



HL-LHC - status of preparation

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LHCP
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HL-LHC - goals

Prepare machine for operation beyond **2025 and up to ~2040**

Operation scenarios for:

- Total integrated luminosity of **3000 fb⁻¹** in around 10-12 years
- An integrated luminosity of **~250 fb⁻¹ per year**
- **Nominal:** levelled luminosity of **5 x 10³⁴ cm⁻²s⁻¹** (events/crossing ~130)
- **Ultimate:** levelled luminosity of **7.5 x 10³⁴ cm⁻²s⁻¹** (events/crossing ~200)

Higher Intensity

Increase bunch population

$$\mathcal{L} = \frac{N^2 f_{rev} k_c}{4\pi \beta^* \epsilon_{xy}} F$$

Smaller β^*

Reduced emittance

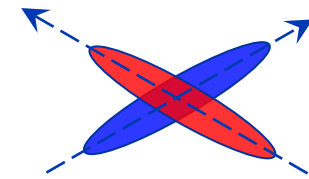
Smaller beam size at IP

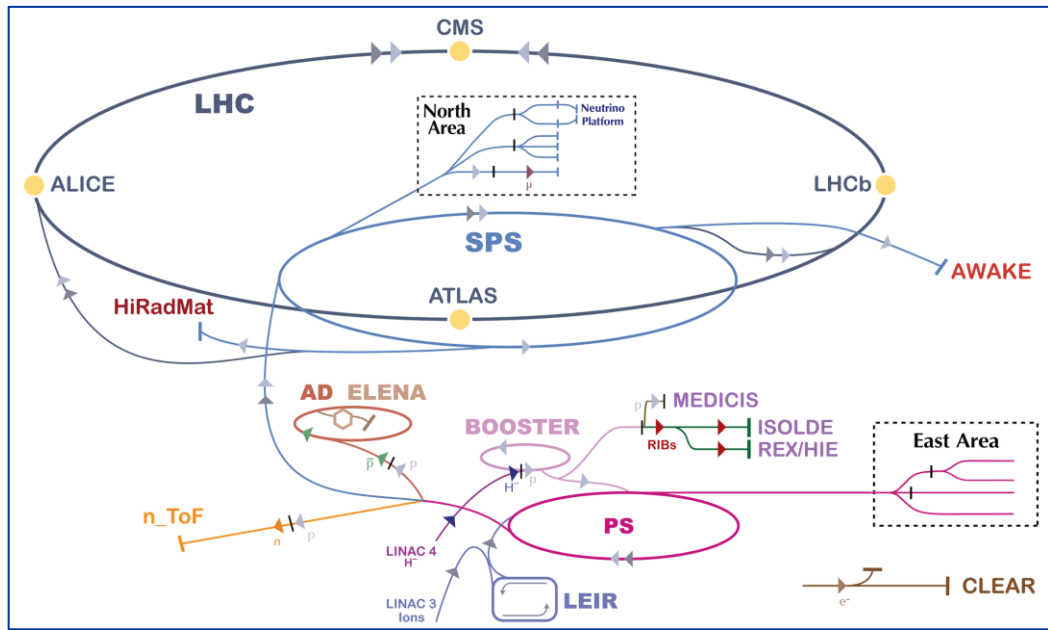
Increase F

Crossing angle reduction factor

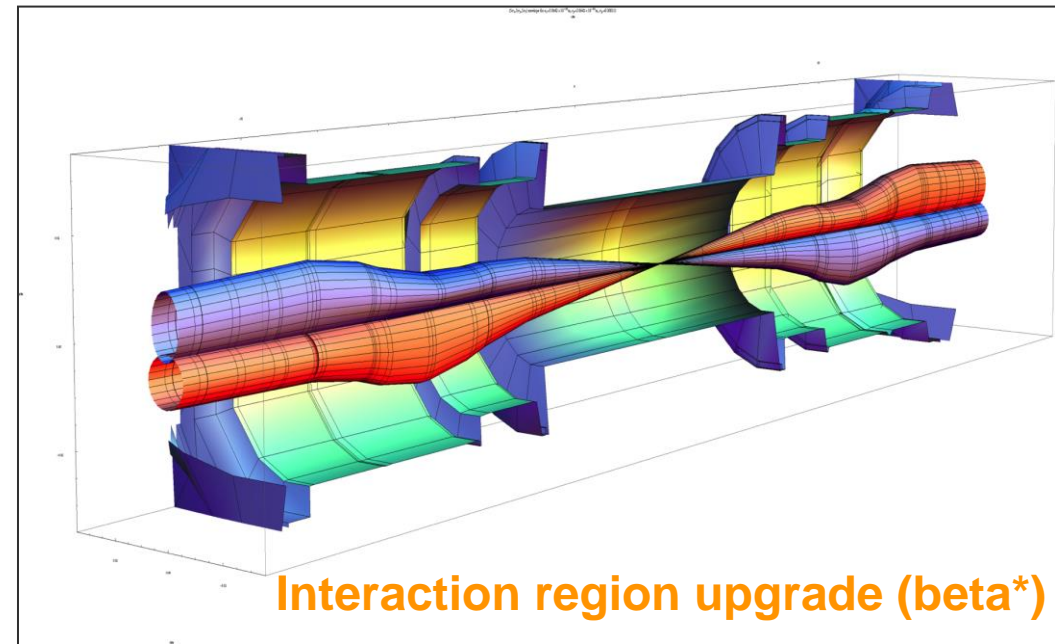
$$\frac{1}{\sqrt{1 + \left(\frac{\sigma_s \phi}{\sigma_x} \frac{\phi}{2}\right)^2}}$$

Shorter bunches, smaller crossing angle, **crab cavities**

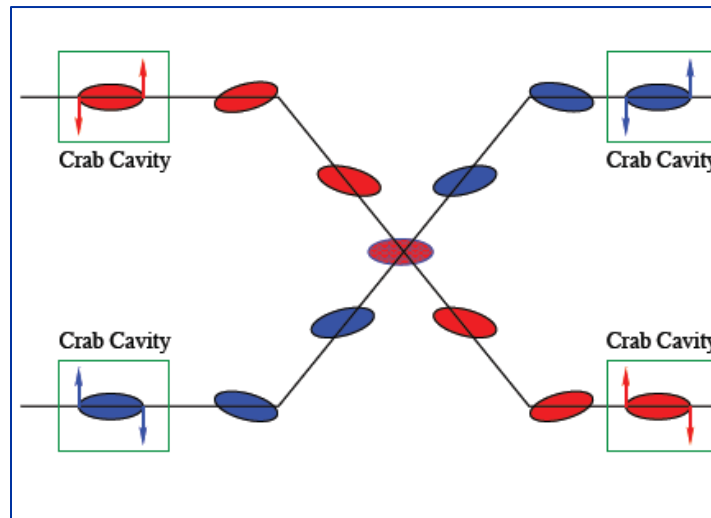




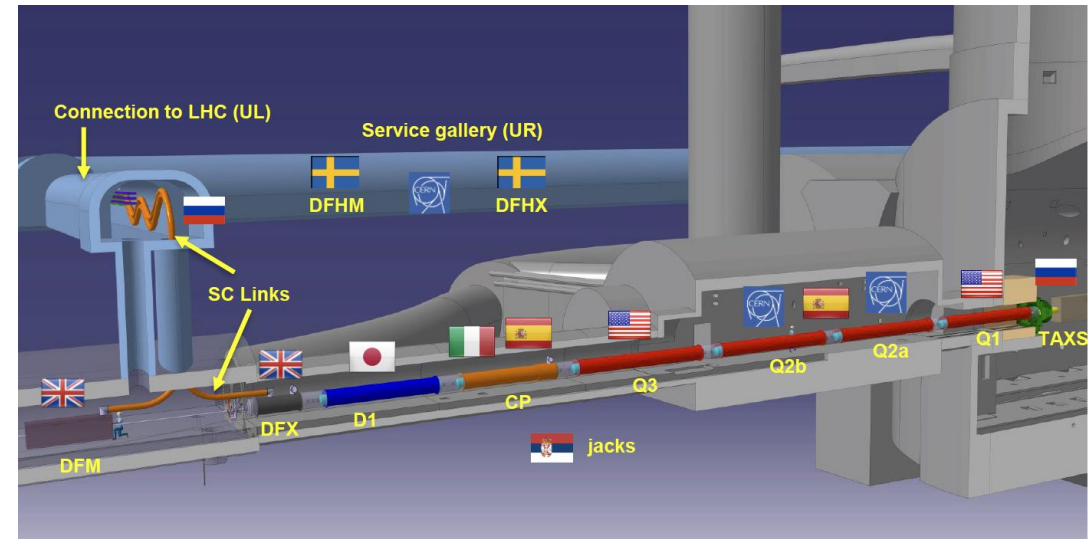
Injector upgrade (bunch population, emittance)



Interaction region upgrade (beta*)

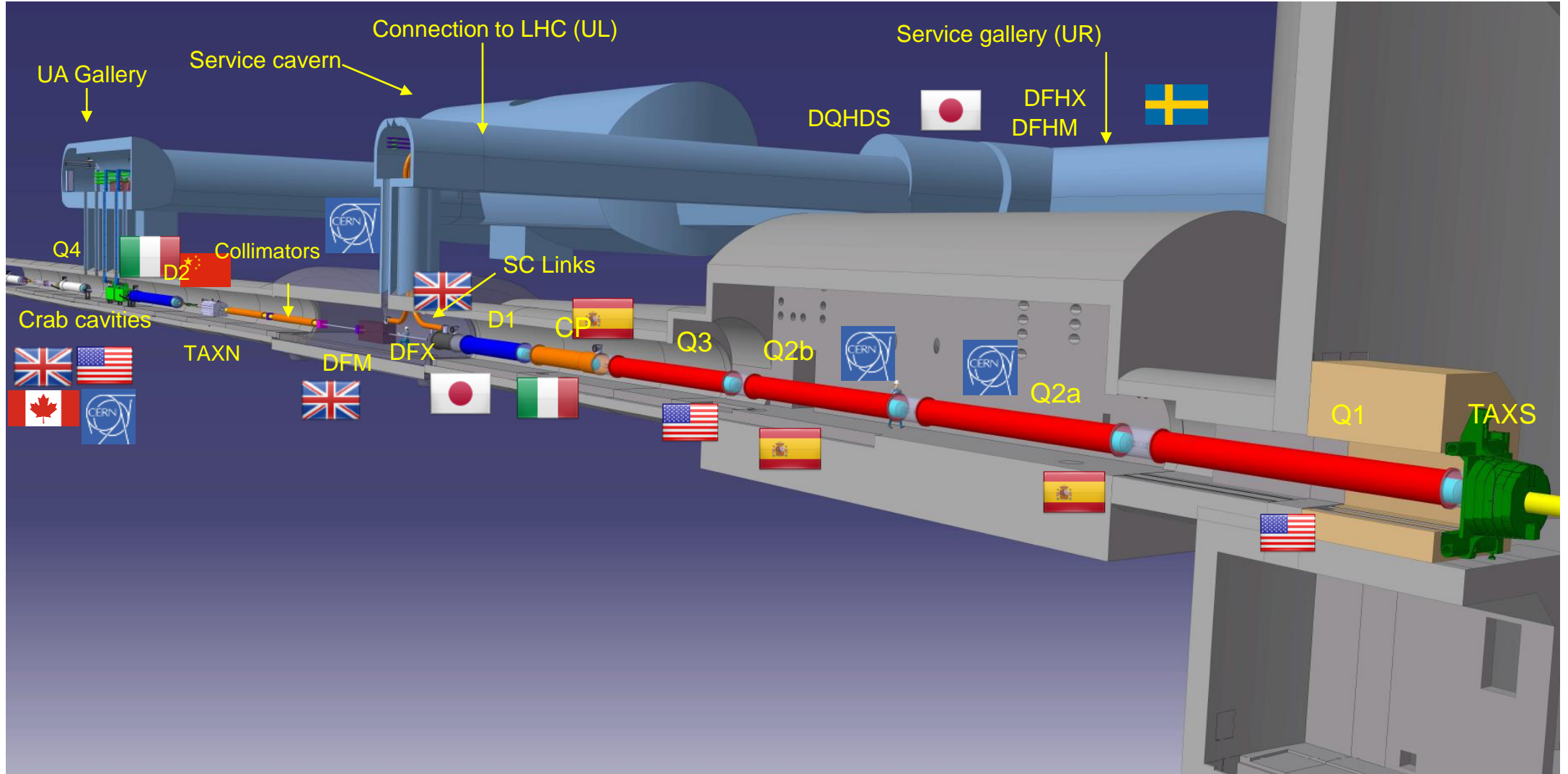


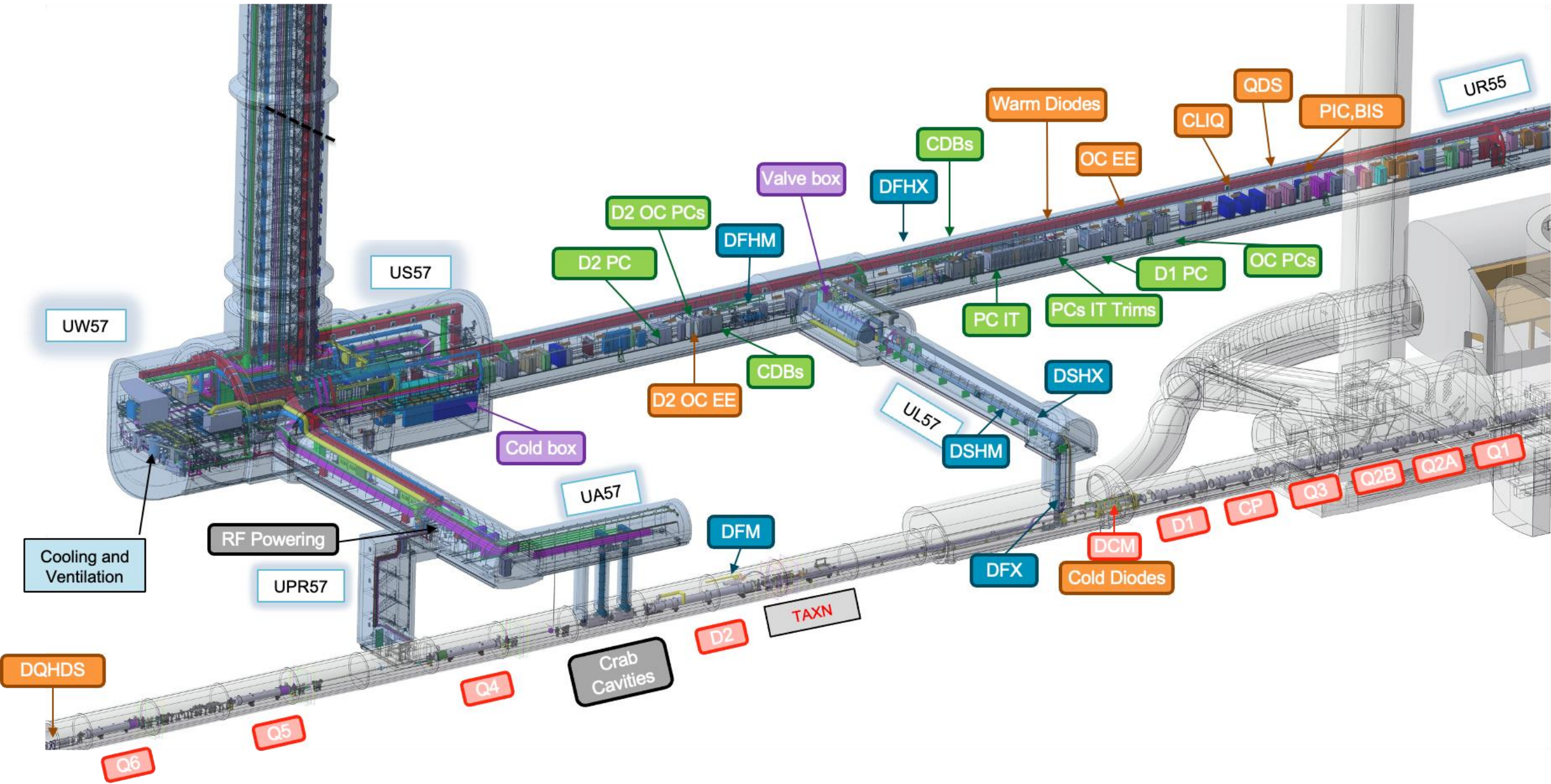
Crossing angle compensation (crabs)



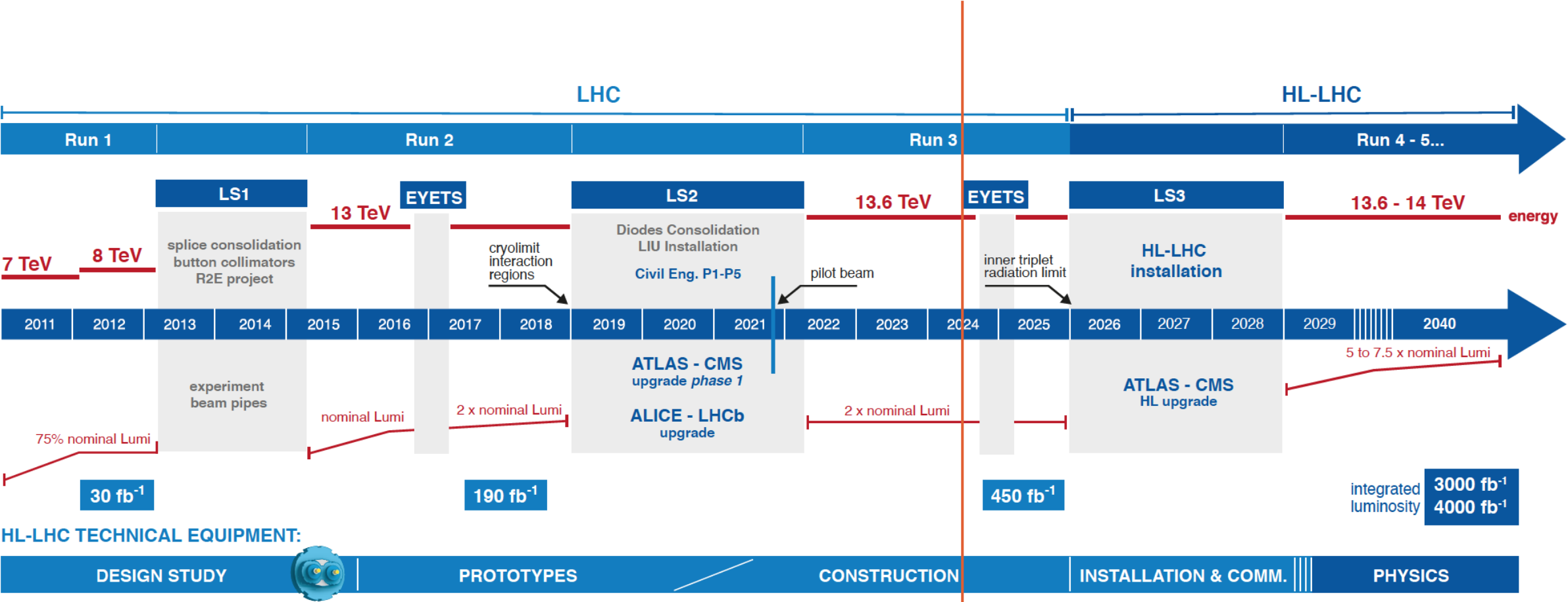
Operate in a high luminosity regime

The realization of HL-LHC as a truly international collaboration

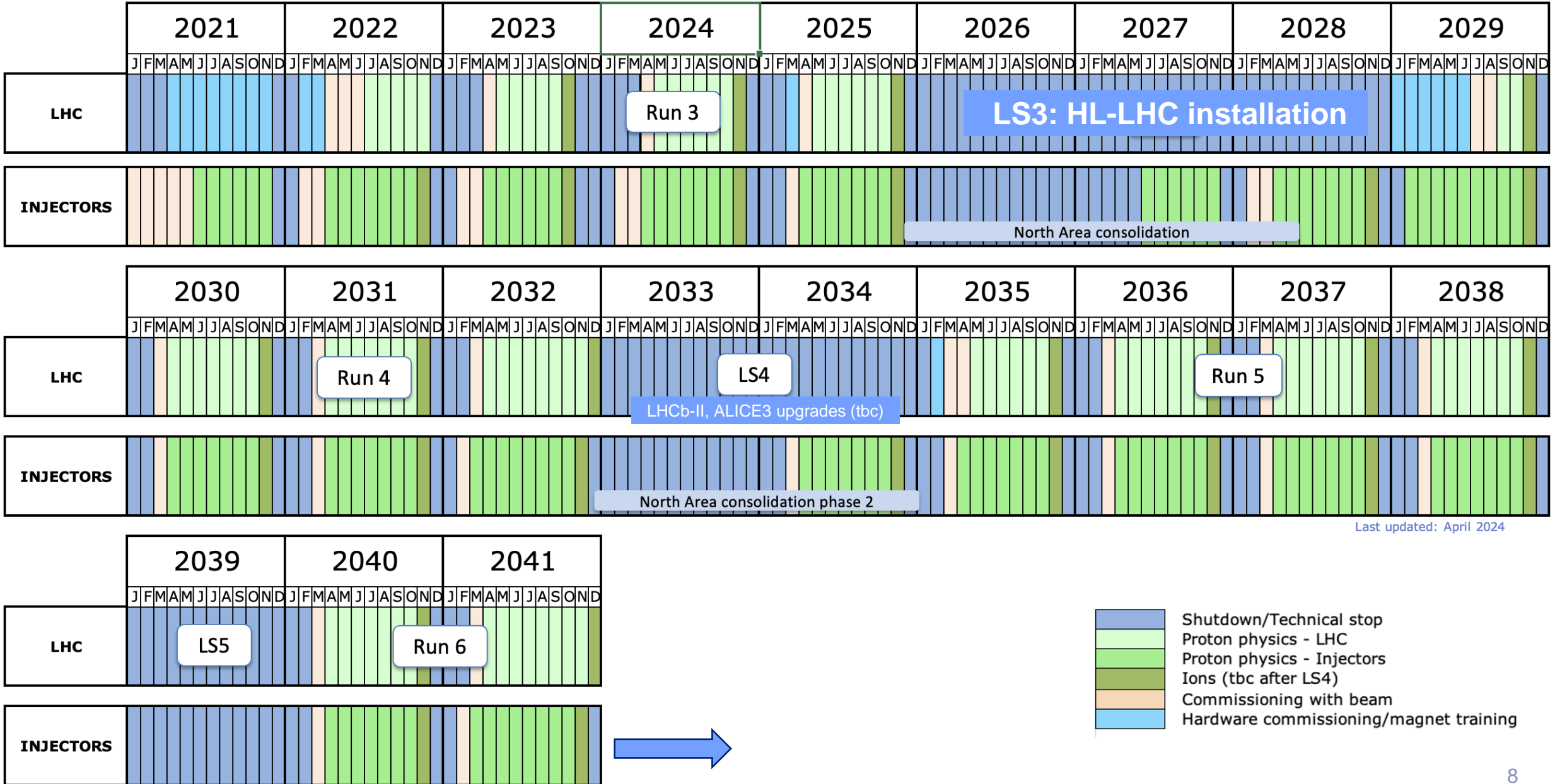




High Luminosity LHC (HL-LHC)

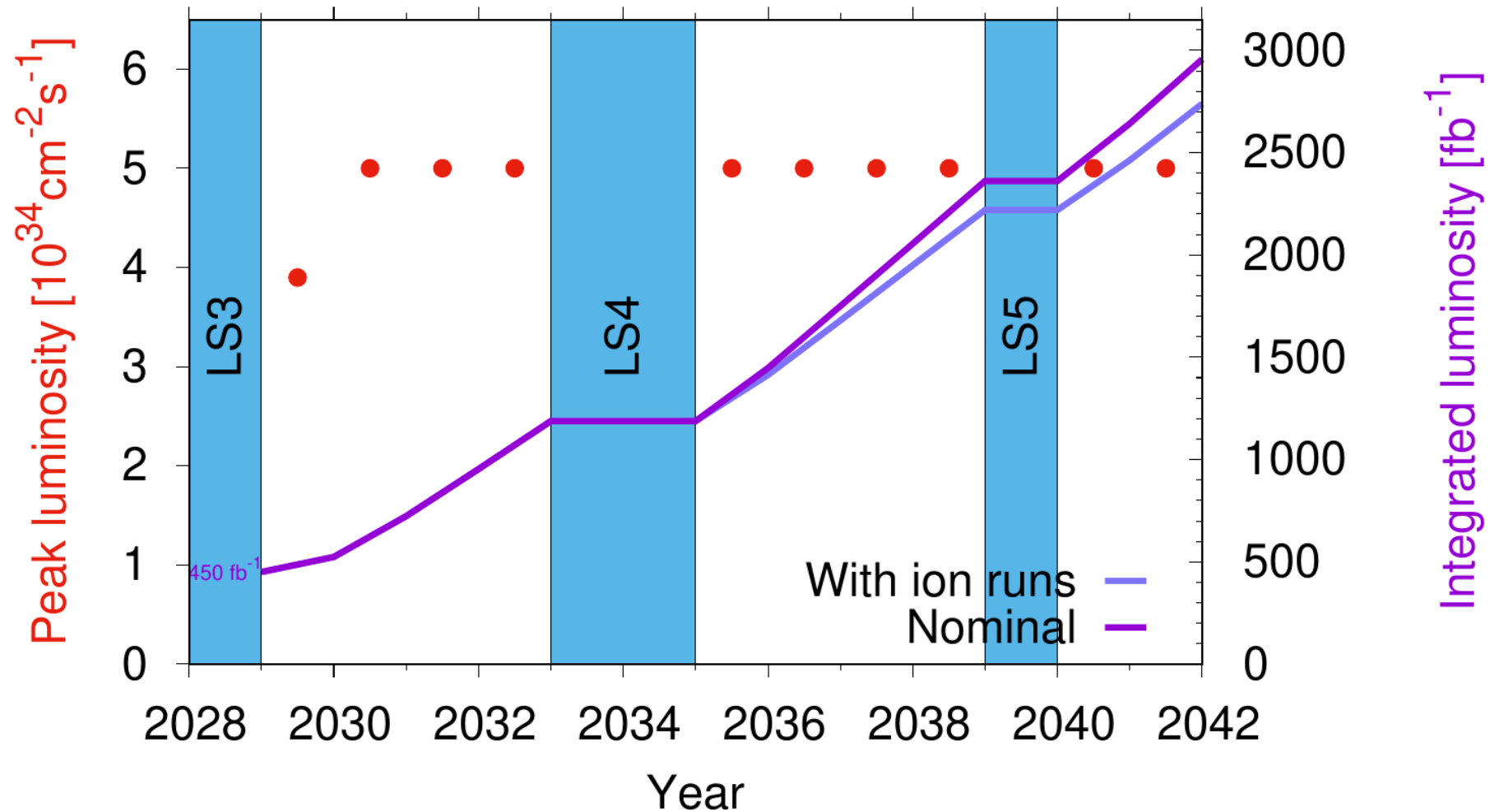


HL-LHC era - indicative timeline



- Shutdown/Technical stop
- Proton physics - LHC
- Proton physics - Injectors
- Ions (tbc after LS4)
- Commissioning with beam
- Hardware commissioning/magnet training

And then another miracle occurs...



A diverse physics programme

ALICE 3 proposed for LS4

LHCb Upgrade II proposed for LS4

Forward physics

- Precision Proton Spectrometer II (PPS II)

Neutrinos

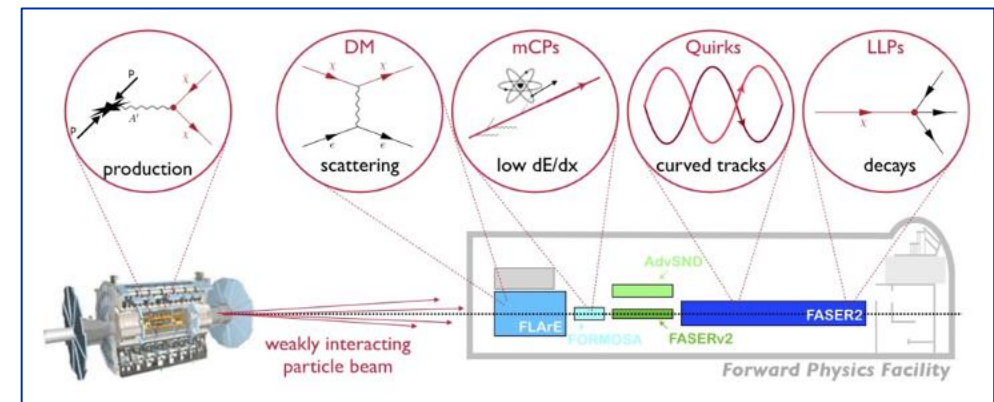
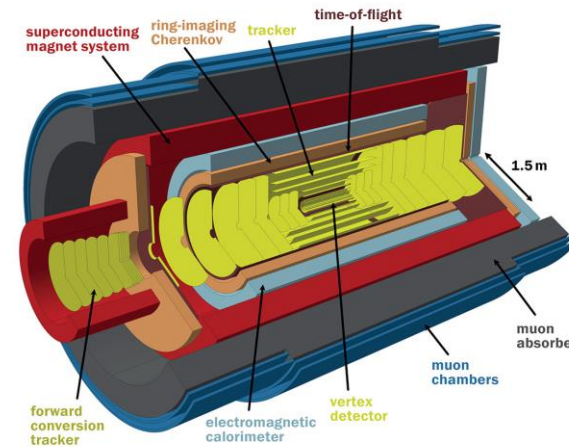
- SND, FASERnu, AdvSND, Forward Physics Facility (FPF)

Long Lived Particles/FIPS

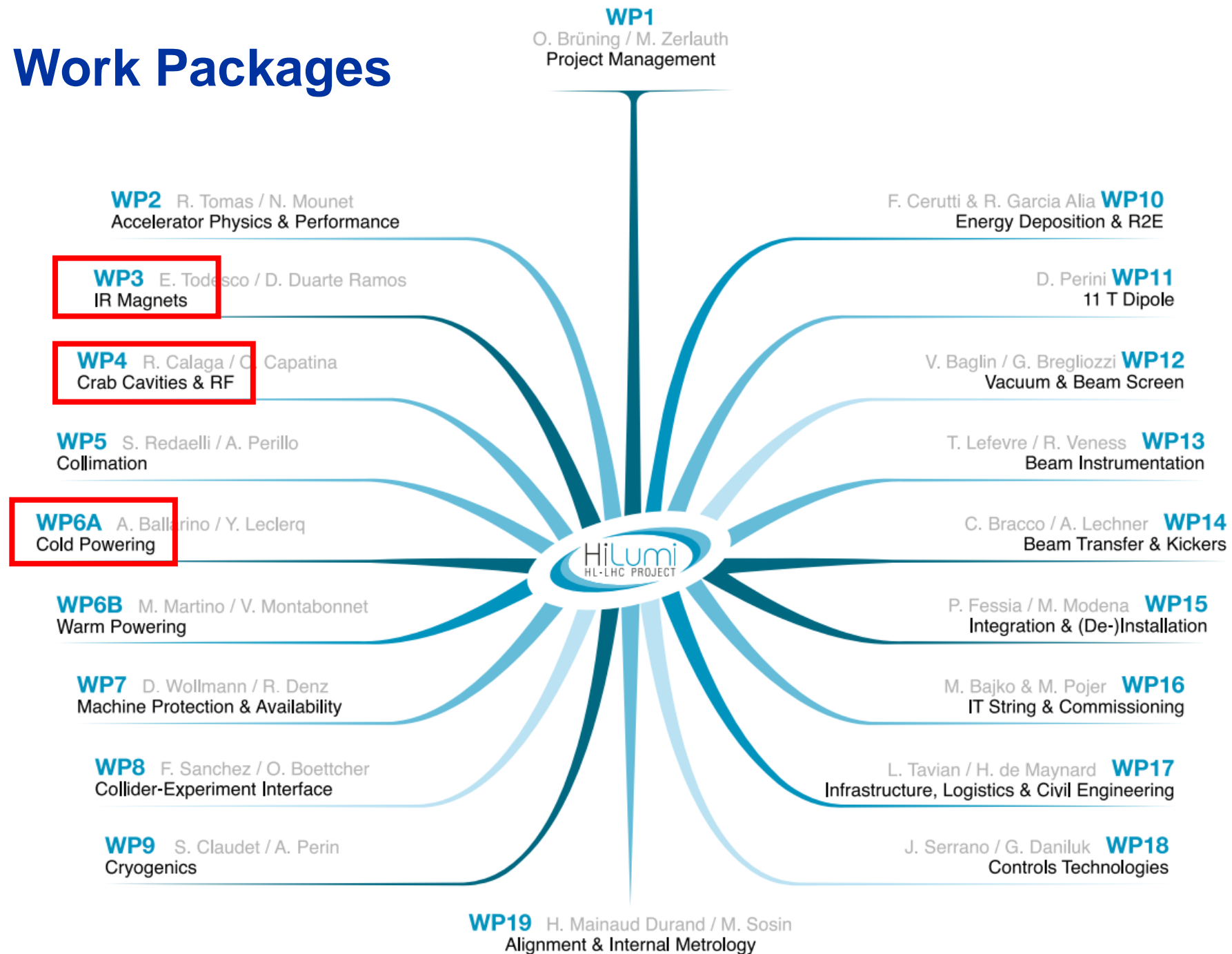
- GPDs, FASER, SND, MoEDAL, milliQan, FPF, CODEX-b, MATHUSLA, (pro)ANUBIS

Fixed target

- SMOG-2@LHCb, LHCspin, TWOCRIST (Λ_c^+ MDM/EDM)



HL-LHC Work Packages



HL-LHC technology landmarks

Series production in Industry well underway

Finished in 2023

HL-LHC has many challenging novelties covering a broad technology spectrum
Technology intensive project!

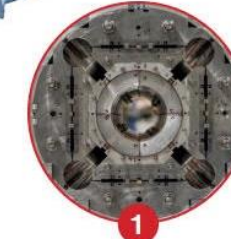
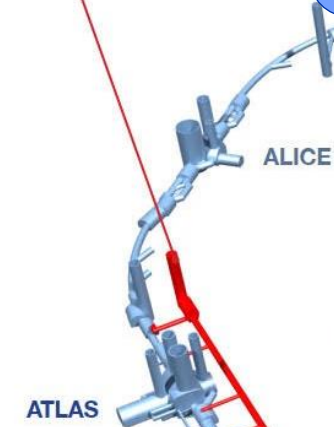
Complete Prototype System installed in SM18 and tested



CIVIL ENGINEERING
2 new 3000m tunnels and 2 new ATLAS and CMS caverns

Fully validated in 2023 and first magnets ready for installation

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



FOCUSING MAGNETS
12 more powerful quadrupole magnets for the ATLAS and CMS experiments designed to provide the final focusing of the beams before collisions.

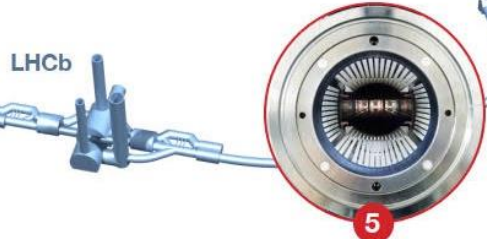


Finished in 2023

CMS



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



COLLIMATORS
15 to 20 additional collimators and replacement of 60 collimators with improved performance to reinforce machine protection.

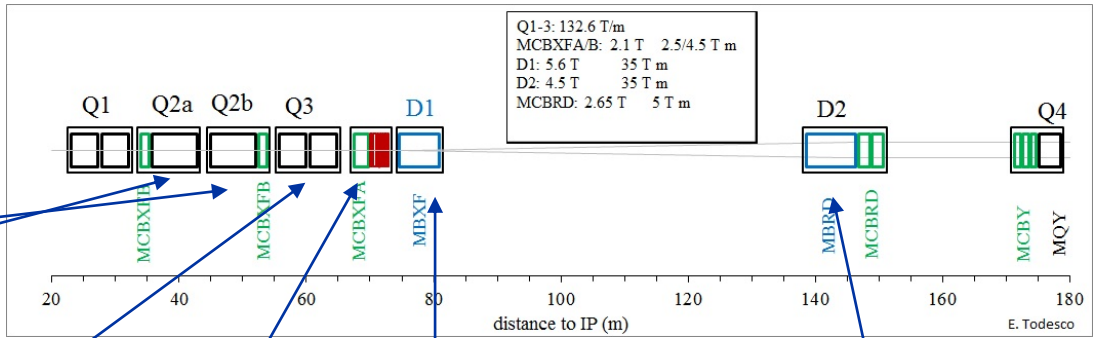
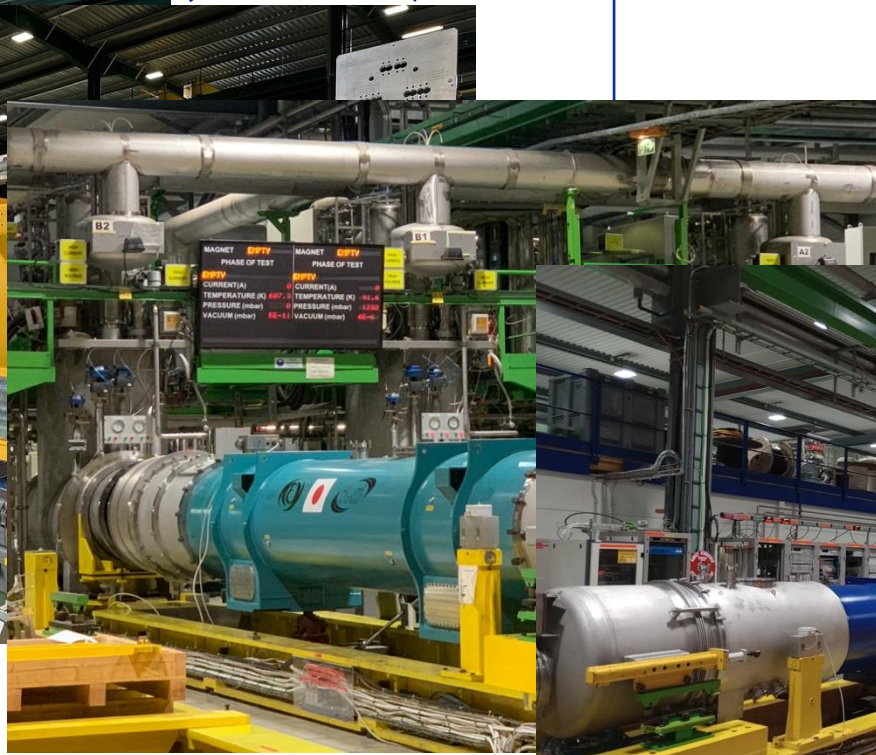
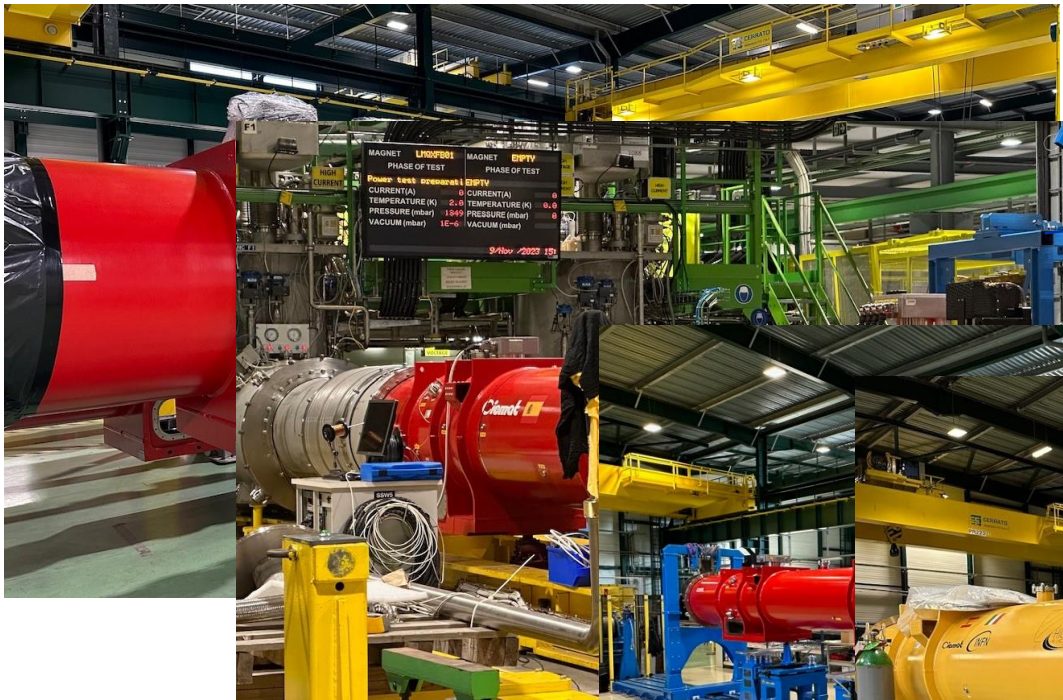


CRYSTAL COLLIMATORS
New crystal collimators in the IR7 cleaning insertion to improve cleaning efficiency during operation with ion beams.

Successfully deployed in 2023 Pb-Pb run

1/2 system already installed for Run 3

Magnets



Magnets

This year will be a crucial year for qualifying HL-LHC magnets and the cold powering system

- repeatability of CERN Nb₃Sn quadrupole performance – confirmed (April)
- test of first complete cold powering system
- electrical robustness of cryomagnets and cold powering system
- horizontal test bench upgrade to be completed



SM18 – this week



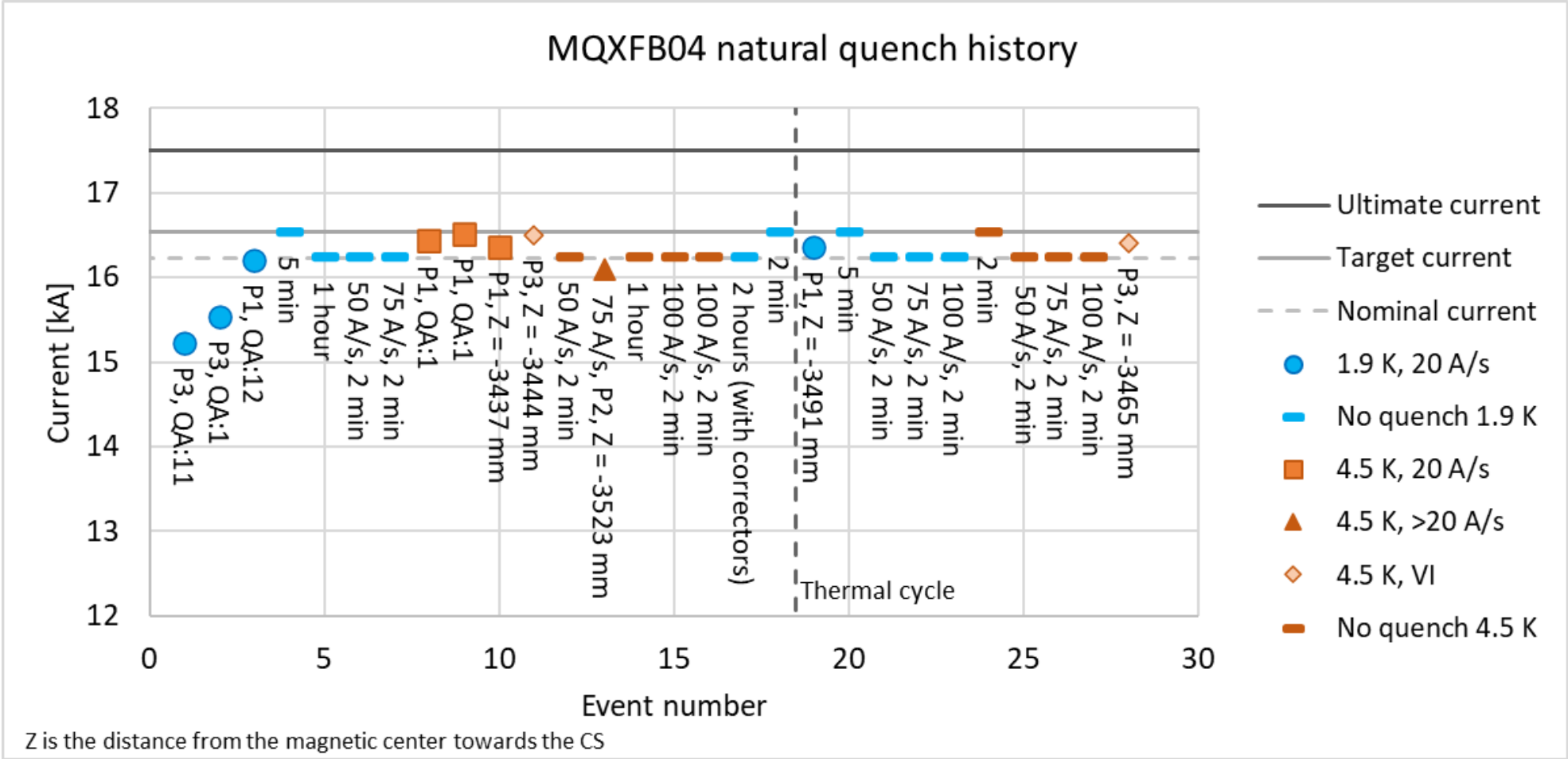
MQXFB04 successfully completed test program



LQXFA01 (Q3 in IT String) placed on bench for cold tests

Latest series CERN inner triplet quarupole (QXFB)

- Increased magnetic field at coil → shift from niobium-titanium to niobium-tin (Nb_3Sn)
- However, Nb_3Sn is brittle – some issues with degradation at prototype phase

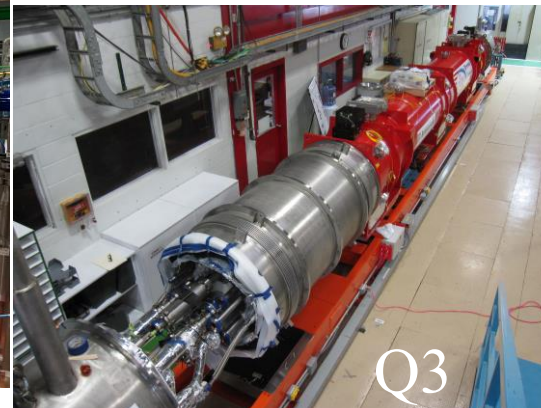
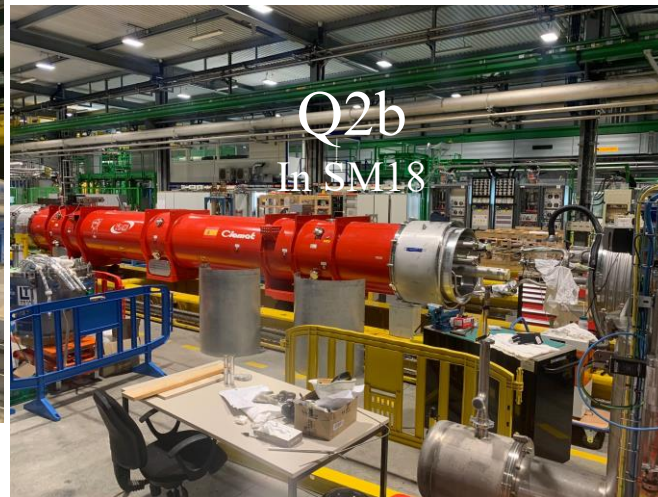


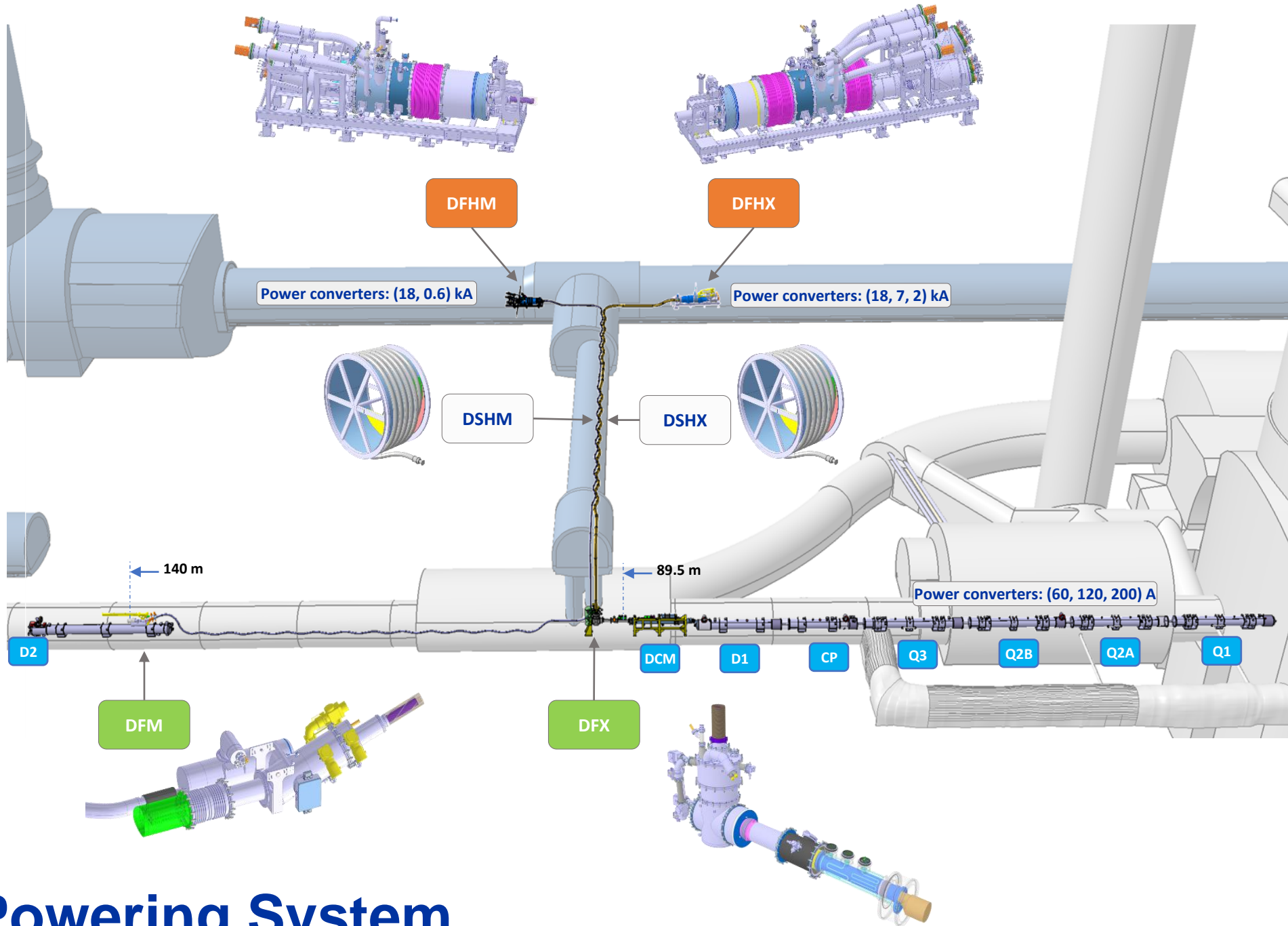


LQXFA01 AKA Q1/Q3 – FIRST QUADRUPOLE CRYO-ASSEMBLY PRODUCED IN THE US BEING TESTED IN SM18

Inner Triplet (IT) String components in preparation

- **Q1**: magnet cold mass being welded → Available in September 224
- **Q2a**: MQXFBP2b completed → **On SM18 Testbench** → Available April 2024
- **Q2b**: MQXFBP3b completed → **Available for Testbench Jan.** → April 2024
- **Q3**: magnet being prepared for shipment to CERN → Available July 2024
- **CP**: cryostating Phase II **ongoing** → Available August 2024
- **D1**: cryostating completed → **Available for Testbench** → Available March 2024

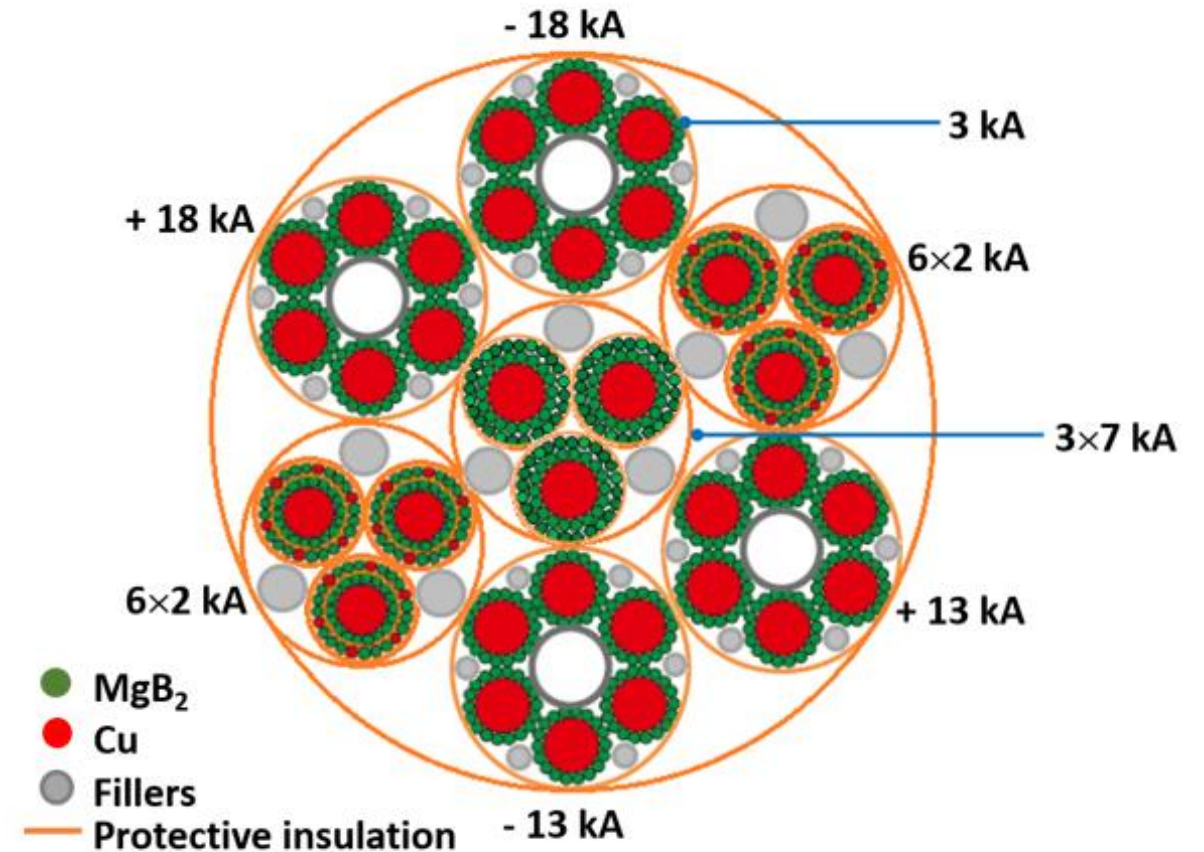


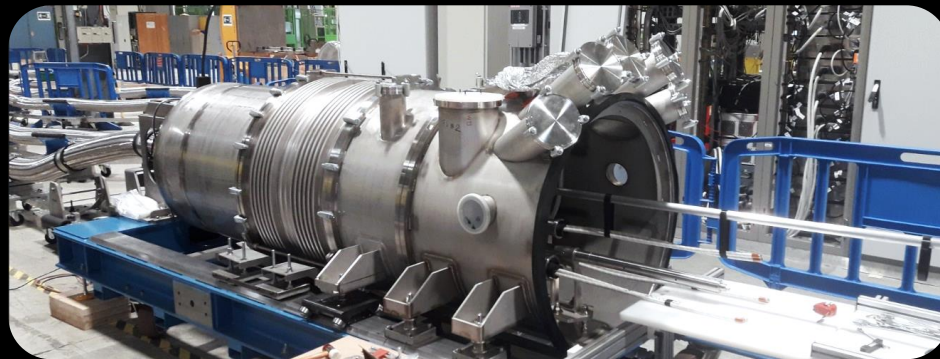
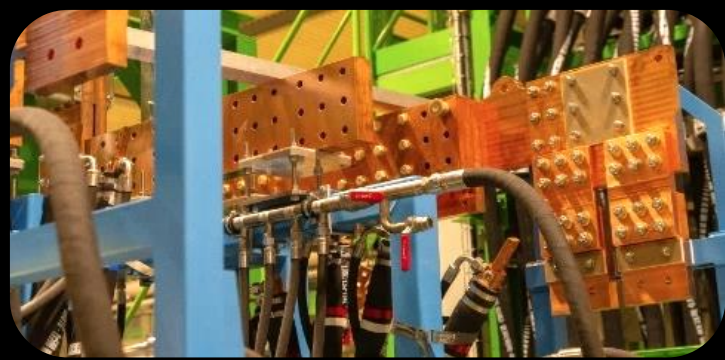


Cold Powering System

Superconducting link

The flexible, double-wall, corrugated cryostat comprises 19 MgB₂ 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.

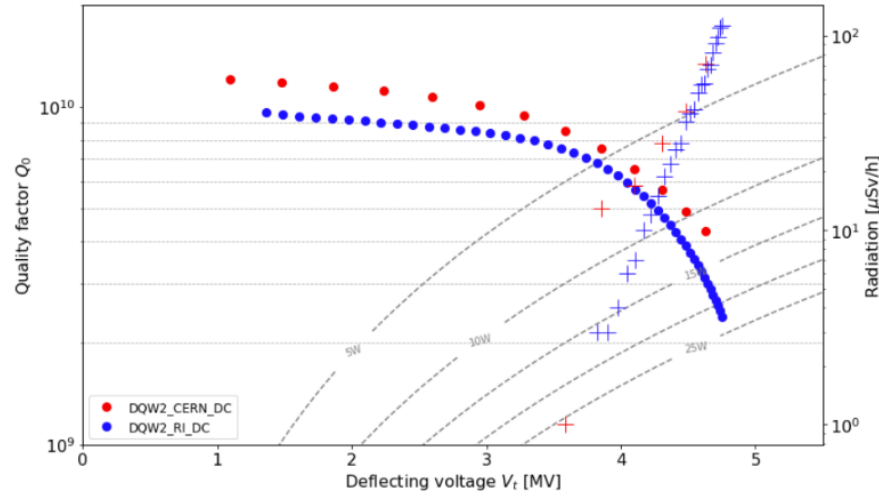
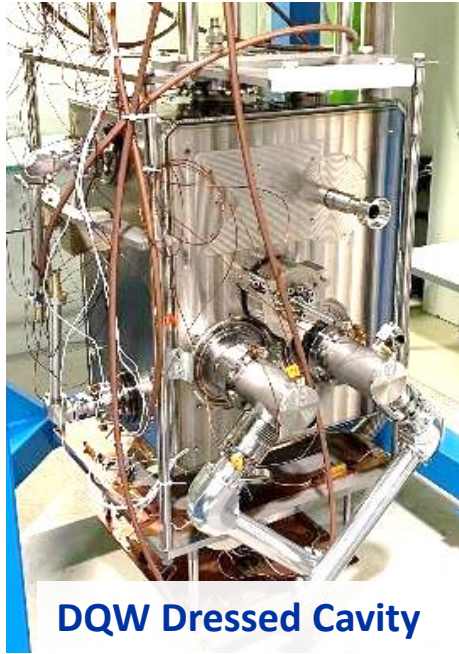




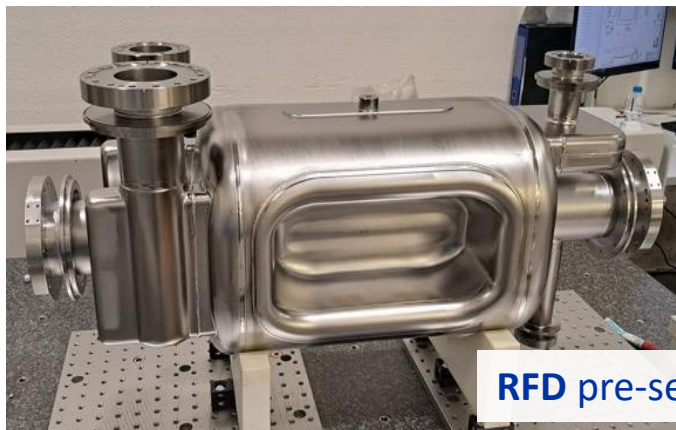
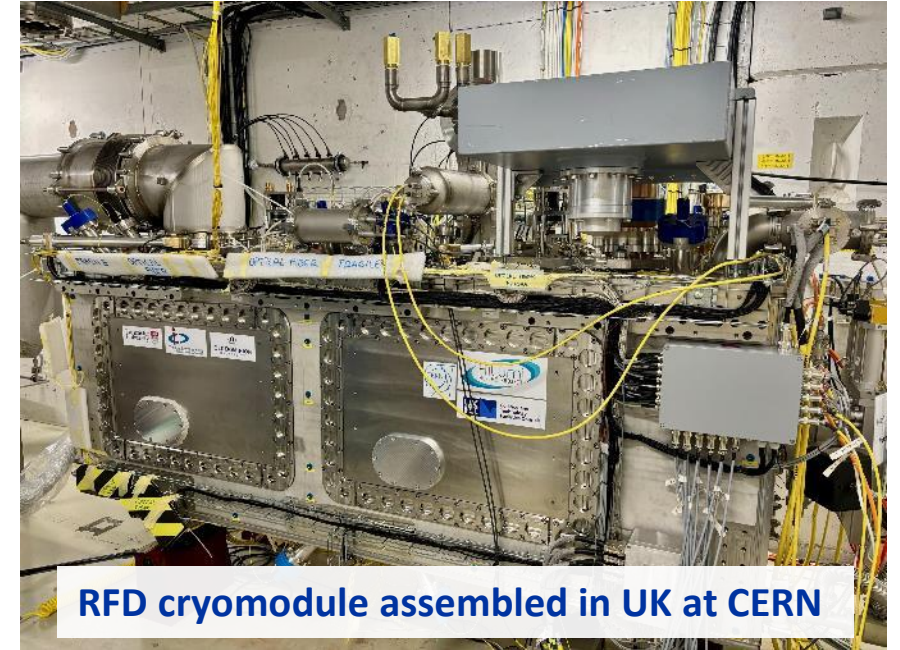
SC-Link-DFHX assembly in pictures
Complete system test of full SC link now complete



Crab Cavity series production well underway

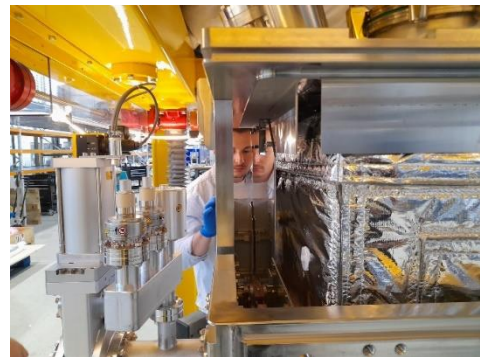
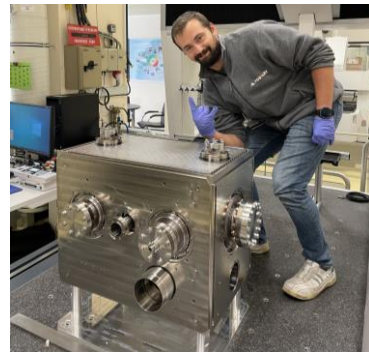
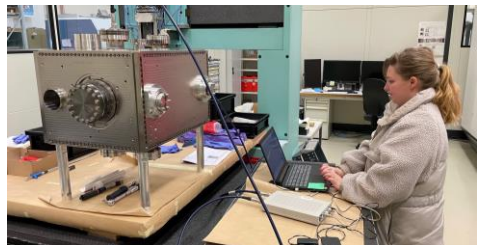


First two series DQW cavities (CERN + RI) reached performance beyond specification!



RFD series fabrication launched at Zanon since May 2023

UK Crab Cavity Cryomodules





RFD cryomodule assembled in UK and being tested in M7 bunker (SM18-CERN) before installation in SPS

HL-LHC LS3 Schedule

LS3 Schedule – TCC October 2023

Q4 2025



Q3 2029

Warm-up and related tests

LSS dismantling after cryo lockout

Cabling dismantling

Core excavation (LHC side)

Cabling installation

LSS installation

Cool-down, related test and HWC



Plus

- Injector Complex
- North Area Consolidation
- ECN3
- Experiments (+CO2 cooling)
- ...

Long Shutdown 3 (LS3) is going to be very busy!

Conclusions

Civil Engineering Work Completed

Nb₃Sn Technology validated

Superconducting Link demonstrated

Crab Cavity Operation and Production demonstrated

"The project is on track for installation during LS3 starting in 2026"

Stay tuned for completion of the IT-String installation in 24 and operation @ cold as of 2025

STILL A LONG WAY TO GO...

Repaired MB Dipole

MQXFBP3

MQXFB02

D1 proto

CP

1st Part of Collimation Upgrade completed

All magnet production on a good track

