



HL-LHC project

O.Brüning, CERN

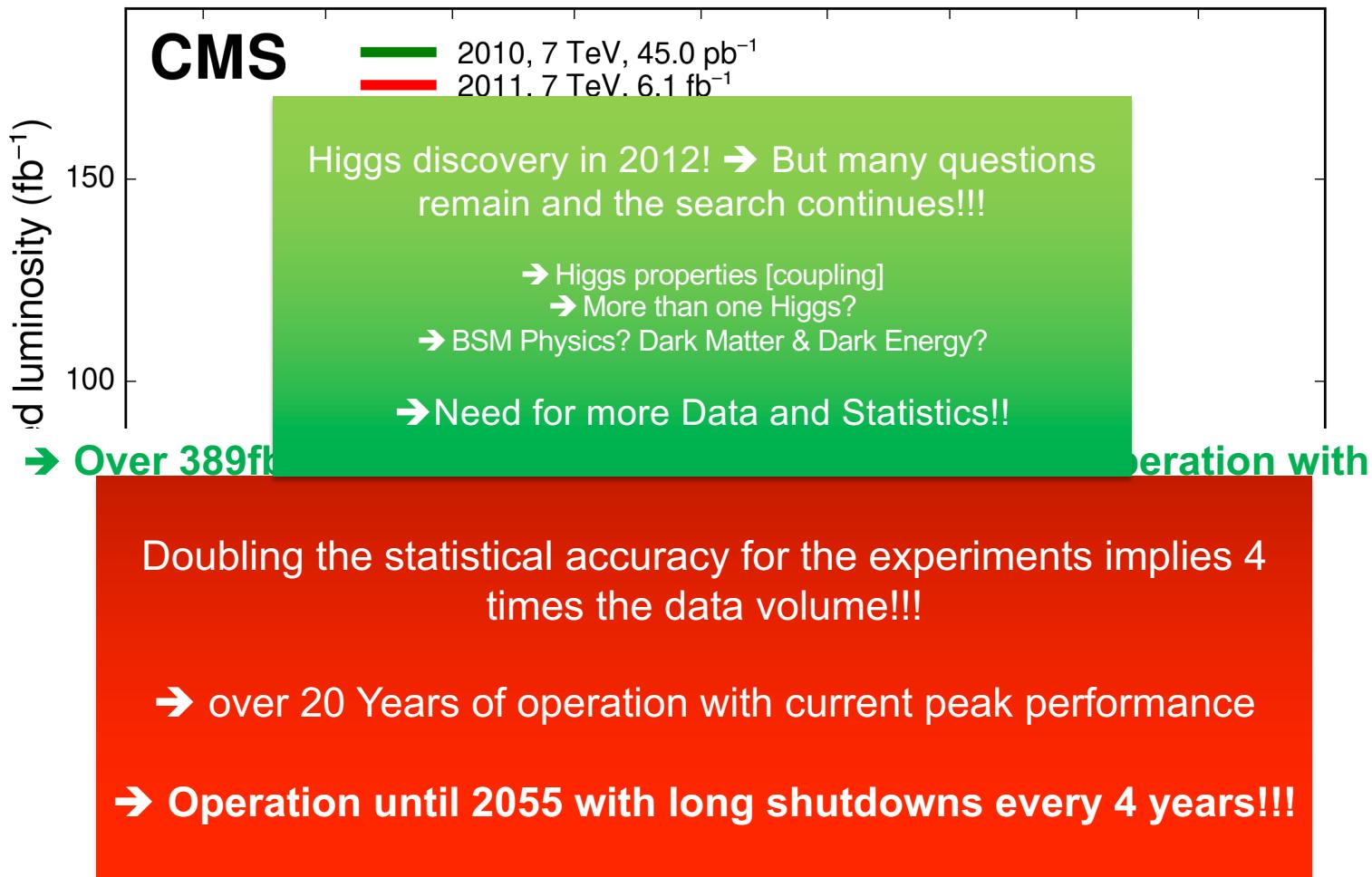
Outline

- **Recap LHC**
- **Introduction HL-LHC → key project goals and challenges**
- **Project Milestones**
- **IT-String Test → Showcase for 2025**

LHC in the Geneva Basin and its Experiments



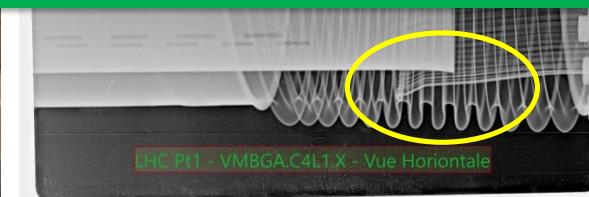
LHC Performance



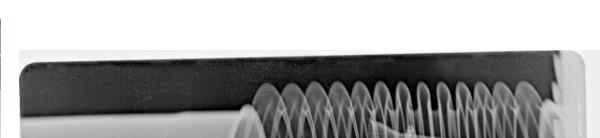
Bellows Module 5: X-ray and Photos after Opening



How it should look



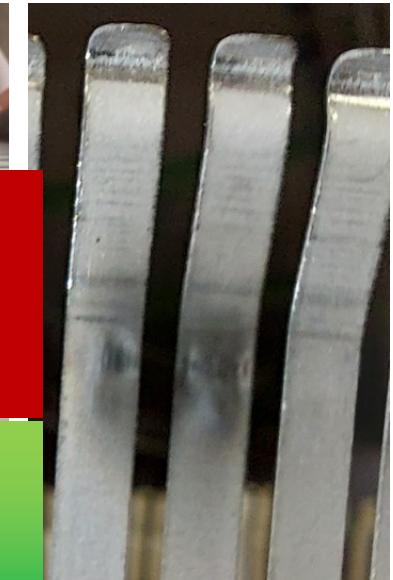
Spring disengaged with
RF fingers not touching



5 Days of Physics Operation Lost



Systematic replacement of these large bellows under preparation



Clear sign of the
spring heating



IR8 IT.L8 Triplet incident in July 2023:

→ End of proton operation in 2023



IR8 IT.L8 Triplet incident

Power glitch cause LHC and AD beam dump 17.07.23

The cause of the events seen at CERN

- A tree fell on two lines 125 kV of Romande Energie which are on the same support towers:
 - Morges — Vaux-sur-Morges
 - Bussigny — Etoy — Vaux-sur-Morges
- The two lines are both connected to Vaux-sur-Morges 220/125 kV substation
- The recording from Romande Energie was at 01:01:08.607 (it is consistent with our last recording at 01:01:08.610) and there were several attempts to re-energize the lines (fast reclosures) before the final trip

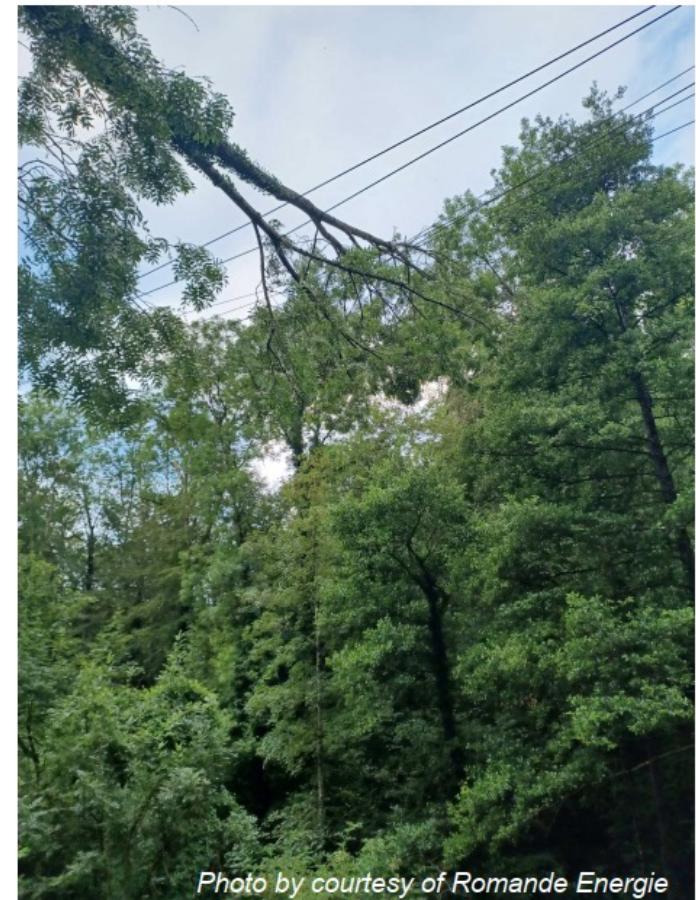


Photo by courtesy of Romande Energie



Advanced Accelerator Cou

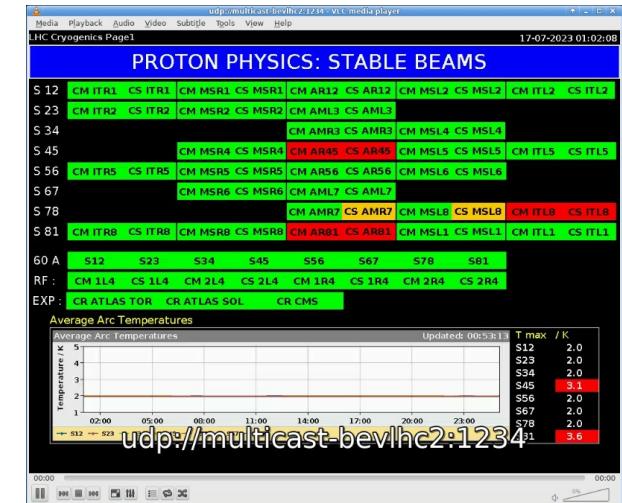
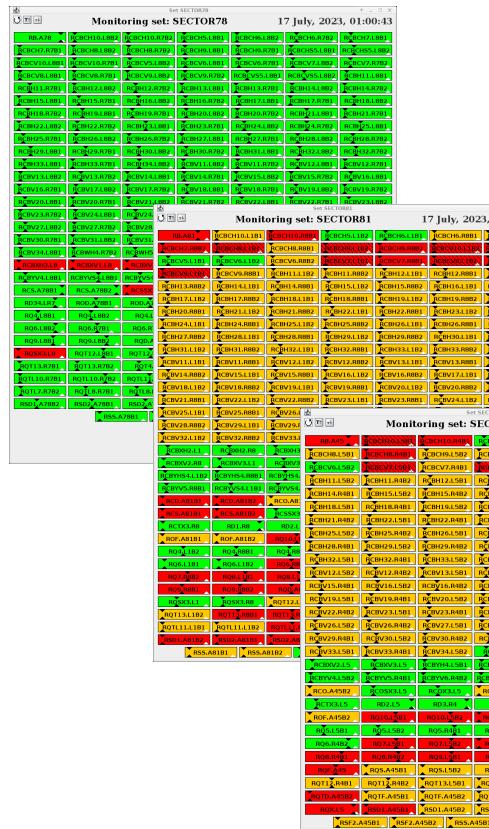


25/07/2023

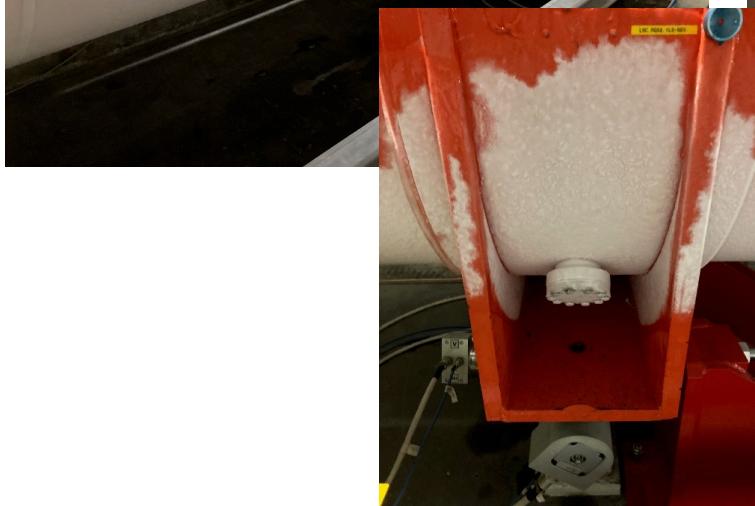
Oliver Brügel CERN

Event sequence

- Beams dumped at 01:00:17 by **RF fault**.
- 370 milliseconds later **several magnets quenched**:
 - RQ7/9/10.R4
 - RQ10.R8
 - RQX.L8
- The heat wave generated by RQX.L8 quench tripped the **IP8 cold compressor**.

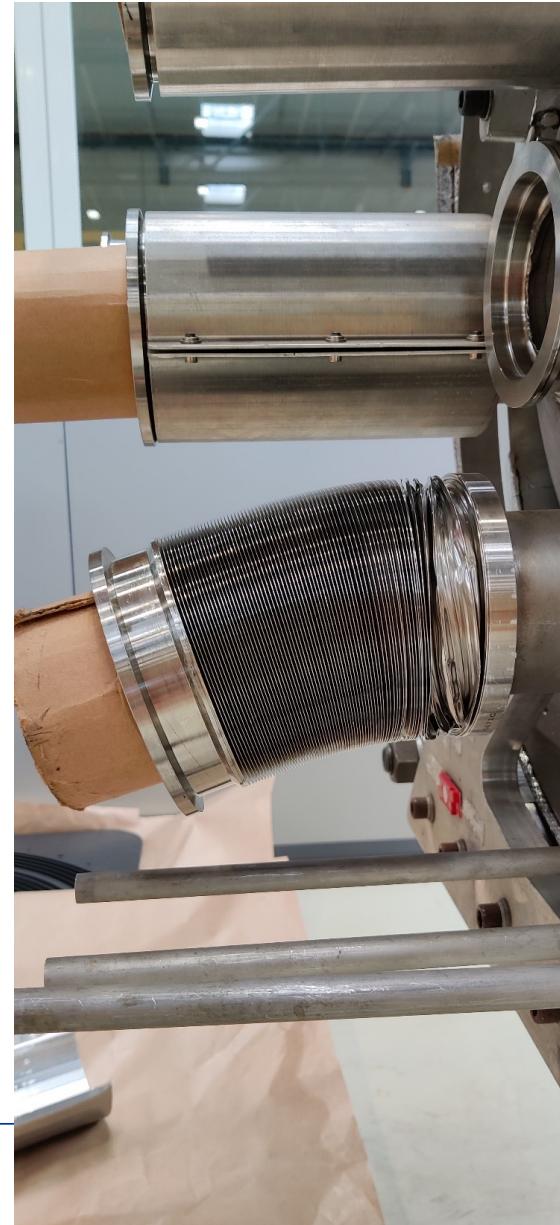
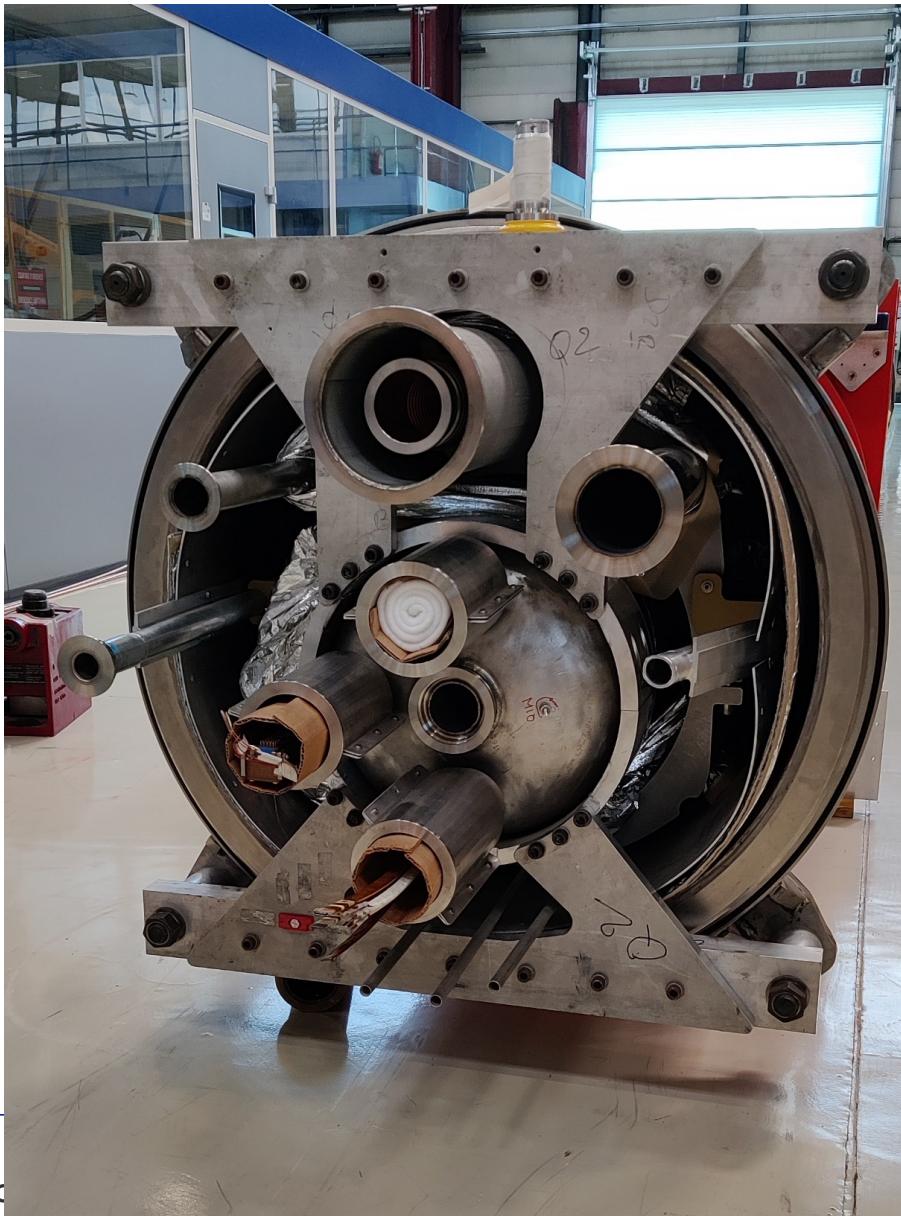


1st tunnel visit



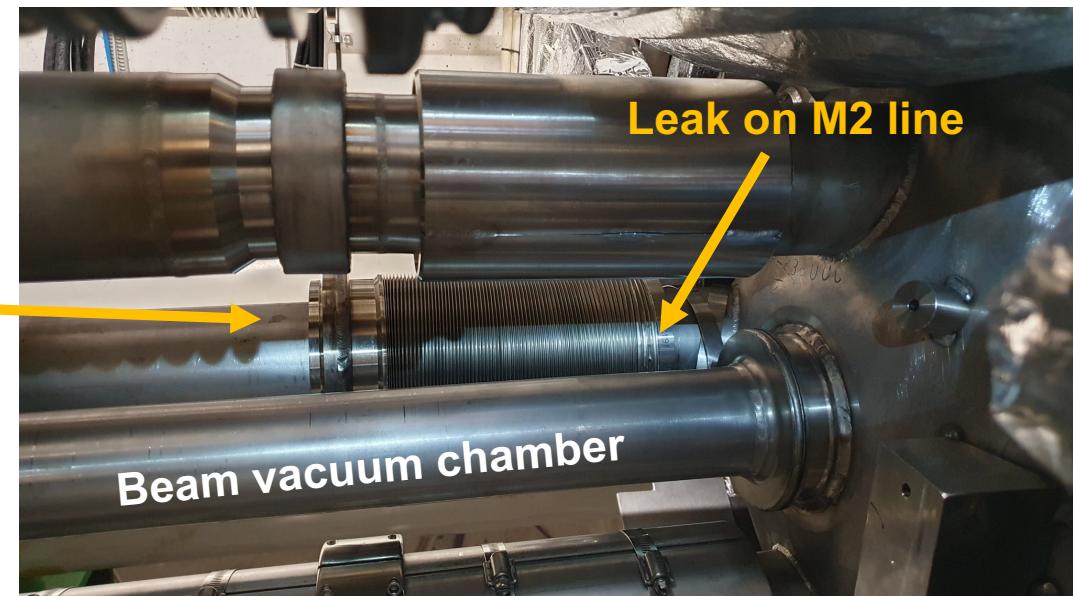
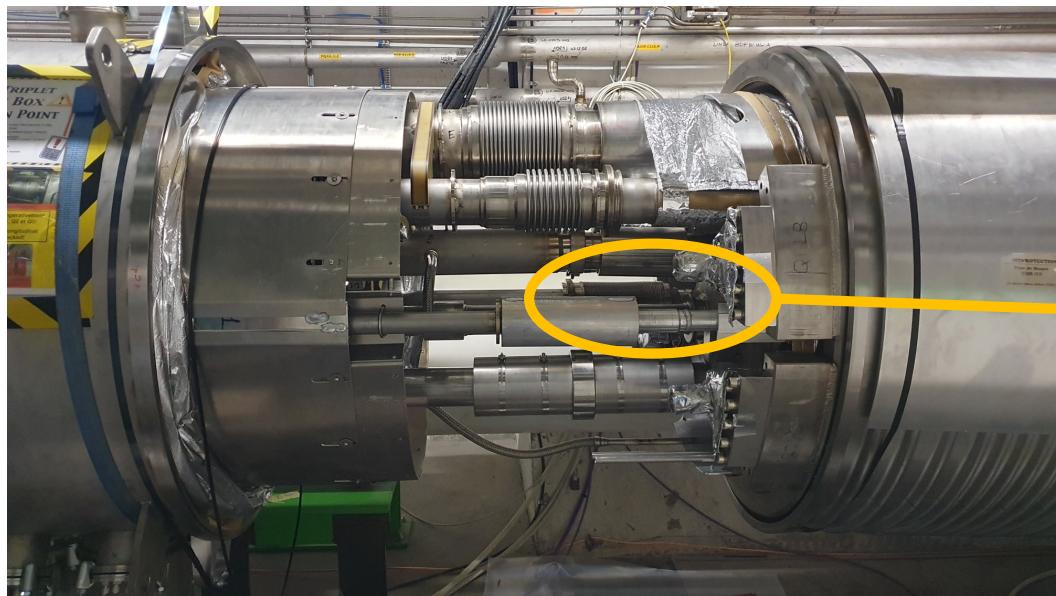
- Condensation on **Q1/2/3**, less on **D1 and DFBX**.
- Ice and condensation gone on Wednesday.





Interconnect opening (3)

- Leak localization with dry air injection into the cold mass: one could feel the leak from the air flow !
- Luckily, the affected line does not contain busbar splices! Only diagnostic cables!!!



Damaged bellow



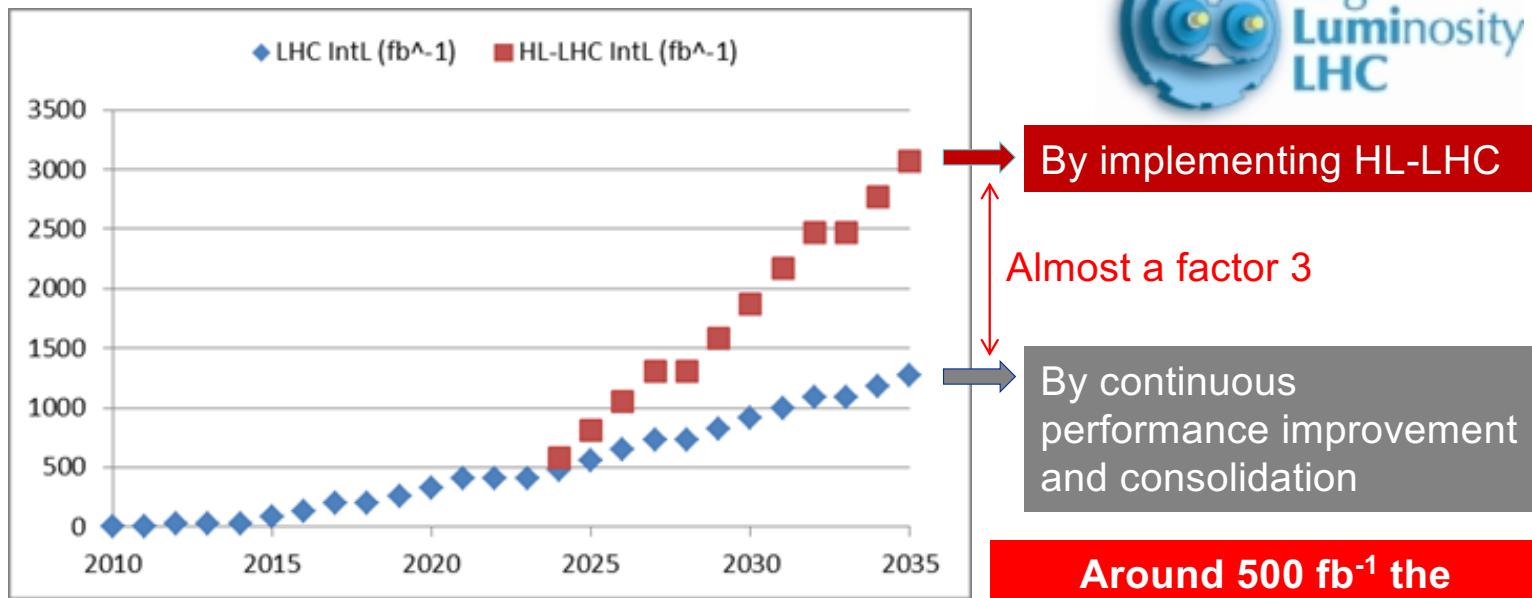
Decision to **replace** the bellow

- Warmup of the triplet magnets
- Arc magnets left floating
- Had about 20 days for the repair work!
- Followed by ca. 1.5 month of cooldown to 1.8K

Spare bellow – tested to 20 bar



High-Luminosity LHC Goals beyond Equipment Consolidation



By implementing HL-LHC

Almost a factor 3

By continuous performance improvement and consolidation

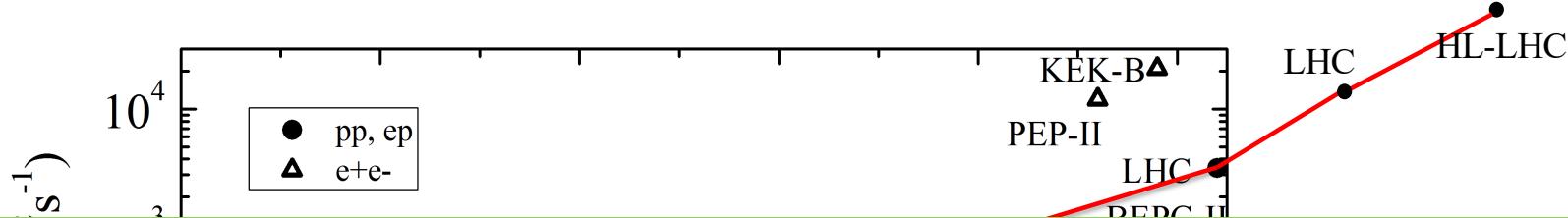
Goal of HL-LHC project:

- 250 – 300 fb^{-1} per year
- **3000 fb^{-1} to 4000 fb^{-1} in about 10 years by 2041**

Around 500 fb^{-1} the present Inner Triplet magnets reach the end of their useful life (due to radiation damage) and must be replaced.



Peak luminosities of Hadron colliders



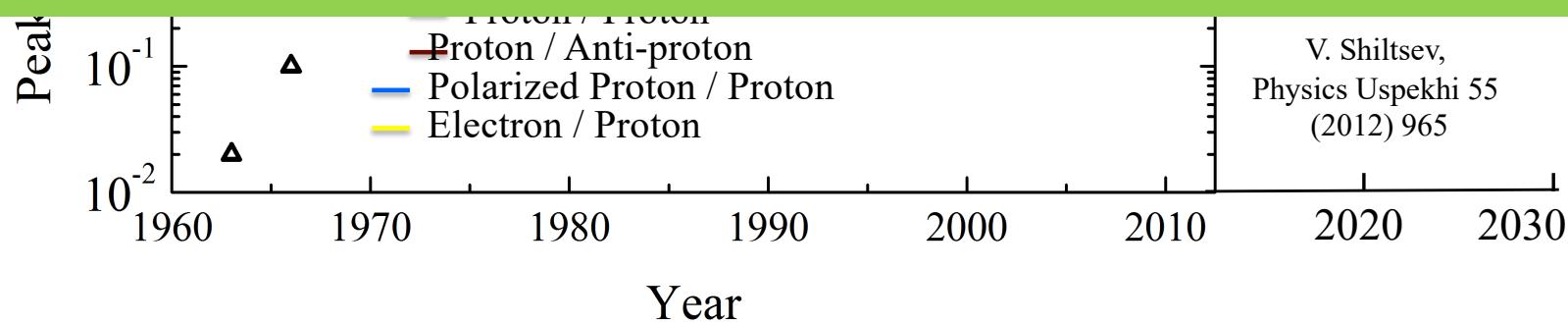
Worldwide Integrated Luminosity prior to LHC: ca. 11 fb^{-1}

x 45

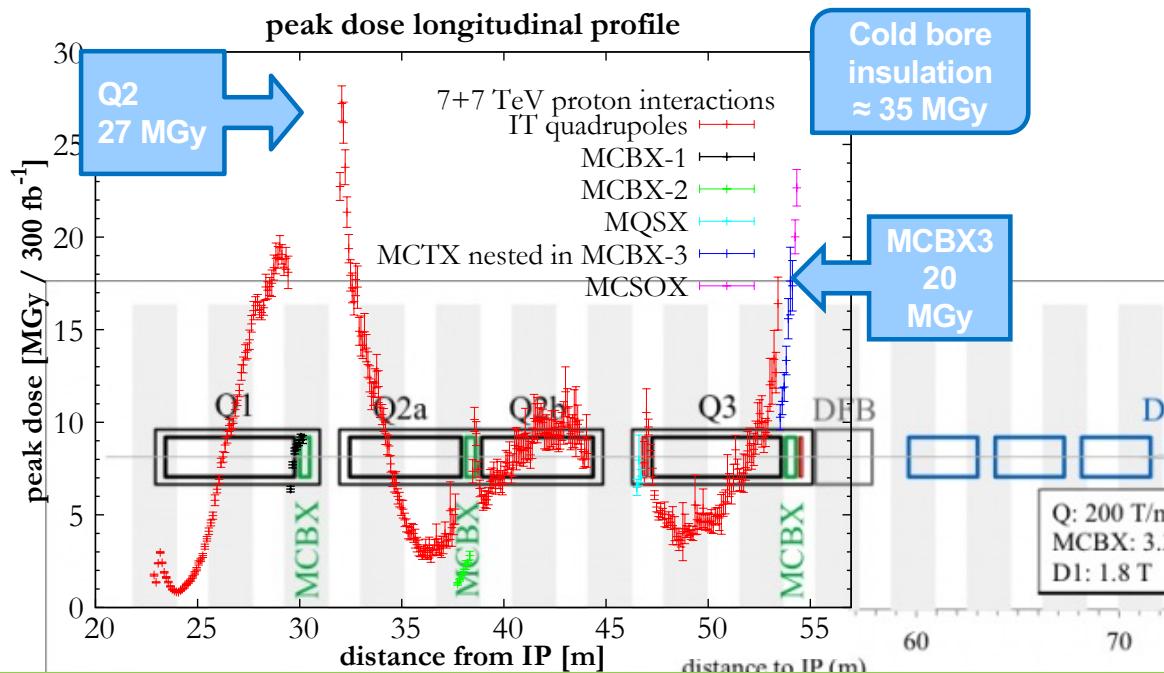
LHC Design Goal: 300 fb^{-1} → LHC likely to reach end of Run3: $> 500 \text{ fb}^{-1}$

HL-LHC goal: 3000 fb^{-1} to 4000 fb^{-1} !

x 8



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



→ End of the LHC triplet lifetime by End Run3 in 2026 [over 500fb⁻¹]

→ Need to replace triplets in the LHC after 2026 to keep the machine operational

→ replace with design for higher performance!!!

→ HL-LHC goal: 10 times the LHC data Volume → requires radiation hard magnets that can tolerate over 3ab⁻¹!!!

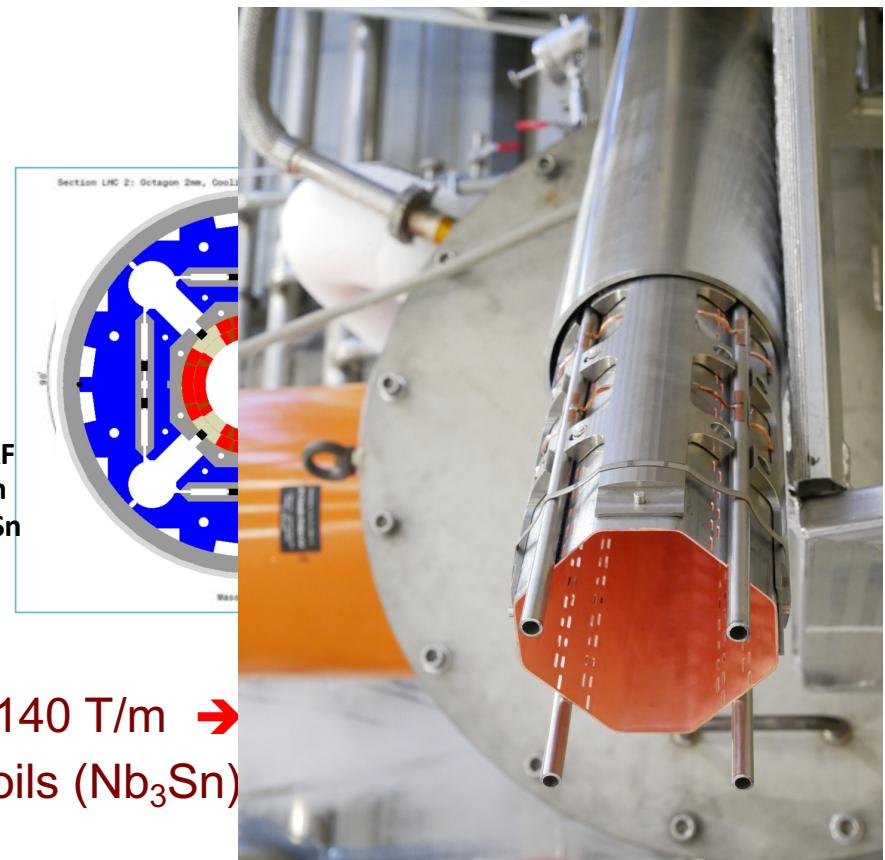
HL-LHC technical bottleneck: Radiation damage to triplet magnets

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 → 8T peak field at coils → 12T field at coils (Nb_3Sn)

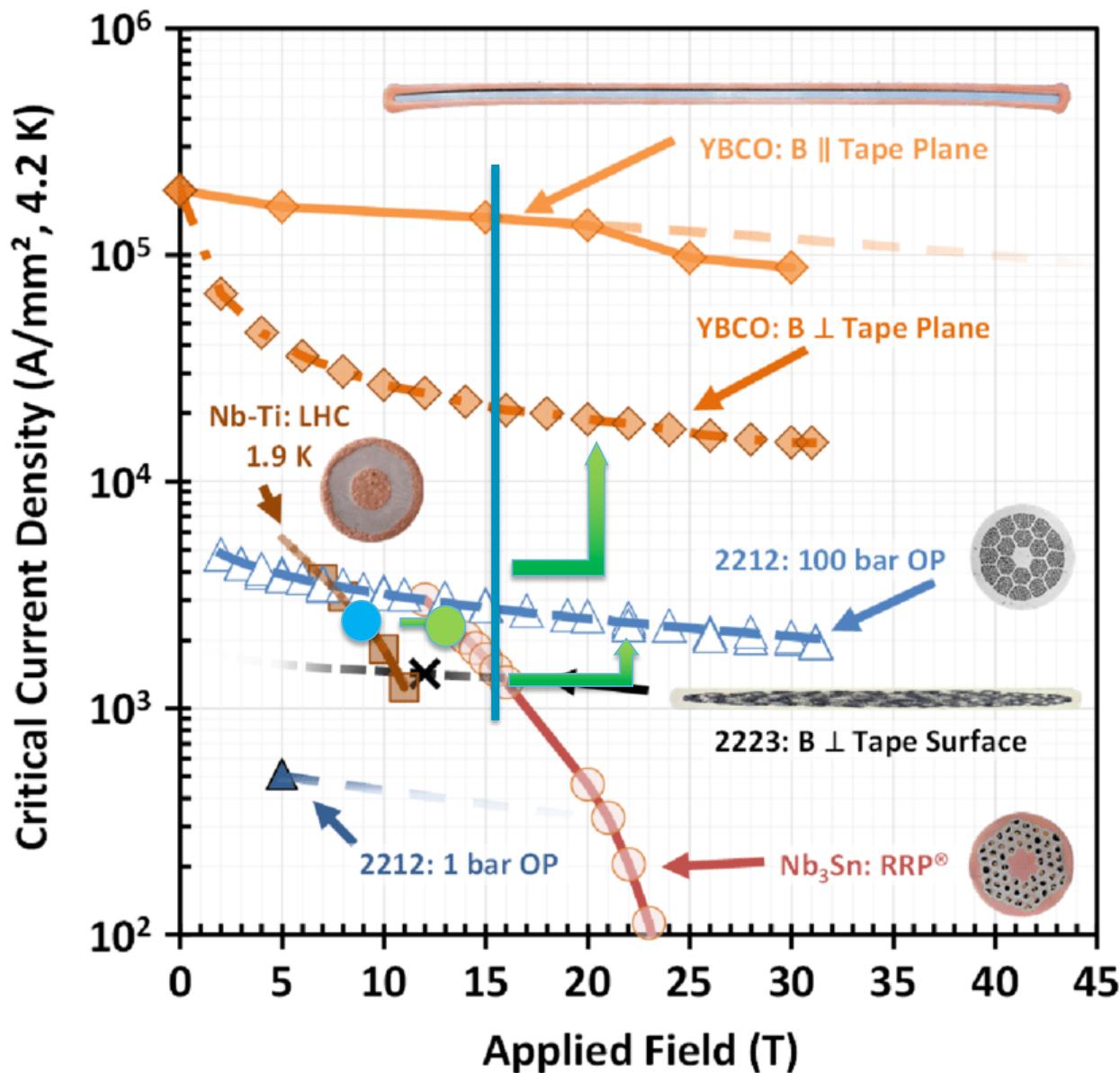
US-LARP MQXF
magnet design
Based on Nb_3Sn
technology



SC Magnet Technology

source:
D. C. Larbalestier @ Researchgate

More SC for the same field
→ Cost!



Nb_3Sn

- HL-LHC with 11-12T
- 16 T for HEP?
- Almost a commodity!
 - 15-20 t per year for MRI
 - ITER needs 500 t
- ca 5 times cost of LHC Nb-Ti
- Brittle material

HTS (needed → 20 T)
→ on going R&D!

- Bi-2212: cost today 2-5 x Nb_3Sn
- YBCO: cost today 10 x Nb_3Sn

LHC Magnet Technology:
Thousands of fine Nb-Ti filaments well
separated along km of wires
Industrial production via extrusion

Fine filaments of Nb-Ti in a Cu matrix (for an LHC dipole wire)

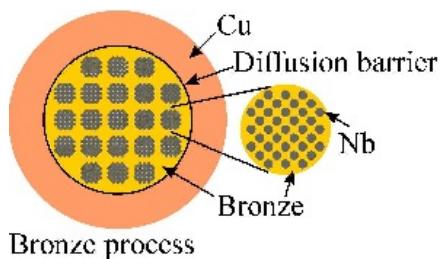
Cable of 15 kA!)

Multi-wire cable: the way to 10-100 kA!

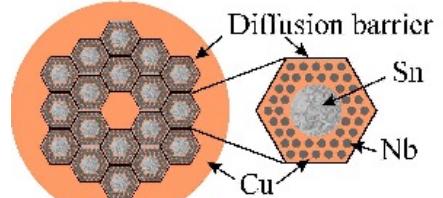
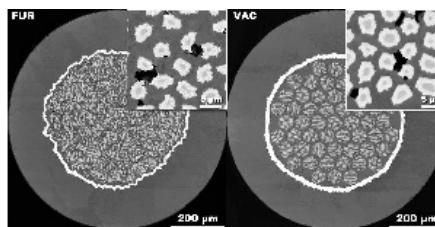
The Nb_3Sn SC Challenge:

Nb_3Sn is **brittle** and cannot be drawn in final form – contrary to NbTi

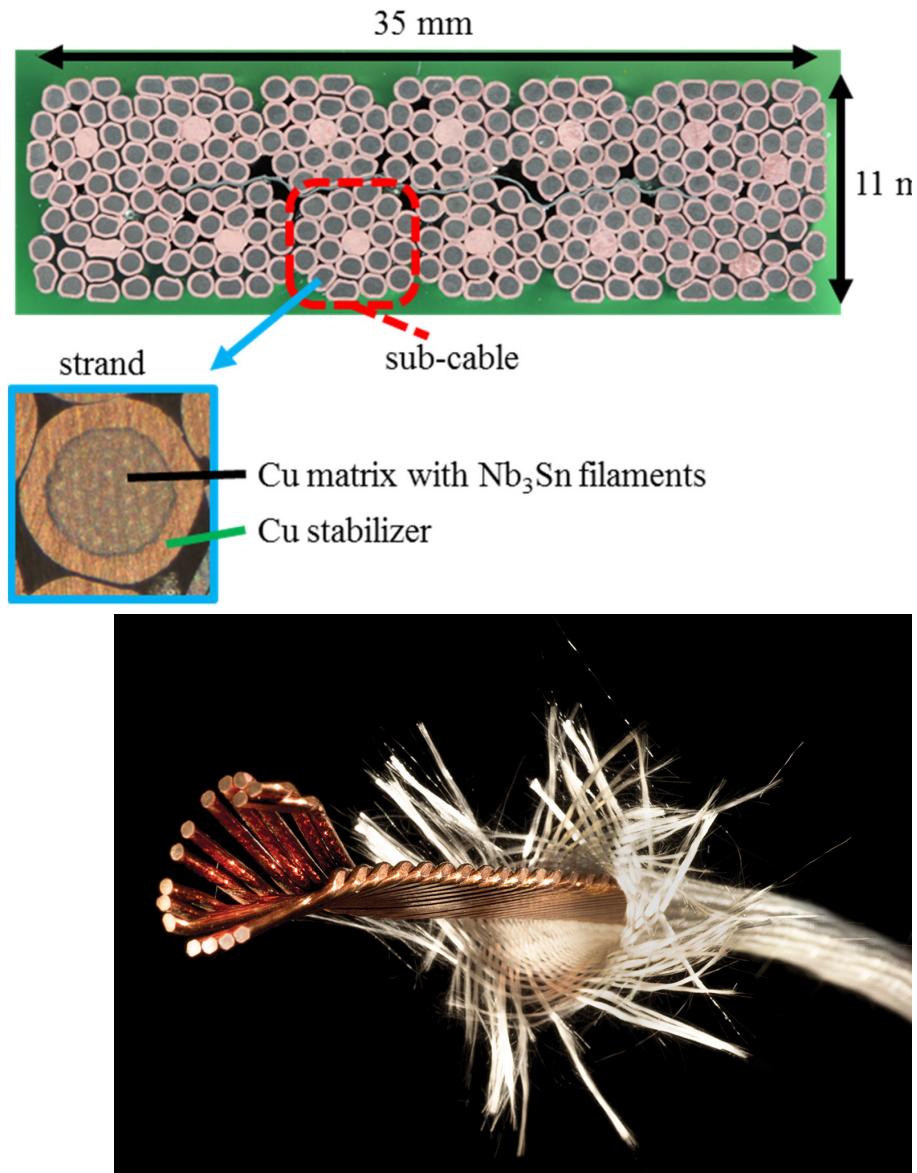
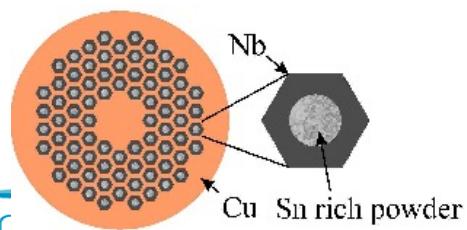
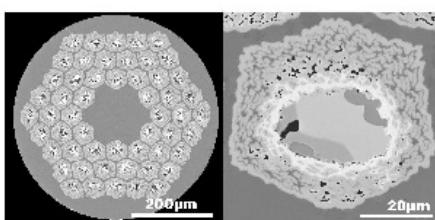
Strand is drawn before cable is formed before the wire is heat-treated to form the Nb_3Sn superconductor!



Bronze process

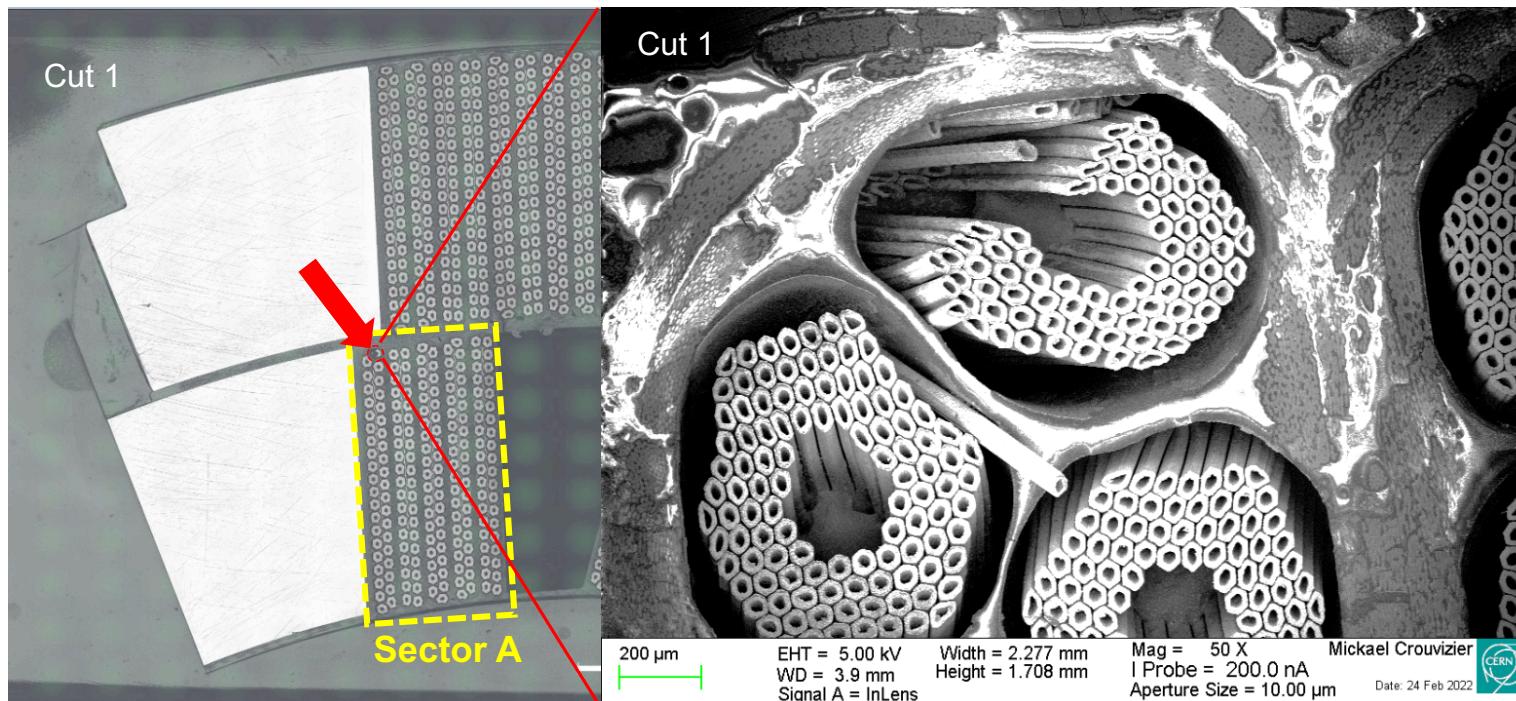


Internal Sn process



Challenges in Nb3Sn Magnet Technology

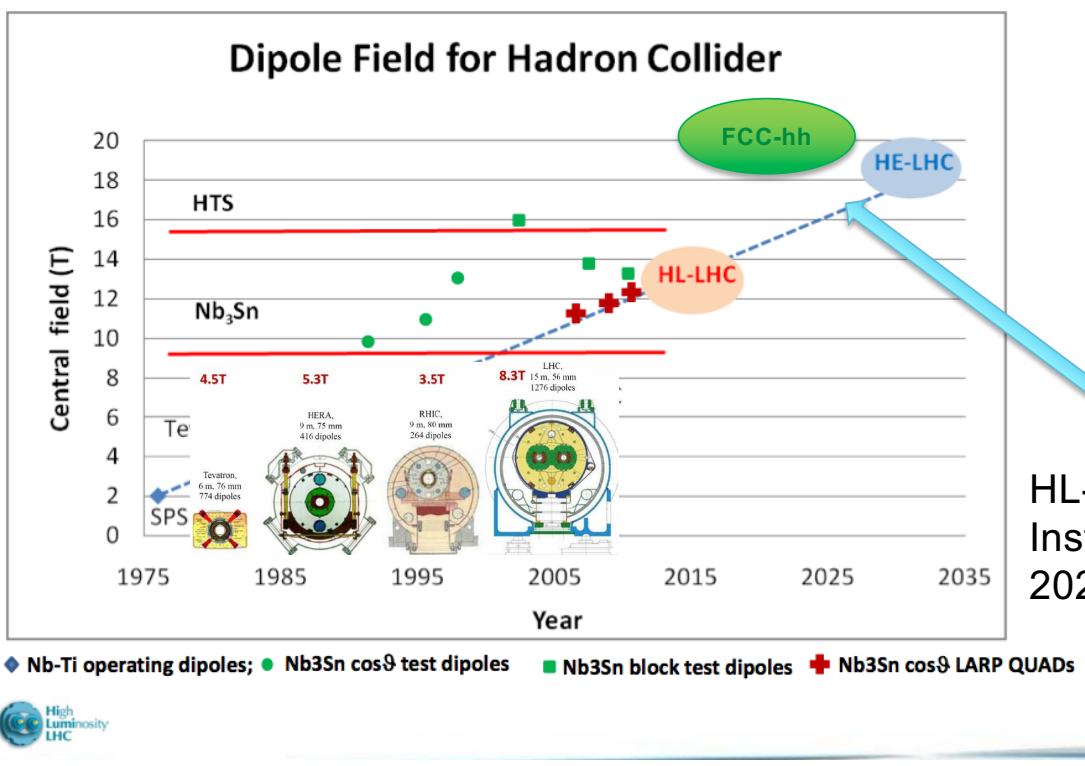
- MQXFBP1 performance limitation (6.5 TeV) analysis had a **significant breakthrough** in January 2022: analysis of limiting coil 108
 - Broken filaments in a strand always in the same position of the cross-section, in several sections close to the transition in the poles –in agreement with voltage tap and quench antenna localization



Broken filaments in coil 108, limiting MQXFBP1 (M. Crouvizer, A. Moros, S. Sgobba, et al.)

High Field SC Magnets

Magnet development requires substantial R&D effort!!!



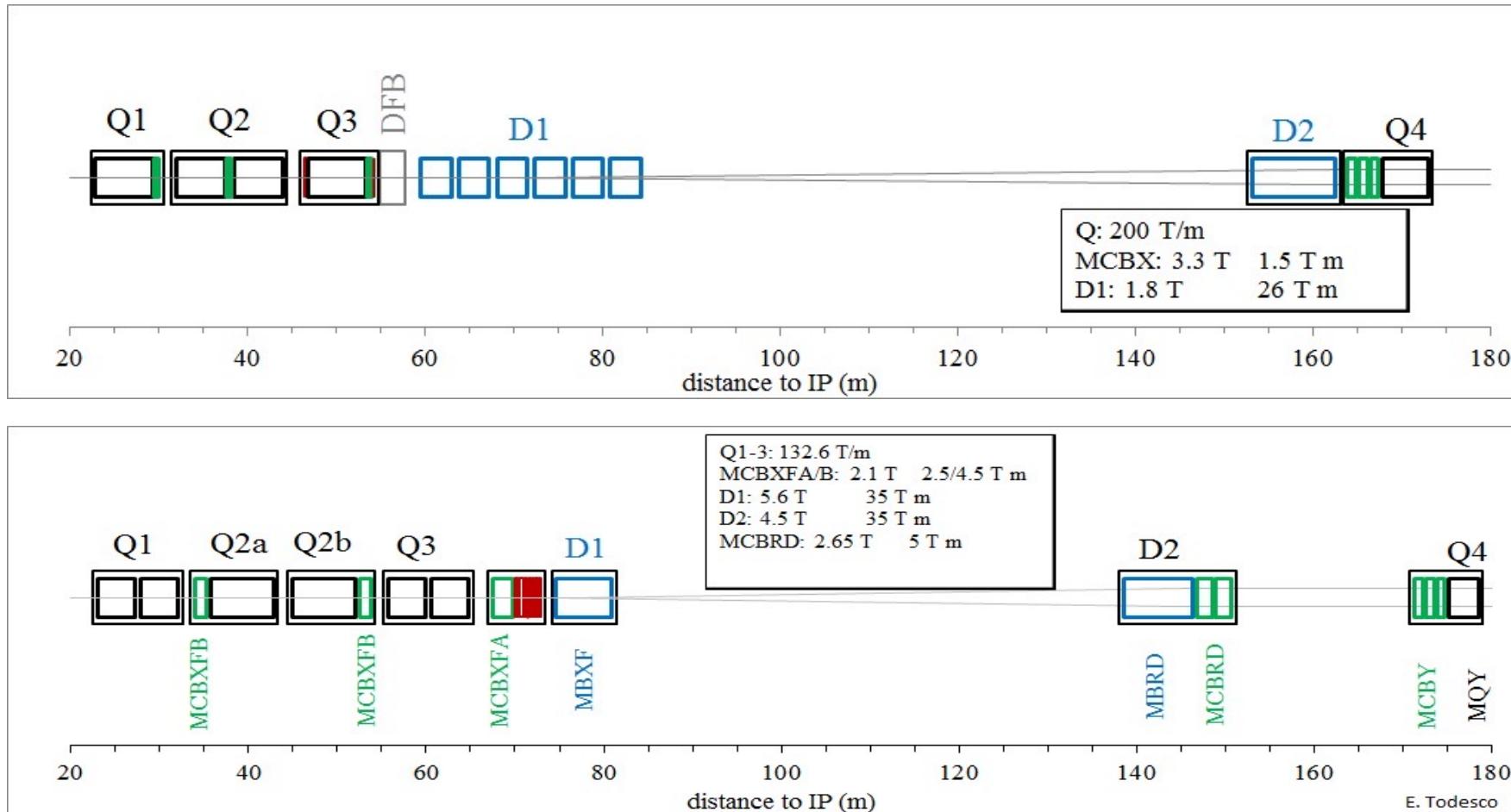
Ca. 30 years of NbTi magnet development leading up to the LHC dipole magnets!

Transition from NbTi to Nb₃Sn: requires similar length of R&D!

HL-LHC led the R&D for 11-15T magnets based on Nb₃Sn technology:

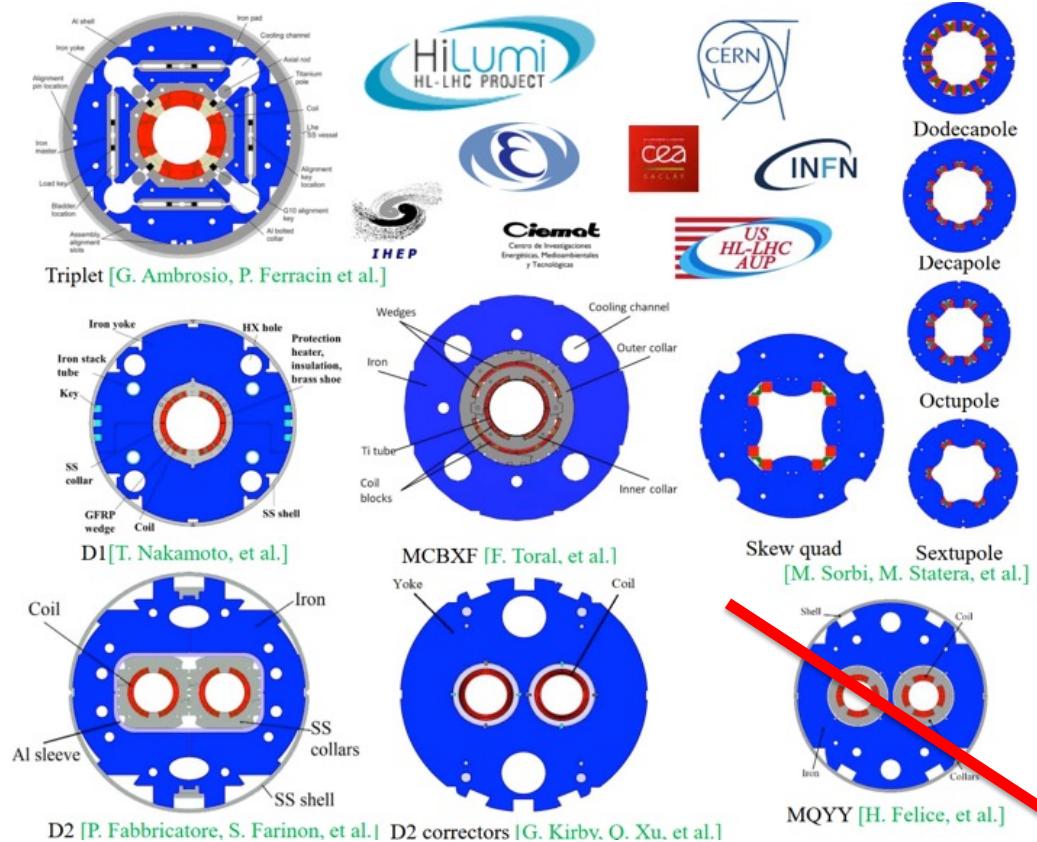
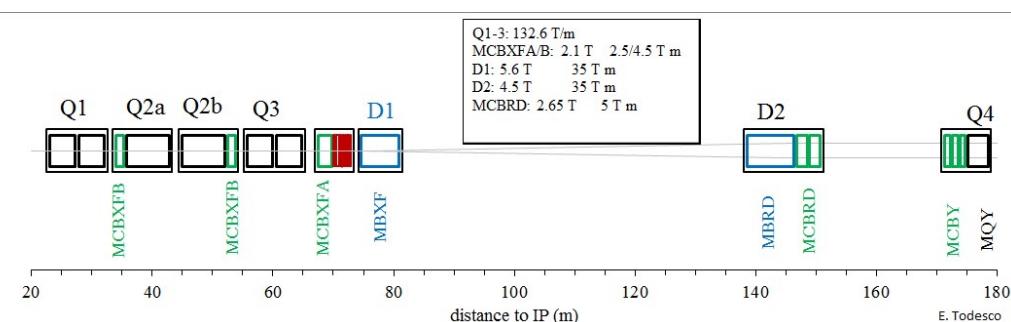
- Started in early 2000
- over 25 years program
- Ready for installation in 2028

New HL-LHC Triplet Layout:



Magnet Upgrade Scope

- Design, engineering, construction, test and installation the **Insertion Region (IR) magnets** of IR1 and IR5 for the HL-LHC upgrade.
 - Q1/Q3 cryomagnets: from AUP (US)
 - Q2: from CERN
 - MCBXF nested corrector magnets: from CIEMAT (Spain)
 - HO corrector magnets: from INFN-LASA (Italy) [completed]
 - D1 cold masses: from KEK (Japan)
 - D2 magnets: from INFN-Ge (Italy)
 - D2 corrector magnets: from IHEP (China)
 - DCM: from CERN



IN-KIND CONTRIBUTIONS



EU in-kind collaboration

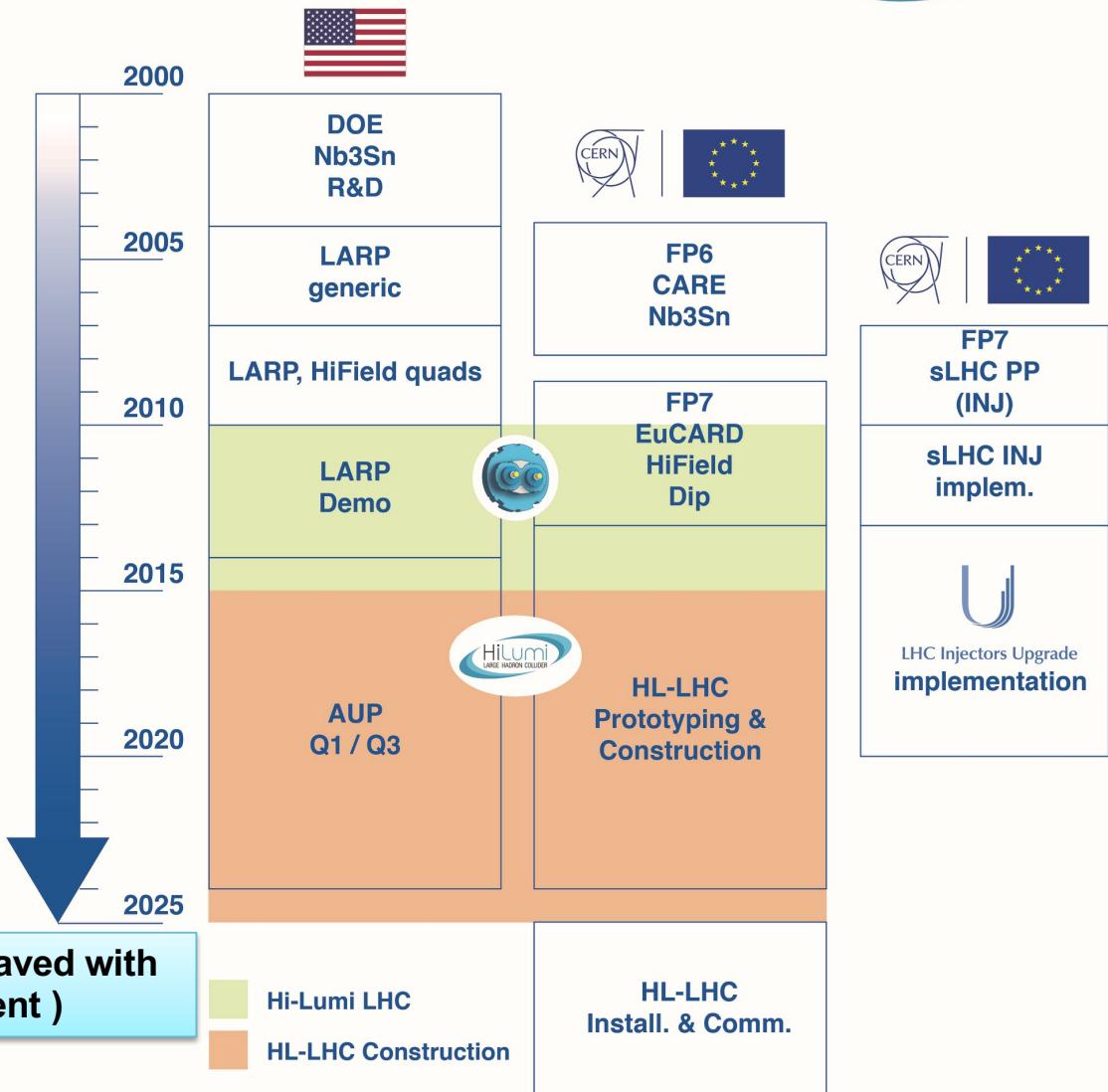


Collaboration with personnel

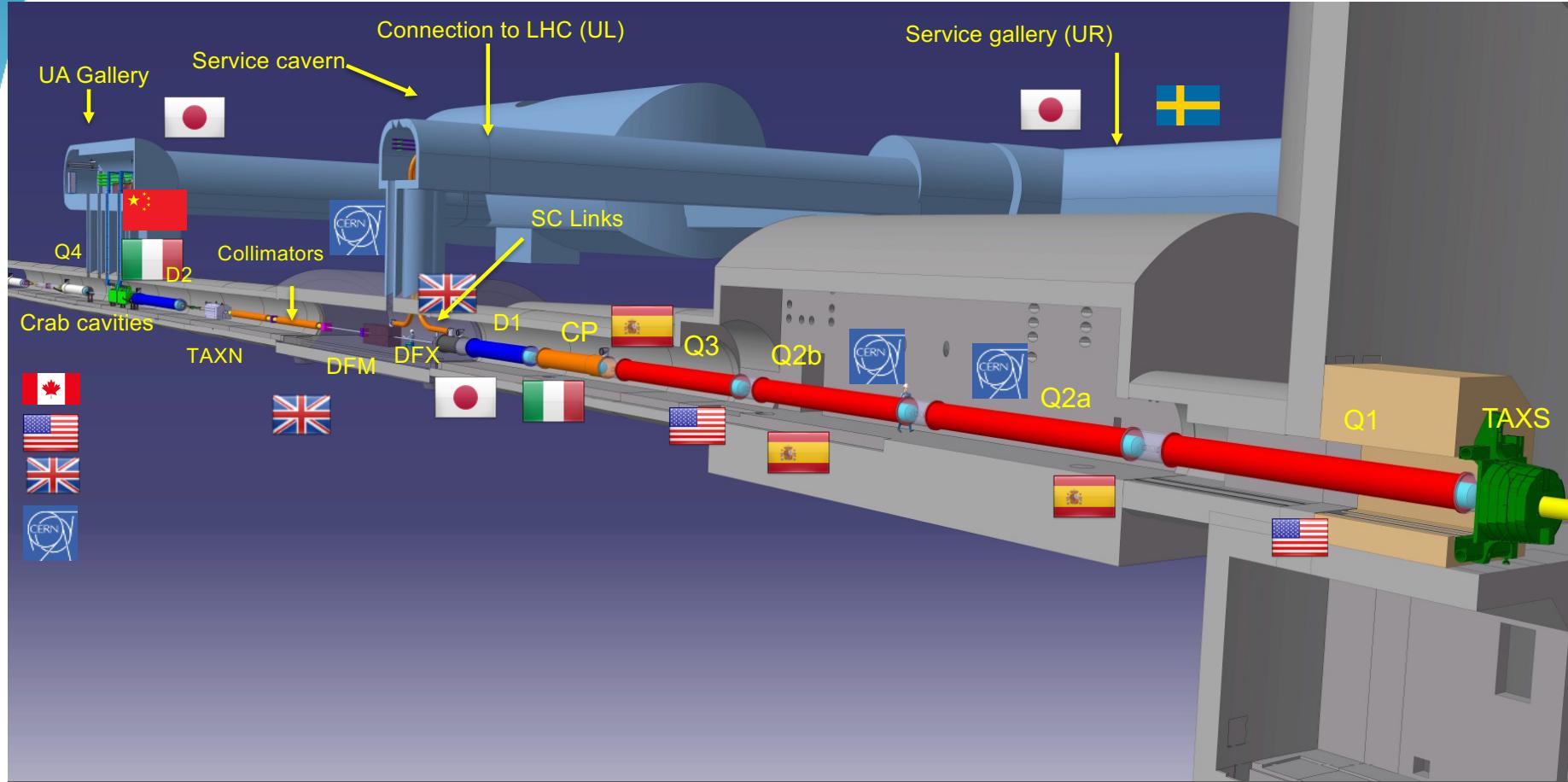


				
<p>BINP+... Absorbers CC ampli. C. Leads e-lens</p>				<p>CERN - KEK R&D</p>
	<p>TRIUMF</p>		<p>IHEP</p>	<p>KEK D1 design & construction</p>

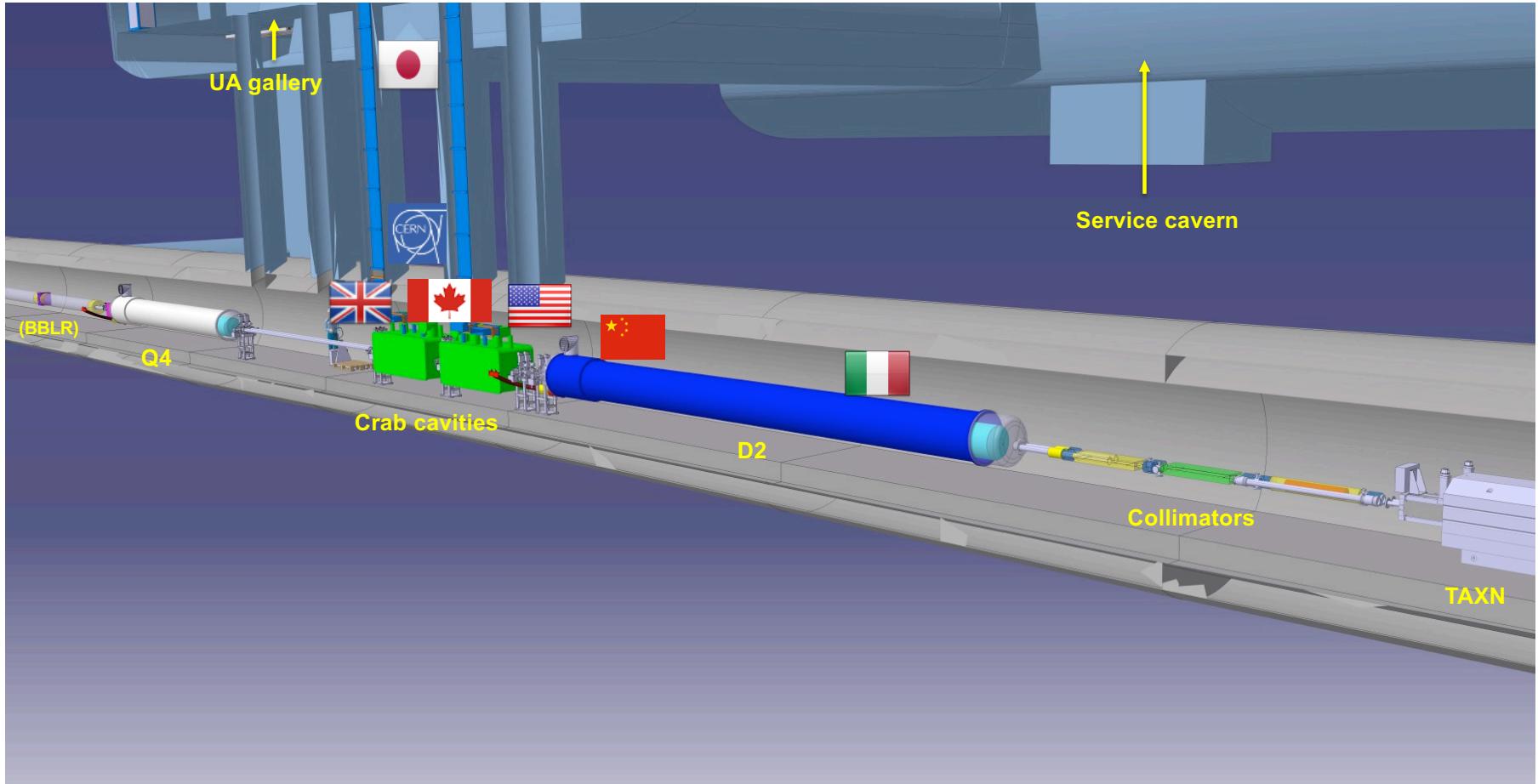
Schedule is complex since in-kinds are interleaved with our works: we do not receive finished equipment)



The Insertion Region (up to Q4)



The MS region with in-kind contributions



TDR V1.0 - The last version of the TDR including the added scope - 2020



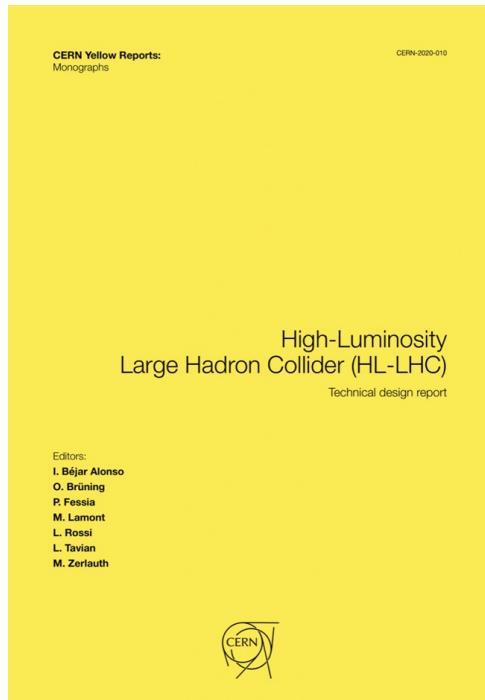
V0.1 Published in electronic version for the October 2016 Cost & Schedule review

[EDMS: 1723851](#)

and as CERN Yellow Book in October 2017

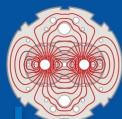


Advanced Accelerator Course; October, 2025



Updated Version V 1.0 published as
CERN Yellow Book in December 2020
<https://e-publishing.cern.ch/index.php/CYRM/issue/view/127>

Oliver Brüning CERN



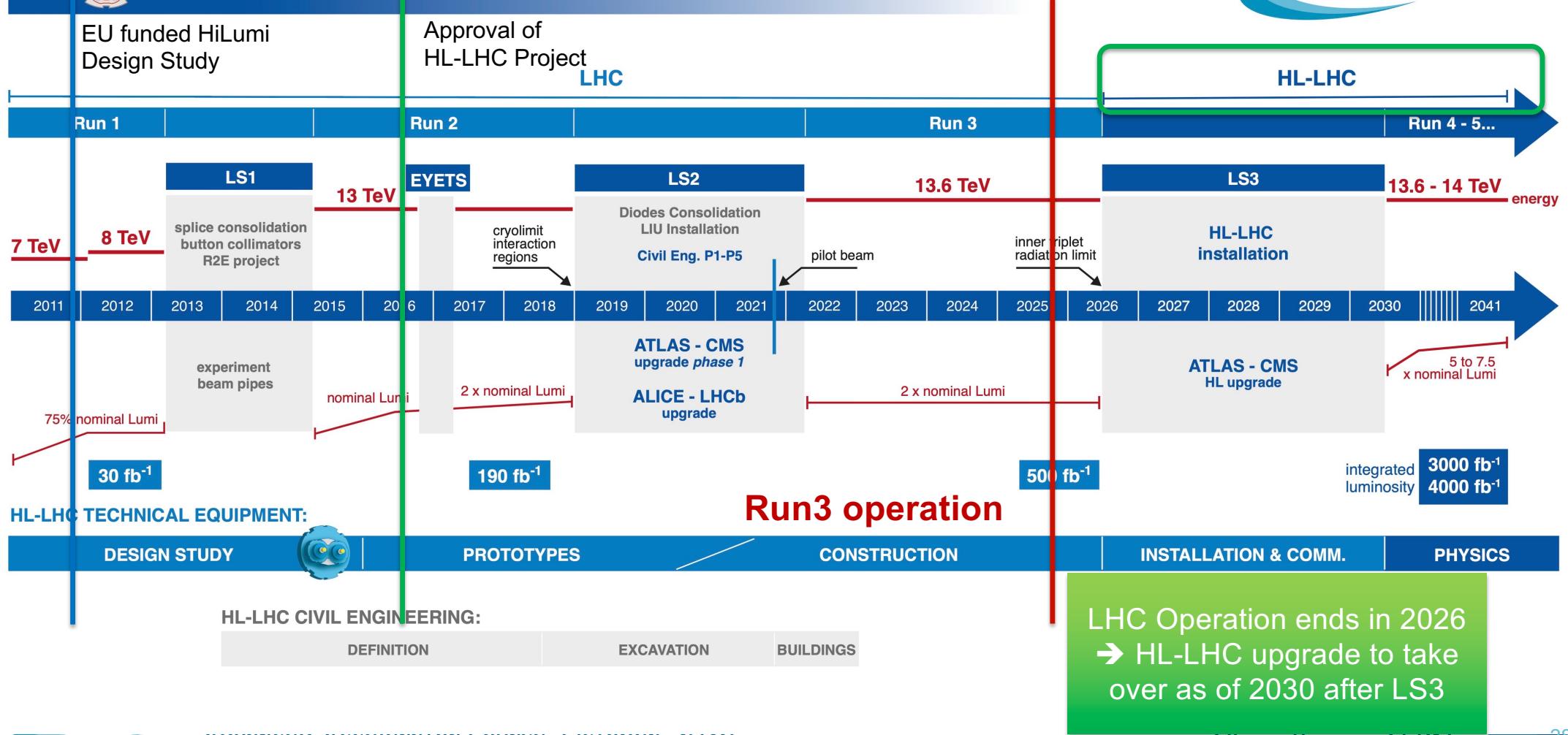
LHC / HL-LHC Plan



EU funded HiLumi Design Study

Approval of HL-LHC Project

LHC



Goal of HL-LHC upgrade project

- Prepare machine for operation beyond **2026** and up to **~2041**
- Operation scenarios for:
 - Total integrated luminosity of **3000fb⁻¹ to 4000fb⁻¹** in around 10-12 years [ca. 10x LHC]

■ An integrated

■ **Nominal**: le

■ **Ultimate**: le

Need to overcome several limitations in the existing LHC machine!!!

Ca. 1BCHF CtC Project

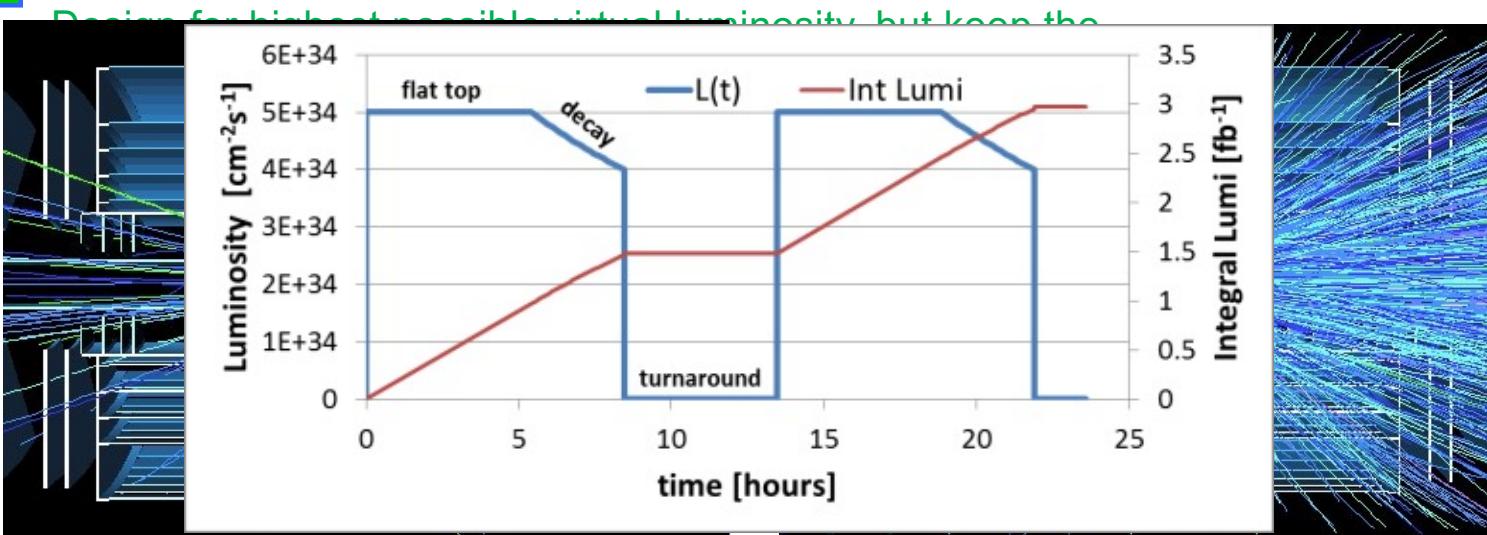
→ Operation with levelled luminosity!

→ **High machine efficiency and reliability are key upgrade ingredients!**

→ **A challenge as well for the experiments!**

Luminosity optimization:

- Luminosity Levelling at the luminosity frontier:



- Lifetime proportional to total particles:

$$\tau_{eff} = \frac{N_{tot}}{n_{IP} \cdot \sigma_{tot} \cdot L_{leveled}}$$

- Luminosity limitations:
[for Hadron Collider]
 - Event rate and pileup
 - Debris from the IP [quench protection]
 - Heat load and radiation in magnets

Luminosity optimization: Beam Lifetime

■ Fill length:

$$\frac{dN_{tot}}{dt} = -n_{IP} \cdot \sigma_{tot} \cdot L \quad \rightarrow \quad \tau_{eff} = \frac{N_{tot}}{n_{IP} \cdot \sigma_{tot} \cdot L_0}$$

■ Example LHC: $\sigma_{tot} \approx 100\text{mbarn}$ [10^{-25}cm^2]; 2 IPs; $N_{tot} \approx 3 \cdot 10^{14}$

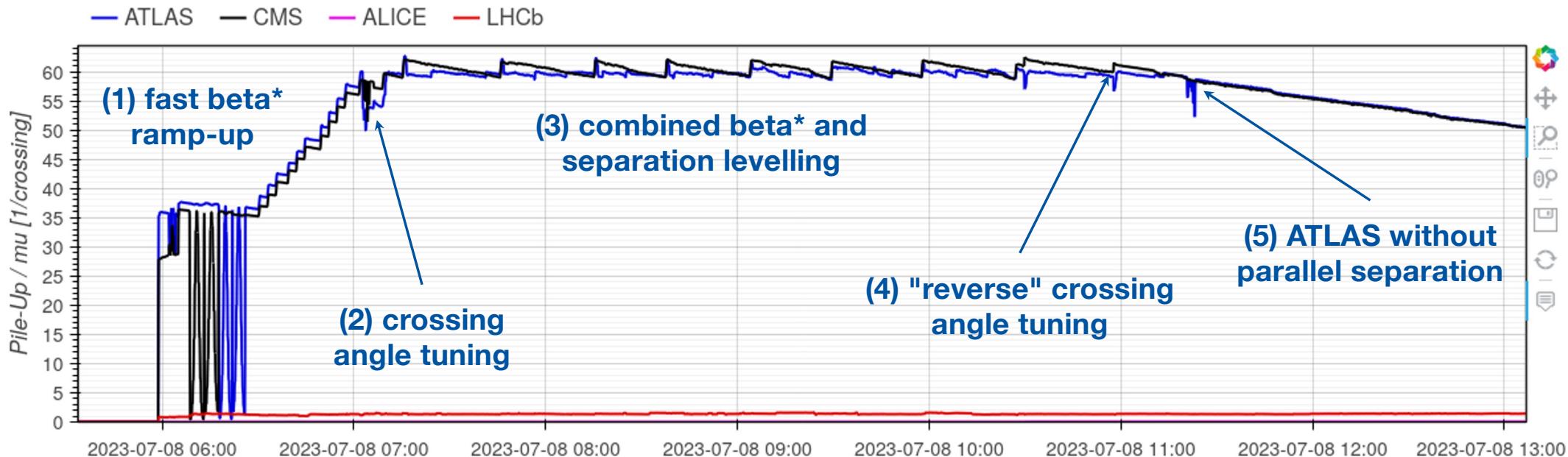
Nominal Luminosity: $L_0 = 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow \tau_{eff} \approx 42 \text{ hours}$

10 x Luminosity: $L_0 = 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow \tau_{eff} \approx 4 \text{ hours}$

→ Efficient operation requires that the average fill length [data taking for physics] is significantly longer than the time required for preparing a new fill for physics!!!

Orchestration of collisions in 2023

ca 5 hours of levelling



1. fast beta* levelling ramp up to $\mu=58$ in ATLAS (~40mins @ 1.6E11 ppb)
2. crossing angle tuning to reduce ATLAS wrt CMS (-10urad once ATLAS @ max PU)
3. combined beta*/separation levelling
4. crossing angle tuning back to nominal (once $\beta^* = 30\text{cm}$)
5. ATLAS levelling not effective anymore – operation without parallel separation

Physics Fill Performance to Date

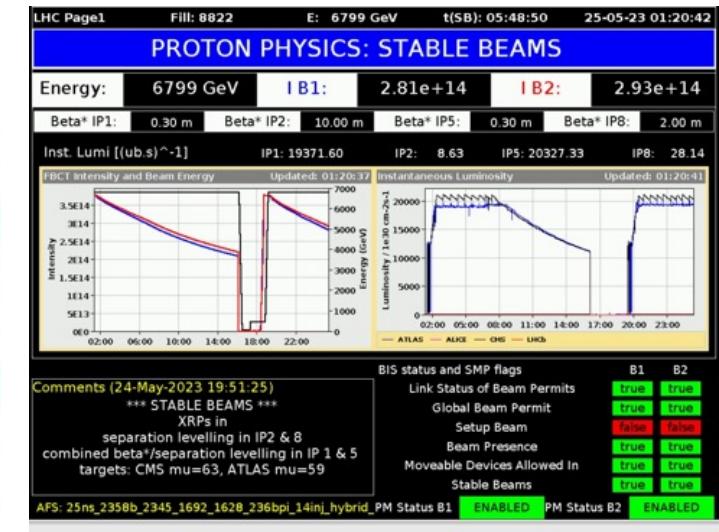
Two fills of ca 12 hours back to back

- New record: Integrated luminosity of 1.2 fb^{-1} in 24h !
- Peak levelling just above $2.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Pileup targets ATLAS/CMS = 63 / 59

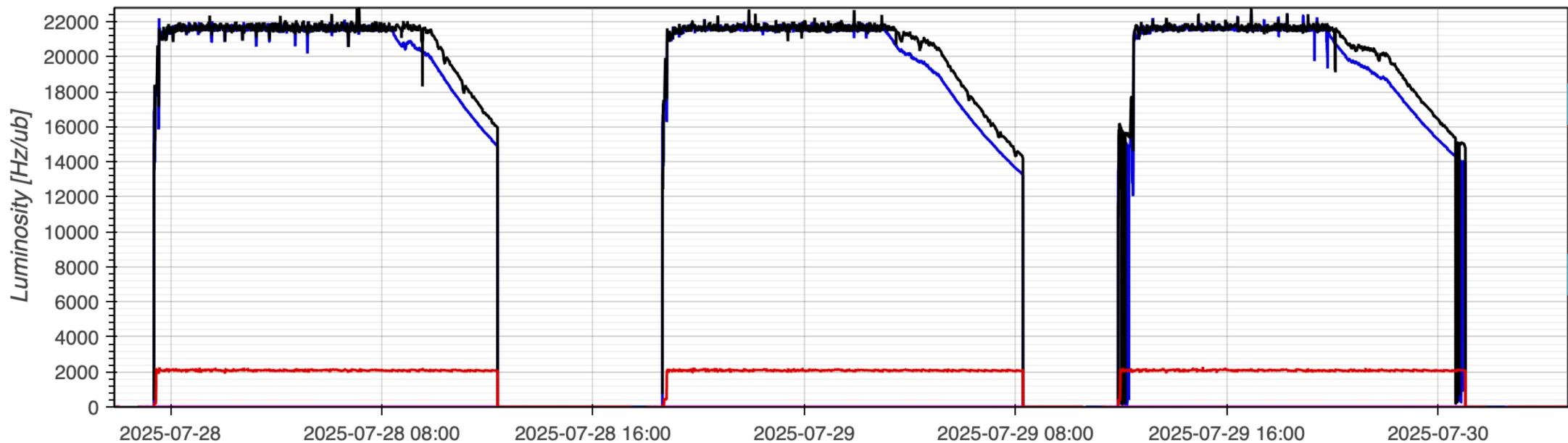


24th to 25th of May 2023

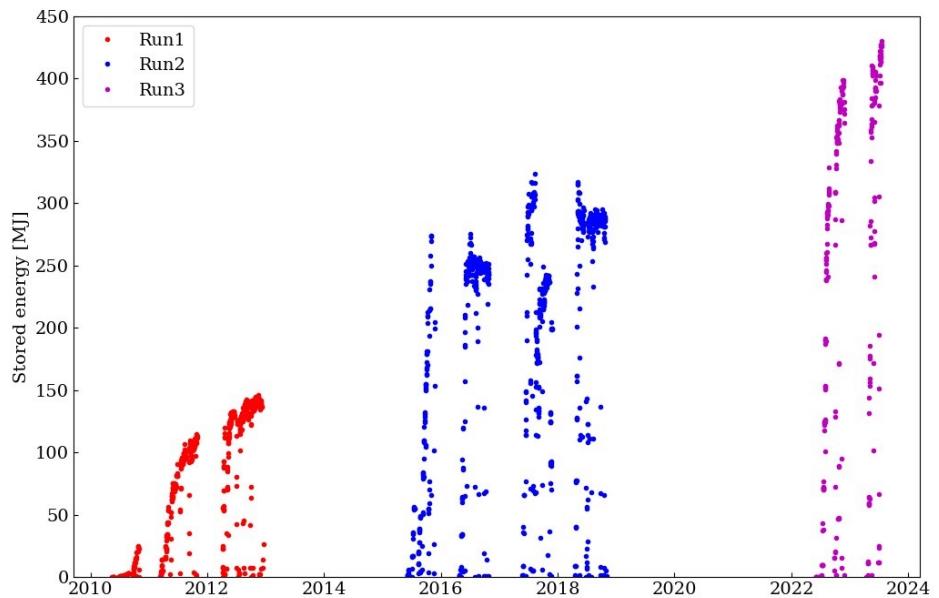
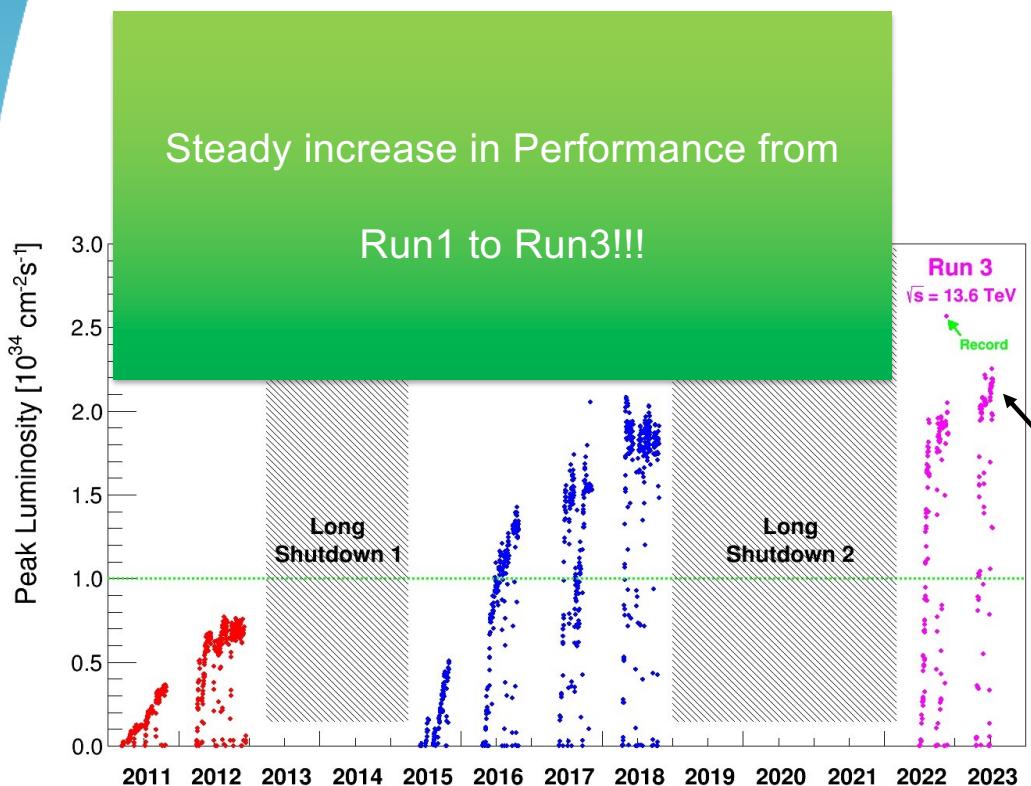
Max energy per beam at start of stable beams:
425 MJ with 2464 bunches
 $1.59 \times 10^{11} \text{ p/b}$ (Injected: 1.61)



Example: levelled fills in 2024



Comparison of the 3 LHC Running Periods



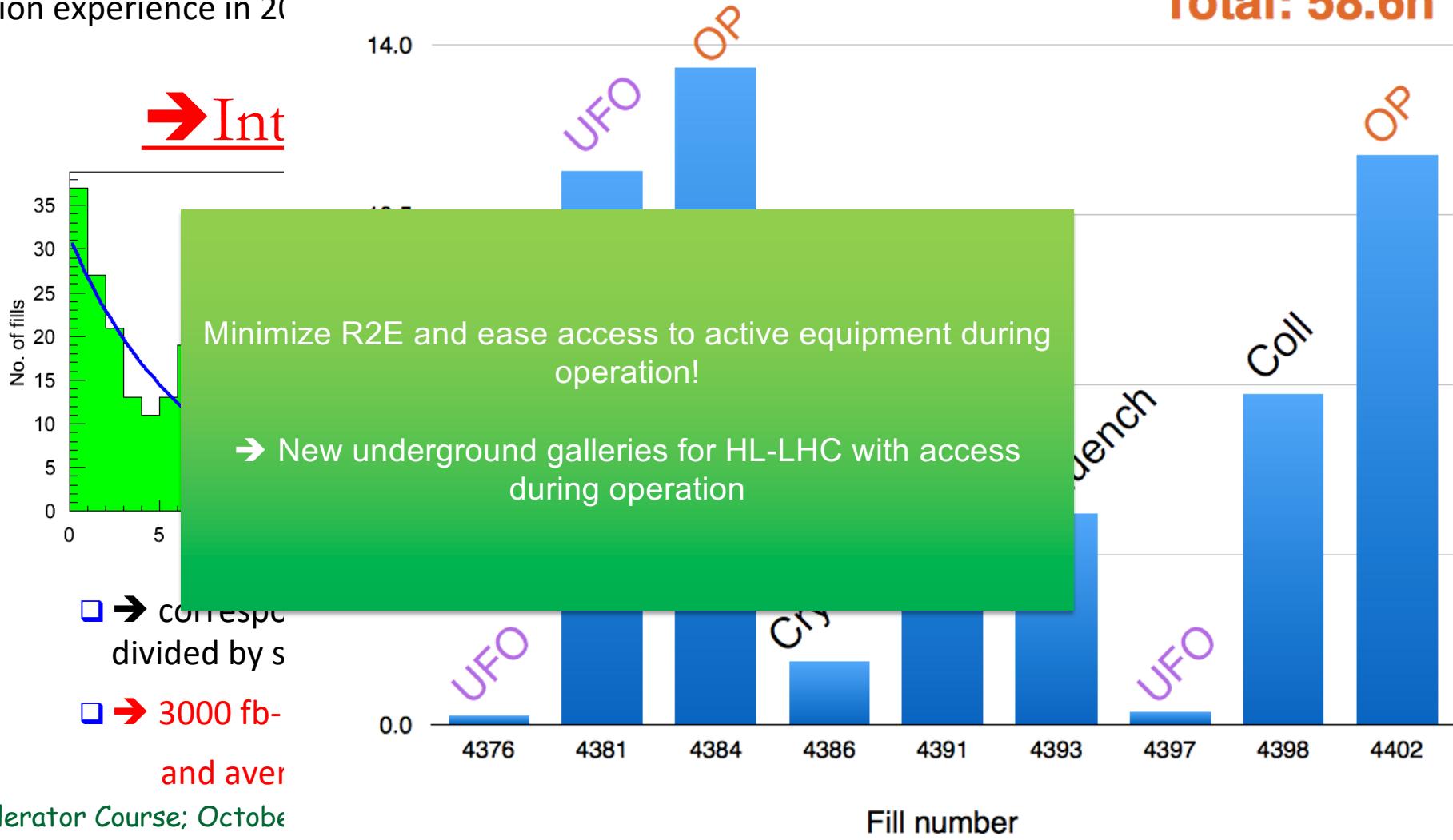
Stored energy record of 425 MJ
with 2464 bunches @ $1.6\text{E}11 \text{ ppb}$ (@ start of Stable Beams) .

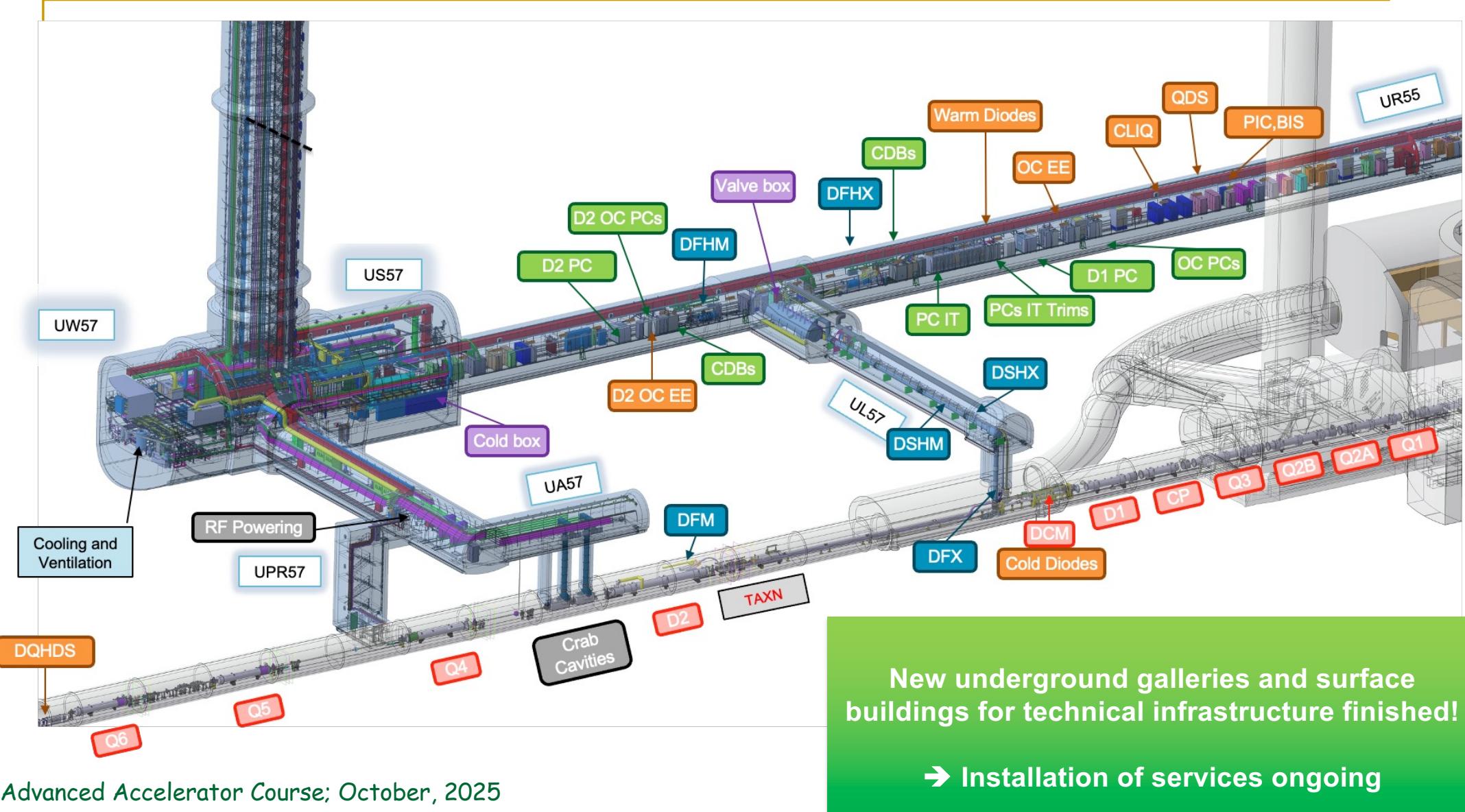
Levelled Luminosity → requires efficiency!

HL-LHC Challenge: Machine Efficiency

□ Operation experience in 2016

Total: 58.6h





Performance optimization: Peak Luminosity

■ Luminosity recipe (round beams):

$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot \gamma \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot F(\phi, \beta^*, \varepsilon, \sigma_s)$$

- 1) maximize bunch intensities
- 2) minimize the beam emittance
- 3) minimize beam size (constant beam power);
- 4) maximize number of bunches (beam power);
- 5) compensate for ‘F’;
- 6) Improve machine ‘Efficiency’

beam aborts and maximize luminosity lifetime!

- LIU Project & LHC collim.
- magnet aperture
- X-ing angle
- Crab Cavities
- Minimize number of

Suggestion: beam parameters and how to get there

Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)
Beam energy in collision [TeV]	7	7
N_b	1,15E+11	2,2E+11
n_b^{12}	2808	2760
N_{tot}	3,2E+14	6,1E+14
Beam current [A]	0,58	1,1
Half Crossing angle [μ rad]	142,5	250
Minimum β^* [m]	0,55	0,15
ϵ_n [μ m]	3,75	2,50
ϵ_L [eVs]	2,5	3,03
Piwinski parameter	0,65	2,66
Peak Luminosity without crab-cavity [$\text{cm}^{-2} \text{ s}^{-1}$]	1,00E+34	8,1E+34
Virtual Luminosity with crab-cavity: $L_{peak} * R1/R0$ [$\text{cm}^{-2} \text{ s}^{-1}$]	-	1,70E+35
Events / crossing without levelling and without crab-cavity	27	212
Levelled Luminosity [$\text{cm}^{-2} \text{ s}^{-1}$]	-	5,0E+34 ⁴
Events / crossing (with leveling and crab-cavities for HL-LHC) ⁷	27	131
Leveling time [h] (assuming no emittance growth) ⁷	-	7,2
n_b / injection	288	288
ϵ_n at SPS extraction [μ m] ³	3,5	2,1

LHC Magnet system
LHC injector complex;
HL-LHC new collimation

HL-LHC triplet magnets

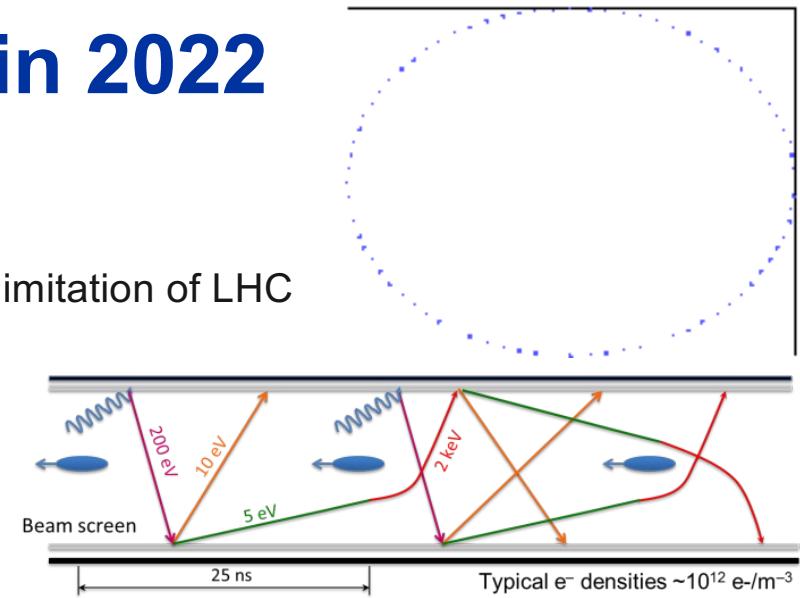
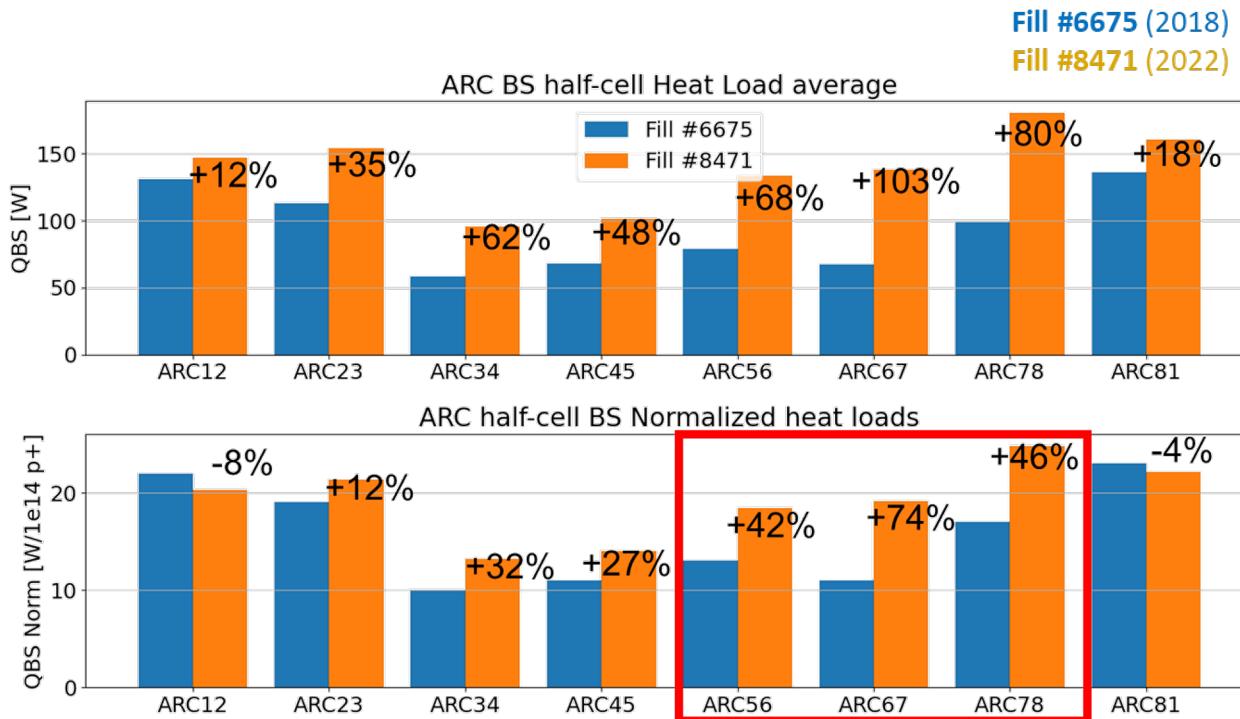
HL-LHC crab cavities
HL-LHC new IR collimation

Machine operation &
availability

LHC injector complex

Electron Cloud: What we Learnt in 2022

- Dealing with electron cloud
 - Sector 7-8 emerged degraded from LS2, determining heat load limitation of LHC



Long Shutdown 1 (2013-2015)

- Provoked significant degradation of heat loads in S12 & S23 & S78 & S81

Long Shutdown 2 (2019-2022)

- Provoked significant degradation of heat loads in S56 & S67 & S78

Electron Cloud: Intensity Reach for 2023 and Beyond

- The intensity reach for different filling schemes is determined by the limitation in S78

	4x72b	5x48b	5x36b	hyb-48b	hyb-36b	8b+4e
N bunches	2760	2748	2496	2452	2464	1972
Intensity	1.1e11	1.2e11	1.5e11	1.75e11	2e11	-
Int. limit [fb ⁻¹]	0.89	0.89	1.19	1.19	1.24	1.09 -1%

But can we count on stable secondary emission yields over the coming years or do we need to be prepared for a further degradation during LS3?

- Hybrid 56

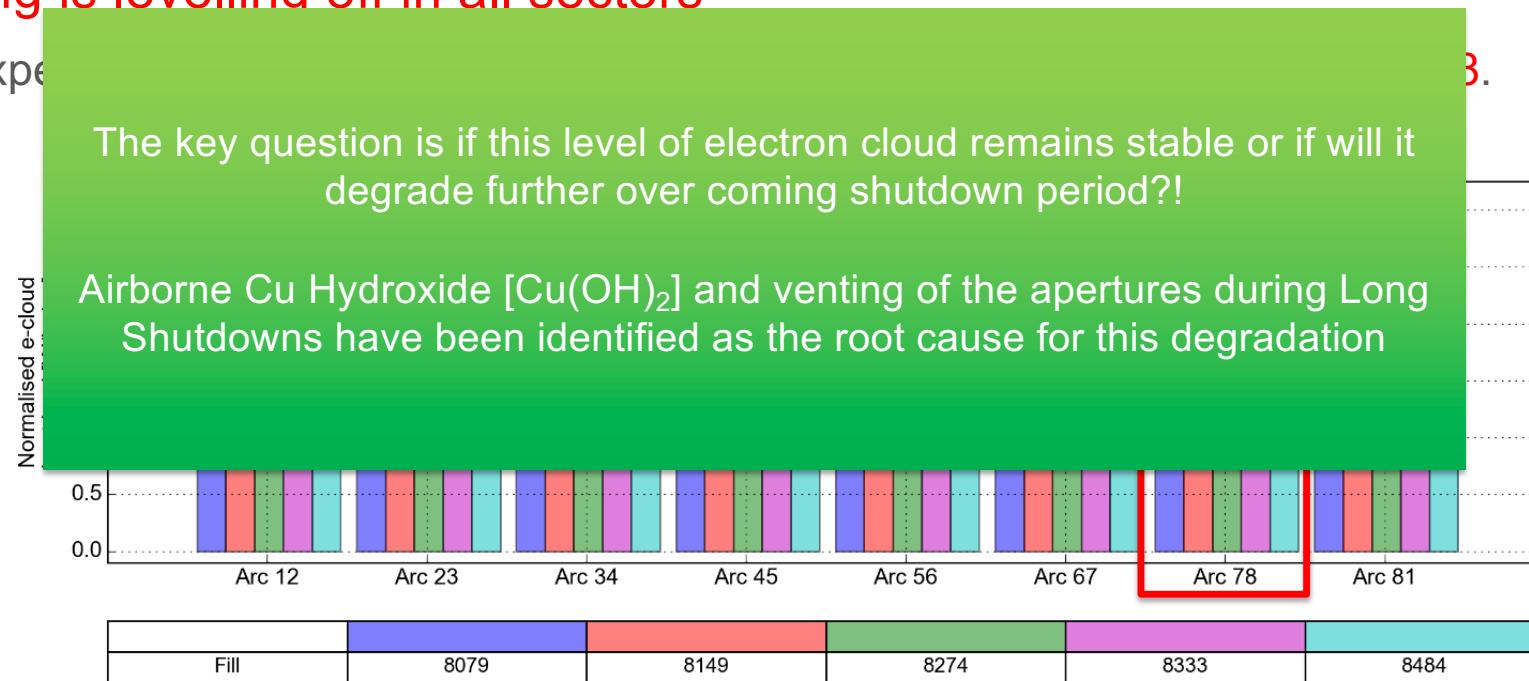
- Use of hybrid
- Run 3 bunches

reached to date
LHC upgrade



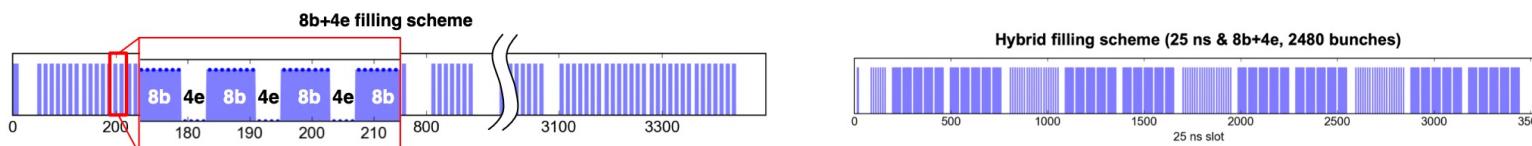
Electron-cloud: HL-LHC Prospect

- The electron cloud situation has degraded further during LS2:
Increase of heat load from e-cloud, in particular in **sector 78**
→ limits the intensity reach.
- Scrubbing is levelling off in all sectors
- → not expected to improve

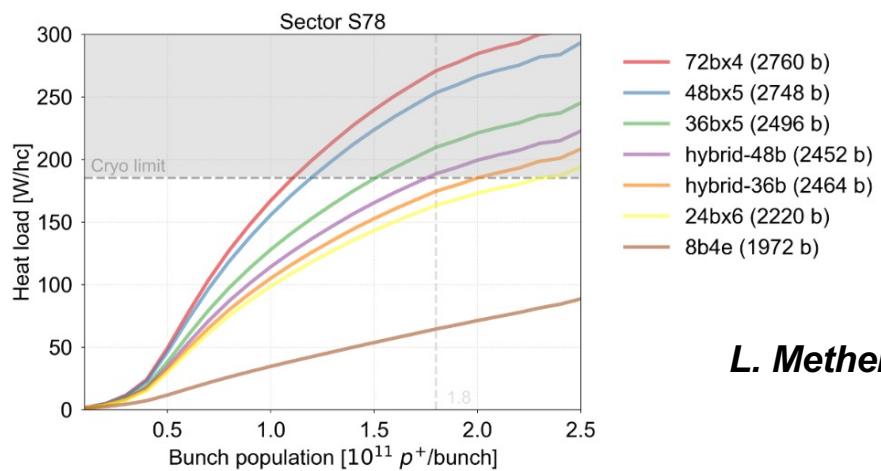


Electron-cloud: filling scheme mitigation

- **8b+4e** very effective to reduce heat load (>55%) but limits the bunches to <2000
- **Hybrid schemes** (mix 25 ns with 8b+4e) is the best compromise (& tuneable)



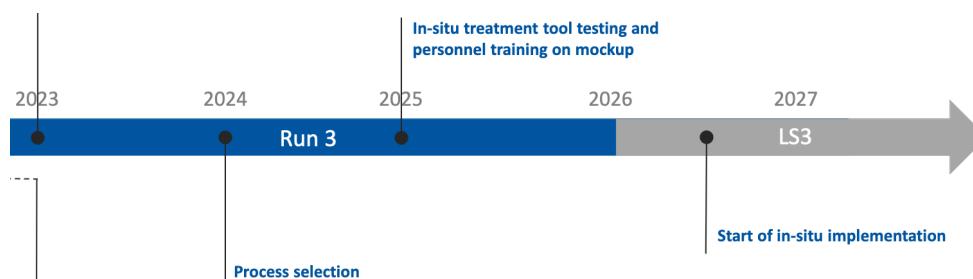
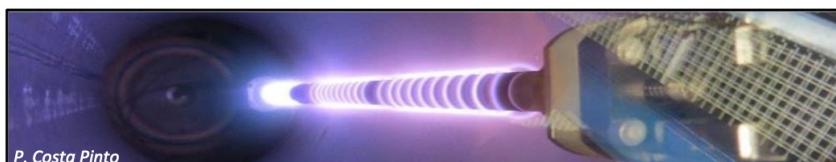
- ⇒ Strong impact of **filling scheme** on intensity reach:



L. Mether, LHC Chamonix workshop, 23/01/2023

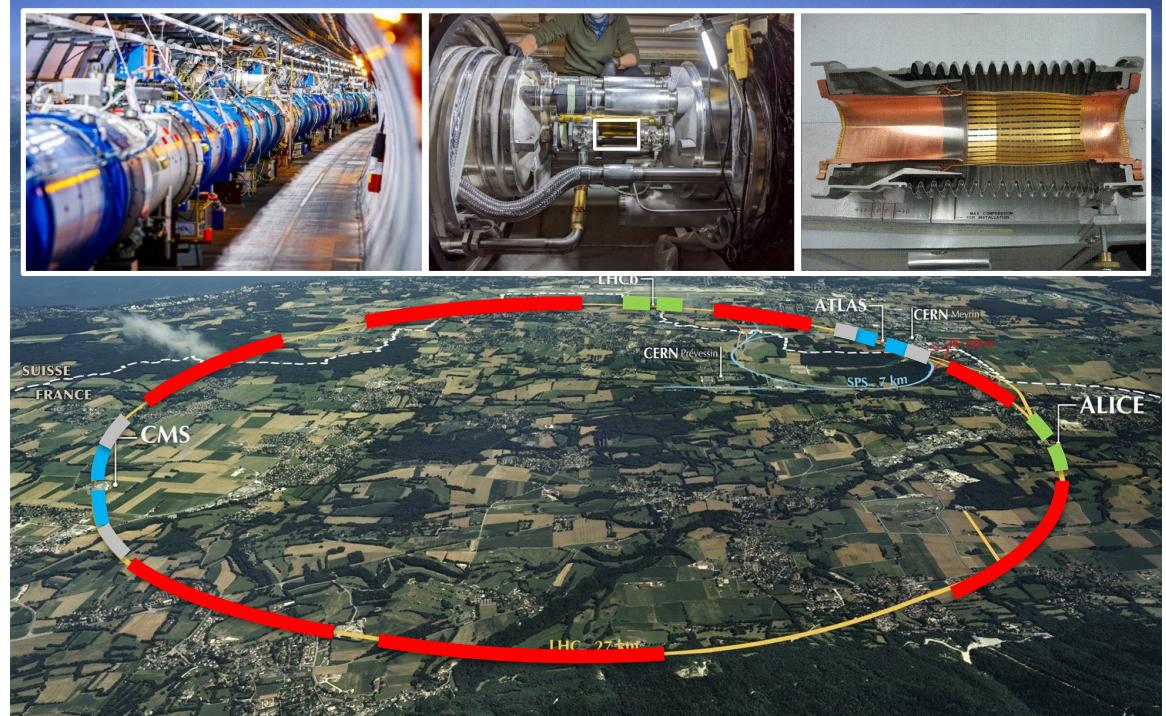
e-cloud: mitigations

- Beam stability is also degraded → one needs to address the root cause and not only the heat load with e.g. cryogenics upgrade.
- Ideal cure: **in situ surface treatment** (see *V. Petit, LHC Chamonix workshop, 23/01/2023*)
 - Plasma-assisted CuO reduction and carbon recovery (PE-CVD)
 - Carbon coating (10-20 nm) by sputtering (PVD)



⇒ Project proposed (see *M. Lamont, LHC “Chamonix” workshop summary, 25/03/2023*)

Beam Screen Treatment in the LHC arcs



Mitigation strategy

Deposit a **thin amorphous carbon layer** on selected arc beam screens

→ recover **conditioning efficiency**

→ ensure **surface robustness** against ventings (LS)

→ profit from **HL-LHC coating developments**

→ adapt process to **increase coating speed**, and cope with new beam line geometry constraints (**one half-cell coated in one passage**)

In. Triplets IP2/8
In-situ
190 m total

In. Triplets IP1/5
Ex-situ
320 m total

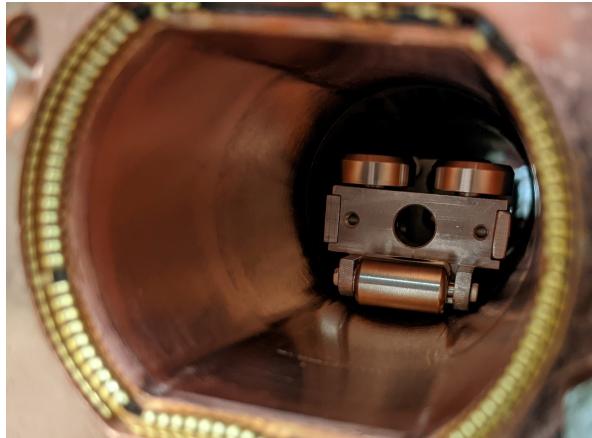
Matching sections
Ex-situ, in magnet
20 m total

Arcs
In-situ
≈ 12 km total

BST

Coating train

- New design to cope with **changing cross section**, limit **lateral friction** and **risk of mechanical failure**
- **Validation of the mechanical design** (ensures **no damage to components**)
- **Assembly test in limited space** (check assembly feasibility, define need for specific tooling, assembly procedure...)

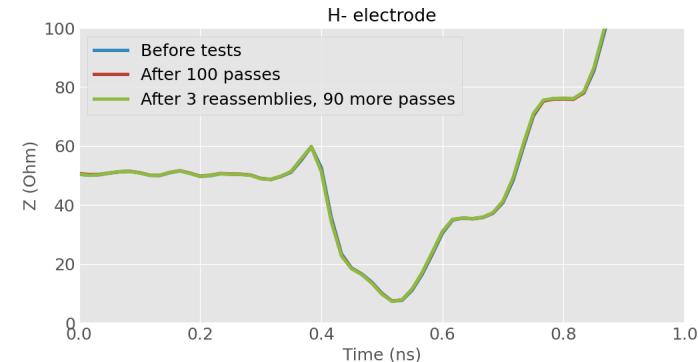


Thanks to TE-MSC



Advanced Accelerator Course; October, 2025

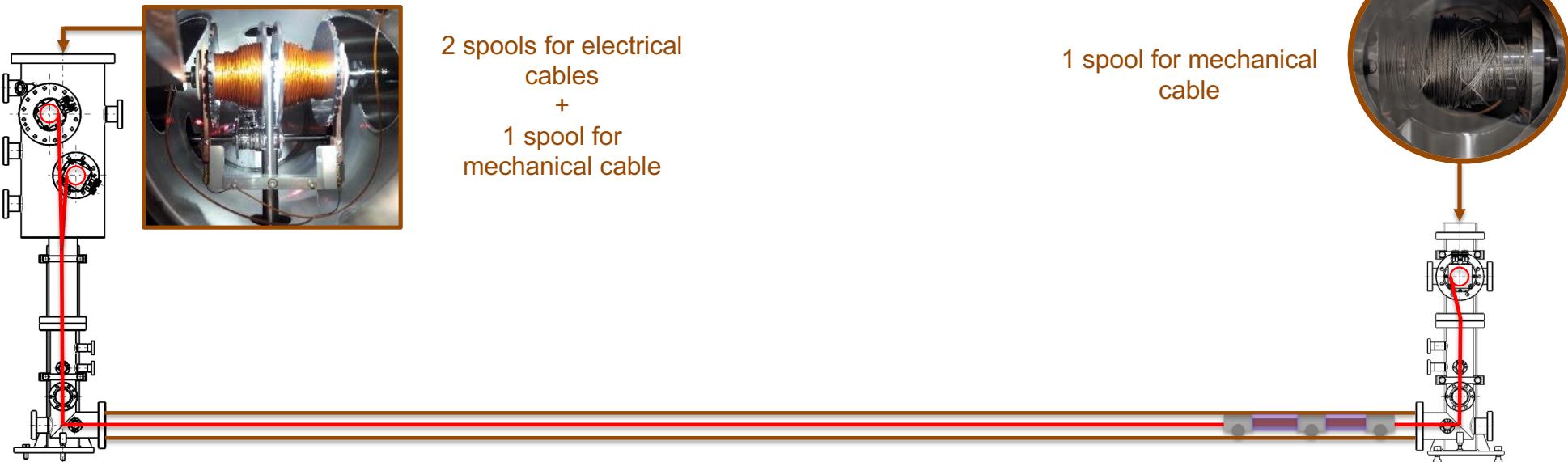
BPM qualification after 200 train passages



M. Krupa SY-BI, [EDMS 3161981](#)

Oliver Brüning CERN

Coping with arc curvature

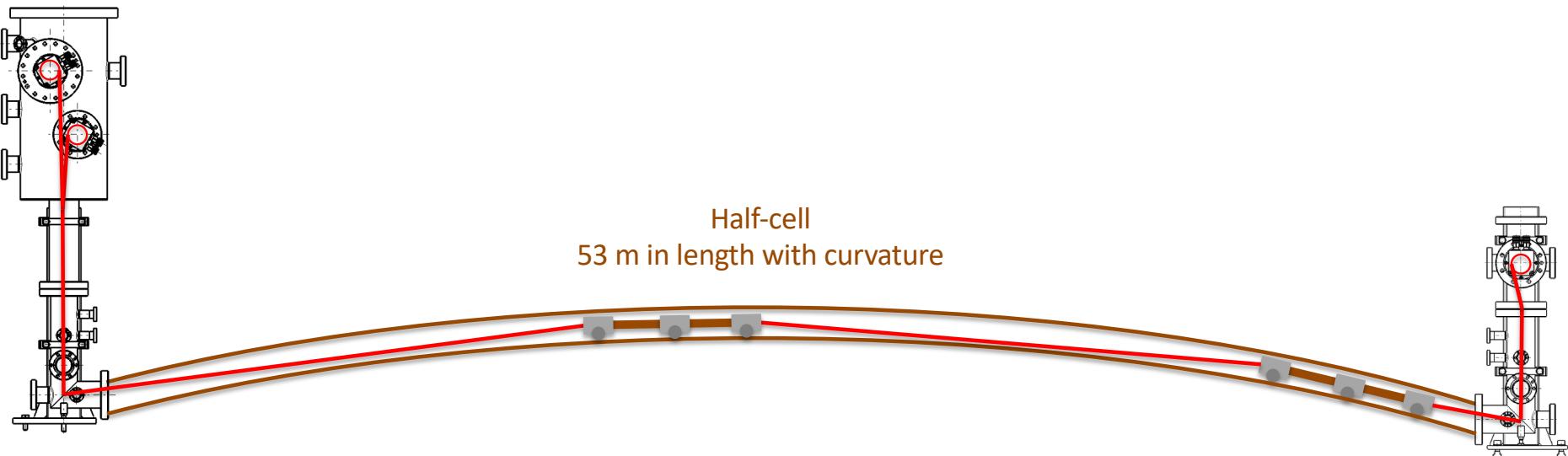


System developed for Q5L8 (LS2) and HL-LHC beam screen coating:

- Plasma powering: **electrical cables**
- Train displacement: **mechanical pulling and braking cables**

→ **In-vacuum spool system** with automated rolling/unrolling by external motors

Coping with arc curvature



Beam Screen Treatment in the arcs:

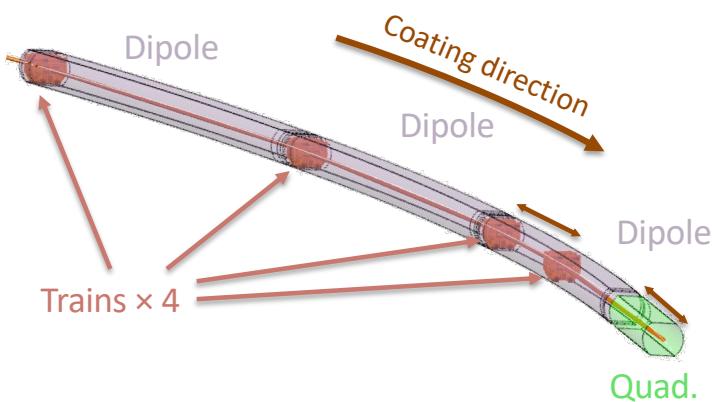
- Curvature → **no line of sight** over 53 m
- **Cables will scratch the beam screen**, on its inner face with respect to curvature

→ Unacceptable: **wearing of cables, risk of Kapton chips** (electrical cable)

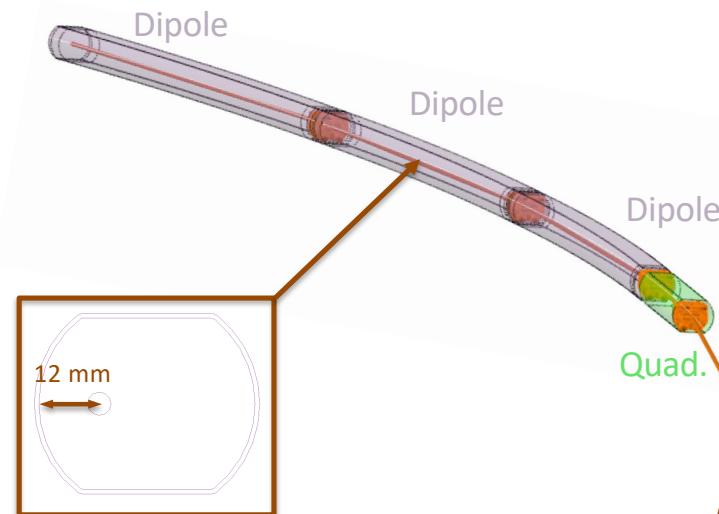
→ Use **several trains to recenter the cables** in the beam screen... and **coat several sections simultaneously**

Coping with arc curvature – 4-train configuration

Start of half-cell beam line coating



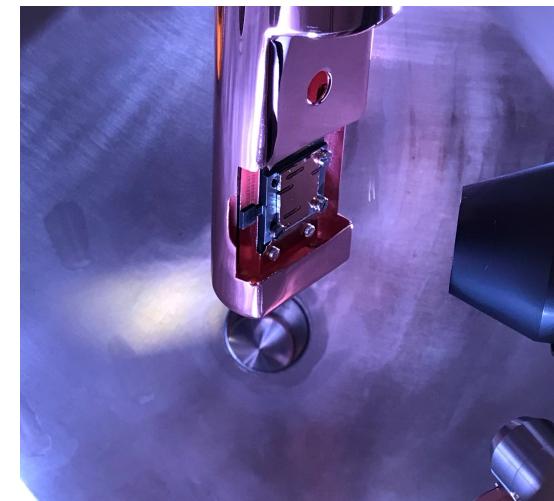
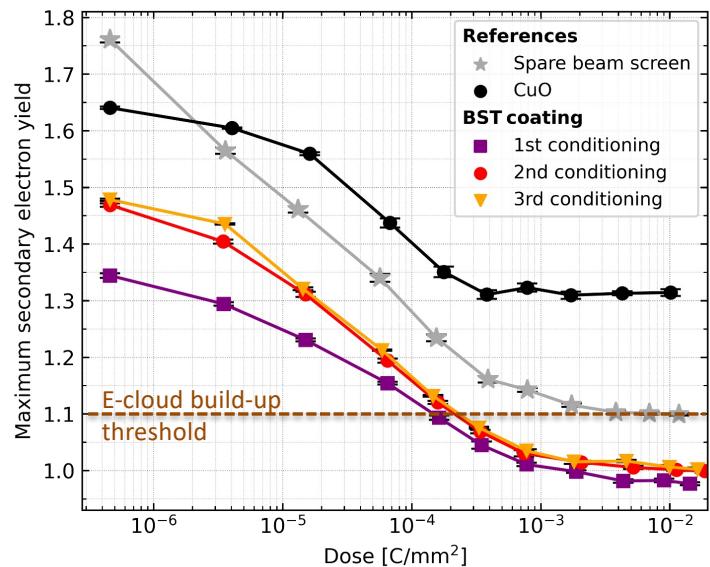
End of half-cell beam line coating



F. Santangelo TE-VSC

- **4 trains** are necessary to ensure no contact between the beam screen and the cables
- Mechanical **validation** on **1:1 scale mock-up**

Coating conditioning at 15K and robustness against ageing



Higher coating speed → Thinner coating (10 nm)
Coating over 53 m → Higher base pressure

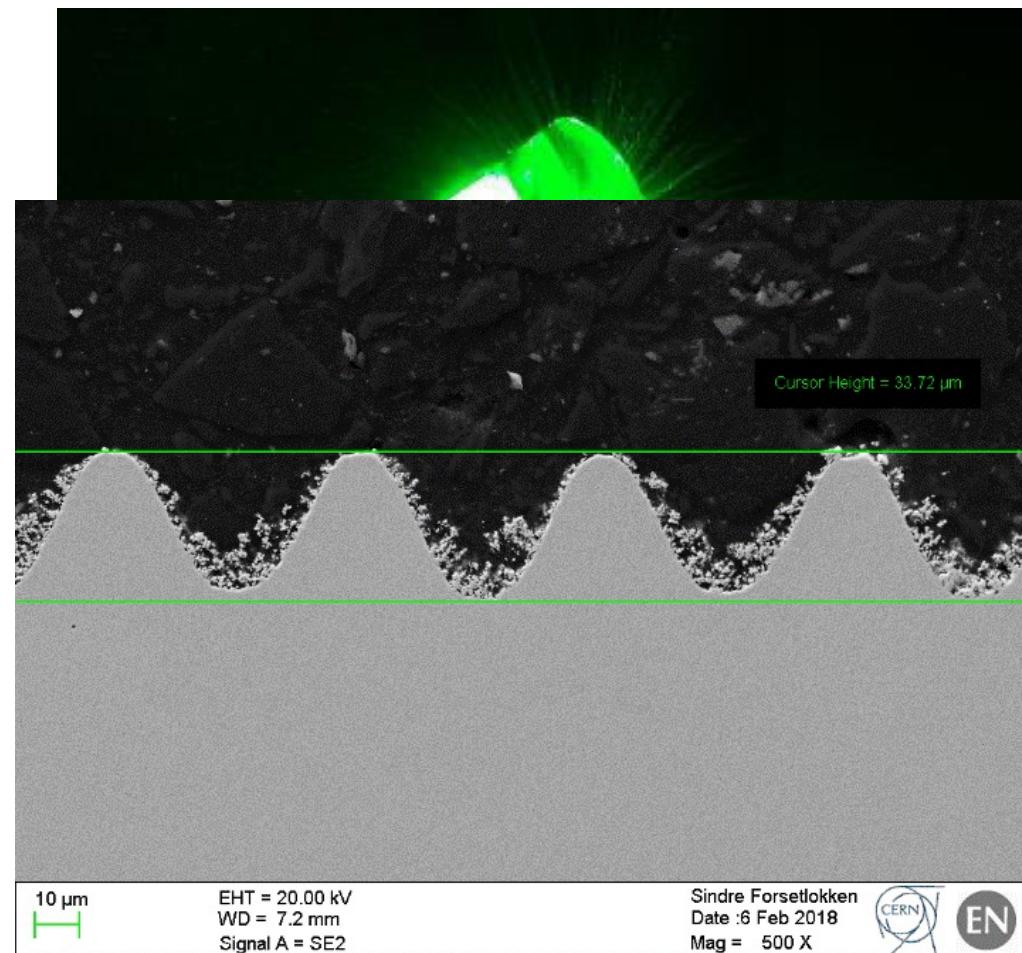
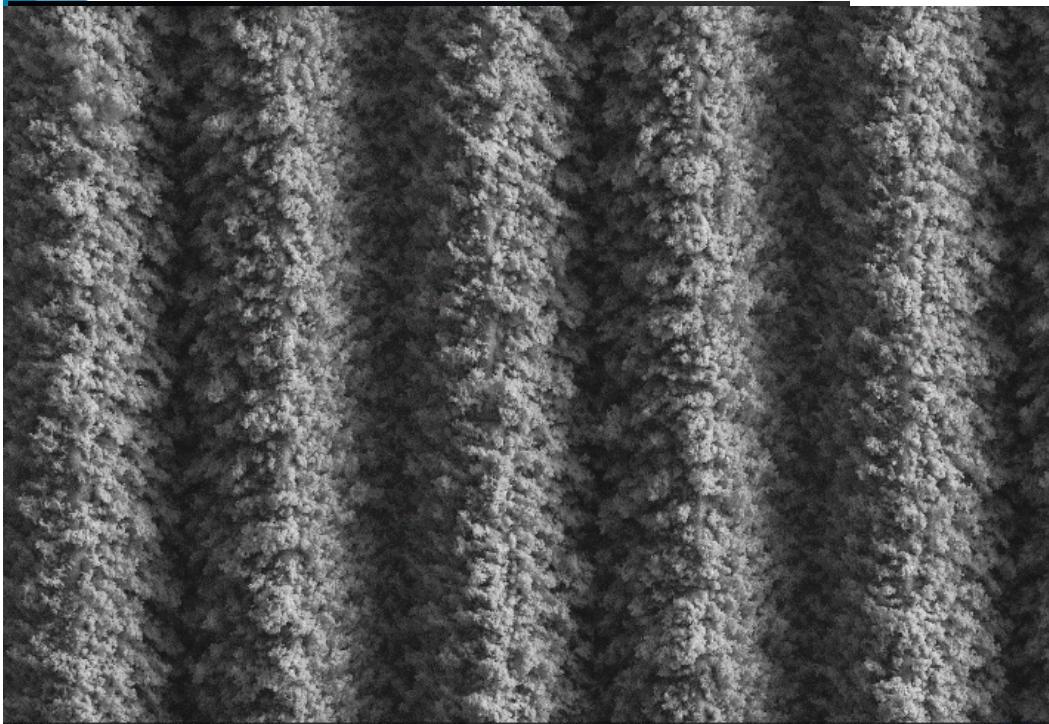


higher “as coated” SEY than standard carbon coatings
(Q5L8 and HL-LHC inner triplet beam screens)

On-going ageing cycles: electron irradiation at 15 K ↔ humid atmosphere storage at RT (3+ months)

Coating on CuO (preliminary 1 train configuration): **3 successful cycles**

LESS: Laser Engineered Surface Structures



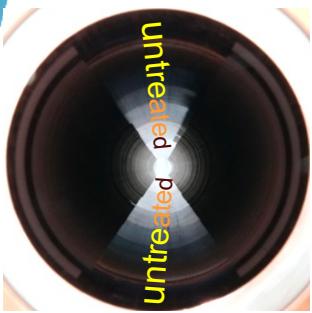
Oliver Brüning CERN

Laser surface treatment of beam screens

supported by HL-LHC-UK2 in collaboration with



Demonstrator + BLMs in LHC Vacsec.C5R6.B



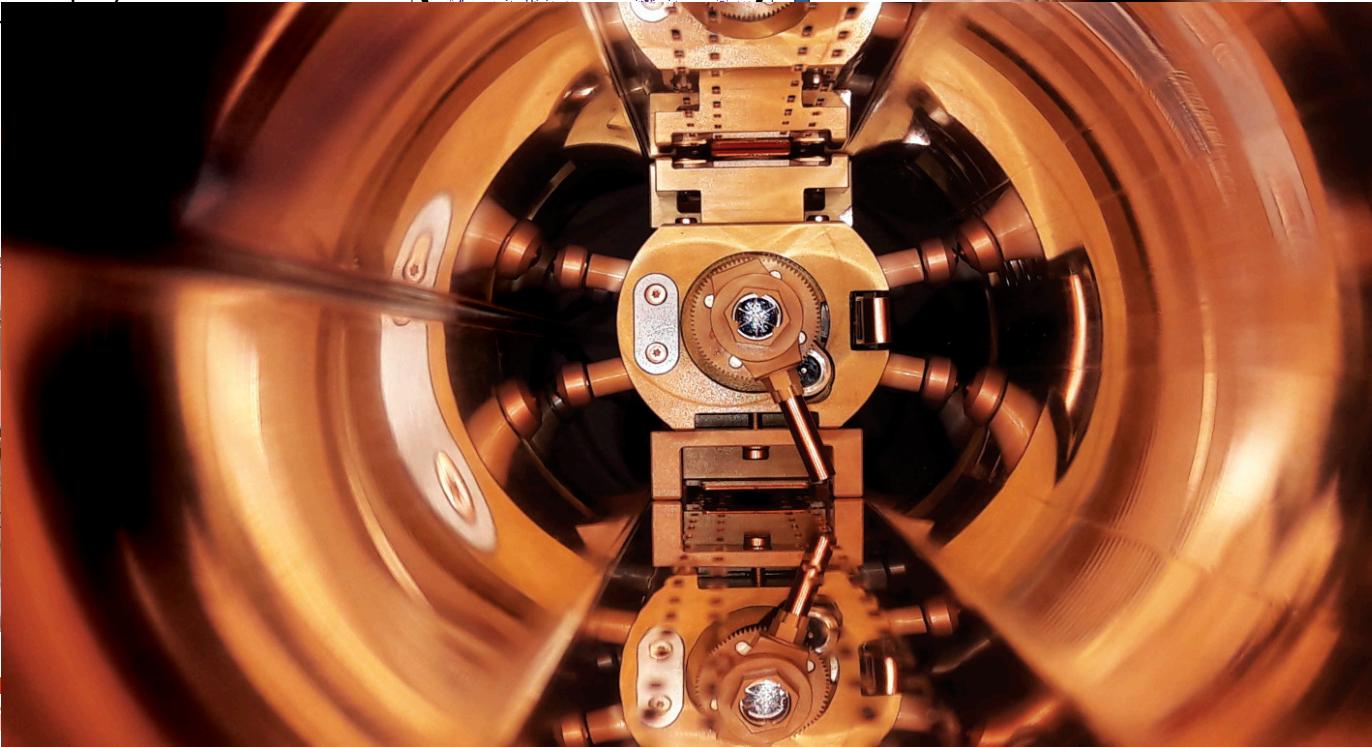
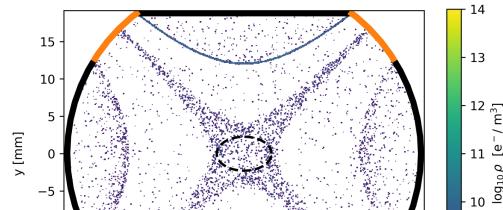
UFOs of $\leq 2 \times 10^5$ p⁺ collisions ($d = 4-6 \mu\text{m}$) - small compared to LHC standard events
→ not harmful for operation
→ Low quantity
→ continuation of data acquisition

Automation mock-up with 10.8 m beam screen



Alternative option to laser treatment in magnet: laser beam screens instead of a-C coating + installation in

4×20° treatment strategy for Q5 standalone magnets



Technology Landmarks

Finished in 2023



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.

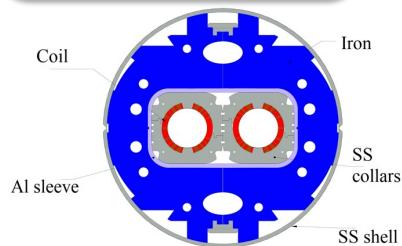


Series production started in Industry

Nb-Ti Separation

dipoles

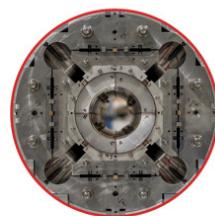
First series magnets delivered to CERN



Finished in 2023

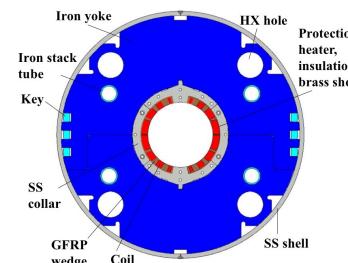
Fully validated in 2023 and first magnets ready for installation

LHCb



MAGNETS

Hydrogenated superconducting dipole magnets for the ATLAS and CMS experiments, for the final focusing before collisions.



Complete Prototype System validated in 2024

SUPERCONDUCTING LINKS

Transmission lines based on a high-temperature superconductor to carry the very high currents to the magnets from the power supplies installed in the new service tunnels near ATLAS and CMS.

½ system already installed for Run3

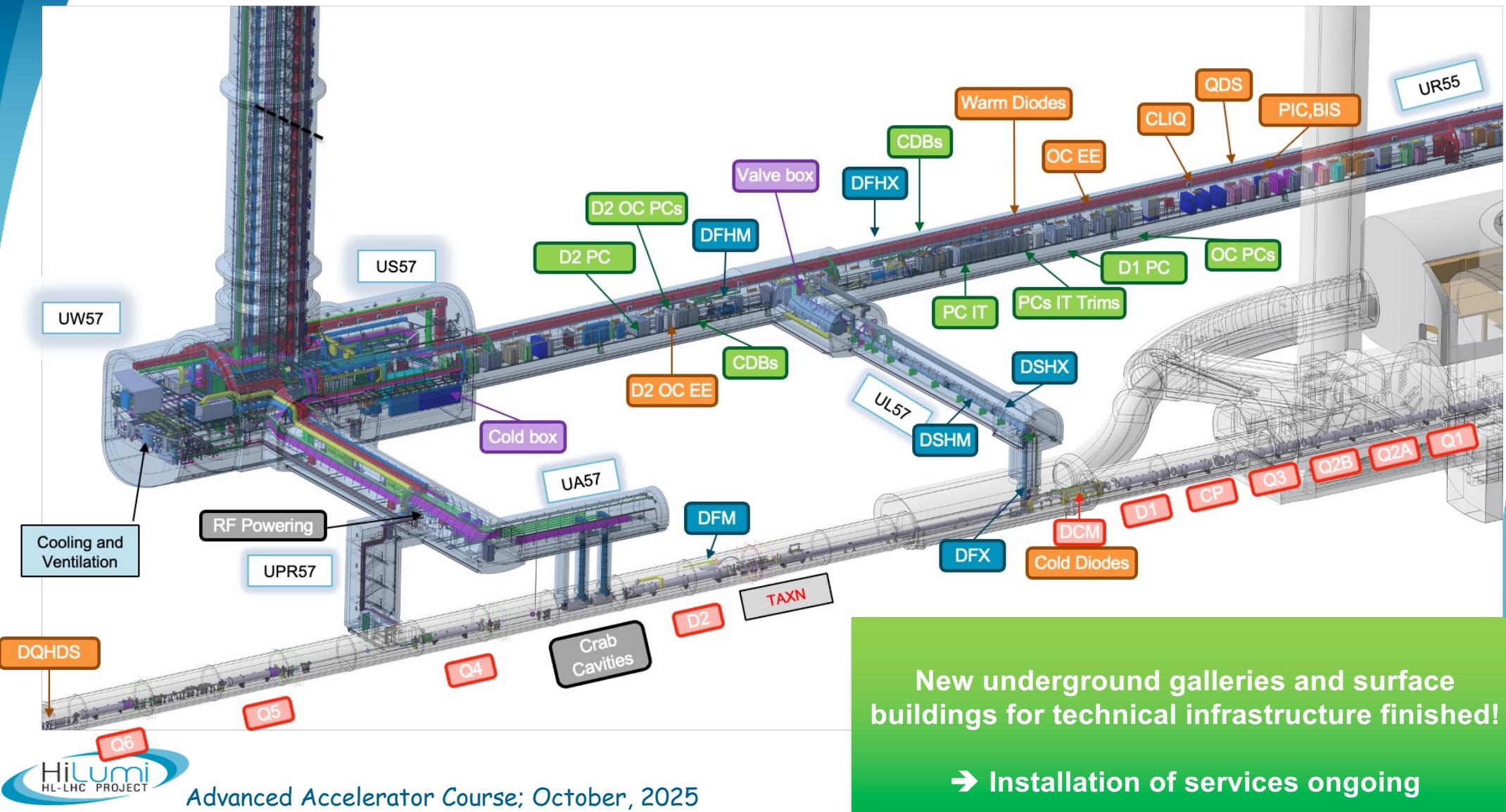
COLLIMATORS

151 crystal collimators successfully deployed in 2023 Pb-Pb run. Half of series [3/6] completed

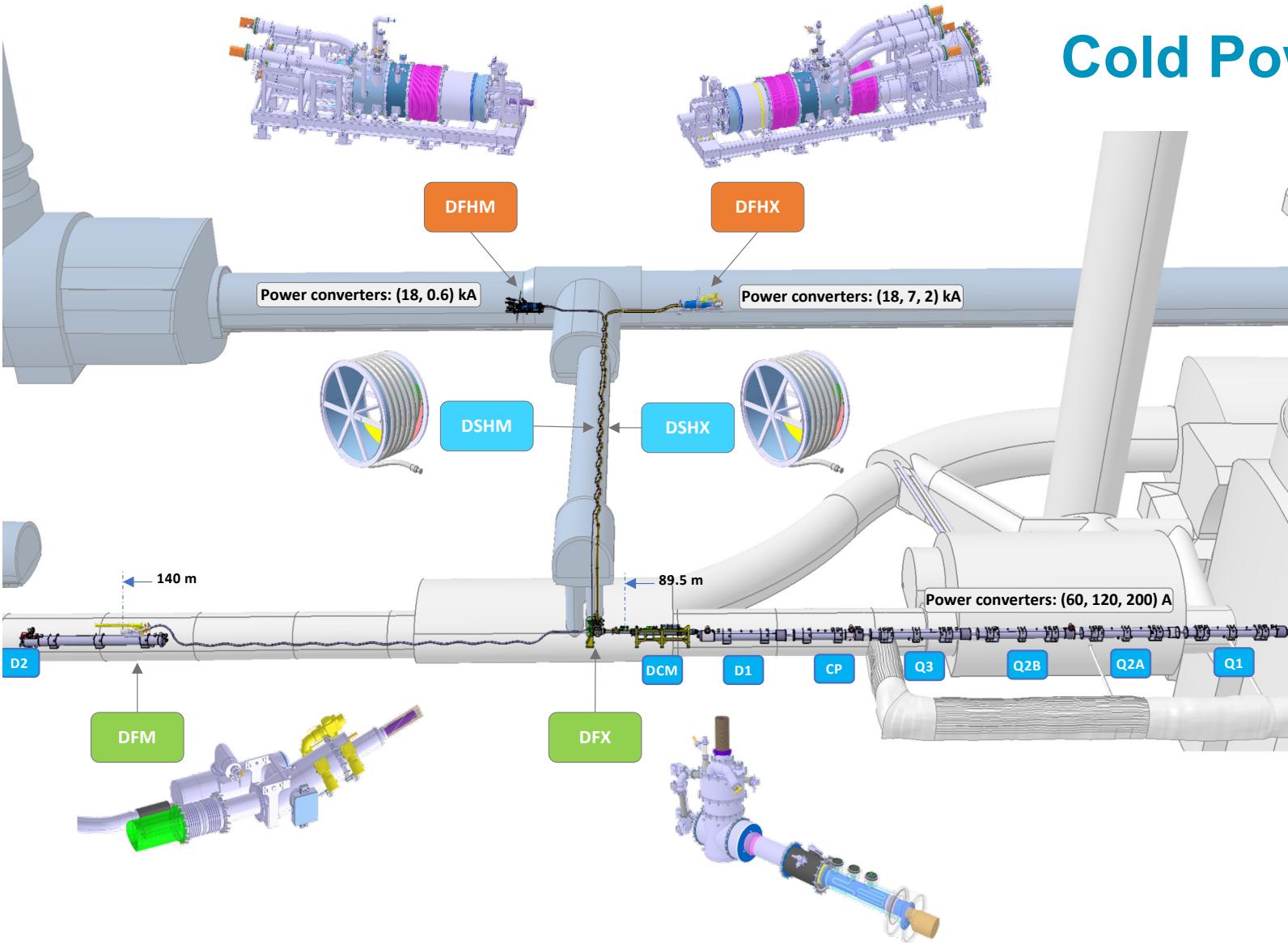
Prototype validated by CERN & Half of series [3/6] completed

ver 2024-02-01

CERN February 2024



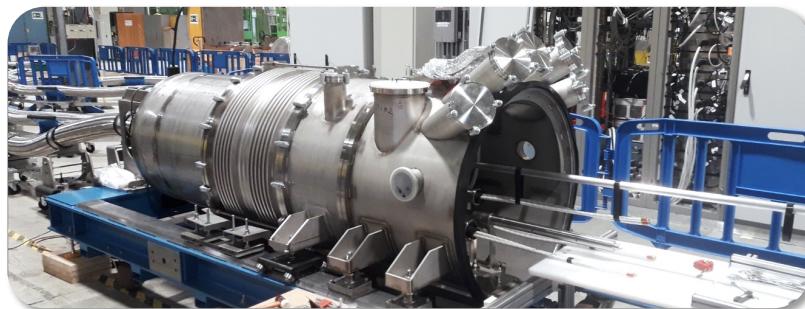
Cold Powering System



Superconducting link to minimize thermal losses when transporting over 100kA over 100m!

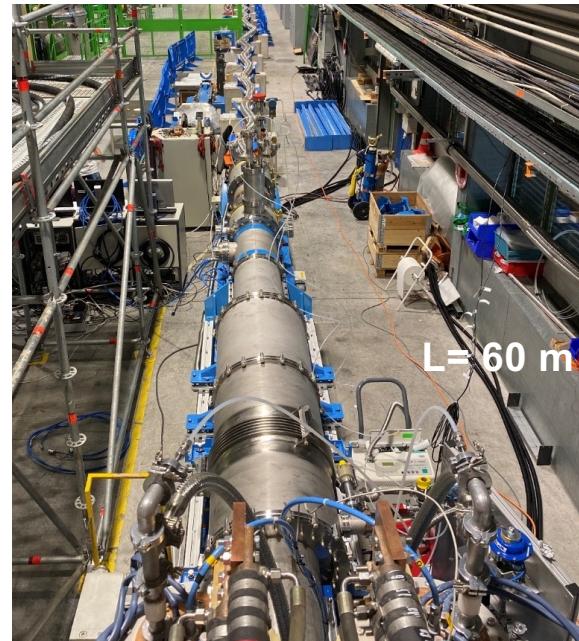
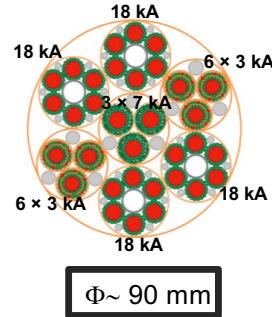
→ High Temperature Superconductor, MgB_2 operating at ca. 20K to 30K

→ Cooling with gaseous He from liquid He boil off



Flexible MgB₂ superconducting links

MgB₂ cable:
 $\Phi \sim 90 \text{ mm}$
 $|I_{\text{tot}}| > 100 \text{ kA} @ 25 \text{ K}$



System demonstrator
in SM 18
DEMO2
Demonstration of **2 x 20kA + 2 x 7kA** in June
in MgB₂ @ 30K
in flexible cryostat
over 60m [54kA total]

MgB₂ Cable Assemblies (1/2)

Received from ICAS all MgB₂ series cables

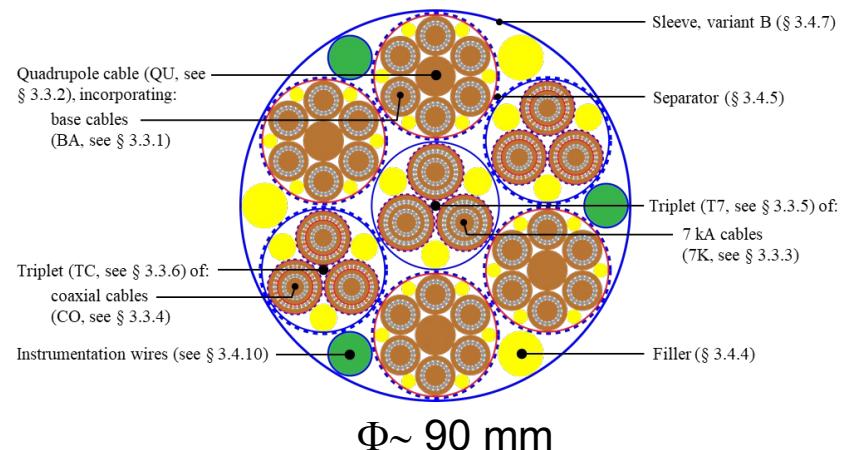


Successfully HV tested both in industry and at CERN



To be produced: 5+5 Units

Advanced Accelerator Course; October, 2025



- Wire grading and cable map approval procedures established
- Continuous tests at CERN of extracted strands from each constituent cable before approving further operations – **694 test pieces in 2021**
- Production planned to be completed by end 2022

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SC Link Cryostats

Received all series SC Link cryostat for Triplets – produced in industry

Leak/pressure tests at the company



Delivery & Reception @ CERN



Final length for Triplets: 74.5 m

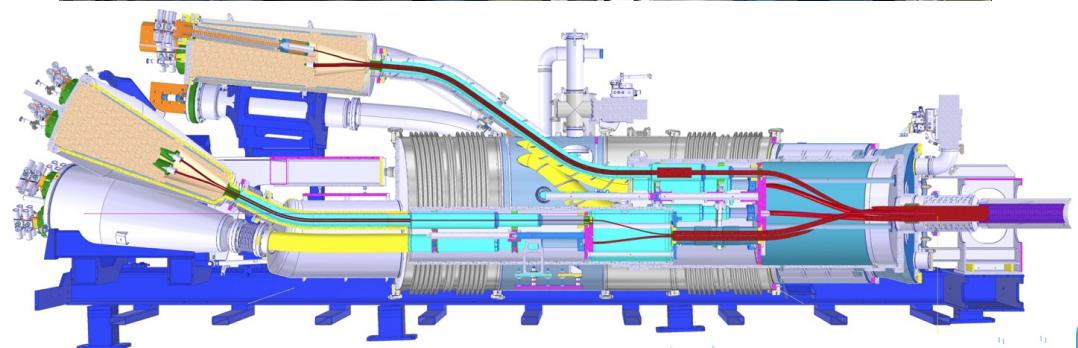
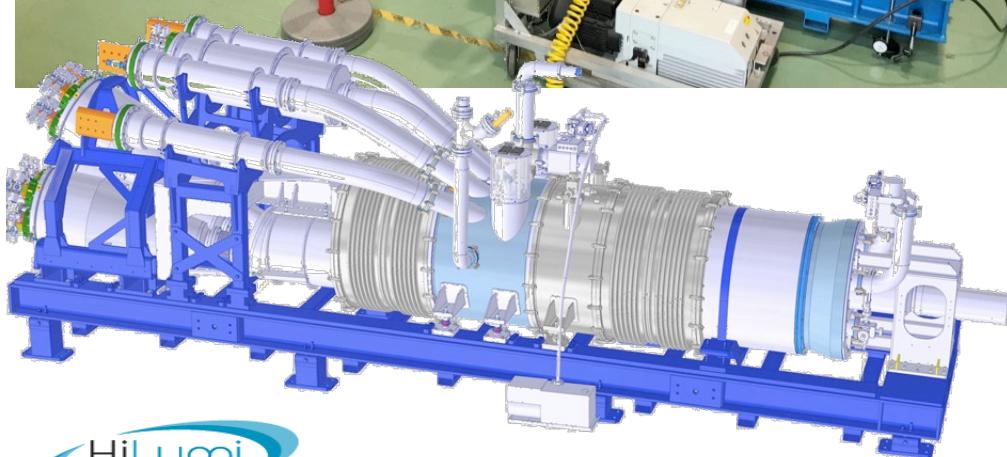
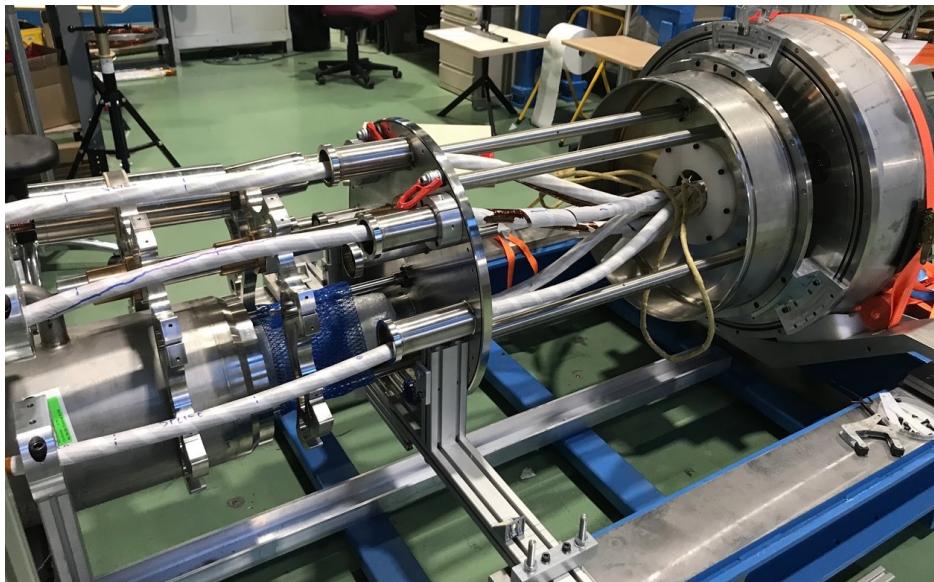
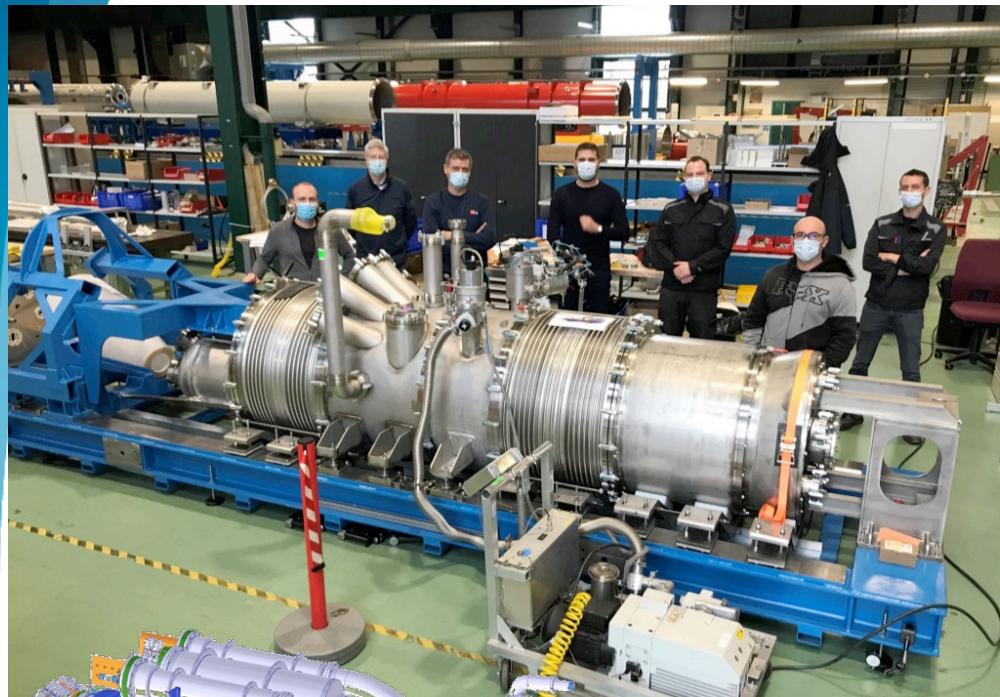
Optimization of leak test **procedure**

Visual and endoscopic inspections, dimension controls

Advanced Accelerator Course; October, 2025

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First DFHX constructed @ CERN (2/3)

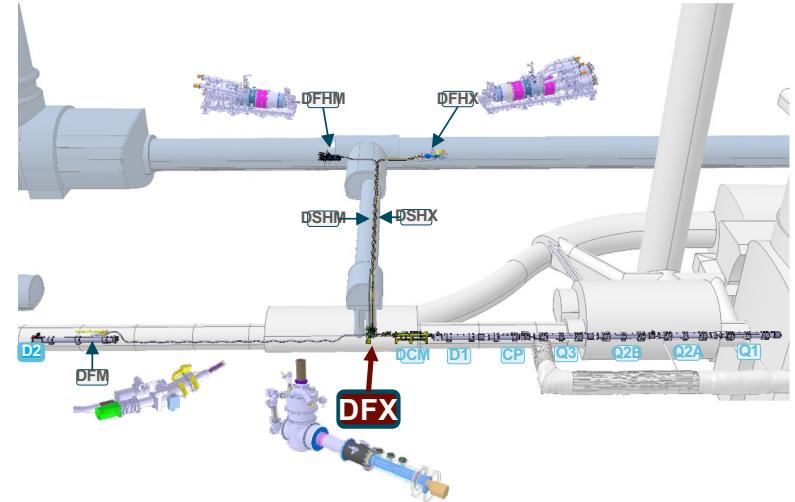


Completed **blank assembly** of DFHX and
studied of MgB₂/HTS routing

Oliver Brüning CERN

DFX Cryostat

Completed pre-series DFX by SOTON (UK1) !



CERN-UK1 collaboration under addendum #4 of KE3299/TE/HL-LHC

Design, Manufacturing, QC & CE certification under the responsibility of **Southampton University**

PRR 3 March 2020. **1.5 intense years** from raw material procurement to completion of qualification and **CE certification** by notified body

Completed in March 2022 at LTI Metaltech & delivered to CERN

MgB₂ Superconductor and 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.



Advanced Accelerator Course; October, 2025

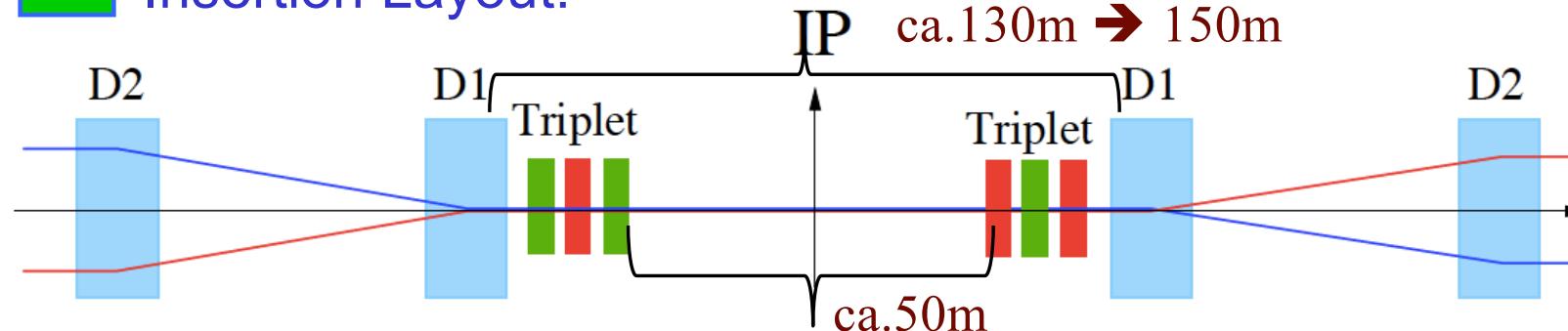
Complete Prototype system demonstration in 2024



Oliver Brüning CERN

LHC Challenges: Crossing Angle at Interaction Points

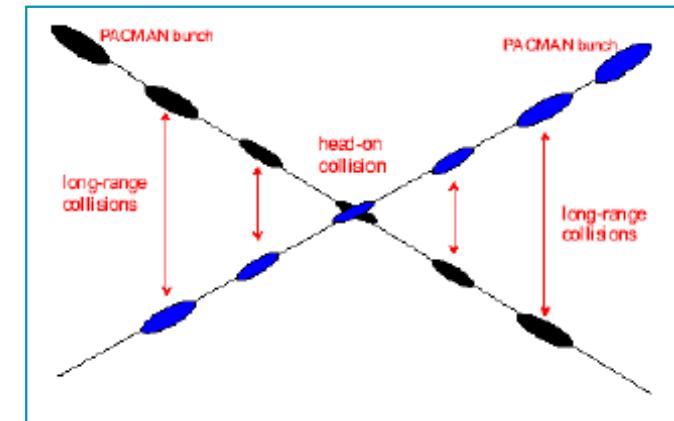
■ Insertion Layout:



■ Parasitic bunch encounters:

Operation with ca. 2800 bunches @ 25ns spacing
→ approximately 30 unwanted collisions per
Interaction Region (IR) in the LHC
→ even more for HL-LHC!

→ Operation requires crossing angle



■ non-linear fields from long-range beam-beam interaction:

efficient operation requires large beam separation at unwanted collision points
→ Separation of $10 - 12 \sigma$ → large magnet apertures next to the experiments!!
→ at the limit of magnet technology!!!

HL-LHC Upgrade Ingredients: Crab Cavities

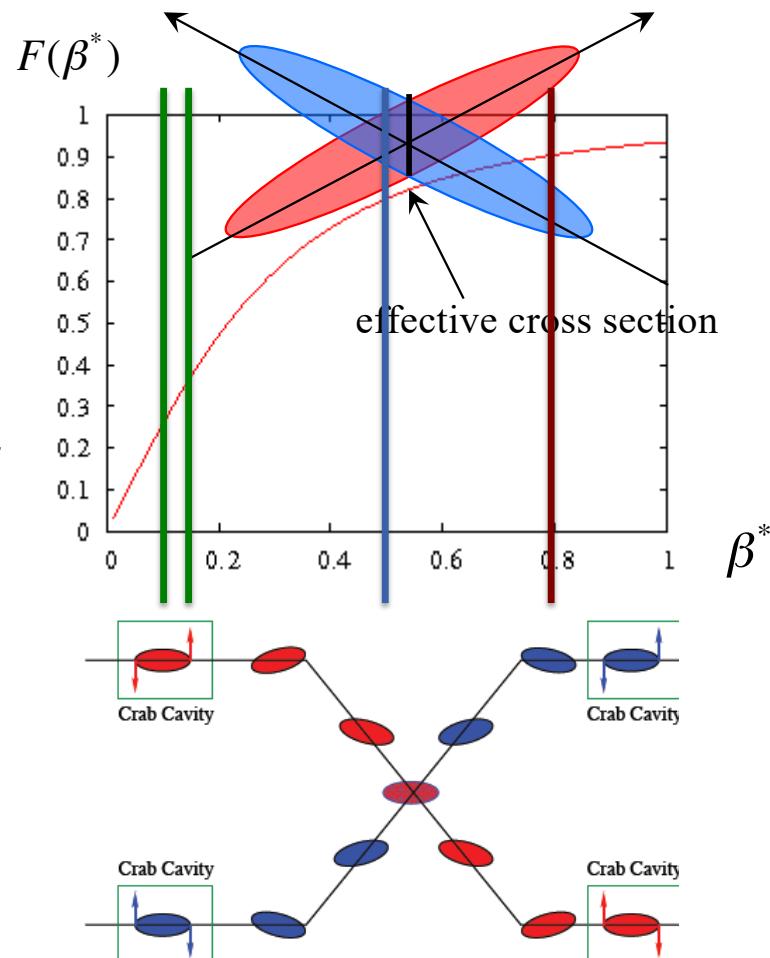
■ **Crab Cavities luminosity**

Reduction Factor:

- Reduces the effect of geometrical reduction factor
- Independent for each IP

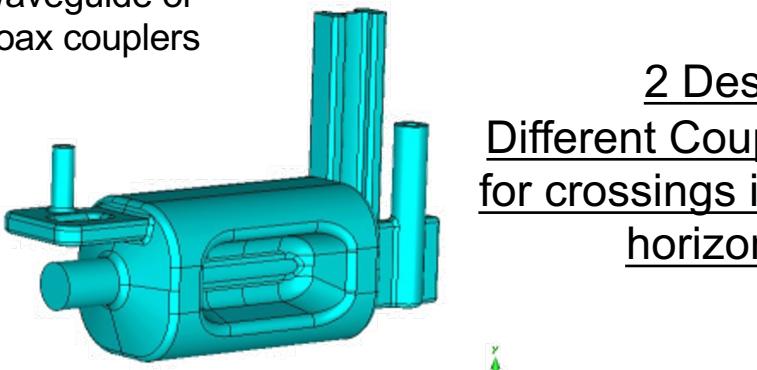
$$F = \frac{1}{\sqrt{1 + \Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2 \sigma_x}$$

- Noise from cavities to beam
→ Beam size; losses and phase control!!!
- Challenging space constraints:
→ requires novel compact cavity design

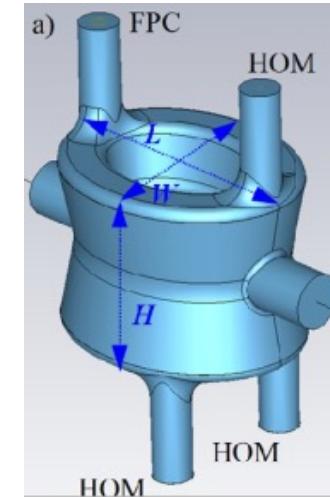


HL-LHC cavity designs

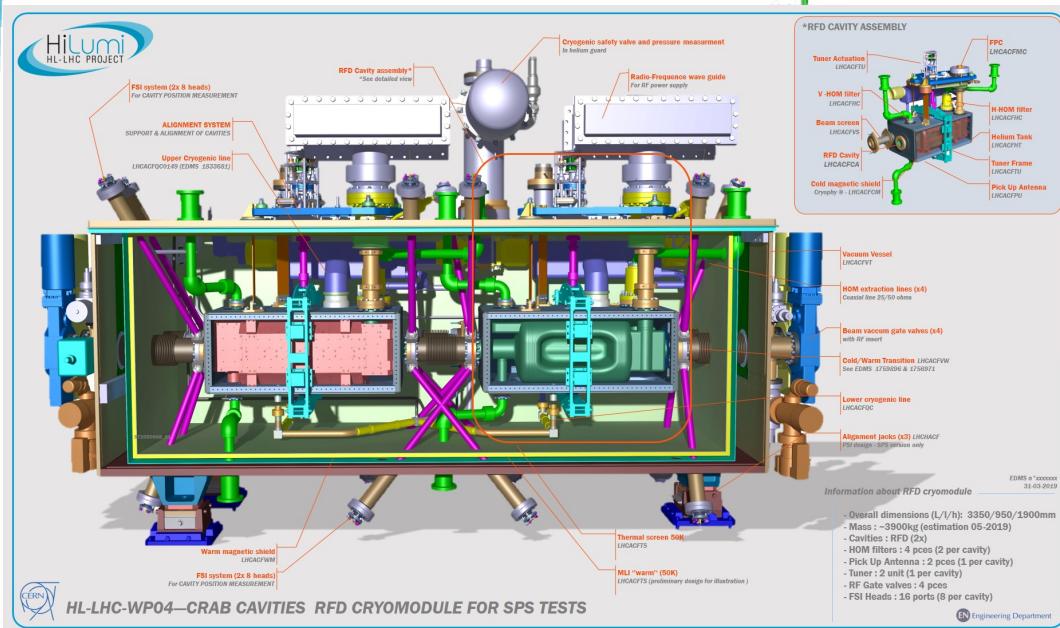
RF Dipole: Waveguide or waveguide-coax couplers



2 Designs with
Different Coupler concepts and
for crossings in the vertical and
horizontal planes



Double $\frac{1}{4}$ -wave:
 Coaxial couplers with
 hook-type antenna



Present baseline: 4 cavities / IP / side \rightarrow 16 total

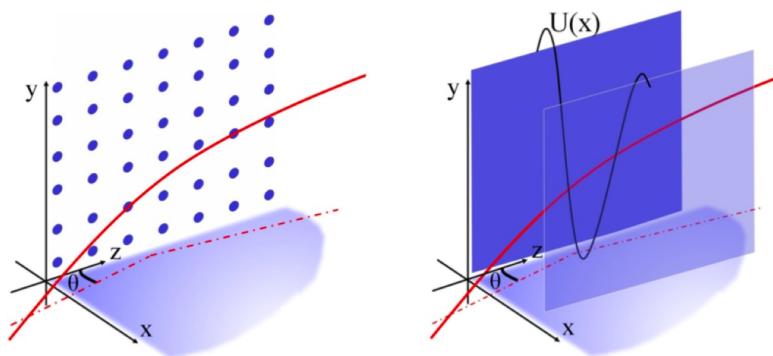
Present baseline: 2 cavities within one common cryostat \rightarrow need 4 cryo-modules per CC type

Oliver Brüning CERN

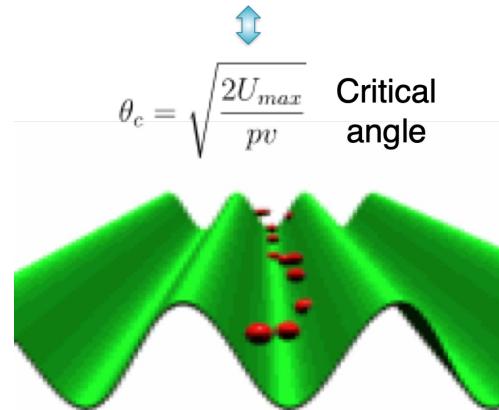


Ion Collimation: Planar channeling in bent crystal

Pure crystals with regular lattices

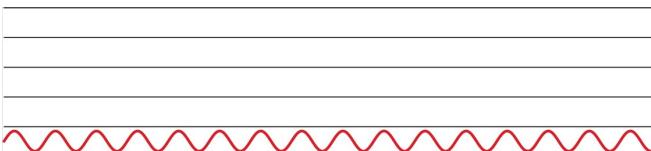


If the protons have $p_T < U_{max}$

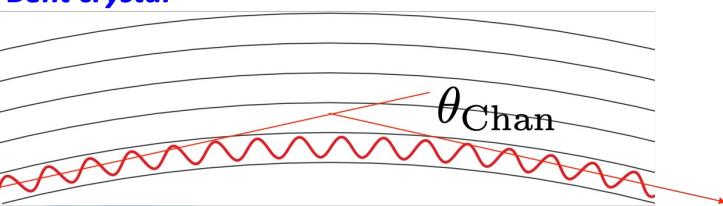


Critical angle at the LHC energy frontier (Si crystals):
 LHC 450 GeV = 9.4 μrad
 LHC 6.5 TeV = 2.4 μrad

Straight crystal: oscillations between planes



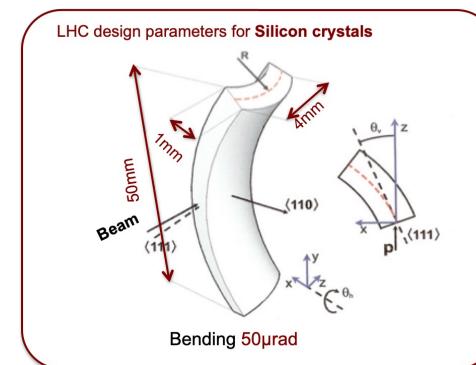
Bent crystal



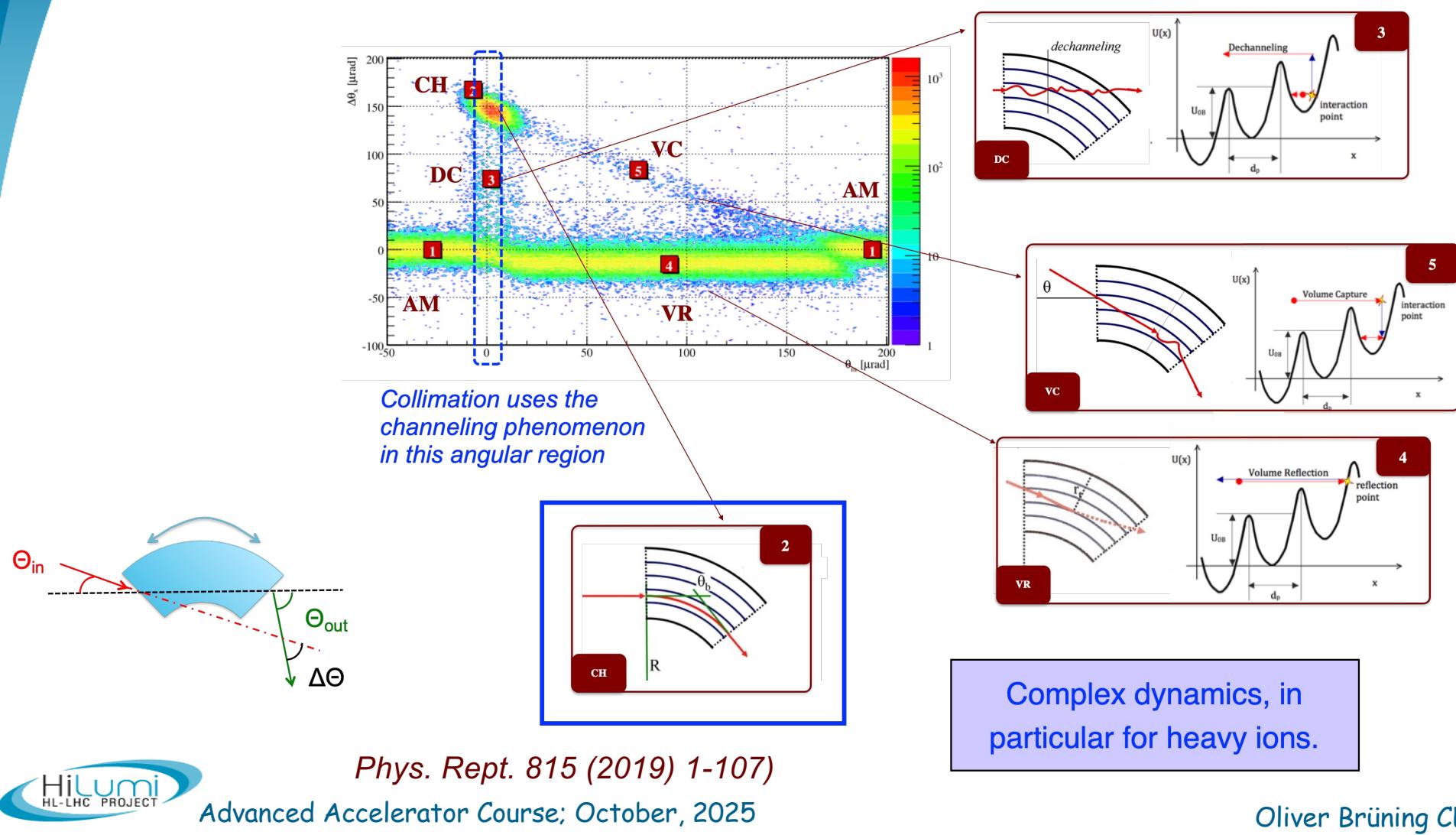
Bent crystal → net kick of the trajectory for particles trapped for the full crystal length!

Equivalent magnetic field close to 300 T (4 mm crystal)

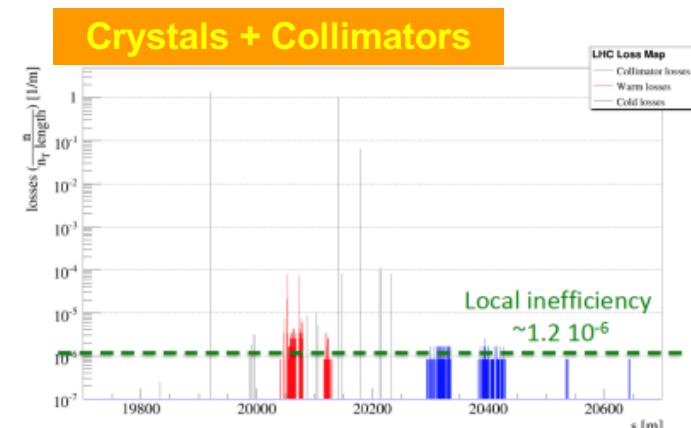
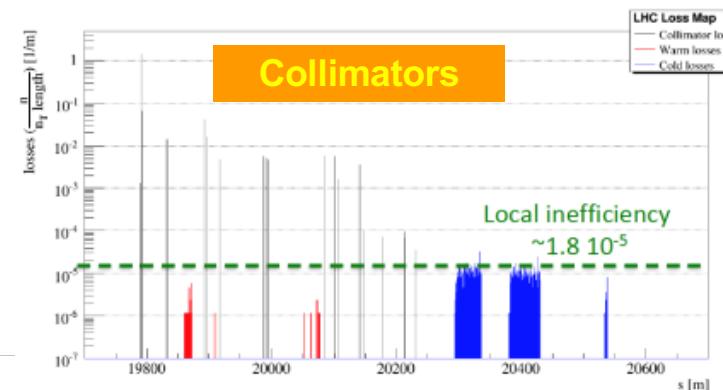
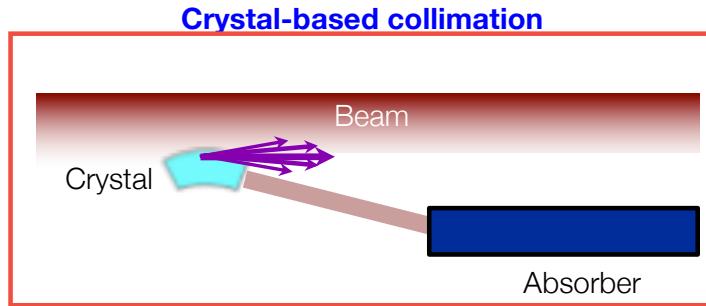
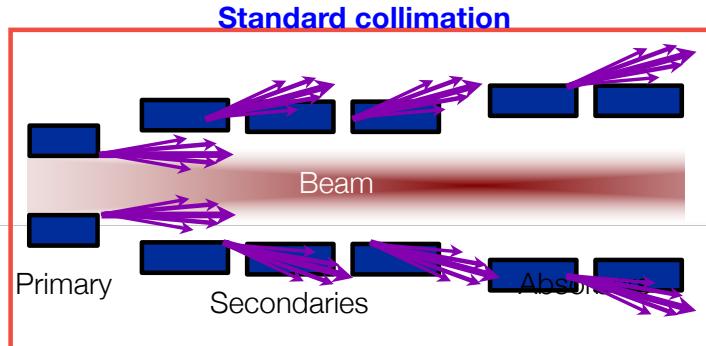
$$\theta_c = \sqrt{\frac{2U_{max}}{pv}} \left(1 - \frac{R_c}{R} \right)$$



Coherent interactions



Crystal collimation



- Feasibility demonstrated at the LHC in Run 2 with a prototype setup, at 6.5 TeV (example above for proton beams)
- Now used as baseline upgrade scenario to dispersion suppression collimation for heavy-ion beams
- Critical: angular control with sub-μrad accuracy to ensure channeling

Installation of Crystal Collimators for the Ion Run

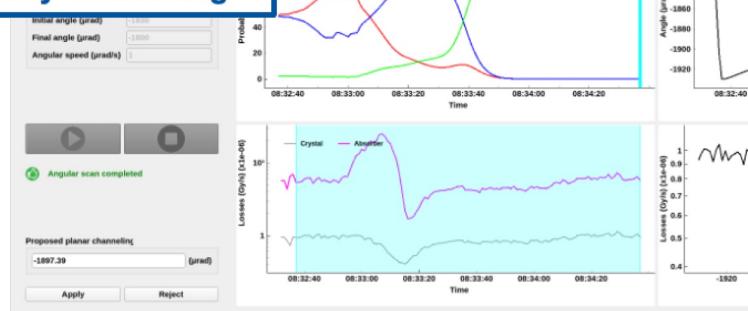
- Full crystal collimation system (4 crystals, one per beam per plane) available since 2023. Specs: 4 mm, 50 μ rad bending
- Used operationally for lead ion beam collimation.
- Tests in 2025 with new



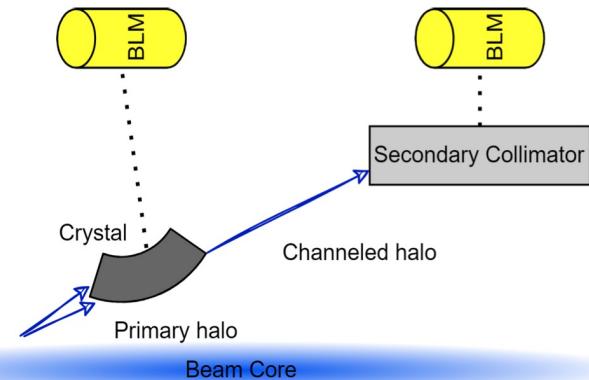
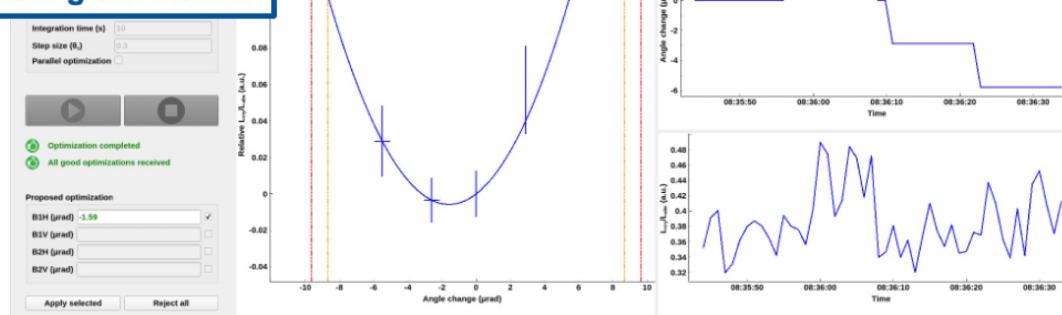
A new generation of crystal collimators are installed in the LHC tunnel to provide improved capabilities for ion beam operation in the HL-LHC era

Crystal setup assisted by Machine Learning (ML)

Machine Learning to identify channeling



Optimization of channeling orientation



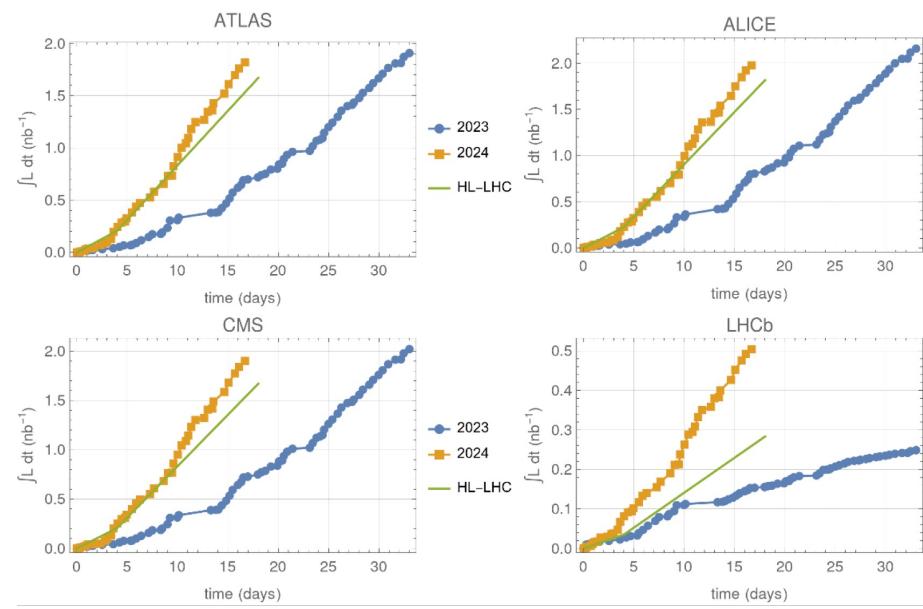
- ML is used to detect potential loss of channeling
- Key inputs: BLM at key-collimator locations
- Target output: Crystal angular error from optimal channeling orientation
 - Through identification of the “amorphous” and channeling orientations
- Feed-forward neural network — FNN — being used; simulation framework to train the model

Ion luminosity production in 2024

	Bunch intensity	Max. stored beam energy
2023	$1.6 \times 10^8 \text{ Pb/bunch}$	17.3 MJ
2024	$2.3 \times 10^8 \text{ Pb/bunch}$	26.9 MJ
HL-LHC	$1.8 \times 10^8 \text{ Pb/bunch}$	20.5 MJ

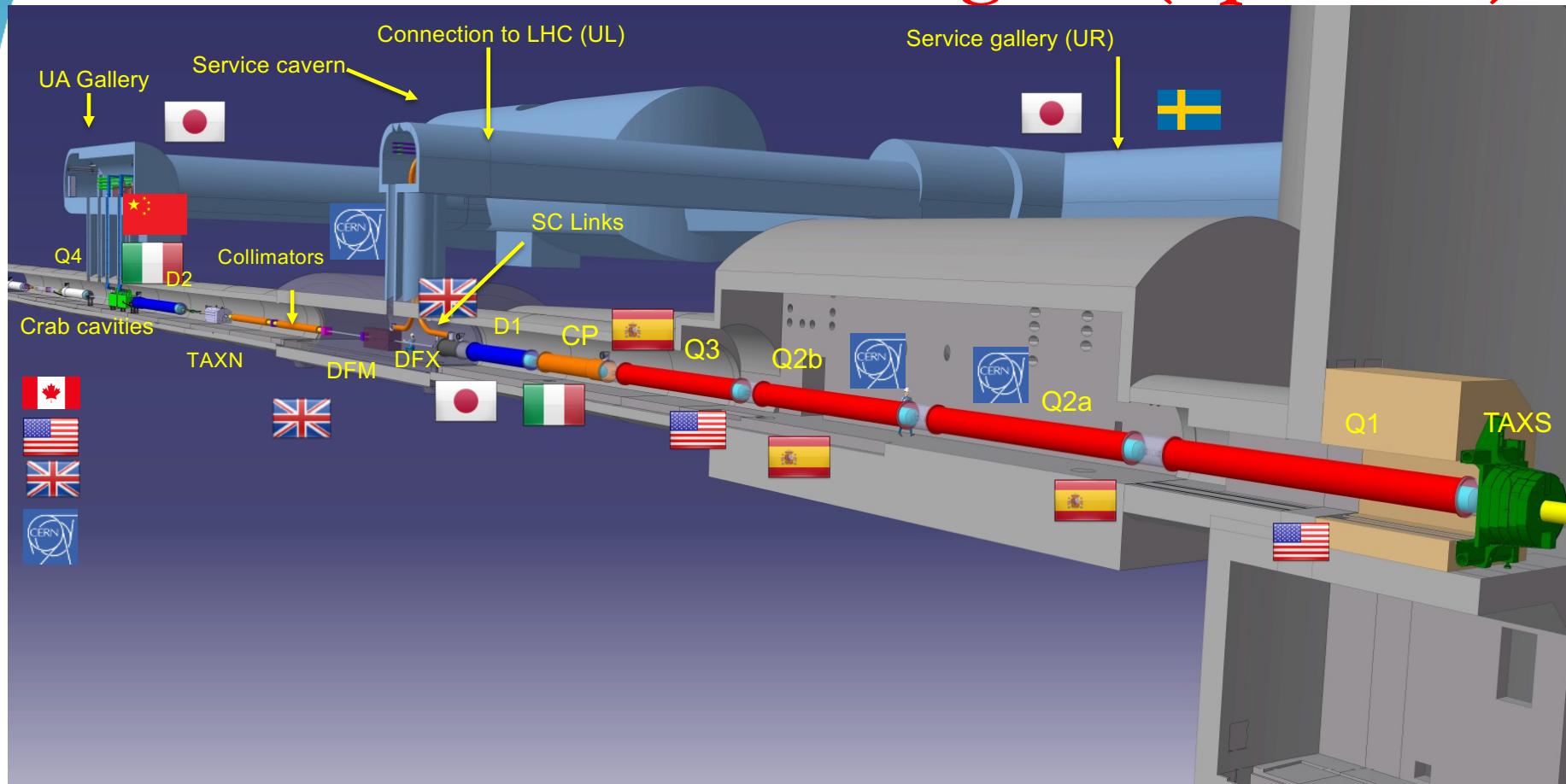
Luminosity production

- Proton-proton reference run (7 days) completed
- ALICE, ATLAS, CMS
 - Reached target of 1.9 nb^{-1} , 2h levelling at $6.4 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$
 - Almost same luminosity in 2024 as 2023, in half the time
 - Mean daily production: $142 \text{ } \mu\text{b}^{-1}$
 - HL-LHC projection was: $118 \text{ } \mu\text{b}^{-1}$
- LHCb
 - About double the luminosity in 2024 than in 2023, in half the time
 - Mean daily production: $37 \text{ } \mu\text{b}^{-1}$
 - HL-LHC projection was: $20 \text{ } \mu\text{b}^{-1}$



Luminosity production during the 2024 ion run in the four IPs

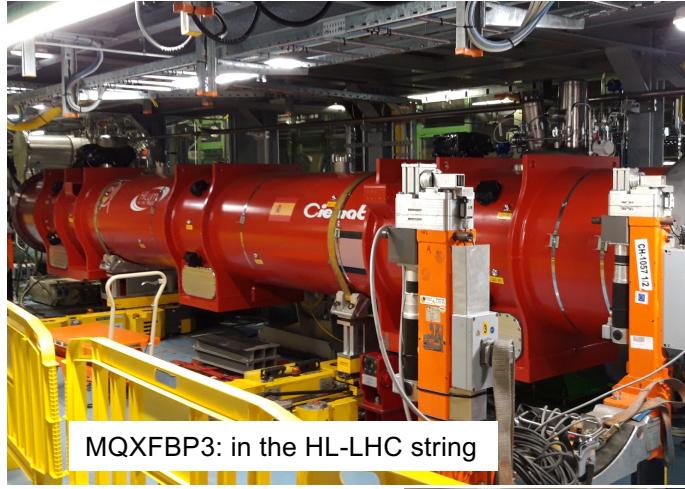
International Collaboration: The Insertion Region (up to Q4)



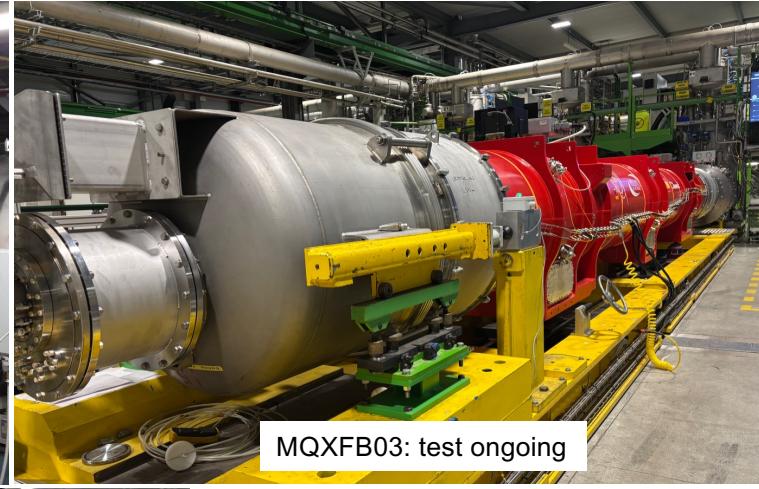
At full production speed! Ca. 50% of Cold-Mass-Assemblies done



MQXFBP2: being prepared for the HL-LHC string



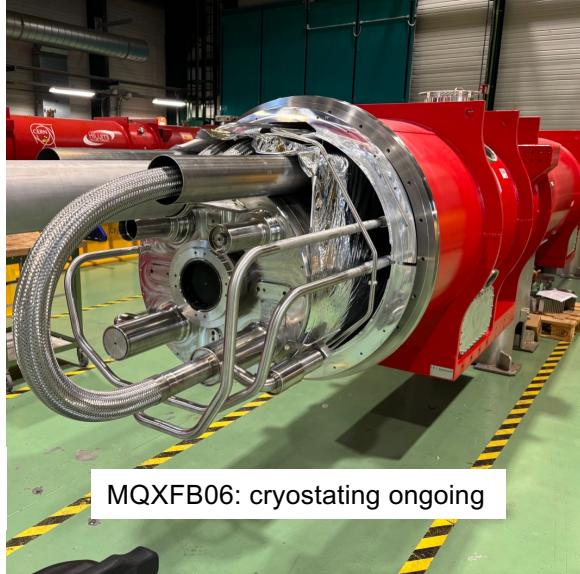
MQXFBP3: in the HL-LHC string



MQXFB03: test ongoing



MQXFB04: fully qualified for HL-LHC ✓
MQXFB05: fully qualified for HL-LHC ✓



MQXFB06: cryostating ongoing



MQXFB07: cold mass finishing



MQXFB08: magnet assembled

Q1/Q3: Status and progress in the US: also ca 50% done



Susana Izquierdo Bermudez
@ Chamonix 2025

Achievements in the last 12 months:

- The second cryo-assembly (Q1 for the string) has been successfully tested and arrived at CERN.
- 5 magnets assembled, **4 passed the vertical test**.
- AUP can work in two cold masses in parallel, the issues with electrical integrity have been solved.

Issues and concerns:

- 4 out of 13 virgin magnets failed during vertical testing
 - Coil replacement has been demonstrated in 3 cases, but has impact on cost and schedule.
- In the current working schedule, the **last magnet for installation (LMQXFA10)** arrives **beginning of 2027**.
- The critical path is now in the **vertical testing**.
- Flattop quenches in one of the magnets in the first cryo-assembly tested at CERN.



LMQXFA01 and LMQXFA02 at CERN, being prepared for the string



LMQXFA03 ready to be installed in the horizontal test facility



LMQXFA04 cold mass close to completion



LMQXFA05 longitudinal welding completed



LMQXFA06 magnets being prepared

Coil FNAL																								
Coil BNL																								
Magnet assembly	3	4	5	6	10	11	14b	8b	7b	15	13b	18	12b	16	17b	19	20	21	22	23	24			
V test (BNL)	3	4	5	6	10	11	14b	8b	7b	15	13b	18	12b											
cold mass	LQXFA01		LQXFA02		LQXFA03		LQXFA04		LQXFA05		LQXFA06		LQXFA07		LQXFA08		LQXFA09		LQXFA10					
H test (FNAL)							test at CERN		test at CERN				test at CERN											
H test (CERN)				to the string																				

Accepted

On-going

To do

Spares in grey

Remark: not-conformed coils not shown

Advanced Accelerator Course; October, 2025

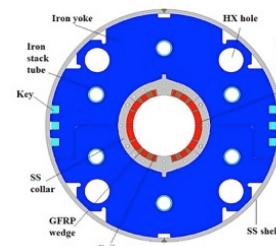


Oliver Brüning CERN

D1: Status and progress

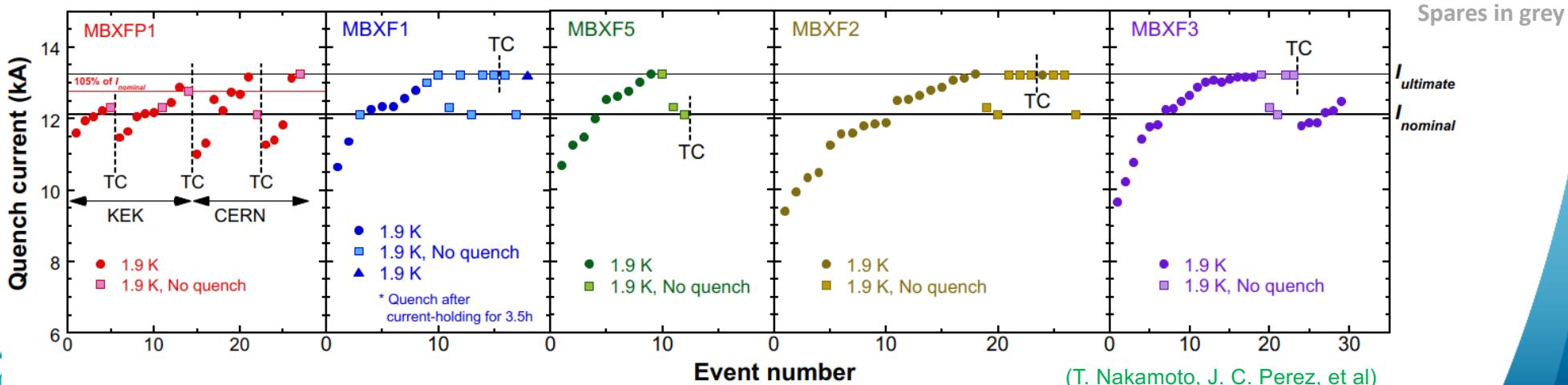


- **Achievements in the last 12 months:**
 - MBXFBP1 is installed in the string
 - MBXF1 was delivered to CERN
 - MBXF2 and MBXF3 test completed, magnets are conform
- **Issues and concerns:**
 - Very sequential production, with a large delay between magnet vertical test and delivery, today the last magnet for installation is MBXF5, ready for installation in mid 2027.

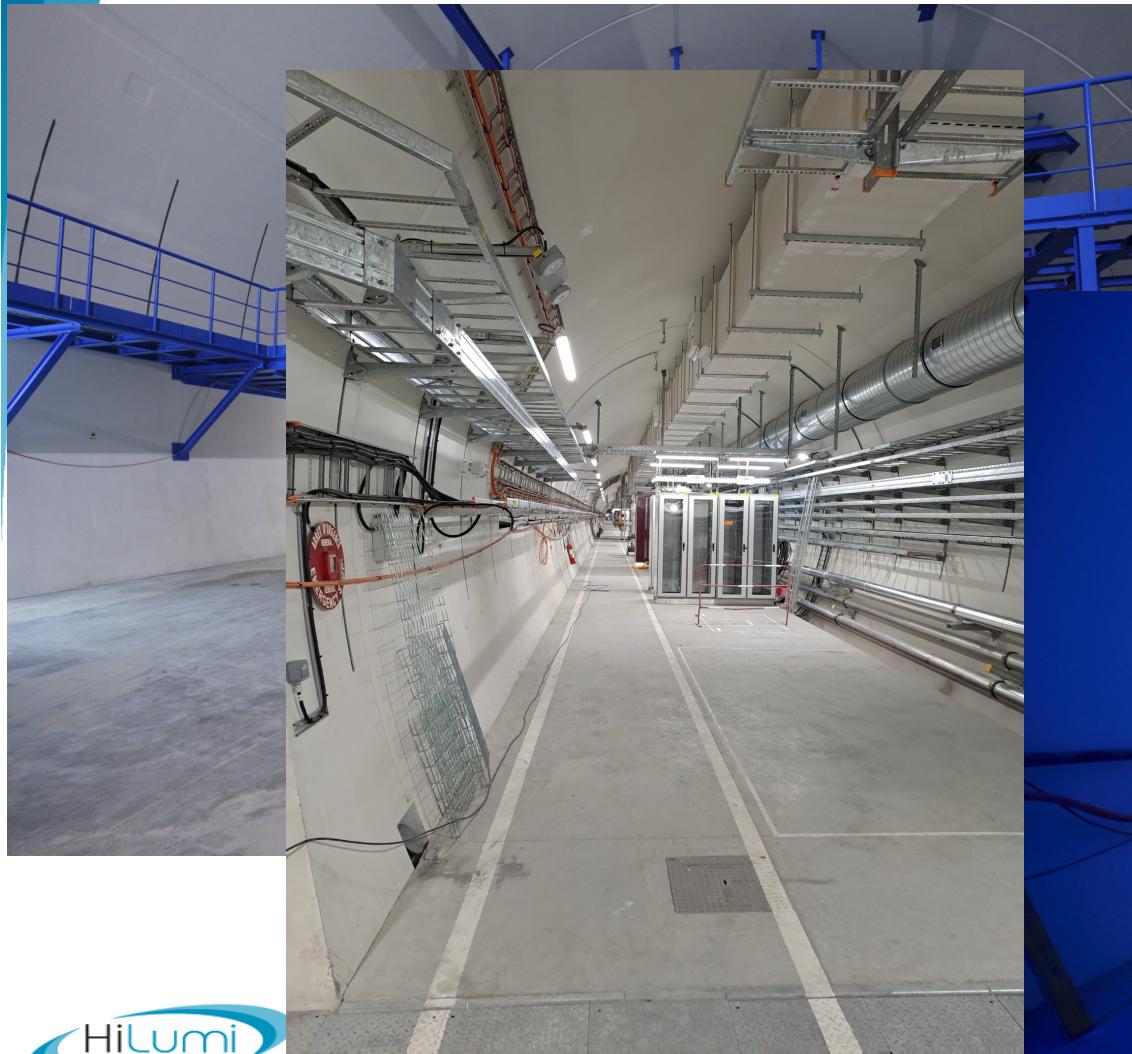


MBXF1 @ CERN, December 2024

Coil										
Magnet										
V test (KEK)										
Cold mass										
H test (CERN)	MBXF1	MBXF2	MBXF3	MBXF4	MBXF5	MBXF6				
	Legend		Completed		In Fabrication		To do			



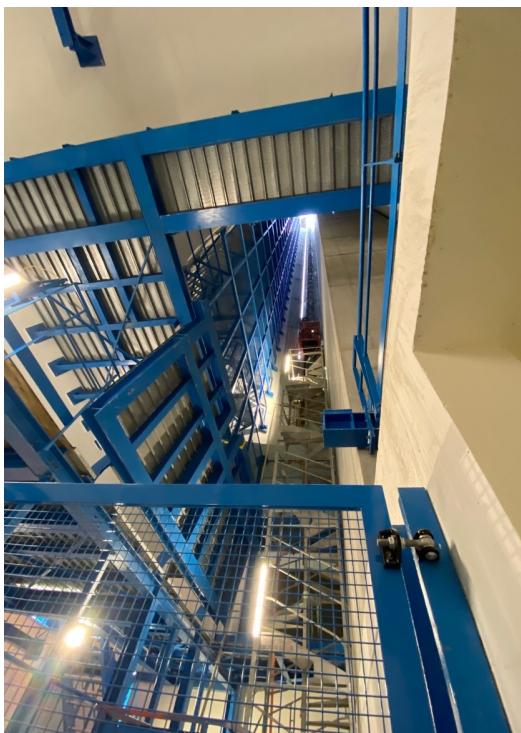
IR1/5 underground civil engineering completed in 2022



Construction Finished End 2022



Ceremony for completion of CE on January 20th 2023



Advanced Accelerator Course; October, 2025

Oliver Brüning CERN

Completion of the civil engineering works: Surface Buildings



Example Point 1

Advanced Accelerator Course; October, 2025

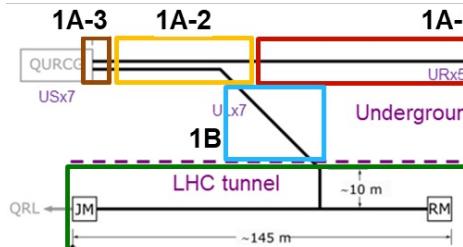
Status of infrastructure installations at P5



Status End 2024

QXL installation (phase 1A-1) + Refrigeration

See presentation by



- Installation of cryogenic distribution line about to start in new underground galleries (first phase 1A-1), with completion of phase 1 required in 2026 (avoiding resource overlap with LS3)
- Installation of refrigeration plants and vertical line (connection through shaft) commencing end 2025
- Activities remain schedule critical due to quantity of remaining design work and coactivity constraints. Additional internal resources are being redeployed to ensure work remains on track, with main focus on Phase 2 (installation in the LHC tunnel)

Refrigerator Manufacturing & Assembly and Installation

Installation of Steel structure in SHM building



Compressor skid arrived last week

4.5 K Cold box Assembly



Cold Compressor Box Assembly

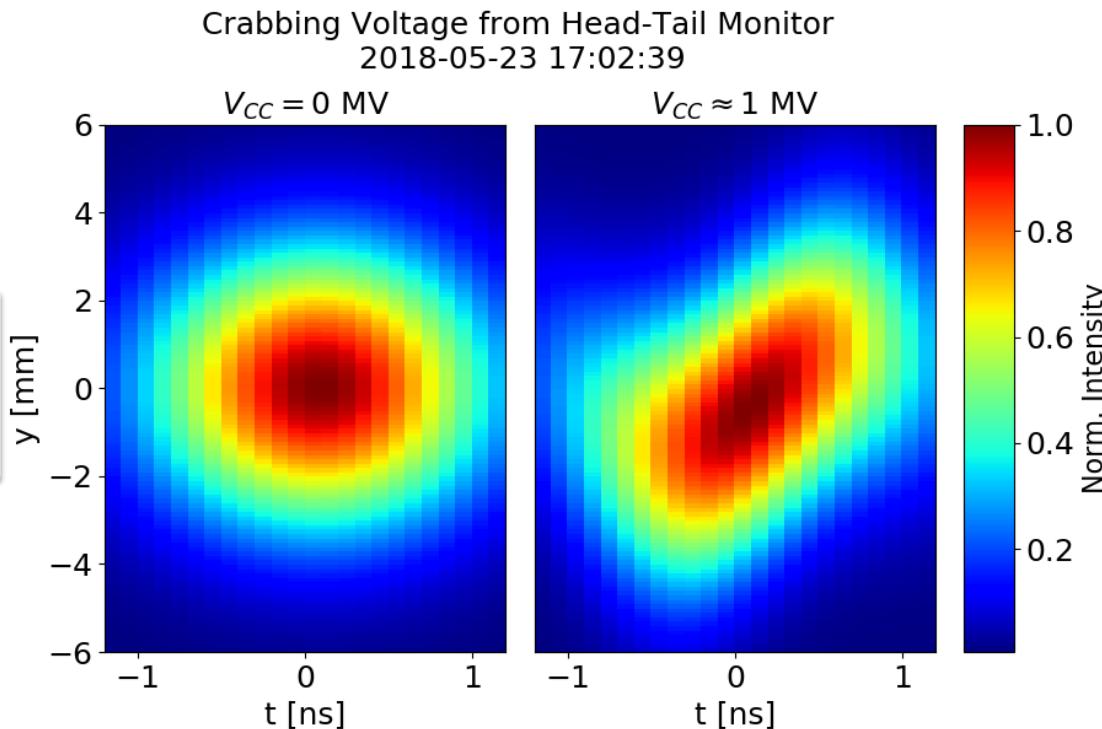


DQW Crab cavity cryo-module for installation in the SPS



First proton crabbing ever!

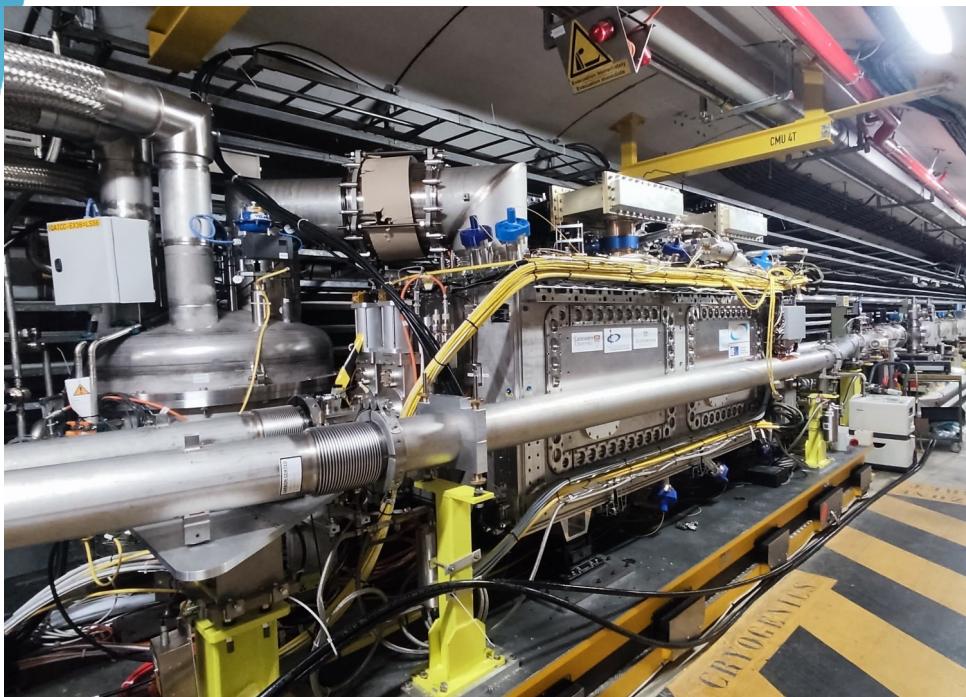
Beam TEST in SPS ongoing between 2018-2023





RFD cryomodule assembled in UK and being tested in
M7 bunker (SM18-CERN) in 2024 before installation in SPS
in YETS 2024 / 2025

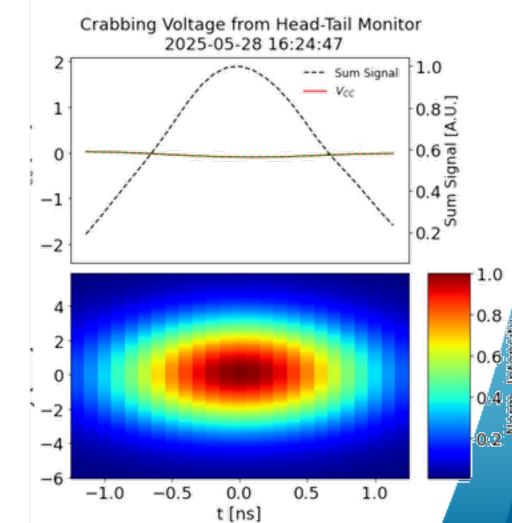
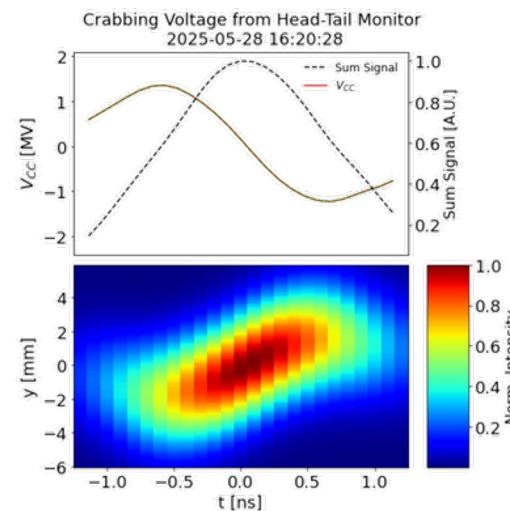
RF Dipole, MD #1



See Rama Calaga on RFD MDs on Thursday parallel session

Despite the non-ideal situation with temperature and vibrations, MD #1 for crab cavity setup with beam was successfully carried out at 1 MV /cavity in 2025

Horizontal crabbing with protons – for the first time !



Oliver Brüning CERN

LS3 Schedule: Latest Version [October'25] fits into 47 months!

LSS dismantling after cryo lockout

Cabling dismantling

Core excavation (LHC side)

Cabling installation

LSS installation

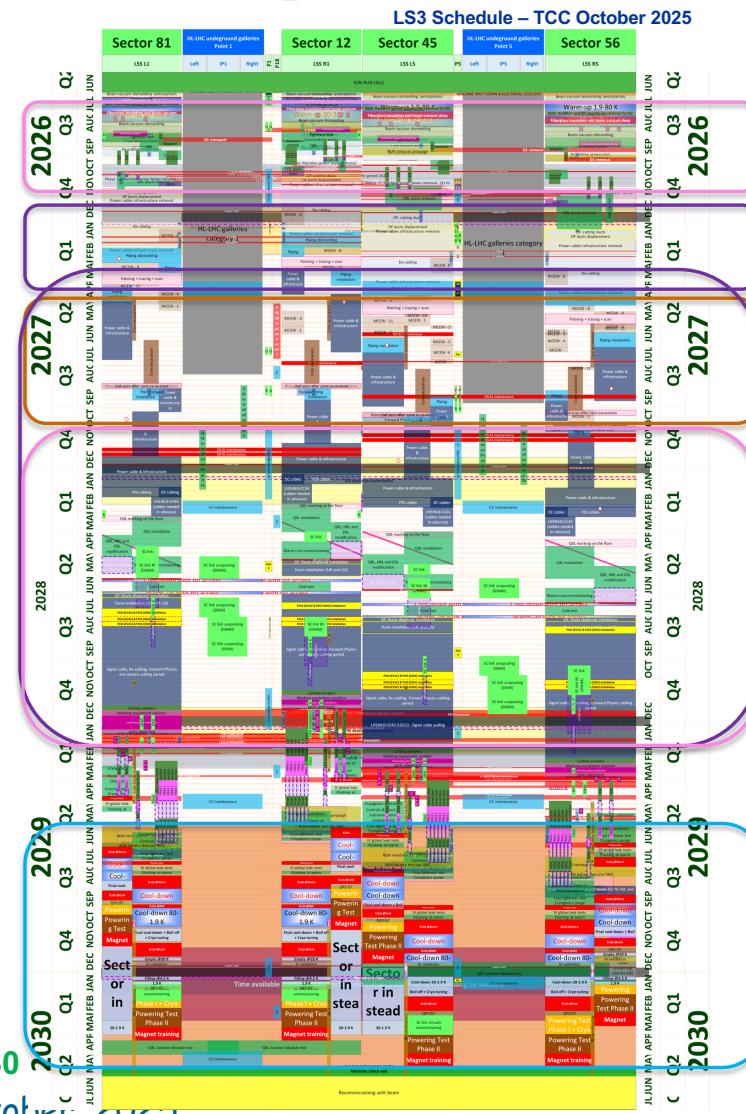
Triplet installation planned for Q1 to Q2 2029

CC installation planned for Q4 '28 to Q2 '29

Cool-down, related test and HWC

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

Q2 2026



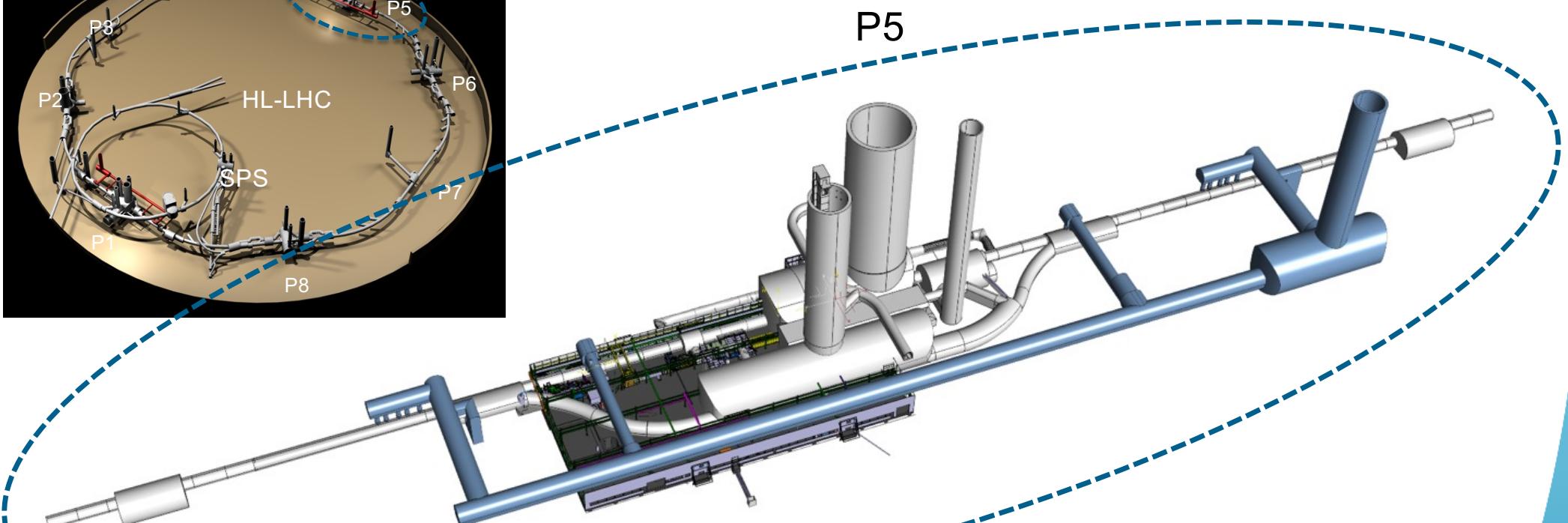
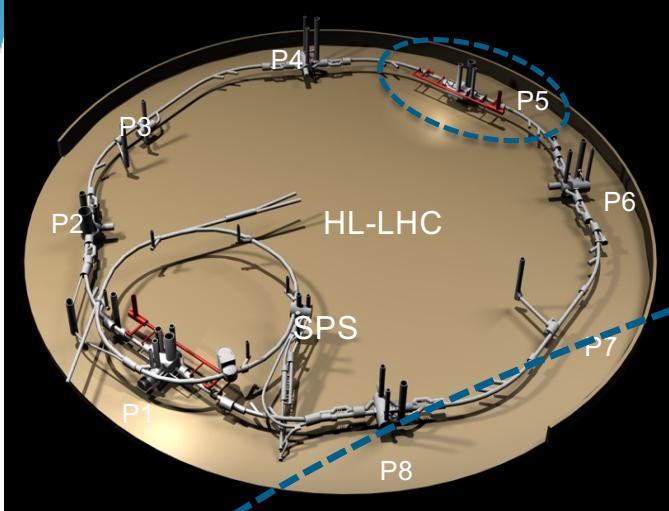
Plus

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

It fits, but with a success oriented planning

→ Currently working on options to provide additional flexibility

Next Milestone: HL-LHC IT STRING: P5L



The IT STRING Scope

The **scope** of the IT STRING is to represent, as best as reasonably achievable in a surface building, the various operation modes to **STUDY and VALIDATE the COLLECTIVE BEHAVIOUR** of the different systems of the HL-LHC's IT zone (magnets, magnet protection, cryogenics of the magnets and of the superconducting link, magnet powering, vacuum, alignment, interconnections between magnets, and the superconducting link itself).

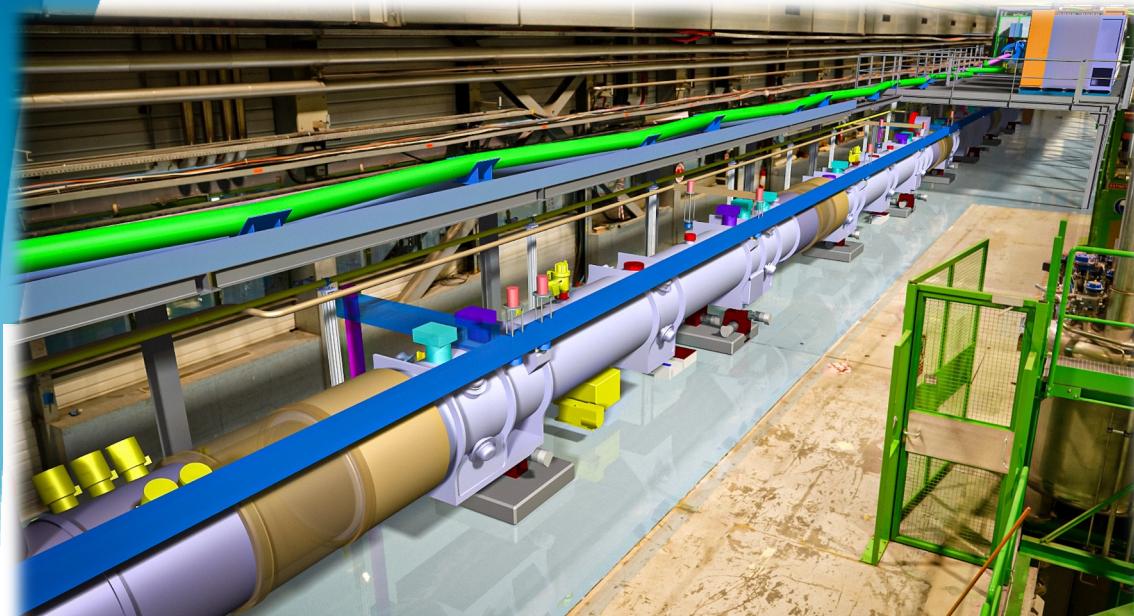
Installation of IT-String started and will proceed throughout 2025.

Cooldown and Start of powering planned for End 2025



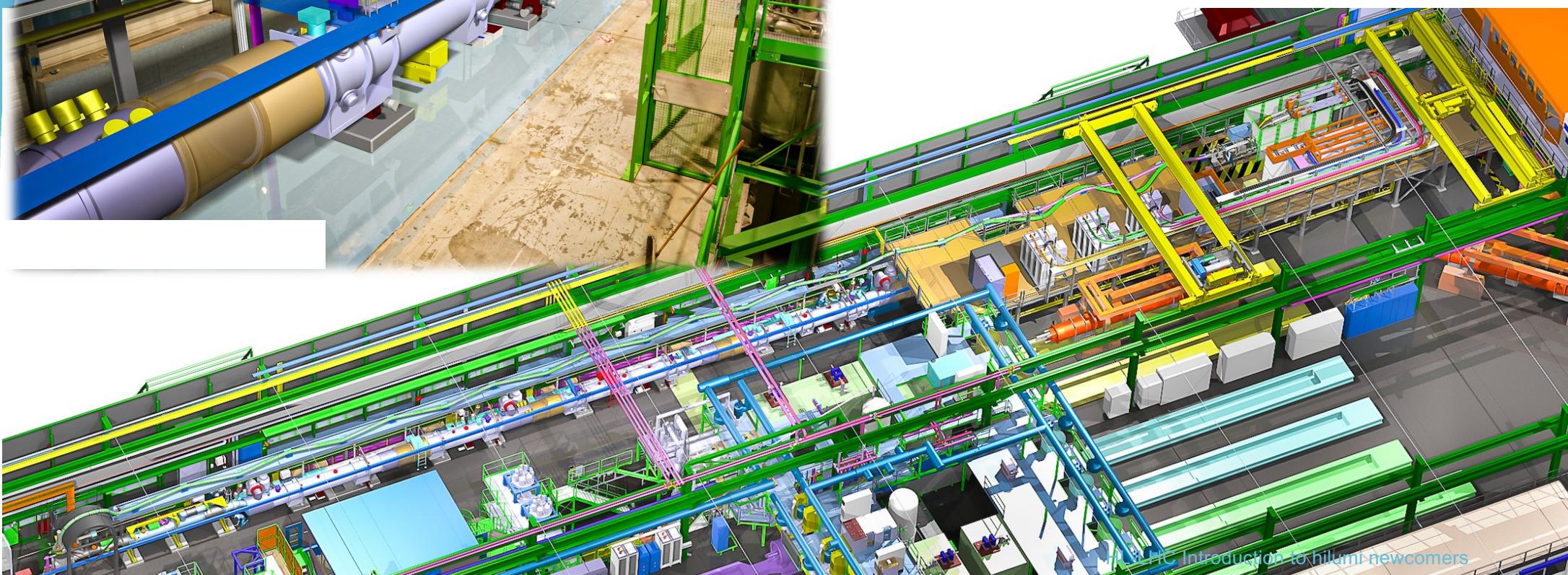
The **IT STRING** will deliver the first complete experience
of installing and operating the IT zone

IT String Installation in SM18: Q1 up to D1 inclusive!

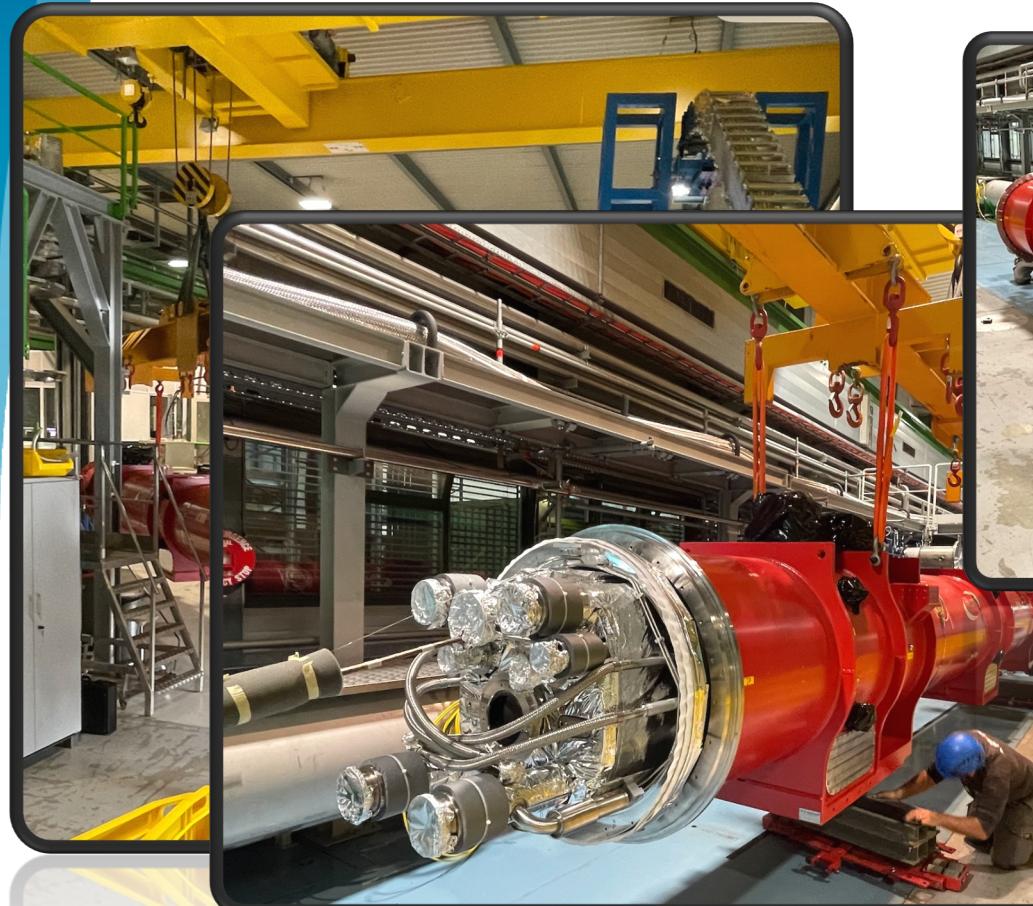


Installation started and foreseen until 2023

→ Operation planned in 2024 and 2025



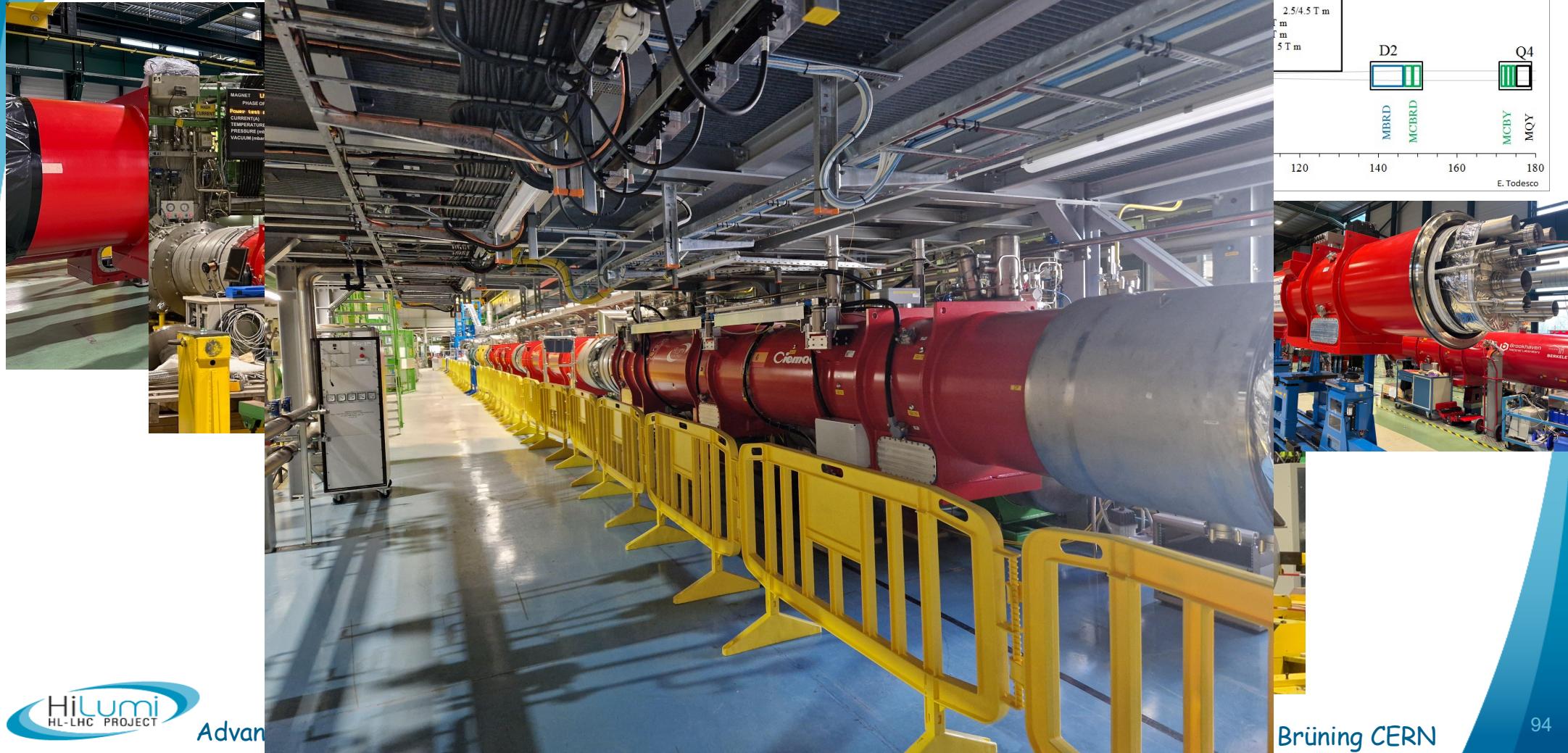
Q2a cold mass installation

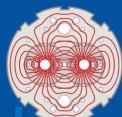


Sc Link INSTALLATION IN THE IT STRING



IT-String Installation





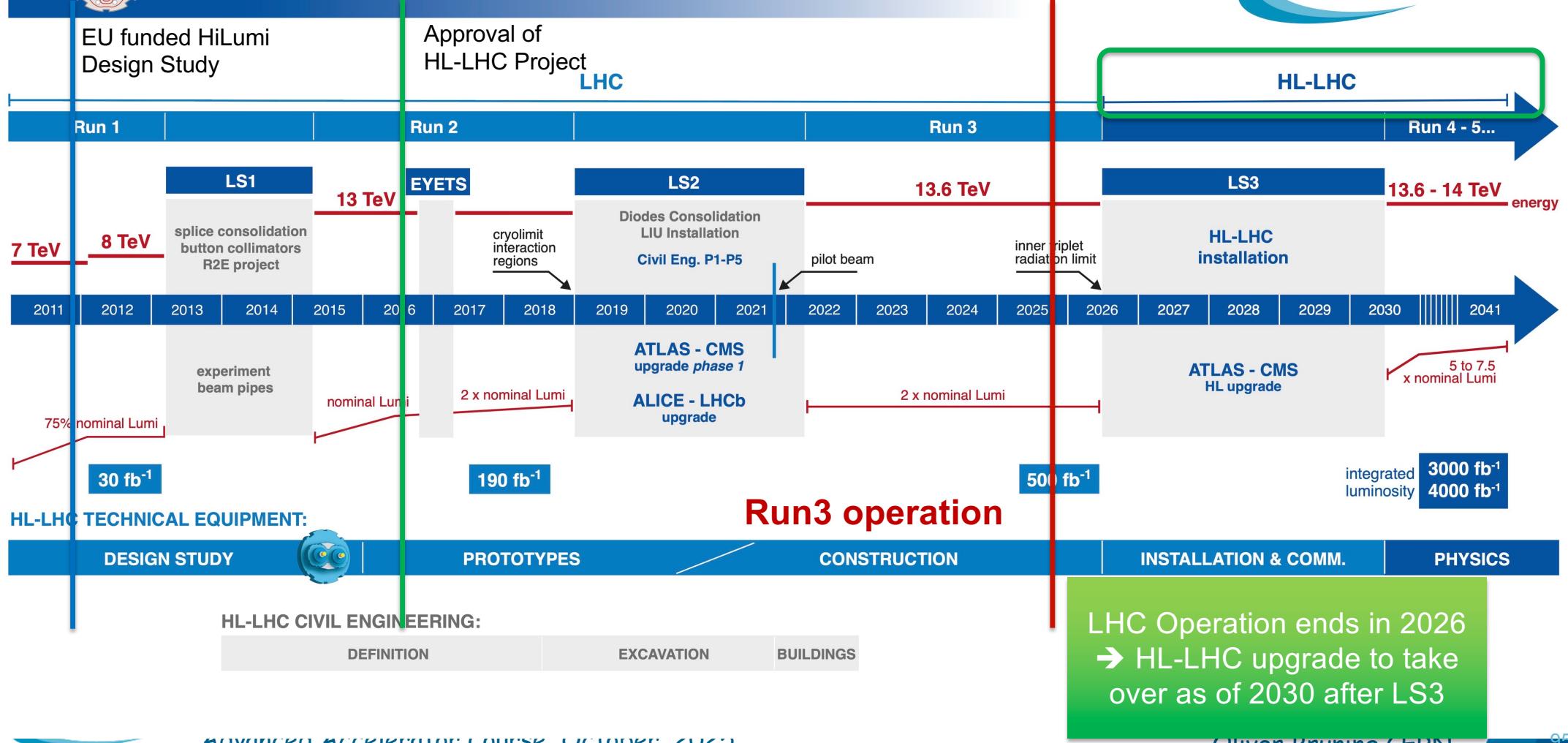
LHC / HL-LHC Plan



EU funded HiLumi Design Study

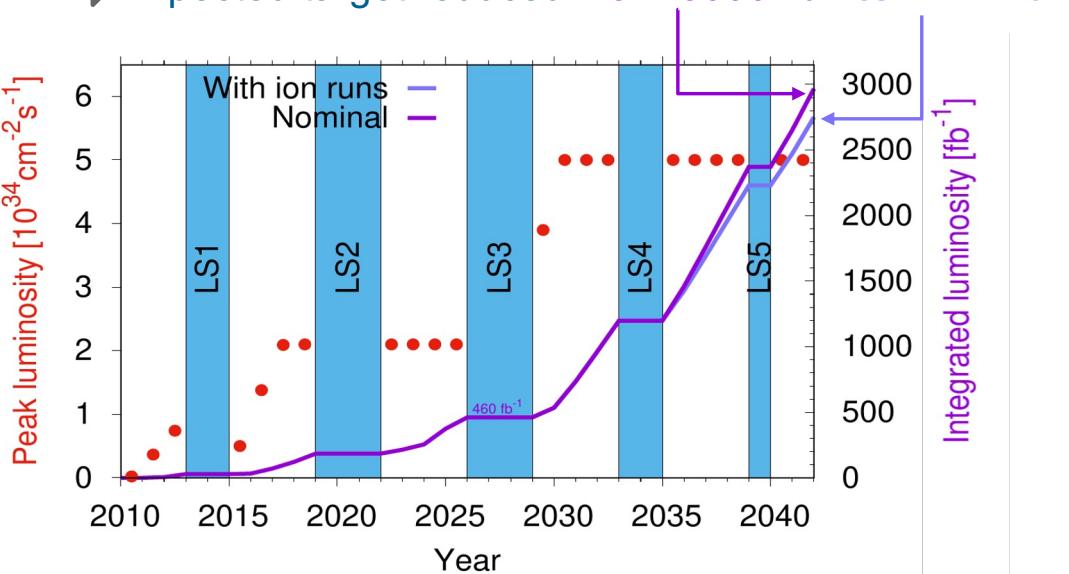
Approval of HL-LHC Project

LHC



HL-LHC physics production

- Ions physics run recently approved in 2031-2041



- How could 3000 fb^{-1} could be recovered?

Machine could provide higher pile-up to compensate, if requested by experiments

Limit considering engineering margins PU = 200

Run	Year	Reference PU	Reference (fb^{-1})	New Baseline PU	New Baseline (fb^{-1})
4	2030	100	32	100	32
	2031	132	206	132	206
	2032	132	237	132	237
	2033	132	234	132	234
5	2036	132	208	170	239
	2037	132	271	170	311
	2038	132	276	170	317
	2039	132	276	170	317
	2040	132	229	170	262
	2041	132	284	170	325
Sum Run 4 Run 5		2251			
Sum all runs (+520)		2771			

LS3 Schedule: Latest Version [October'25] fits into 47 months!

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Cabling dismantling

Core excavation (LHC side)

Cabling installation

LSS installation

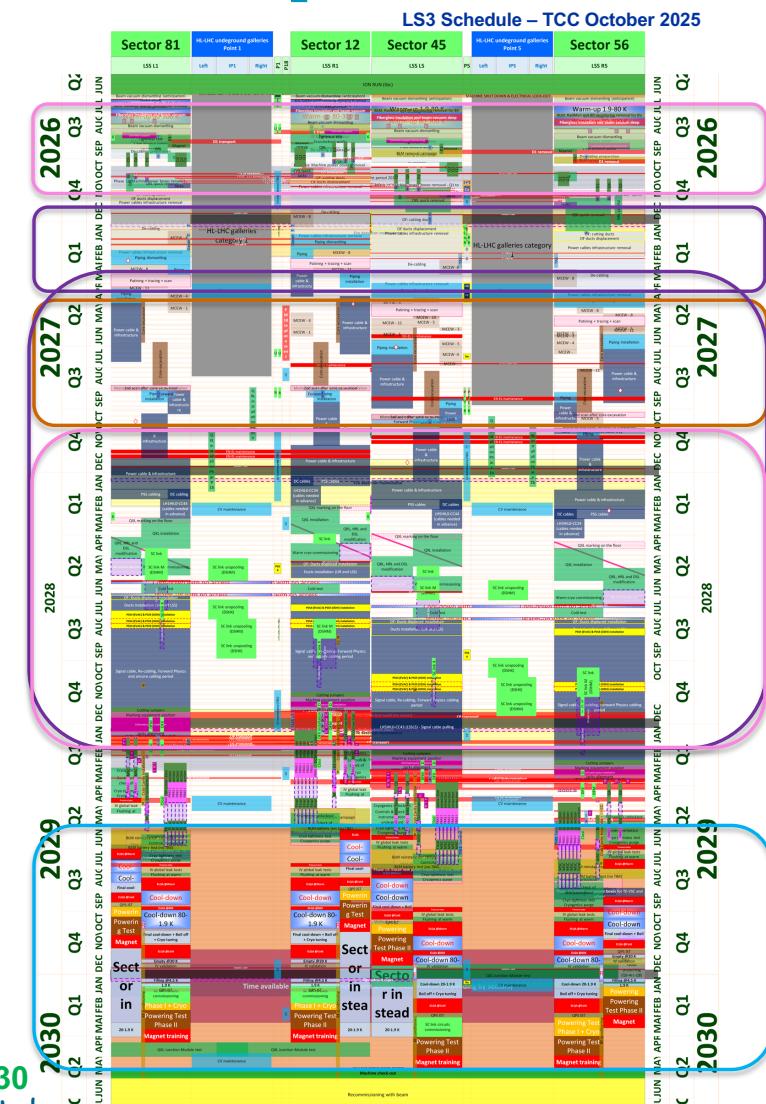
Triplet installation planned for Q1 to Q2 2029

CC installation planned for Q4 '28 to Q2 '29

Cool-down, related test and HWC

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

Q2 2030
se; October, 2023



Plus

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

It fits, but with a success oriented planning

→ Currently working on options to provide additional flexibility

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Directions in High Energy Physics — Vol. 31

THE HIGH LUMINOSITY LARGE HADRON COLLIDER

New Machine for Illuminating the Mysteries of the Universe
Second Edition

Editors

Oliver Brüning and Lucio Rossi



 World Scientific

LHC Summary



CERN COURIER

January/February 2024 cerncourier.com

Reporting on international high-energy physics

HIGH-LUMINOSITY LHC ON TRACK

Published in 2024 and available
as
Open Access Publication
<https://doi.org/10.1142/13487>
ISBN: 978-981-127-894-5

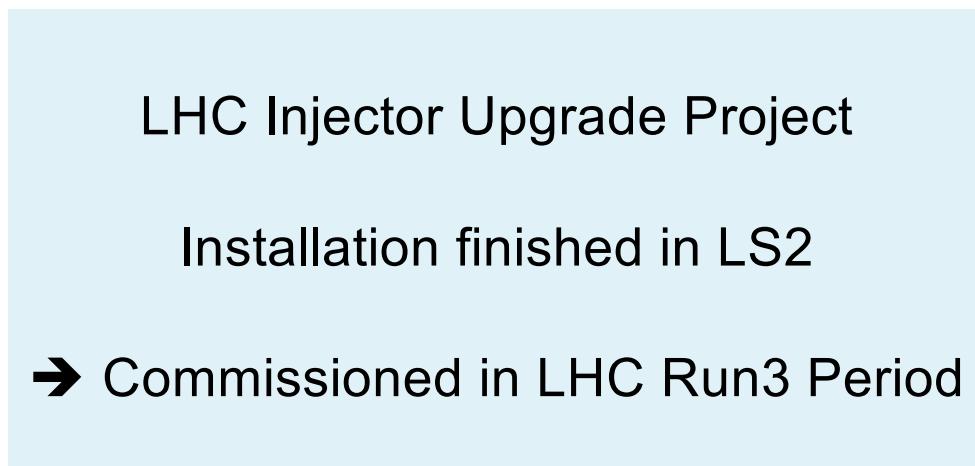


Questions?

The LHC is NOT a Standalone Machine

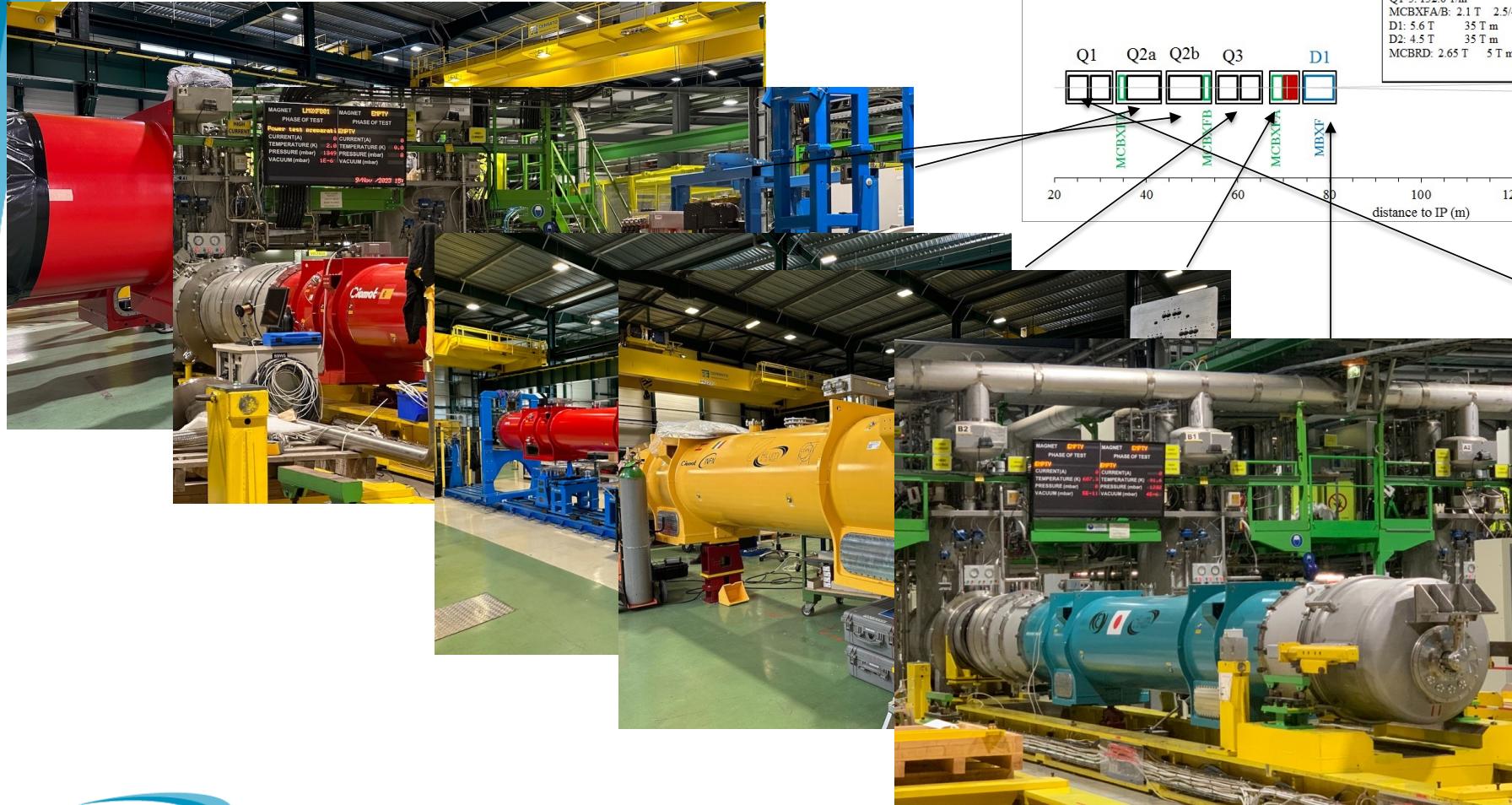
The LHC performance fully relies on the **performance of its injector complex**

- By itself **one of the largest accelerator facility in the world** with its own diverse and, for many aspects, unique physics program



- LHC : $2 \times (0.45 - 7)$ TeV
- SPS : 26 – 450 GeV
- PS : 2 - 26 GeV
- PSB : 0.16 - 2 GeV
- Linac 4: 0-160 MeV H-

Magnet Validation for IT-String



Being tested @ FNAL;
Expected @ CERN by
November 2024

LHC (Large Hadron Collider): Magnet Technology

14 TeV proton-proton accelerator-
collider built in the LEP tunnel →
requires ca. 9T magnets!!!

→ 200000 times the
earth magnetic field!!

→ Not feasible with
Normal conducting magnets

1983 : First studies for the LHC project
1988 : First magnet model (feasibility)
1994 : Approval by the CERN Council
1996-1999: Series production industrialisation
1998 : Declaration of Public Utility &
Start of civil engineering
1998-2000: Placement of main production contracts
2004 : Start of the LHC installation
2005-2007: Magnets Installation in the tunnel
2006-2008: Hardware commissioning
2008-2009: Beam commissioning and repair

As of 2010: Physics exploitation



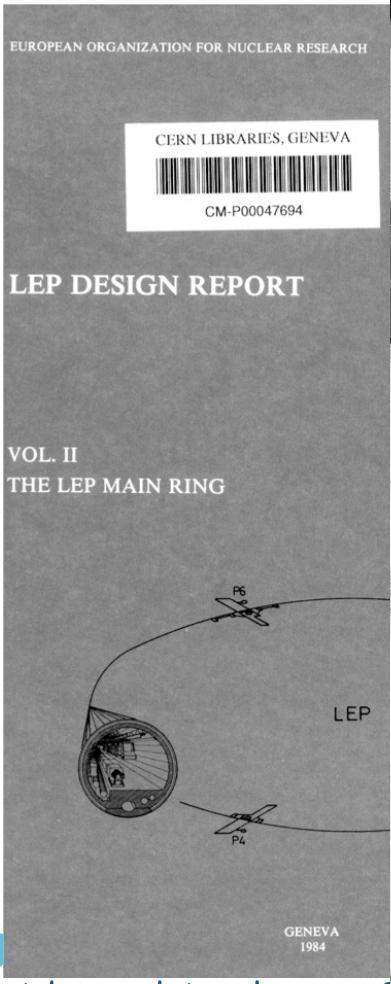
Ca. 20 years magnet development!!!



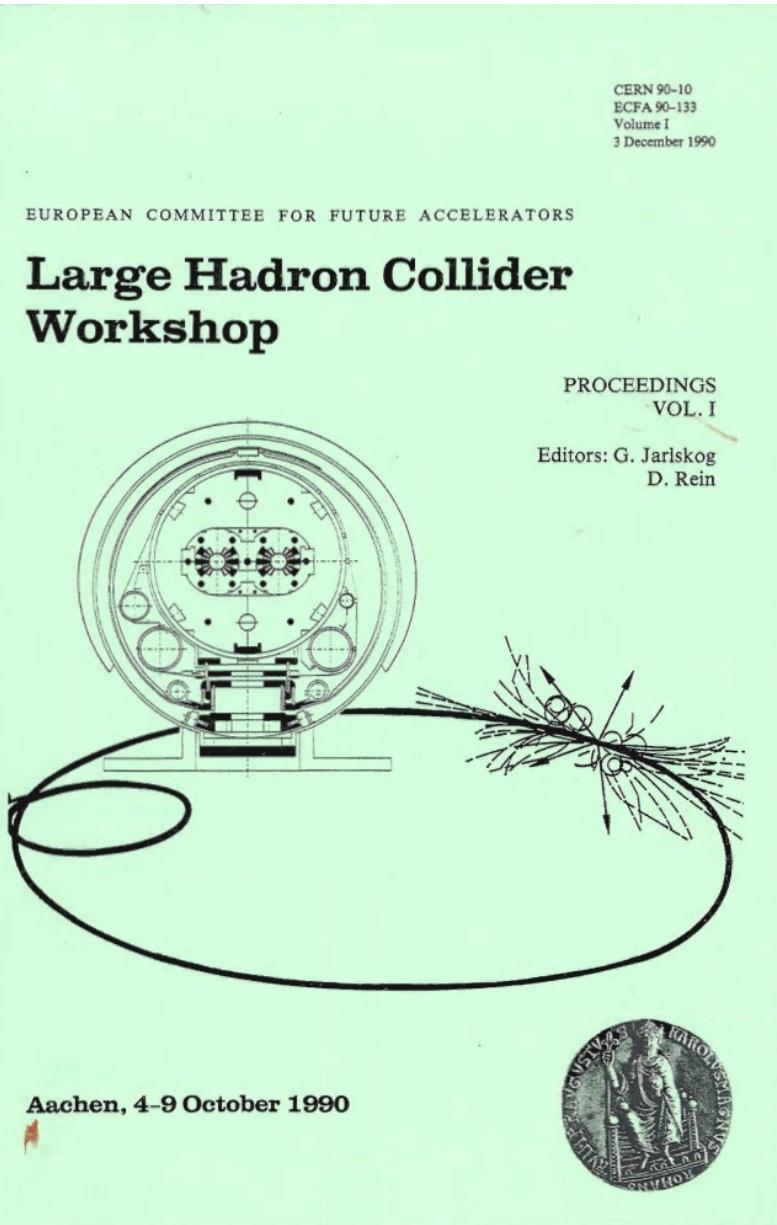
Ca. 30 years machine development!!!

LHC: was already 1989 to 2000

LEP
Design
Report
1984

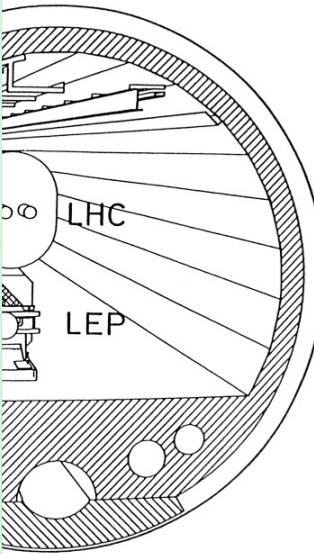


Advanced Accelerator
Concepts



Start of LEP

ECFA 84/85
CERN 84-10
5 September 1984



ADRON COLLIDER
E LEP TUNNEL

Vol. I

THE ECFA-CERN WORKSHOP

at Lausanne and Geneva,
21-27 March 1984

Oliver Brüning CERN

Lausanne
ECFA-CERN
Workshop
1984

LHC Magnet Technology:
Thousands of fine Nb-Ti filaments well
separated along km of wires
Industrial production via extrusion

Fine filaments of Nb-Ti in a Cu matrix (for an LHC dipole wire)

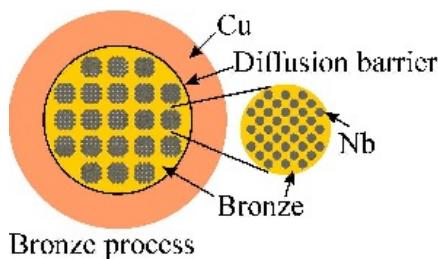
Cable of 15 kA!)



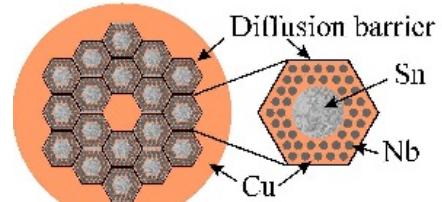
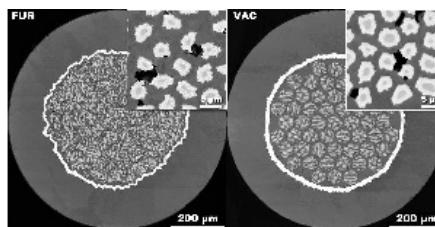
The Nb_3Sn SC Challenge:

Nb_3Sn is **brittle** and cannot be drawn in final form – contrary to NbTi

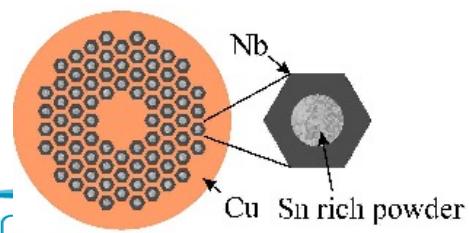
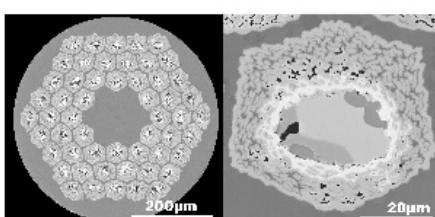
Strand is drawn before cable is formed before the wire is heat-treated to form the Nb_3Sn superconductor!



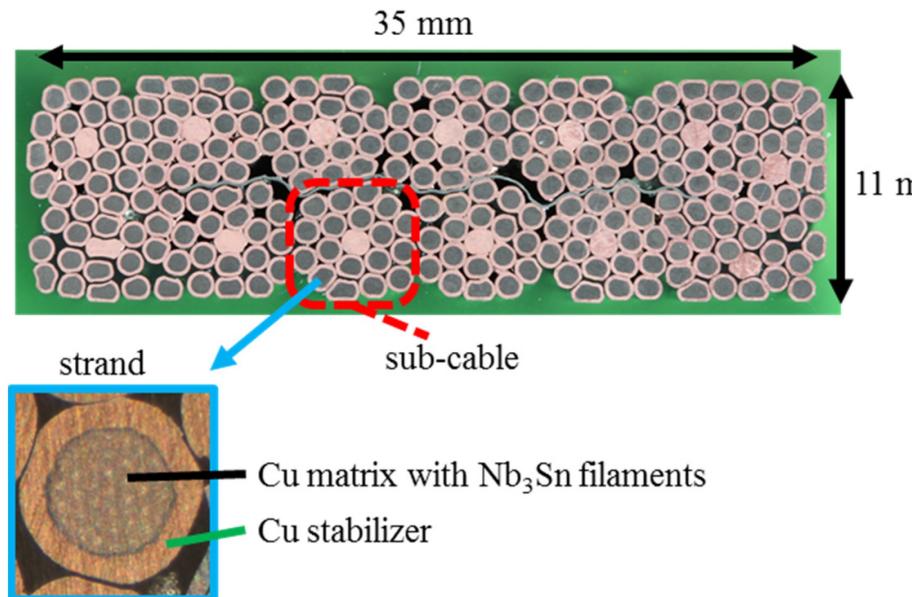
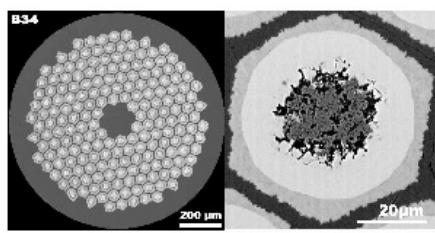
Bronze process



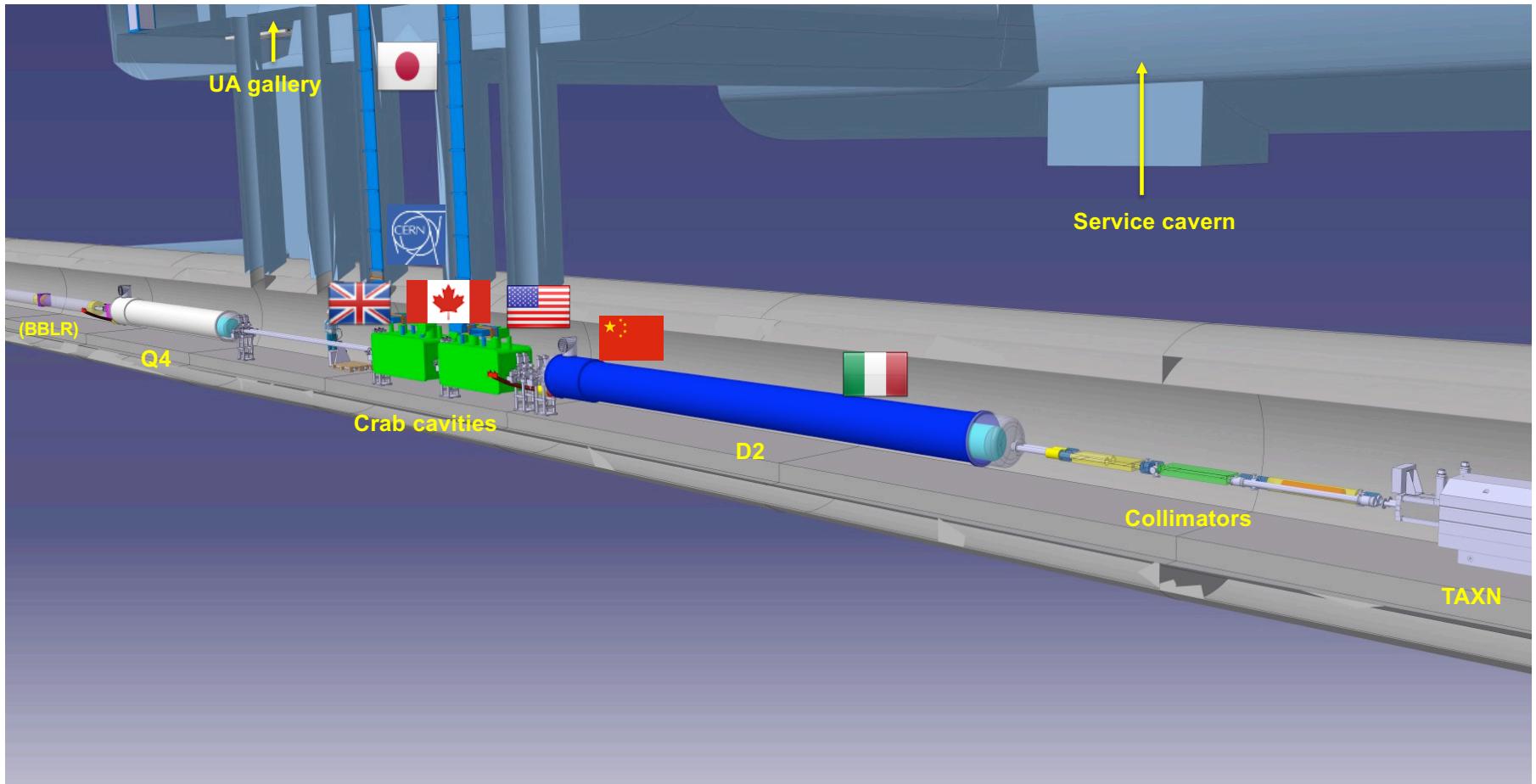
Internal Sn process



HiLur
HL-LHC PRO-PIT process



The MS region with in-kind contributions





The magnet featured 3 quenches at flat top during magnetic measurement @ CERN after 1.5h, 3h and over 11h holding current

- Origin still to be understood
- But fully operational @ 6.8TeV

