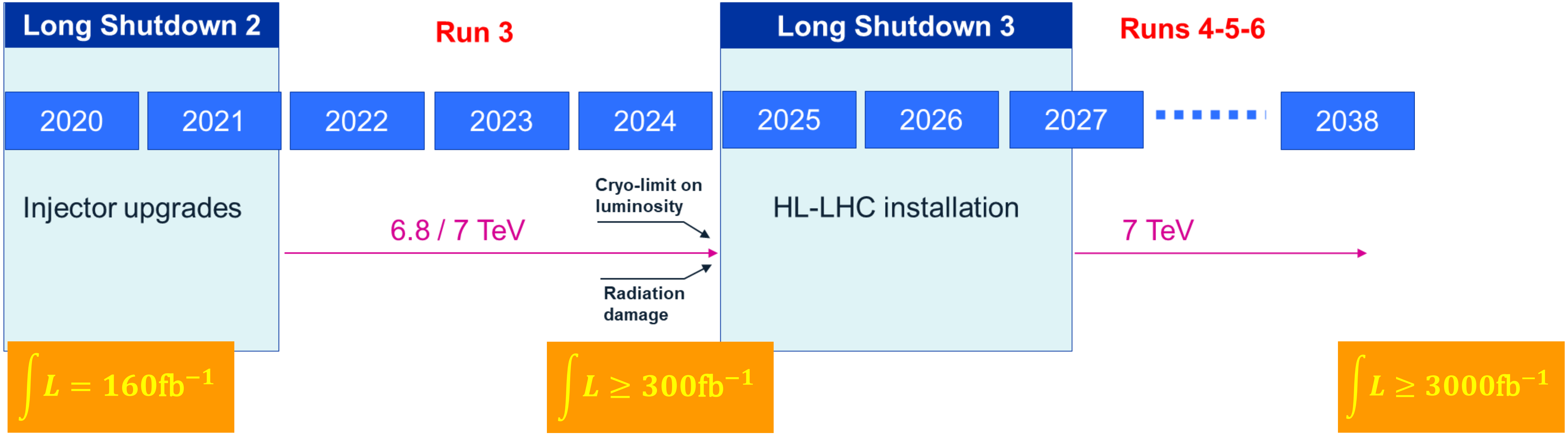
- 2.5-2.7 nb^{-1} collected during a 30d Pb ion run in ALICE a bit less in ATLAS/CMS, 0.5 nb^{-1} in LHCb



Each year of Run 3 will see an ion run (Pb-Pb or p-Pb), a short Oxygen run (O-O, p-O) will take place in 2023 or 2024.

HL-LHC

HL-LHC



Enable LHC to deliver ~250 fb^{-1}/year in ATLAS/CMS (leveling at ~140 evts/xing)

- Complete redesign of the machine in the regions next to ATLAS and CMS to achieve smaller beam size at the experiments
- Profit fully from the increased beam intensity provided by the LS2 injector upgrade

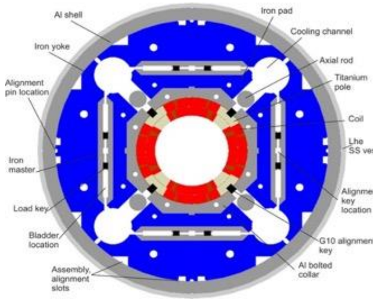
HL-LHC magnets

New wide-aperture superconducting magnets for the experimental regions

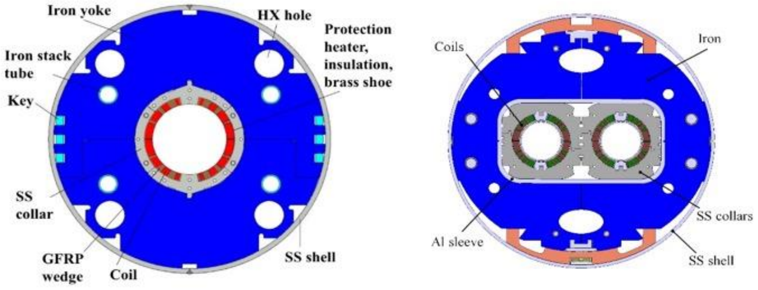
- A significant fraction of the aperture used for shielding to minimize radiation to the coils
- Completing prototyping and testing phase and entering production phase for most of the components

Key components of HL-LHC are new final focus quadrupoles with Nb_3Sn coils (~12 T peak field!)

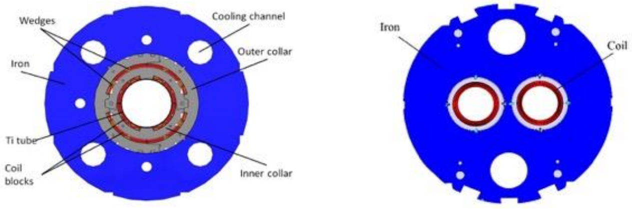
Final focus quadrupole



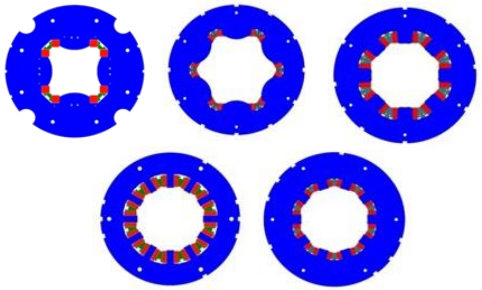
Separation/recombination dipoles



Dipole correctors



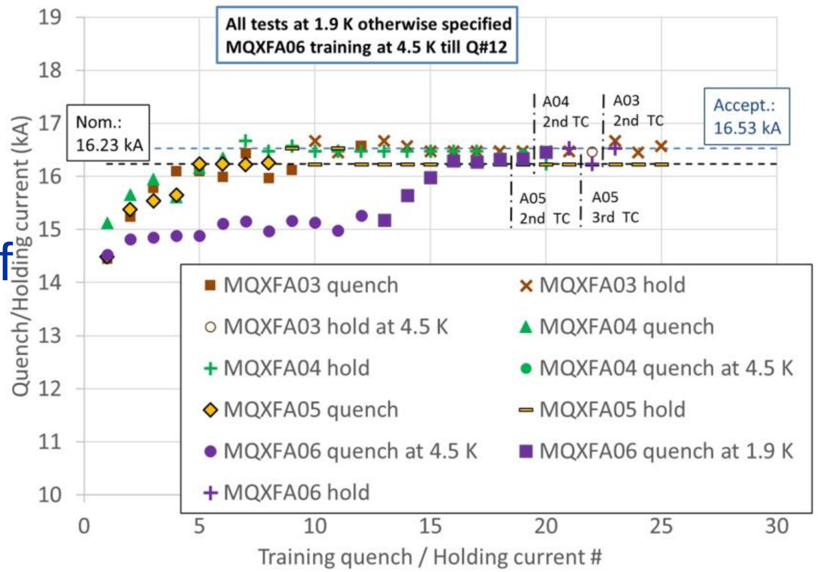
Higher order correctors



HL-LHC Triplet Quadrupoles

4 US AUP Q1/Q3 quadrupoles passed successfully vertical tests:

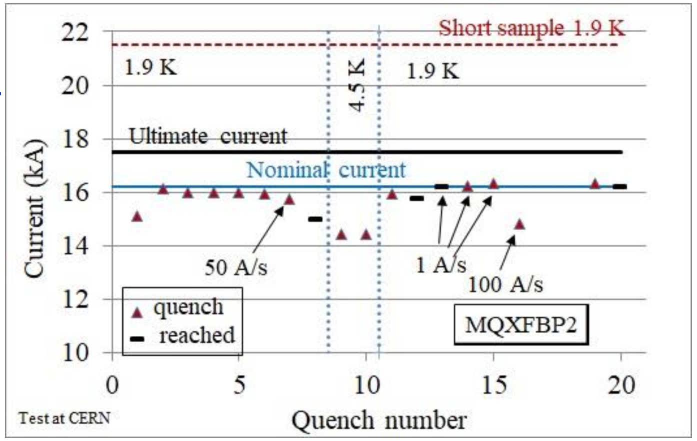
- First horizontal test of a magnet (consisting of two quadrupoles in common cryostat) planned for 2021



4 m long Q1/Q3 magnet / US-AUP

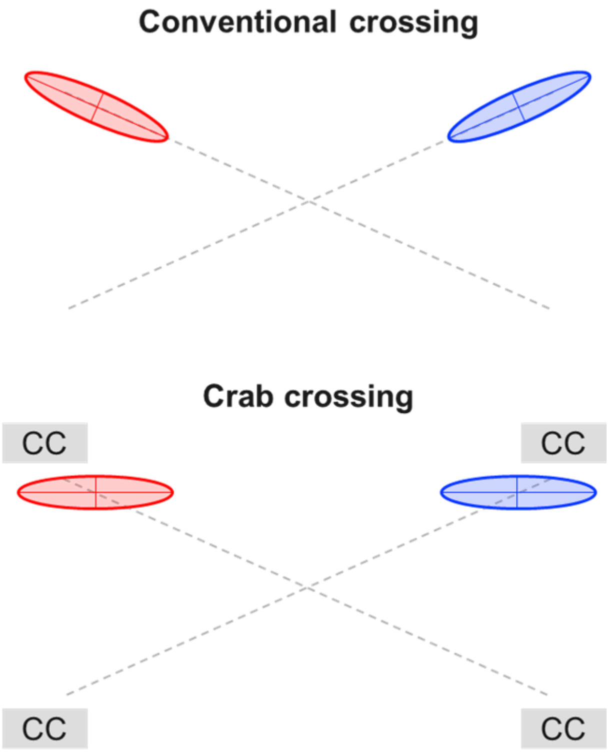
2 CERN Q2 prototypes tested:

- The first reached 6.5 TeV equivalent without quench the second 7 TeV after slow and special training cycles. Both were limited by a single identified coil
- Magnet protection system worked as planned
- All main concepts have been proven up to 7 TeV equivalent



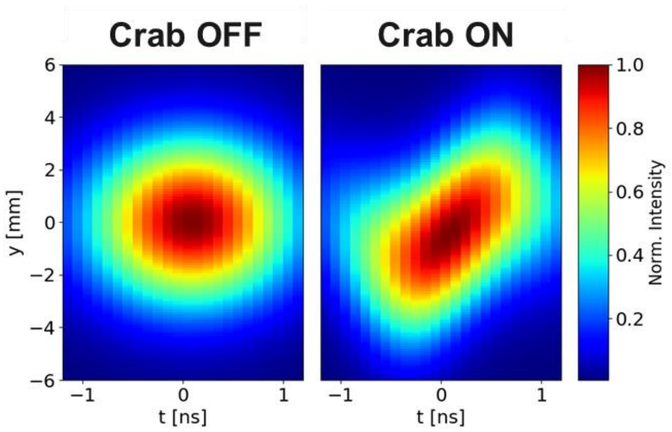
7.2 m long CERN Q2 prototype

HL-LHC Crab cavities



Crab cavities will be installed (first in a hadron collider) on each side of the IPs to tilt the bunches and maximise the bunch overlap.

- 2 types (DQW and RFD) according to the crabbing plane

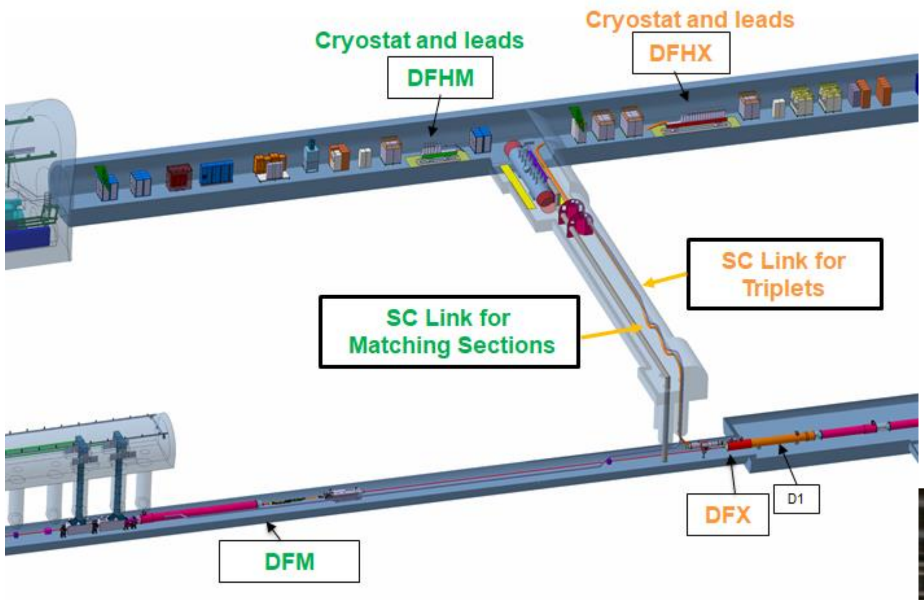


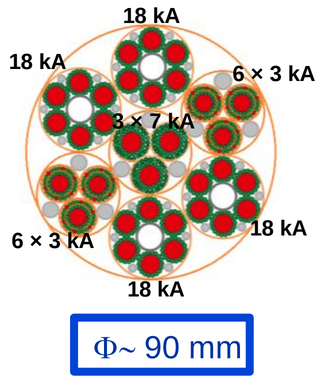
A prototype has been tested in the CERN SPS ring

- First crabbing of a proton beam demonstrated in 2018

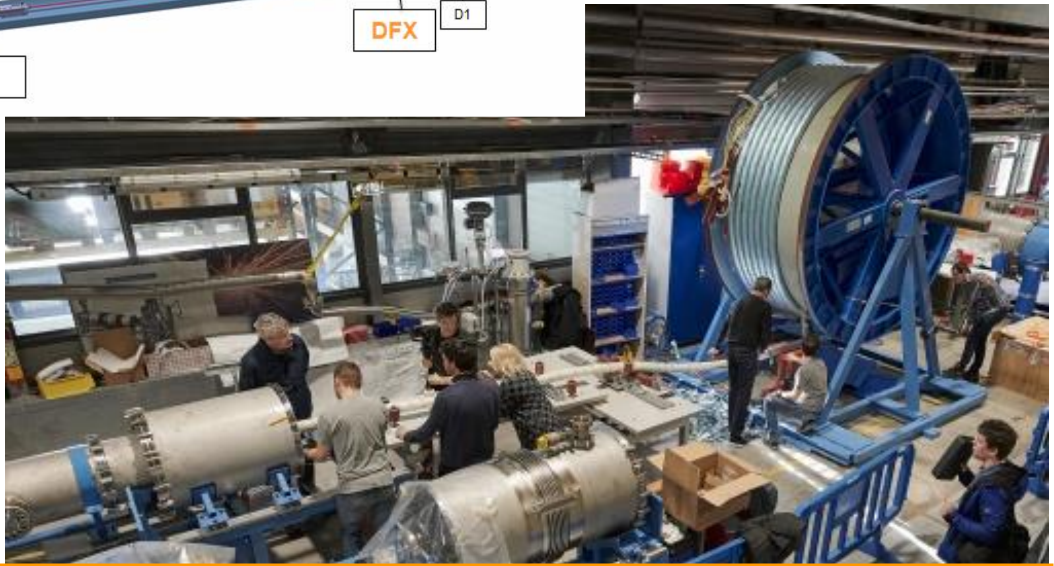
HL-LHC: Superconducting Link for HL-LHC Magnets

MgB_2 (HTS) cable will be used to transport the high current ($|I_{tot}|$ > 100 kA @ 25 K) from the galleries to the tunnel





Successful demonstration of 2 x 20kA + 2 x 7kA in June in MgB_2 @ 30 K in flexible cryostat over 60m



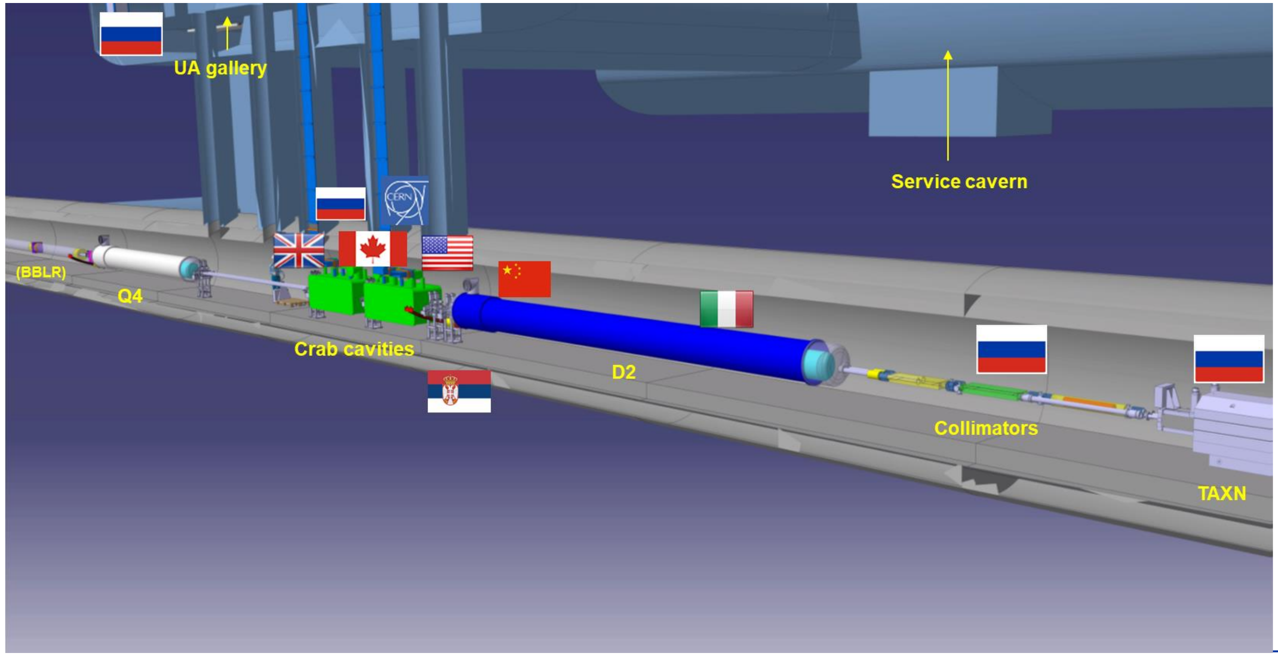
Demonstrator in the SM18 Magnet Test Facility

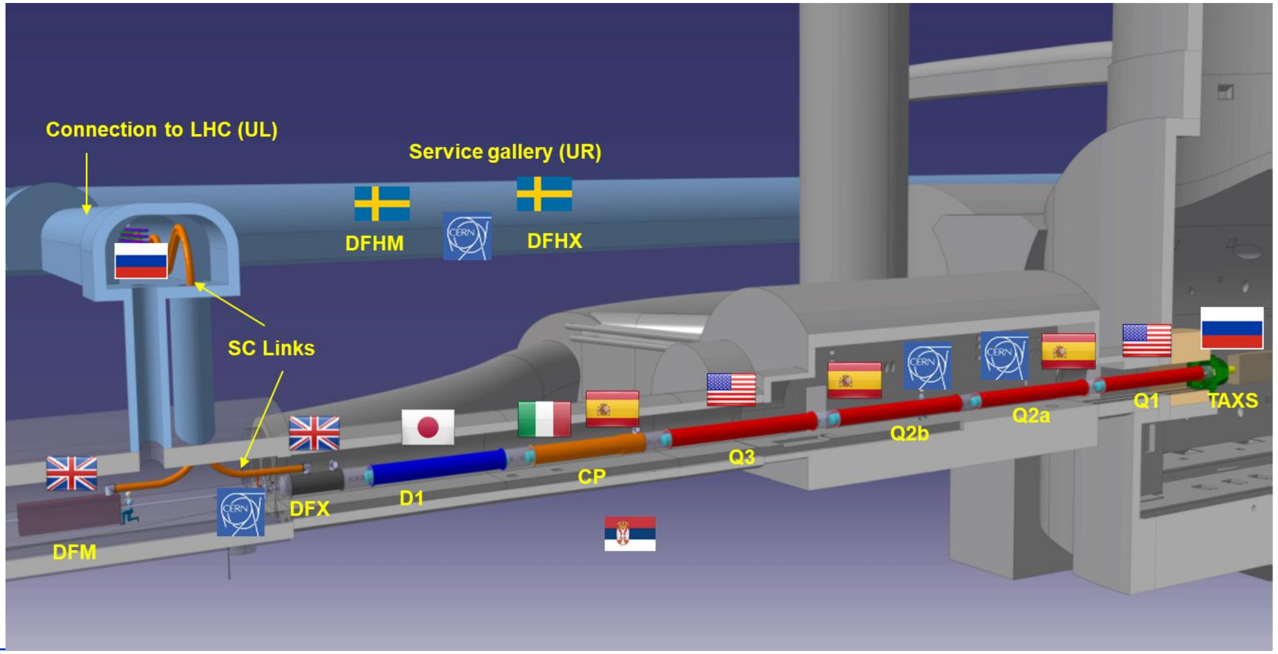
HL-LHC: Truly International Collaboration

D1 and D2 Prototypes expected in 2021 then start of series production

Non-linear triplet magnet corrector magnets 50% completed

Triplet Orbit corrector magnets: Industrial contract launched in 2021





Conclusions

Preparation of Run 3 in full swing for beam operation in March 2022

- Beam test in the second half of October 2021

Magnet training target energy was lowered from 7 TeV to 6.8 TeV pending risk analysis for training to 7 TeV

- 6 out of 8 sector ready for 6.8 TeV, 3 out of 8 sectors ready for 7 TeV

Following the upgrade of the LHC injectors during LS2, the beam intensity will be increased by ~50% during Run 3

- operation at a levelled luminosity of 2×10^{34} $cm^{-2}s^{-1}$ over up to 12 hours

HL-LHC is already taking shape in the LHC, preparing for component production and installation in LS3

home.cern

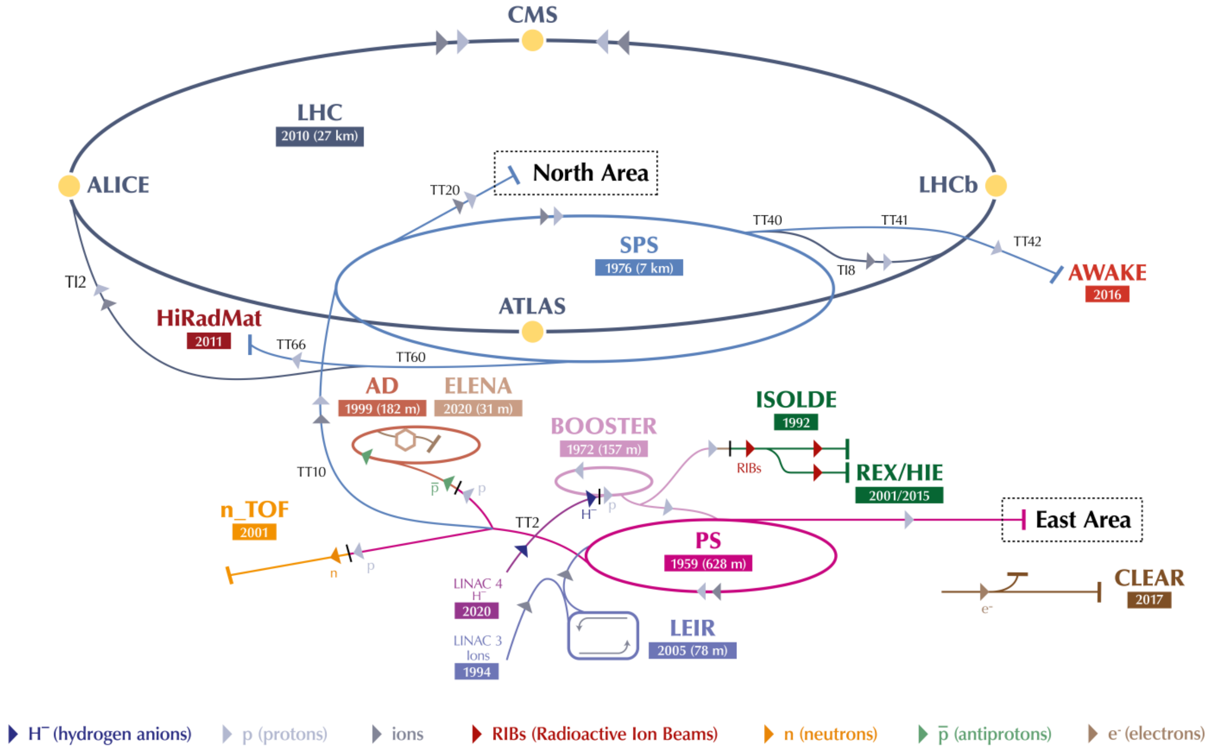
Long Shutdown 2

Driven by major upgrades of the LHC injectors to reach HL-LHC beam parameter targets

$$L = \frac{k N_b^{\,2} f \gamma}{4\pi\beta^{*}\ \varepsilon^{*}} F$$

Beam parameters are defined by the injector chain:

- Booster defines the brightness N_b/ε
- PS defines the bunch spacing & train structure (k)
- SPS assembles trains (k) and boosts the energy



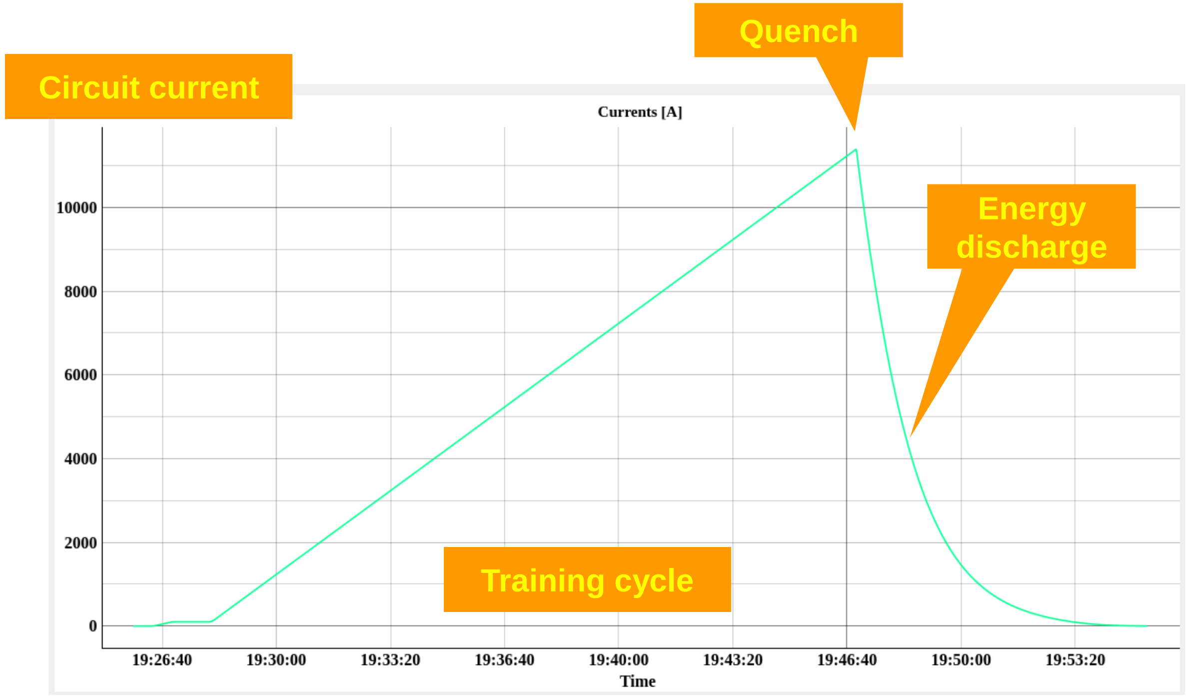
Magnet training

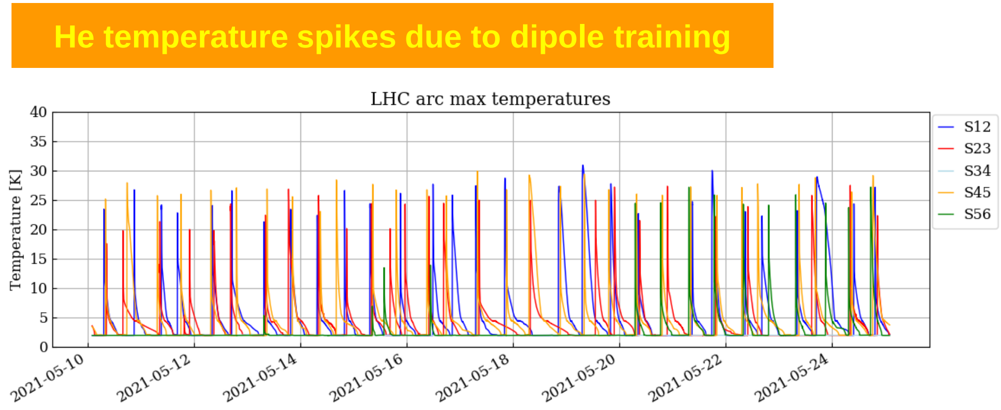
Quenches are provoked by small energy deposition in the coils (~mJ): friction, cooling issue, beam loss…

SC magnets can loose (part of) their training memory after a warm-up to room temperature

During magnet training, the circuit is ramped to the target current until one of 154 magnets quenches, leading to a powering abort

- ~8 hours cryogenic recovery time after a quench at high field
- ~2 training cycles/day until the desired current is reached without quenches



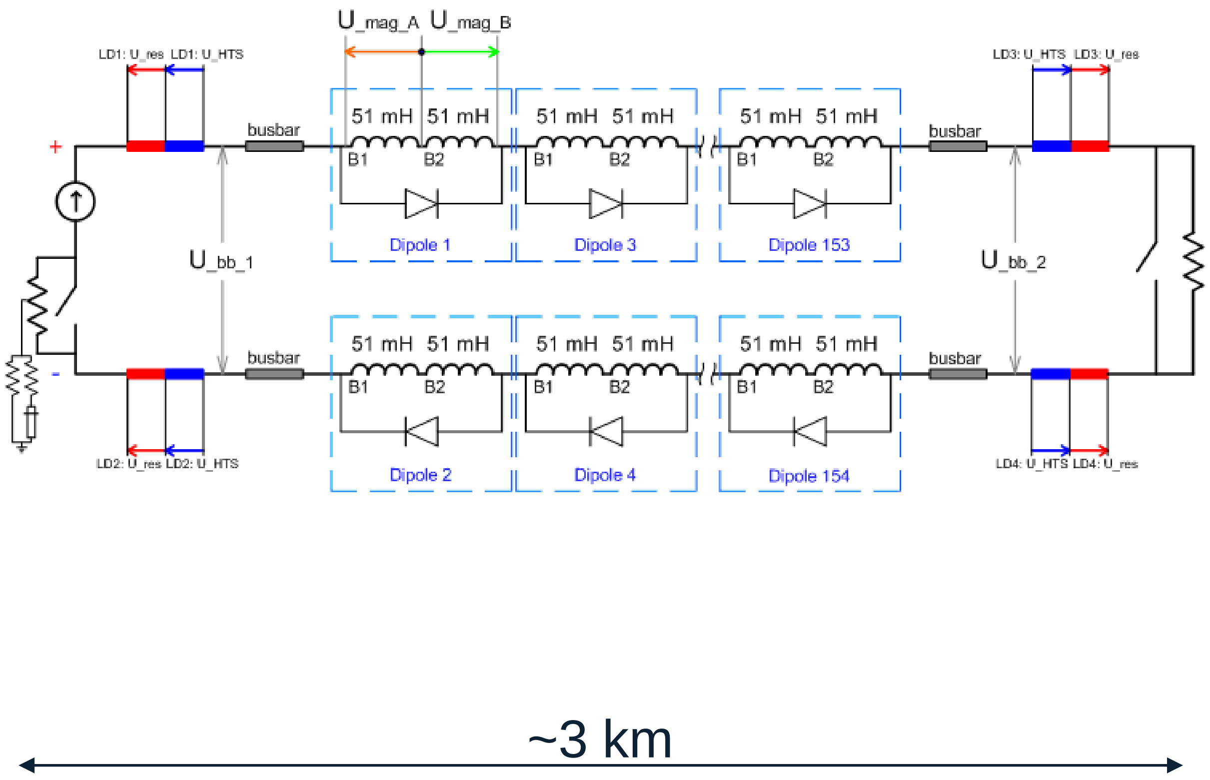


Main dipole circuits

LHC dipole magnets are grouped into 8 circuits of 154 magnets per sector (=one arc) powered by one power converter

In case of a magnet quench, the diode associated to each magnet start conducting and bypasses the coils, the circuit must be stopped and the energy stored in the circuit must be safely discharged into dump resistors

- Stored energy @ 7 TeV ~ 1 GJ



LHC parameters

Between the 2015 and 2018 β* (from 80 to 25 cm) and beam normalized emittance ε* (from 3 to 1.8 μm) were progressively reduced, boosting the performance through smaller IP beam sizes

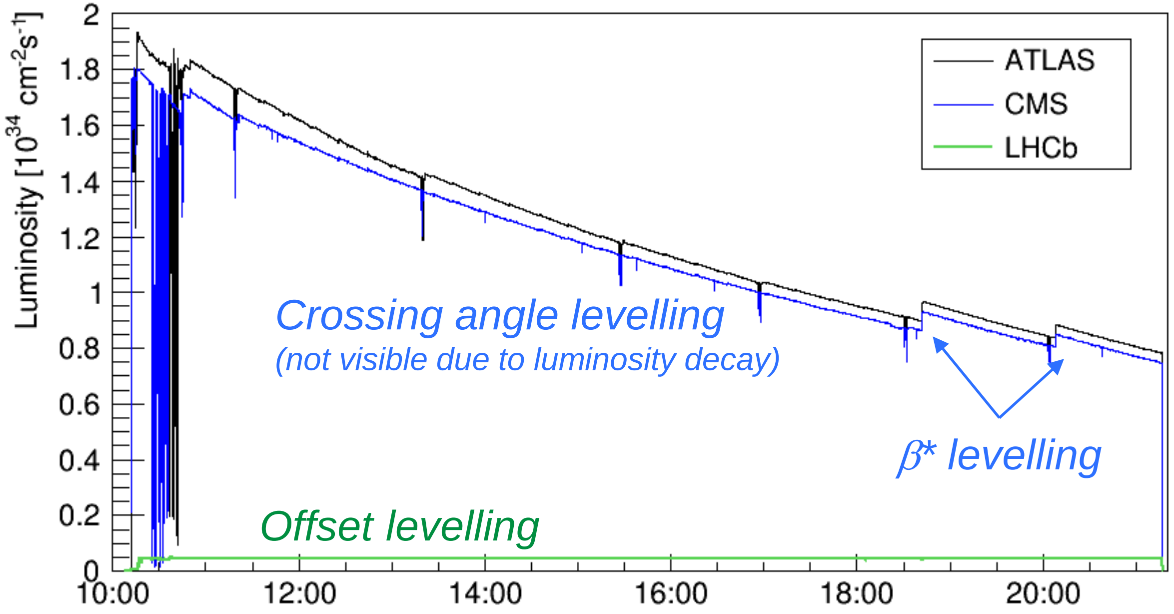
- Reflects the improved understanding and control of beams and machine

Parameter	Design	2018	Run 3
Bunch population N_b (10^{11} p)	1.15	~1.1	~1.8
No. bunches k	2780	2556	2748
Normalized emittance ε* (μm)	3.5	~1.8	1.8-2.4
β* (cm)	55	30 / 25	150 - 25
Full crossing angle (μrad)	285	320 - 260	320 - 260
Peak/Virtual luminosity (10^{34} $cm^{-2}s^{-1}$)	1.0	~2.1	~4-5

Luminosity levelling in Run 2

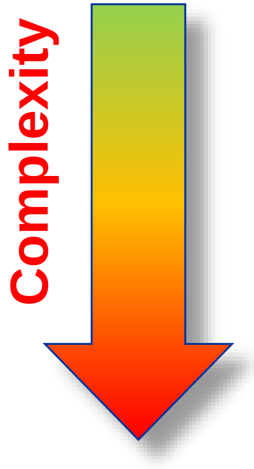
All three levelling techniques were used during operation in Run 2

- Crossing angle and β* levelling enhanced the luminosity at lower bunch intensity for ATLAS and CMS, when the pile up was already reduced.
    - Important test of β* levelling for Run 3.
- Offset levelling is used in LHCb / ALICE to ensure constant luminosity.
    - Over the entire duration of fills.

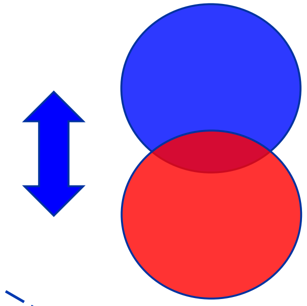


Luminosity levelling

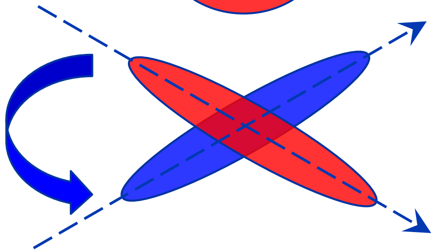
When the virtual luminosity is too high, it can be adapted dynamically (and smoothly !) while in collision to cope with experiment and HW limitations



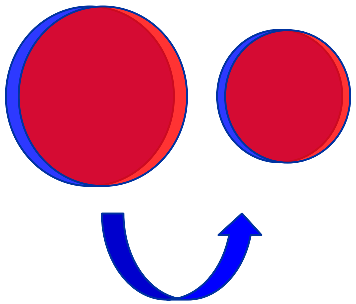
Levelling by beam offset (since **2011**)
Operationally easy, issues with beam stability



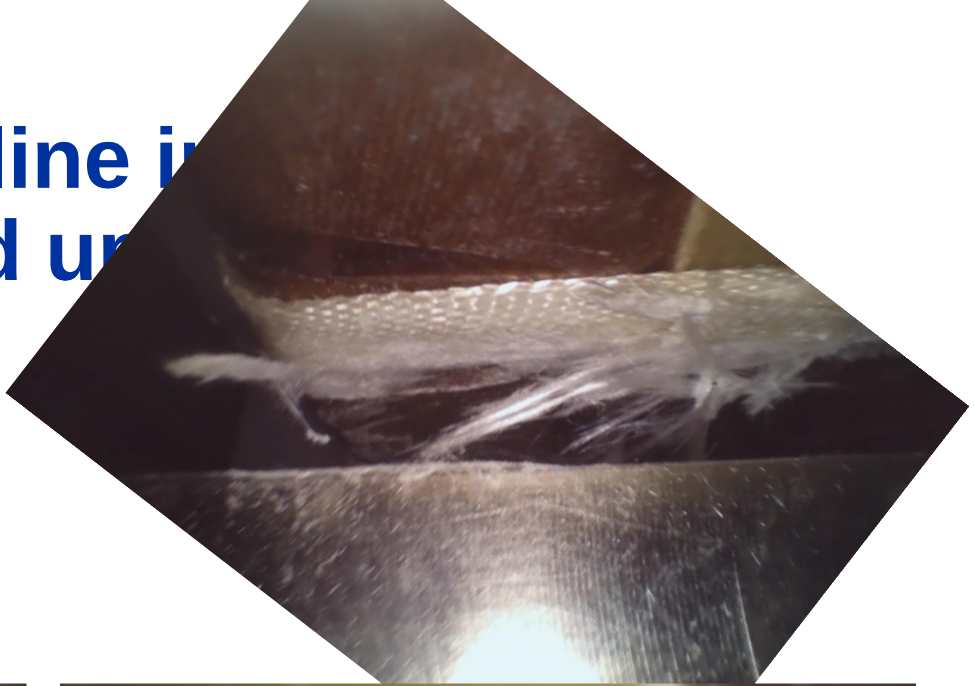
Levelling by crossing angle (since **2017**)
Limited tuning range

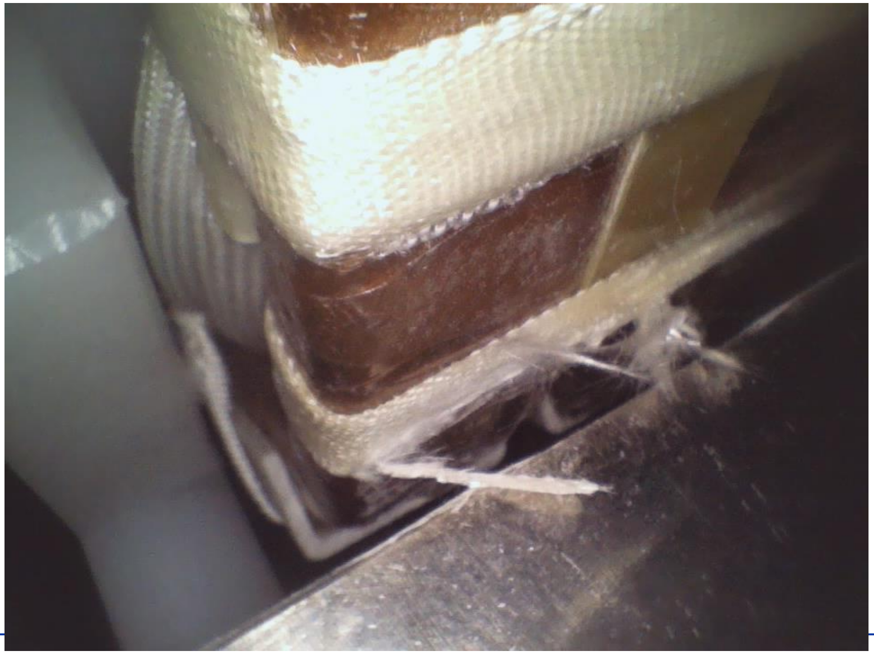


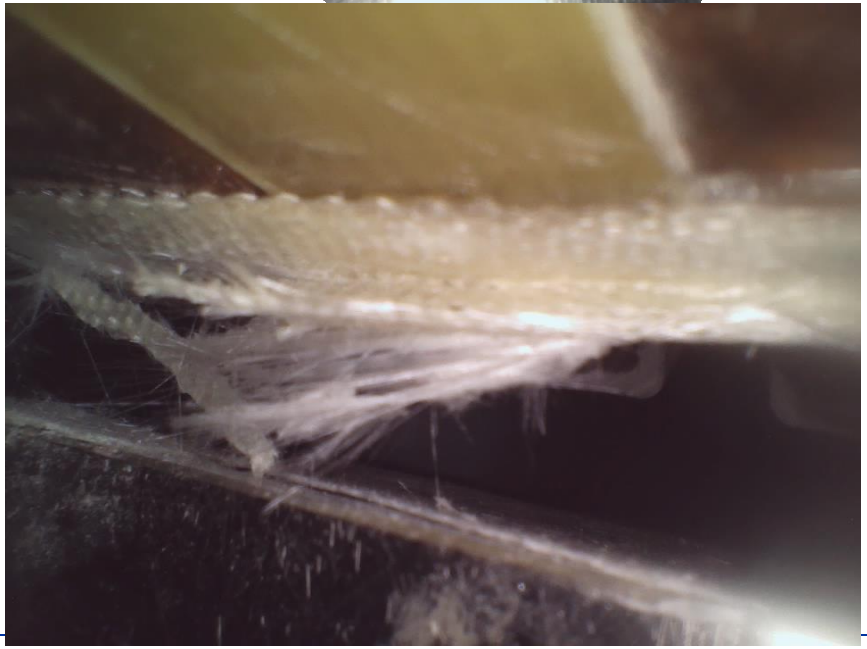
Levelling by β^* (= beam size at IP) (since **2018**)
Operationally complex, preferred for beam dynamics



RQF.A67 busbar: M1 line i
Busbars slightly lifted u





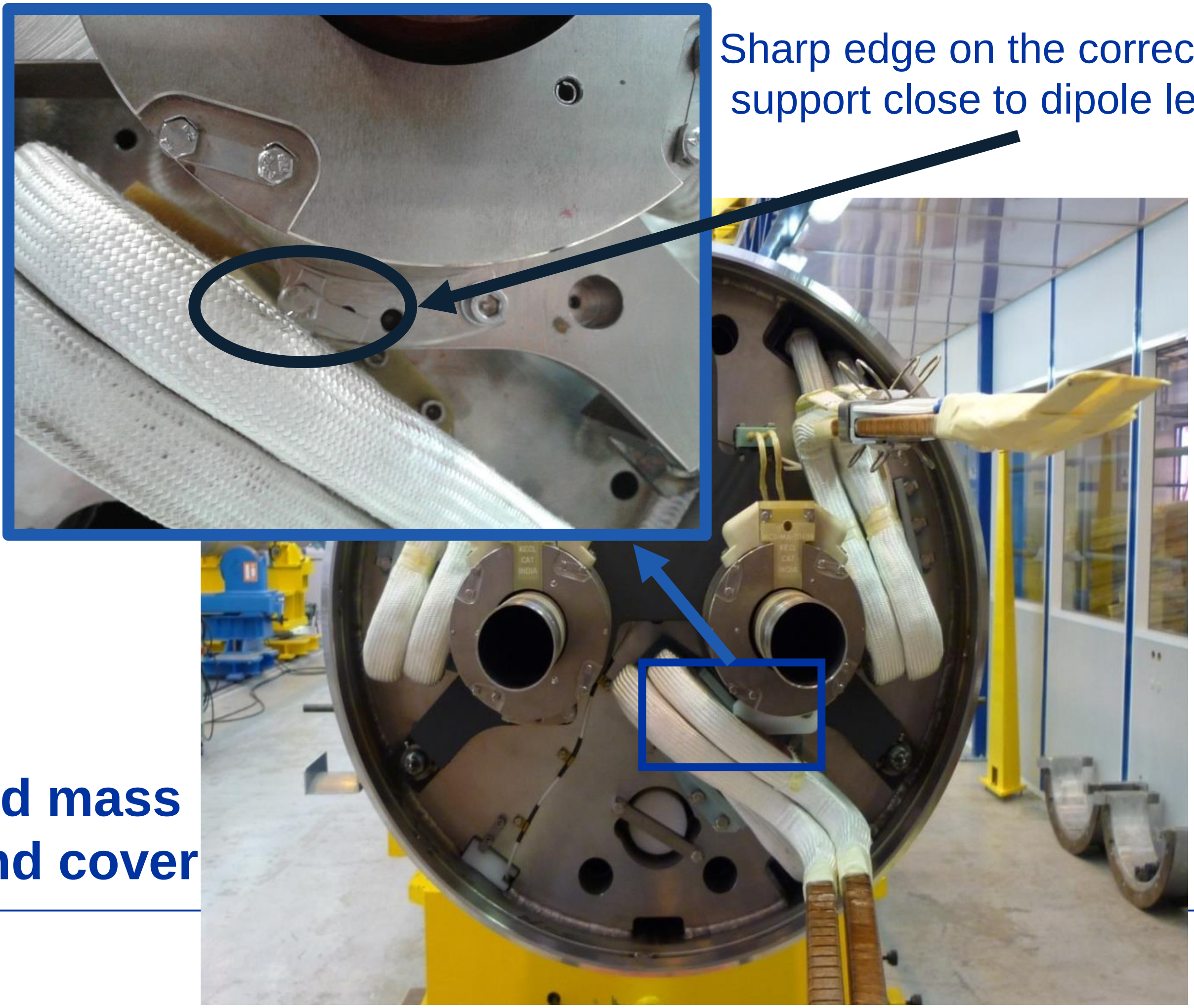


MB configuration

It is the second time that this issue occurred during a cool down (first one in sector 67 in 2009) and five other cases were detected at warm, with three during LS2.

The lyras are flexible leads that follow the thermal contraction of the dipoles.

At warm the RB lyra is very closed to the corrector support



Sharp edge on the corrector support close to dipole lead

Dipole cold mass without end cover

MB.C22R8 Lyra

On 5th Jan. 2021, the interconnection was open and the RB line cut (M3). The lyra was inspected with an endoscope.

The lead was found in contact with the corrector support and by pushing on the bus-bars, the fault to ground could be reproduced.