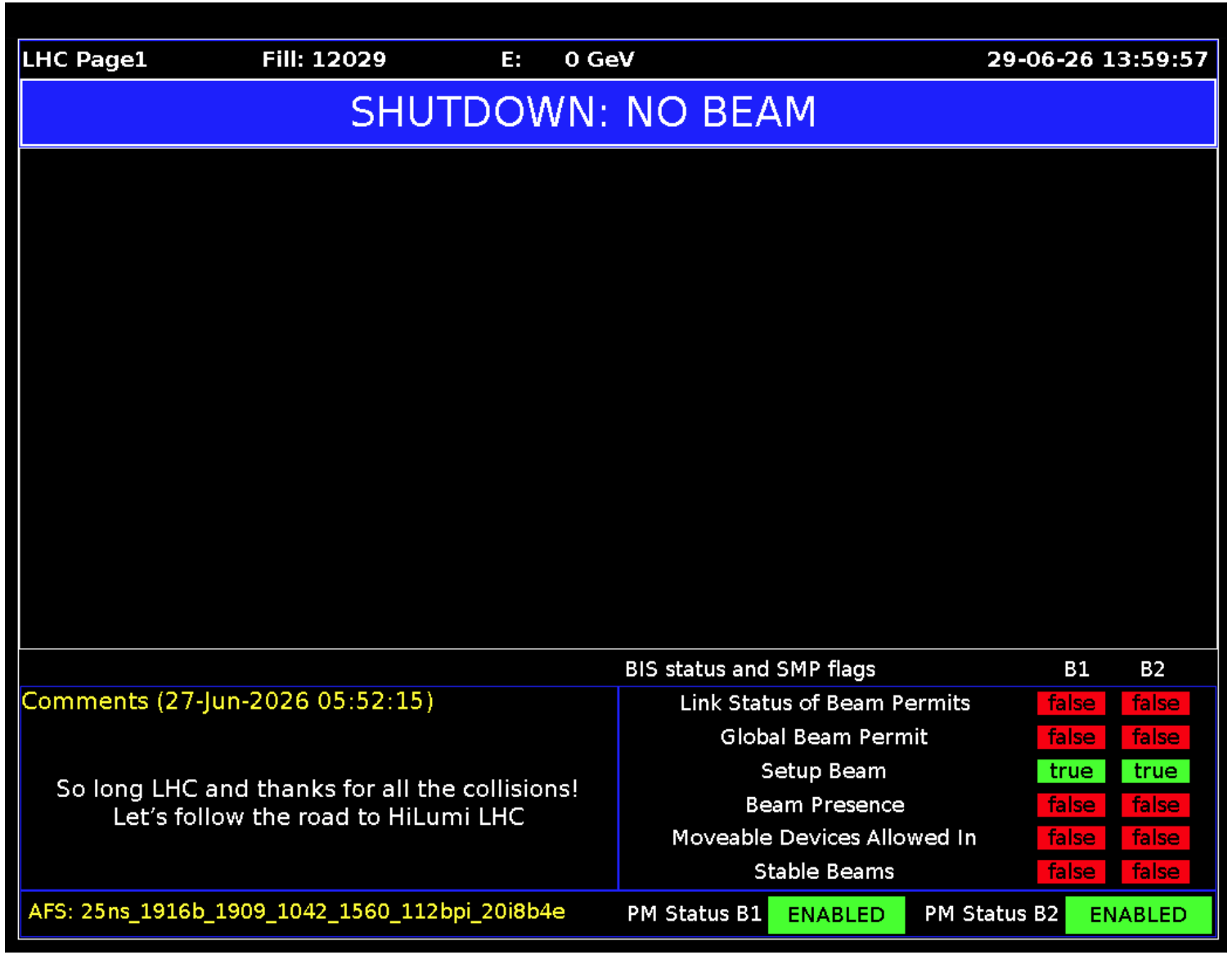


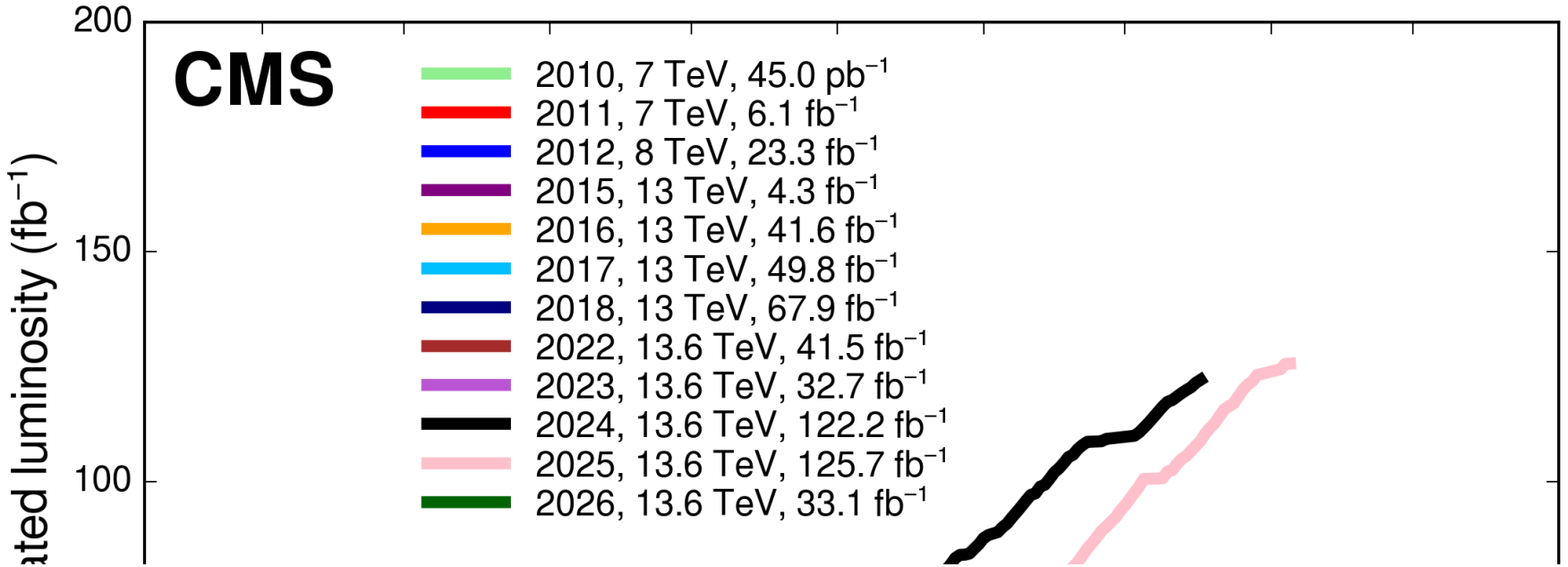
Status of HL-LHC

O. Brüning CERN

The HL-LHC transformation has started!



LHC Performance

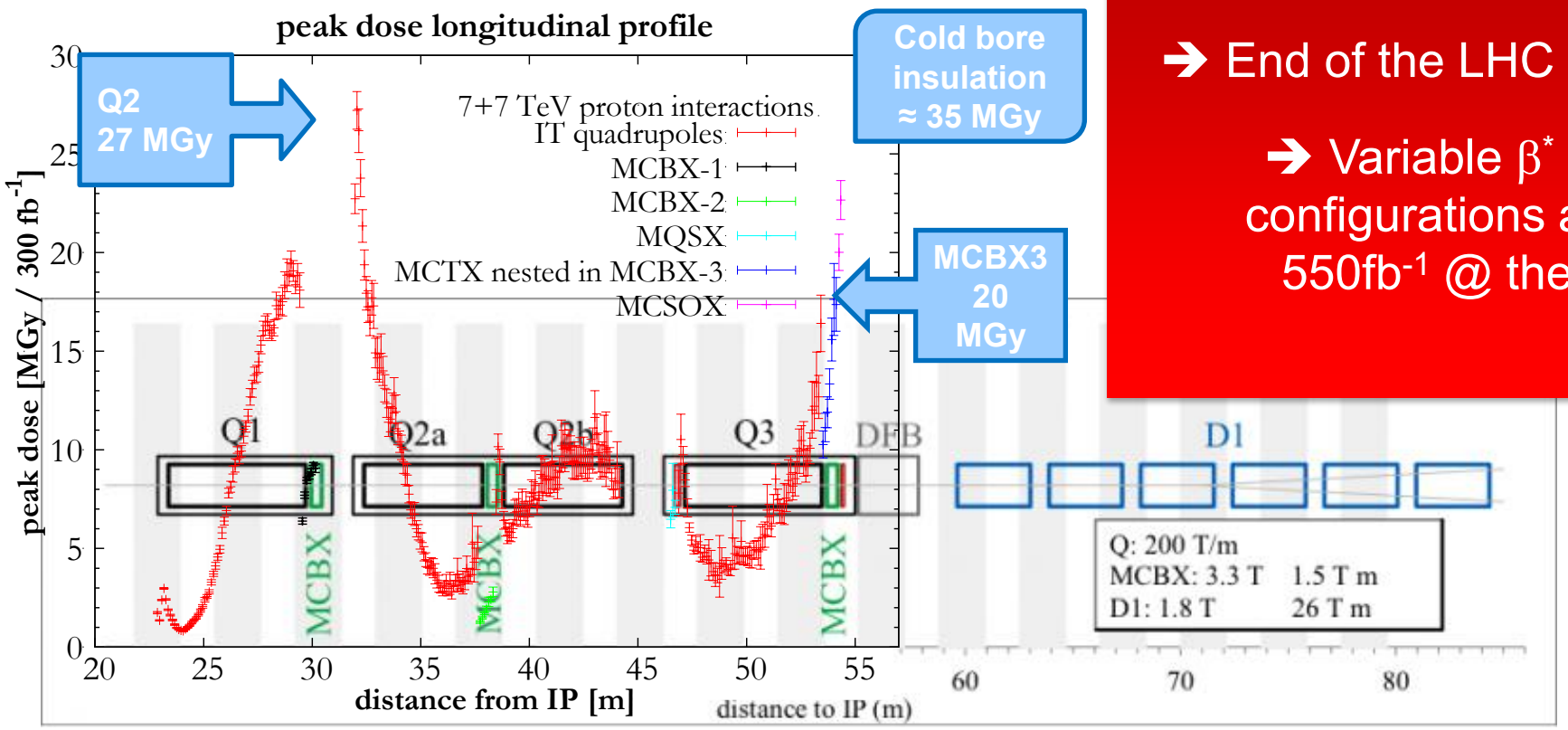


➔ almost 550fb^{-1} over 12 years of operation ➔ over 500fb^{-1} at 13 TeV or higher energy with

almost l ation!

Why stop the machine and Upgrade now?

LHC Lifetime Limitation:
Debris from the IP & Radiation damage to magnets!



➔ End of the LHC triplet lifetime @ 300fb^{-1}

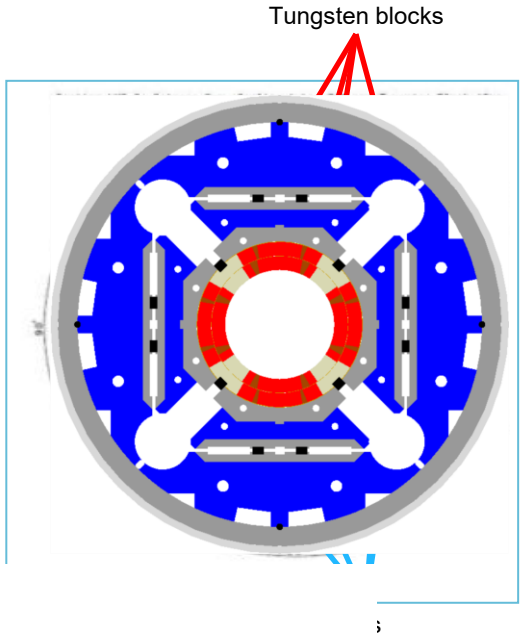
➔ Variable β^* and crossing angle configurations allowed operation up to 550fb^{-1} @ the end of Run3 in 2026

➔ HL-LHC goal: 10 times the LHC data Volume within 10 years of operation within the lifetime limit of new triplet magnets

HL-LHC technology challange: Radiation hard triplet magnets

Need to replace existing triplet magnets with radiation hard system such that the new magnet coils receive a similar radiation dose @ 10 times higher integrated luminosity!!!!!

➔ Shielding!



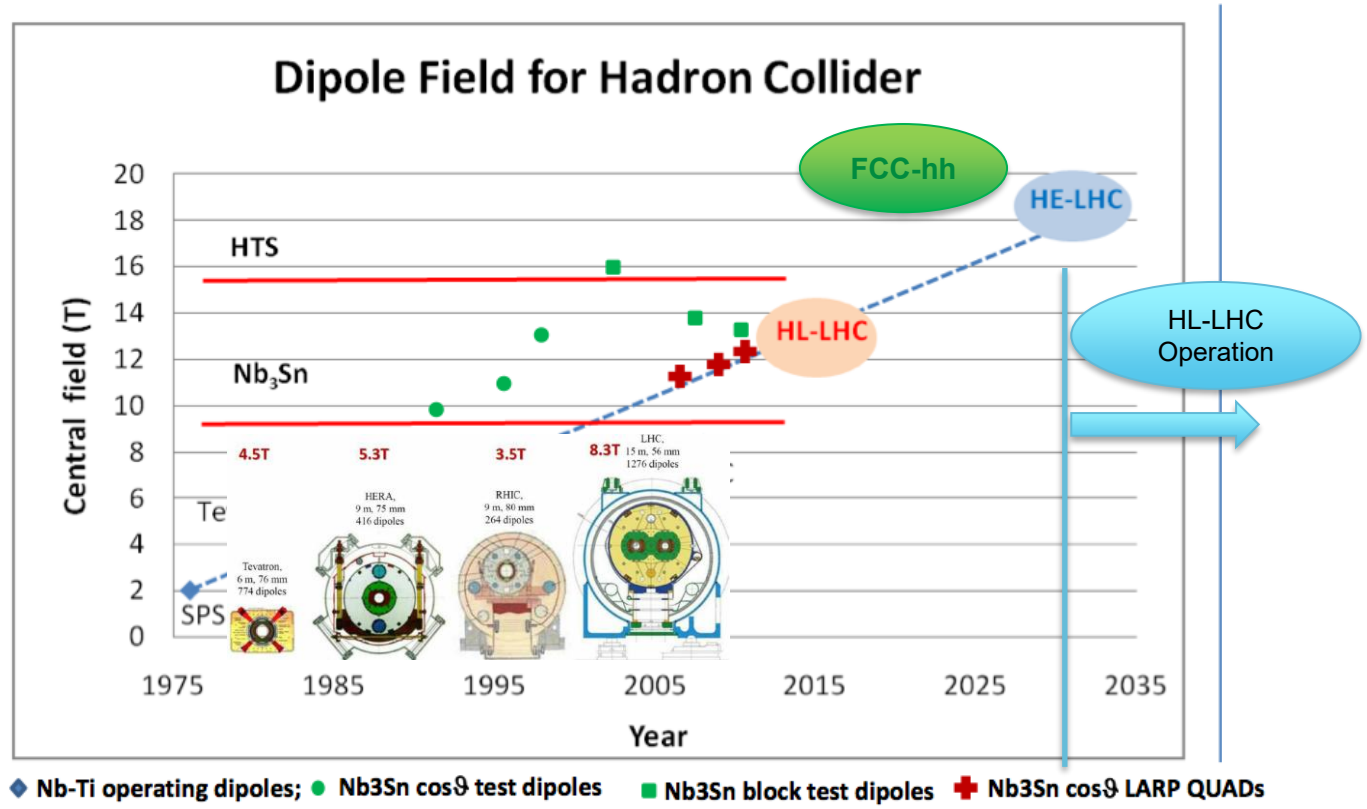
- ➔ Requires larger aperture!
- ➔ New magnet technology!

- ➔ 70mm at 210 T/m ➔150mm diameter 140 T/m ➔ Longer magnets

  8T peak field at coils ➔ 12T field at coils (Nb_3Sn)!!! ➔ New Superconductor

High Field SC Magnets

Development Timescales for Magnet development!!!



Ca. 30 years of Nb-Ti magnet R&D leading up to the LHC dipole magnets!

Transition from Nb-Ti to Nb_3Sn: required similar length of R&D!

HL-LHC led the R&D for 11-15T magnets based on Nb_3Sn technology:

➔ Started in early 2000

➔15-20 years R&D program

➔ Ready for installation by 2025

➔ Ready for operation by 2029

➔ ca. 30 years of development!!!

In addition, the HL-LHC accelerator needs to be a highly reliable and efficient machine!

Technology Landmarks



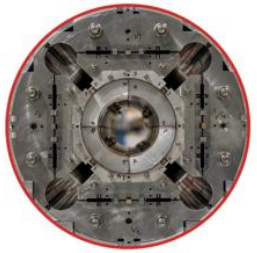
Finished in 2023

Upgrade of the Injector Complex ➔ LIU project

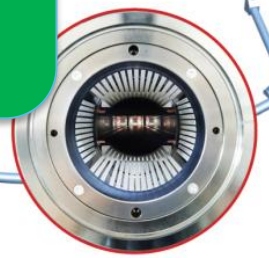
Implemented during LS2 ➔ increased beam intensities as of 2022

Complete Prototype System validated in 2024 ➔ Series production close to completion





Magnet series production finished and cryo-stating close to completion



½ system already installed for Run3



Series production close to completion in Industry Cryo-assembly ongoing

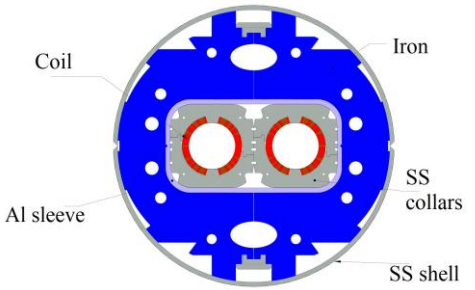


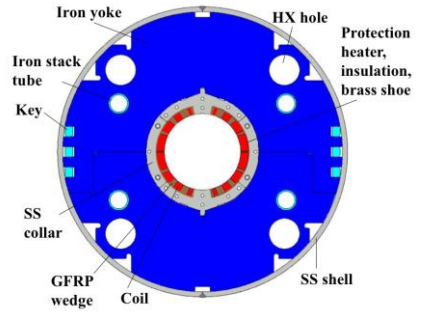
Finished in 2023



Successfully deployed in Pb-Pb operation since 2023

Super Conducting Separation / Recombination dipole magnets: D1 & D2





D1/D2 Magnets required for LS3 installation already delivered to CERN

NEW TECHNOLOGIES FOR THE HIGH-LUMINOSITY LHC

CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near ATLAS and CMS.

"CRAB" CAVITIES
16 superconducting "crab" cavities for the ATLAS and CMS experiments to tilt the beams before collisions.

LHC TUNNEL

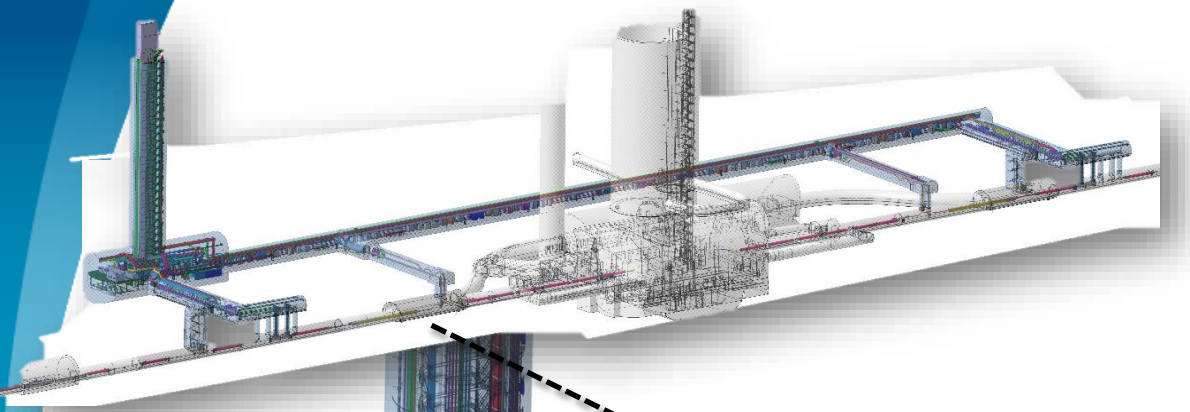
ALICE

CMS

SUPERCONDUCTING LINKS
ctrical transmission lines based on a high-
nperature superconductor to carry the very
igh DC currents to the magnets from the
wering systems installed in the new service
tunnels near ATLAS and CMS.

COLLIMATORS

Civil Engineering and new galleries



IR1/5 civil engineering completed in 2022





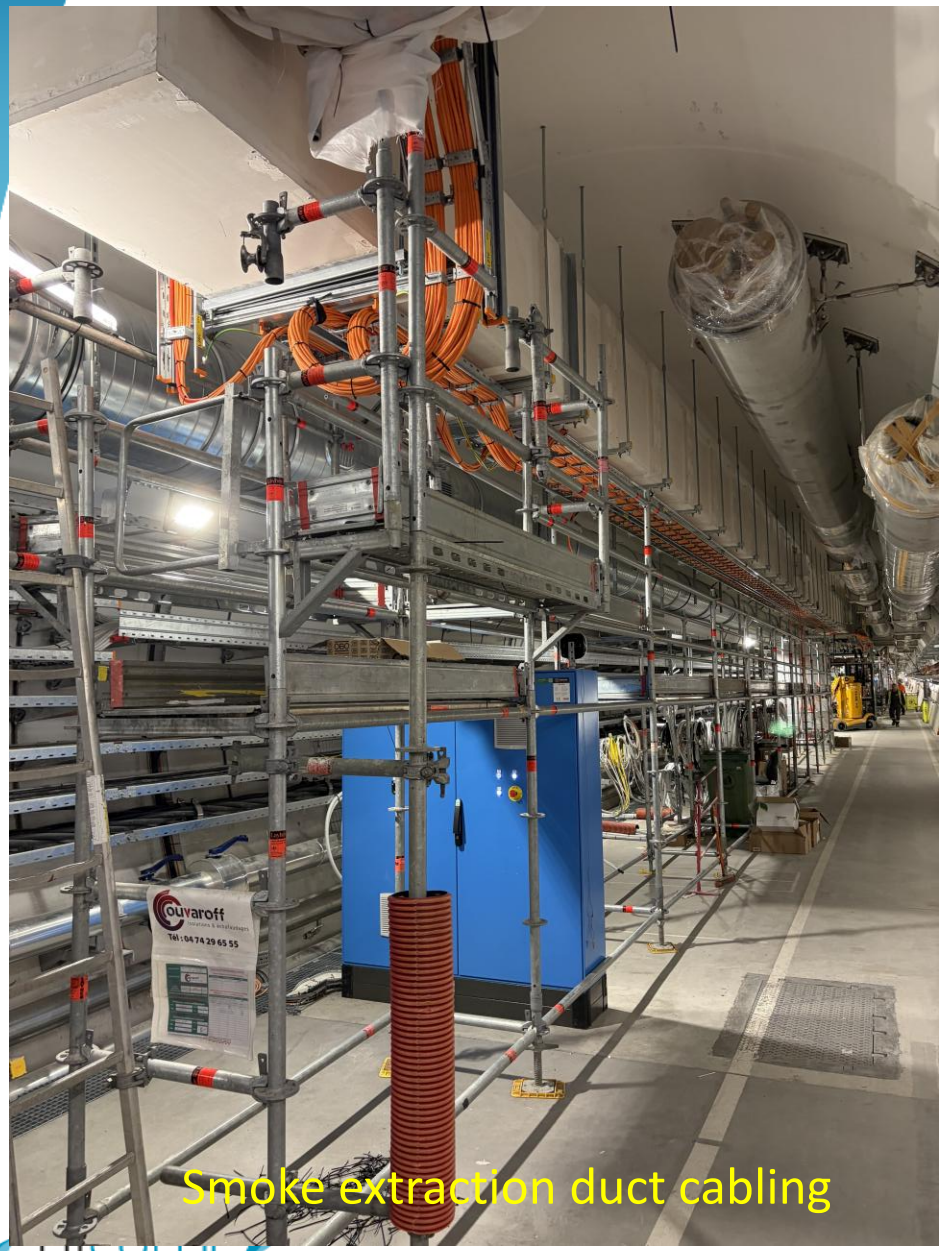








Infrastructure installations in HL galleries



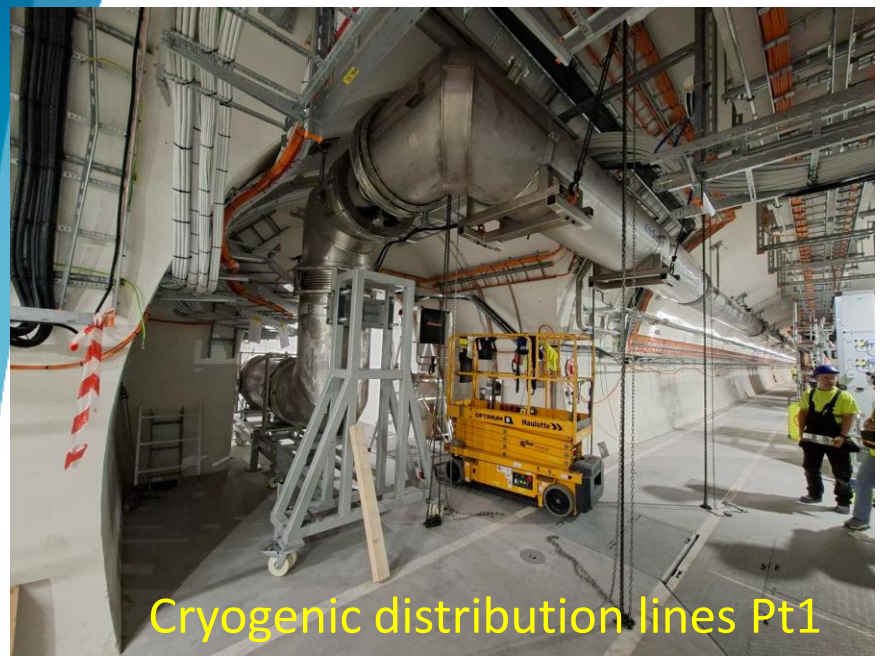


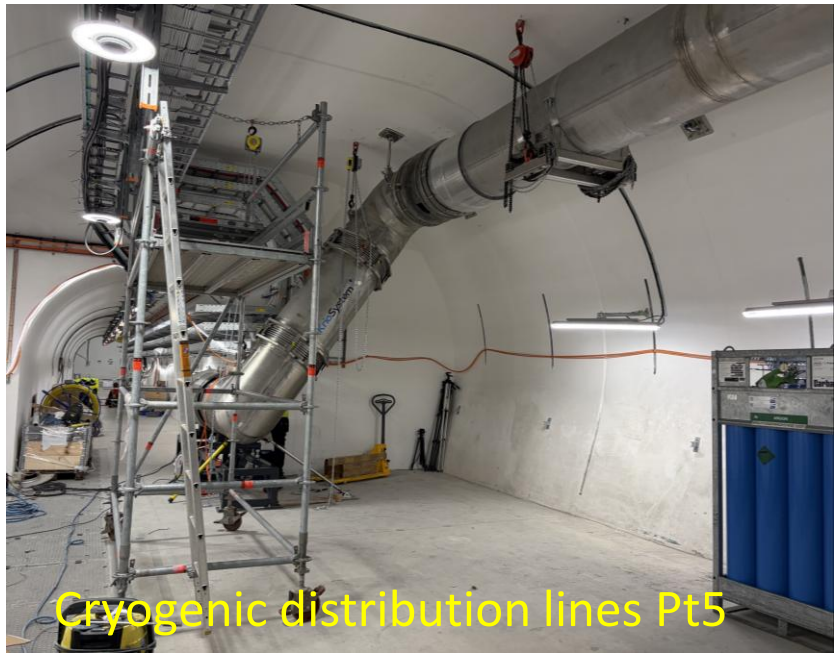






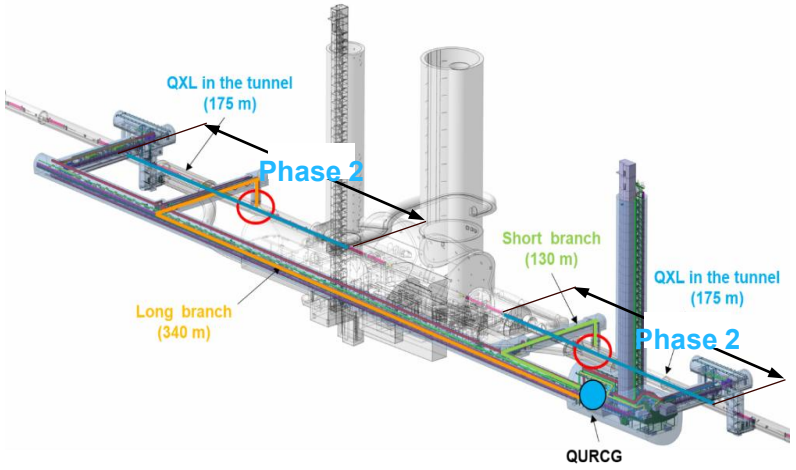
Cryogenic distribution line installations in new galleries


Cryogenic distribution lines Pt1


Cryogenic distribution lines Pt5

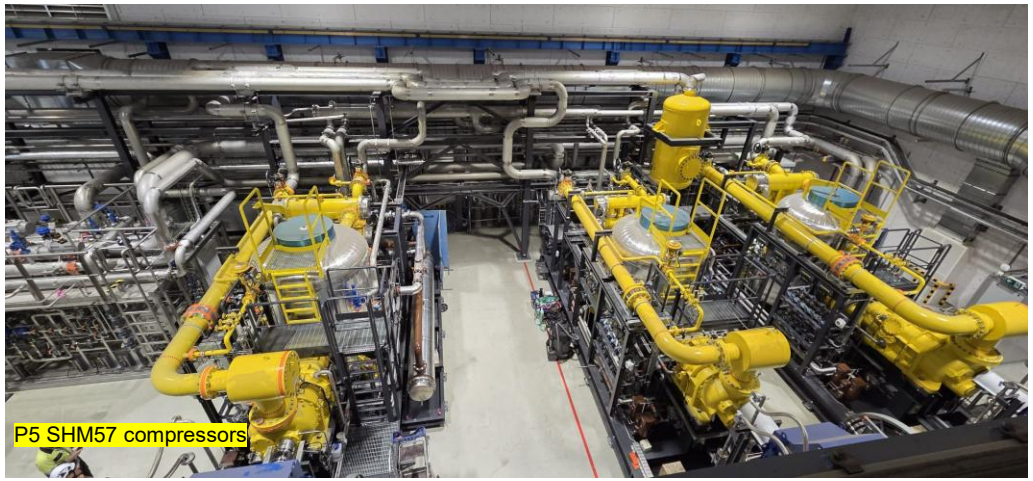

Phase 1 A-2 installation completed in Pt1, and pressure tests done Leak test of the long branch ongoing


installation of Z-pieces in UL57



Video: Pt1 Refrigeration system installation

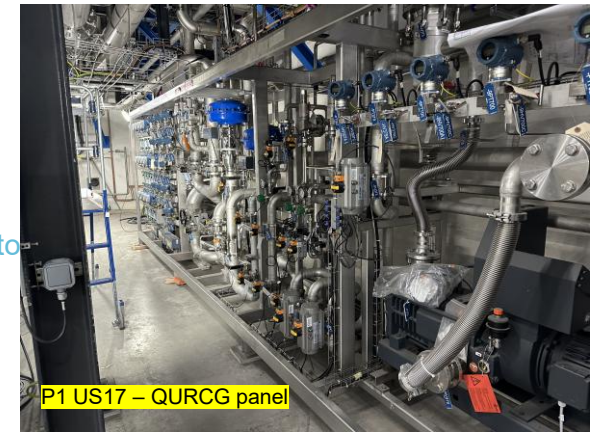
Refrigerator Installation quasi completed, commissioning ongoing


P5 SHM57 compressors


P5 US57 QURCG @P5


P1 QPLG

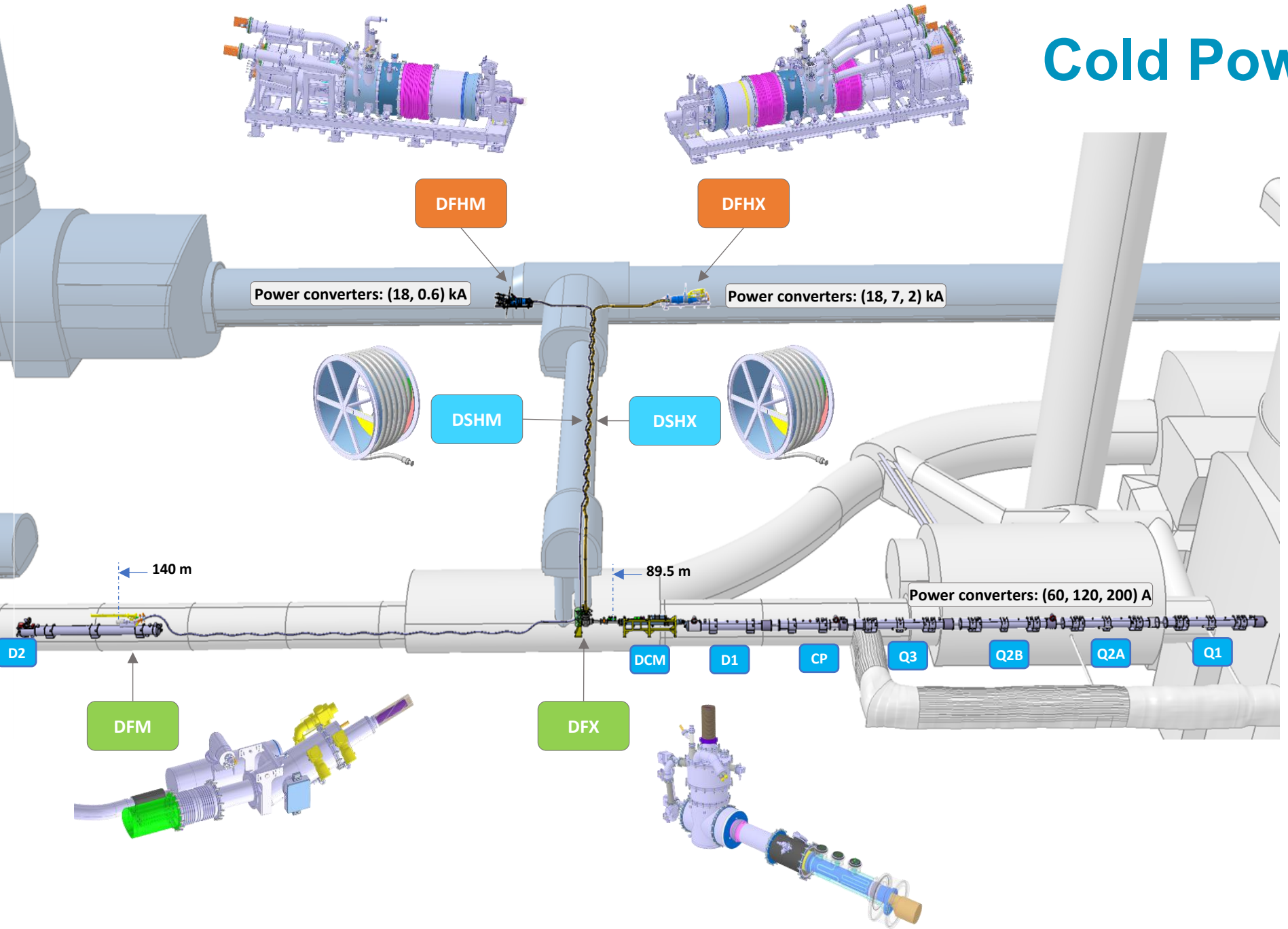

P1 US17 – QURCG piping and QPLG


P1 US17 – QURCG panel


P1 SD 17 QSRG

Video: Pt1 Refrigeration system installation

Cold Powering System



Requires transport of over 100kA over a distance of ca. 100m

➔ Requires a superconducting powering system to avoid excessive Ohmic losses

Validation of complete Superconducting link system in 2024

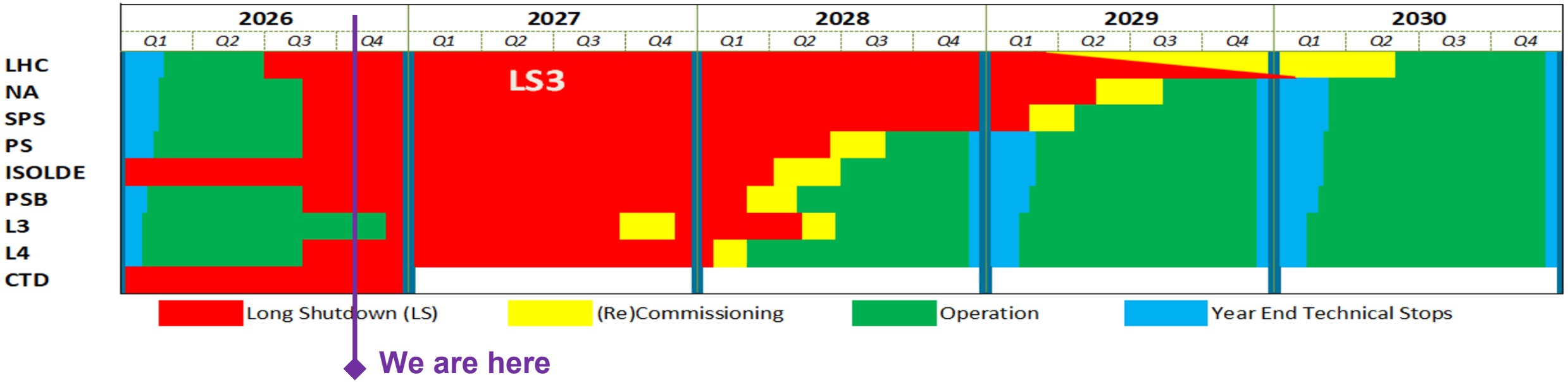
The flexible, double-wall, corrugated cryostat comprises 19 MgB_2 superconducting cables in a single assembly, twisted together to form a compact bundle. These 19 superconducting cables can transfer altogether a DC current of about 120 kA at ~20 K.





Protective insulation - 13 kA

LS3 started for [almost] all accelerators by now



LS3 start

- CTD: 02.06.2025 ✓
- ISOLDE: 08.12.2025 ✓
- LHC: 29.06.2026 ✓
- Injectors: 31.08.2026 ✓
- L3: 30.11.2026

Injectors Operation restart

- L4: March 2028
- PSB: May 2028
- PS: Aug 2028
- SPS: April/May 2029

LHC restart

- 1st sectors cooldown: Early 2029
- Final HW Com (P1&5): January 2030
- Caverns closure: Mid May 2030
- Beam valves opening: End May 2030

NA stands for North Area, CTD for CNGS Target area Dismantling

HL-LHC LS3 Schedule: 47 very busy months

Long Straight Section [LSS] dismantling after cryo lockout

Cabling dismantling

Core excavation (LHC side)

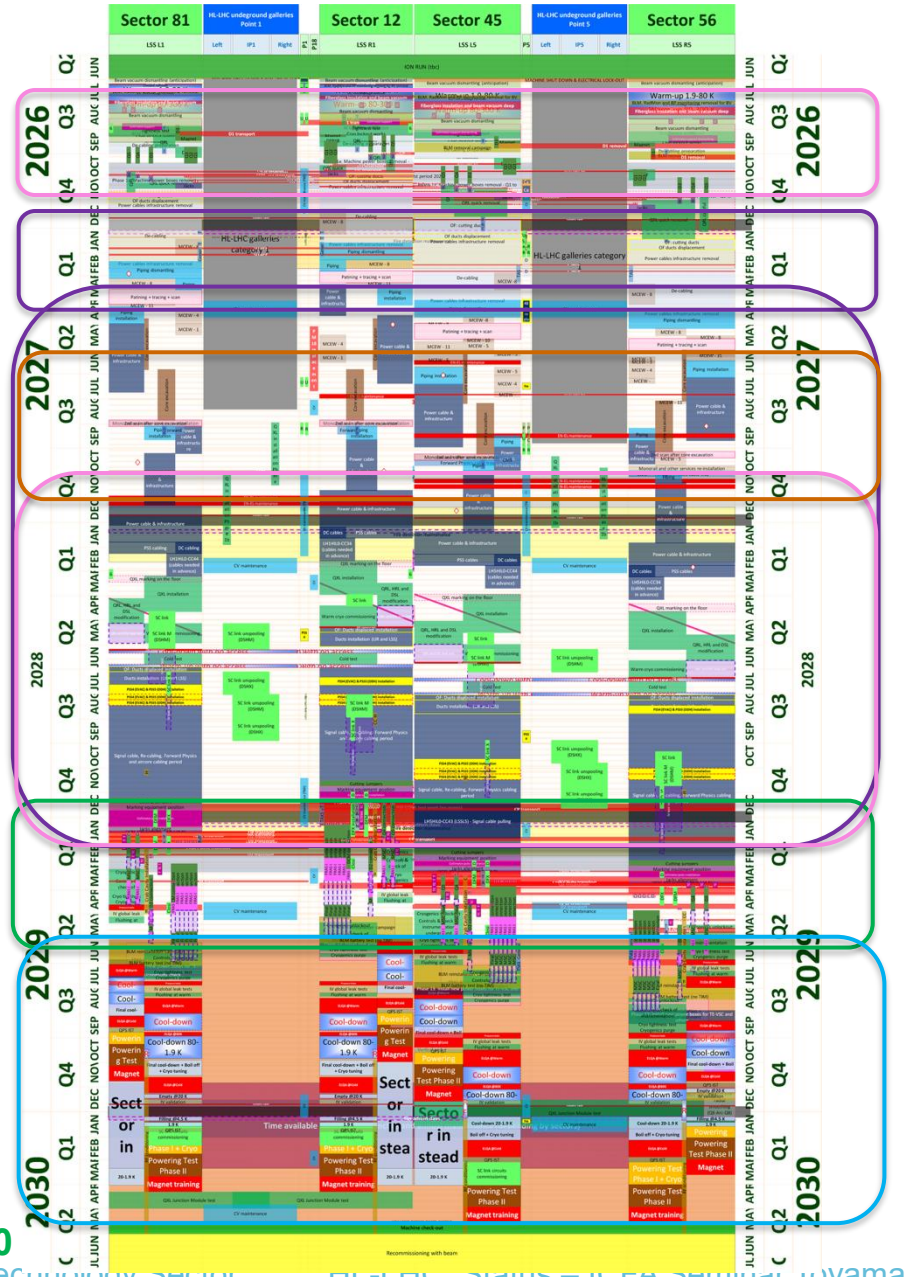
Cabling installation

New Long Straight Section installation

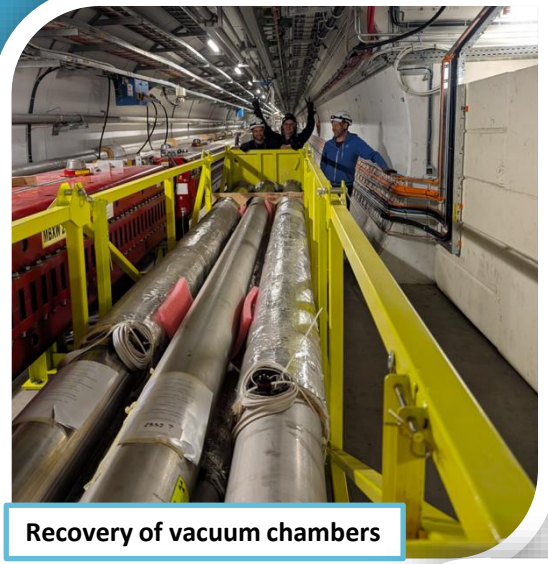
Triplet installation planned for Q1 to Q2 2029

CC installation planned for Q4 ‘28 to Q2 ‘29

Cool-down, related tests and Hardware Commissioning

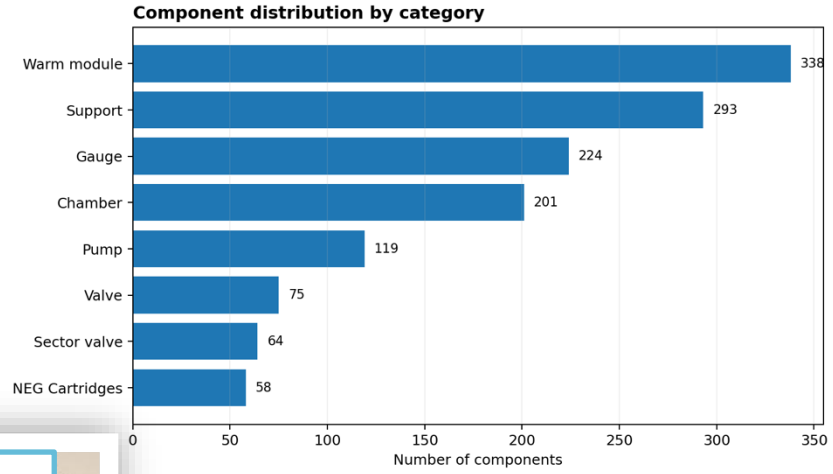


4 months in - Excellent start into LS3: Beam vacuum dismantling



Recovery of vacuum chambers

Total components	Total length [m]
1372	≈890 m





Sector Valves Assembly



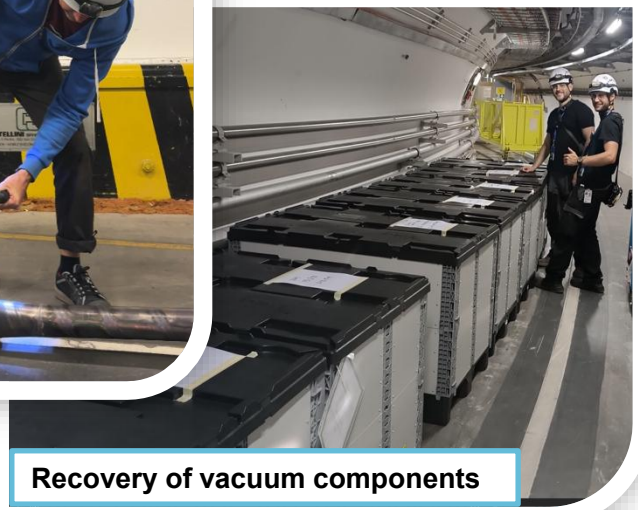
Empty Tunnel



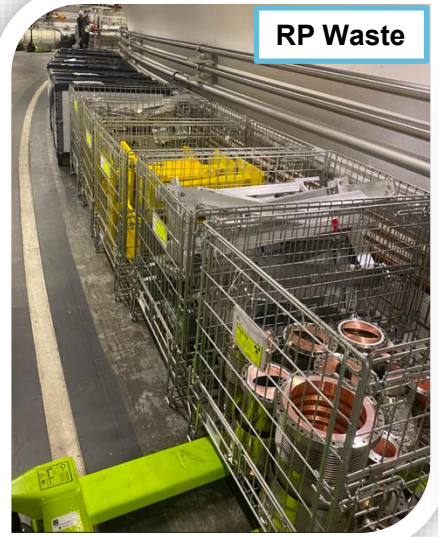
Recovering Parts



Cutting Chambers



Recovery of vacuum components



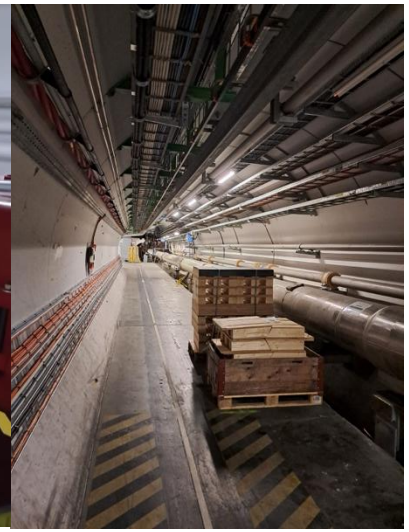
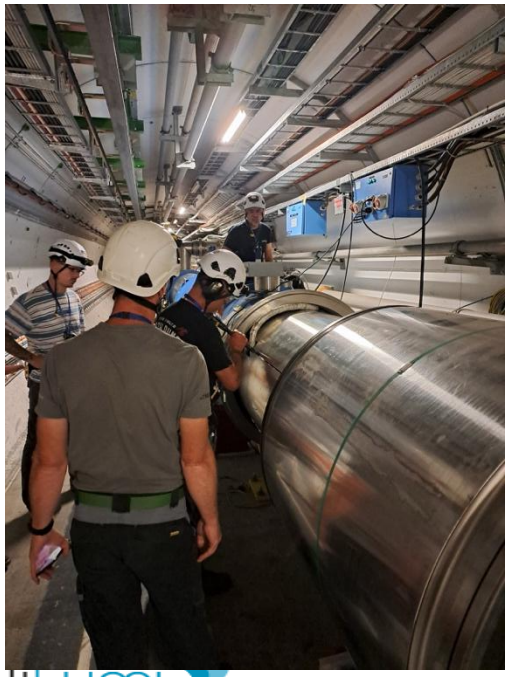
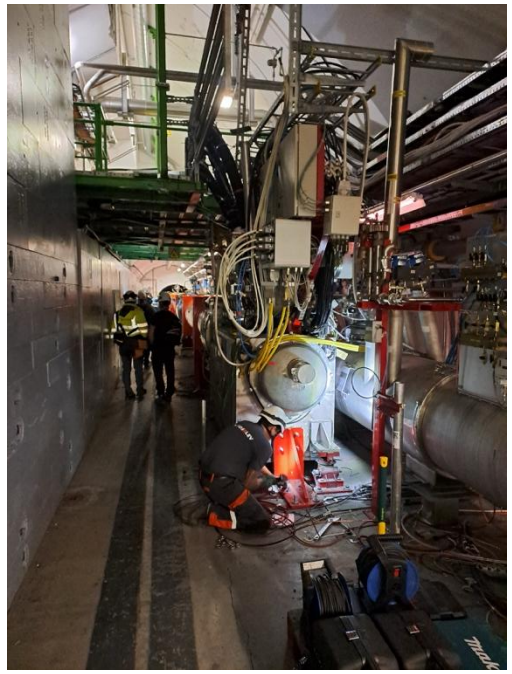
RP Waste

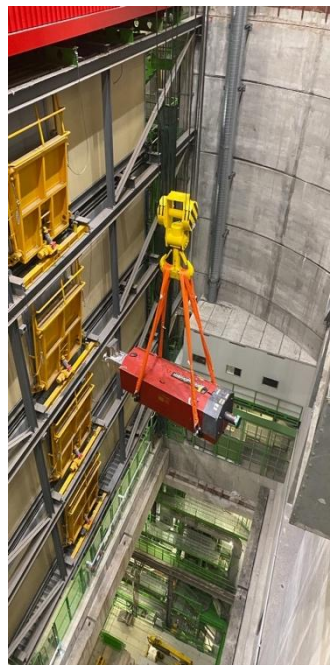
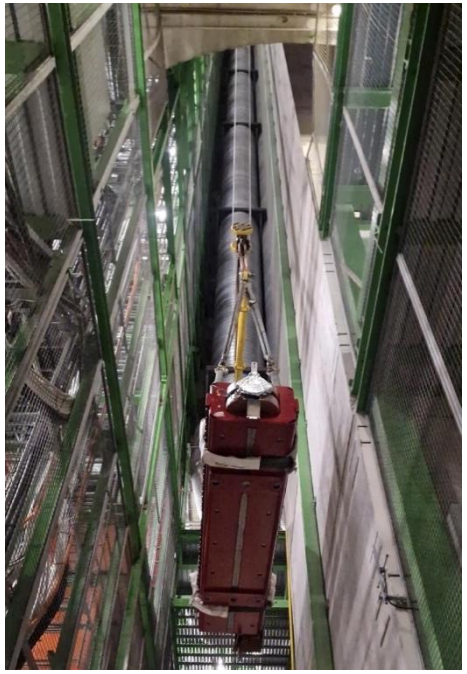


Heavy handling and logistic

4 months in - Excellent start into LS3: D1 and TAN removal

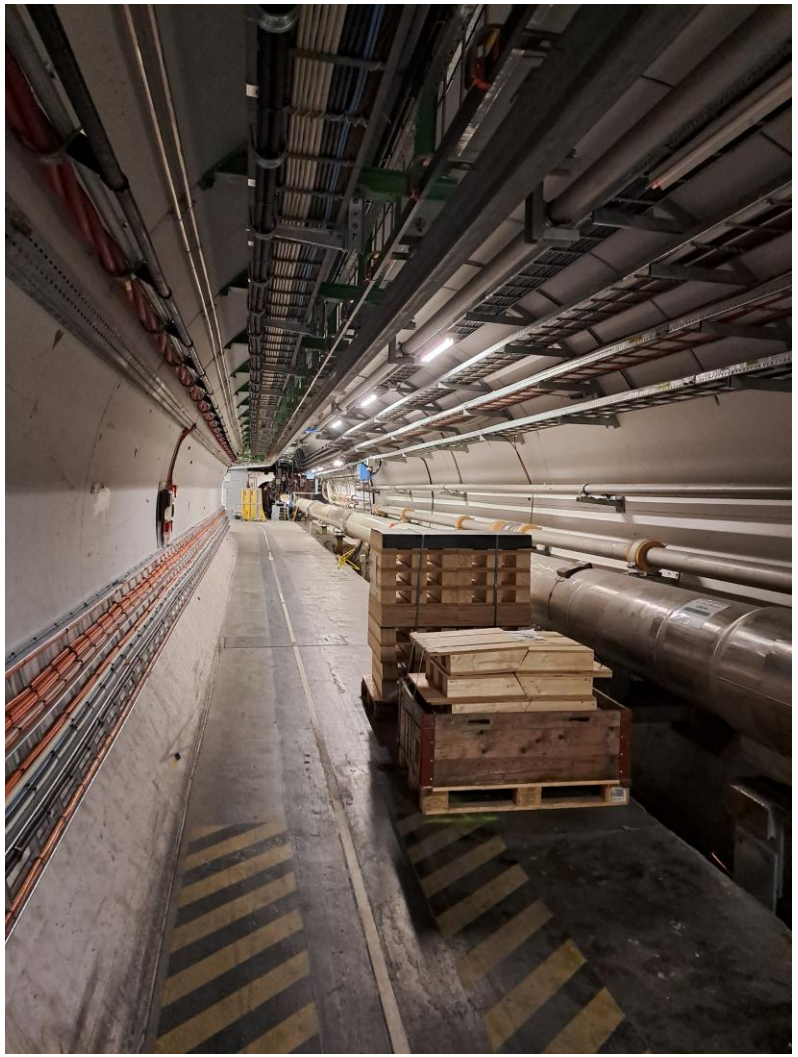


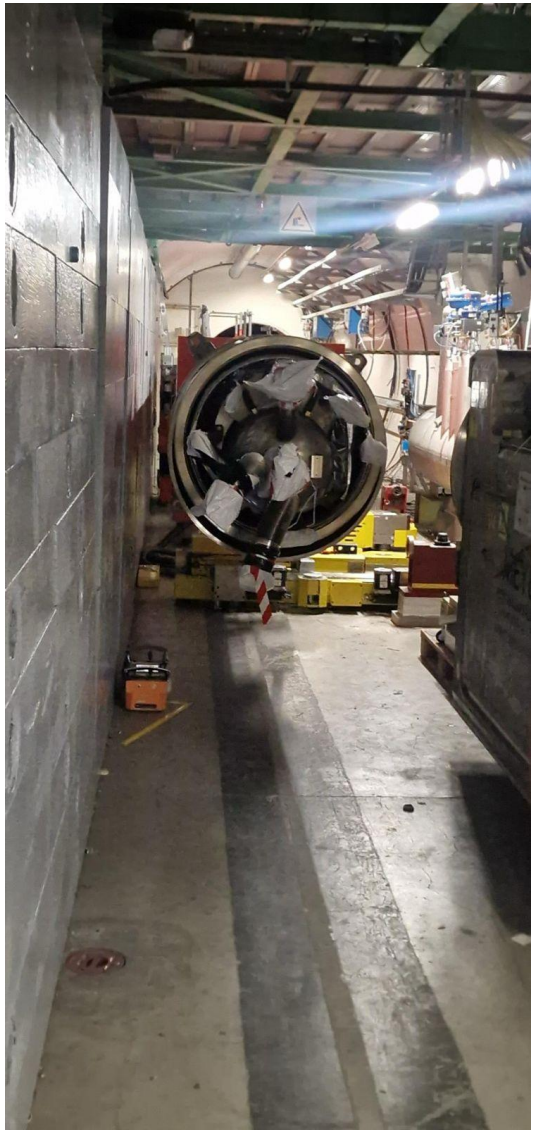
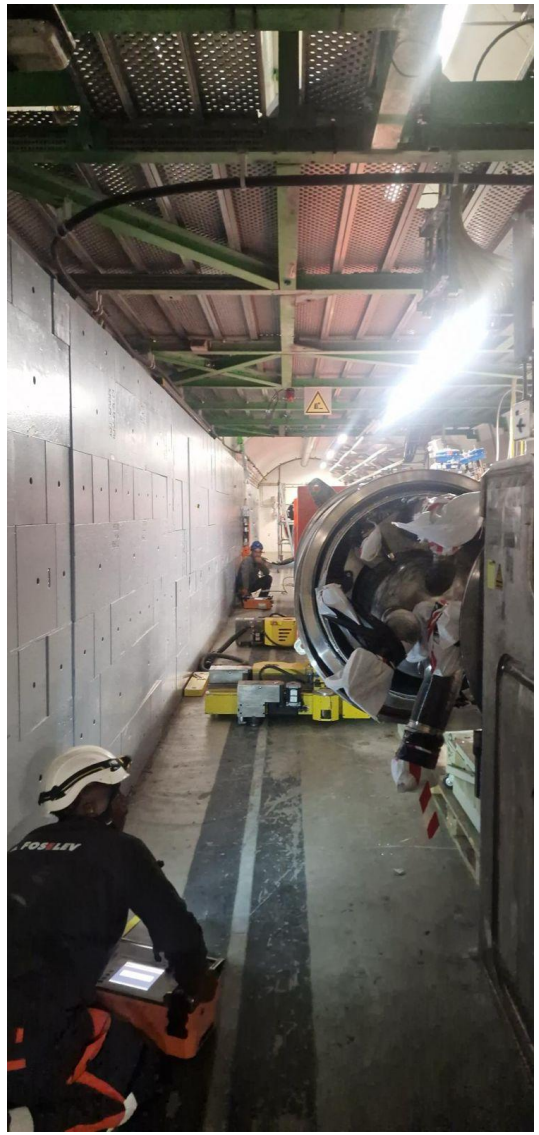
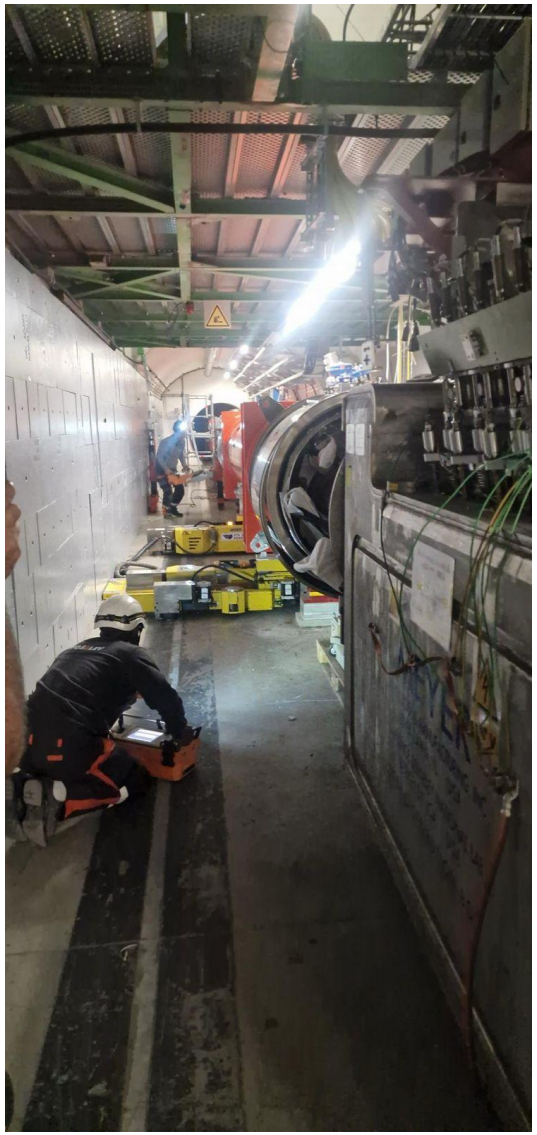



Start of de-installation of cold elements





De-installation of cold elements: first triplet magnet removal [Q3]

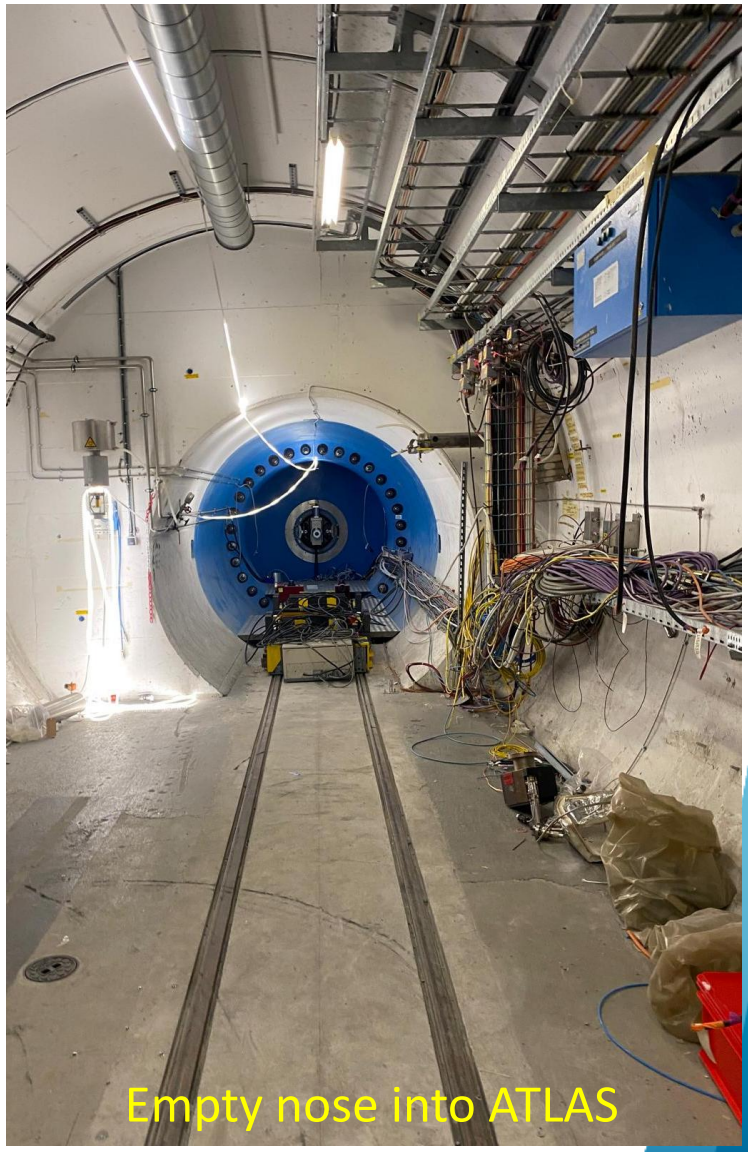
Cryo Distribution Line and complete Triplet removal


All hands on deck for the critical path!

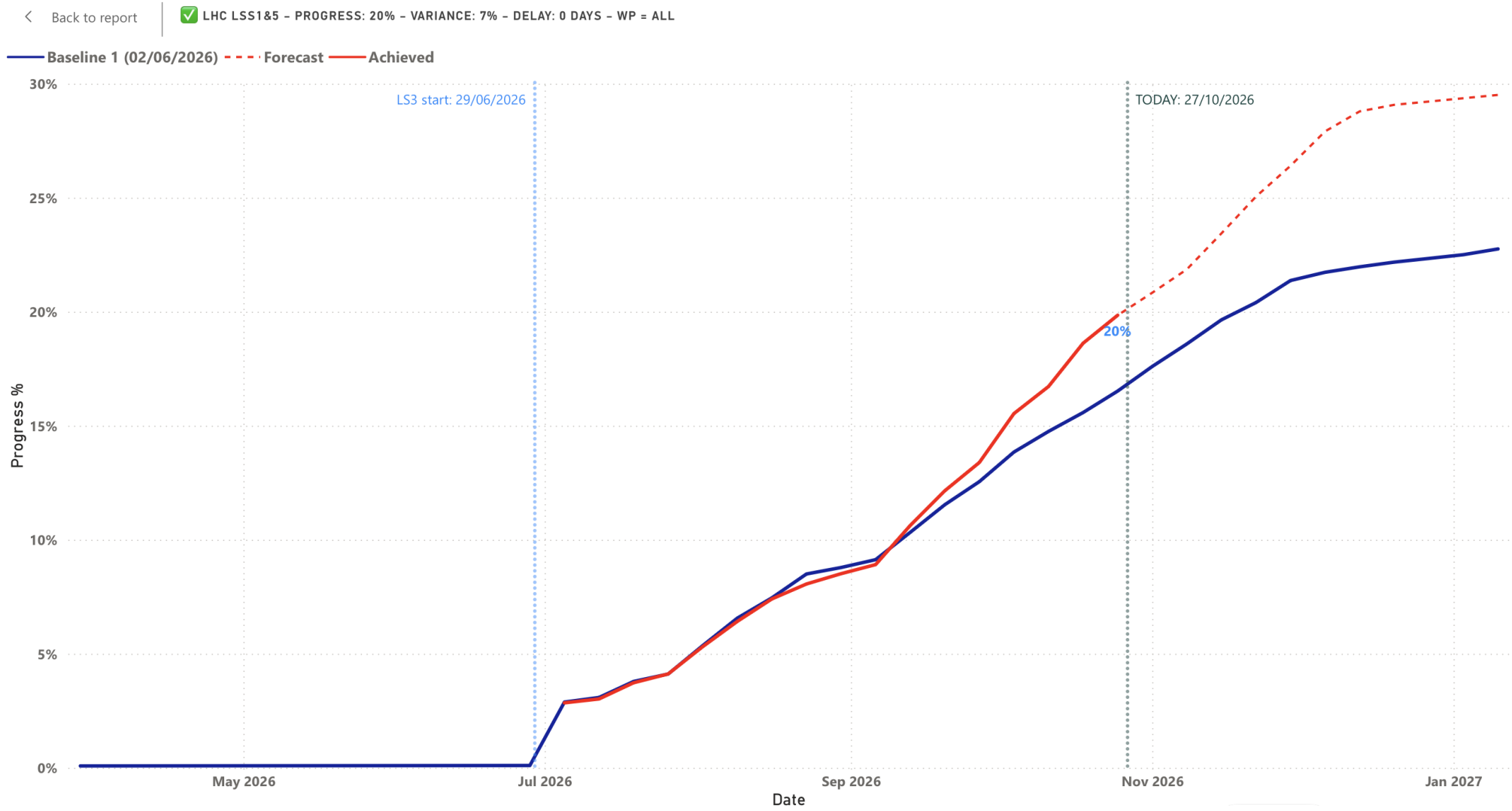

LSS after decabling and QRL removal



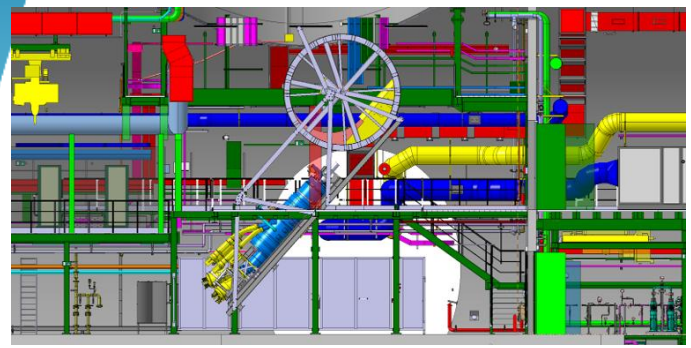
Removal of Q1

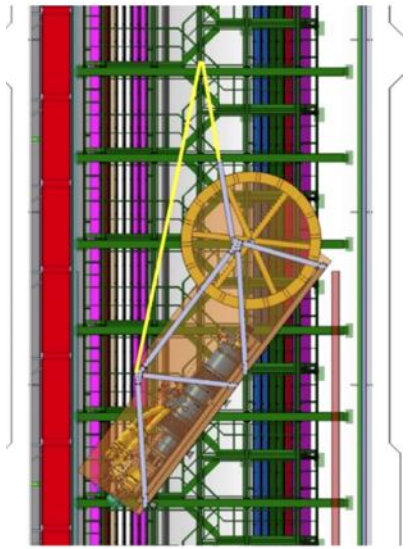

Empty nose into ATLAS

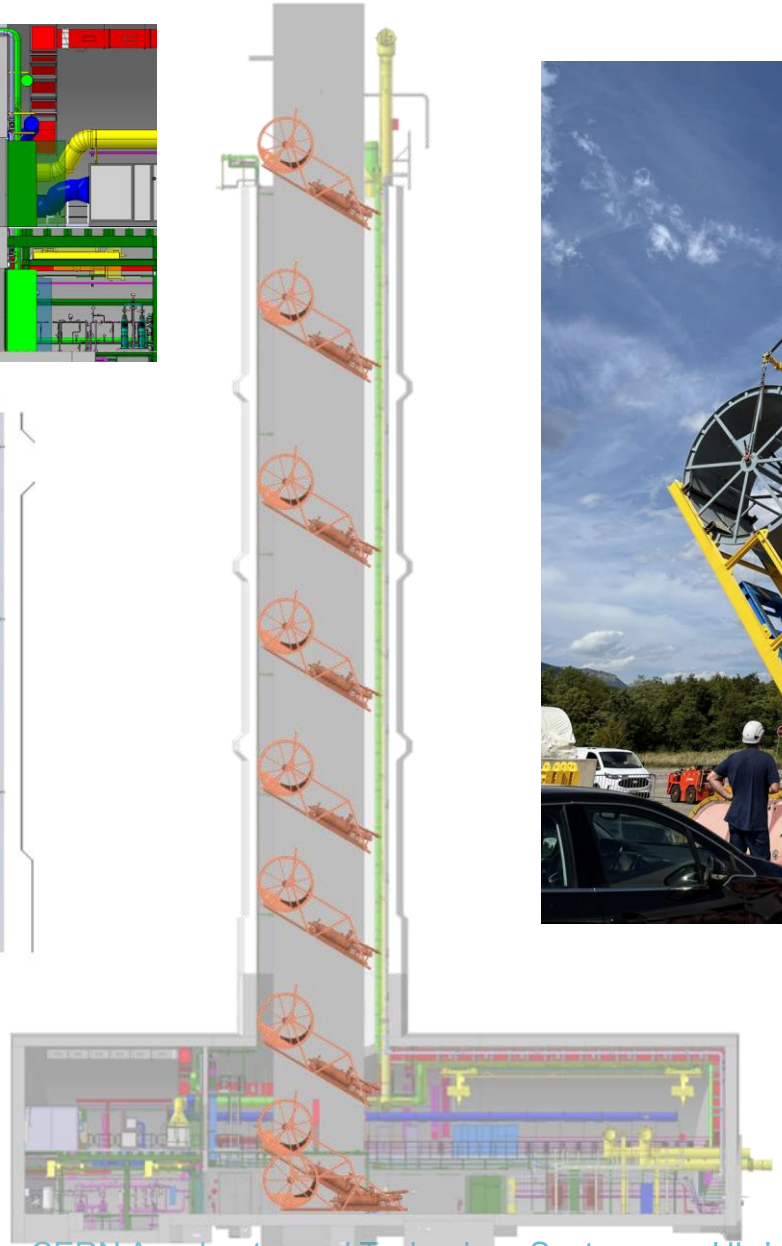
Dashboard Long Straight Sections Point 1 and Point 5



Increasing focus on Installation studies and trials







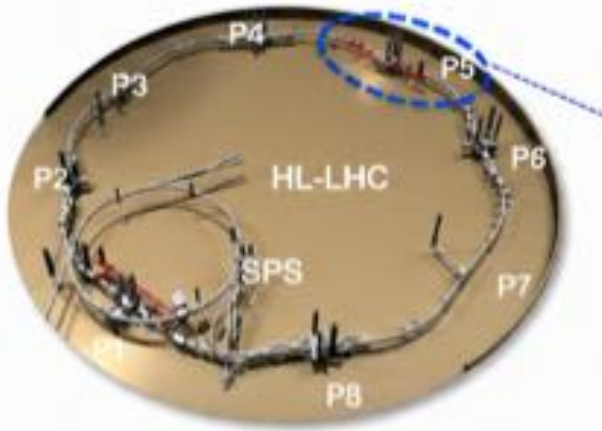




IT string Operation Highlights



> A key step towards the HiLumi era of the LHC is what we call the HL-LHC IT STRING: a full-scale test of the new superconducting magnets and powering systems including alignment systems.



POWERING TO TARGET WITHOUT TRAINING
RQX circuit reached target current without training.
Several 12 h plateaus of all combined circuits successfully achieved. Operation cycles completed and protection mechanisms worked as expected. MITs < 25 as designed.

POWER CONVERTERS STABILITY
Converters demonstrated excellent stability of 0.7 ppm over 12 h.

MAGNET MOTION UNDER POWERING
Controlled movement of magnets up to 100 µm while powering to nominal current was successfully performed.

CRYOGENIC PERFORMANCE DURING HIGH-ENERGY QUENCH
38 MJ of energy successfully dumped into the bath.
Cold mass pressure remained < 20 bara and maximum temperature reached 35 K.

RECOVERY OBSERVATION
Recovery time after highest-energy quenches is longer than initially predicted.



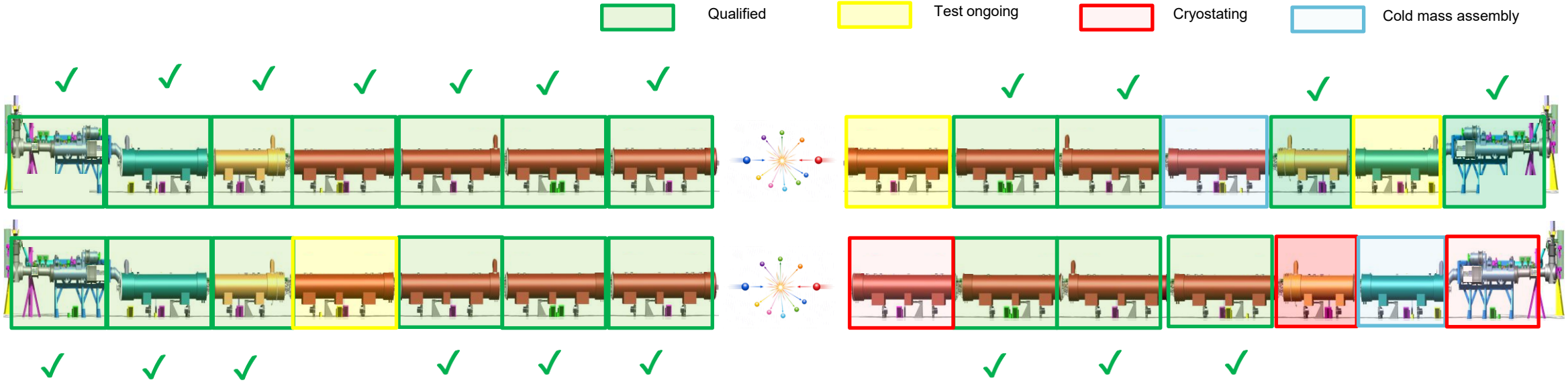
we are here



Phase 1 program completed ahead of schedule: second cooldown after TC completed

Magnet production and busbar systems

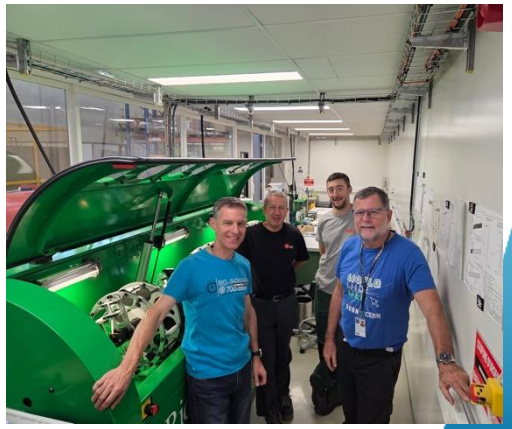
- The series production of the magnets for HL-LHC is approaching completion across the entire collaboration
  - All magnets required for HL-LHC installation that undergo vertical testing have now been qualified, and 70% of the cryo-assemblies containing new magnets have been completed.



Cable fabrication @ B163

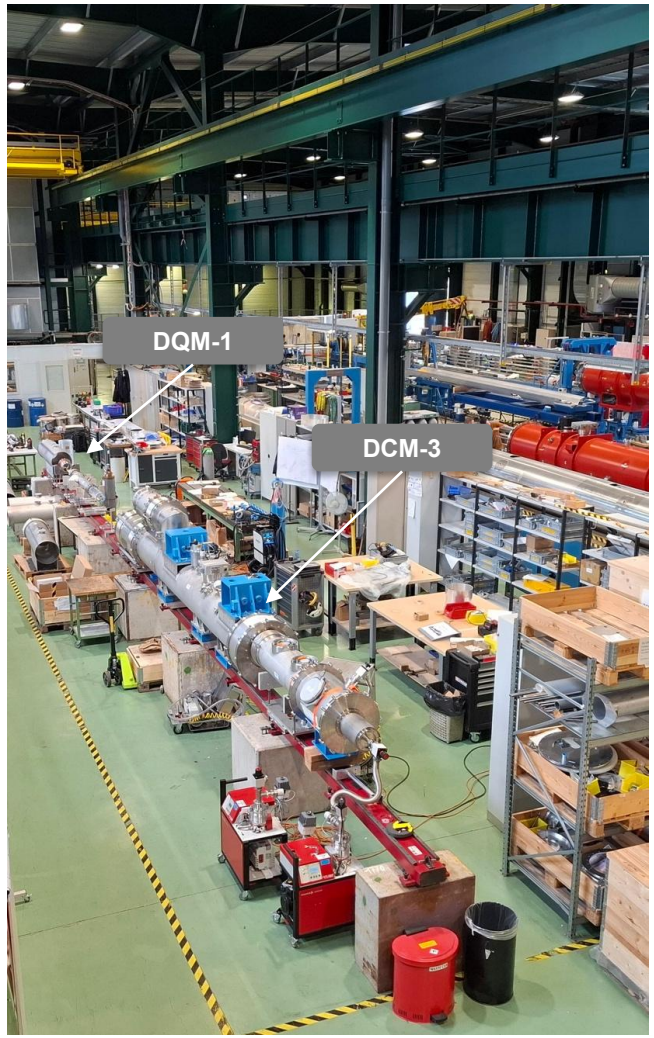


Cable insulation @ B180



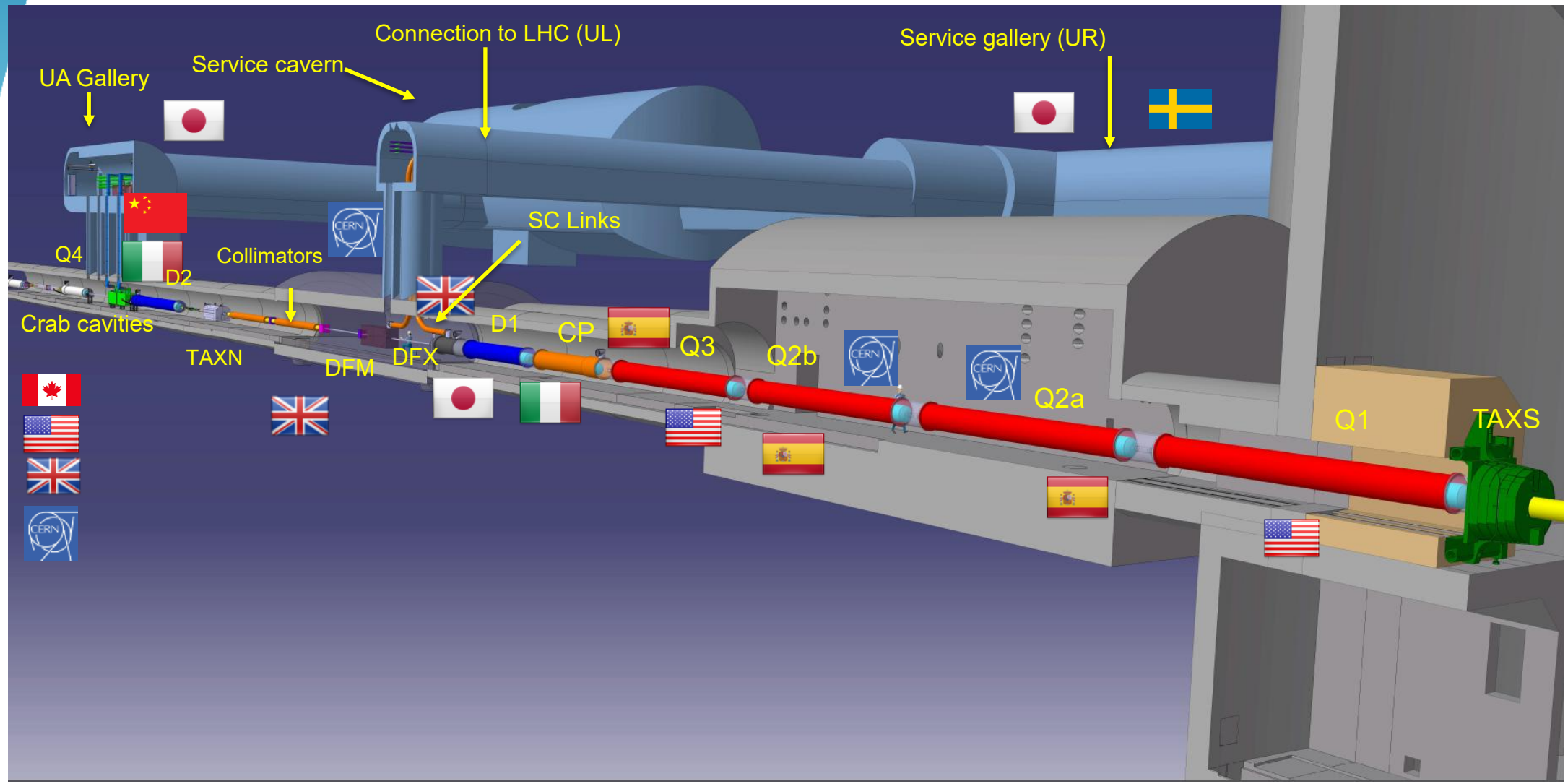
- Busbar system redesigned based on IT-String feedback.
  - Key features already implemented during the IT-String repair → Positive results so far: system performs as expected
  - Production on track:
    - Cable produced and insulated at CERN
    - Mock-ups ongoing to optimize routing and line conditioning

Magnet Cryostating in full swing [SMI2] for testing and installation





International Collaboration with in-kind contributions are at the heart of the HL-LHC project

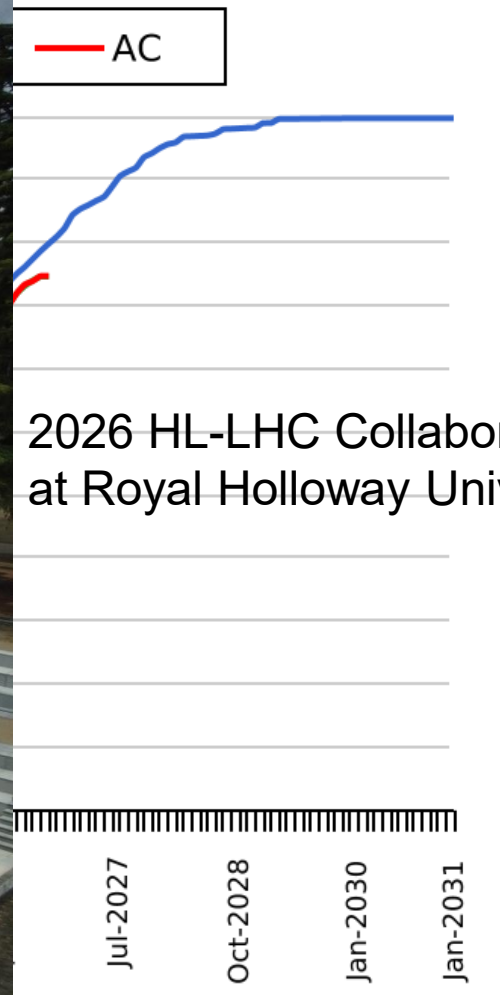






In-kind contributions to the HL-LHC project





2026 HL-LHC Collaboration meeting
at Royal Holloway University near London

Asia and Europe

Schedule Critical Components: HL-LHC Crab Cavities [2 types]

- First series **DQW** cryomodule jointly done by UK-STFC & CERN in SM18 for cold test
  - DQW cavity testing on track for the next cryomodules and second cryomodule advancing well at UK-STFC
- First series **RFD** cavity tested at TRIUMF, cryostating to start. Remaining cavities at different stages of fabrication & testing [AUP]
  - **Cryo-stating at TRIUMF delayed by about 1 year**
  - CERN mitigation: production of 2 cryomodules at CERN
  - **It fits into the schedule, but no margins left!**
- High power RF components acceptance tests being finalized and series components delivery underway
- Faraday cages Point 1 & 5 installed, services being finalized



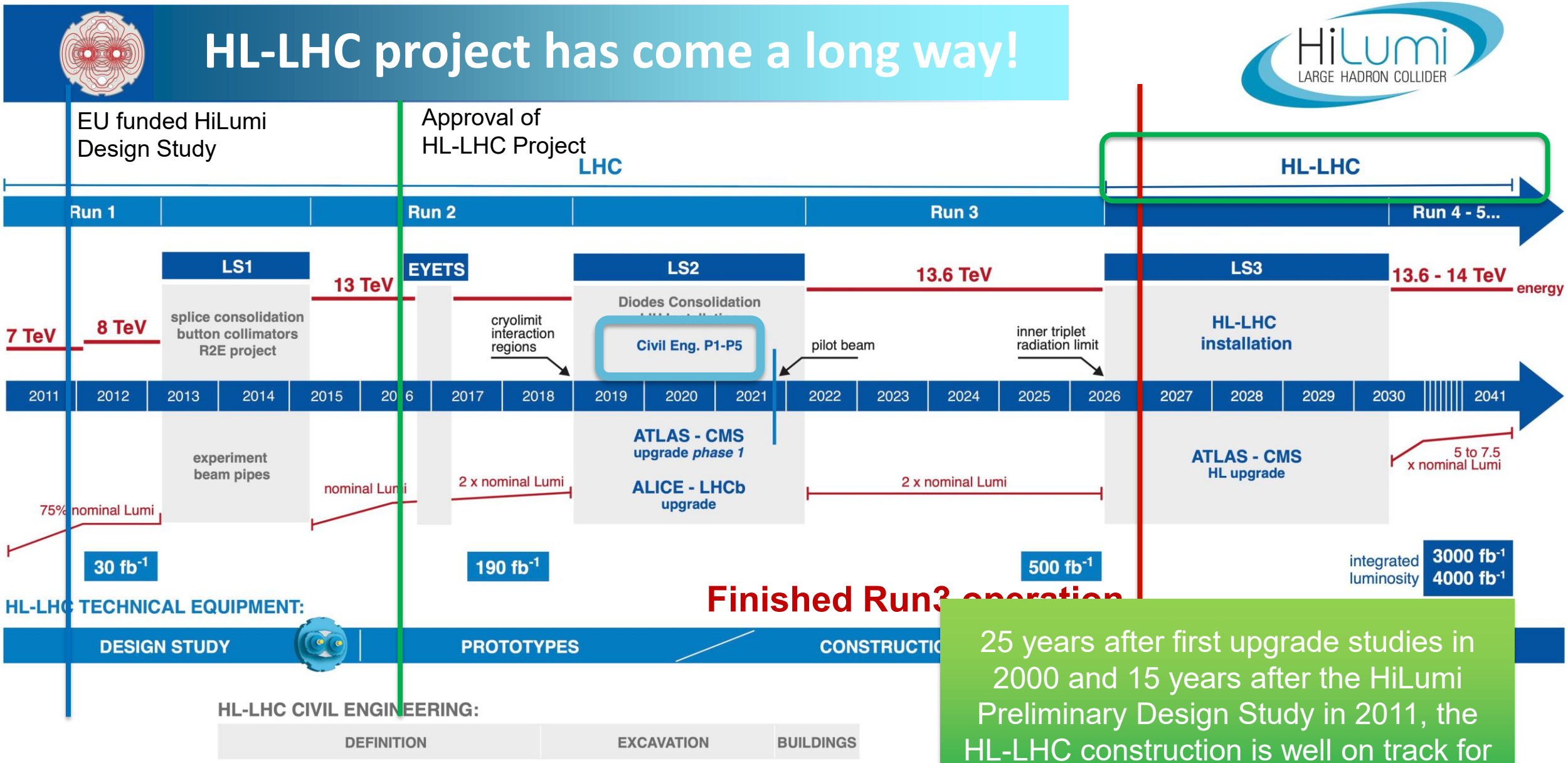
THALES IOT trolley



Faraday cage (LHC-P5)



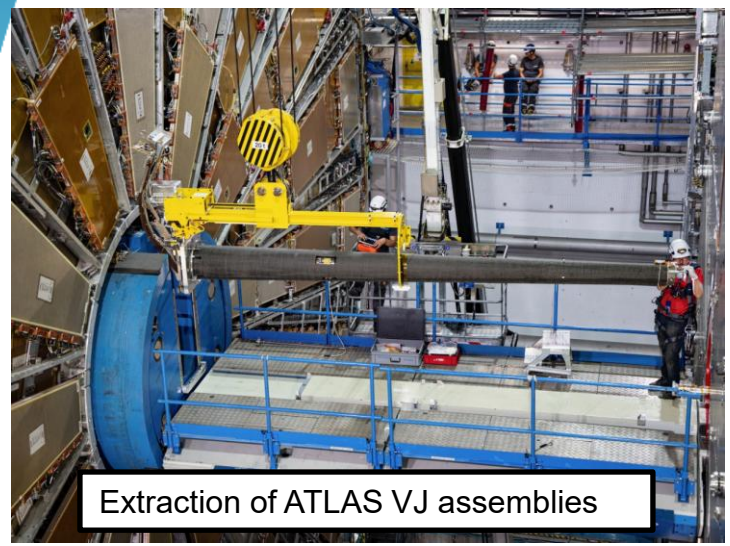
HL-LHC project has come a long way!



Finished Run3 operation

25 years after first upgrade studies in 2000 and 15 years after the HiLumi Preliminary Design Study in 2011, the HL-LHC construction is well on track for start of operation in 2030

Beam Vacuum activities on the Large Experiments



Extraction of ATLAS VJ assemblies



Decoupling of the CMS forward region



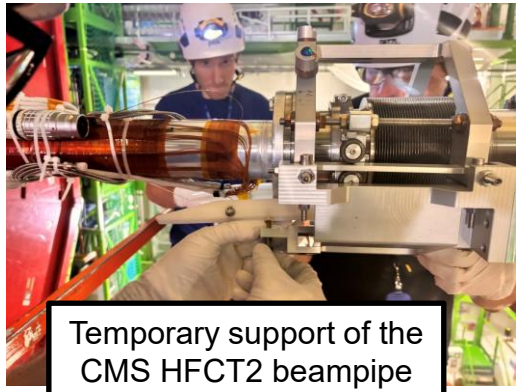
RB24 vacuum chambers quitting the ALICE Miniframe



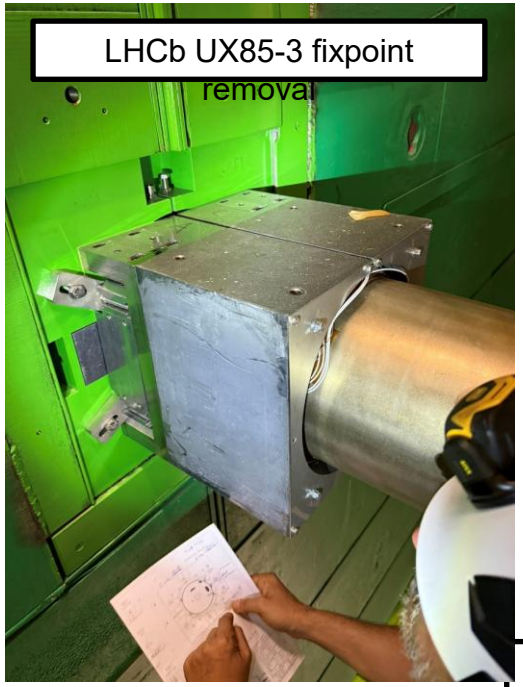
Removal of CMS central chamber supports



Beampipe protections in LHCb



Temporary support of the CMS HFCT2 beampipe



LHCb UX85-3 fixpoint removal

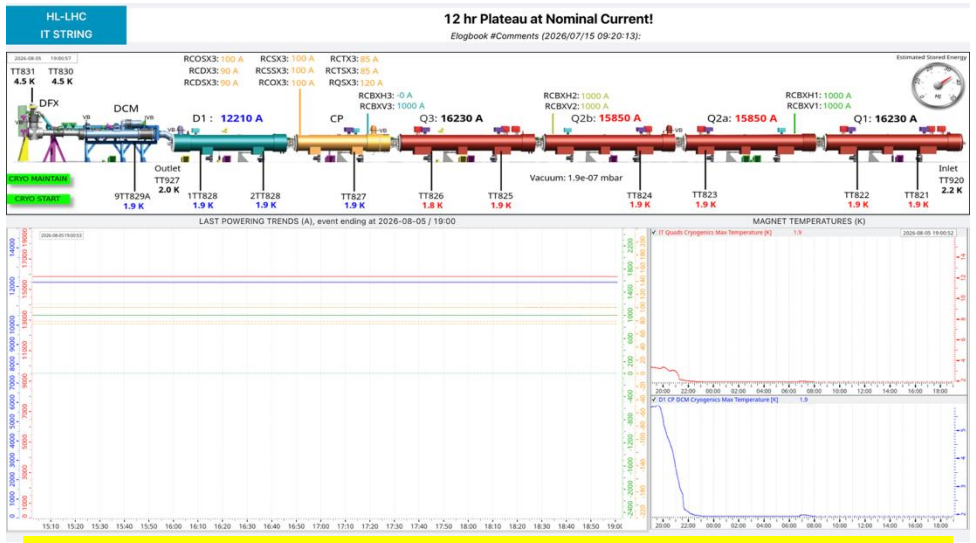


Dismantling of ALICE sector valve

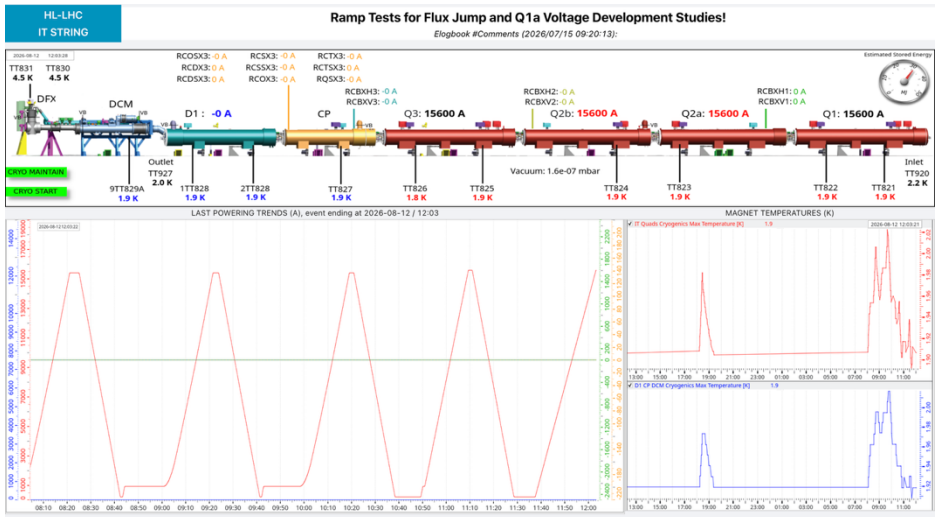


Extraction of CMS HFCT2 chamber

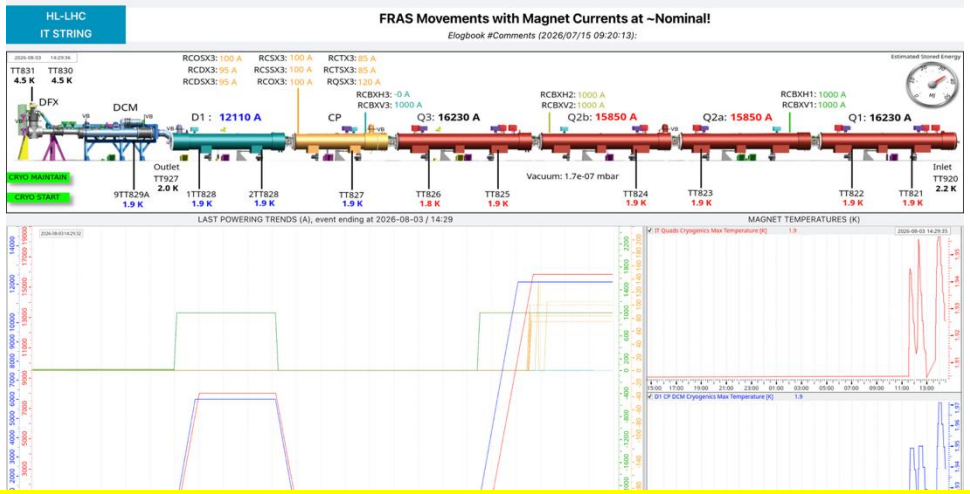
HL-LHC IT STRING – Powering tests in Phase 1



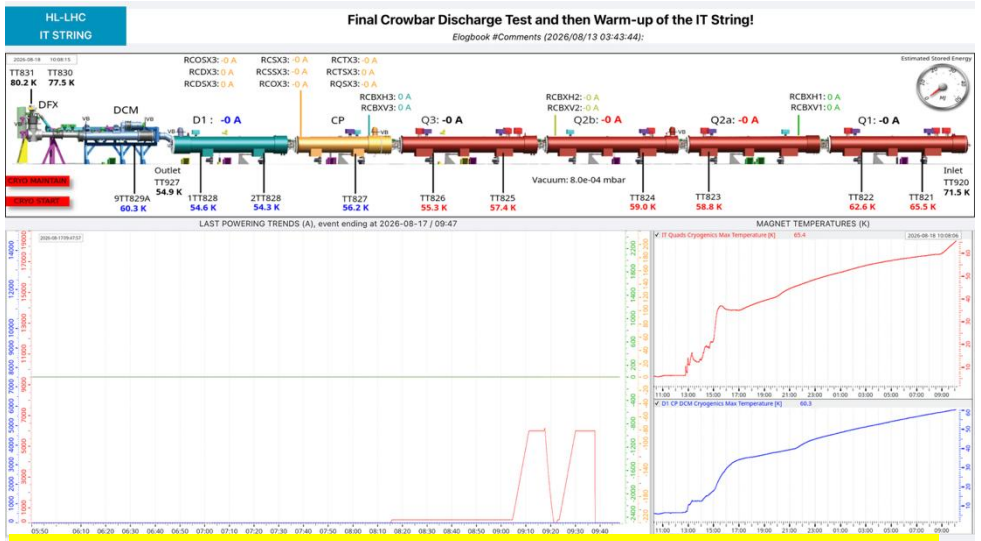
12 hours on Grouped Circuits at Target Current



Ramp Tests for Flux Jump and Q1a Voltage Development



FRAS Movements at Nominal Current with Vertical and Radial Movements at 100 um - No quench observed and no pick-up on the QDS signals

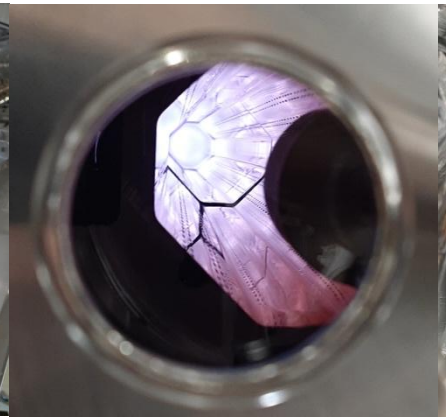


Warm-up of the IT String

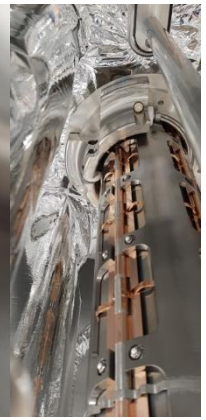
HL-LHC Beam Screen Production & Integration



Assembly



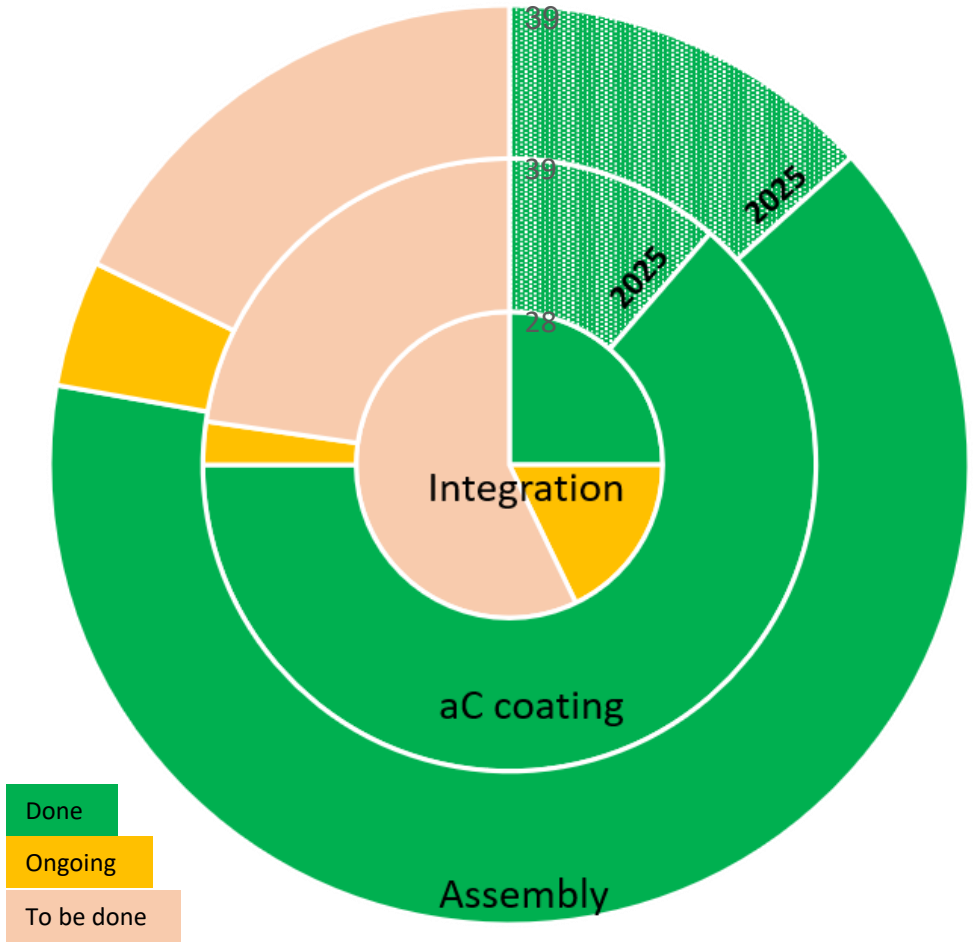
aC coating



Insertion

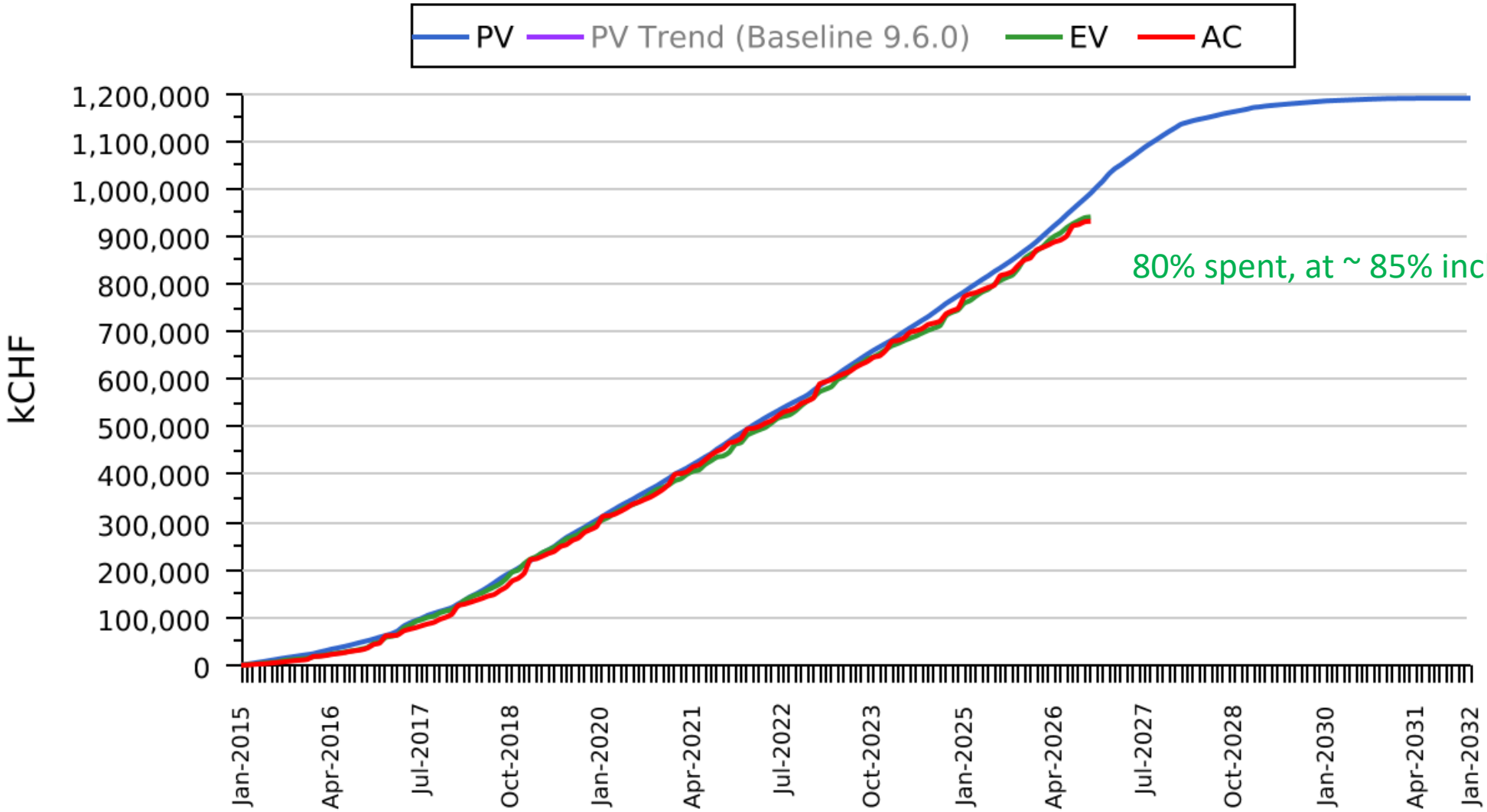


Beam screen integration completed in one corrector package and six final focusing magnets



Progress since 2025 HL-LHC collaboration meeting

EVM status of HL-LHC project –BL 9.6.0



80% spent, at ~ 85% incl commitments

~109.3 MCHF (September 2026) from North America, Asia and Europe