



HL-LHC project

O.Brüning, CERN

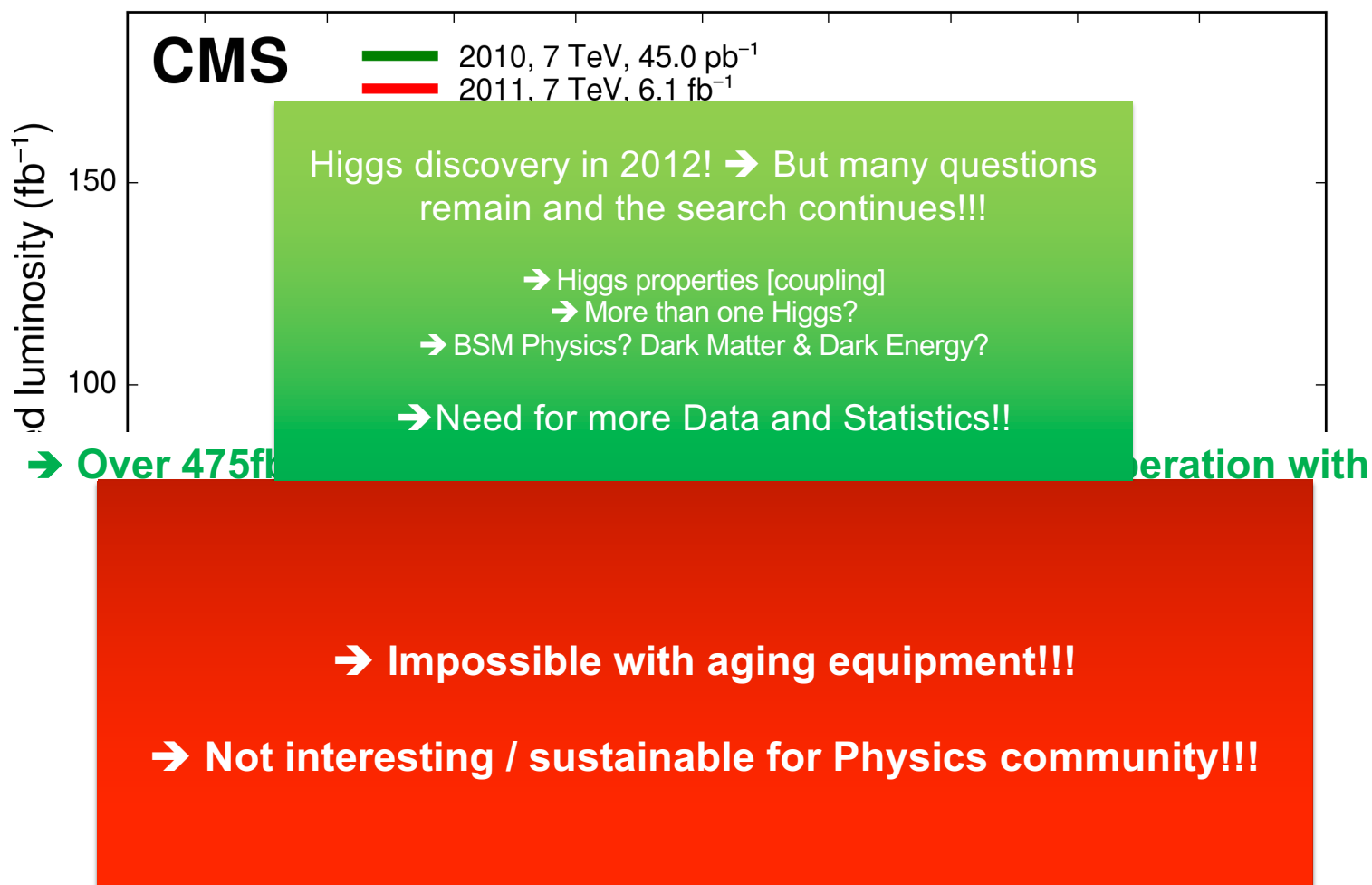
Outline

- **Recap LHC**
- **Introduction HL-LHC → key project goals and challenges**
- **Project Milestones**
- **IT-String Test → Showcase for 2025**
- **LS3 Outlook**

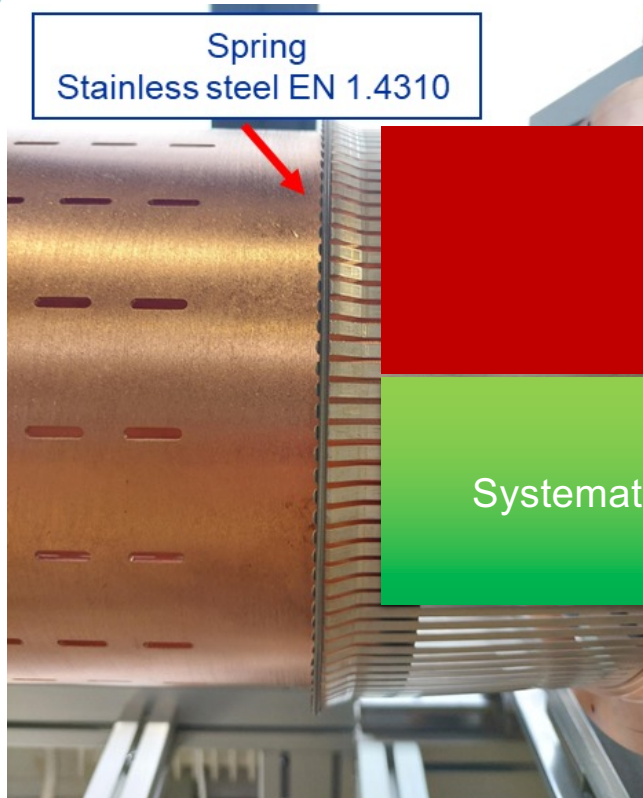
LHC in the Geneva Basin and its Experiments



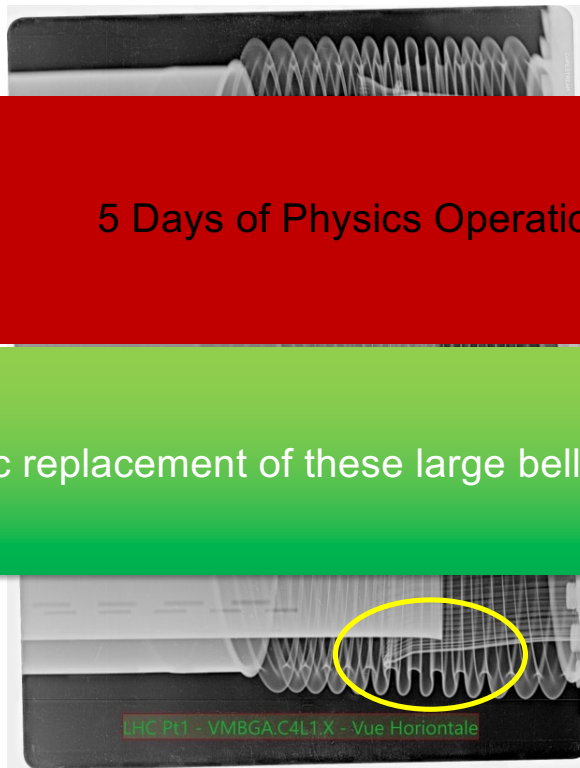
LHC Performance



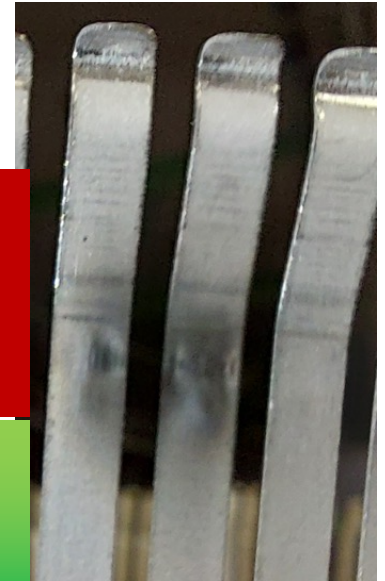
Bellows Module 5: X-ray and Photos after Opening



How it should look



Spring disengaged with RF fingers not touching



Clear sign of the spring heating

Example Triplet incident in July 2023: [IR8 IT.L8]

➔ Early 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

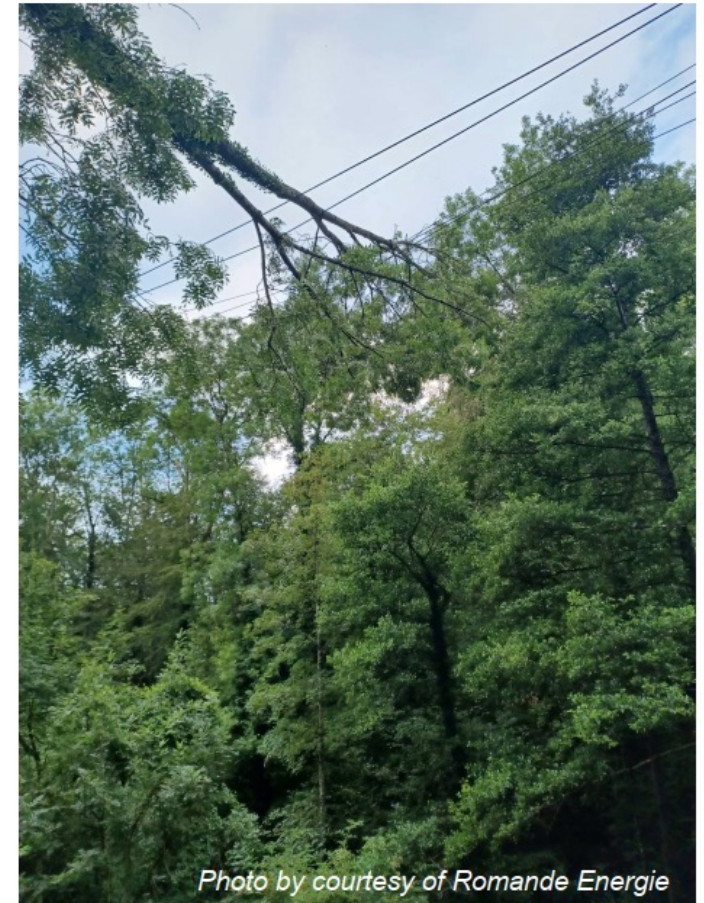
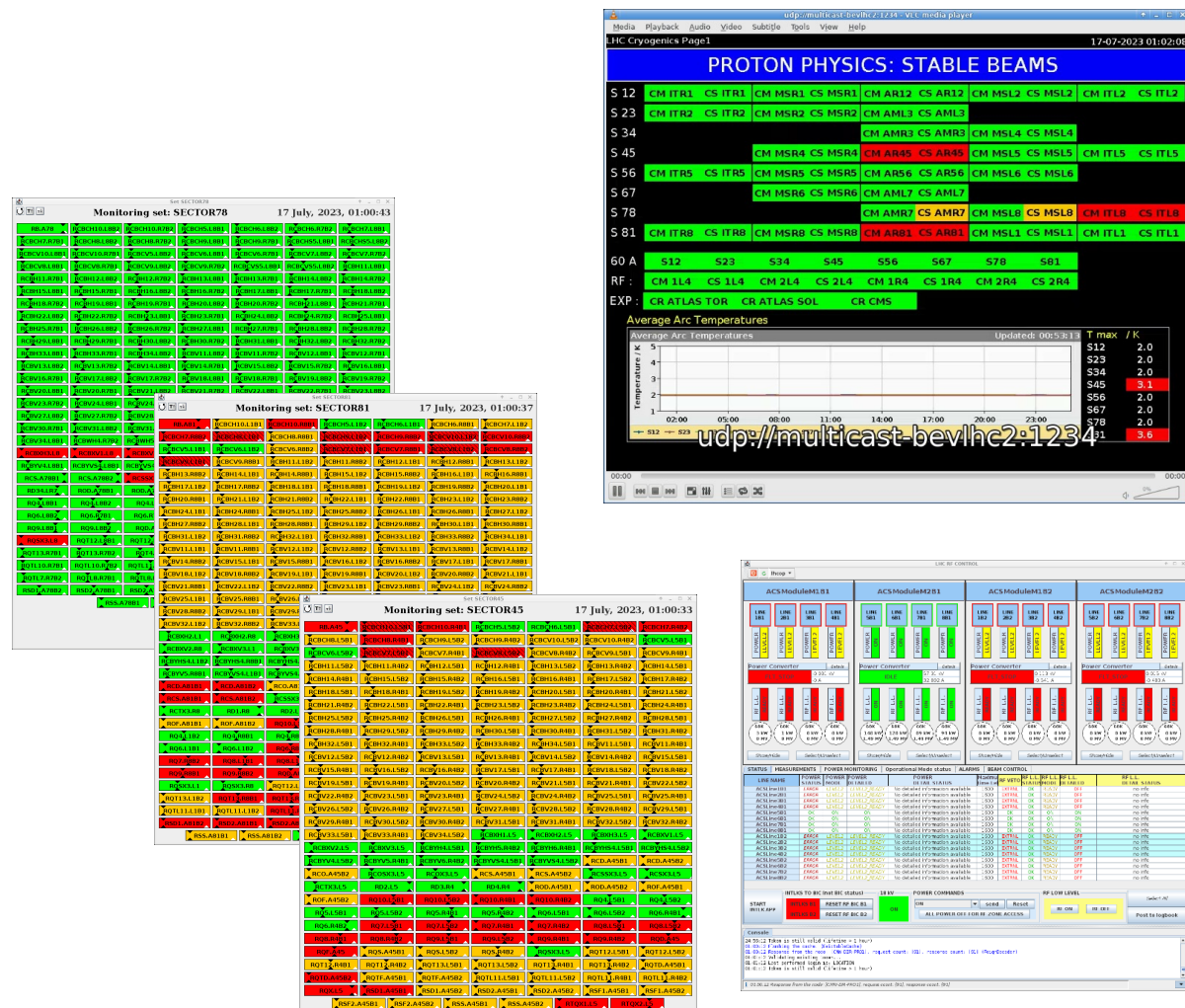


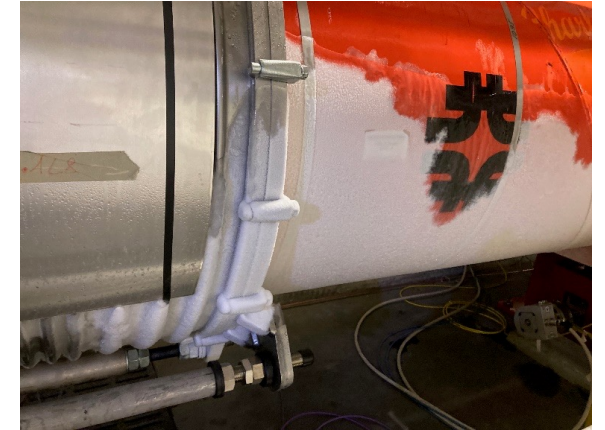
Photo by courtesy of Romande Energie

Event sequence

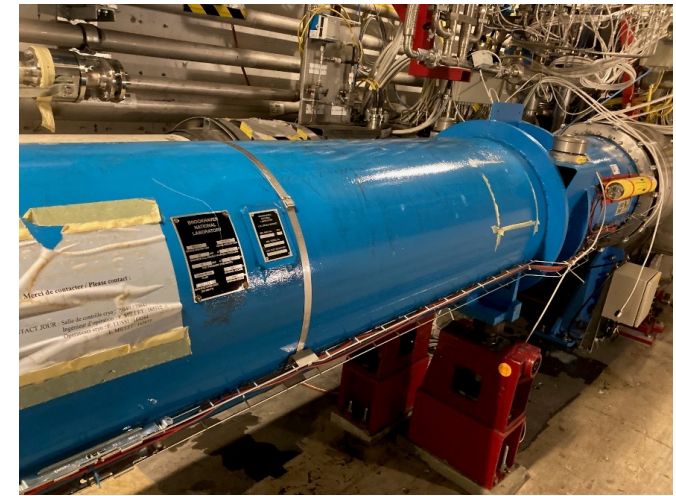
- Beams dumped at 01:00:17 by **RF fault**.
- 370 milliseconds later **several magnets quenched**:
 - RQ7/9/10.R4
 - RQ10.R8
 - RQX.L8
- The heat wave generated by RQX.L8 quench tripped the **IP8 cold compressor**.

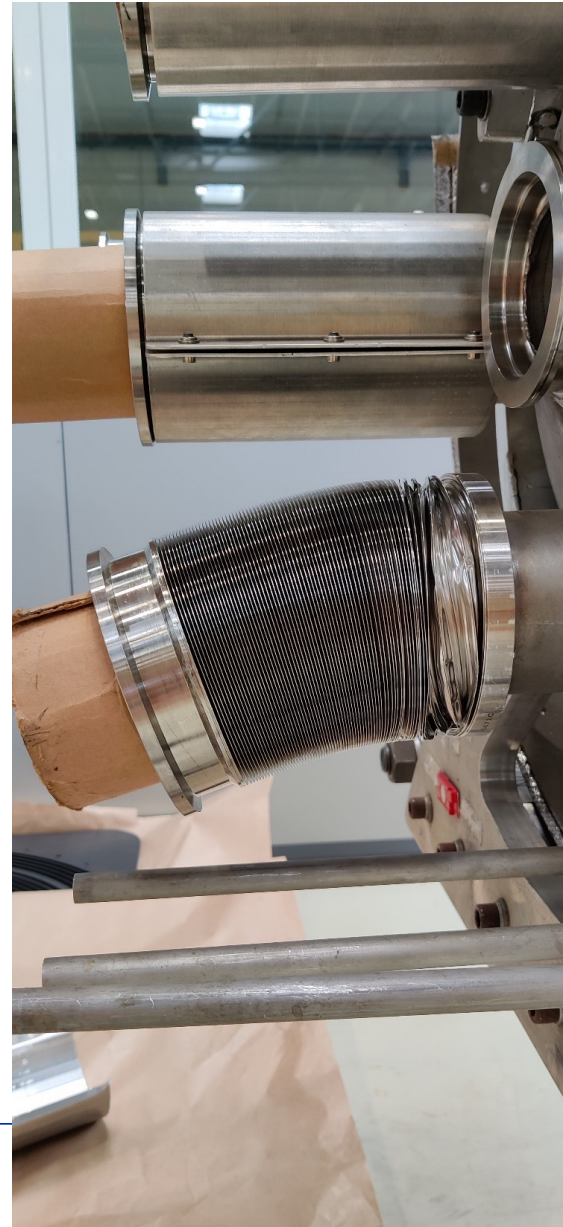
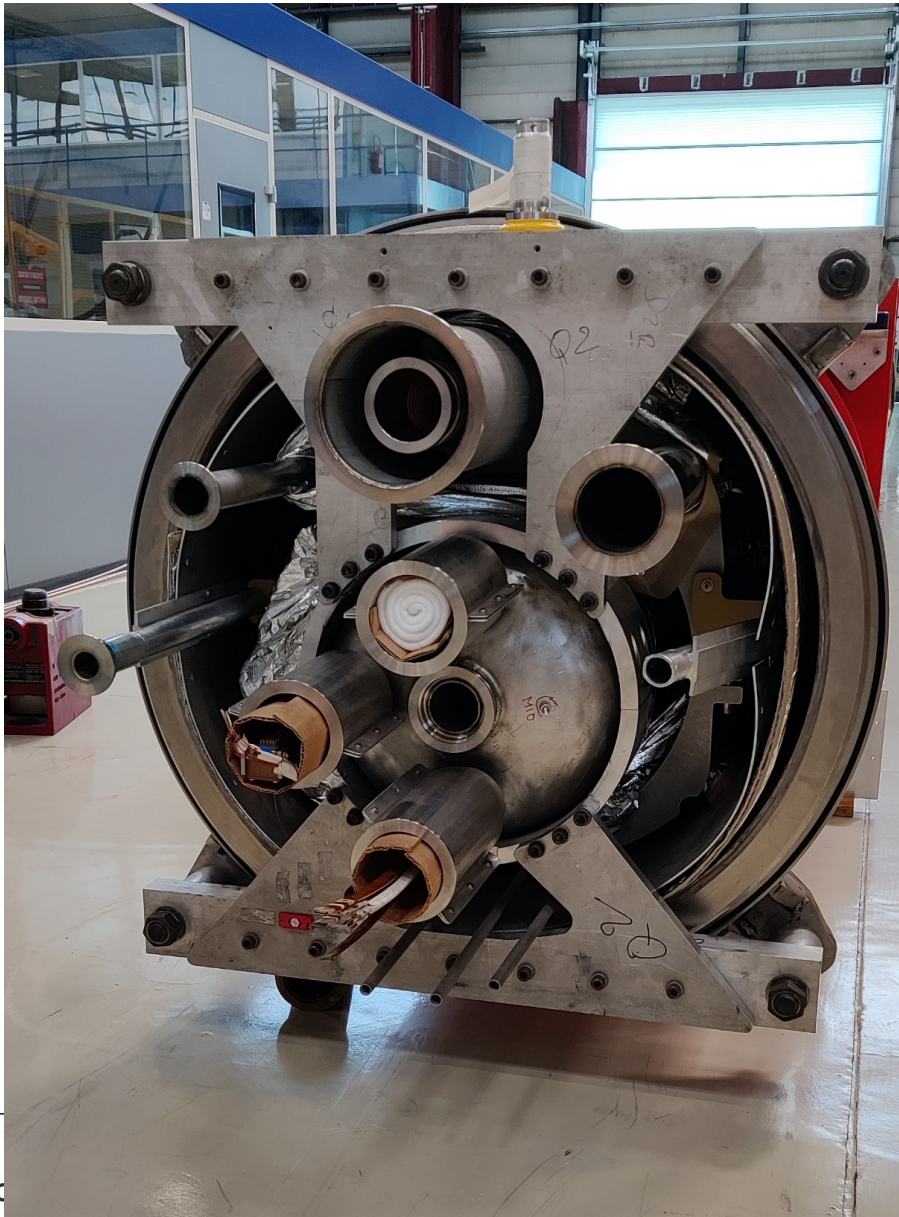


1st tunnel visit



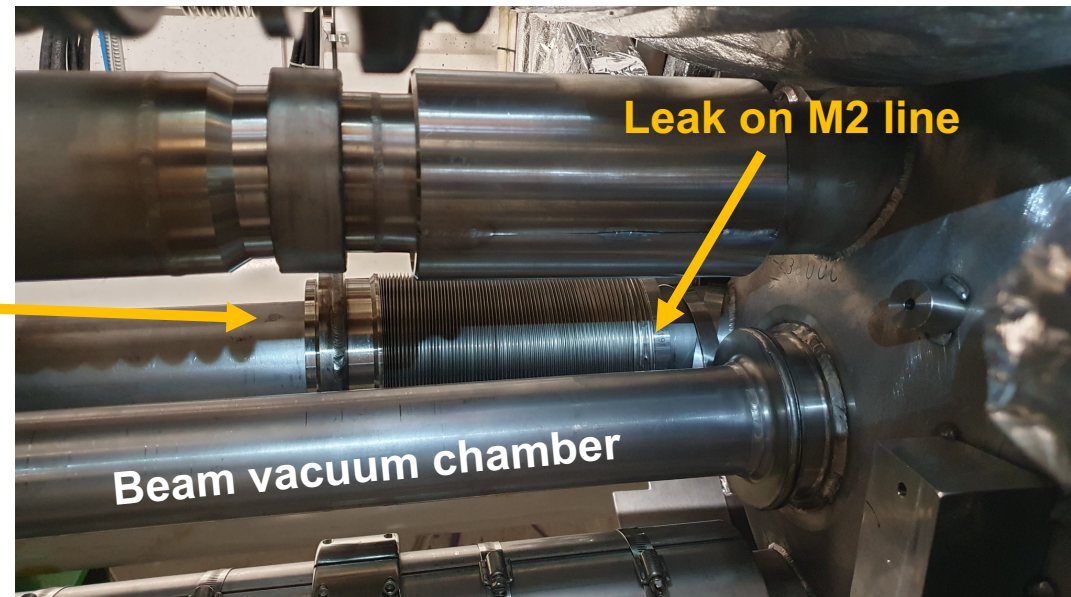
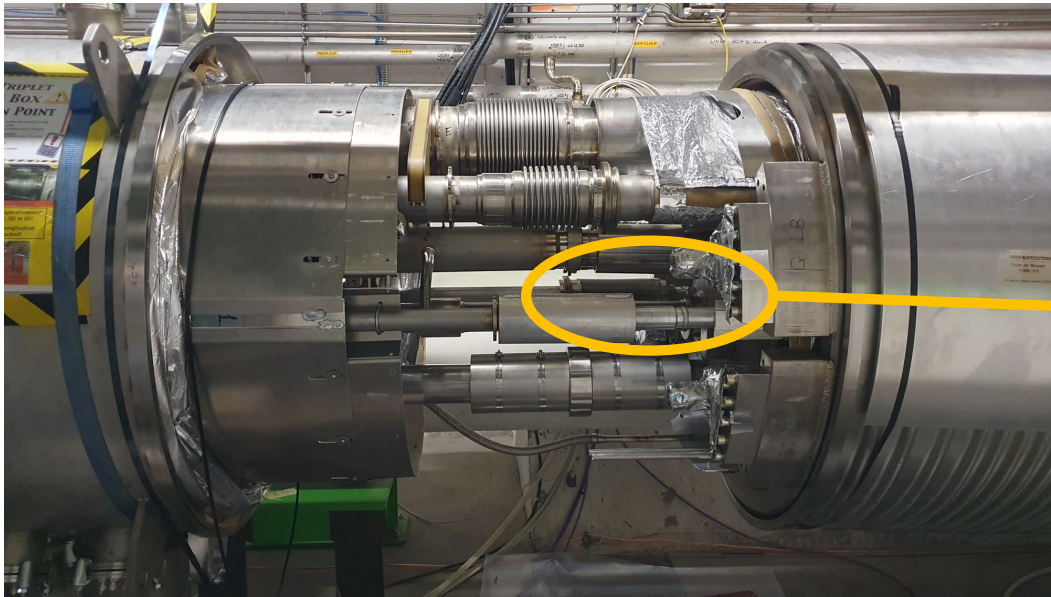
- Condensation on **Q1/2/3**, less on **D1** and **DFBX**.
- Ice and condensation gone on Wednesday.





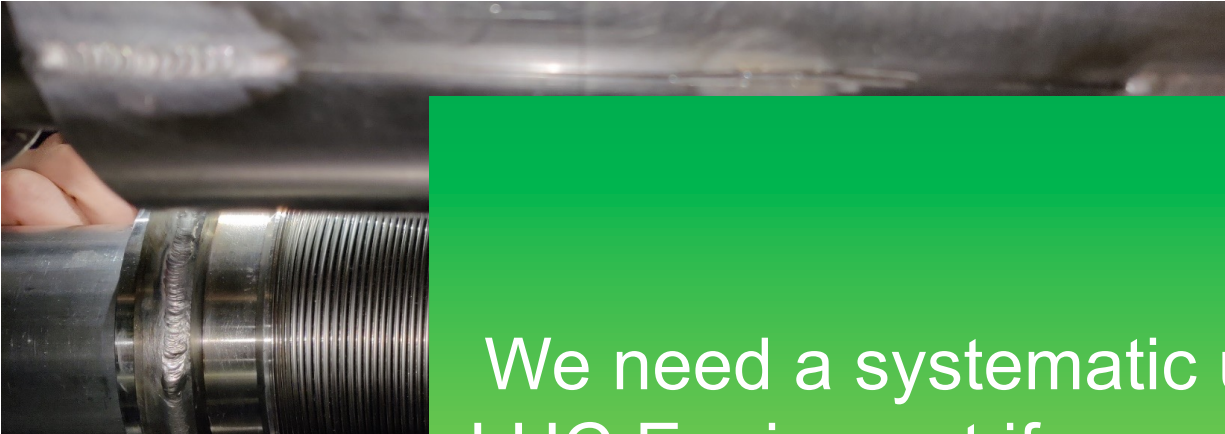
Interconnect opening (3)

- 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

Spare bellow – tested to 20 bar



We need a systematic upgrade of the LHC Equipment if we want to continue running!

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



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:** lev
- **Ultimate:** lev

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

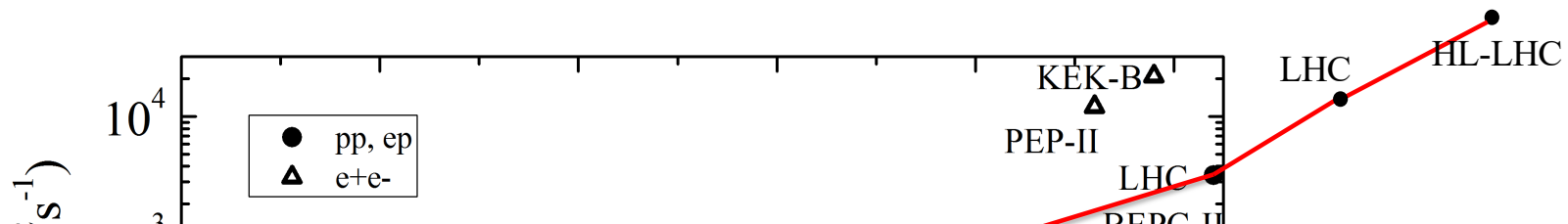
Ca. 1BCHF CtC Project

→ Operation with levelled luminosity!

→ High machine efficiency and reliability are key upgrade ingredients!

→ A challenge as well for the experiments!

Peak luminosities of Hadron colliders



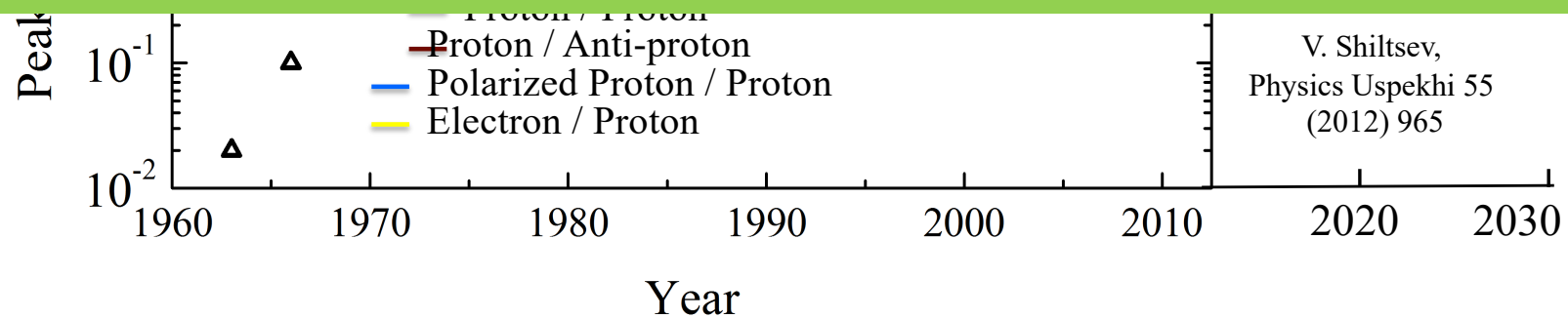
Worldwide Integrated Luminosity prior to LHC: ca. 11 fb^{-1}

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

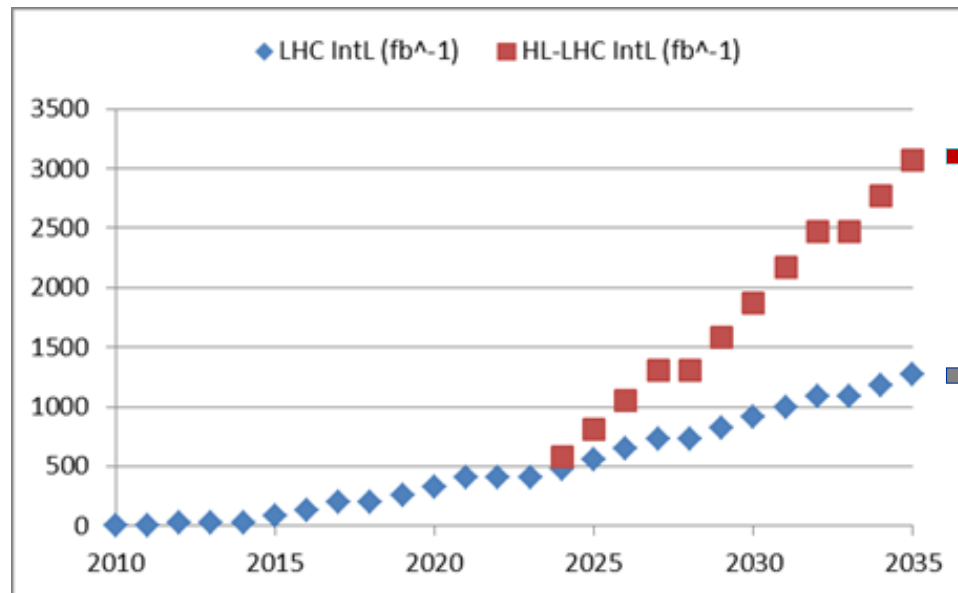
HL-LHC goal: 3000 fb^{-1} to 4000 fb^{-1} !

x 45

x 8



High-Luminosity LHC Goals beyond Equipment Consolidation



By implementing HL-LHC

Almost a factor 3

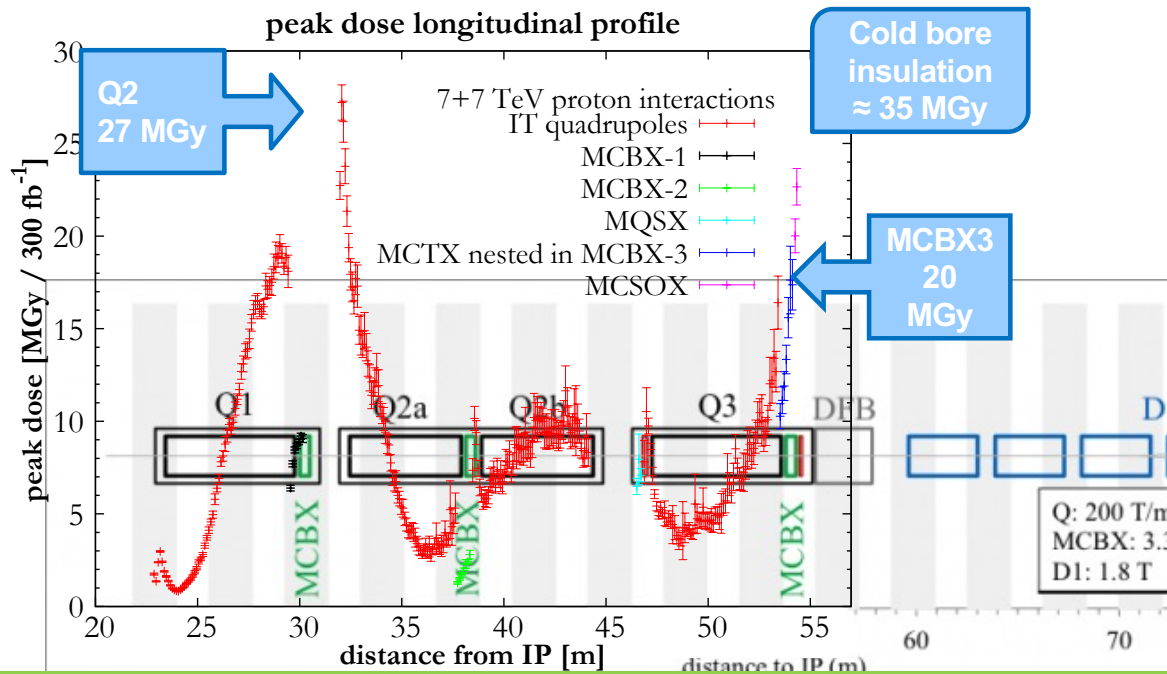
By continuous performance improvement and consolidation

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.

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

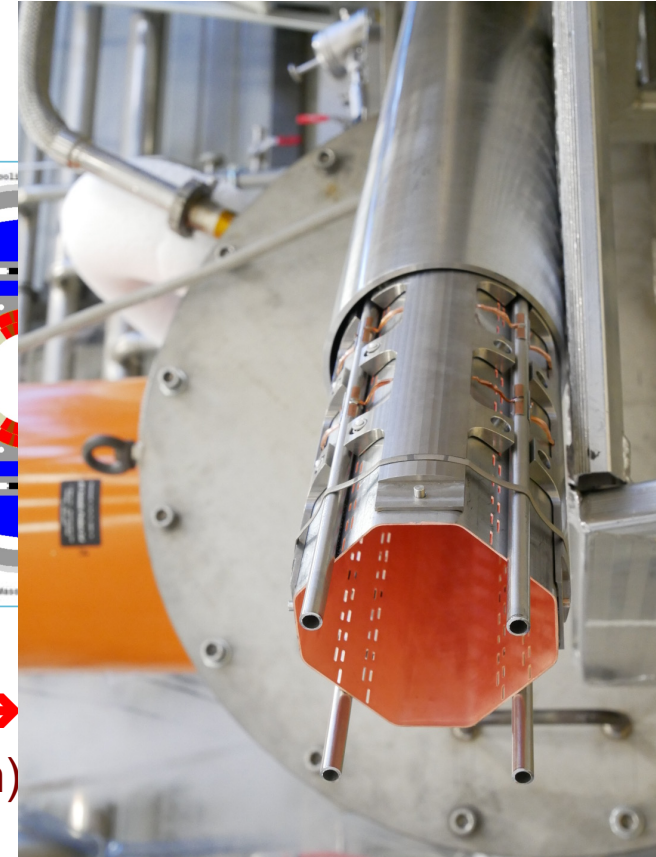
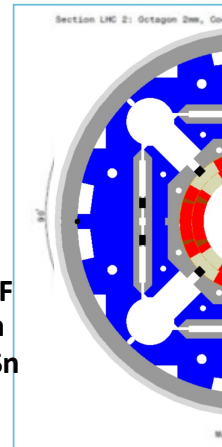
Need to replace existing triplet magnets with radiation hard system such that the new magnet coils receive a similar radiation dose @ 10 times higher integrated luminosity!!!!

→ Shielding!

- Requires larger aperture!
- New magnet technology!

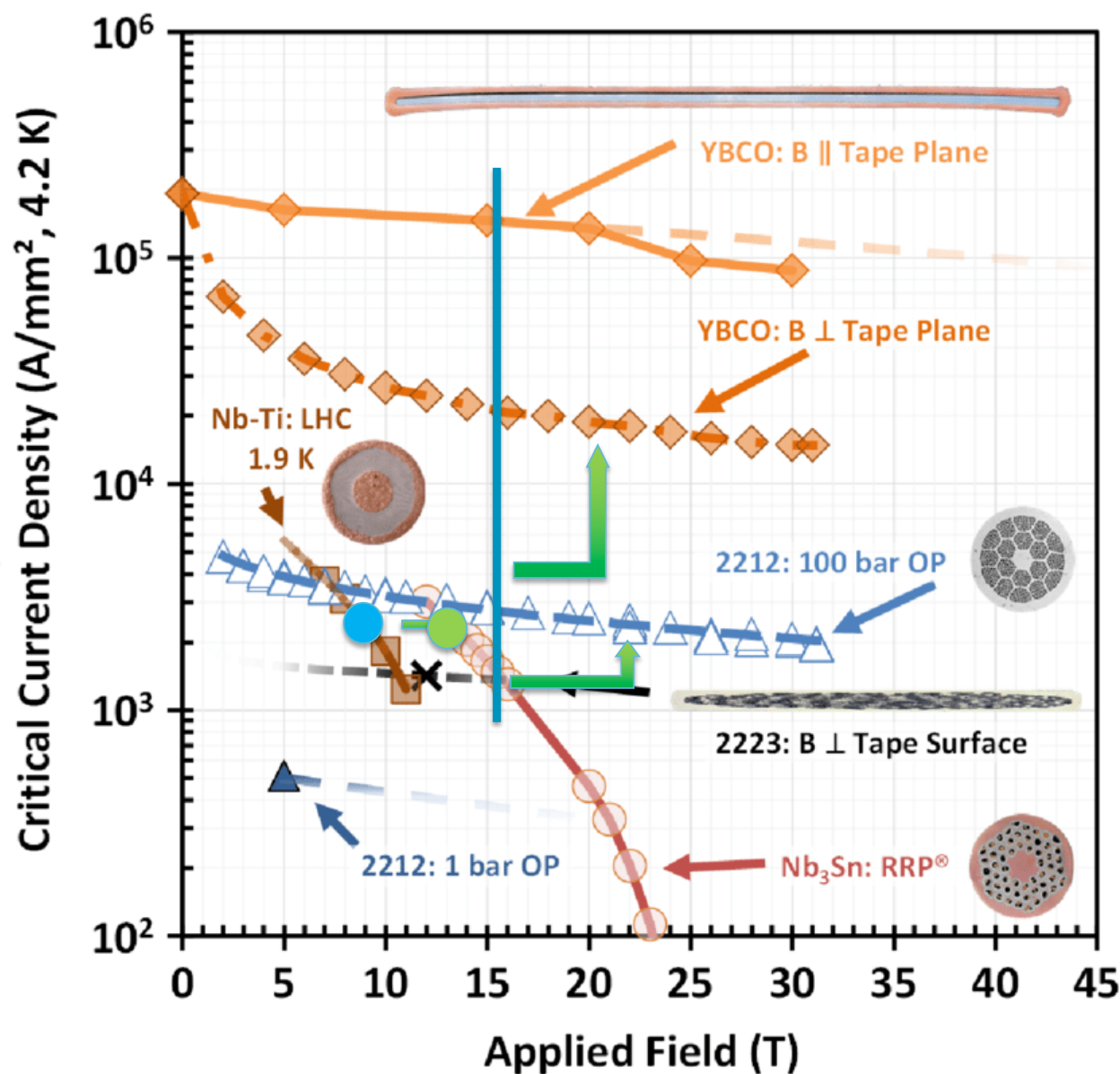
→ 70mm at 210 T/m → 150mm diameter 140 T/m → 8T peak field at coils → 12T field at coils (Nb₃Sn)

US-LARP MQXF magnet design
Based on Nb₃Sn technology



SC Magnet Technology

source:
D. C. Larbalestier @ Researchgate



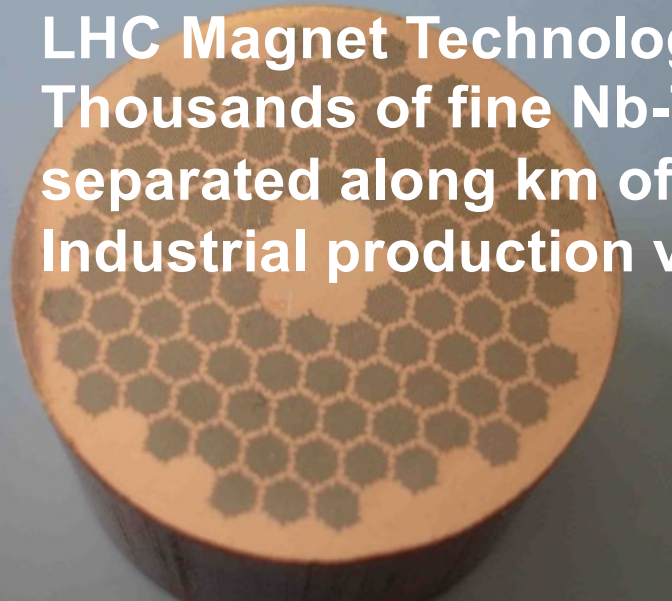
Nb₃Sn

- 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**

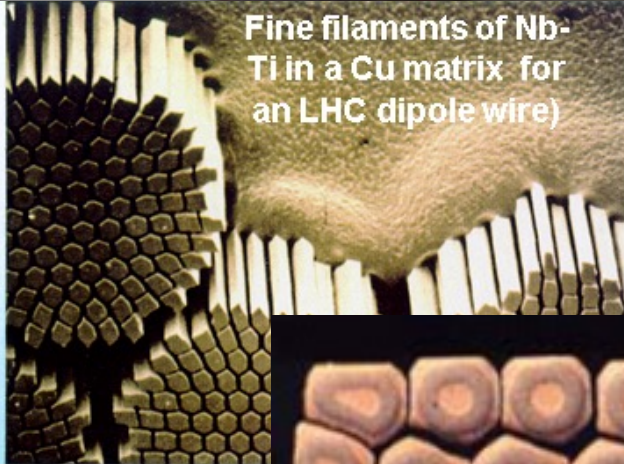
HTS (needed $\rightarrow$ 20 T)
 $\rightarrow$ on going R&D!

- Bi-2212: cost today 2-5 x Nb₃Sn
- YBCO: cost today 10 x Nb₃Sn

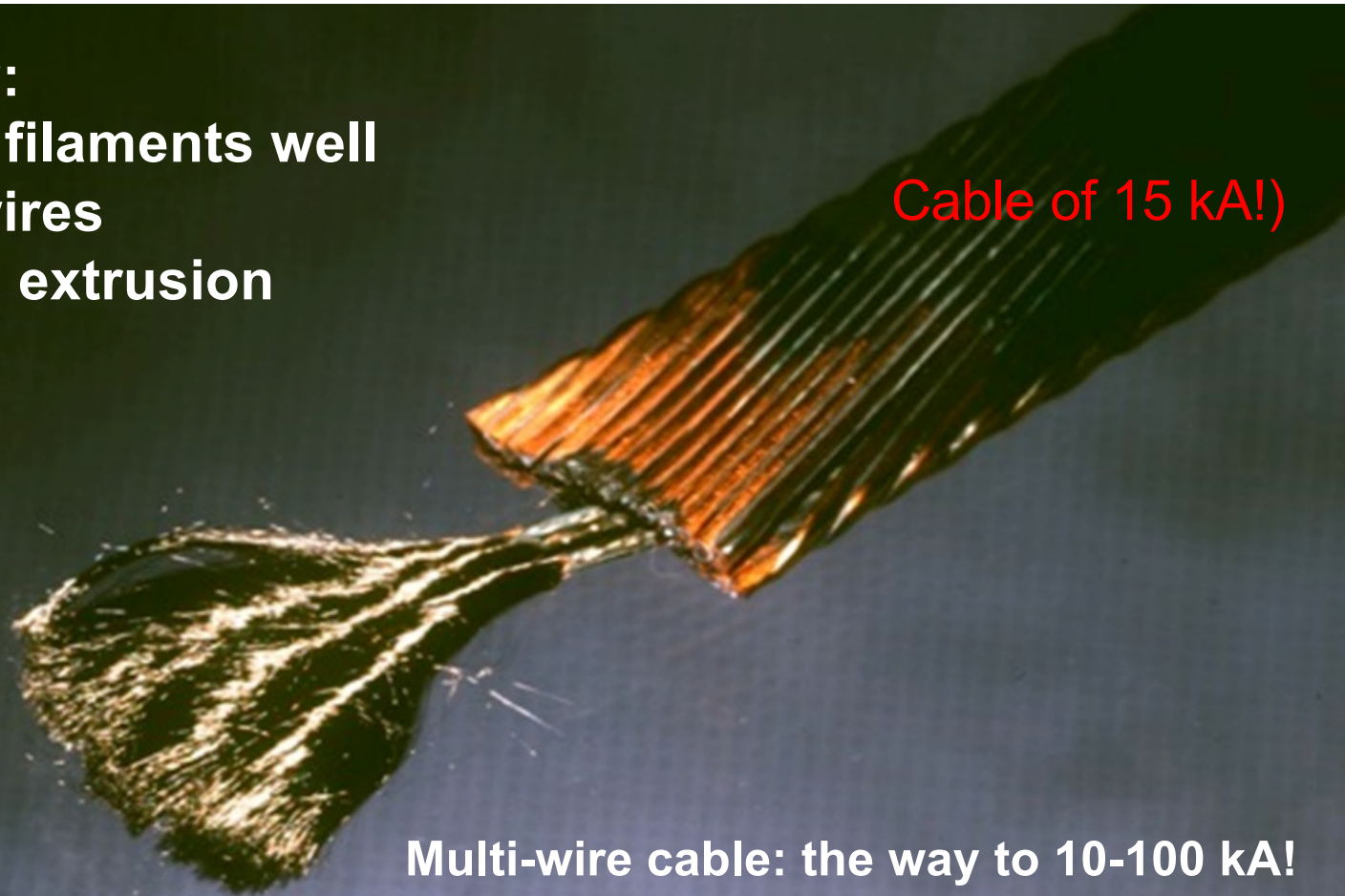
LHC Magnet Technology:
Thousands of fine Nb-Ti filaments well
separated along km of wires
Industrial production via extrusion



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



Cable of 15 kA!

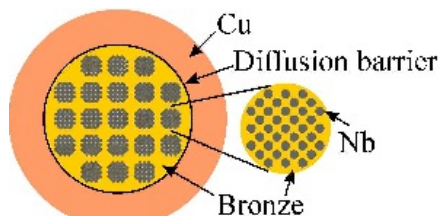


Multi-wire cable: the way to 10-100 kA!

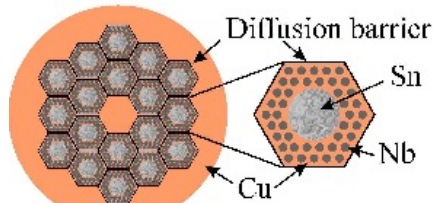
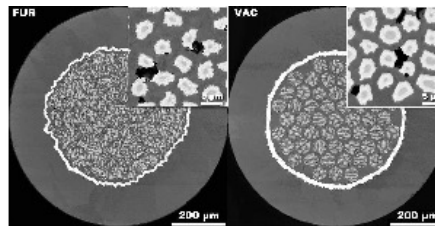


The Nb₃Sn SC Challenge:

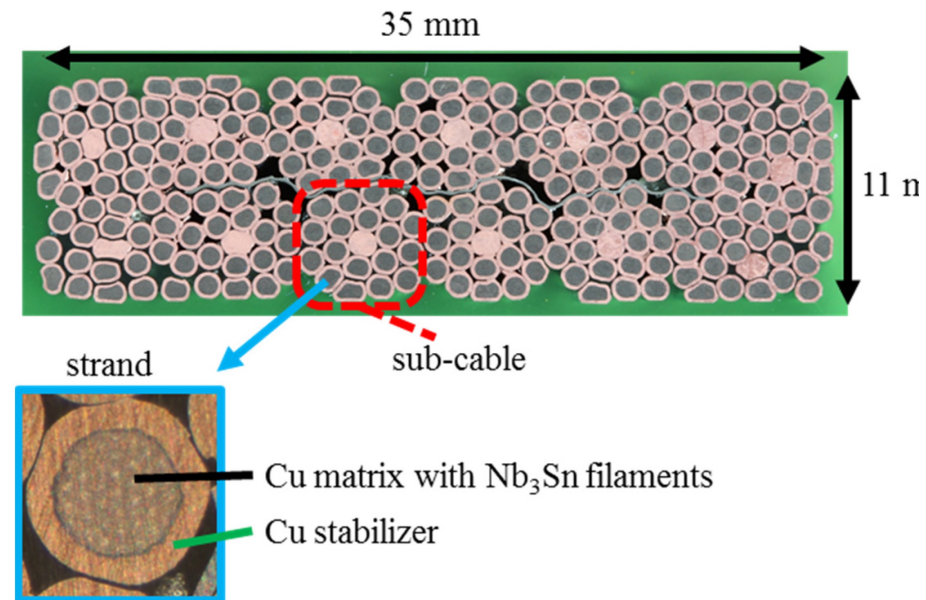
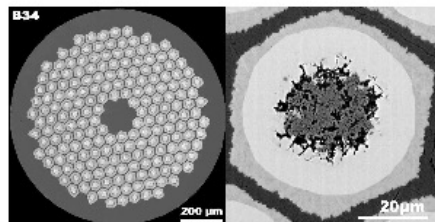
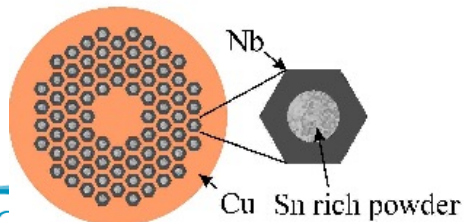
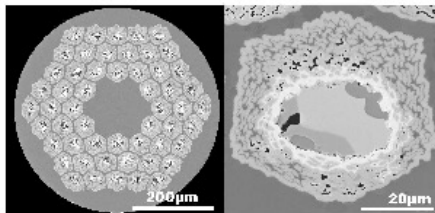
Nb₃Sn is brittle and cannot be drawn in final form – contrary to NbTi
Strand is drawn before cable is formed before the wire is heat-treated to form the Nb₃Sn superconductor!



Bronze process

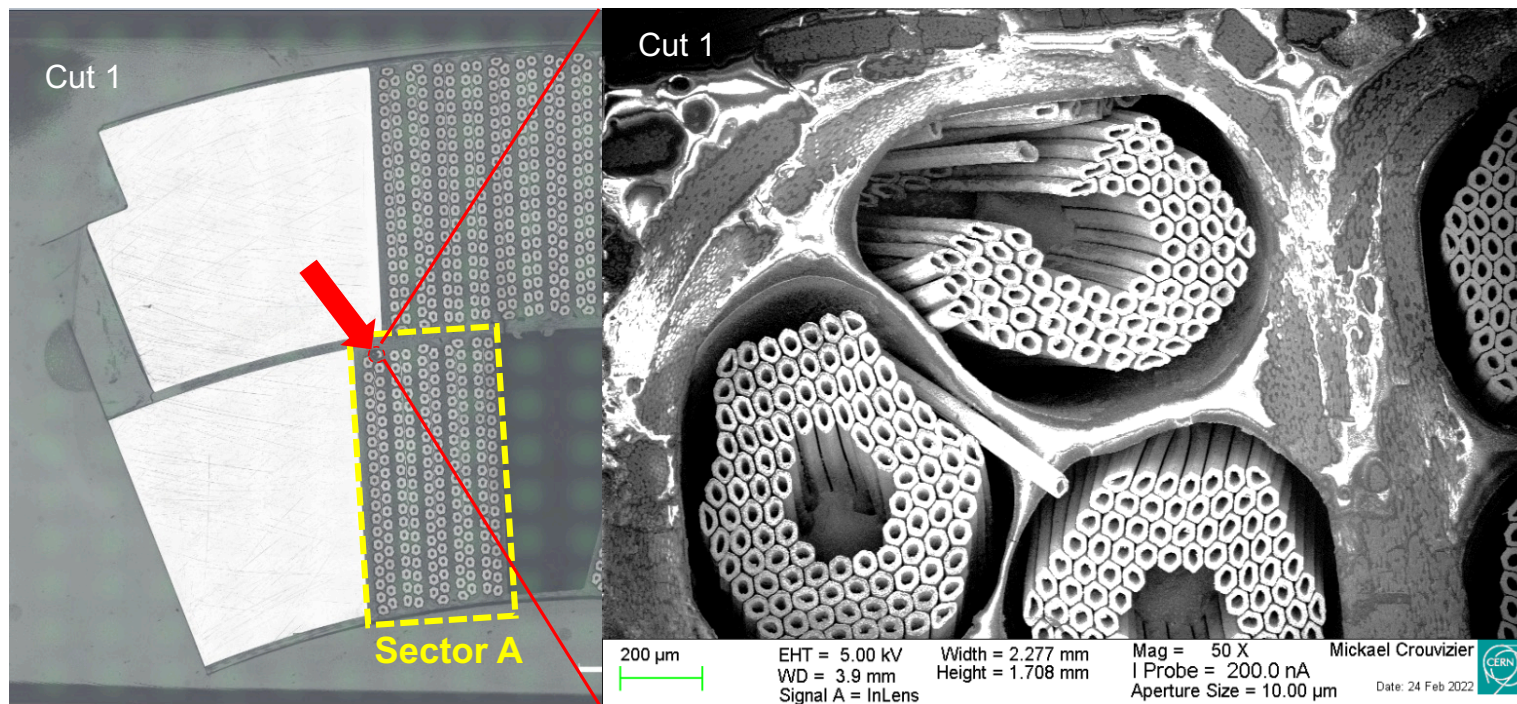


Internal Sn process



Challenges in Nb₃Sn Magnet Technology

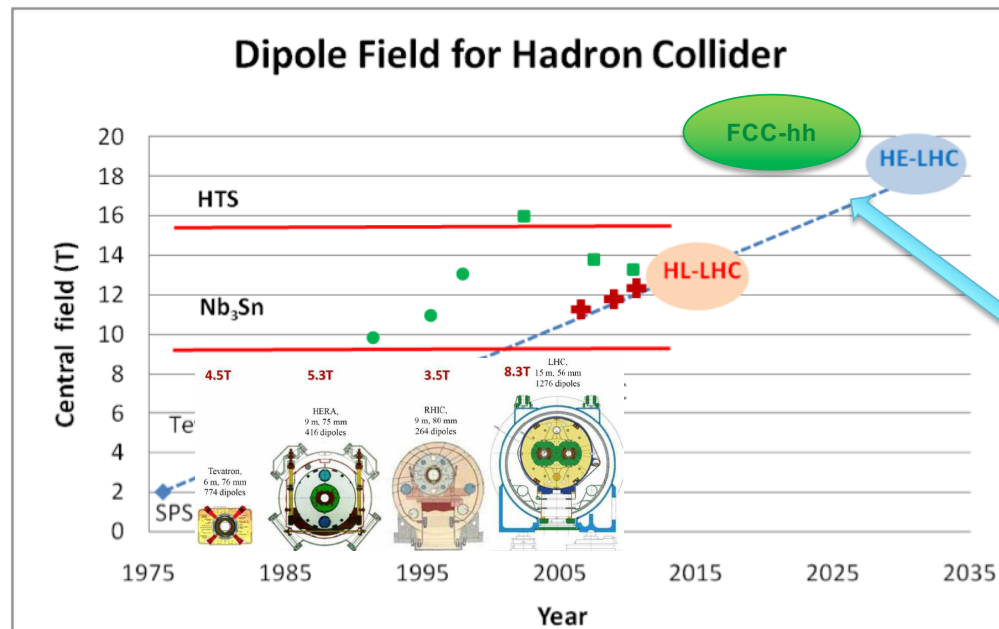
- MQXFBP1 performance limitation (6.5 TeV) analysis had a **significant breakthrough** in January 2022: analysis of limiting coil 108
 - Broken filaments in a strand always in the same position of the cross-section, in several sections close to the transition in the poles –in agreement with voltage tap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



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

High Field SC Magnets

Magnet development requires substantial R&D effort!!!



HL-LHC magnet
Installation from
2028 to 2029

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

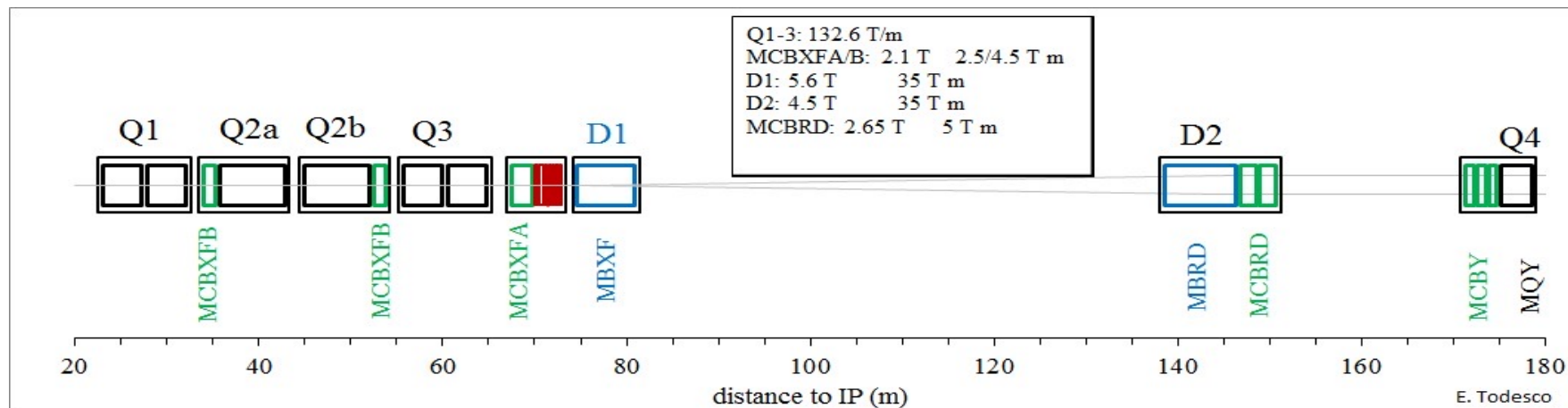
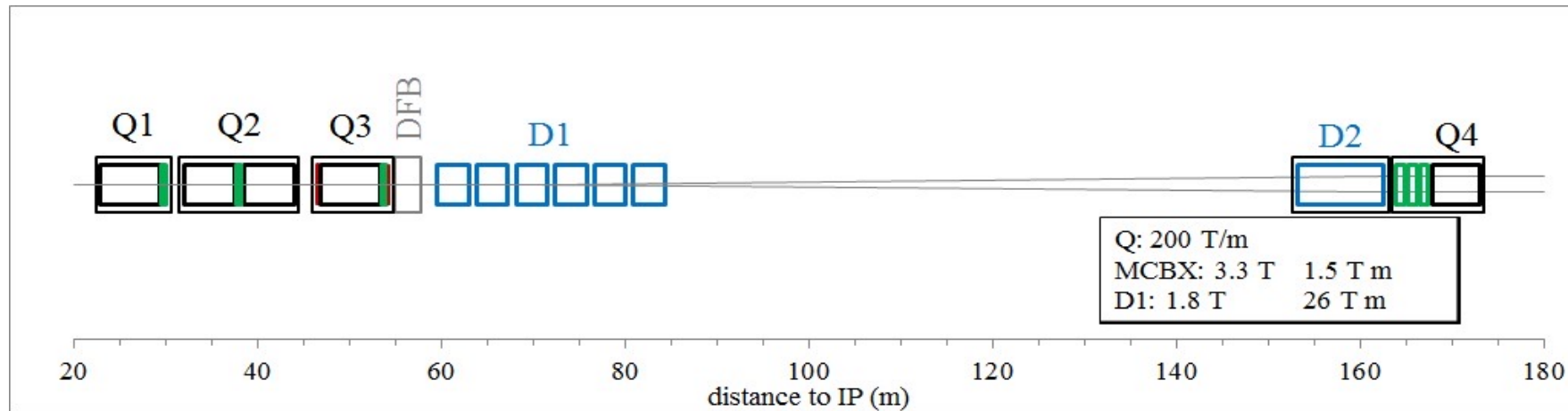
Transition from NbTi to Nb₃Sn: requires similar length of R&D!

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:



-
 D
in
a

-
- Q1 Q2a Q2b Q3 D1 D2 Q4
- MCBXFB MCBXFA MCBY MBYF
- distance to IP (m)
- E. Todesco
- Q1-3: 132.6 T/m
MCBXFA/B: 2.1 T 2.5/4.5 T/m
D1: 5.6 T 35 T/m
D2: 4.5 T 35 T/m
MCBRD: 2.65 T 5 T/m



IN-KIND CONTRIBUTIONS



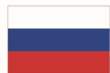
EU in-kind collaboration



Collaboration with personnel



CERN -
KEK R&D



BINP+...
Absorbers
CC ampli.
C. Leads
e-lens
LBDS

BLM
Crystal
Coll.



TRIUMF
CC
cryostat



IHEP
CCT
correctors

KEK D1
design &
construction

2000

2005

2010

2015

2020

2025



DOE
Nb3Sn
R&D

LARP
generic

LARP, HiField quads

LARP
Demo

AUP
Q1 / Q3



FP6
CARE
Nb3Sn

FP7
EuCARD
HiField
Dip



FP7
sLHC PP
(INJ)

sLHC INJ
implem.



LHC Injectors Upgrade
implementation



HL-LHC
Prototyping &
Construction

HL-LHC
Install. & Comm.

Hi-Lumi LHC

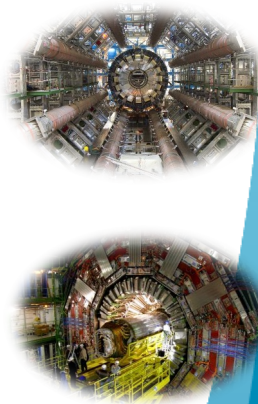
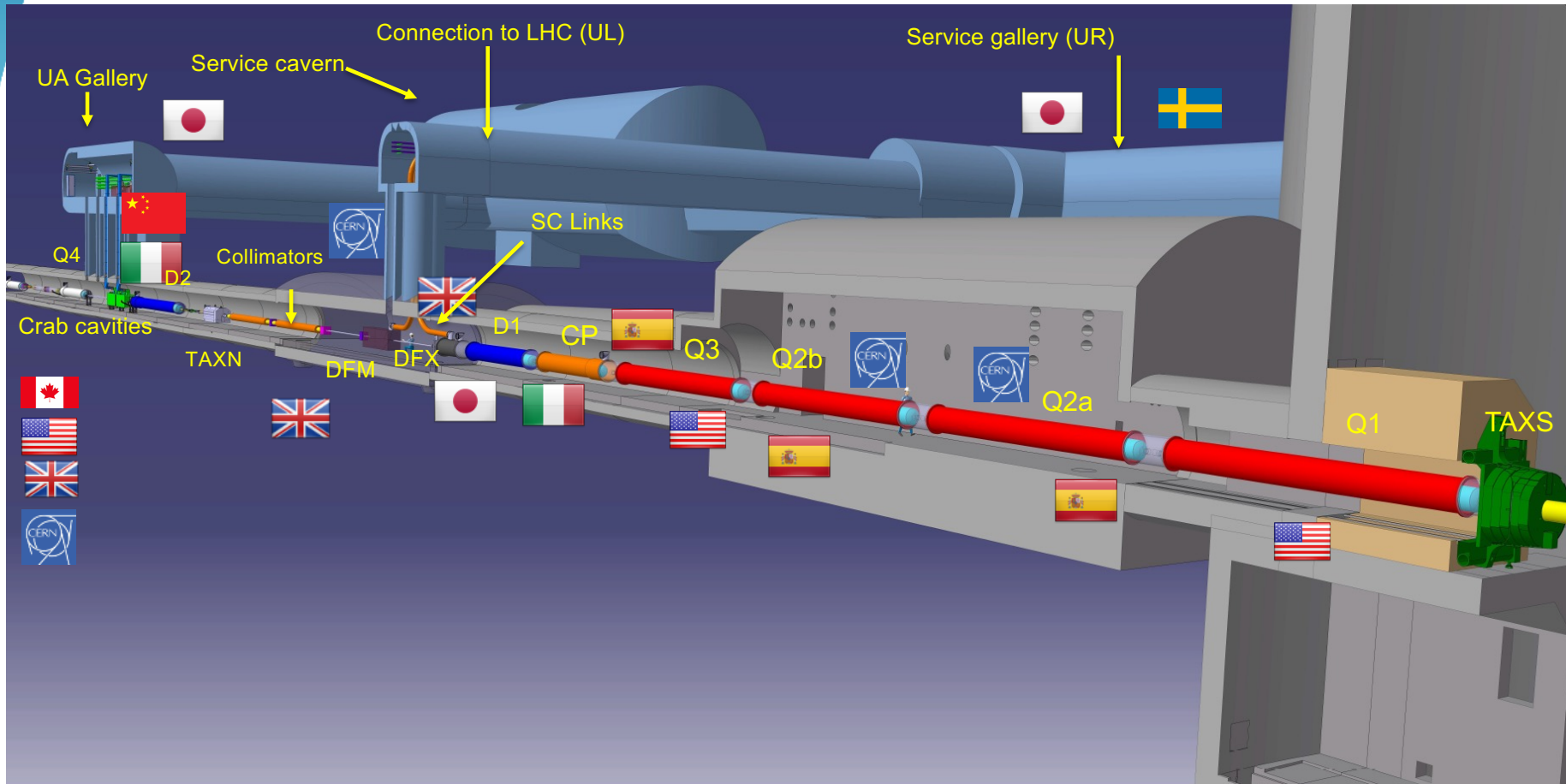
HL-LHC Construction

HiLumi: a
global
project
since the
start

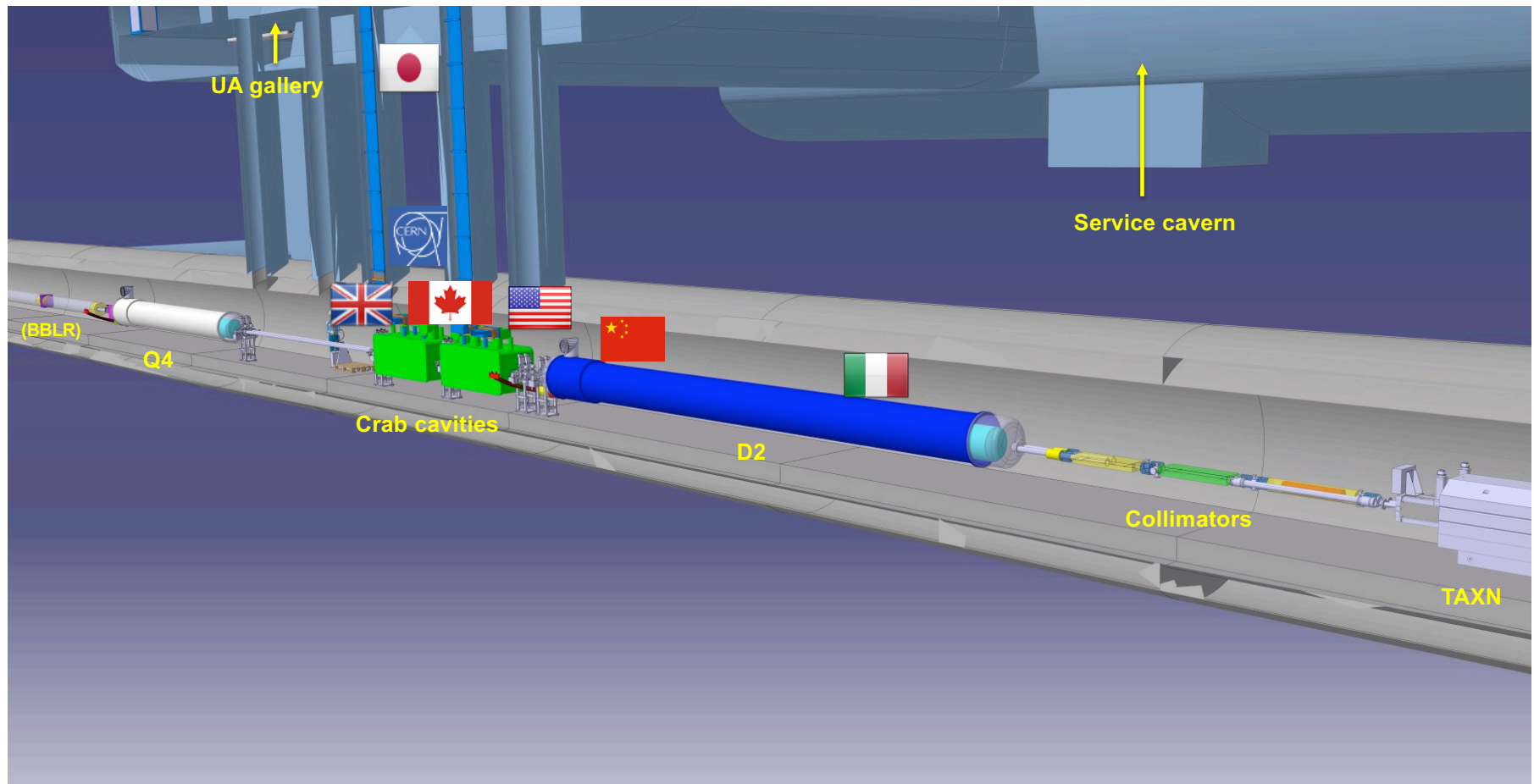
Schedule is complex since in-kinds are interleaved with
our works: we do not receive finished equipment)



The Insertion Region (up to Q4)



The MS region with in-kind contributions



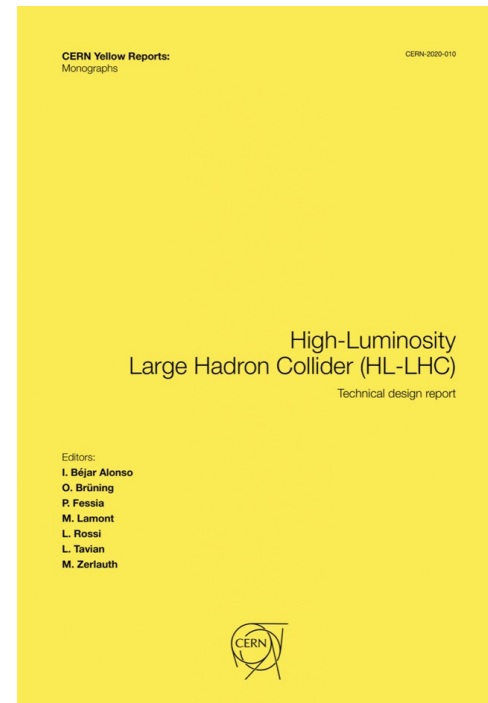
TDR V1.0 - The last version of the TDR including the added scope - 2020



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

[EDMS: 1723851](https://cds.cern.ch/record/1723851)

and as CERN Yellow Book in October 2017



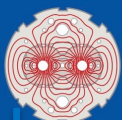
Updated Version V 1.0 published as
CERN Yellow Book in December 2020

<https://e-publishing.cern.ch/index.php/CYRM/issue/view/127>

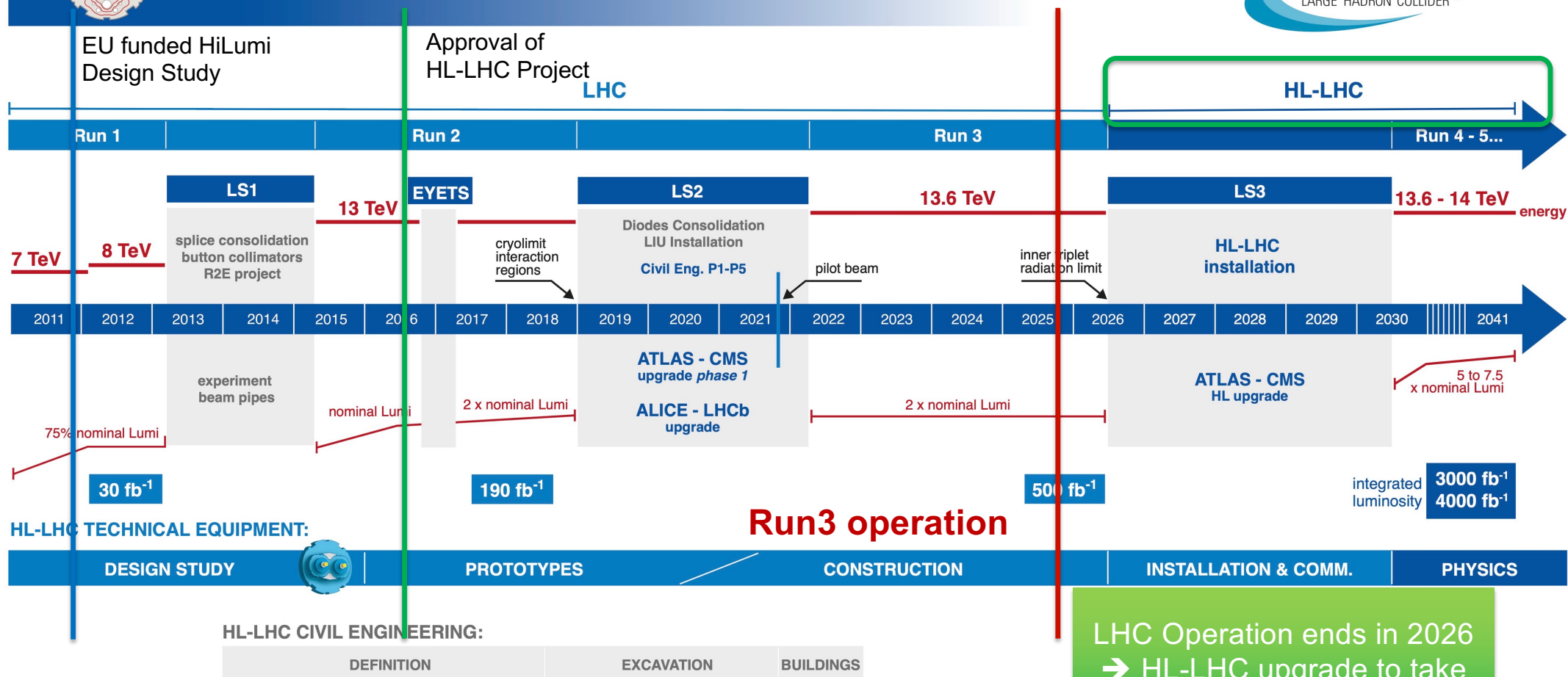


Advanced Accelerator Course; October, 2025

Oliver Brüning CERN



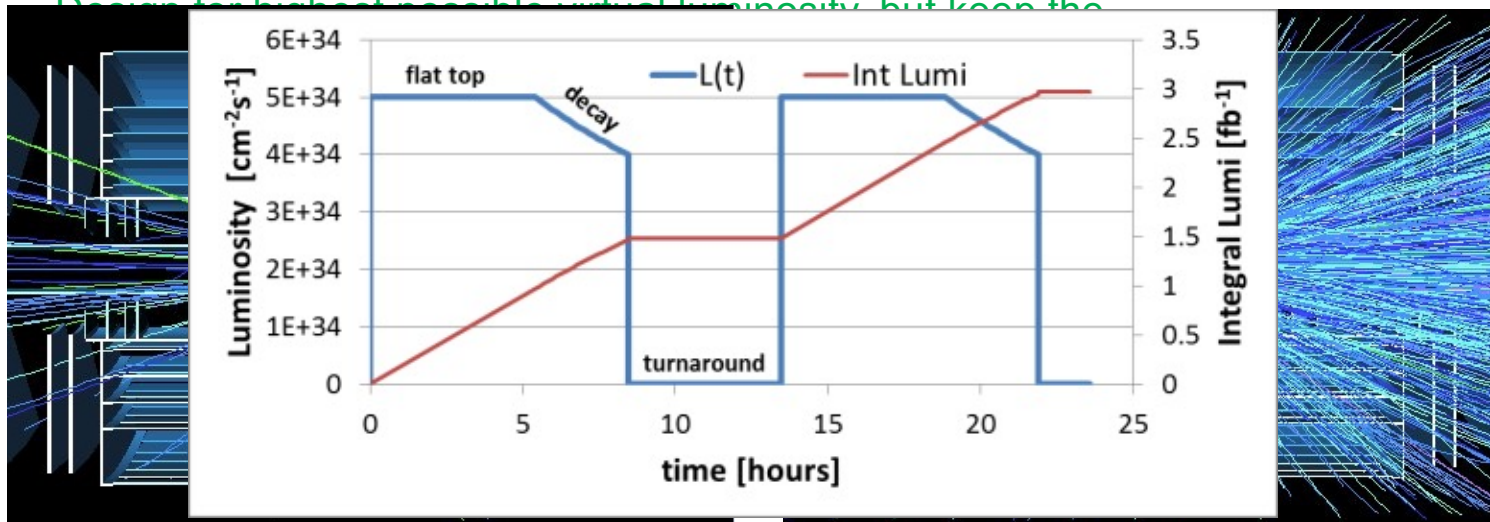
LHC / HL-LHC Plan



LHC Operation ends in 2026
→ HL-LHC upgrade to take over as of 2030 after LS3

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; $N_{tot} \approx 3 \cdot 10^{14}$

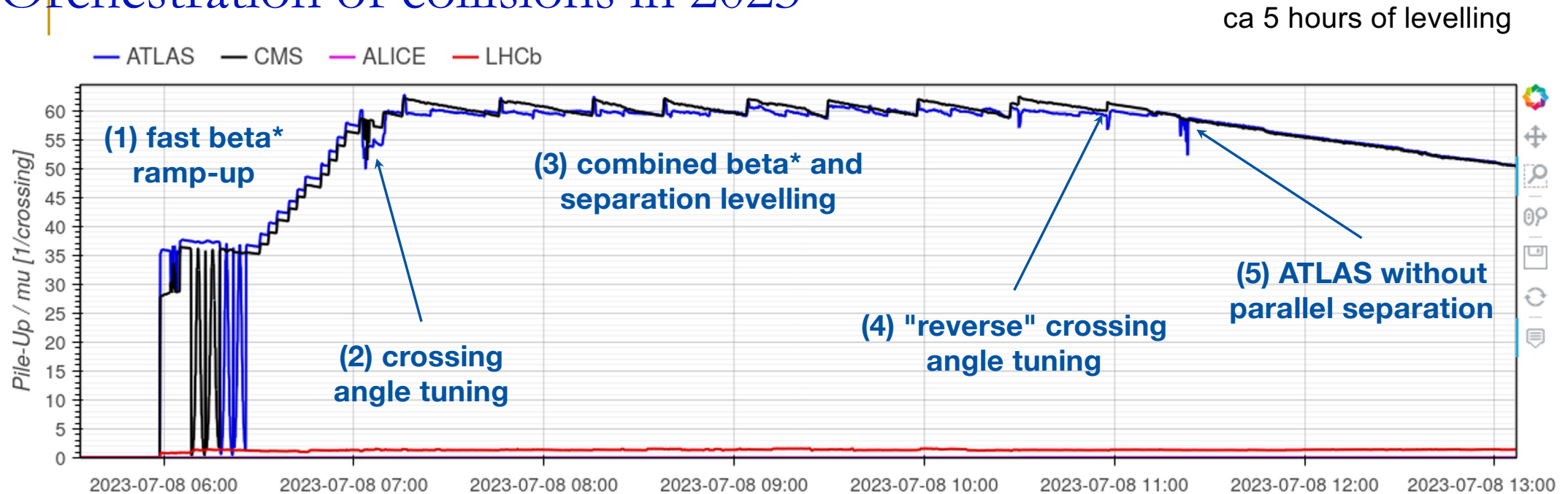
Nominal Luminosity: $L_0 = 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow \tau_{eff} \approx 42 \text{ hours}$

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!!! → Level at

$L_0 = 5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with more protons → $\tau_{eff} > 10 \text{ hours}$

Orchestration of collisions in 2023



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

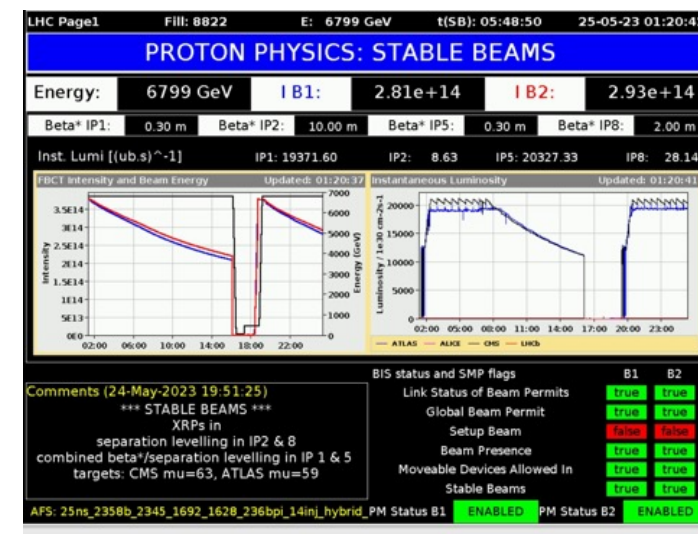
Two fills of ca 12 hours
back to back

- **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
 - Thanks to combined separation β^* levelling and separation levelling we can deliver different pile up to ATLAS and CMS

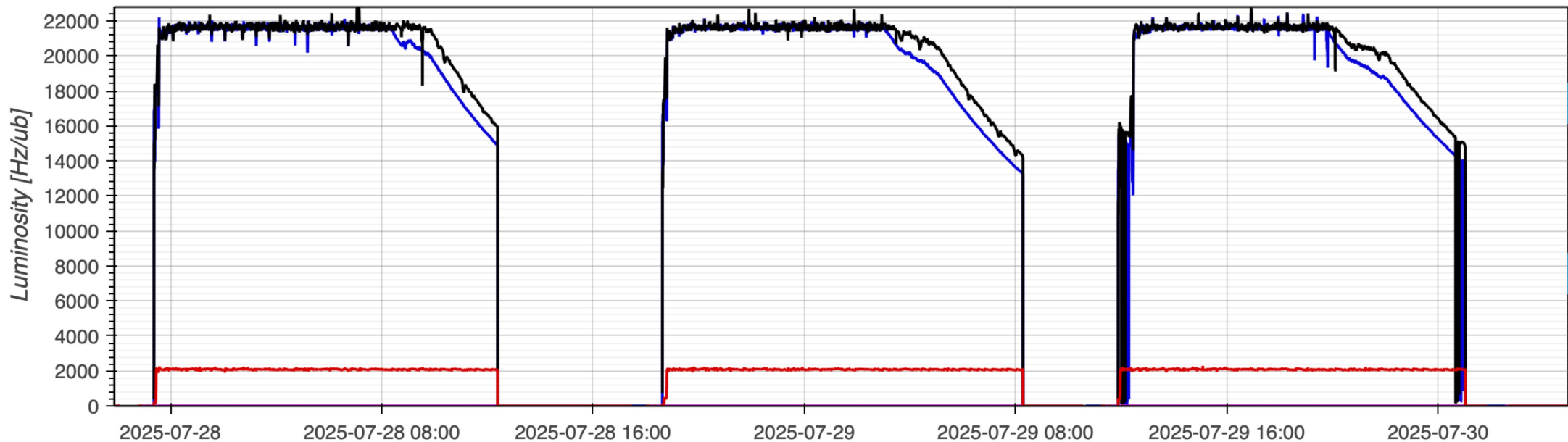
Max energy per beam at start of
stable beams:
425 MJ with 2464 bunches
 1.59×10^{11} p/b (Injected: 1.61)



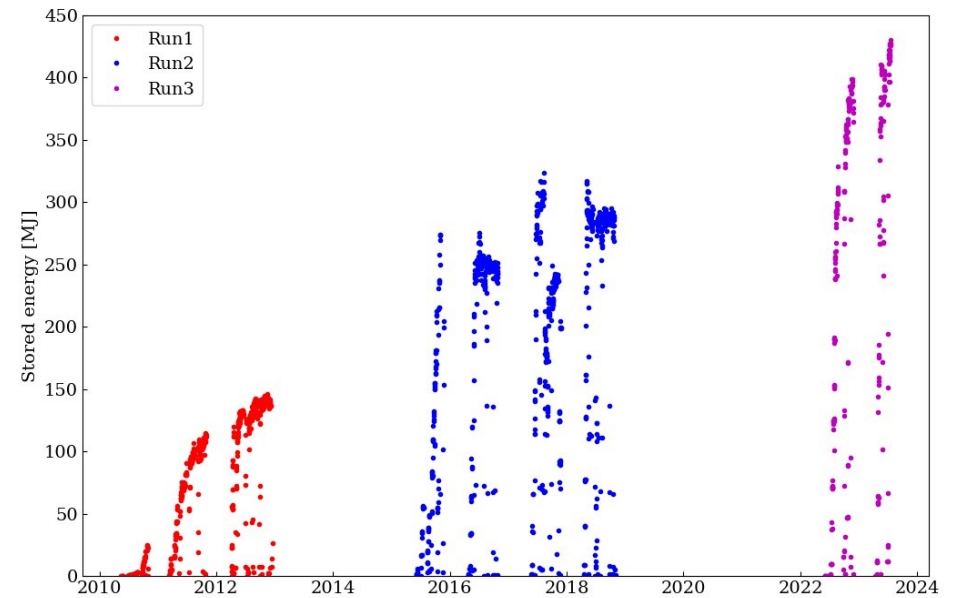
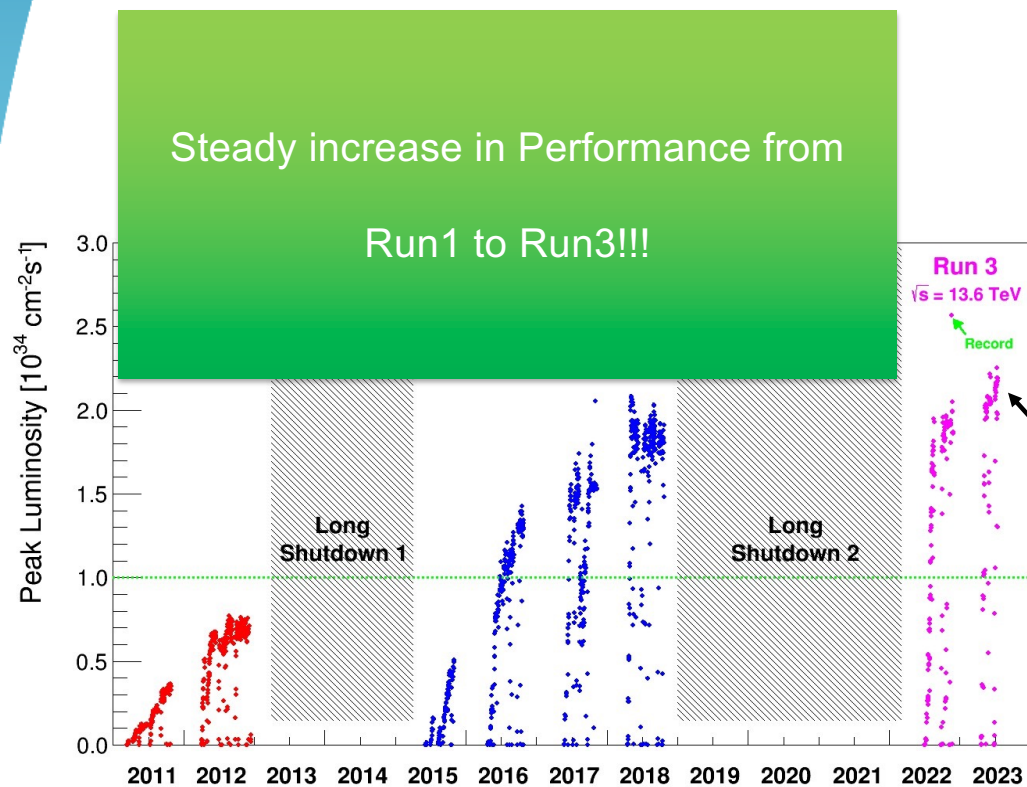
24th to 25th of May 2023



Example: levelled fills in 2024



Comparison of the 3 LHC Running Periods



Higher peak luminosity linked to higher pile-up

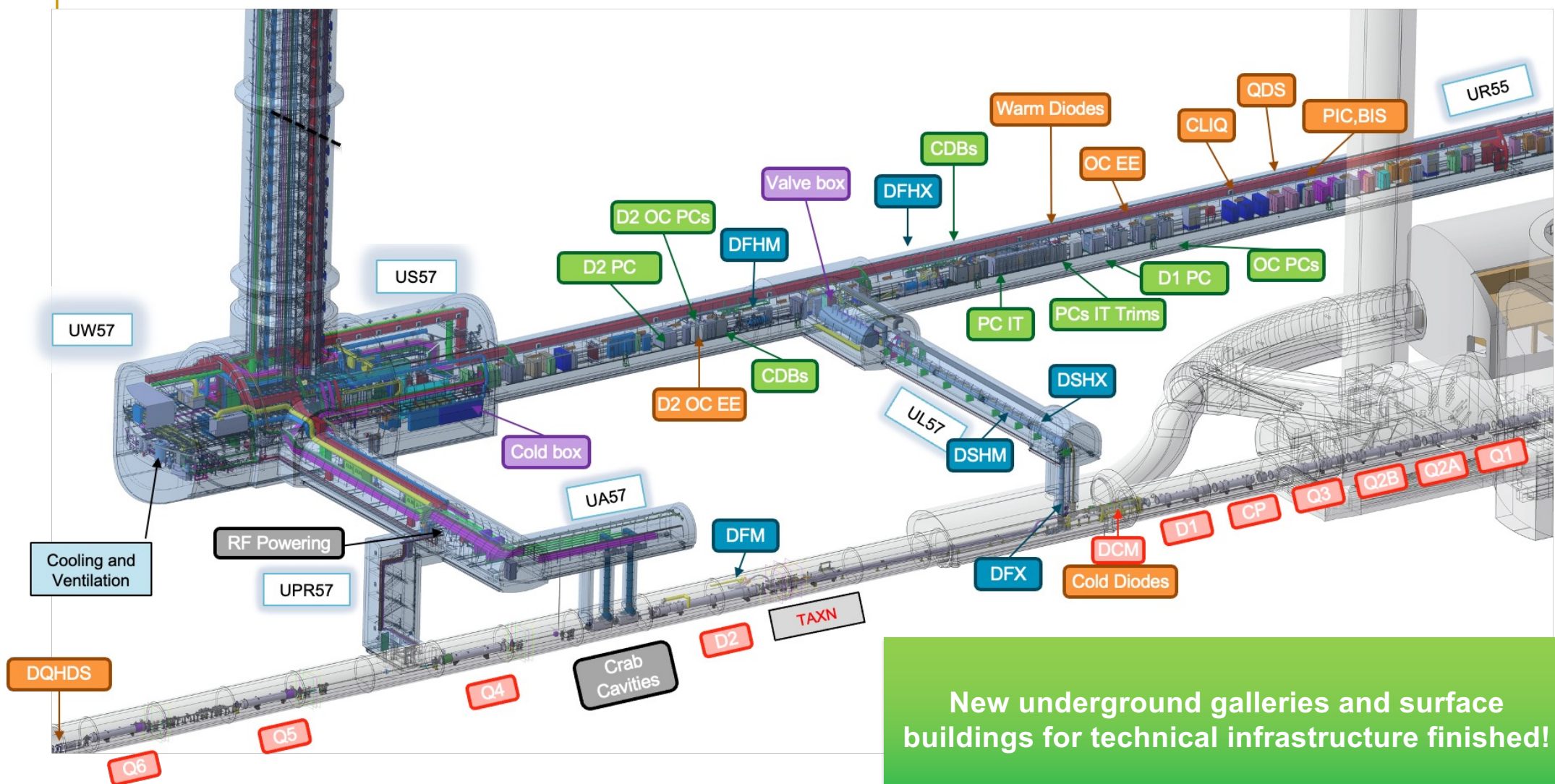
Stored energy record of 425 MJ
with 2464 bunches @ $1.6 \text{ E}11$ ppb (@ start of Stable Beams) .

Levelled Luminosity → requires efficiency!

❑ Operation experience in 20

→ Int





New underground galleries and surface buildings for technical infrastructure finished!

➔ Installation of services ongoing

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 ➔ LIU Project & LHC collim.
- 2) minimize the beam emittance ➔ magnet aperture
- 3) minimize beam size (constant beam power); ➔ X-ing angle
- 4) maximize number of bunches (beam power); ➔ Crab Cavities
- 5) compensate for 'F'; ➔ Minimize number of
- 6) Improve machine 'Efficiency'

beam aborts and maximize luminosity lifetime!

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: $L_{peak} \cdot R1/R0$ [$\text{cm}^{-2} \text{s}^{-1}$]	-	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

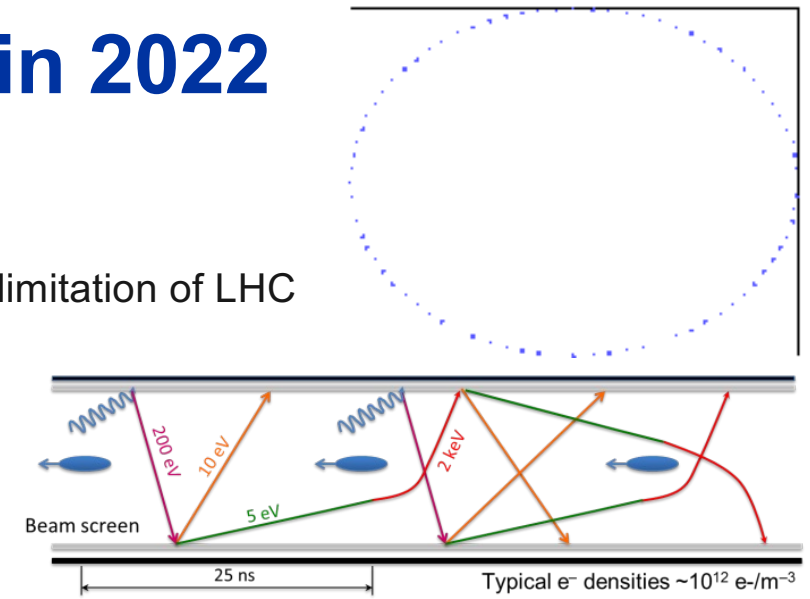
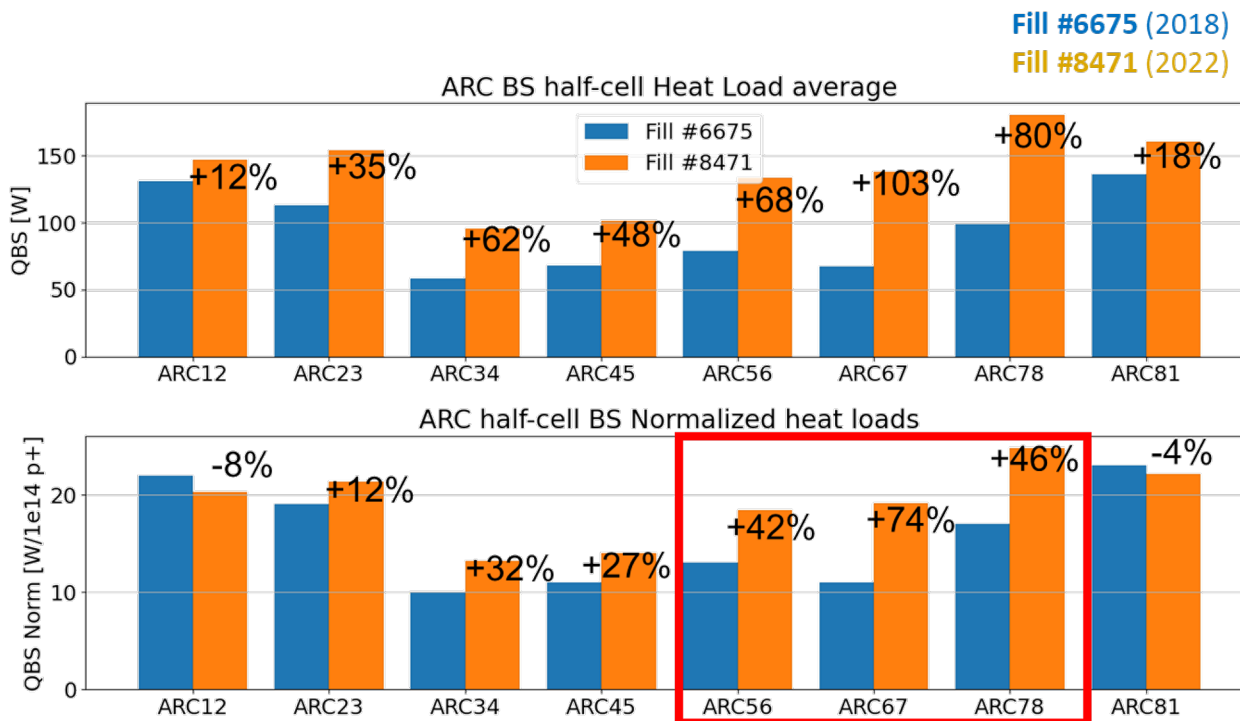
Machine operation &
availability

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. lum. / [fb ⁻¹]	0.88	0.88	1.18	1.18	1.21	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 filling scheme reached to date
- Run 3 bunch spacing 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**

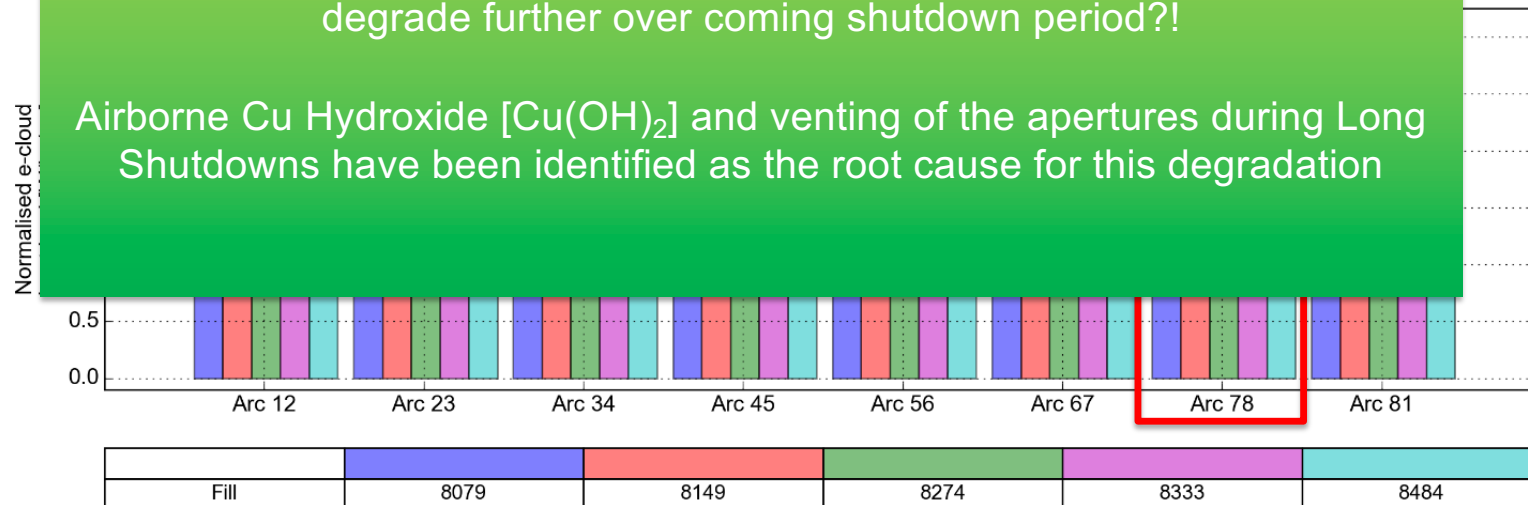
→ limits the intensity reach.

- **Scrubbing is levelling off in all sectors**

- → not expected

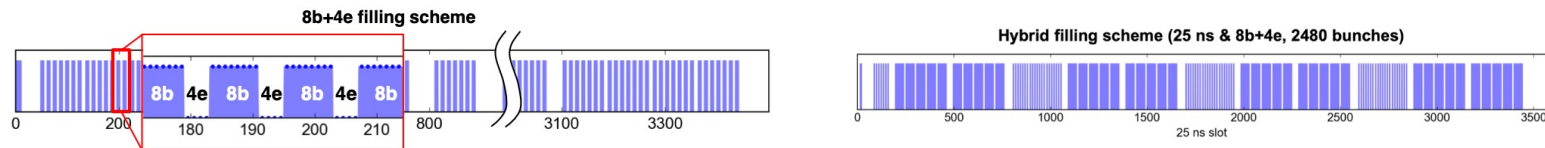
The key question is if this level of electron cloud remains stable or if will it degrade further over coming shutdown period?!

Airborne Cu Hydroxide $[\text{Cu}(\text{OH})_2]$ and venting of the apertures during Long Shutdowns have been identified as the root cause for this degradation

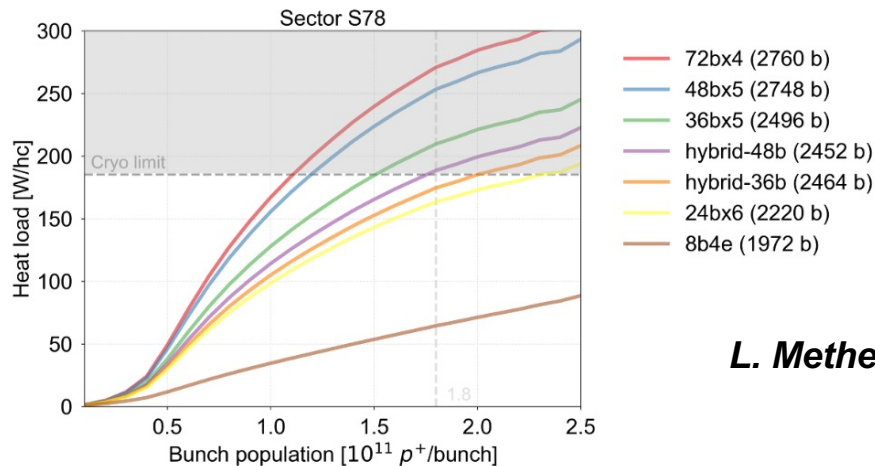


Electron-cloud: filling scheme mitigation

- 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)



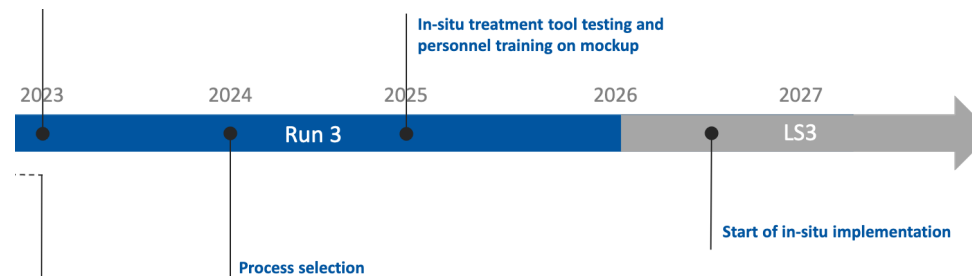
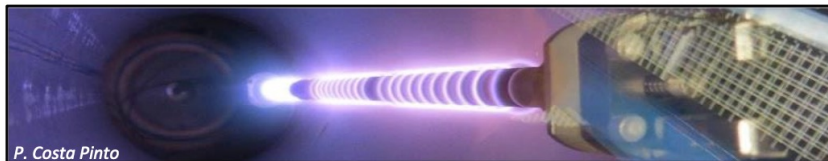
- ⇒ Strong impact of filling scheme on intensity reach:



L. Methner, [LHC Chamonix workshop](#), 23/01/2023

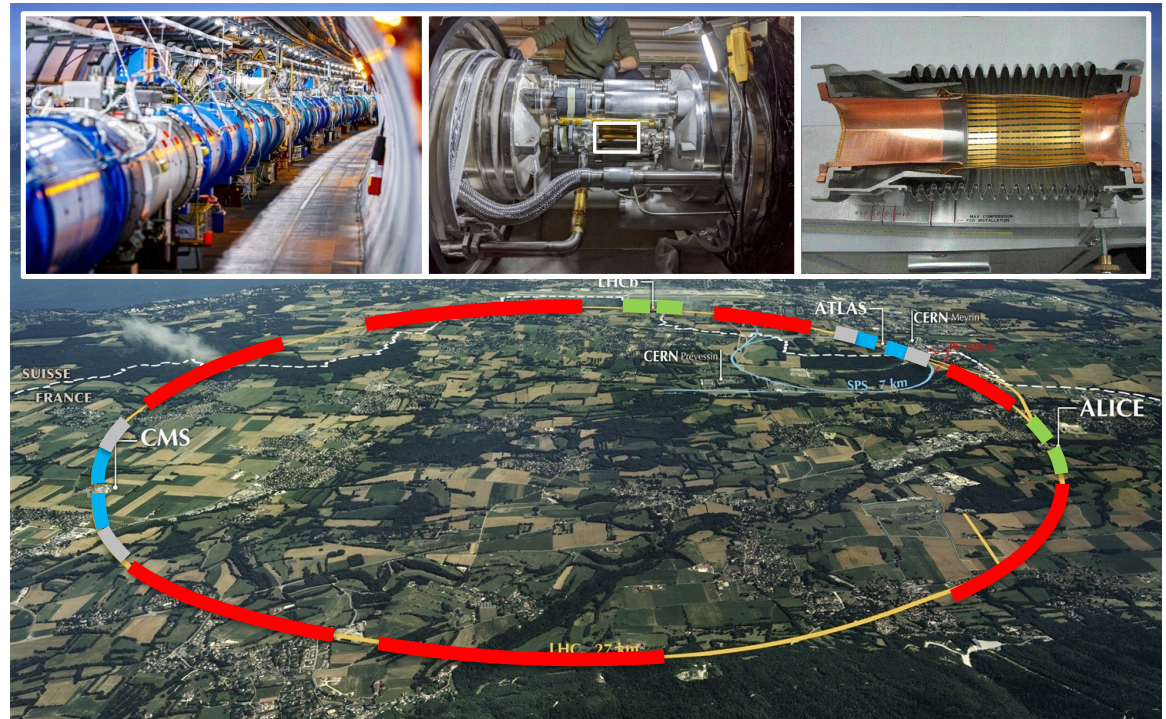
e-cloud: mitigations

- **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

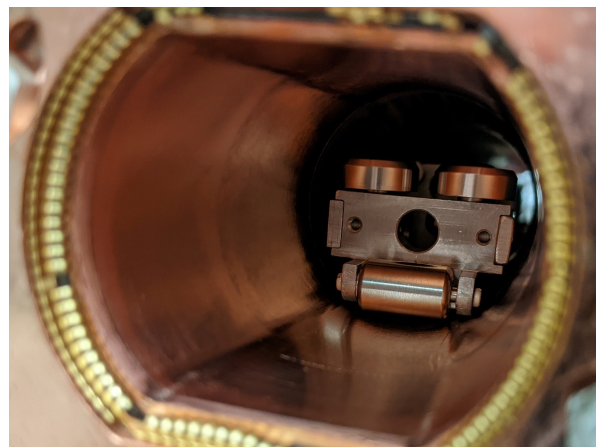
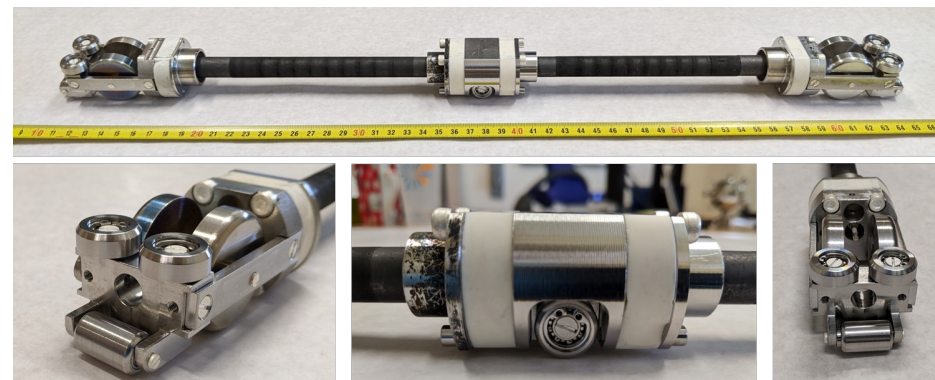
Matching sections
Ex-situ, in magnet
20 m total

Arcs
In-situ
≈ 12 km total

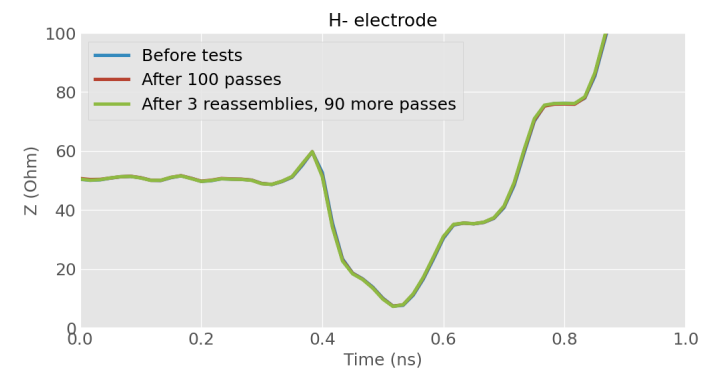
BST

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...)



BPM qualification after 200 train passages



Thanks to TE-MSC

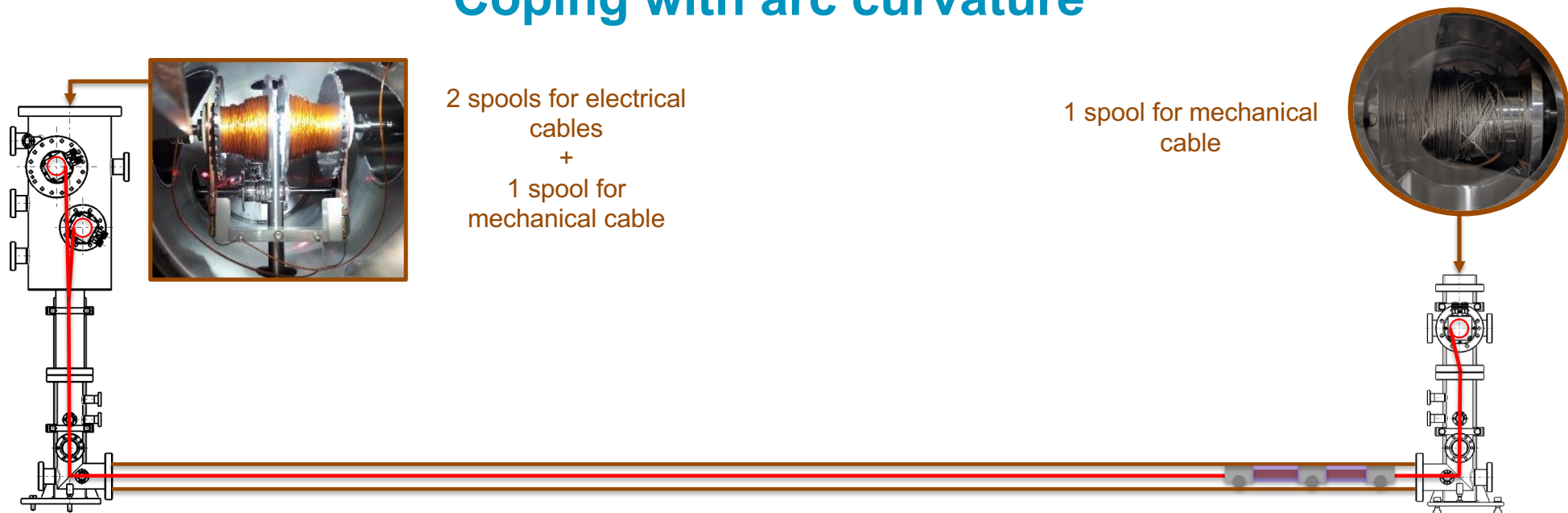


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M. Krupa SY-BI, [EDMS 3161981](#)

Oliver Brüning CERN

Coping with arc curvature

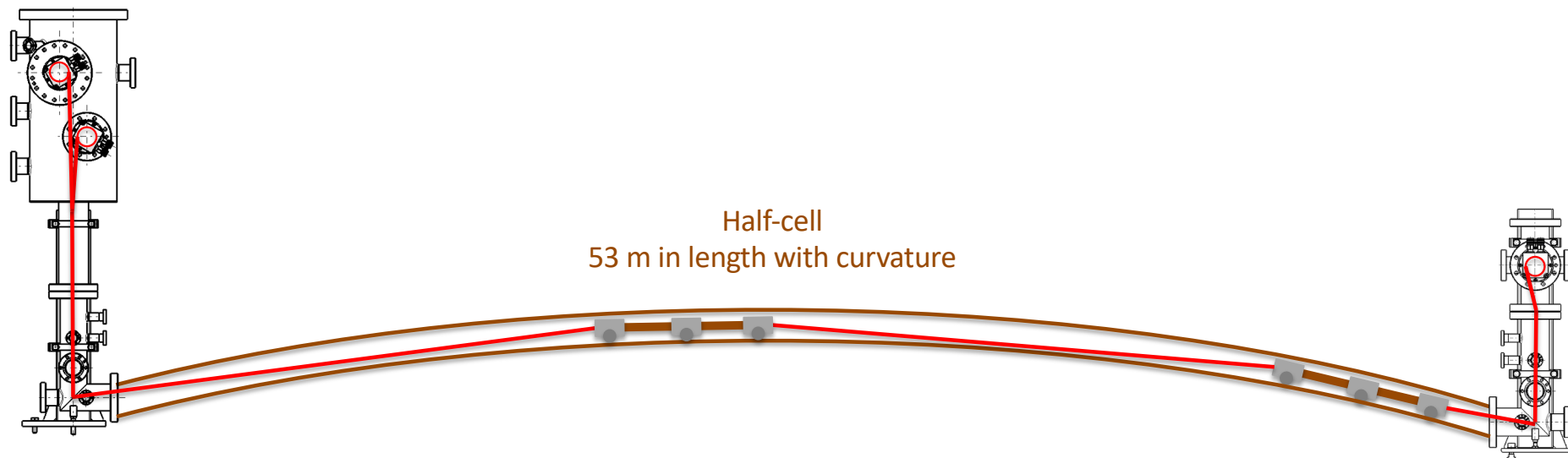


System developed for Q5L8 (LS2) and HL-LHC beam screen coating:

- 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:

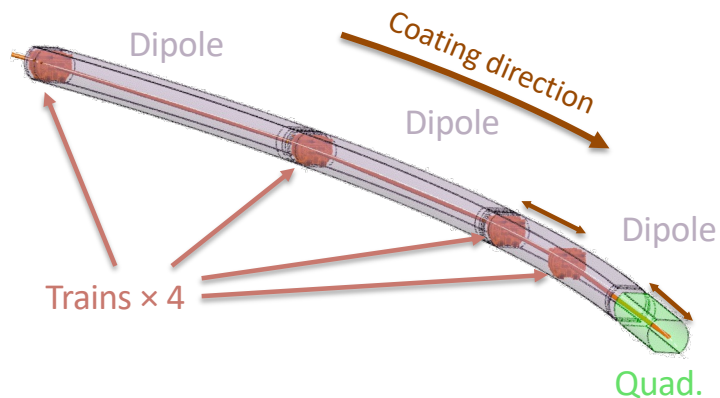
- Curvature → **no line of sight** over 53 m
- **Cables** will **scratch the beam screen**, on its inner face with respect to curvature

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

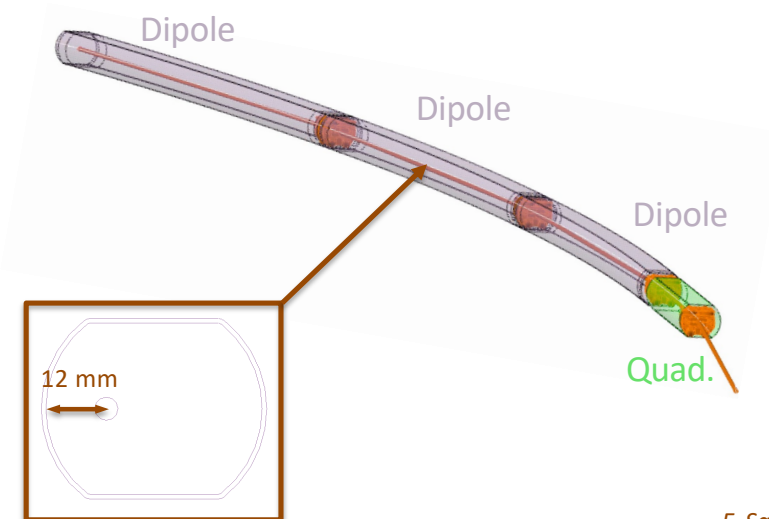
→ Use **several trains** to **recenter the cables** in the beam screen... and **coat several sections simultaneously**

Coping with arc curvature – 4-train configuration

Start of half-cell beam line coating



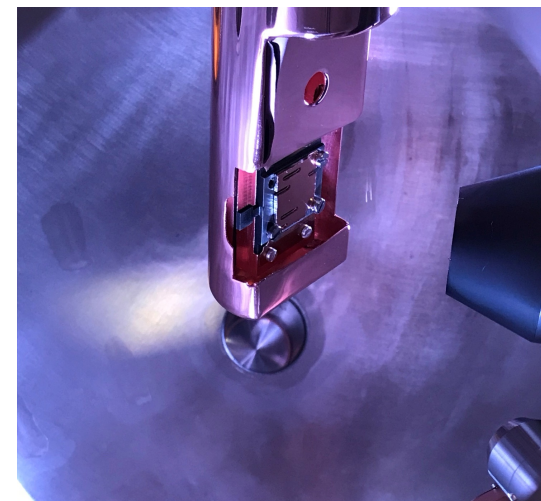
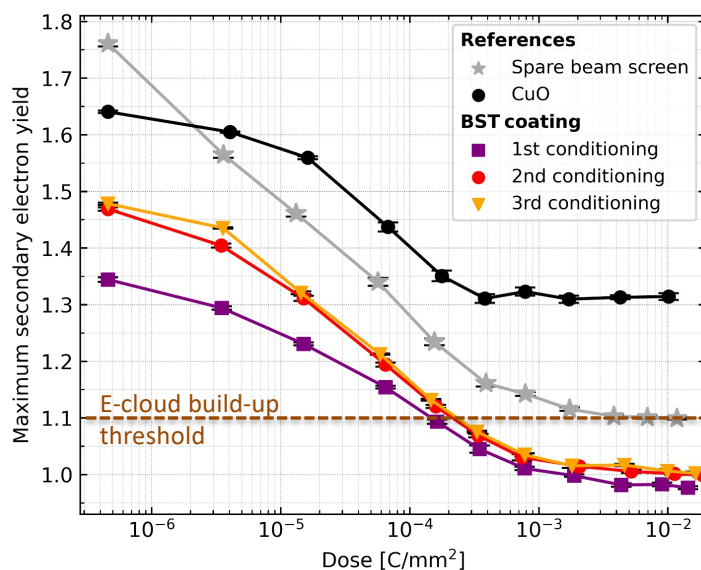
End of half-cell beam line coating



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



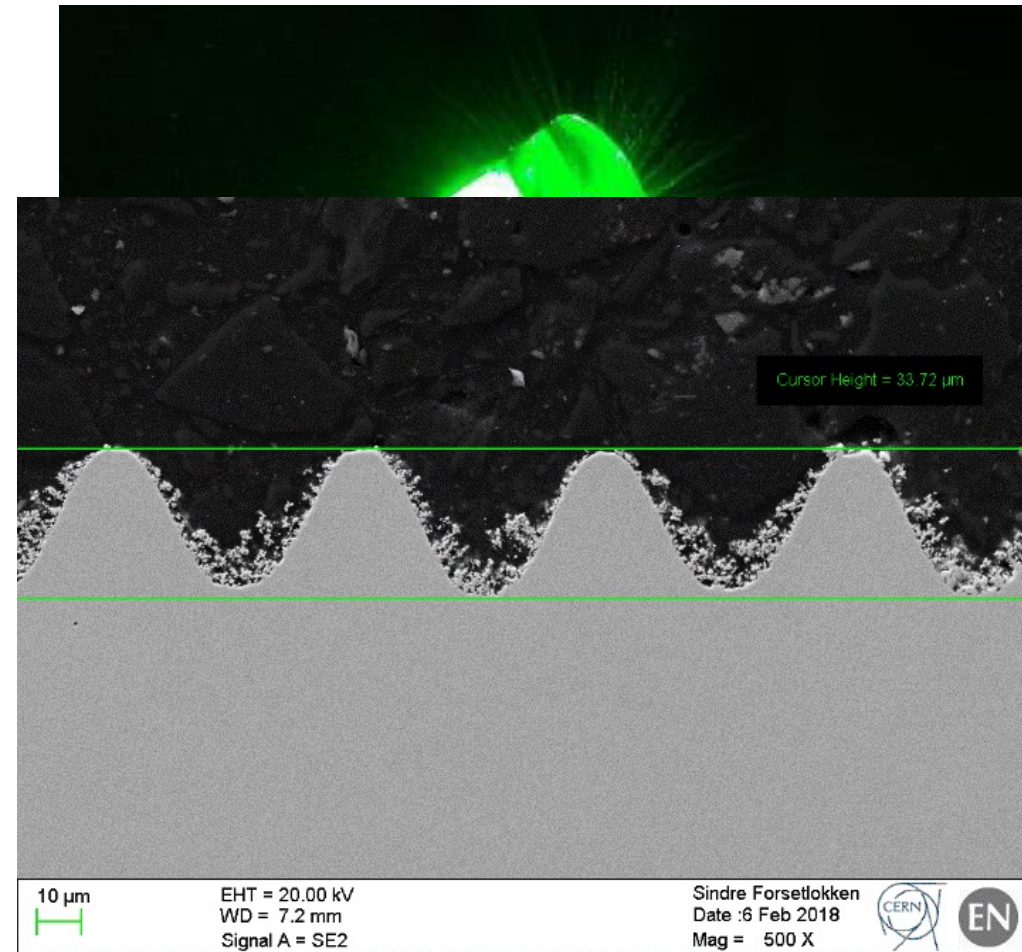
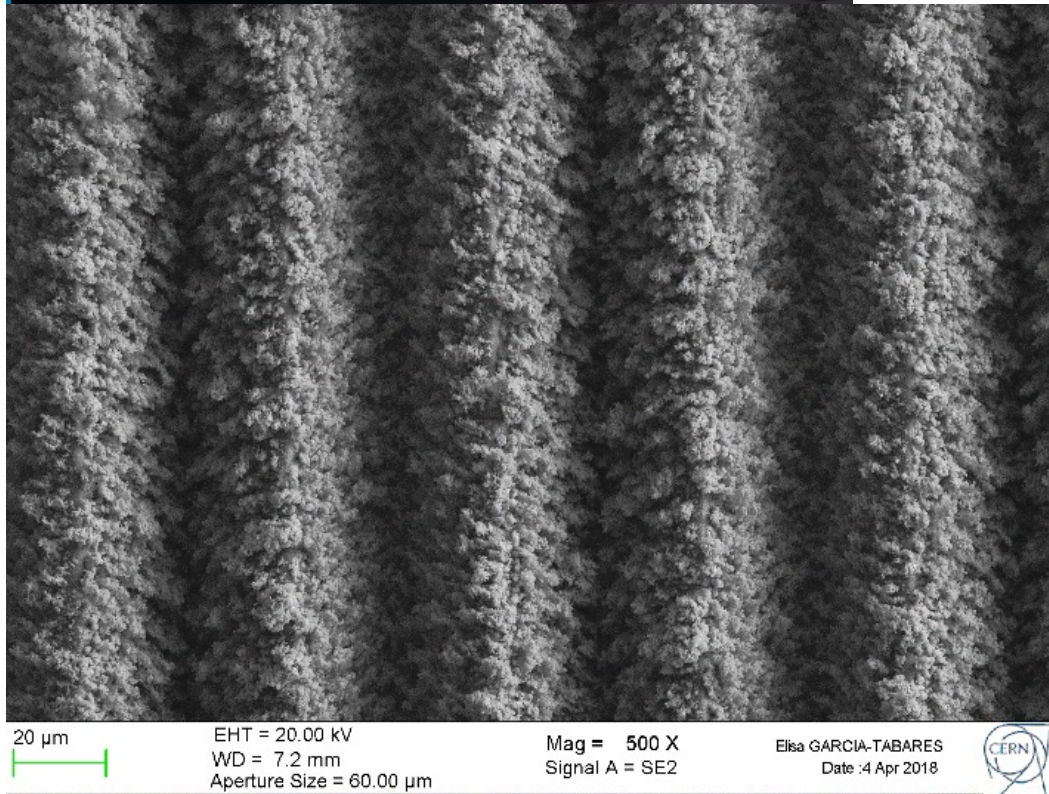
Higher coating speed → Thinner coating (10 nm)
Coating over 53 m → Higher base pressure



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**

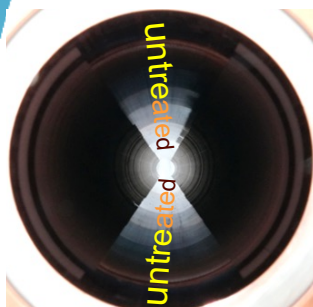
LESS: Laser Engineered Surface Structures



Laser surface treatment of beam screens supported by HL-LHC-UK2 in collaboration with



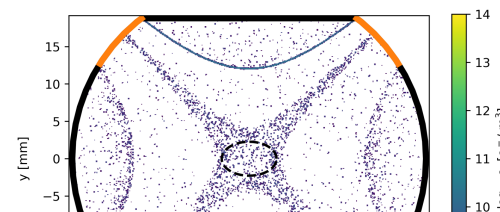
Demonstrator + BLMs in LHC Vacsec.C5R6.B



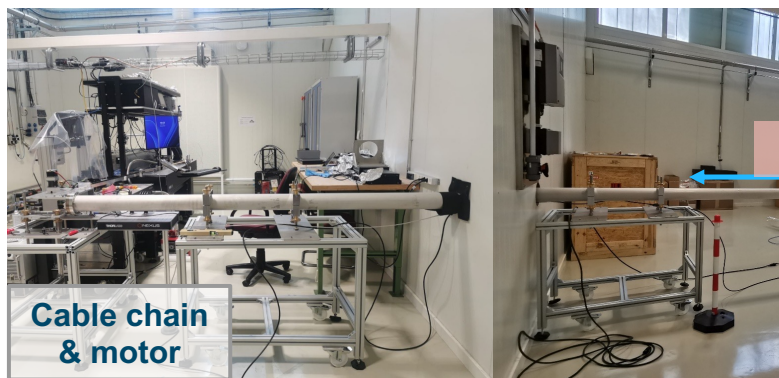
UFOs of $\leq 2 \times 10^5$ p⁺ collisions ($d = 4-6 \mu\text{m}$) - small compared to LHC standard event

- **not harmful** for operation
- Low quantity
- continuation of data acquisition

4×20° treatment strategy for Q5 standalone magnets

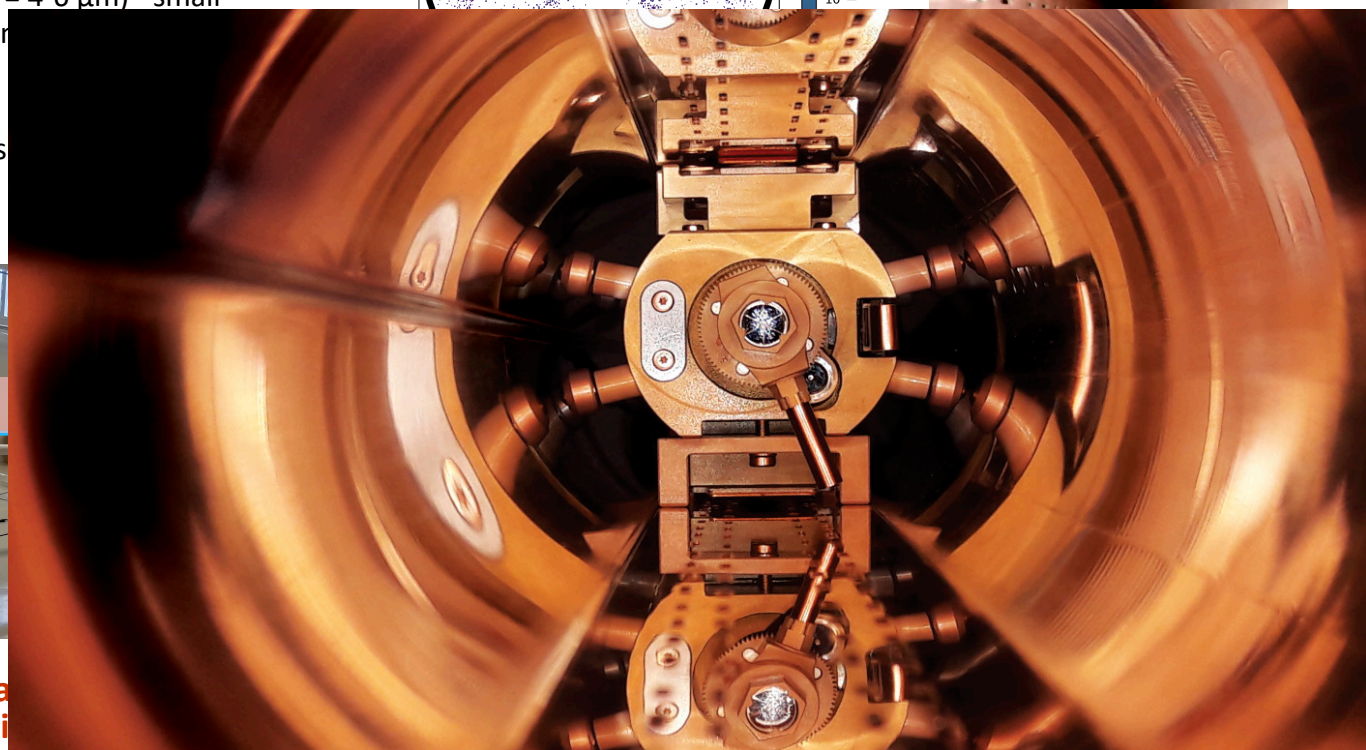


Automation mock-up with 10.8 m beam screen



Cable chain & motor

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



magnets



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Technology Landmarks

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

First series magnets delivered to CERN

Nb-Ti
Separ
dipole

Finished in 2023

Finished in 2023

Fully validated in 2023 and first magnets ready for installation

MAGNETS

drupole magnets
IS experiments,
the final focusing
re collisions.

Complete Prototype
System validated in
2024

PERCONDUCTING LINKS

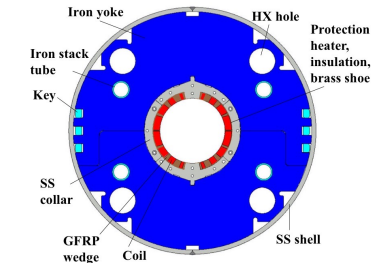
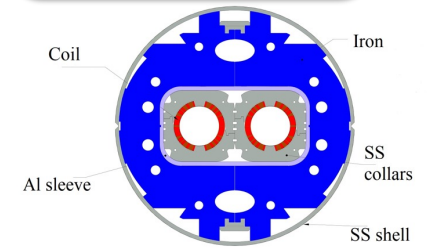
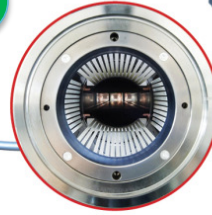
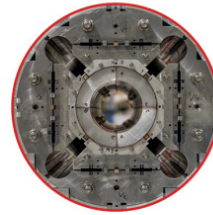
½ system already installed for Run3

COLLIMATORS

CRYSTAL COLLIMATORS
Successfully
deployed in 2023
Pb-Pb run

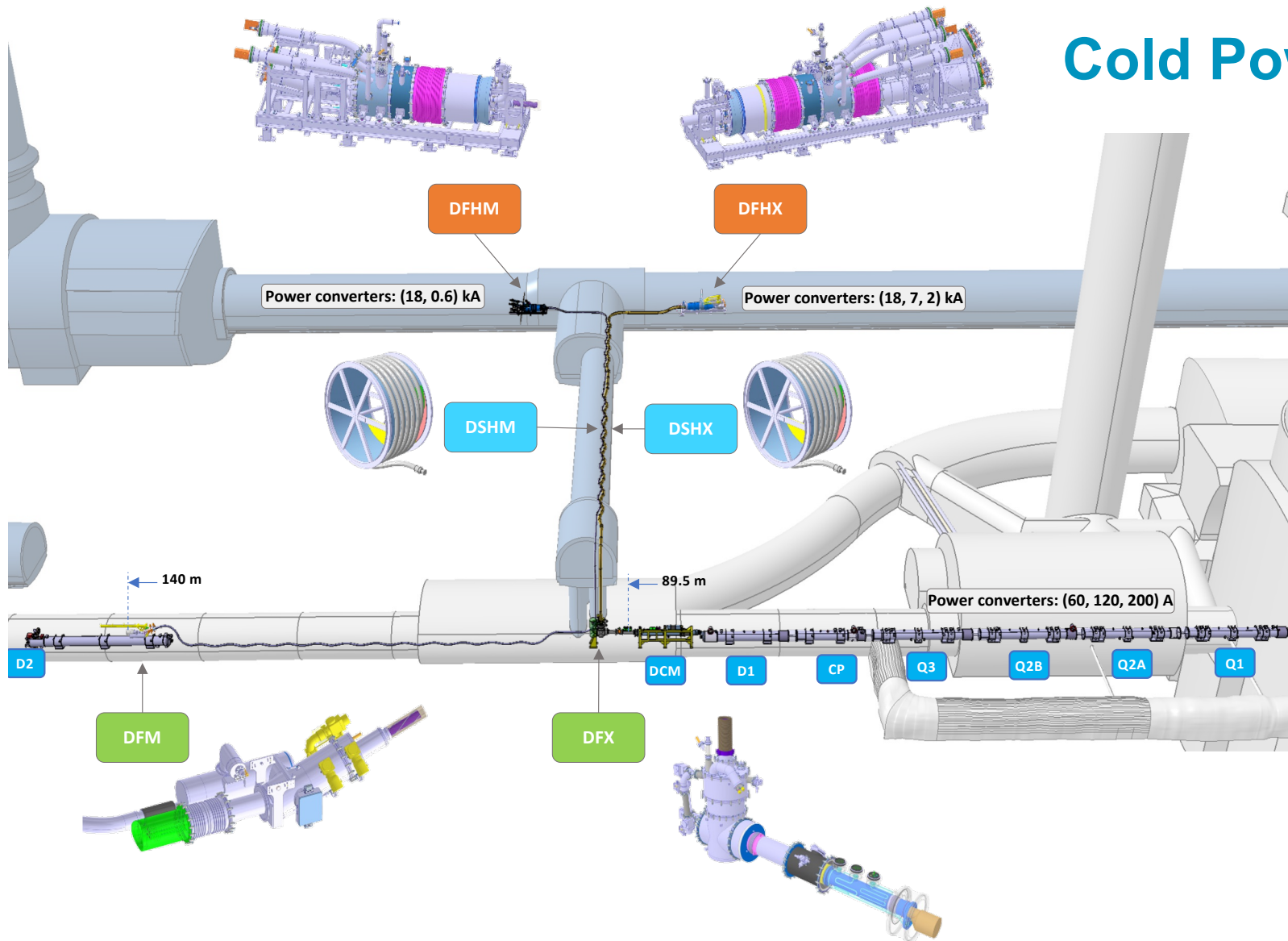
CRYSTAL COLLIMATORS

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





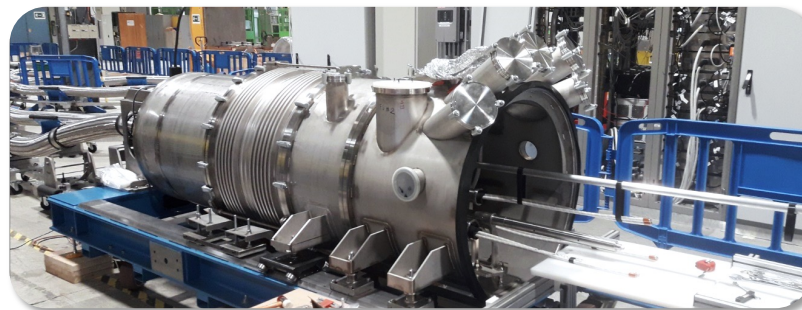
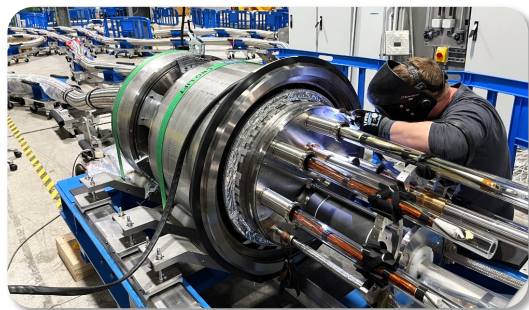
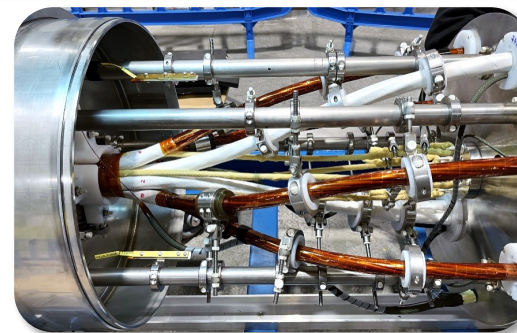
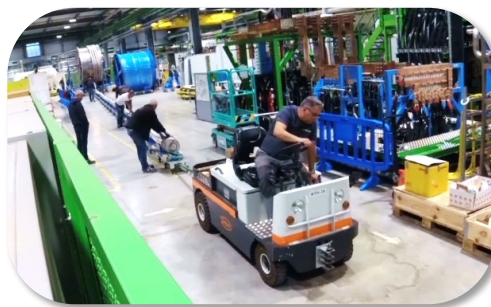
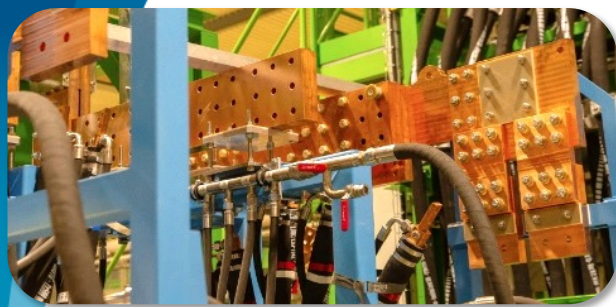
Cold Powering System



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

→ High Temperature Superconductor, MgB₂ operating at ca. 20K to 30K

→ Cooling with gaseous He from liquid He boil off



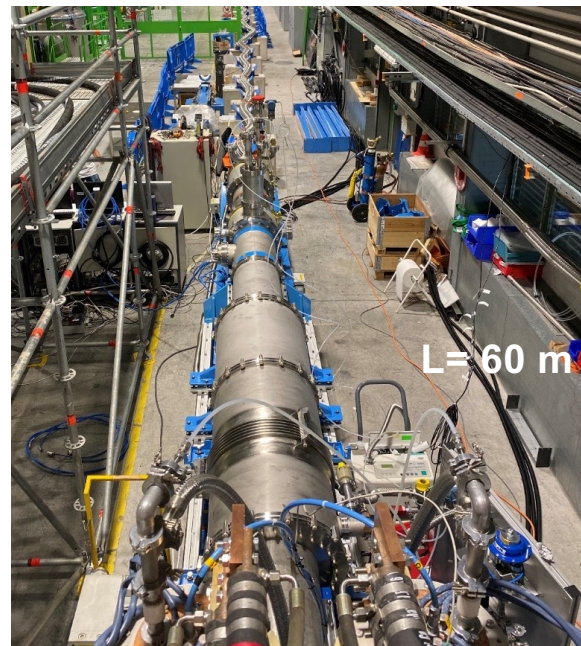
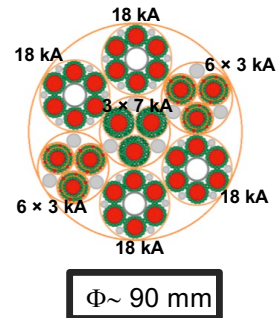
SC-Link-DFHX assembly in pictures

Flexible MgB_2 superconducting links

MgB_2 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 MgB_2 @ 30K
in flexible cryostat
over 60m [54kA total]

MgB₂ Cable Assemblies (1/2)

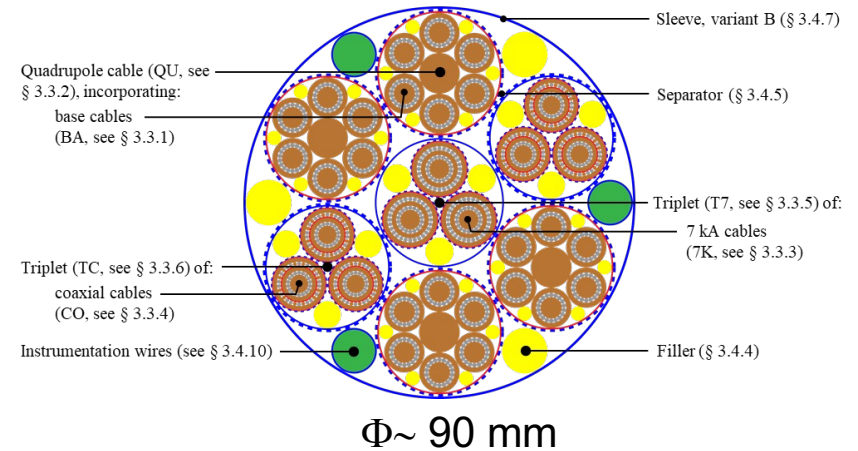
Received from ICAS all MgB₂ series cables



**Successfully HV tested both in industry
and at CERN**



To be produced: 5+5 Units
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- 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

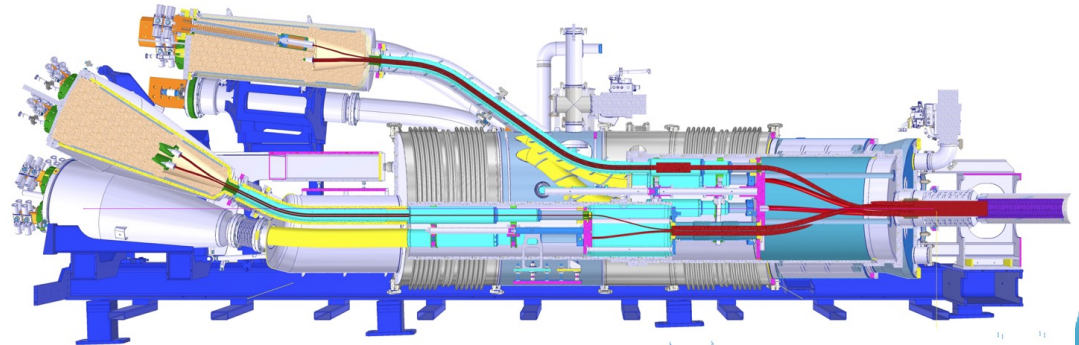
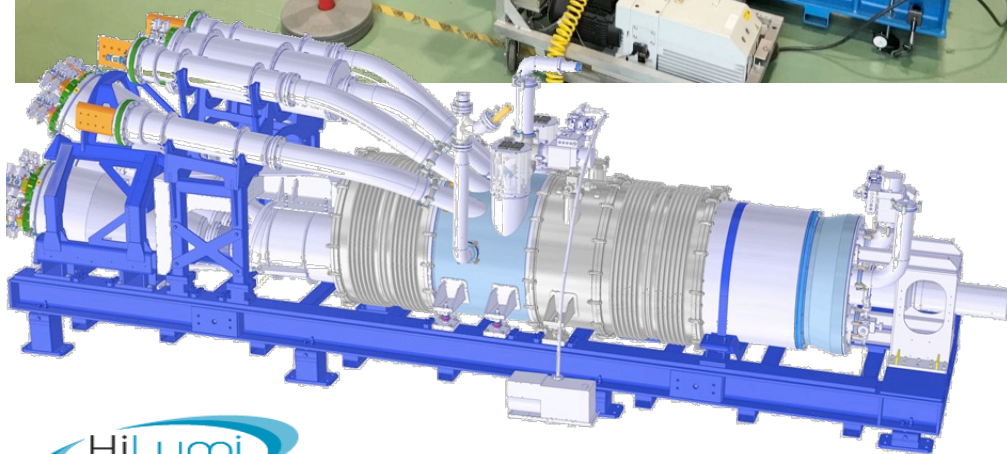
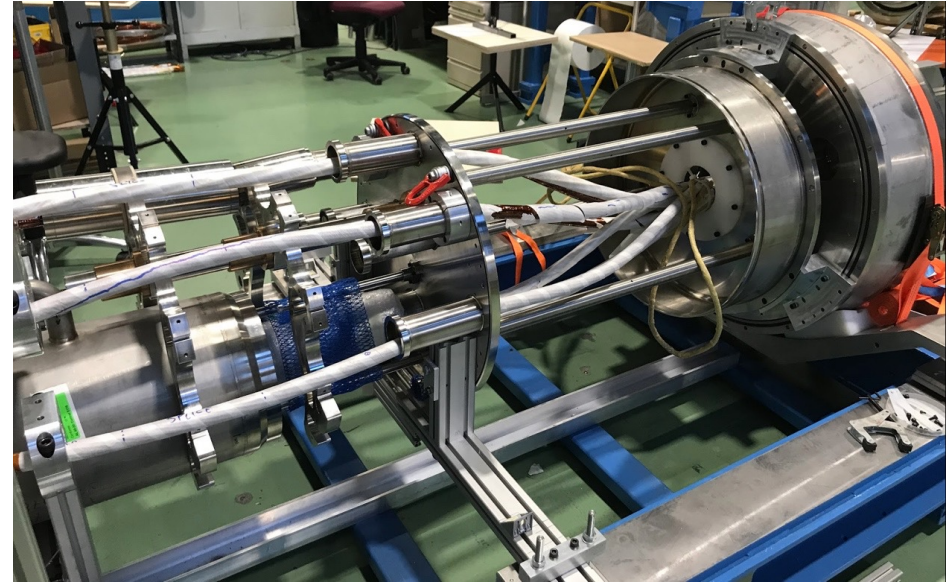


Final length for Triplets: 74.5 m

Optimization of leak test **procedure**

Visual and endoscopic inspections, dimension controls

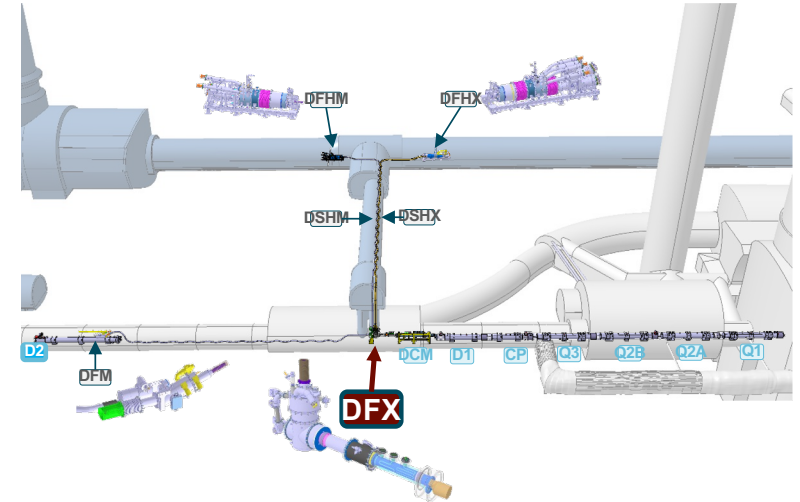
First DFHX constructed @ CERN (2/3)



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

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

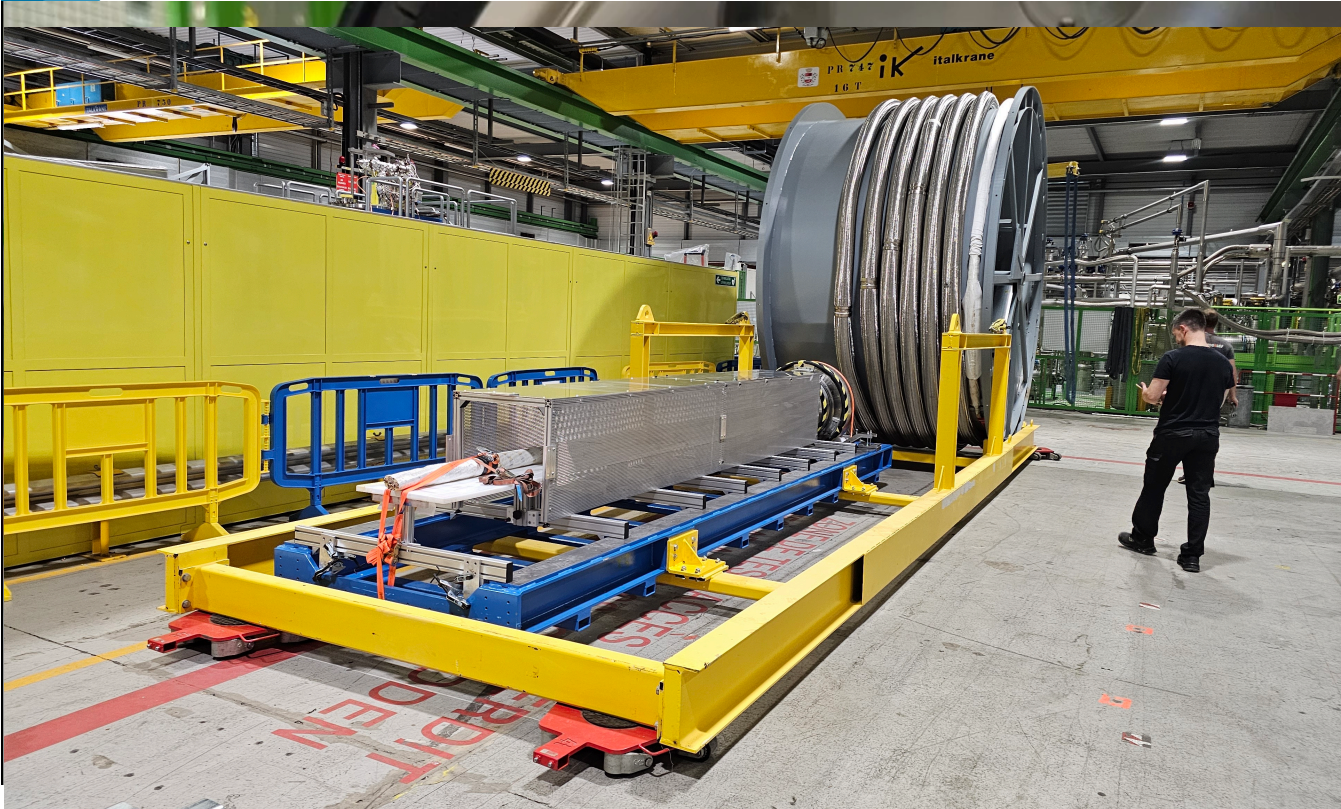
The flexible, double-wall, corrugated cryostat comprises 19 MgB₂ superconducting cables in a single assembly, twisted together to form a compact bundle. These 19 superconducting cables can transfer altogether a DC current of about 120 kA at ~20 K.



Complete Prototype system demonstration in 2024



3rd Superconducting Link Assembly Finished [1 proto + 2 series]

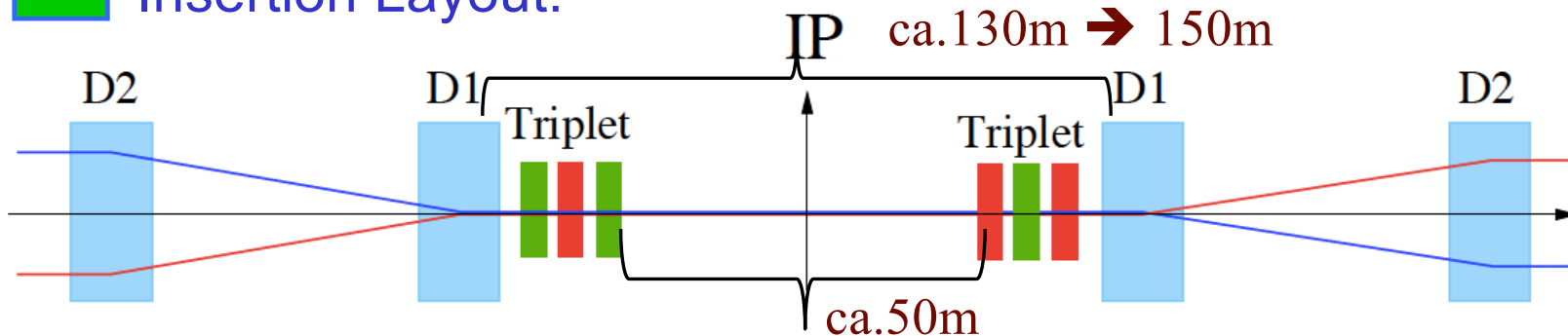


Transport of 2nd series link in September 2025



LHC Challenges: Crossing Angle at Interaction Points

Insertion Layout:

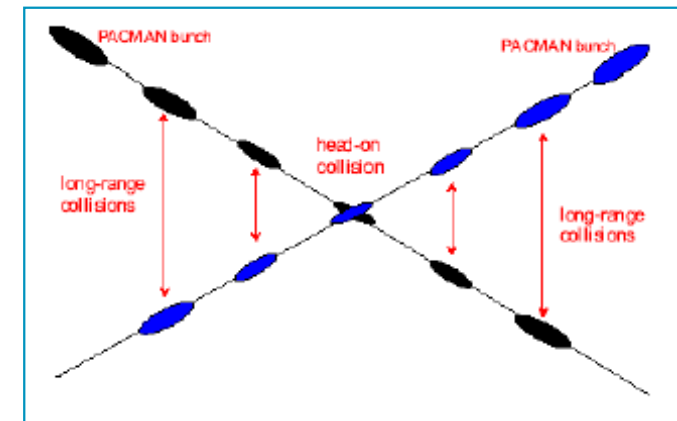


Parasitic bunch encounters:

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 σ → large magnet apertures next to the experiments!!

→ at the limit of magnet technology!!!

HL-LHC Upgrade Ingredients: Crab Cavities

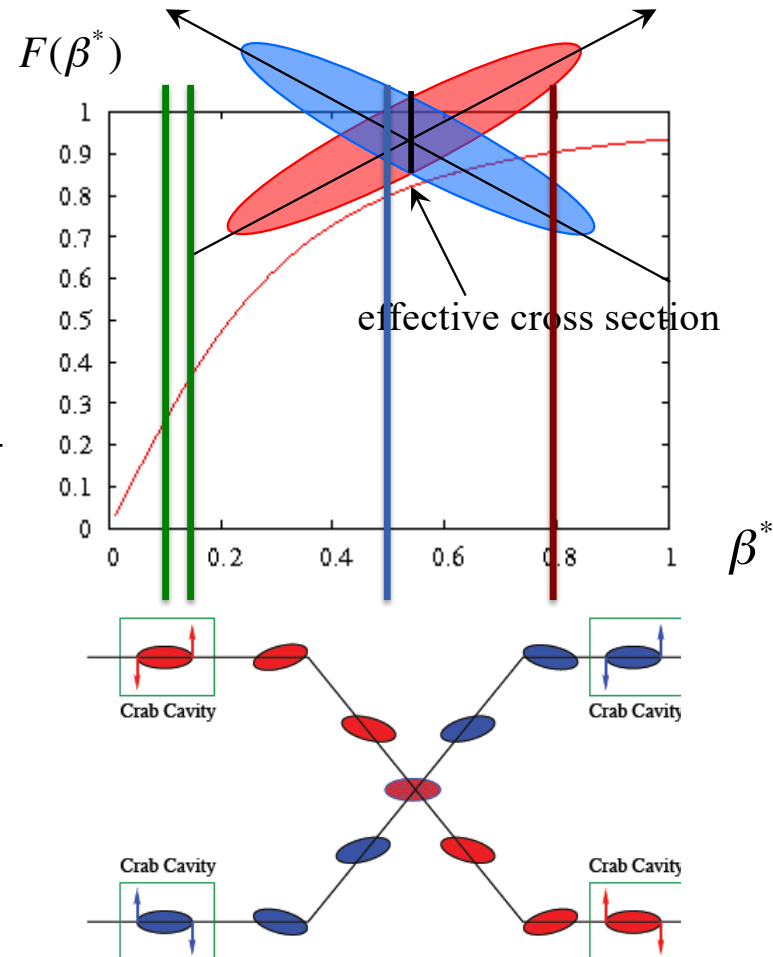
Crab Cavities Luminosity

Reduction Factor:

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

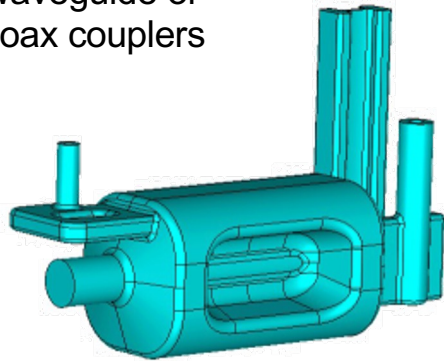
$$F = \frac{1}{\sqrt{1 + \Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

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

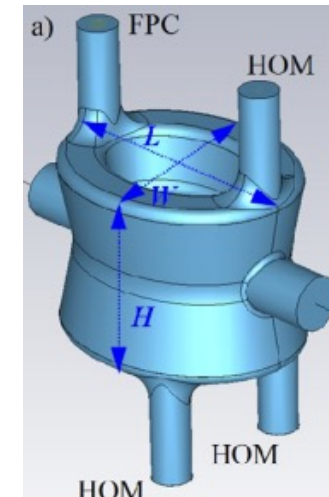


HL-LHC cavity designs

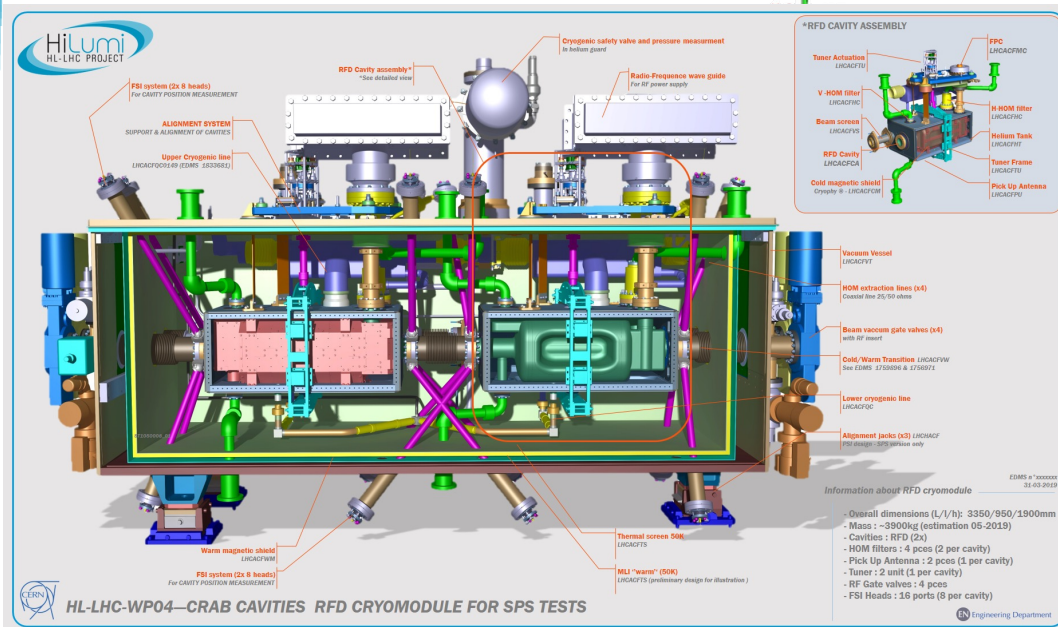
RF Dipole: Waveguide or waveguide-coax couplers



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 → 16 total

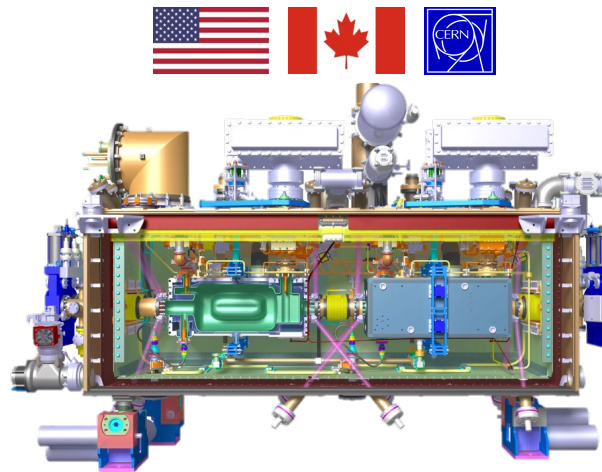
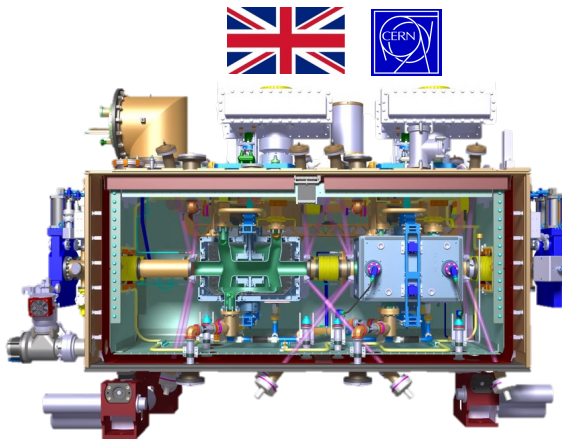
Present baseline: 2 cavities within one common cryostat → need 4 cryo-modules per CC type

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Crab Cavity Series Production

5 DQW cryomodules (Europe)	5 RFD cryomodules (North America)	20 RF Systems (Asia, CERN)
• 10 Cavities to be manufactured at Research Instruments (DE) & CERN • 4 CMs by UK (STFC) & 1 CM at CERN • All cavities & CMs cold tested at CERN	• 10 (+2) Cavities manufactured at Zanon (IT) under US-AUP, 2 Cavities at CERN • 4 CM by TRIUMF-Canada & 1 CM at CERN • CM cold tested at TRIUMF & CERN	• 20 High power amplifiers (IOT) & RF chain lines CERN-KEKB • LLRF (μTCA platform) by CERN



* Several critical components procured, designed & manufactured at CERN (EN-MME, TE-CRG/VSC, BE-GM, SY-RF...) and provided to collaborations

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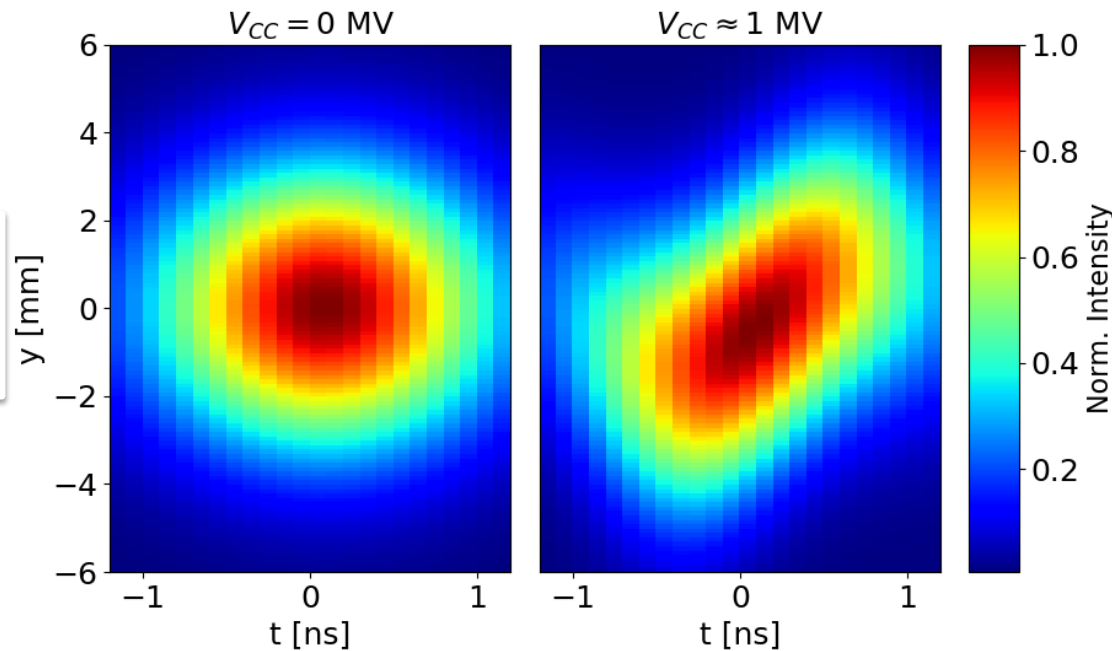
DQW Crab cavity cryo-module for installation in the SPS



First proton crabbing ever!

Beam TEST in SPS ongoing between 2018-2023

Crabbing Voltage from Head-Tail Monitor
2018-05-23 17:02:39

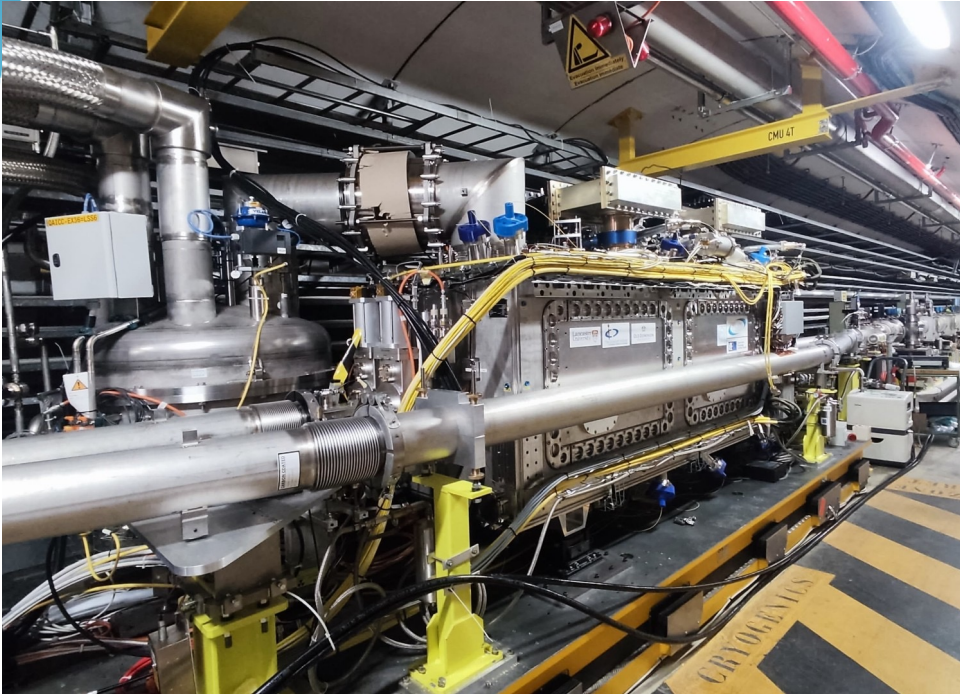


Study and R&D
has been very
useful to obtain
this result



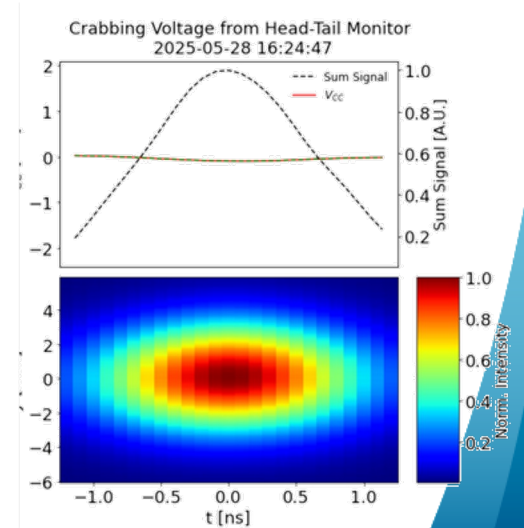
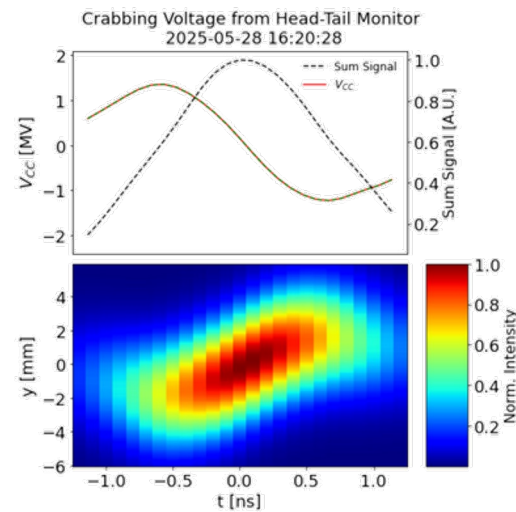
RFD cryomodule assembled in UK and being tested in M7 bunker (SM18-CERN) in 2024 before installation in SPS in YETS 2024 / 2025

RF Dipole, MD #1



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 !



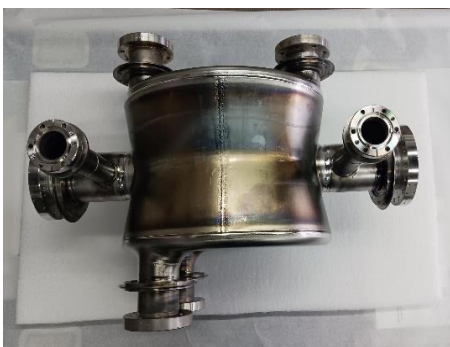
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DQW Series Cavities

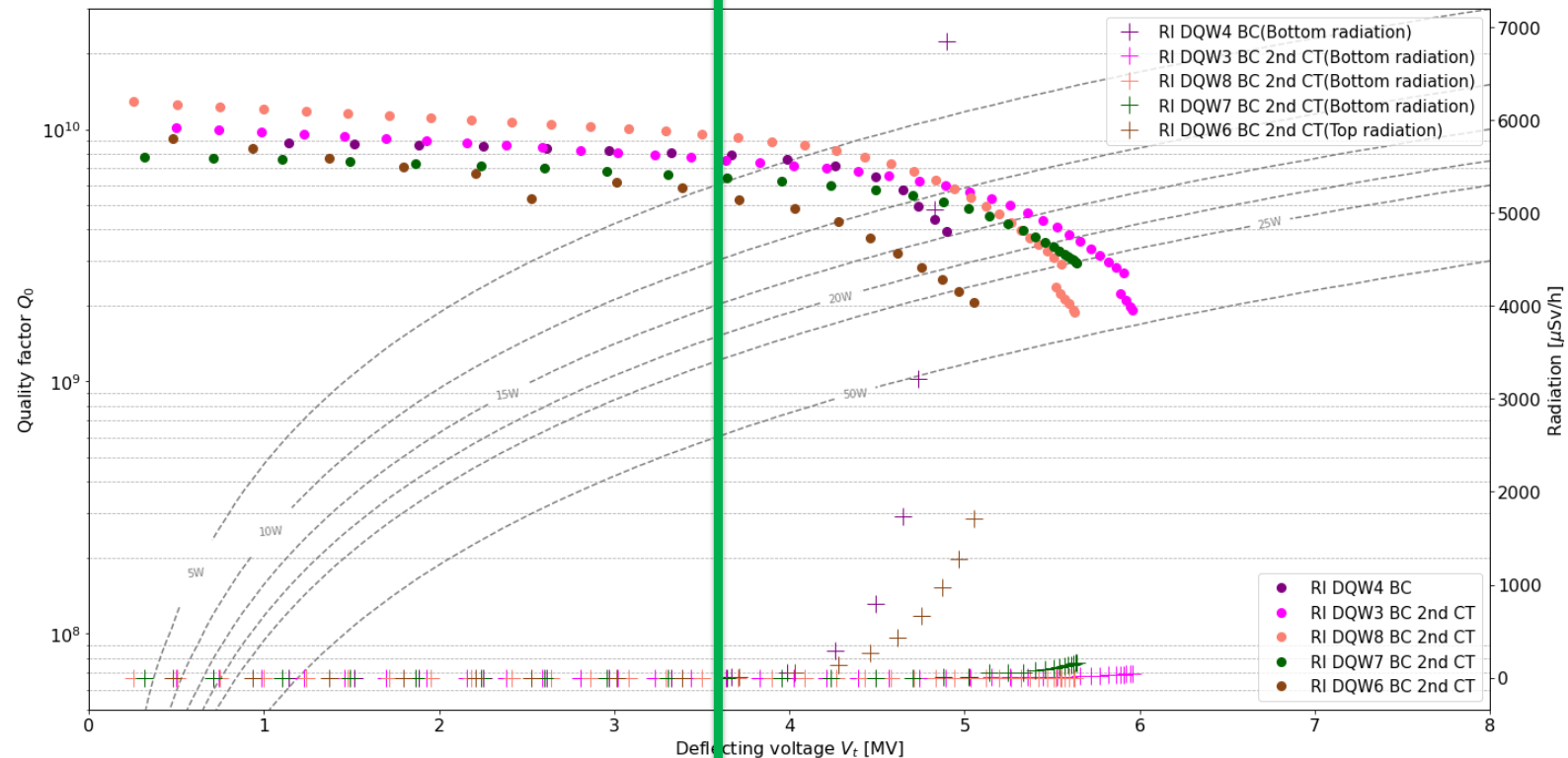
See presentation by Ofelia Capatina later today

All bare cavities manufactured and tested beyond specification

The 1st batch of cavities being cryostated into 1st series module in the UK – on track
2nd batch being shipped to UK

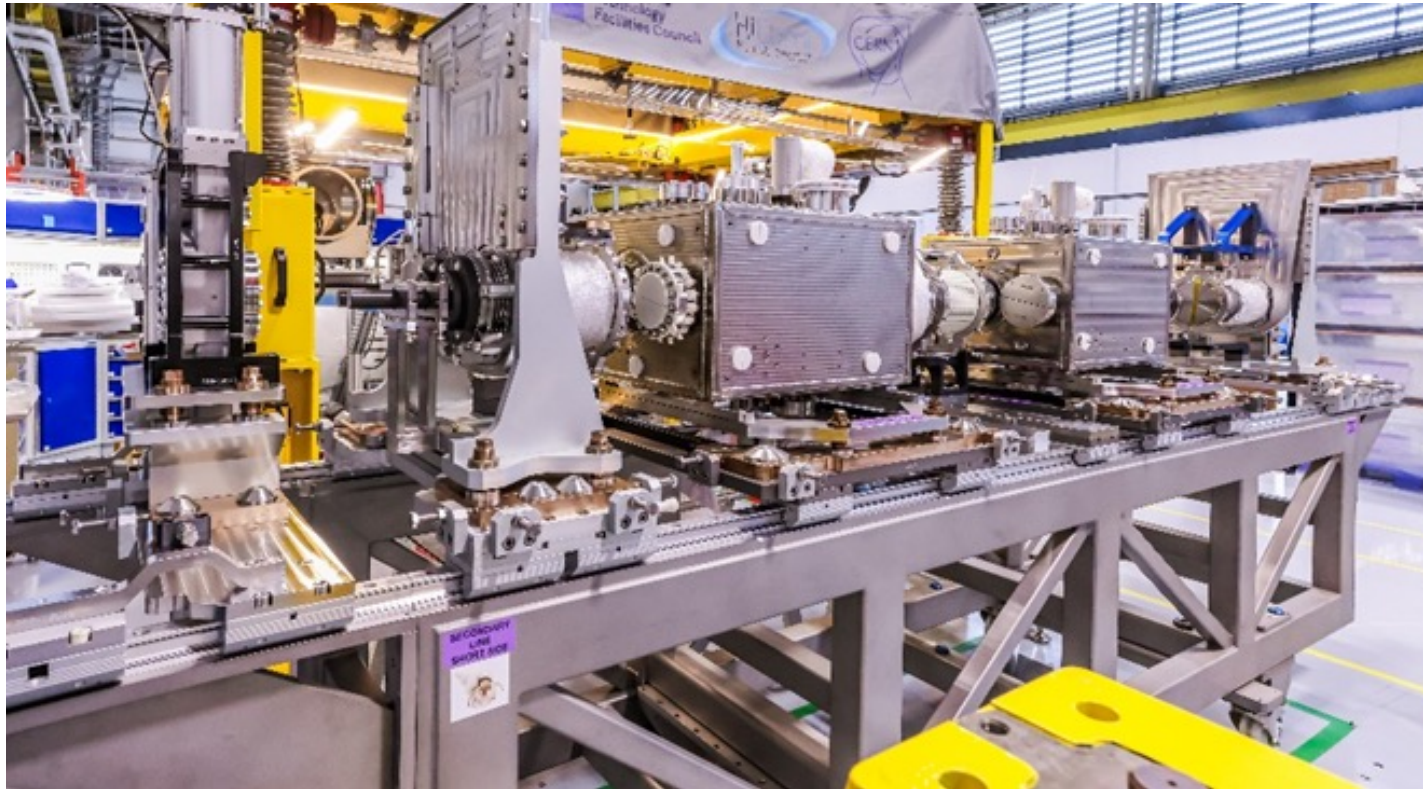


DQW bare cavity testing in SM18



- Following a (light) BCP, all (bare) cavities from RI series production have been validated beyond acceptance criteria

1st set of DQW cavities being cryostated in series DQW Cryomodule in UK



See the presentations by Ofelia Capatina and Niklas Templeton this afternoon for more details

US-AUP: RFD Cavity Status

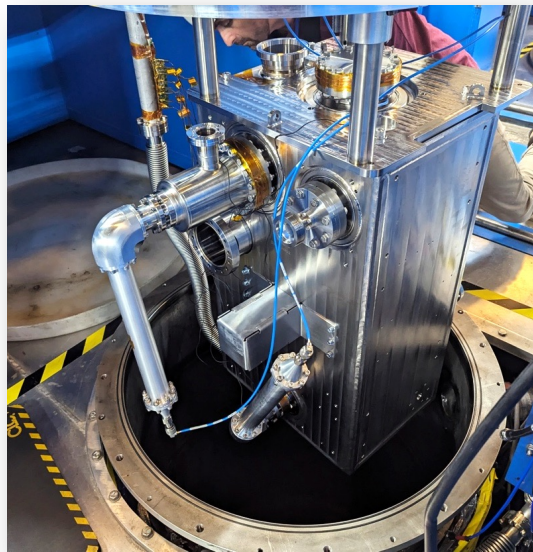
RFD Cavities 1-3



4 cavities manufactured at Zanon (IT) to date

1 bare cavity qualified to specification and being tested in final configuration

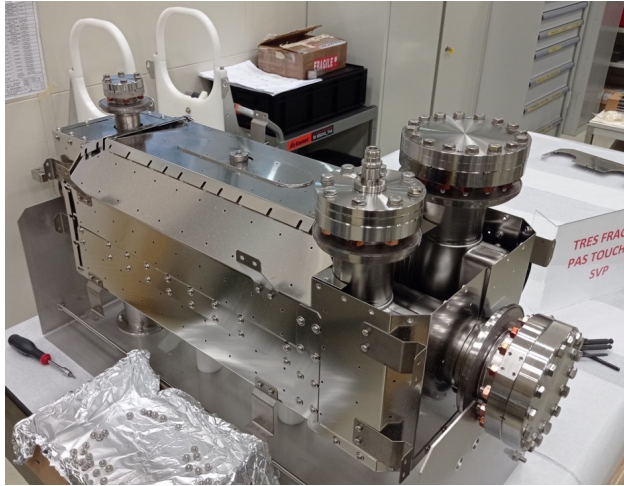
Latest RF tests indicate field limit below specification, **re-processing to improve performance** (as was done for DQW)



RFD2 Dressed with HOMs

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CERN Mitigation, RFD Cavities



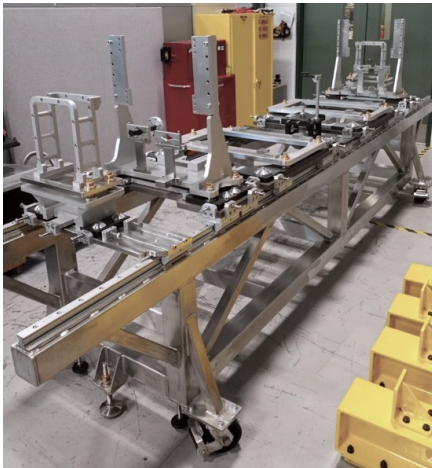
New mitigation strategy (2025) includes manufacturing and testing of 2 RFD cavities to assemble one cryomodule at CERN

1st cavity already built during prototyping phase. Requalified above specification in 2025, being jacketed

2nd cavity fabrication ongoing and on track



TRIUMF: RFD Cryomodule Status



1st prototype cavity from US-AUP successfully tested at TRIUMF - Canada

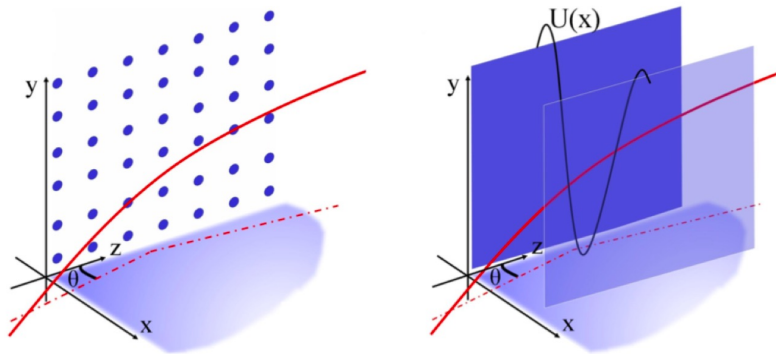
Procurement of major cryomodule components completed for series

All CERN contributions delivered to TRIUMF

Infrastructure upgrades done at TRIUMF to start cryostating

Ion Collimation: Planar channeling in bent crystal

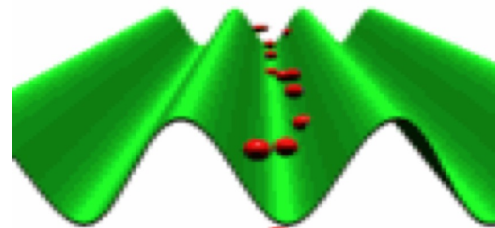
Pure crystals with regular lattices



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

$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$

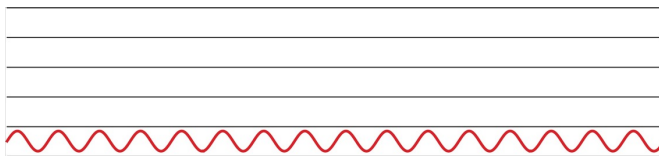
Critical angle



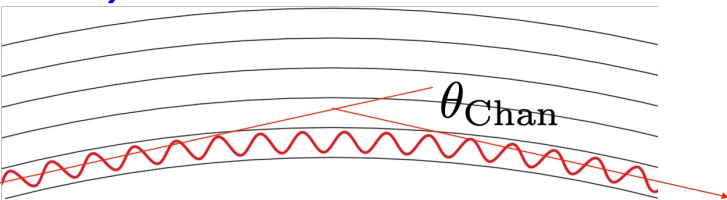
Critical angle at the LHC energy frontier (Si crystals):

LHC 450 GeV = 9.4 μ rad
LHC 6.5 TeV = 2.4 μ rad

Straight crystal: oscillations between planes



Bent crystal

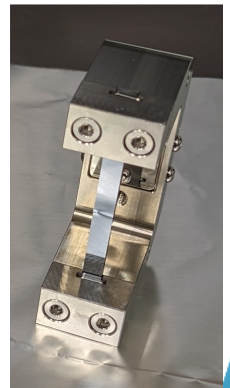
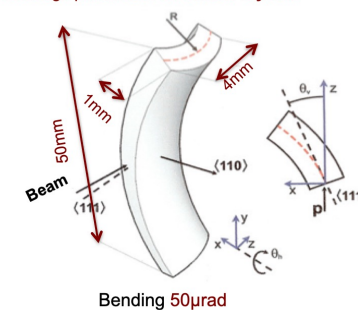


Bent crystal → net kick of the trajectory for particles trapped for the full crystal length!

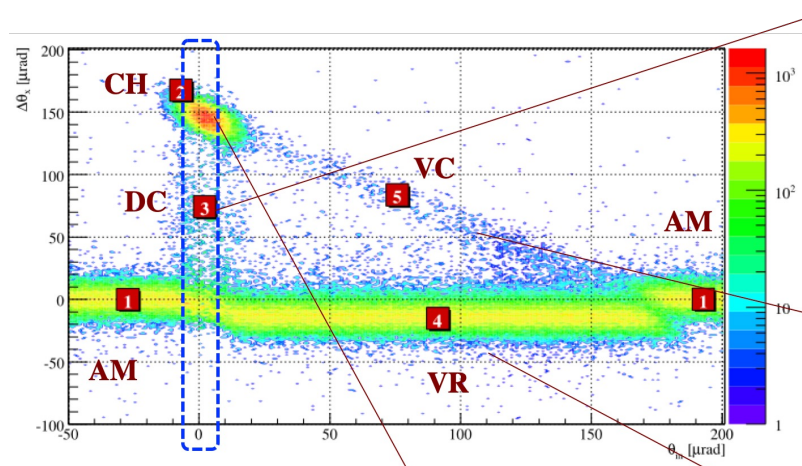
Equivalent magnetic field close to **300 T** (4 mm crystal)

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

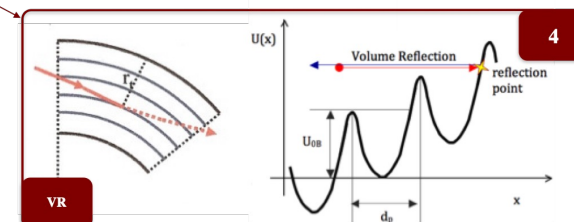
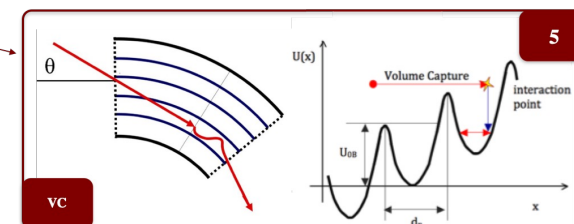
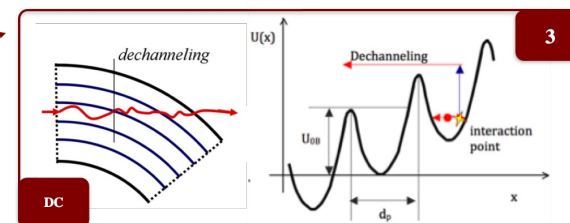
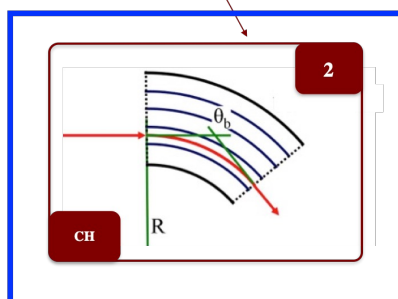
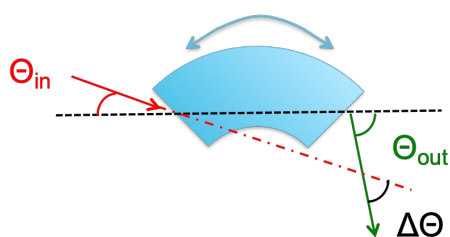
LHC design parameters for **Silicon crystals**



Coherent interactions



Collimation uses the channeling phenomenon in this angular region

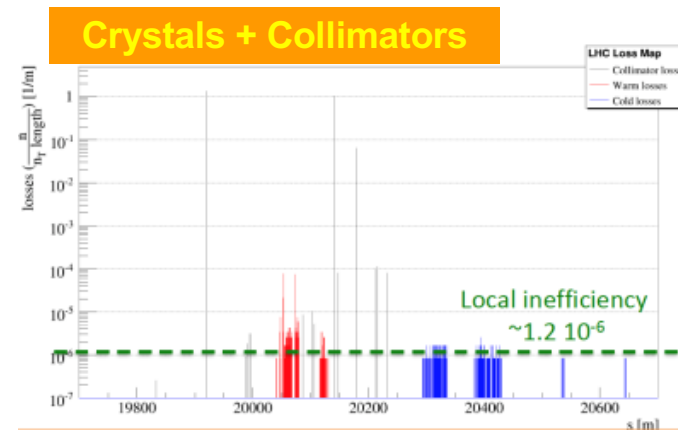
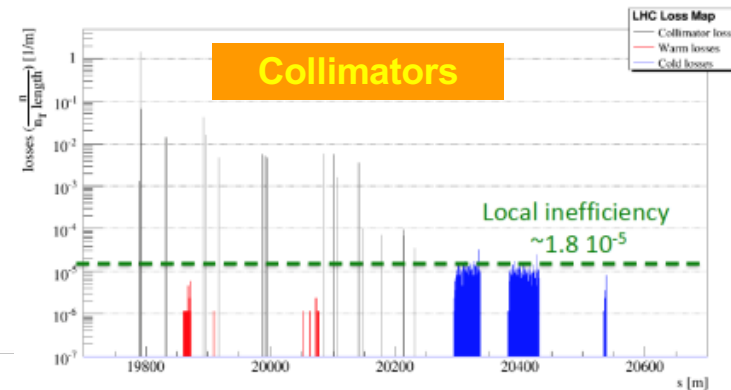
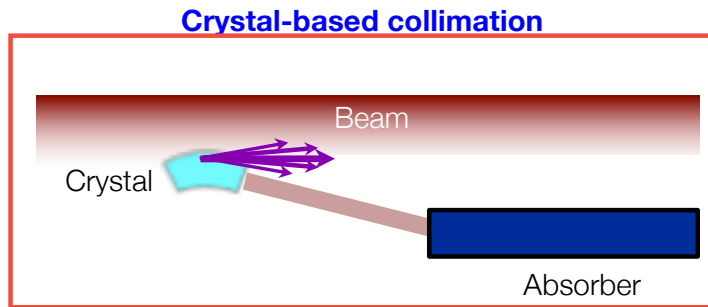
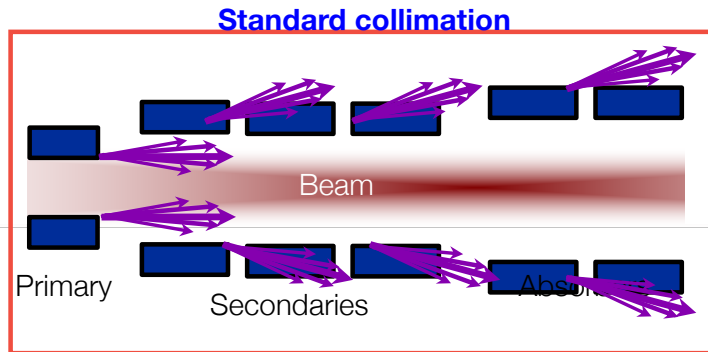


Complex dynamics, in particular for heavy ions.

Phys. Rept. 815 (2019) 1-107

Advanced Accelerator Course; October, 2025

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-prad accuracy to ensure channeling

Installation of Crystal Collimators for the Ion Run

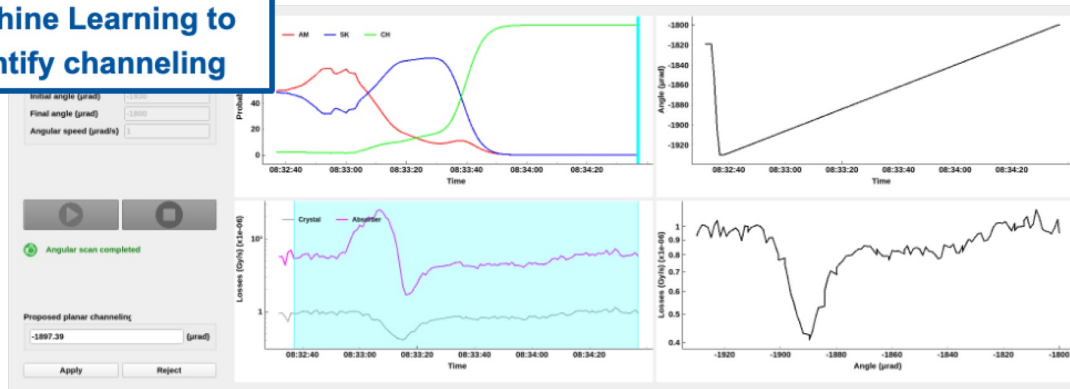
- Full crystal collimation system (4 crystals, one per beam per plane) available since 2023. Specs: 4 mm, 50 μ rad bending
- Used operationally for lead ion beam collimation.
- Tests in 2025 with new



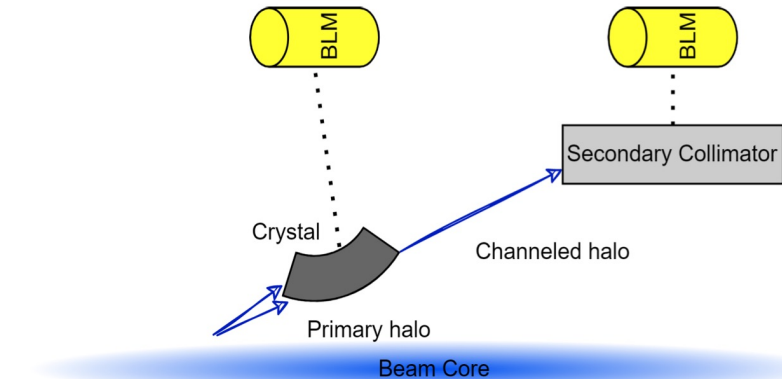
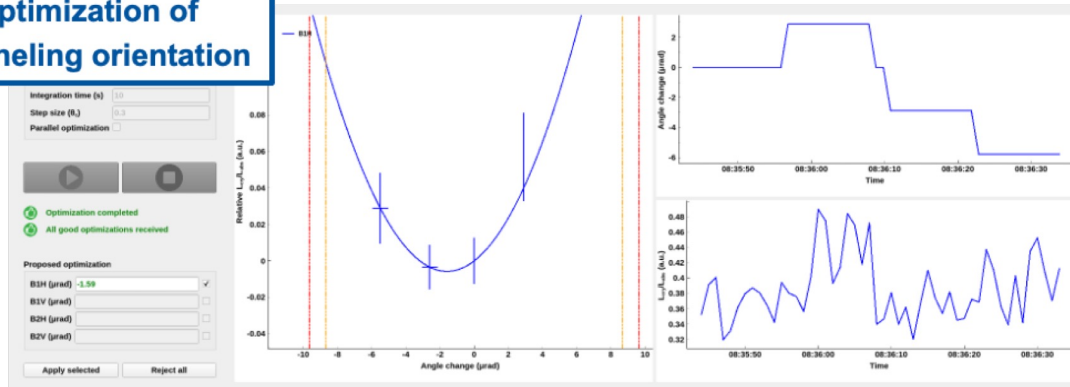
A new generation of crystal collimators are installed in the LHC tunnel to provide improved capabilities for ion beam operation in the HL-LHC era

Crystal setup assisted by Machine Learning (ML)

Machine Learning to identify channeling



Optimization of channeling orientation



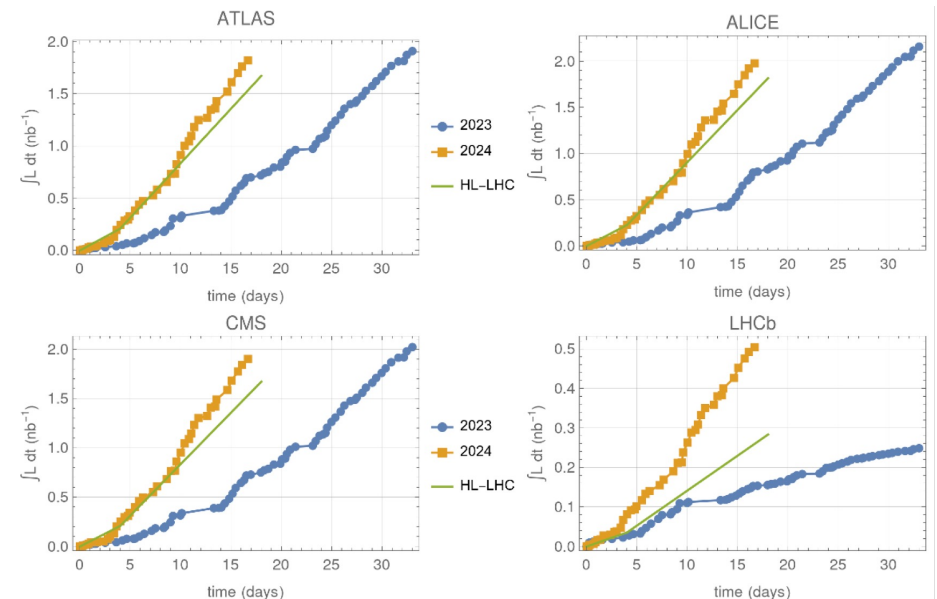
- ML is used to detect potential loss of channeling
- Key inputs: BLM at key-collimator locations
- Target output: Crystal angular error from optimal channeling orientation
 - Through identification of the “amorphous” and channeling orientations
- Feed-forward neural network — FNN — being used; simulation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

Ion luminosity production in 2024

	Bunch intensity	Max. stored beam energy
2023	1.6×10^8 Pb/bunch	17.3 MJ
2024	2.3×10^8 Pb/bunch	26.9 MJ
HL-LHC	1.8×10^8 Pb/bunch	20.5 MJ

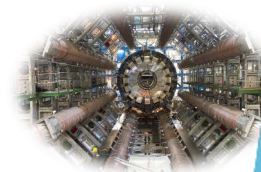
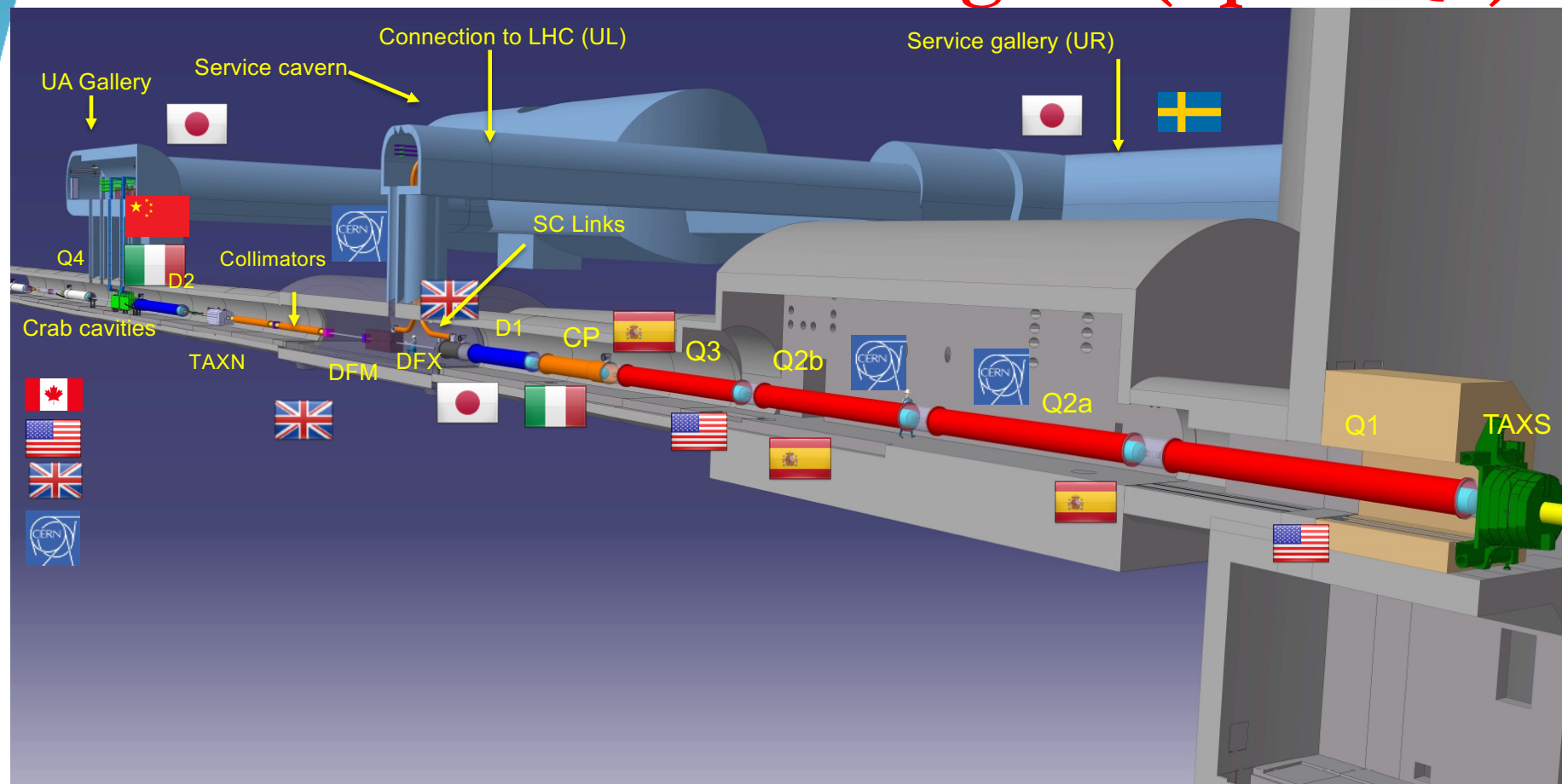
Luminosity production

- 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: $142 \mu\text{b}^{-1}$
 - HL-LHC projection was: $118 \mu\text{b}^{-1}$
- LHCb
 - About double the luminosity in 2024 than in 2023, in half the time
 - Mean daily production: $37 \mu\text{b}^{-1}$
 - HL-LHC projection was: $20 \mu\text{b}^{-1}$



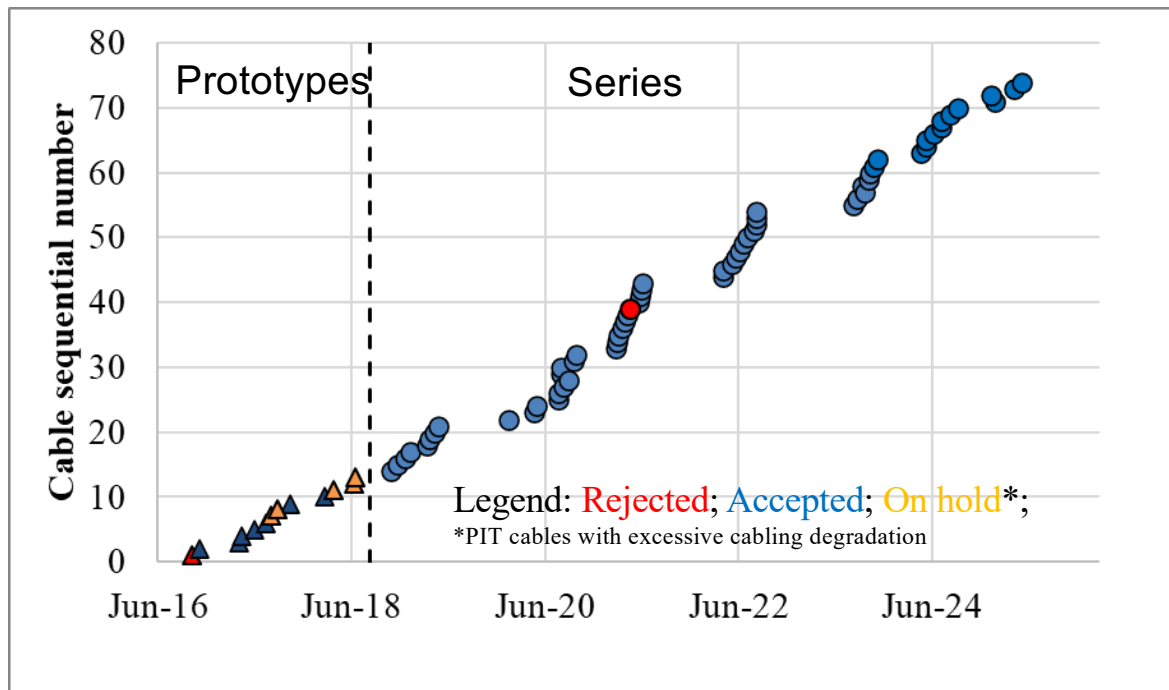
Luminosity production during the 2024 ion run in the four IPs

International Collaboration: The Insertion Region (up to Q4)



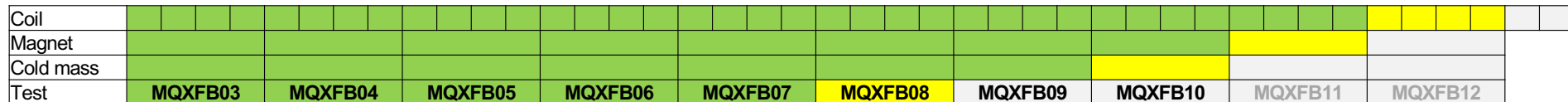
MQXFB - Cabling

- MQXFB cabling is completed! Excellent yield in the MQXFB production: 74 cables produced with only 2 rejected due to a critical NCR
 - 4 cables (PIT) on hold due to excessive cabling degradation.



- **Coil fabrication**

-

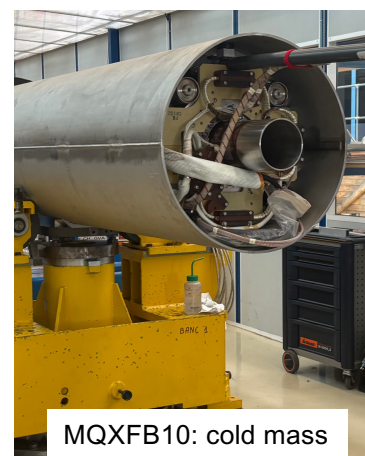
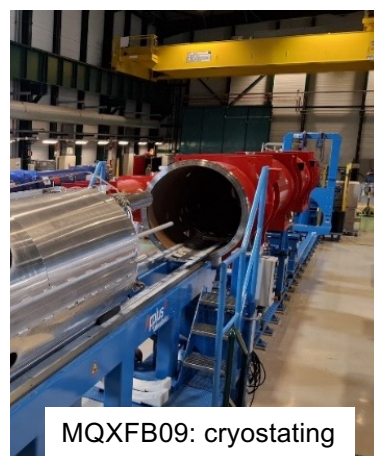


Completed	On-going	To do
-----------	----------	-------

Advanced Accelerator Course; October, 2025

88

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

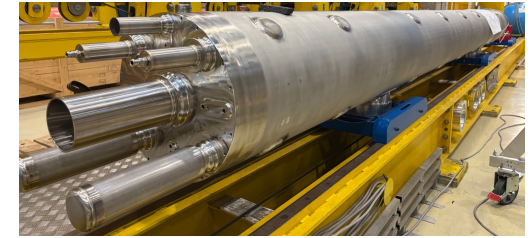
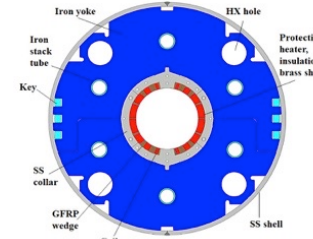
- 4 out of 13 virgin magnets failed during vertical testing
 - Coil replacement has been demonstrated in 3 cases, but has impact on cost and schedule.
- In the current working schedule, the last magnet for installation (LMQXFA10) arrives beginning of 2027
- The critical path is now in the vertical testing.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

[illegible]

Accepted	On-going	To do
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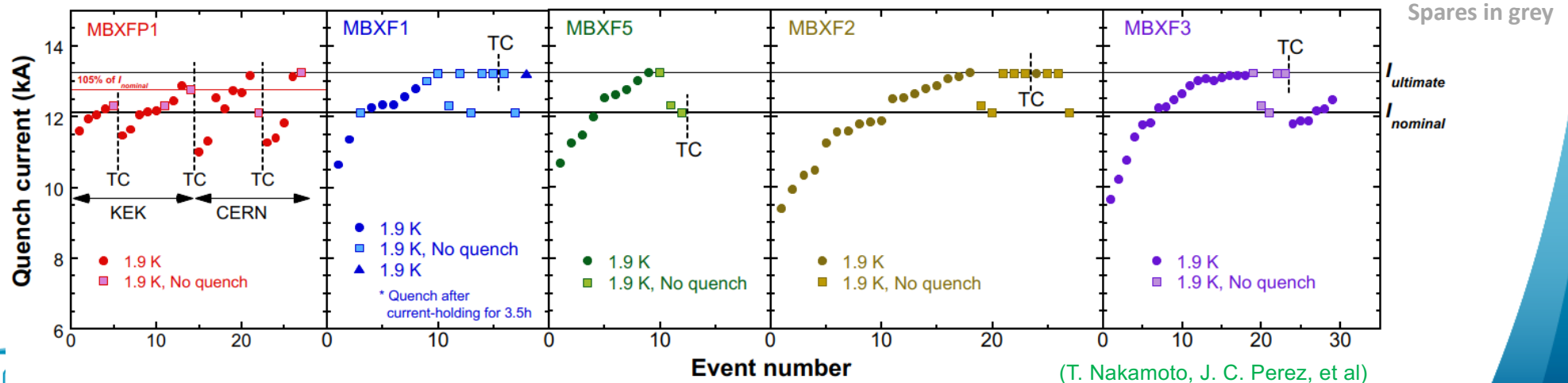
Spares in grey

- **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					



(T. Nakamoto, J. C. Perez, et al)

Oliver Brüning CERN

- The first thermal cycle for the **first series** cold mass is ongoing: the magnet **reached ultimate without quench!**
 - Stable operation at ultimate (8h) and nominal (2x20 h)
- The **third magnet** for installation **was delivered** to CERN
- Electrical integrity remains a challenge, with slow reaction from the manufacturer in case of nonconformities

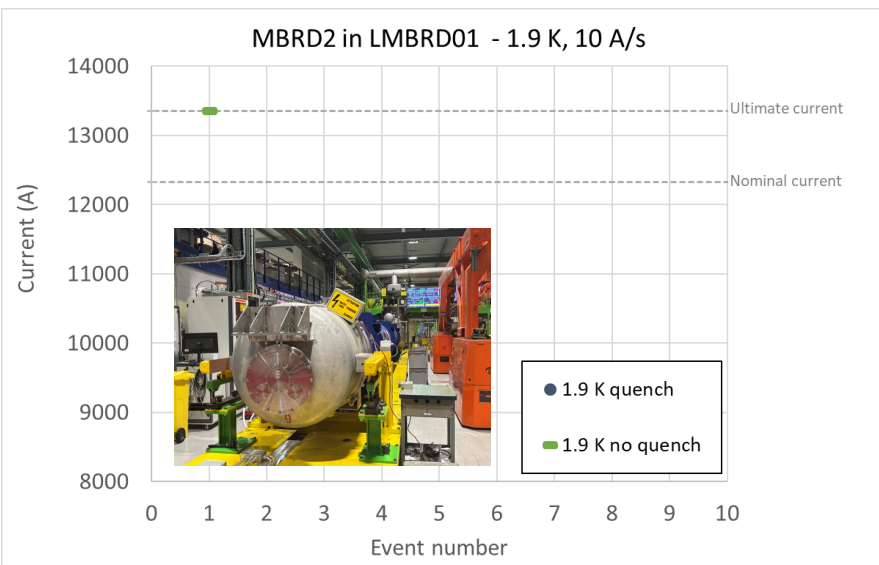
[illegible]

Completed

On-going

To do

Spares in grey



MBRD4 accepted at CERN, June 2025



HL-LHC Shielded Beam Screen Production



Up to 11 meters long with octagonal cross-section;
Cooling capillaries and Tungsten based absorbers;
Stainless steel, Co-laminated with thin Cu sheet;
Amorphous Carbon coated and weighing almost
half a ton in total and ca 150mm diameter

→ had to go for an in-house production



Nico Kos † July 2025



Celebration of 1st completed beam screen in April 2025
Advanced Accelerator Course; October, 2025

Oliver Brüning CERN

Delivery of the 1st Batch of the Series CLIQ Magnet Protection System



See the presentation by Daniel tomorrow for more details

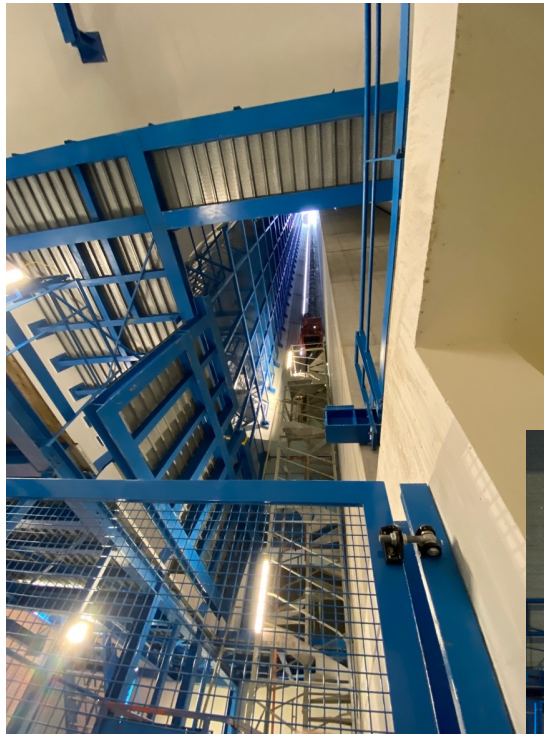
Celebration of delivery in August 2025

IR1/5 underground civil engineering completed in 2022

Construction Finished End 2022



Ceremony for completion of CE on January 20th 2023



HL-LHC PROJECT

Advanced Accelerator Course; October, 2025



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Completion of the civil engineering works: Surface Buildings



Example Point 1

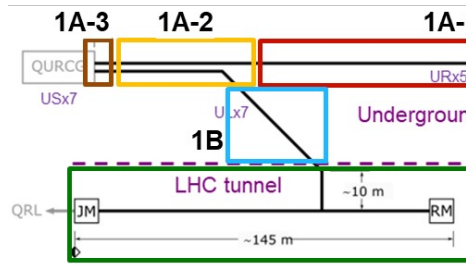
Status of infrastructure installations at P5



Status End 2024

QXL installation (phase 1A-1) + Refrigeration

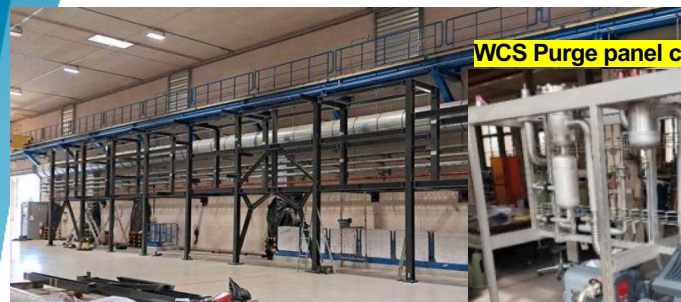
See presentation by



- 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



WCS Purge panel completed



4.5 K Cold box Assembly



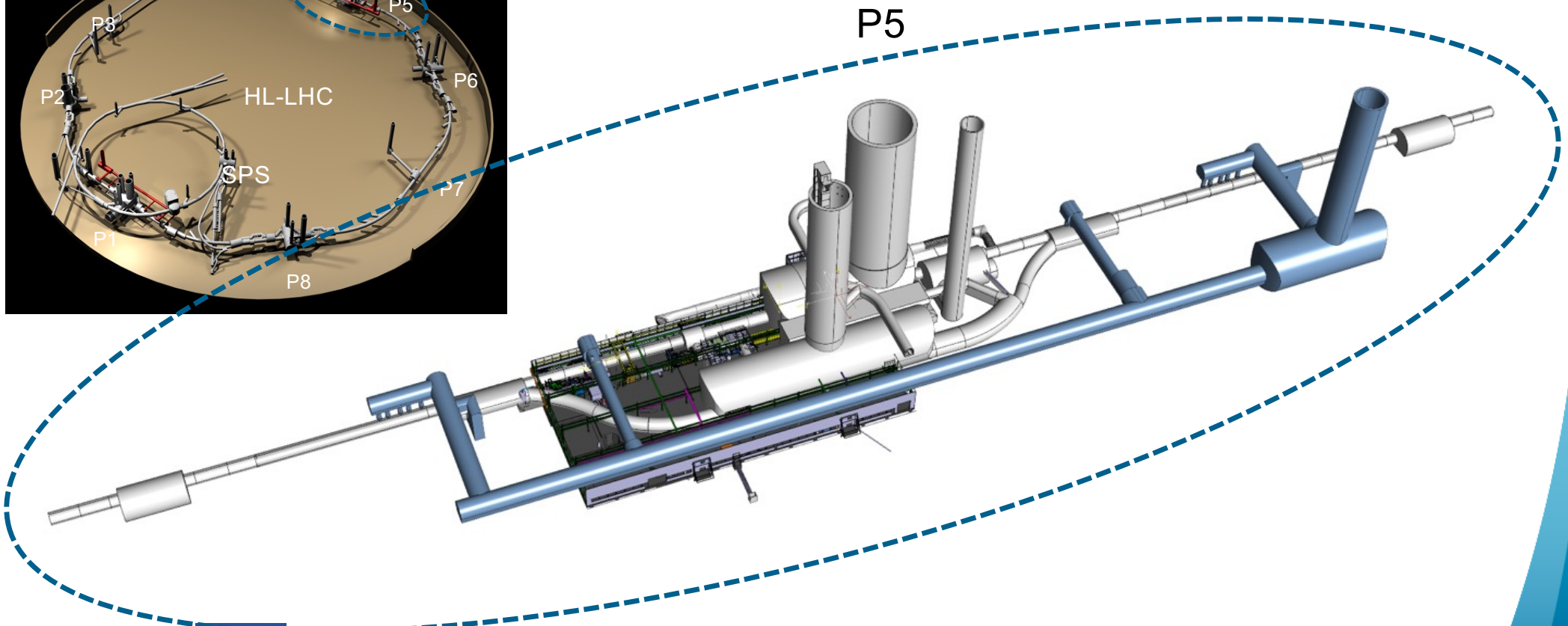
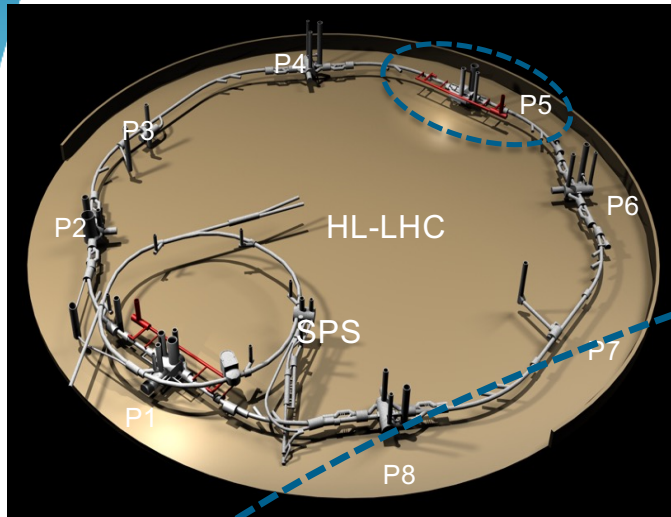
Cold Compressor Box Assembly



Compressor skid arrived last week



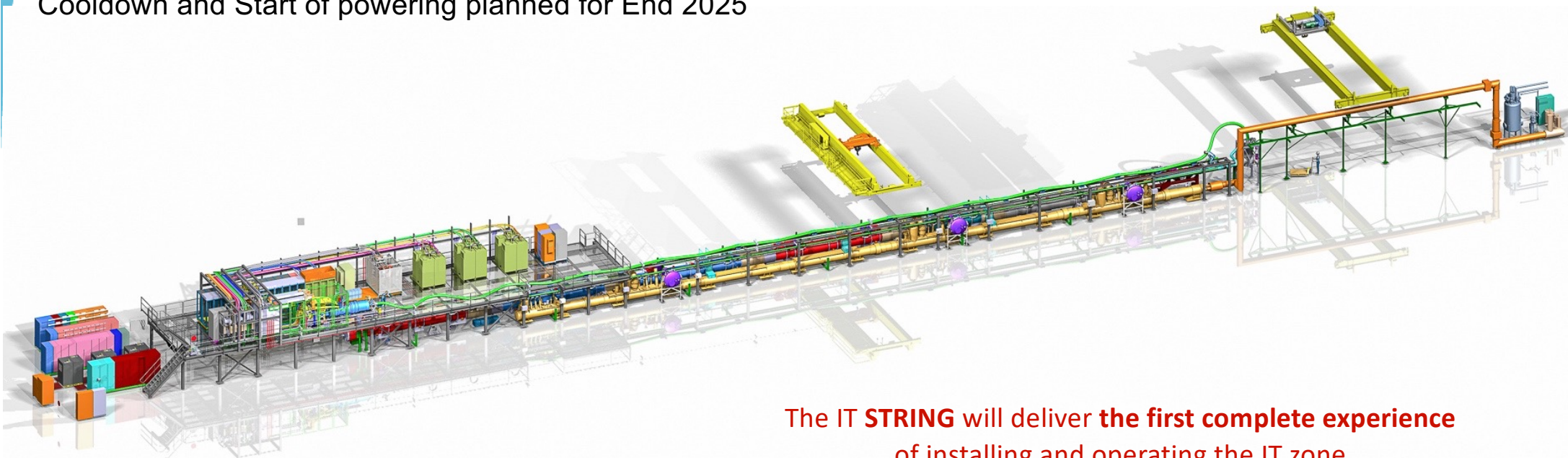
Next Milestone: HL-LHC IT STRING: P5L



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

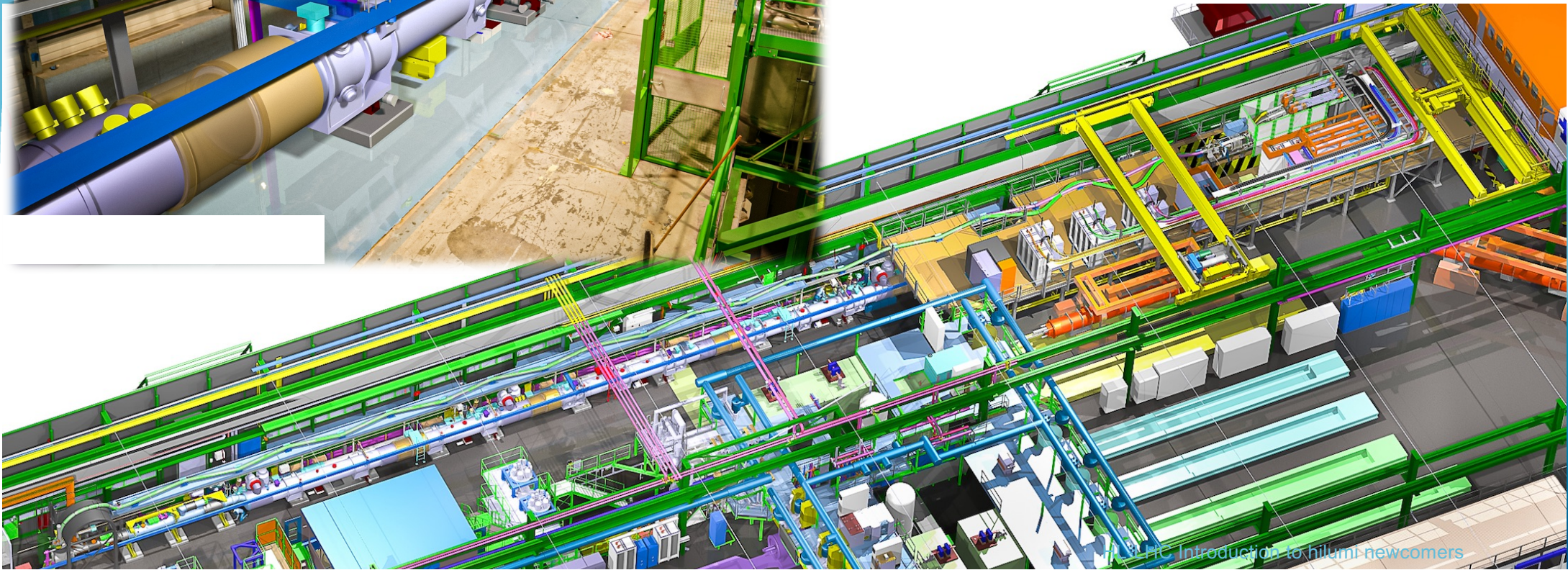
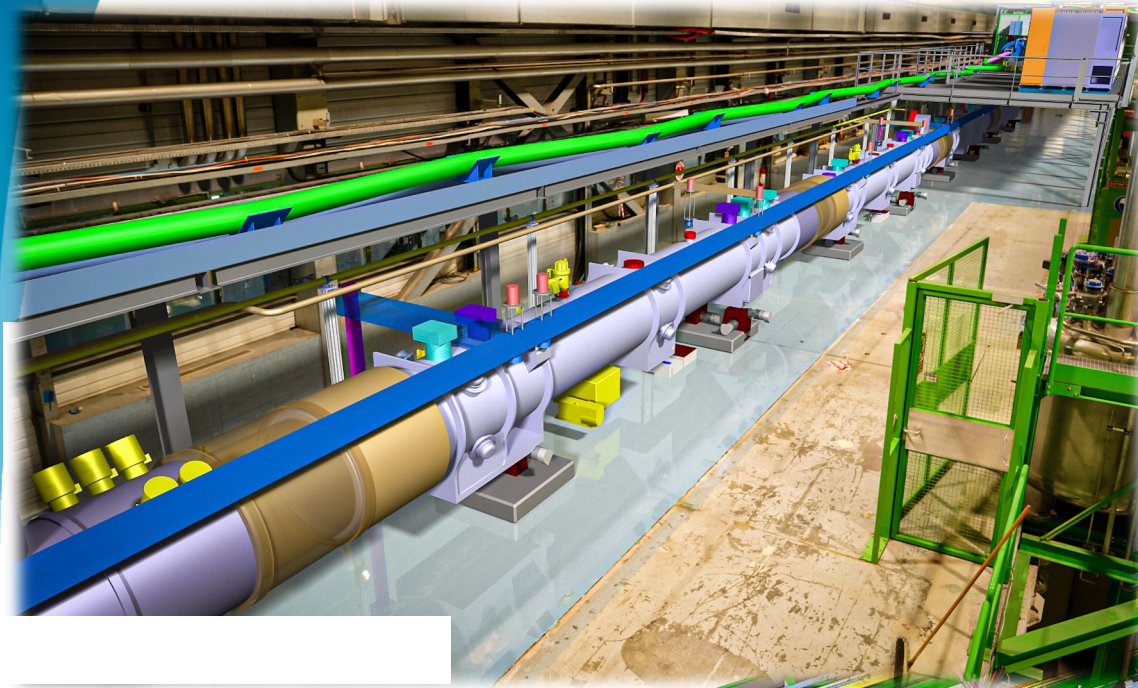


The IT **STRING** will deliver the first complete experience of installing and operating the IT zone

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

Installation started and foreseen until 2023

→ Operation planned in 2024 and 2025



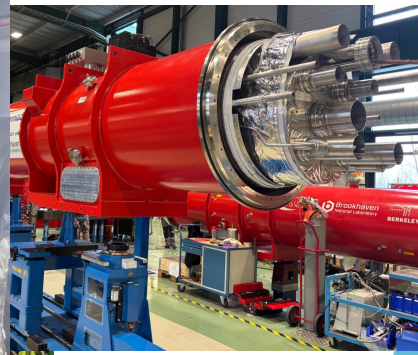
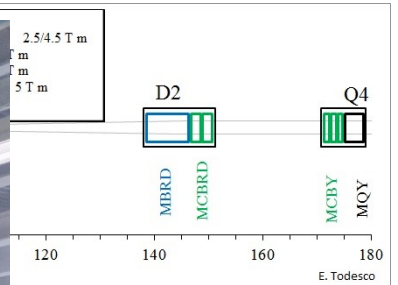
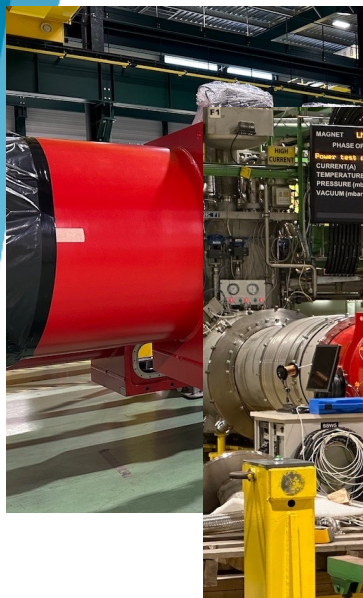
Q2a cold mass installation

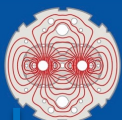


Sc Link INSTALLATION IN THE IT STRING

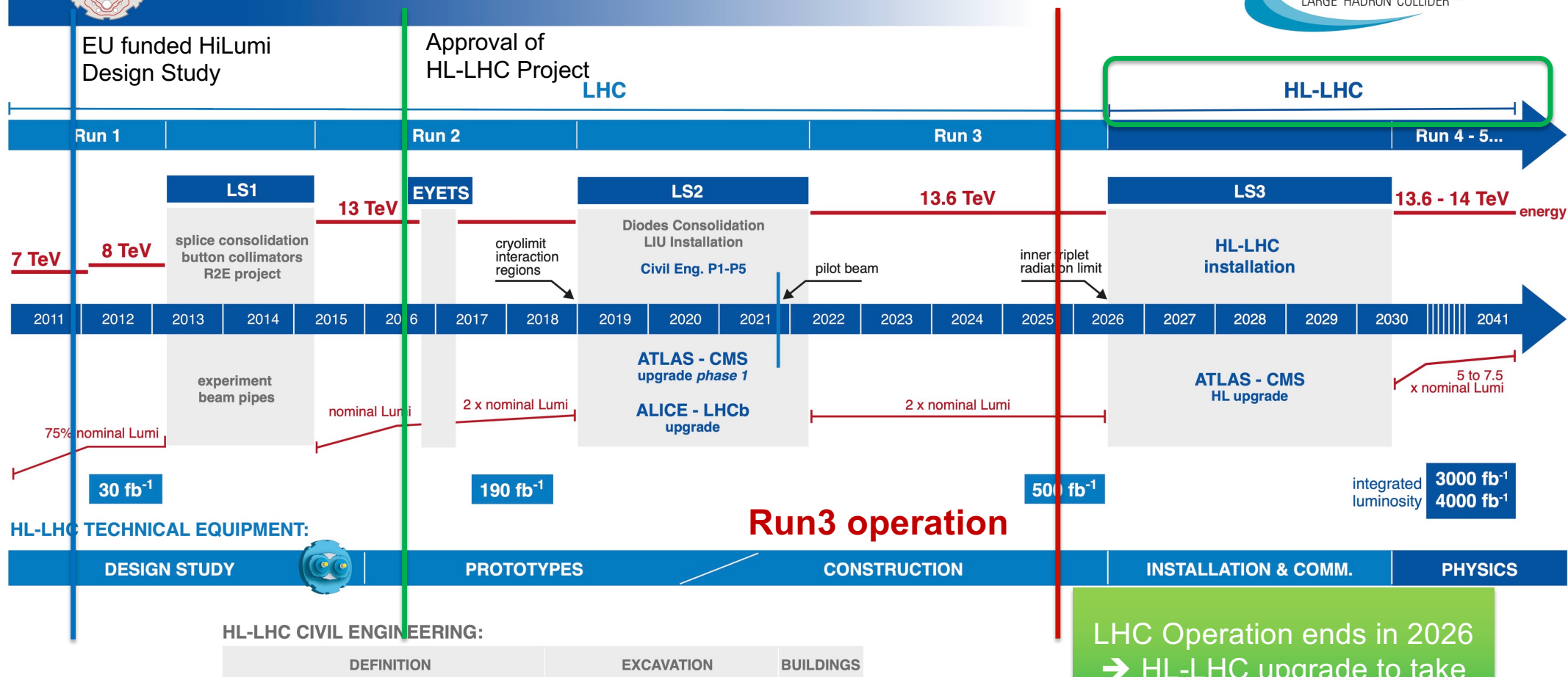


IT-String Installation





LHC / HL-LHC Plan

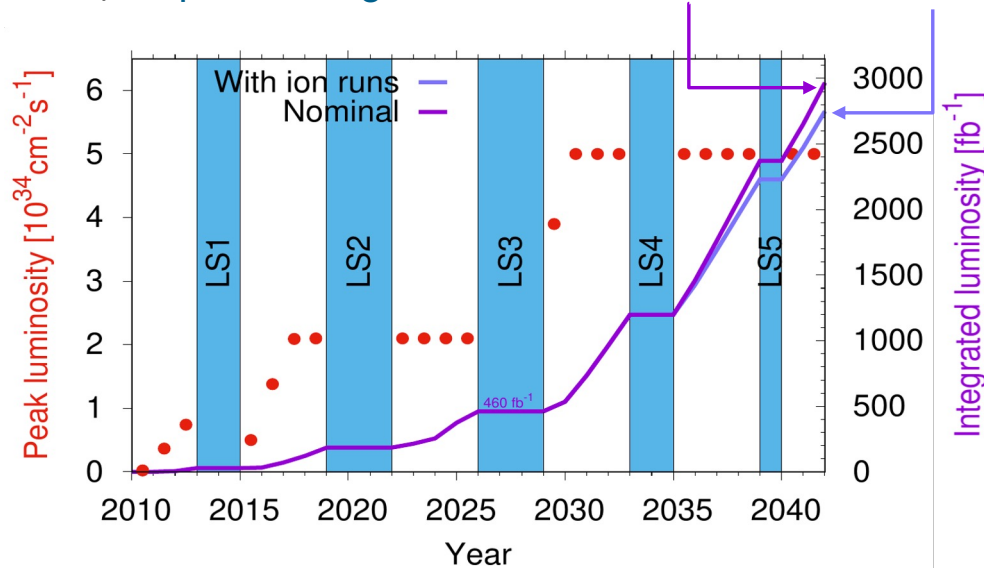


LHC Operation ends in 2026
→ HL-LHC upgrade to take over as of 2030 after LS3

HL-LHC physics production

- Ions physics run recently approved in 2031-2041

Expected target reduced from 3000 fb⁻¹ to 2771 fb⁻¹



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		2480
Sum all runs (+520)			2771		3000

- 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

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

Q2 2026

LS3 Schedule – TCC October 2025

LSS dismantling after cryo lockout

Cabling dismantling

Core excavation (LHC side)

Cabling installation

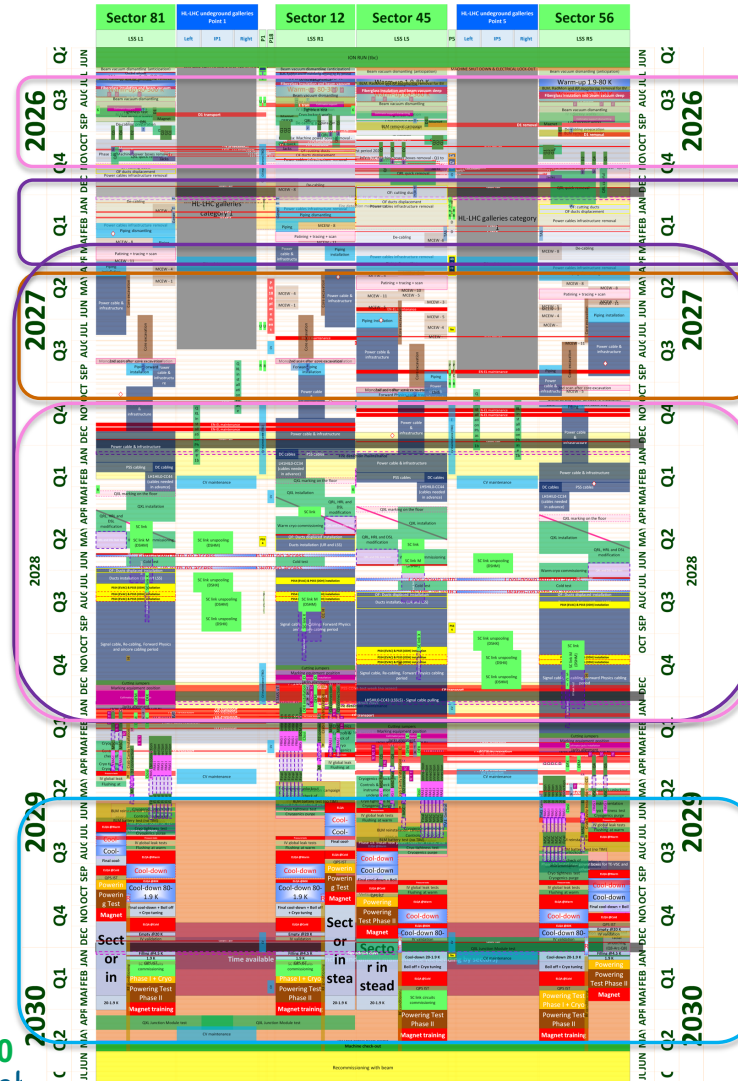
LSS installation

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!**



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

ISSN 1793-1339

Advanced Series on
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

Published in 2024 and available
as

Open Access Publication

<https://doi.org/10.1142/13487>

ISBN: 978-981-127-894-5

HIGH-LUMINOSITY LHC ON TRACK



Questions?

The LHC is NOT a Standalone Machine

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

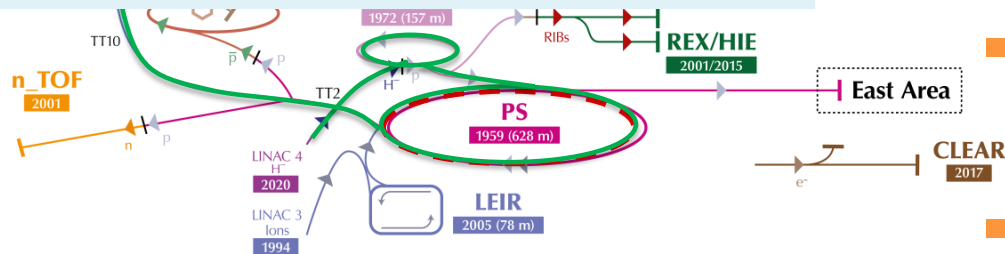
- By itself **one of the largest accelerator facility in the world** with its own diverse and, for many aspects, unique physics program

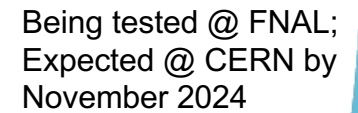
LHC Injector Upgrade Project

Installation finished in LS2

→ Commissioned in LHC Run3 Period

- 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^-





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!!

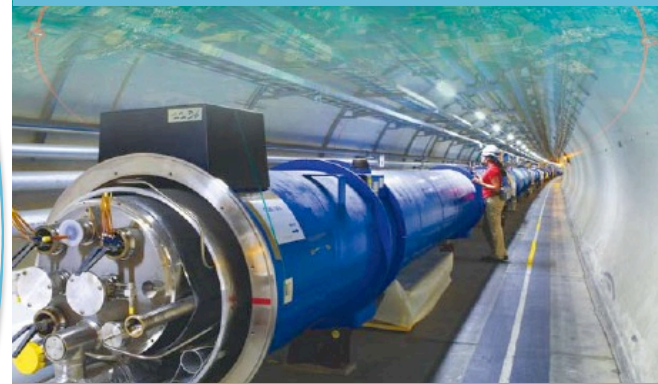
→ Not feasible with Normal conducting magnets

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!!!

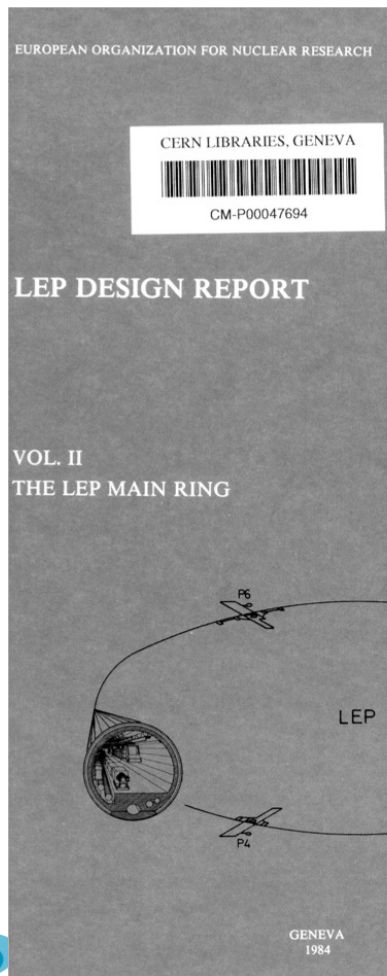


Ca. 30 years machine development!!!

→ Significant Time scale extending well beyond that of a physicist career!!!

LHC: was already planned 1989 to 2000

LEP
Design
Report
1984



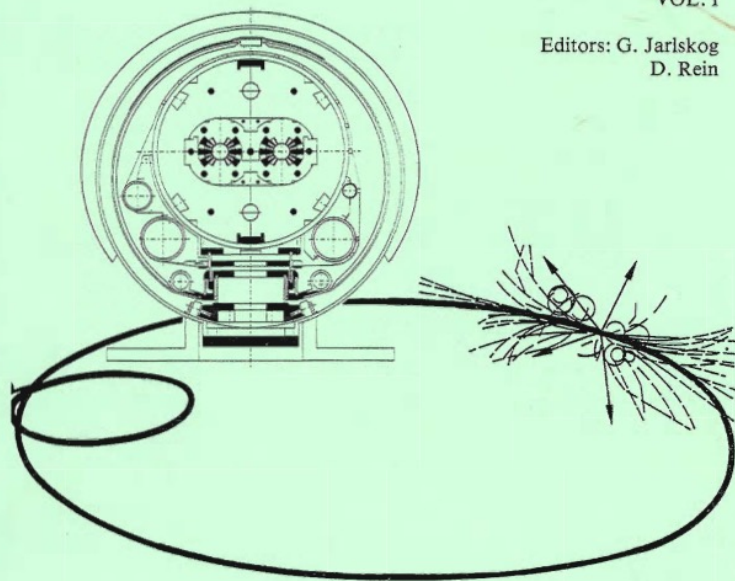
Advanced Accelerator C

EUROPEAN COMMITTEE FOR FUTURE ACCELERATORS

Large Hadron Collider Workshop

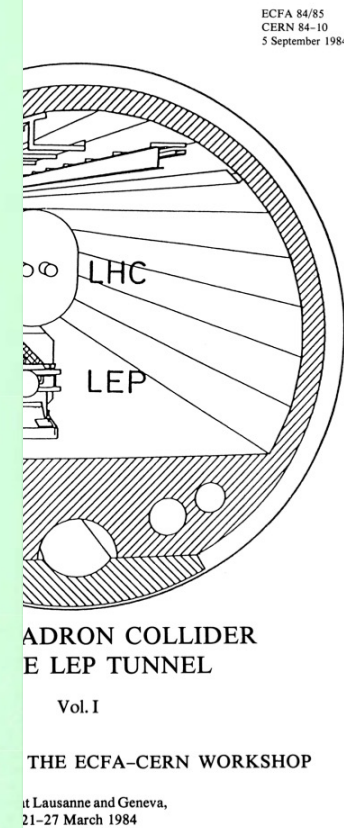
PROCEEDINGS
VOL. I

Editors: G. Jarlskog
D. Rein



Aachen, 4-9 October 1990

Start of LEP



Lausanne
ECFA-CERN
Workshop
1984

Oliver Brüning CERN

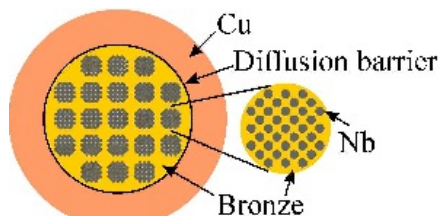
LHC Magnet Technology:
Thousands of fine Nb-Ti filaments well
separated along km of wires
Industrial production via extrusion

Cable of 15 kA!)

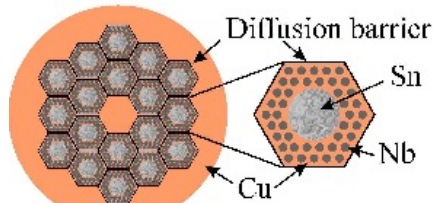
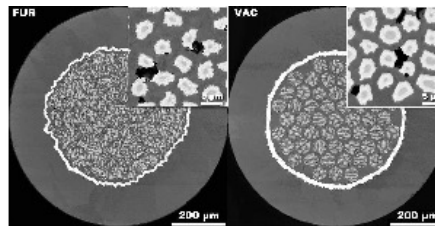
Fine filaments of Nb-Ti in a Cu matrix for an LHC dipole wire)

The Nb₃Sn SC Challenge:

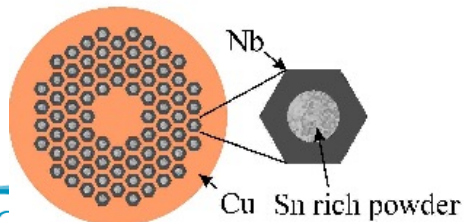
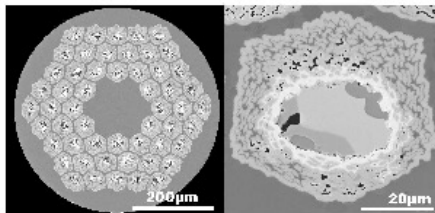
Nb₃Sn is brittle and cannot be drawn in final form – contrary to NbTi
Strand is drawn before cable is formed before the wire is heat-treated to form the Nb₃Sn superconductor!



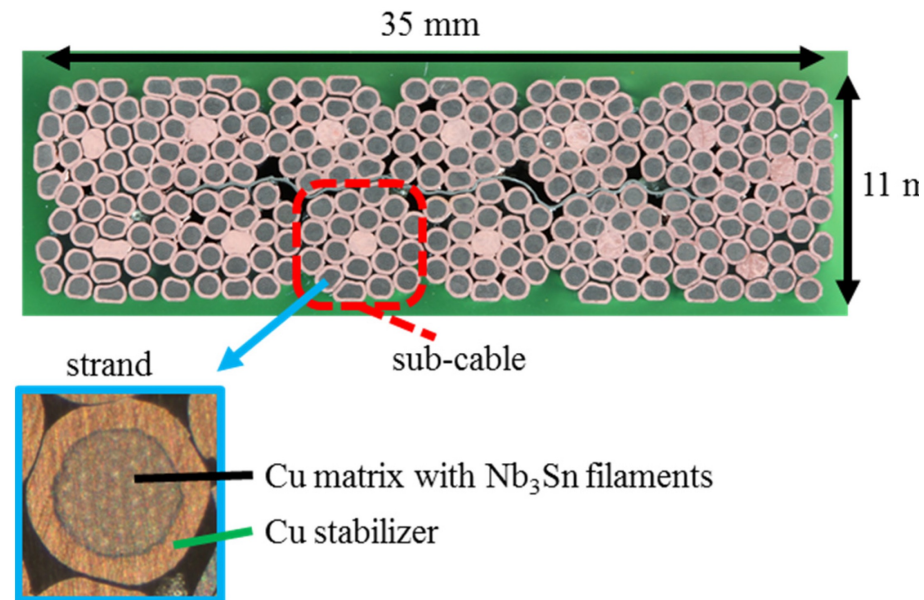
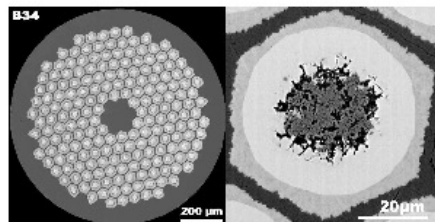
Bronze process



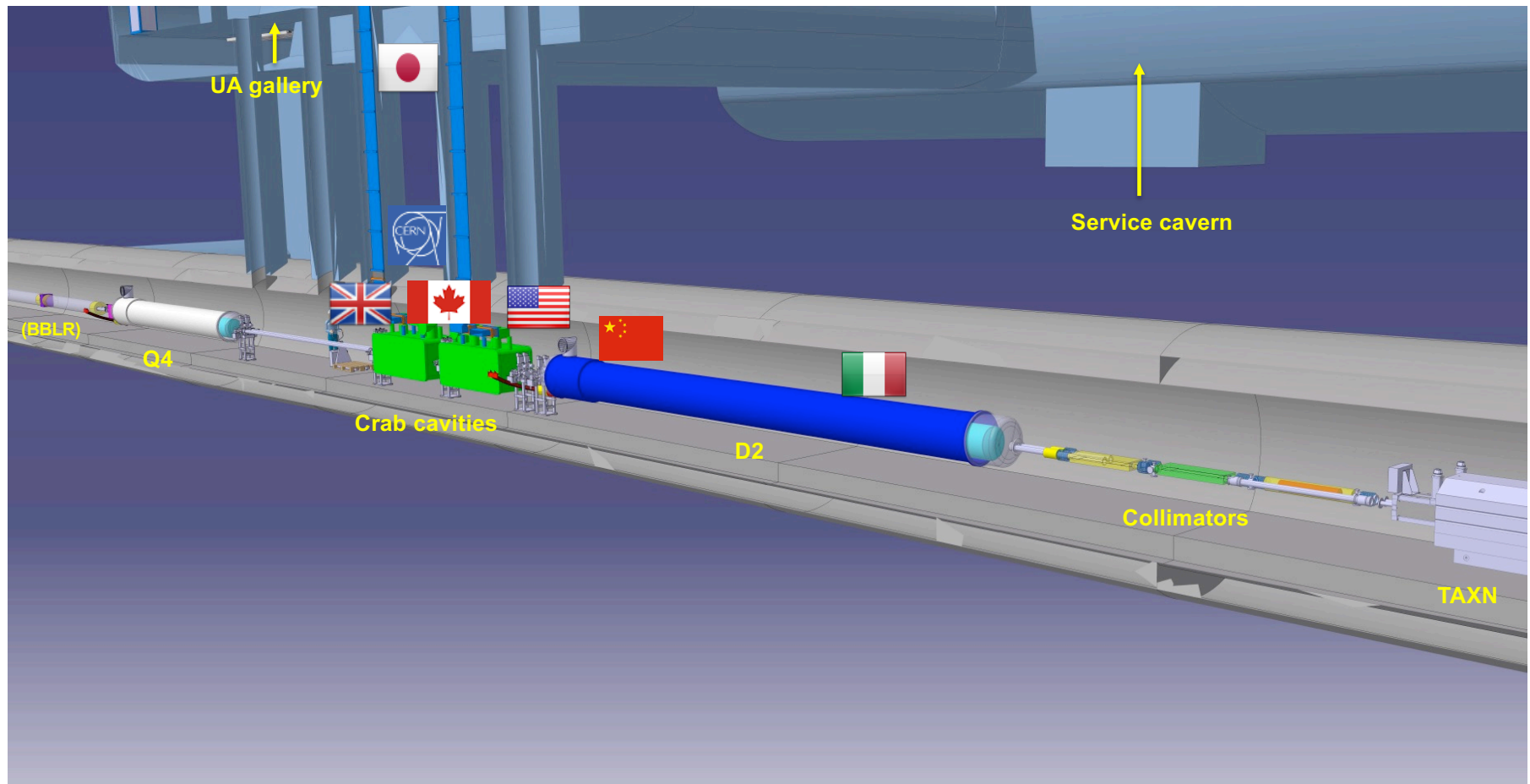
Internal Sn process



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

