HiLumi HL-LHC PROJECT

High-Luminosity LHC project overview and status

Yannis Papaphilippou, CERN

On behalf of the HL-LHC project

Many thanks to

O. Bruning, M. Lamont, R. Tomas and HL-LHC collaborators

for all the material

Corfu2023, Workshop on Future Accelerators – April 24th 2023

Reminder of the HL-LHC Goals

From FP7 HiLumi LHC Design Study application in 2010

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A pea …

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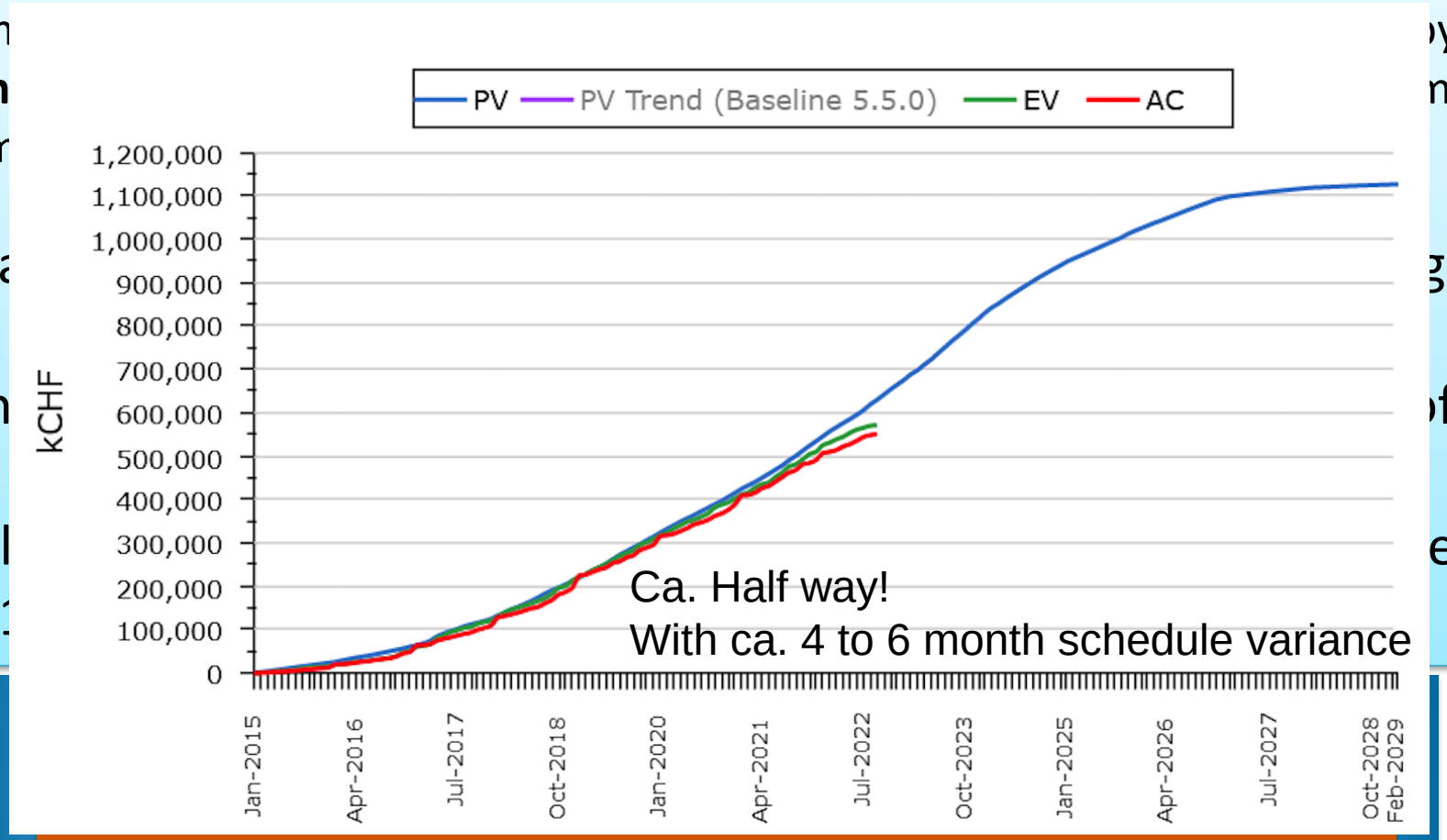
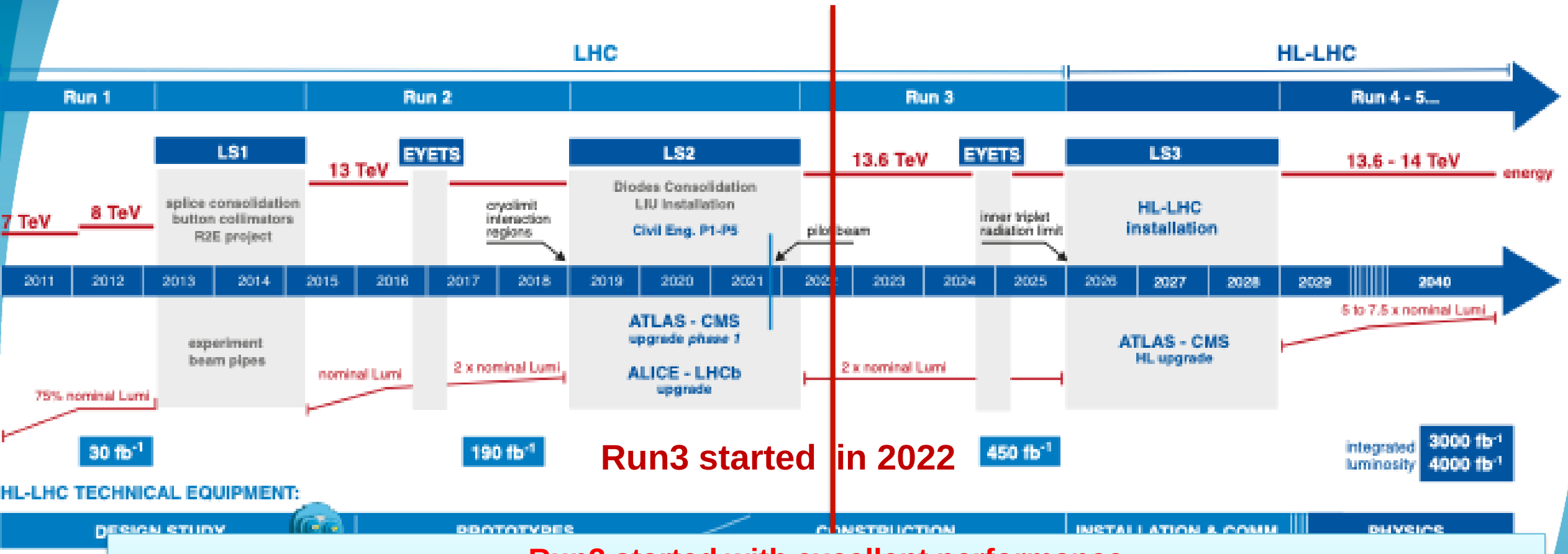


LHC / HL-LHC Plan



Run3 started in 2022

Run3 started with excellent performance

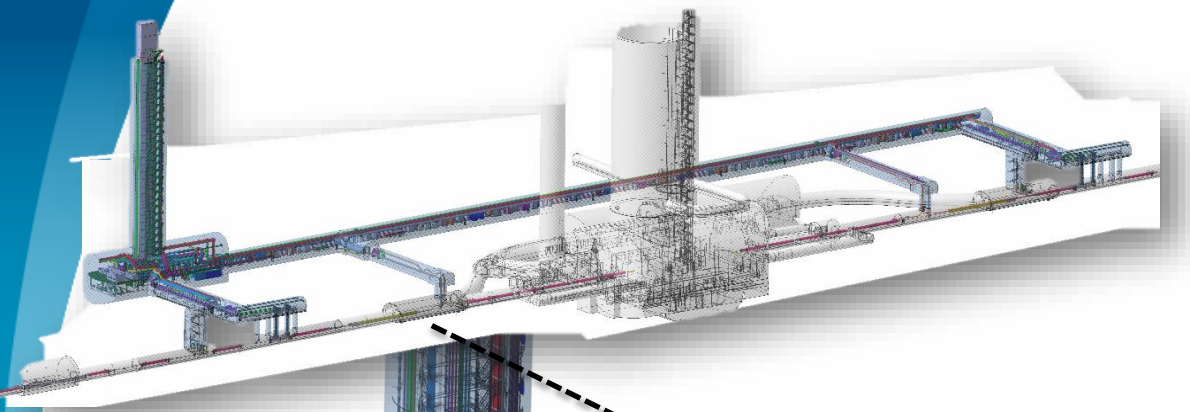
Beam Energy for Run3 fixed @ 6.8 TeV [long training time and need for repairs - RF PIM S23]

LS3 shifted by 1 year and extended to 3 years

➔ HL-LHC keeps the construction schedule unchanged where possible to keep the momentum!

➔ IT String operation still scheduled to start in 2024, but with main operation period in 2025

HL-LHC Scope in 1R and 5R

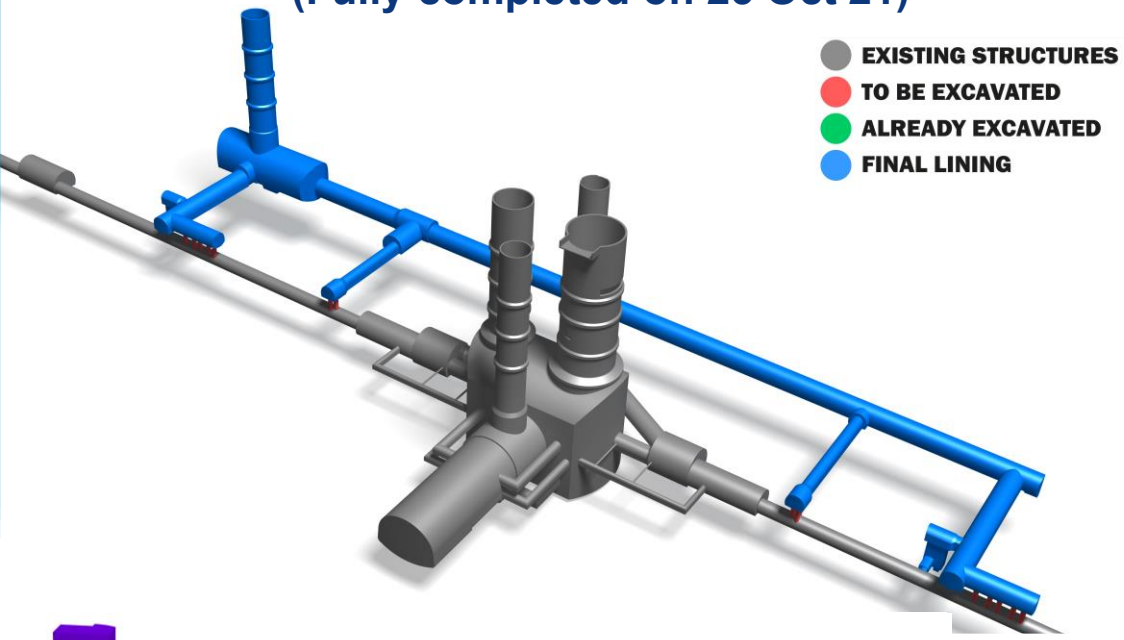


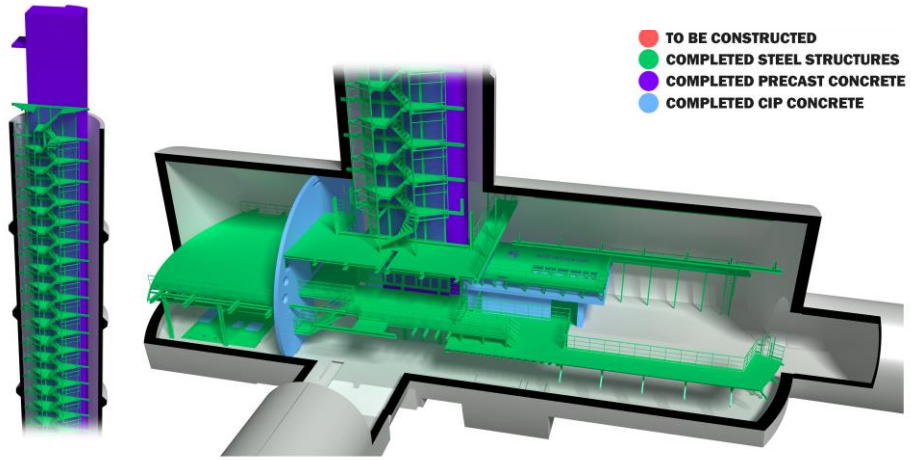
M. Modena and M. Mendes

Underground Civil Engineering Excavation work was completed during LS2!

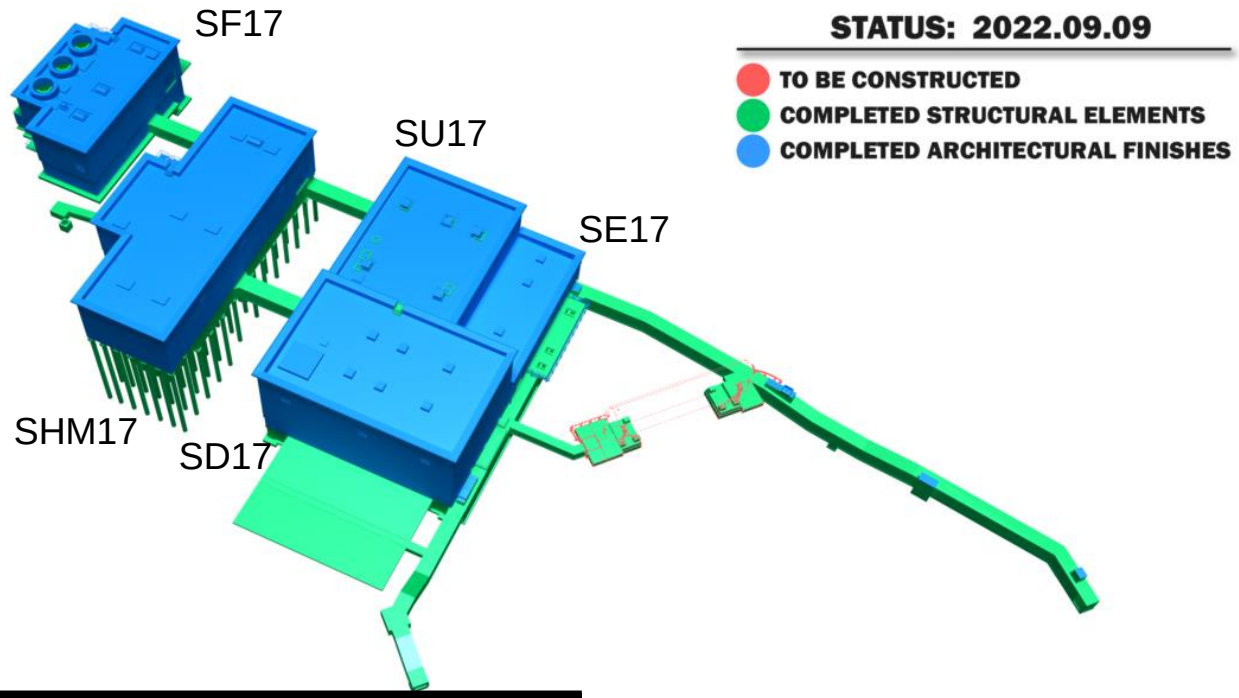
Main civil engineering work at Point 1 (ATLAS)

Underground
(Fully completed on 25 Oct'21)





Surface

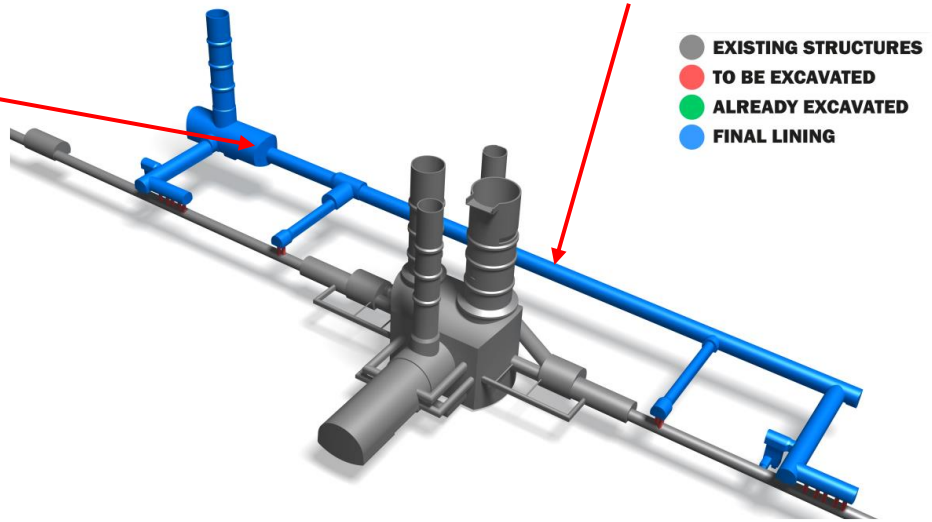


Buildings	Progress [%] / delivery
SF17	100% / delivered
SHM17	100% / delivered
SU17	100% / delivered
SE17	100% / delivered
SD17	100% / delivered
Underground	100% / delivered

Fully completed and delivered by Sep'22 (+ ~1 months w/r to the initial contractual date)

Pieter Mattelaer and Laurent Tavian

Main civil engineering work at Point 1 (ATLAS)



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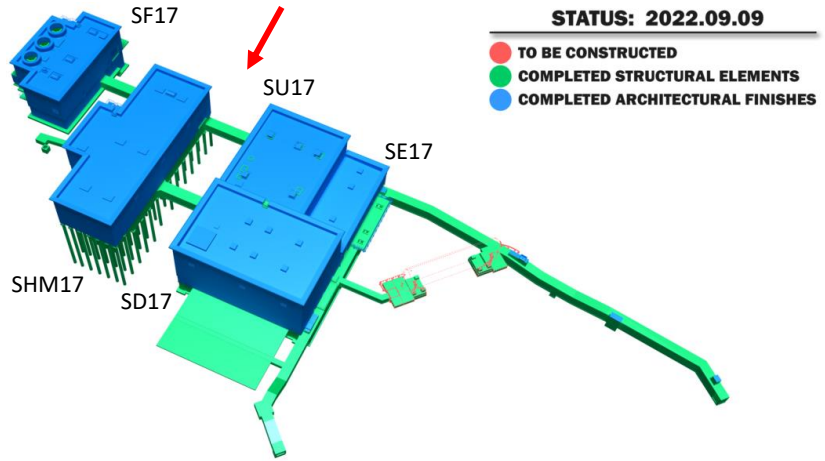
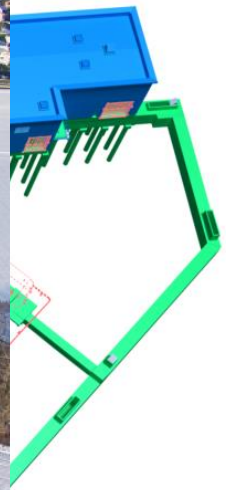


Pieter Mattelaer and
Laurent Tavian

Main civil engineering work at Point 5 (CMS)

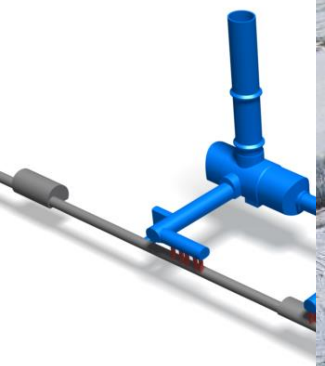
(fully

SHM57



STATUS: 2022.09.09

BE CONSTRUCTED
MPLETED STRUCTURAL ELEMENTS
MPLETED ARCHITECTURAL FINISHES

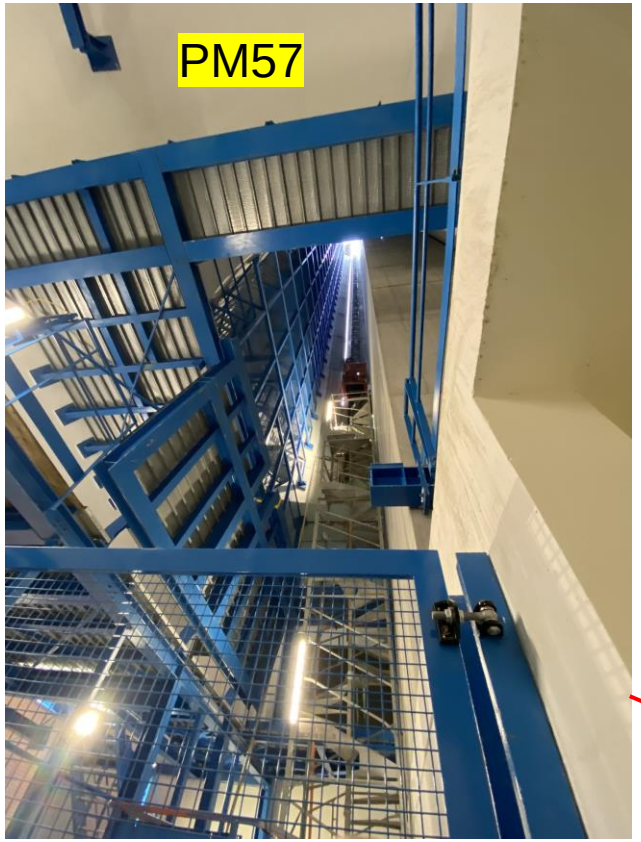


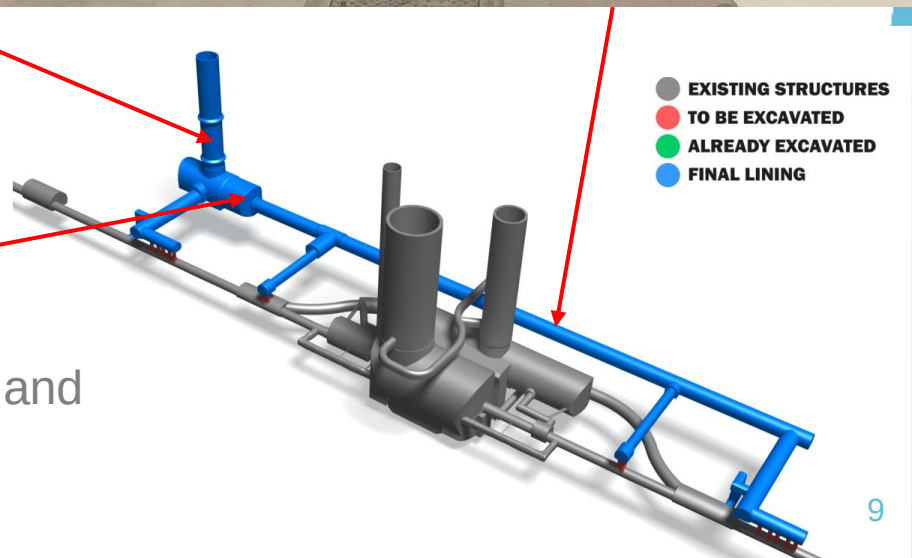
pleted and
by Dec'22 (+ ~2
/r to the initial
al date)

ttelaer and
Laurent Tavian

SD57	100% / delivered
Underground	100% / delivered

Main civil engineering work at Point 5 (CMS)



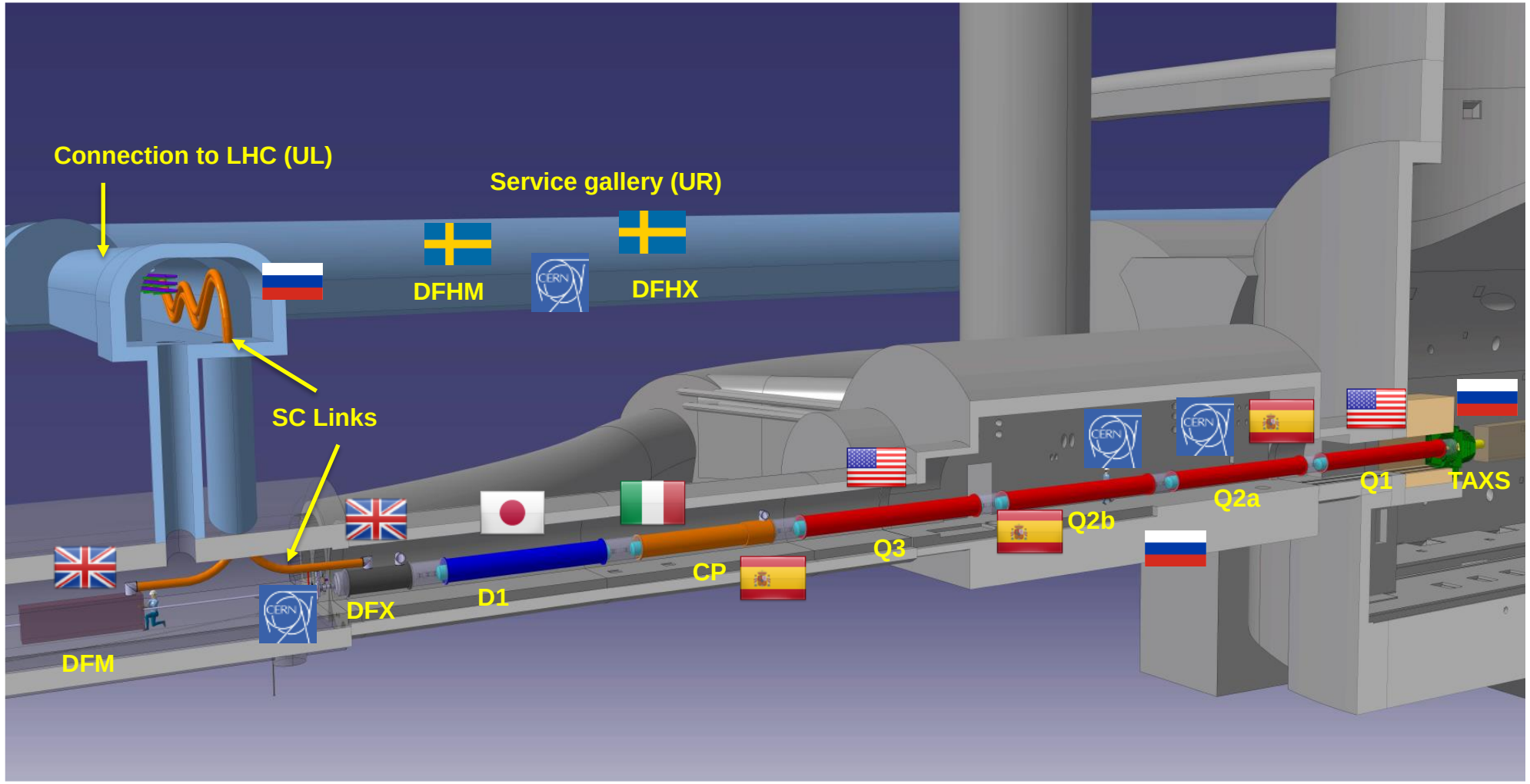


Pieter Mattelaer and
Laurent Tavian

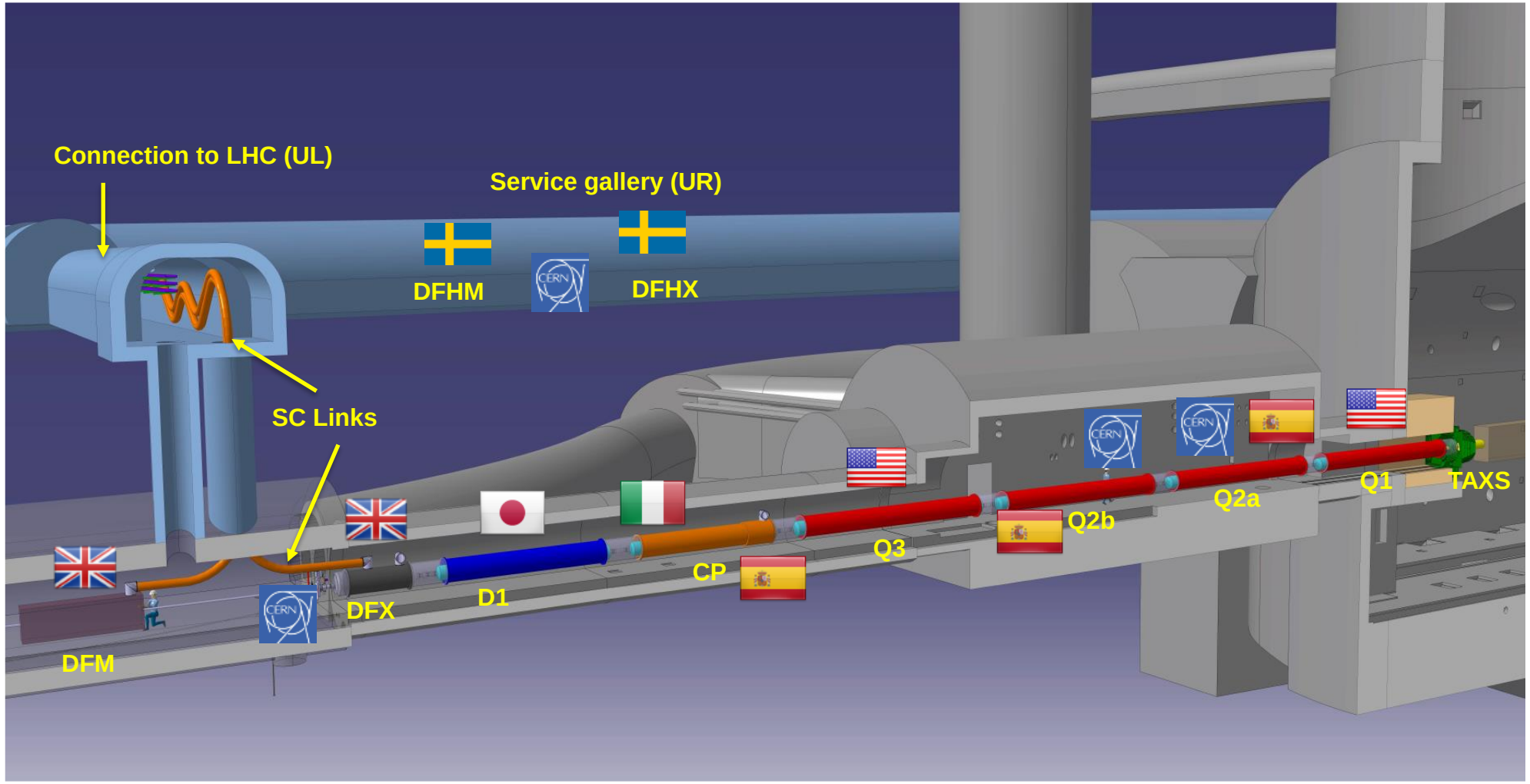
Technical infrastructures in the delivered buildings

- Sectional doors
- Cranes
- Cable trays
- Lighting
- Ventilation system
- Primary water system

International Collaboration

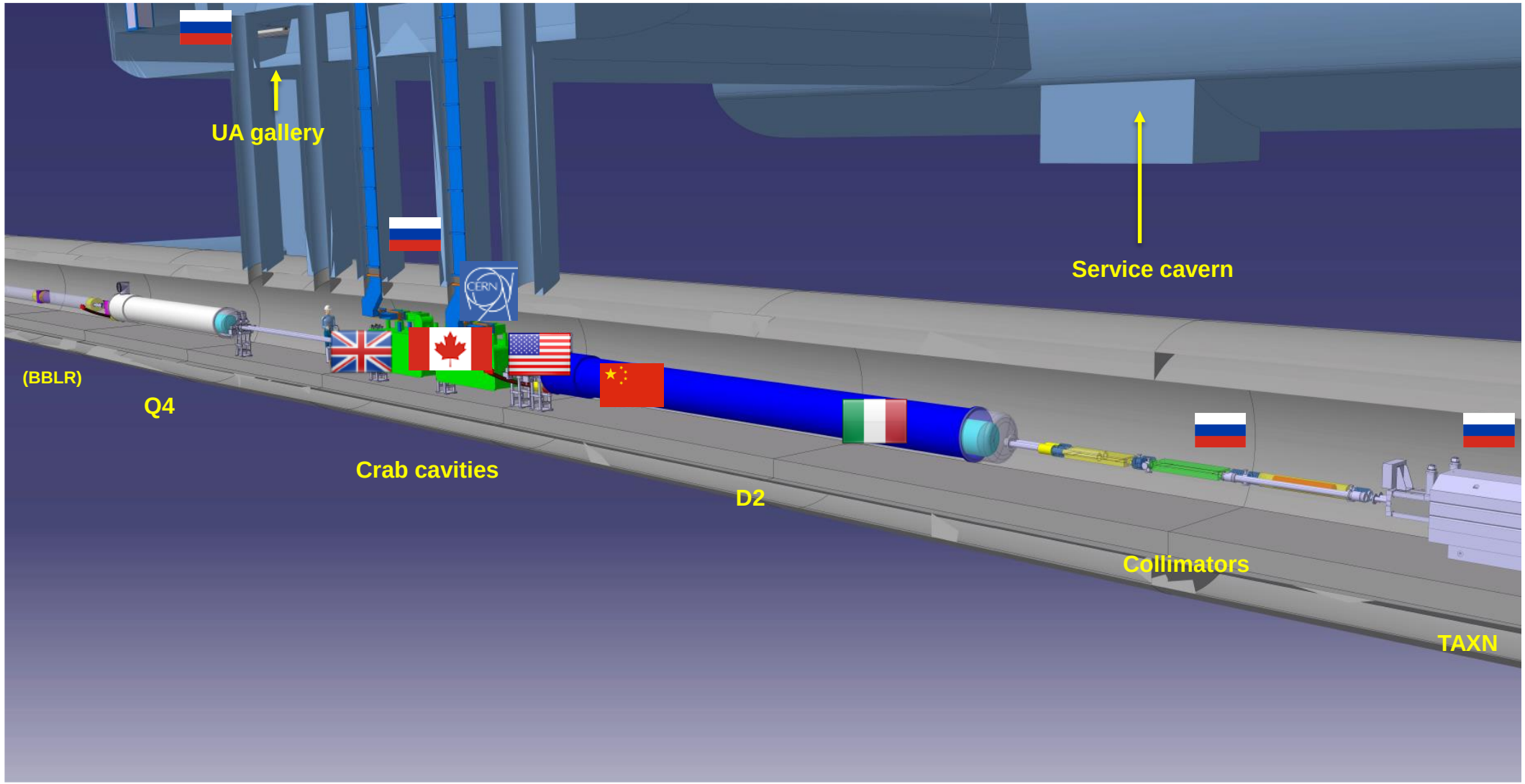


International Collaboration



Cancellation of several Contracts with Russia due to accumulated delays ➔ Plan B implementations

The MS region with in-kind contributions



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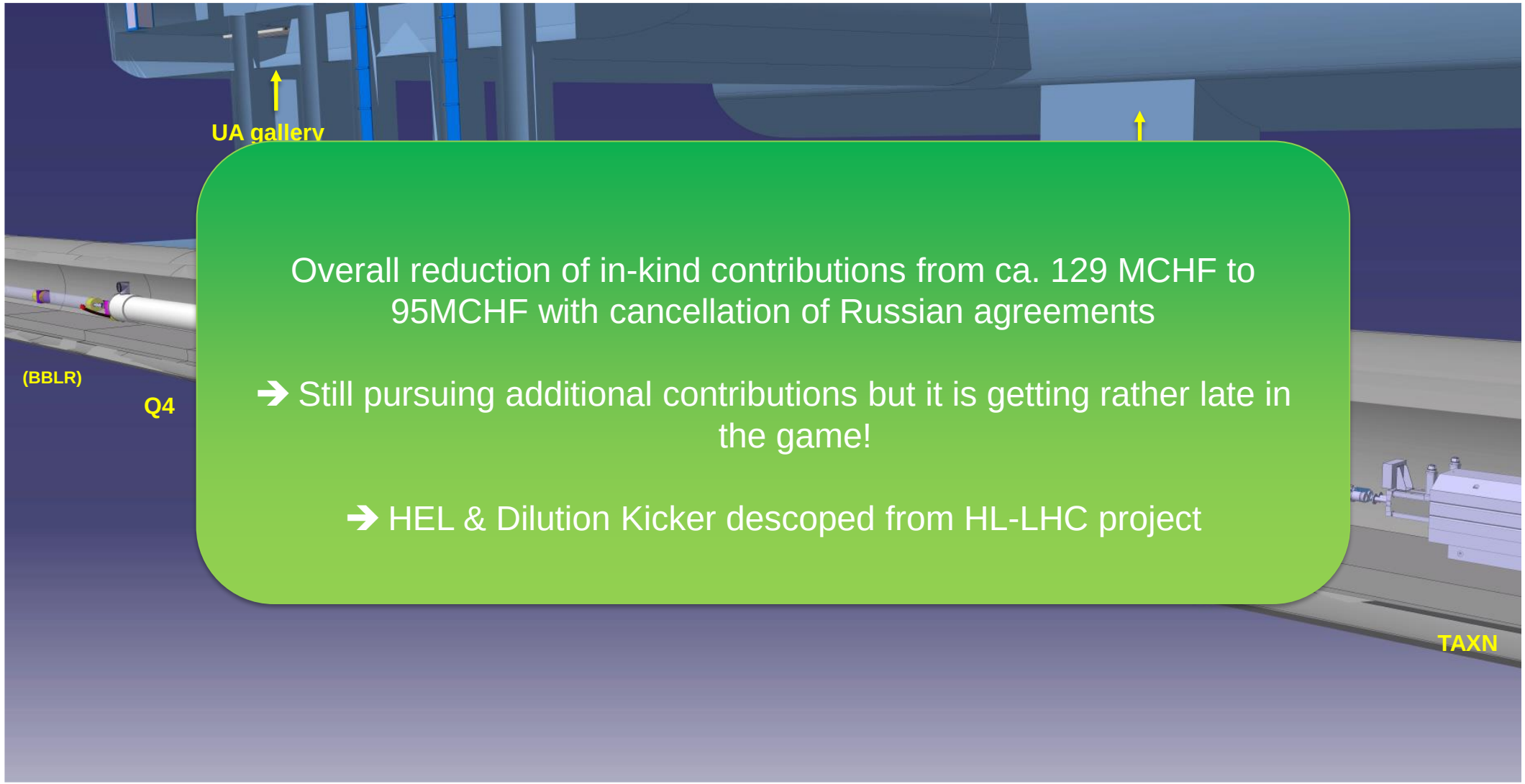


Overall reduction of in-kind contributions from ca. 129 MCHF to 95MCHF with cancellation of Russian agreements

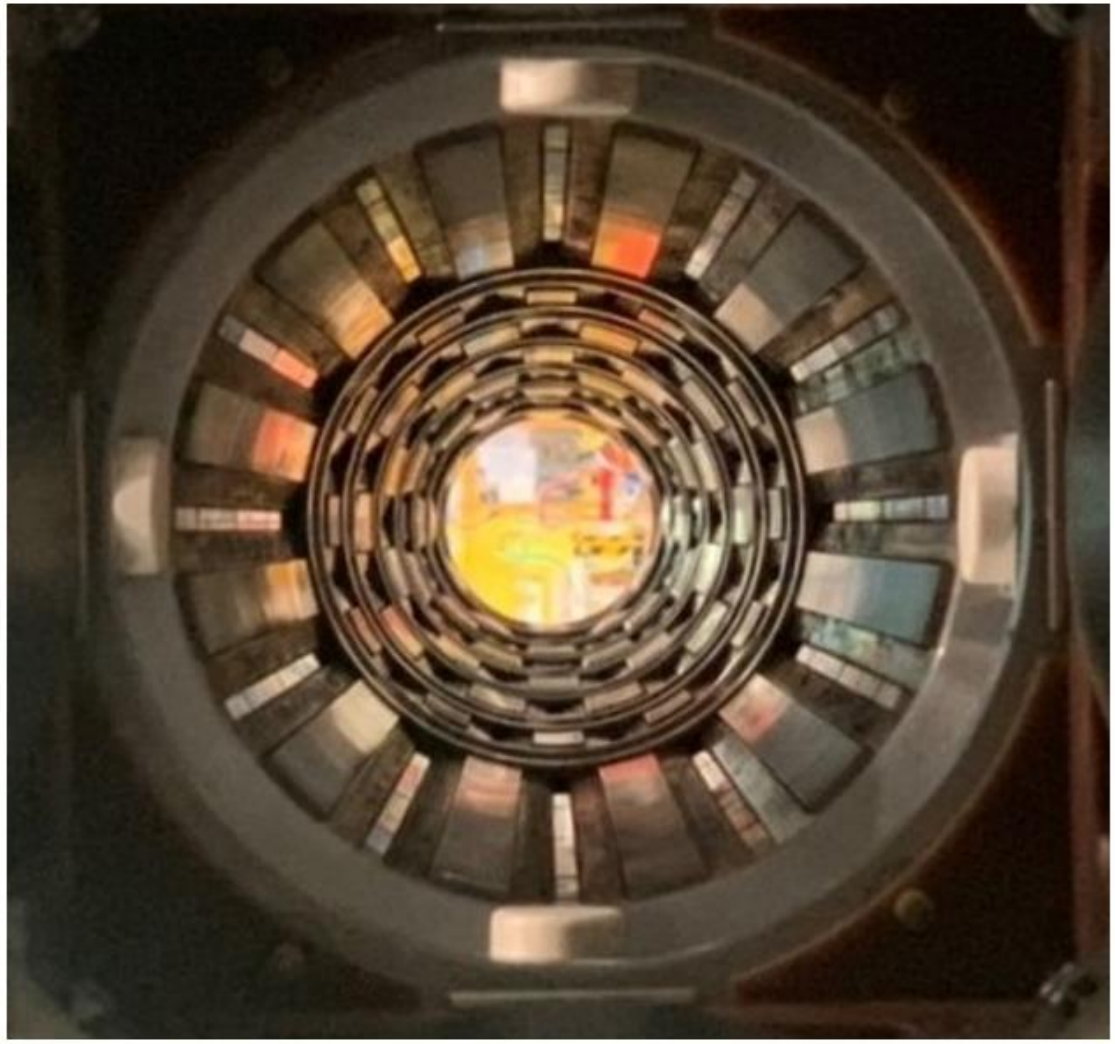
➔ Still pursuing additional contributions but it is getting rather late in the game!

➔ HEL & Dilution Kicker descoped from HL-LHC project

Cancellation of several Contracts with Russia due to accumulated delays ➔ Plan B implementations

Timeline: Main Milestones in 2021

- November 2021: HO corrector manufacturing finished and assembly started ✓

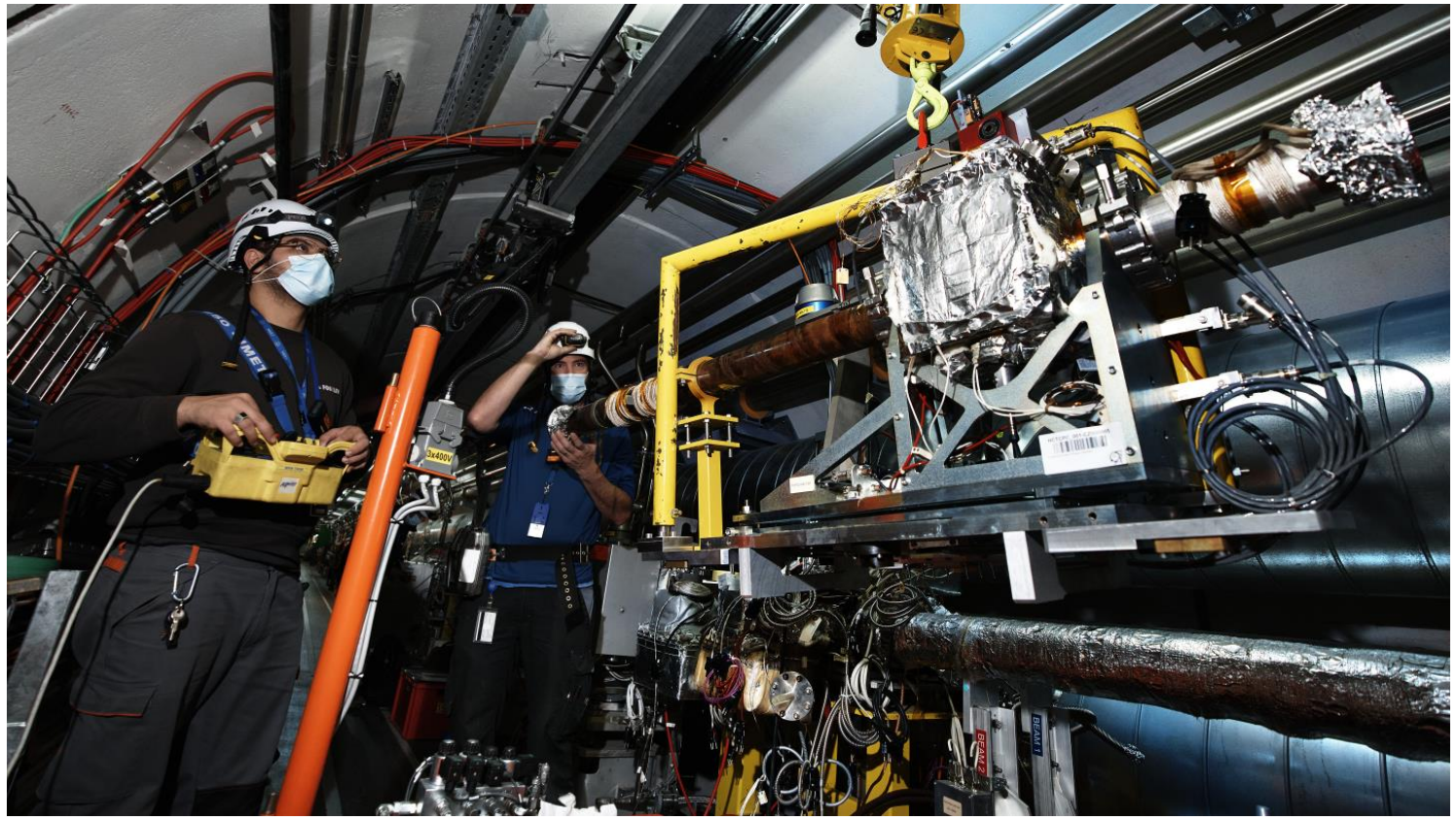


Sequence of higher order corrector magnets and preassembled cold mass of the Corrector Package [CP]

Timeline: Main Milestones in 2021

Stefano Redaelli et al.

- November 2021: HO corrector manufacturing and assembly completed ✓
- November 2021: Shipment of second RFD cavity from CERN to the UK ✓
- November 2021: CERN C&SR #5 ➔ endorsement of presented budget update
  +14.2MCHF CtC increase & [30MCHF to 60MCHF exposure warning] ✓
- November 2021: Installation of two Goniometers with Crystal Collimators in the LHC ✓

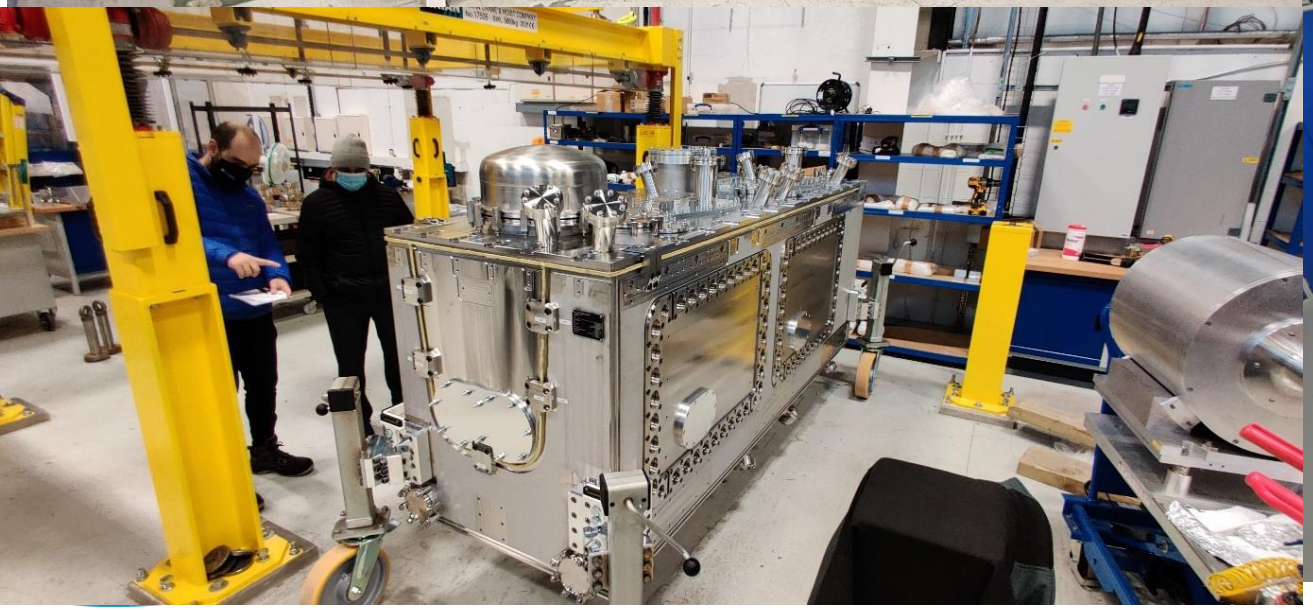


Update on RFD Cryo-Module

RFD Cavity in Transport Frame on arrival at Daresbury Laboratory

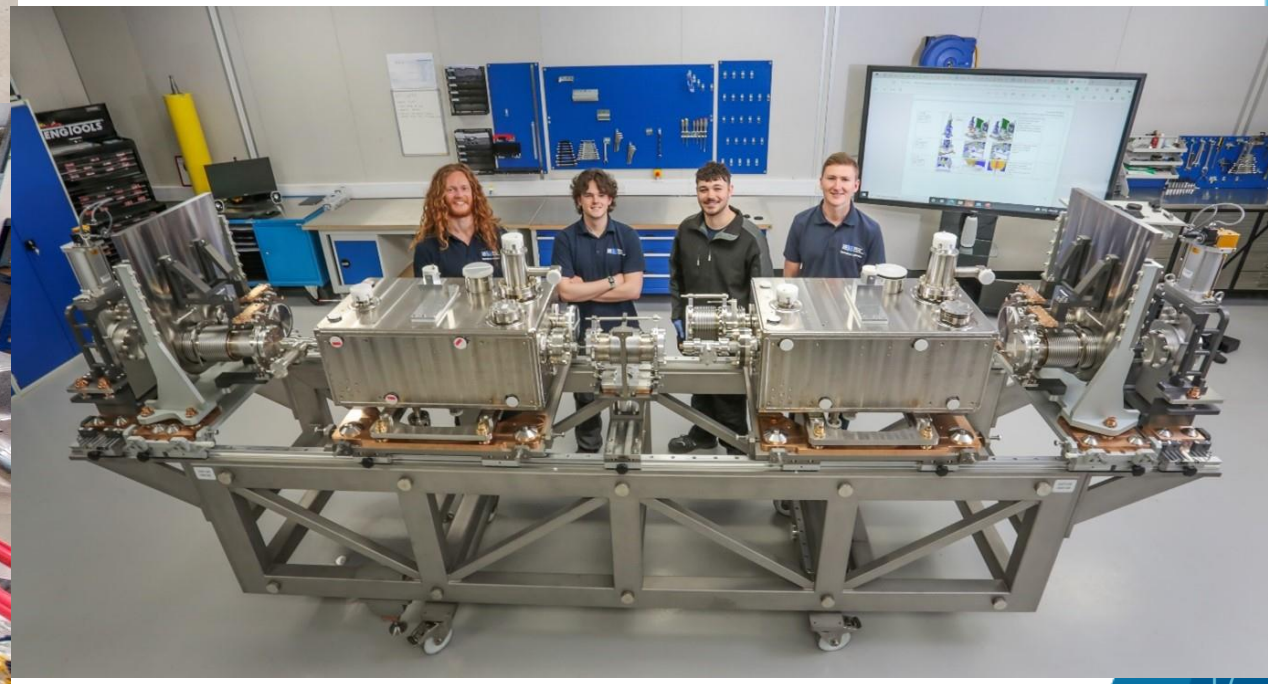
Cryo-Module on critical path for SPS installation during YETS 2022/23!

➔ *Decision to delay installation until 2023/24*



Outer vacuum Chamber

Cavity String prior to Cleanroom assembly

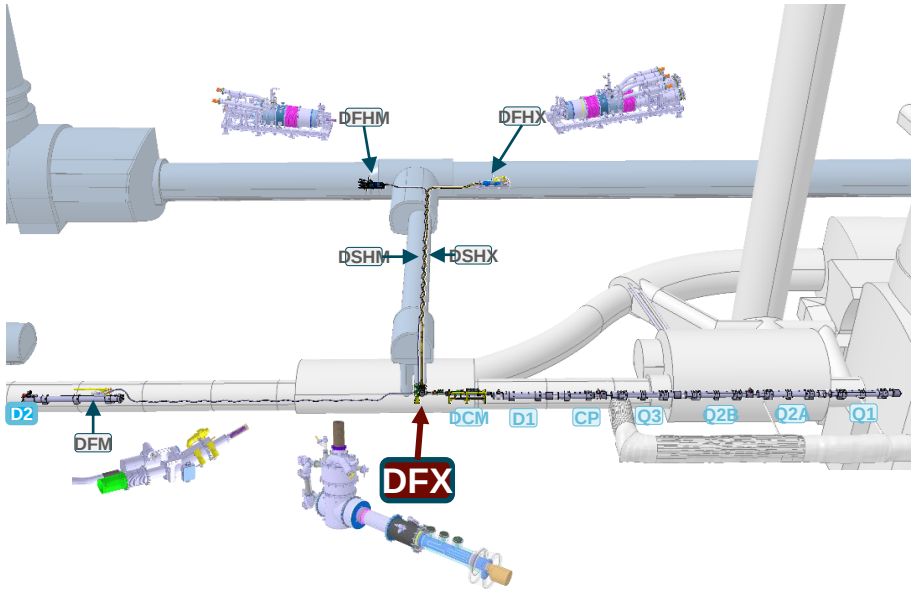


Timeline: Main Milestones in 2022

- January 2022: MQXFA08 fails to reach nominal current in vertical test [after performance limitation of MQXFA07 in September 2021] ➔ coil manufacturing review [both magnet coils were produced during COVID years] ✓
- February 2022: full validation of DQW pre-series bare cavity build in industry ✓
- February 2022: Critical non-conformity of MQXFA09 ➔ requiring disassembly ✓
- **March 2022: DFX Cryostat delivery to 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**

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- **March 2022: Cold-Mass assembly of D2 and nested Canted Cosine Theta corrector magnet** ✓
- **May 2022: Endurance Test on MQXFA05: 50 quenches, 5 TC ➔ magnet remains @ nominal!** ✓
- **May 2022: Test of MCBXFBP2c at CERN in SM18 ➔ reached full operation range at 7.5TeV equivalent current!** ✓

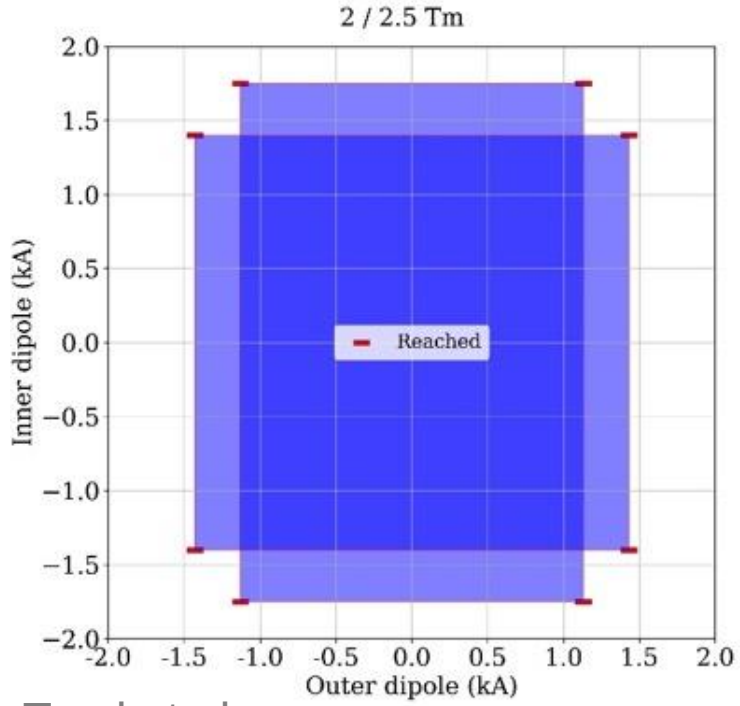
D2 Cold-Mass Assembly

D2 Prototype Col

D2 Prototype on the test bench in SM18

MCBXFBP2c: Cold Powering tests results

Design iteration on length of the inner coil produces successful performance increase!



Fernando Toral et al.

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

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MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD

HiLumi HL-LHC PROJECT

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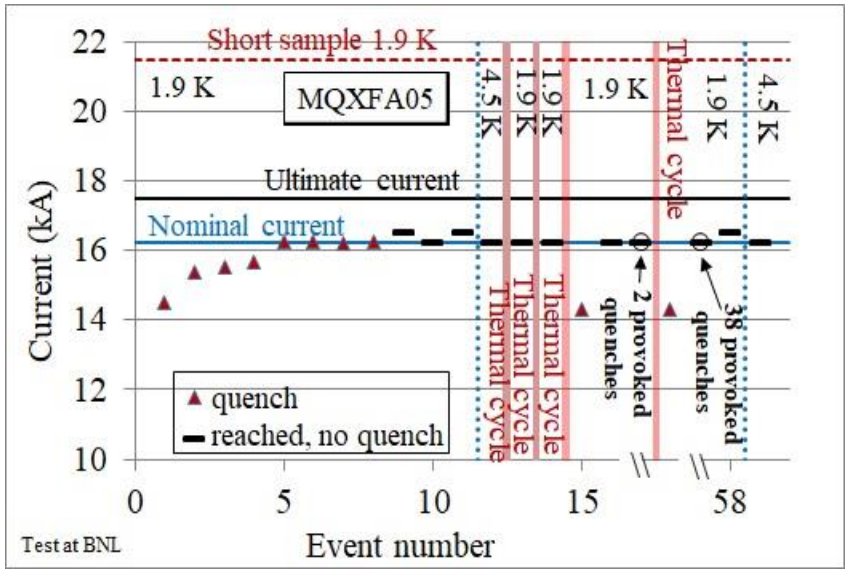
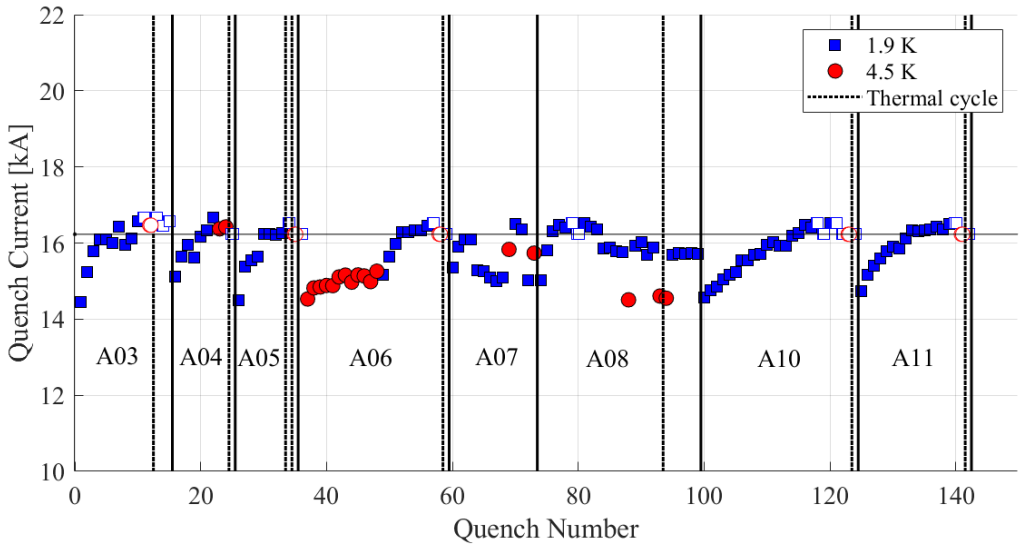
- May 2022: PRR of US Crab Cavity Ancillaries production [HOM and pickup field antennas] ✓
- June 2022: Finance Committee approval of Industrial contract for IP1 and IP5 refrigerators
  ca. +30MCHF CtC ➔ [C-MAC!] ✓
- **July 2022: Successful vertical test of MQXFA10** ✓
- **August 2022: Cryostating of MQXFA03 and MQXFA04 started following a review of the pressure vessel requirements and specifications**

HL magnet production and test status - MQXFA

- AUP is close to 50% MQXFA magnet fabrication
- 6 magnets (out of 8 magnets tested) are accepted and reached I_{nom} + 300 A at 1.9 K,
- No cold mass tested until now, first planned in spring 2023 second in second half of 2023.
- MQXFA05 demonstrated endurance, MQXFA11 resilience

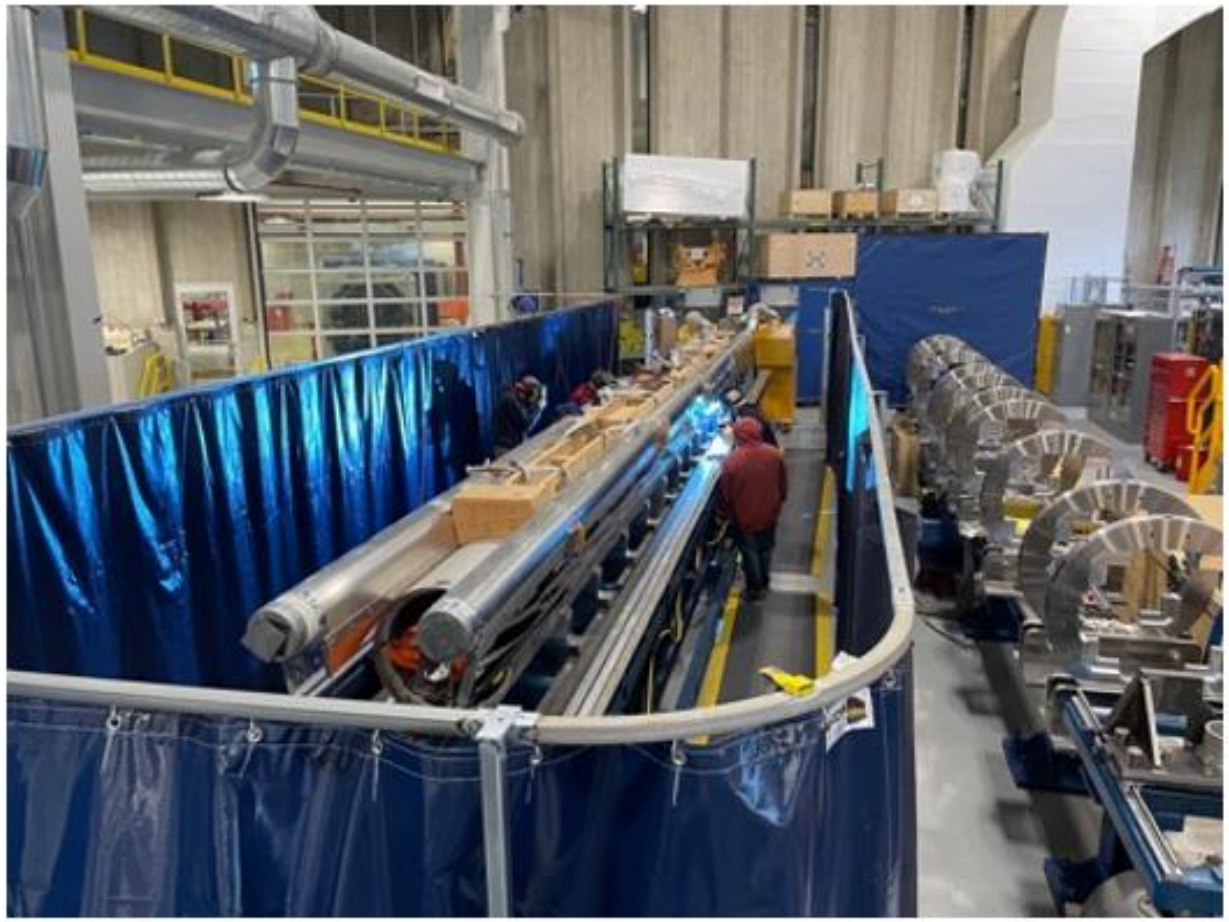




Powering test of conform MQXFA magnets (J. Muratore, B. Ahia, S. Feher et al.)

Update on MQXFA Cryo-Module Assembly

Fitting of bottom SS shell and longitudinal welding

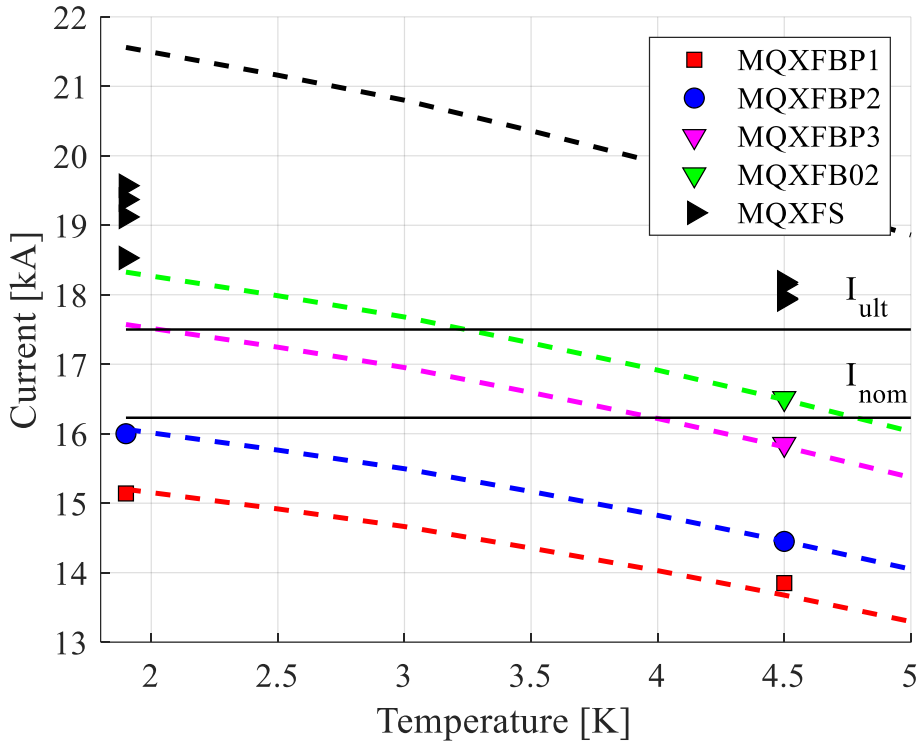


Update on MQXFA Cryo-Module Assembly

Integration of the Cold-Mass components and installation of end plates and pipes Giorgio Apolinari

HL magnet production and test status - MQXFB

- MQXFBP1 and BP2 were limited at 93% and 98% of the nominal current at 1.9 K, 20 A/s ramp.
- Destructive inspections of the coils show a systematic degradation of the conductor in the transitions between poles.
- Possible root causes have been identified and are being addressed:
  - *Cold mass assembly*: new welding procedure implemented in MQXFBP3
  - *Magnet assembly*: improved assembly procedure implemented in MQXFB02
  - *Coil fabrication:* the fabrication of transition coils is ongoing, with a focus on the operations between coil reaction and impregnation.
    -> MQXFB03

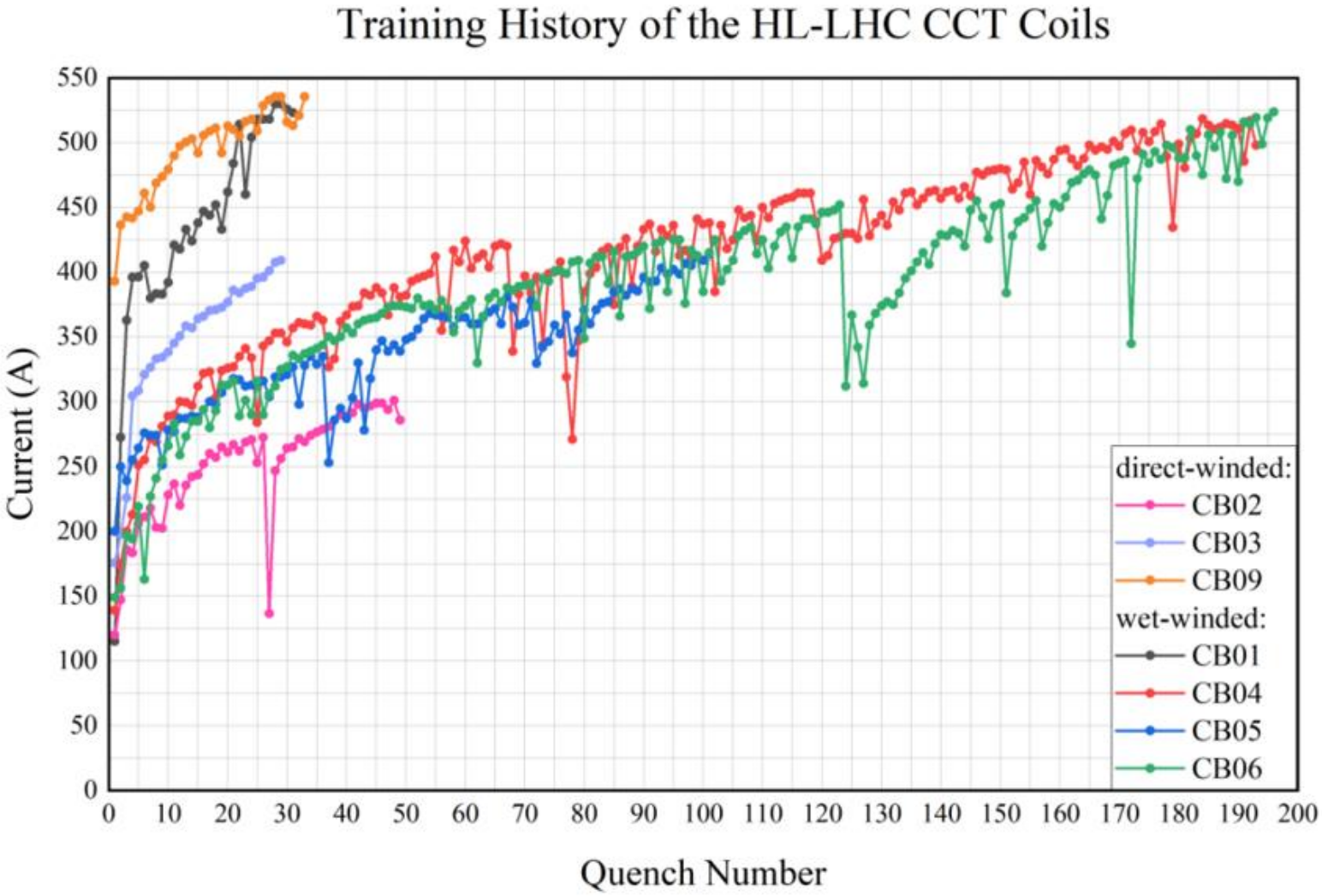


2 MQXFB magnets have successfully passed the acceptance criteria! Limitations at 4.5 K are compatible with operation at ultimate energy with 1.9 K cooling. Both magnets went through several thermal cycles without showing degradation!

Timeline: Main Milestones in 2022

- **July 2022: Canted Cosine Theta Corrector production at BAMA in China ➔ Iteration on former grooves and assembly and impregnation procedure: CB09 and CB12 train faster ✓**

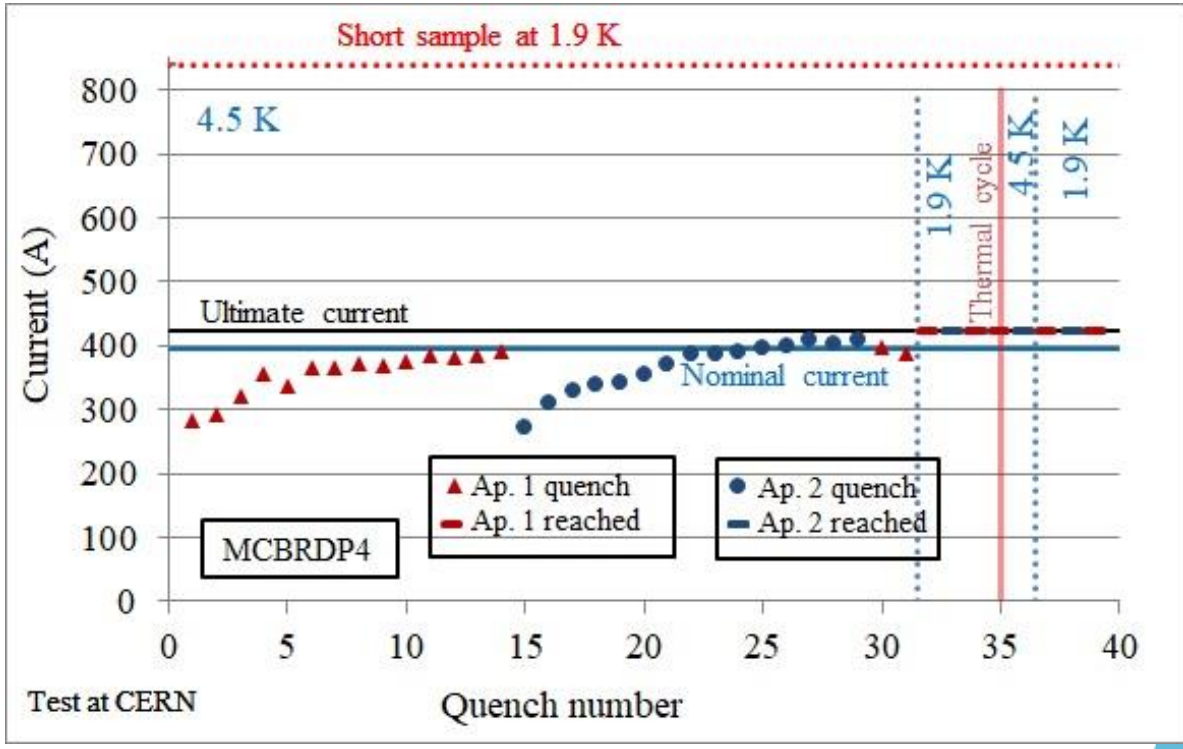
CERN Magnet MCBRDP4 also performs well!



Quingjin et al.

Timeline: Main Milestones in 2022

- End Summer 2022: cold test of 4th CERN MCBRD prototype [D2 corrector]



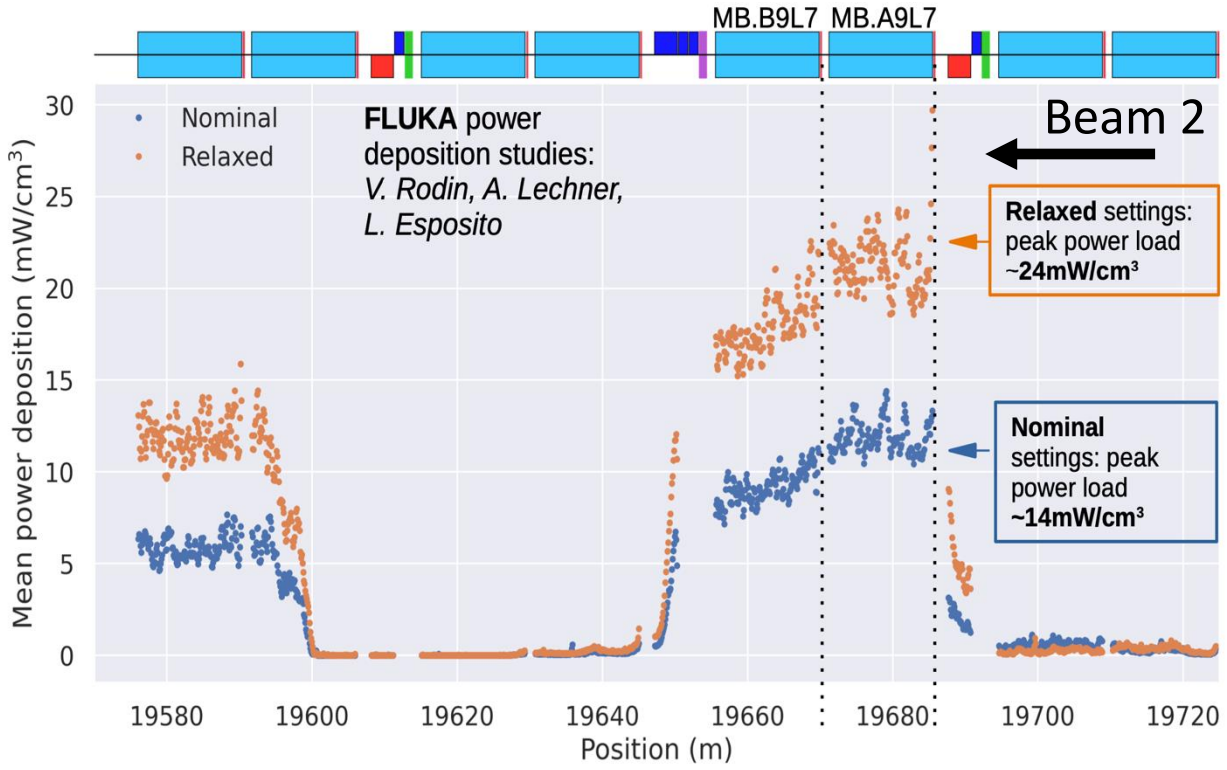
- End Summer 2022: Cold test D2 Cryostat in SM18 now reached ultimate current
- End Summer 2022: cold test of first completed LQXFA cryostat & FNAL, pending assessment of welding issues
- Fall 2022: delivery of D1 Prototype to CERN
- Fall 2022: Cold test of MQXFB02 in SM18 [still using coils from 2020!]
- Fall 2022: Completion of HL-LHC Civil Engineering work
- YETS 2022 / 2023: completion of the Crystal Collimator installation in the LHC

HL-LHC performance in absence of 11T Magnet

- Proton quench test at 6.8 TeV achieved peak losses in the DS dipoles of 15.7-17.0 mW/cm^3 with no quench, to be compared to the 15 mW/cm^3 expected at the HL-LHC at 7 TeV

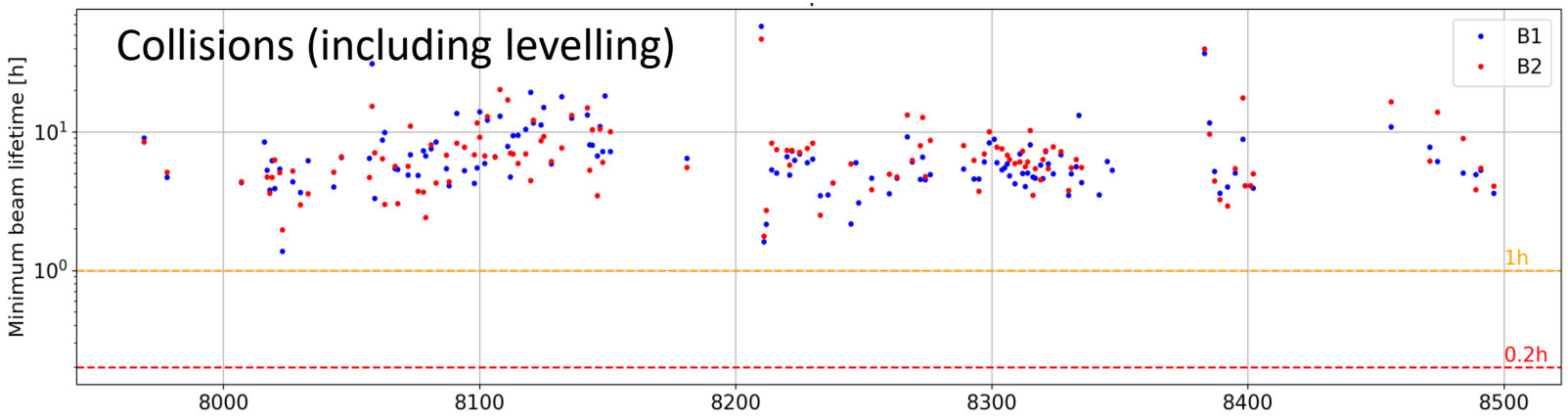
- Confident that there is no need for collimation cleaning upgrade of the present system for HL-LHC, as this translates (for p) to some 30% margin on the HL-LHC design goal

Simulated peak power in coil for different settings

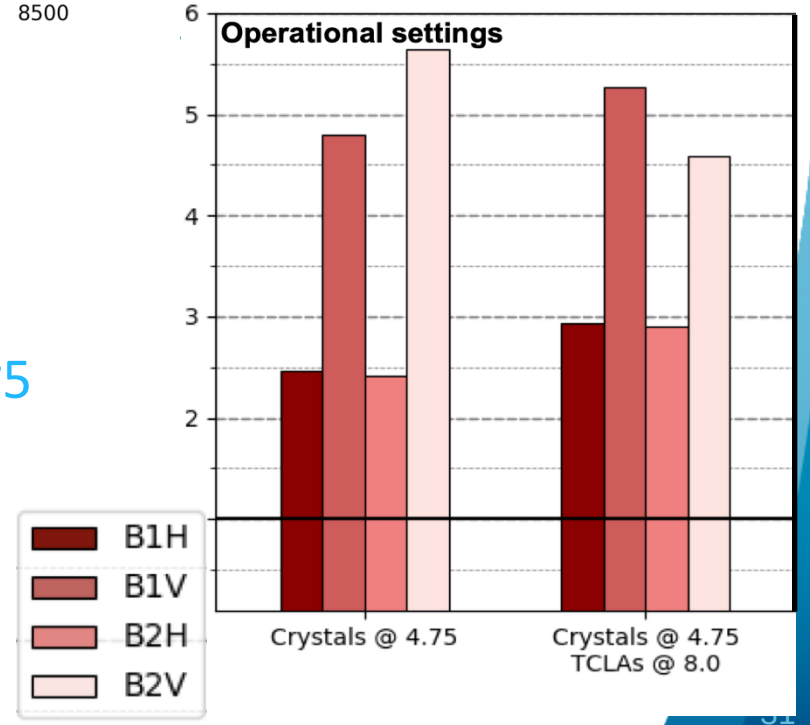


HL-LHC performance in absence of 11T Magnet

- Beam lifetime in 2022 consistently (well) above 0.2h

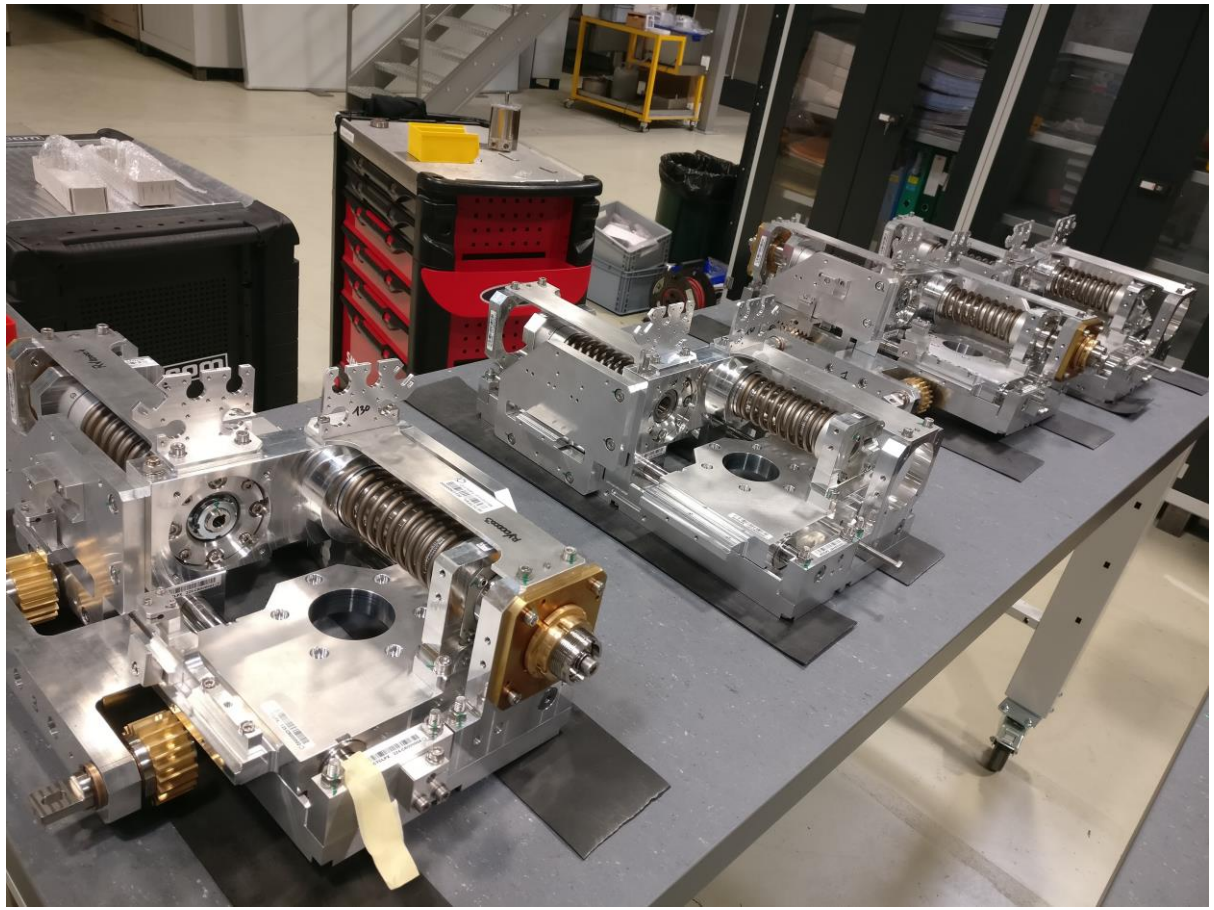


- Crystal collimation adopted in baseline for ion operation
  - Channelling conditions efficiently re-establish also with ion beams both at injection and 6.8 Z TeV!
  - New crystals at 6.8 Z TeV give an improvement by a factor ~5 for the planned operational settings (vertical)
  - H crystals perform less well than in 2018, have now also been replaced in YETS 22/23

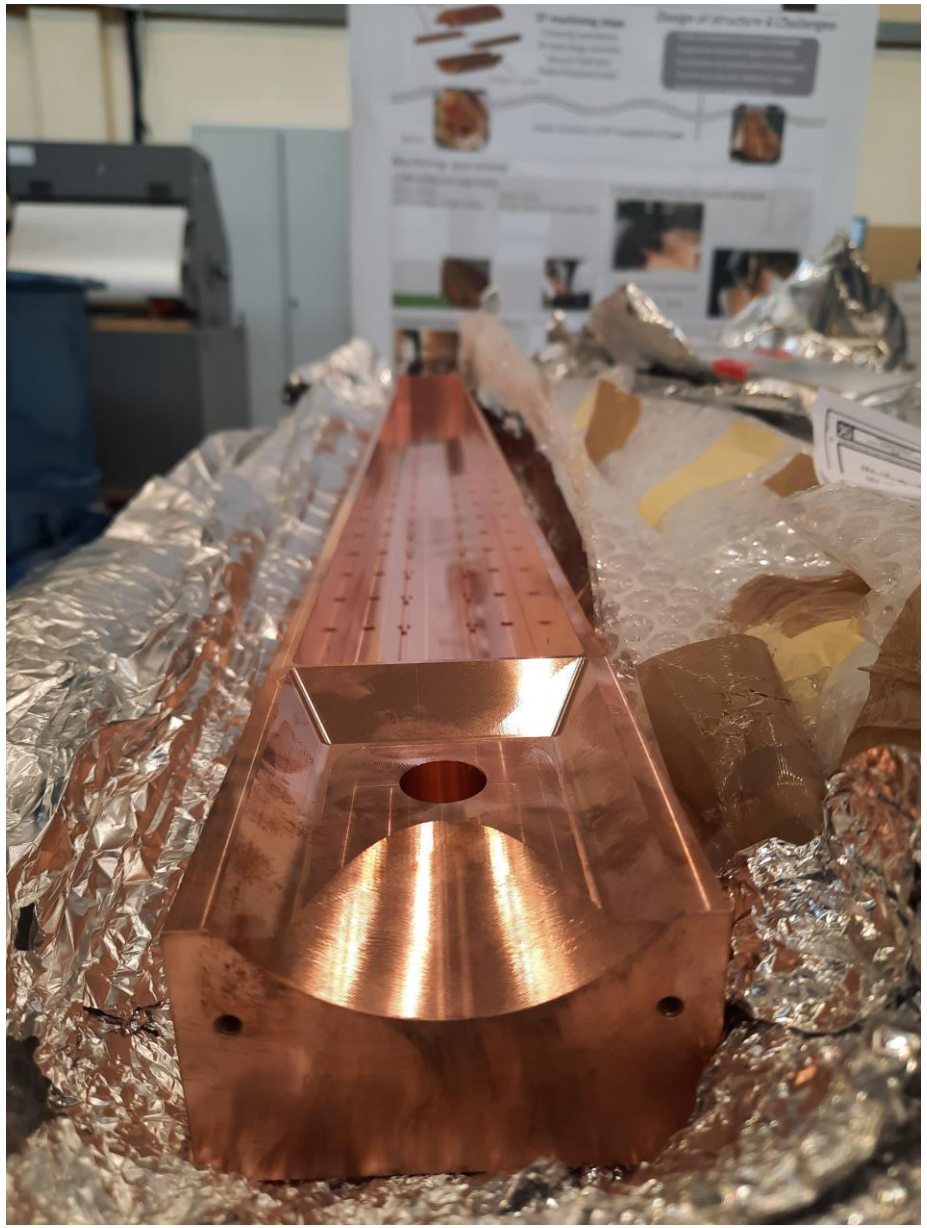


Timeline: Main Milestones in 2022

- Triplet Collimator Prototypes
  TCTCPXH / TCLPX by Fall 2022



Collimator actuation system

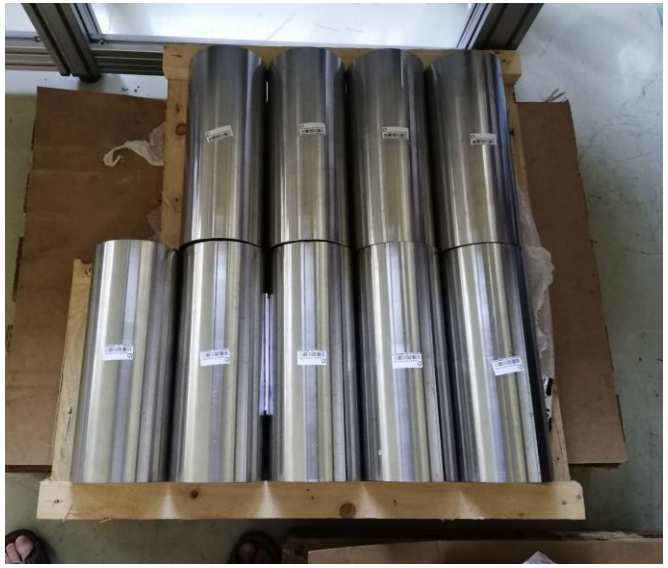


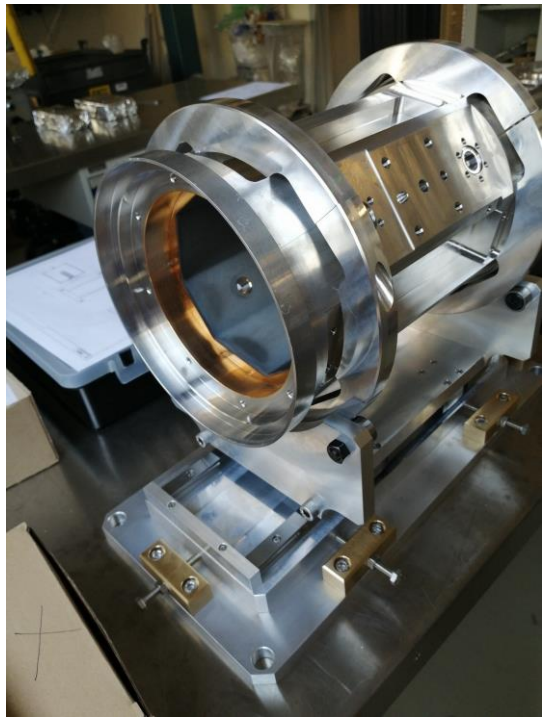
Collimator structural jaw

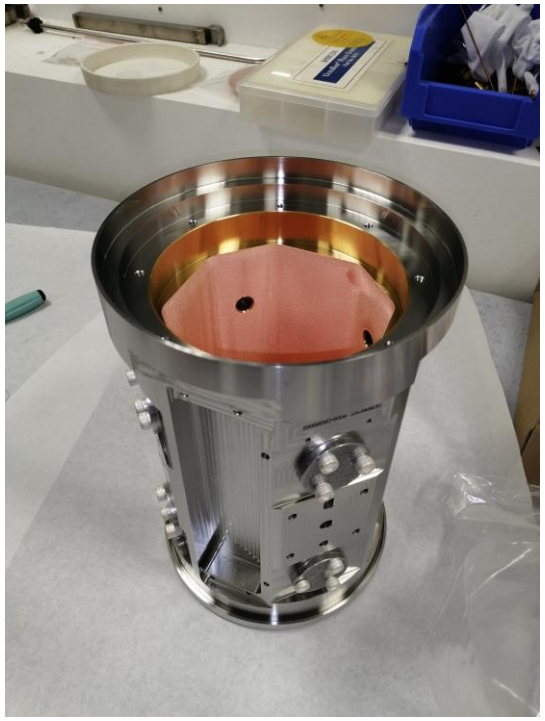
Timeline: Main Milestones in 2022

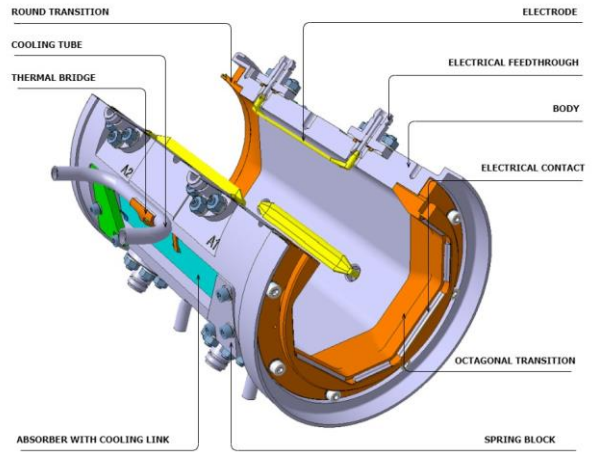
- BPMs:

Series production to start in October 2022





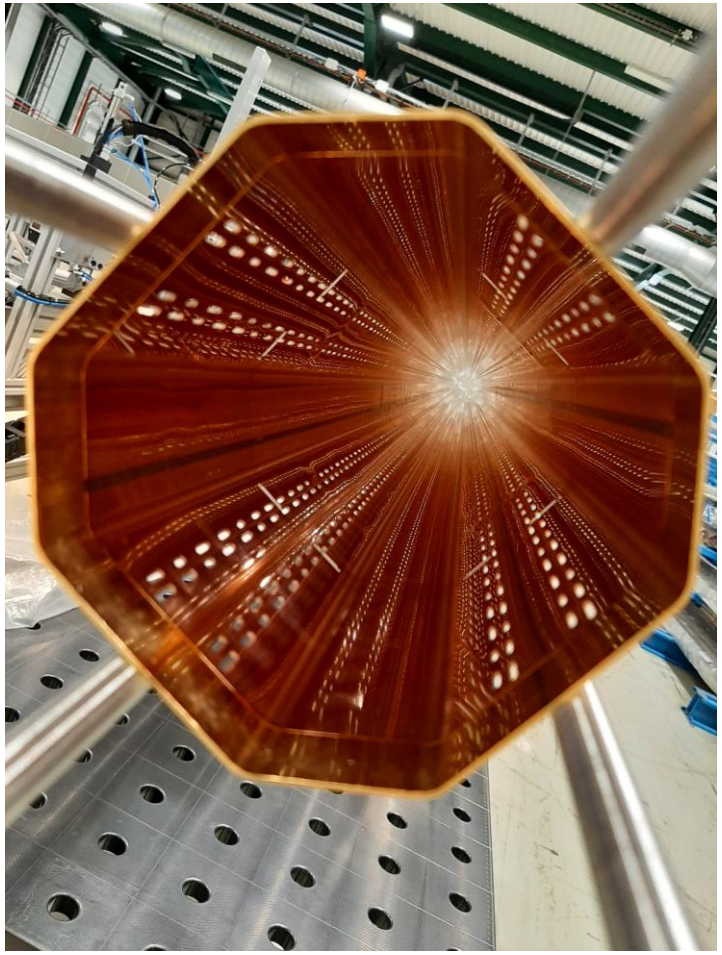


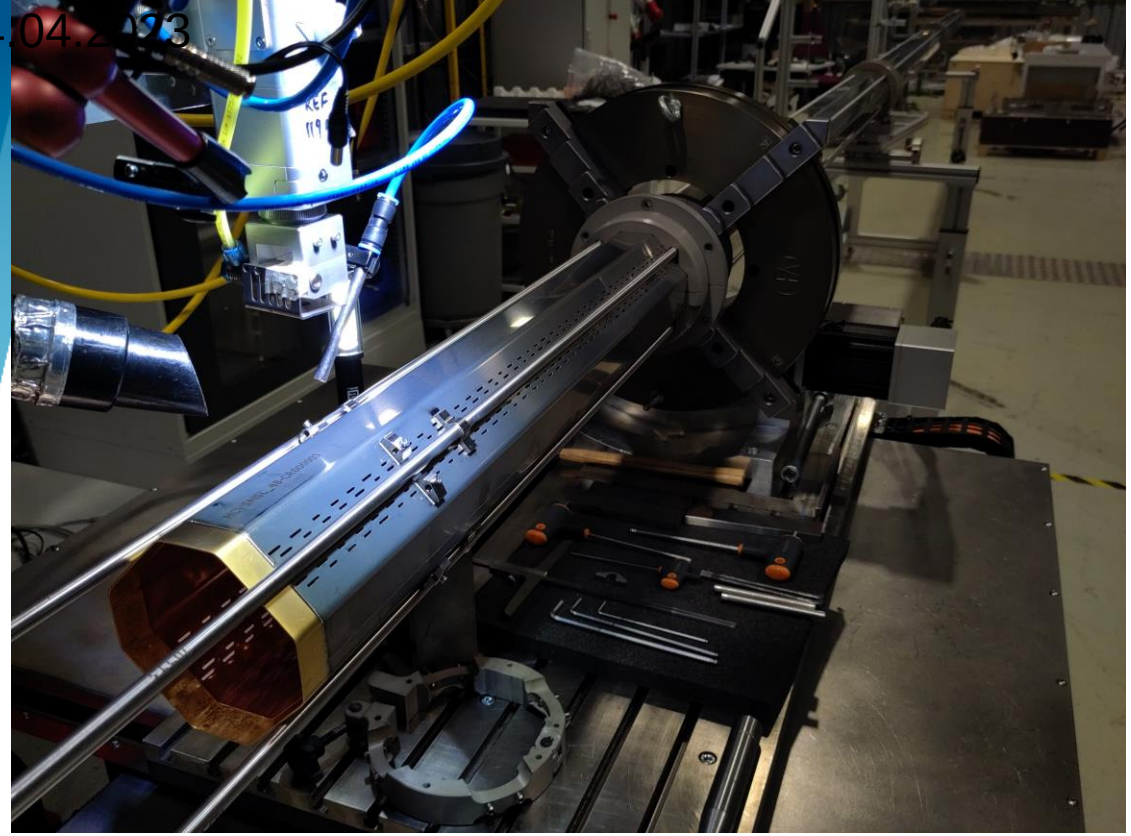


Timeline: Main Milestones in 2022

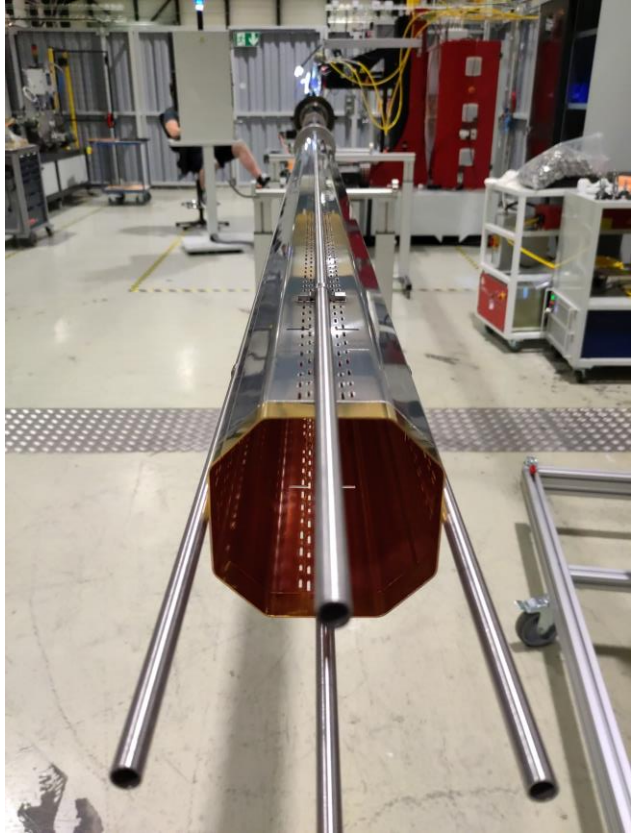
- Beam Screens:
  - End 2022: First Q2 type Beam Screen for the corrector package
  - Mid 2023: First D2 type Beam Screen
  - End 2023: First Q1 type Beam Screen

Cedric Garion





Fixed point laser welding



Fixed point laser welding

Longitudinal laser welding

Fixed point laser welding

Laser cutting simulation

SPS Test Program for CCs

- The DQW module (2021 & 22 & 23). Still in the planning:
  - Demonstrate max stable voltage (nominal required 3.4 MV)
  - Continue Emittance growth studies to understand the x3-4 discrepancy observed in 2018 between measurements & simulations
  - Intensity reach up to 4 batches of 72 bunches with LIU intensities – only possible in 2022 and beyond
  - Study instability limits caused by main CC mode?

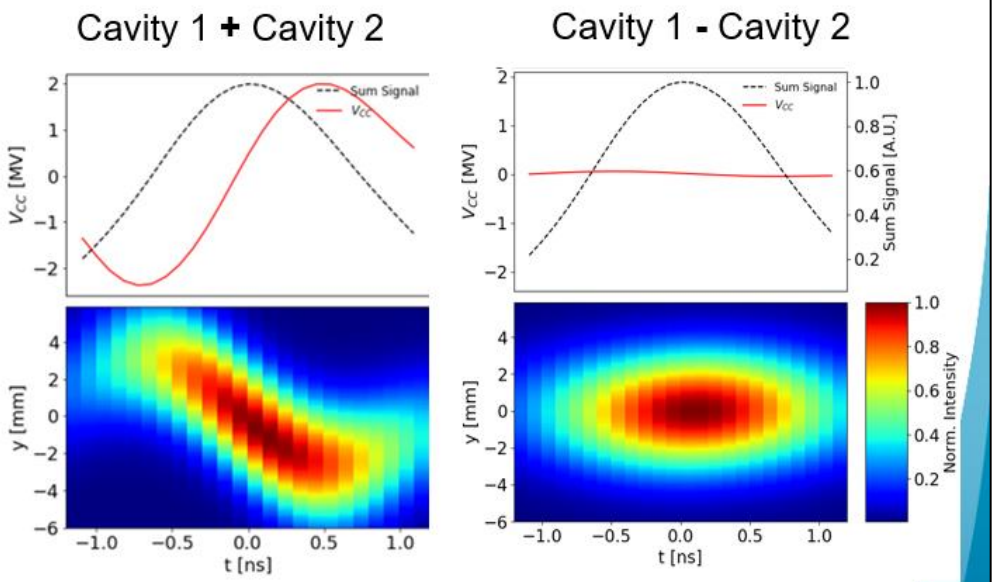
- Swap to RFD module delayed until 2023-24 YETS. Validation program:
  - Max voltage, impedance, cavity alignment & operational aspects
  - Measurement of crabbed beams jitter & potential feedback
  - μTCA development & deployment for crab LLRF (presently on VME)

Crab Cavity Challenges

Rama Calaga

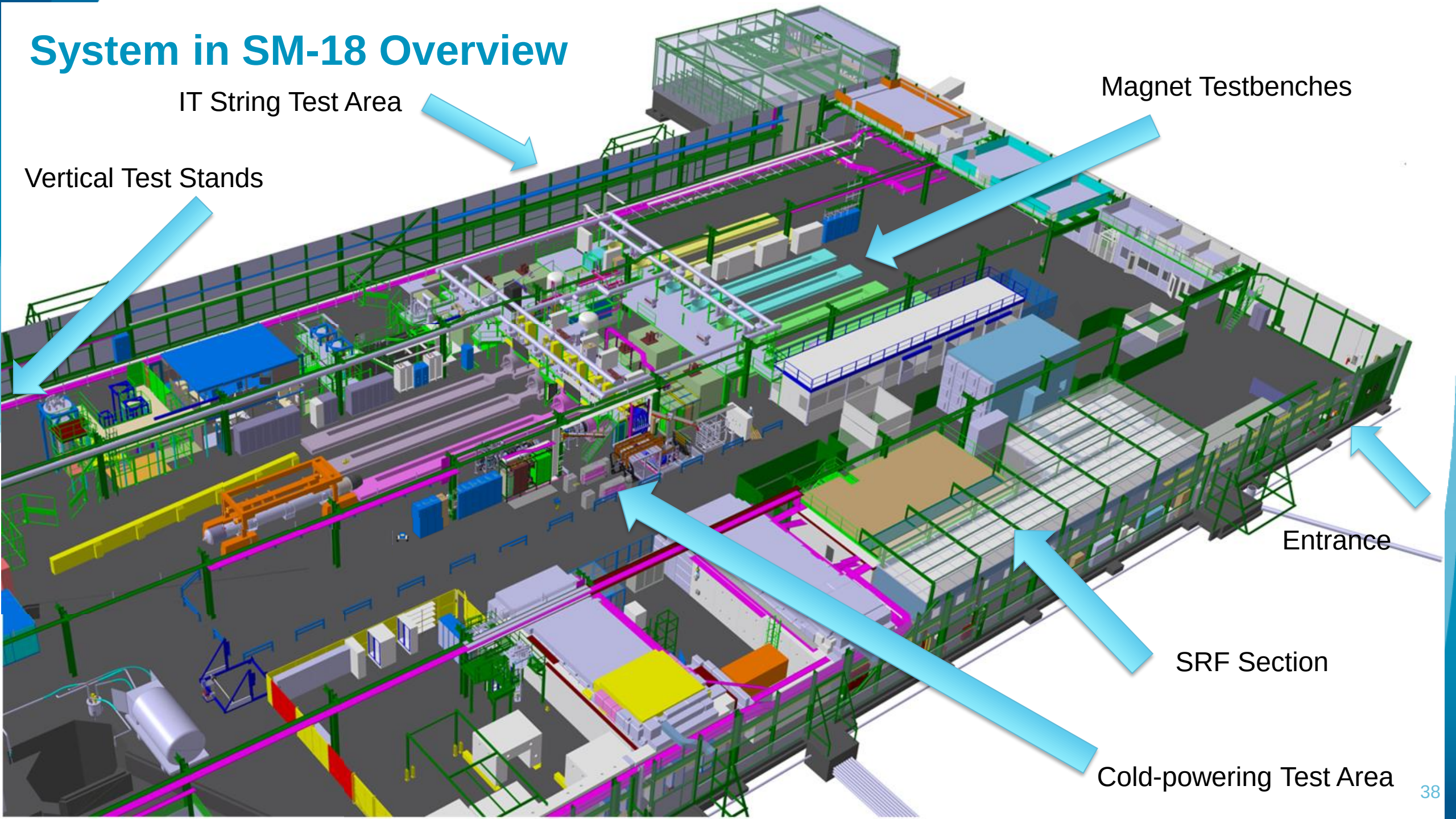
Publicity Slide

- Crabbing of SPS beams routinely done during MDs. Many key aspects (transparency, emittance growth, impedance, hardware issues … studied for HL-LHC)



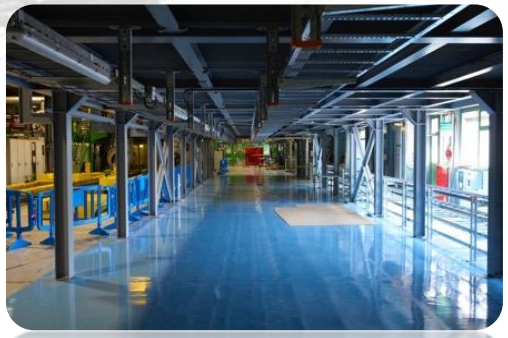
Measurement with head-tail monitor

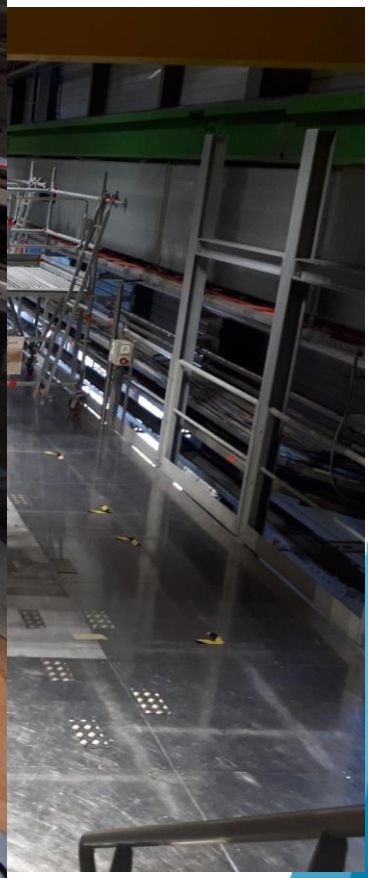
System in SM-18 Overview



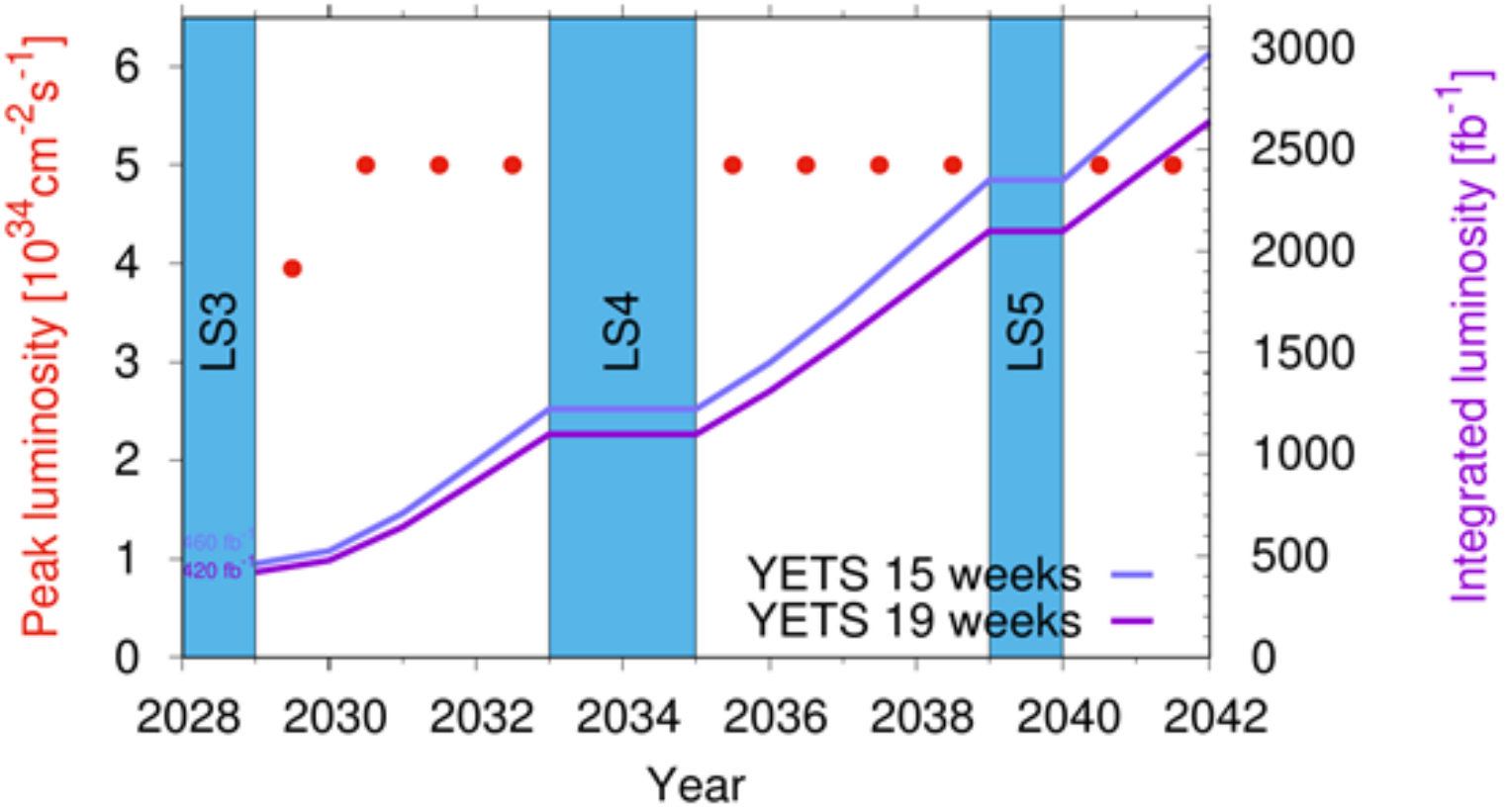
IT String – a very important project milestone closing in!

- IT STRING will allow to study and validate the collective behaviour of the key technologies and systems of the HL-LHC's IT zone (magnets, magnet protection, cryogenics for the magnets and the superconducting link, magnet powering, vacuum, alignment) along with their installation and operation procedures!
- 2023 will see the completion of all technical services and ancillaries, while year 2024 would see the completion of the SC link and magnet installation, IST and first cooldown of the full STRING system.





Baseline HL-LHC schedule and Run 4 ramp-up



- Baseline HL-LHC schedule & performance for ATLAS/CMS with heavy ion runs at the end of each year
  - 2748 bunches, 2.3x10^{11} ppb, 2.5h turn-around, 40% stable-beam efficiency for 7h stable beam duration
    - Run 4 aims at approaching 250 fb^{-1} in the last year for a total of 750 fb^{-1}

BUT…

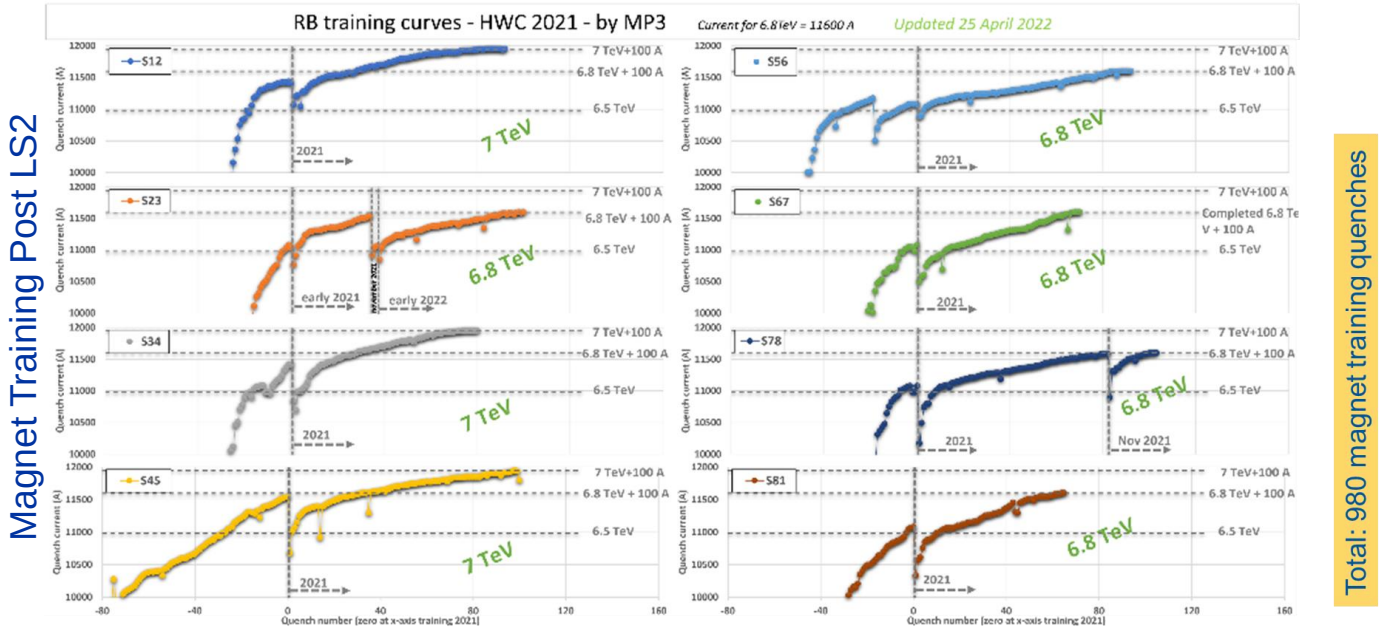
Challenges of Run 4 – Operation Energy?

Total number of quenches

- 14 dipole magnets have quenched 4-5 times but no sign of permanent degradation
- 45% of main dipole magnets have never had a training quench in the LHC since 2008

Estimates to go to 7 TeV

- ~200 training quenches to reach 7 TeV after Run 3
- ~400 re-training quenches required to reach 7 TeV after LS3, assuming 7 TeV reached before LS3 in all sectors



Total: 980 magnet training quenches

All Quenches

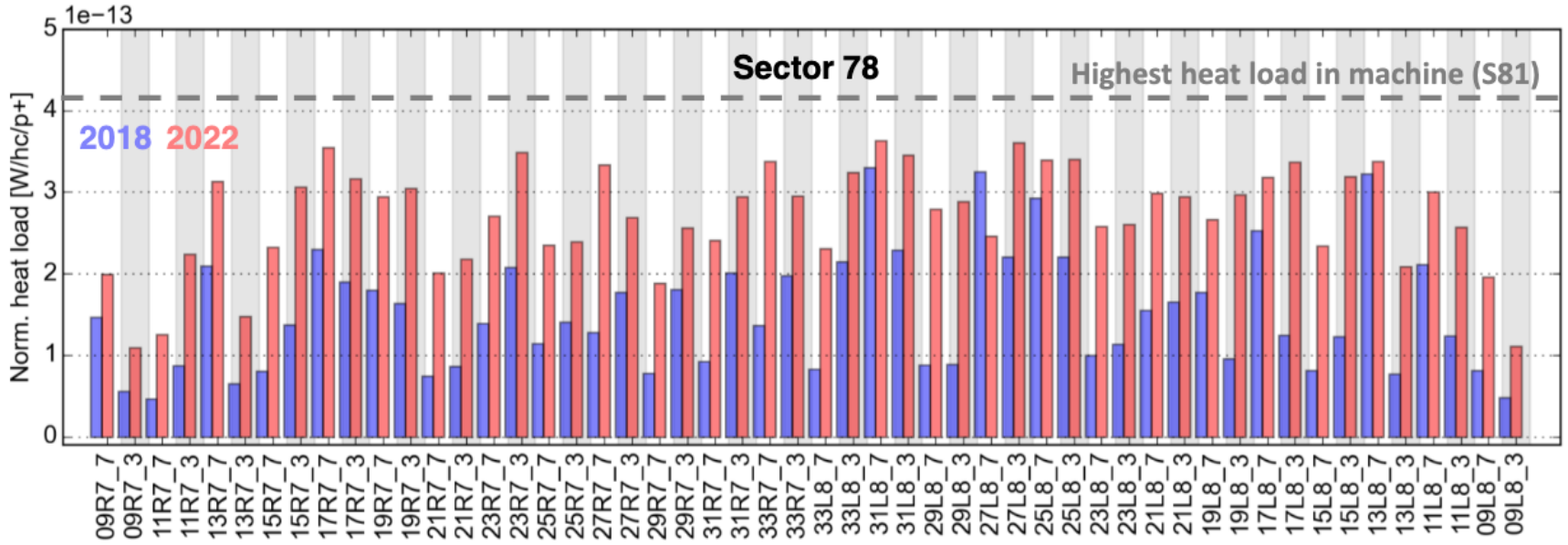
# Quenches in same dipole magnet	# dipole magnets
5	3
4	11
3	56
2	154
1	446
0	562

Further training to 7 TeV will be time consuming and bear considerable risks that might result in additional thermal cycles

e-cloud: LHC conditioning in 2022

- The situation has degraded further during LS2:

  Increase of heat load from e-cloud, in particular in sector 78
  ⟶ limits the intensity reach.



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

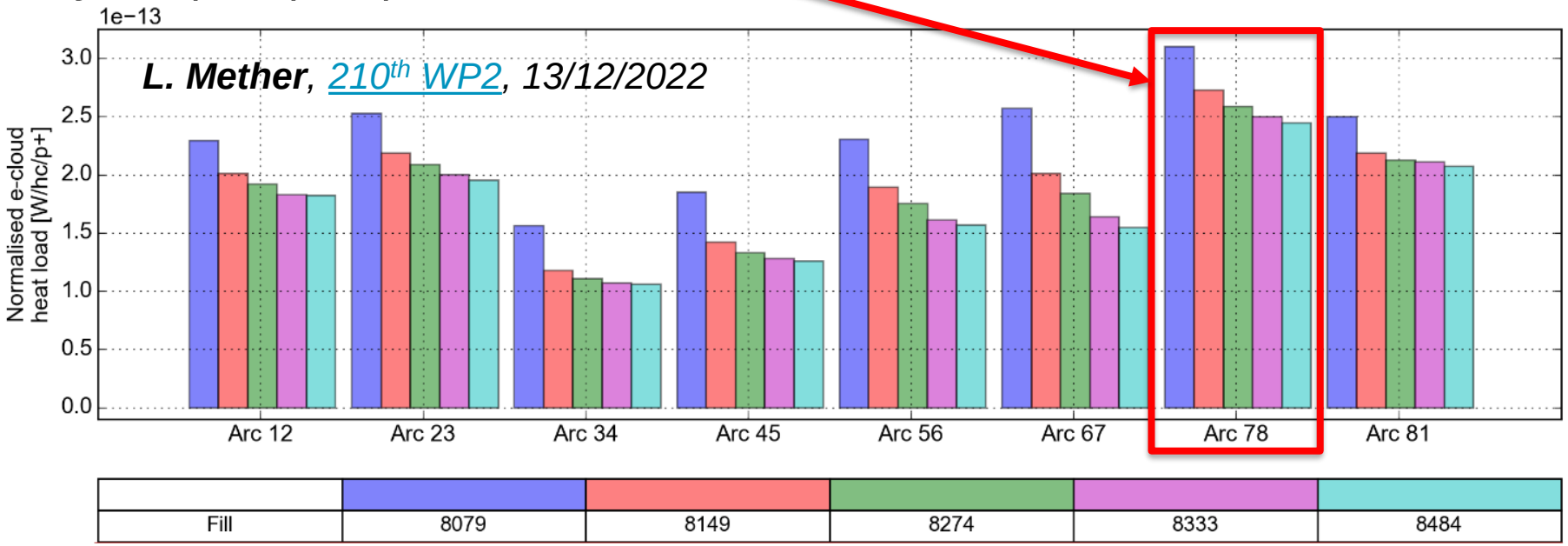
e-cloud

- The 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 expecting much further decrease of secondary emission yield (SEY), in particular for S78.



HL-LHC Electron cloud limitations

- The achievable (HL-)LHC performance critically depends on how beam screen surfaces evolve in future shutdowns
- Due to heat load, the HL baseline scenario is feasible only after beam screen treatment
- Beam stability may cause limitations beyond the heat load after further degradation
- Beam screen treatment is the only cure for both heat load and stability limitations
- 20-40% luminosity gained by treatment based on best and worst case scenarios

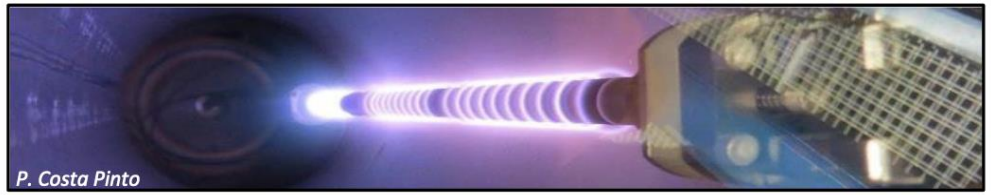
Scenario	Beam	N. bunches	8b4e ratio	S78 heat load [W/hc]	Requires surface treatment	Int. lumi [fb^{-1}/year]	Gain from surface treatm.
Baseline 200	5x48 b	2748	0	> 310	**Yes**	320	Ref.
Best case	Hybrid	**2320**	47%	190	No	270	**19%**
Degraded	Hybrid	**2110**	70%	190	No	245	**31%**
Worst case	8b+4e	**1972**	100%	< 190	No	230	**39%**

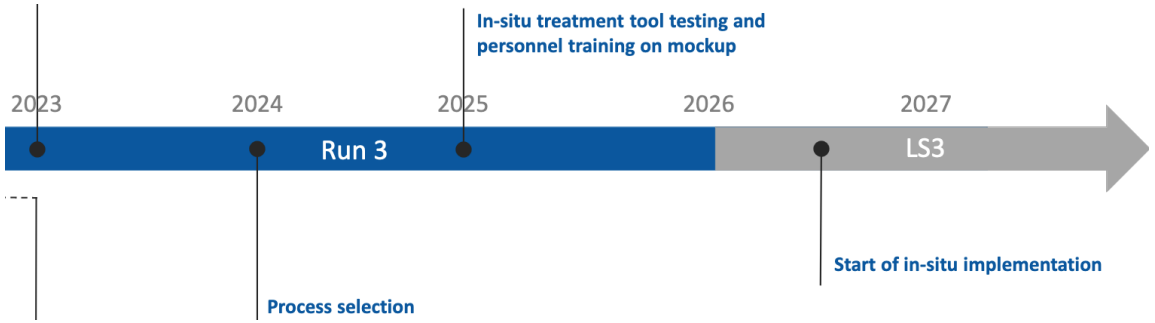
Assuming μ=200, n_b=2.3 x 10^{11} p, L_{lev}= 5-7.5e-34 cm^{-2} s^{-1} *(for more details see talk by R. De Maria)*

Lumi reduction stated for ultimate scenario, smaller for nominal goal of 3000 fb-1

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)

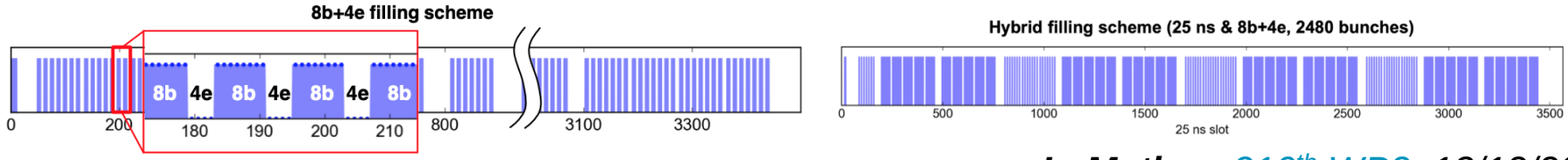




⟹ **Project proposed**

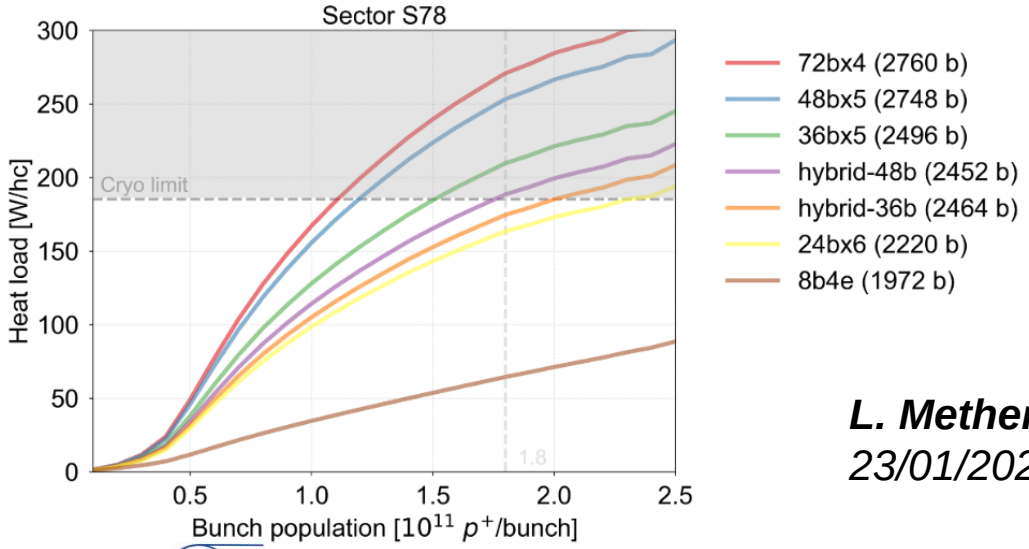
e-cloud: filling scheme mitigation

- 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 (& tunable)



***L. Mether**, [210th WP2], 13/12/2022*

⟹ Strong impact of filling scheme on intensity reach:



***L. Mether**, [LHC Chamonix workshop], 23/01/2023*

Towards an update of Run 4 scenario (protons)

- **e-cloud** is likely to limit the number of bunches in Run 4 ⟶ **8b+4e** or hybrid scheme needed, plus **flat optics** (~ **+5% luminosity**, and help with crab cavity impedance):

# of bunches	PU	Integrated Lumi [1/fb] (Δ[%])		Feasibility from		
				e-cloud	Beam Dynamics	Experiments
2748 (25ns)	132	257	(0%)	No	Yes	Yes
	200	318	(+23%)	No	To be studied	Yes
2200 (hybrid)	140	217	(-16%)	Maybe	Yes	Yes
	200	257	(0%)	Maybe	Studies ongoing	Yes
1972 (8b+4e)	140	194	(-24%)	Yes	Yes	Yes
	200	230	(-10%)	Yes	Yes for DA	Yes
1972 $2.5x10^{11}$	200	253	(-1%)	Exceeding LIU and HL-LHC goals, but worth investigating if possible		

Assumptions:
$\beta^*_{x,y}$ = 18, 9 cm
Half crossing angle = 250 μrad
160 days, eff.=50%

Preliminary input from various teams rather positive, but many studies still needed.

***R. De Maria**, LHC Chamonix workshop, 24/01/2023 (+ input from experiments & WP2)*

Seeing the light at the End of the Tunnel

Project is on track for Series production of HL-LHC components

Thanks for your attention

Timeline: Main Milestones in 2022

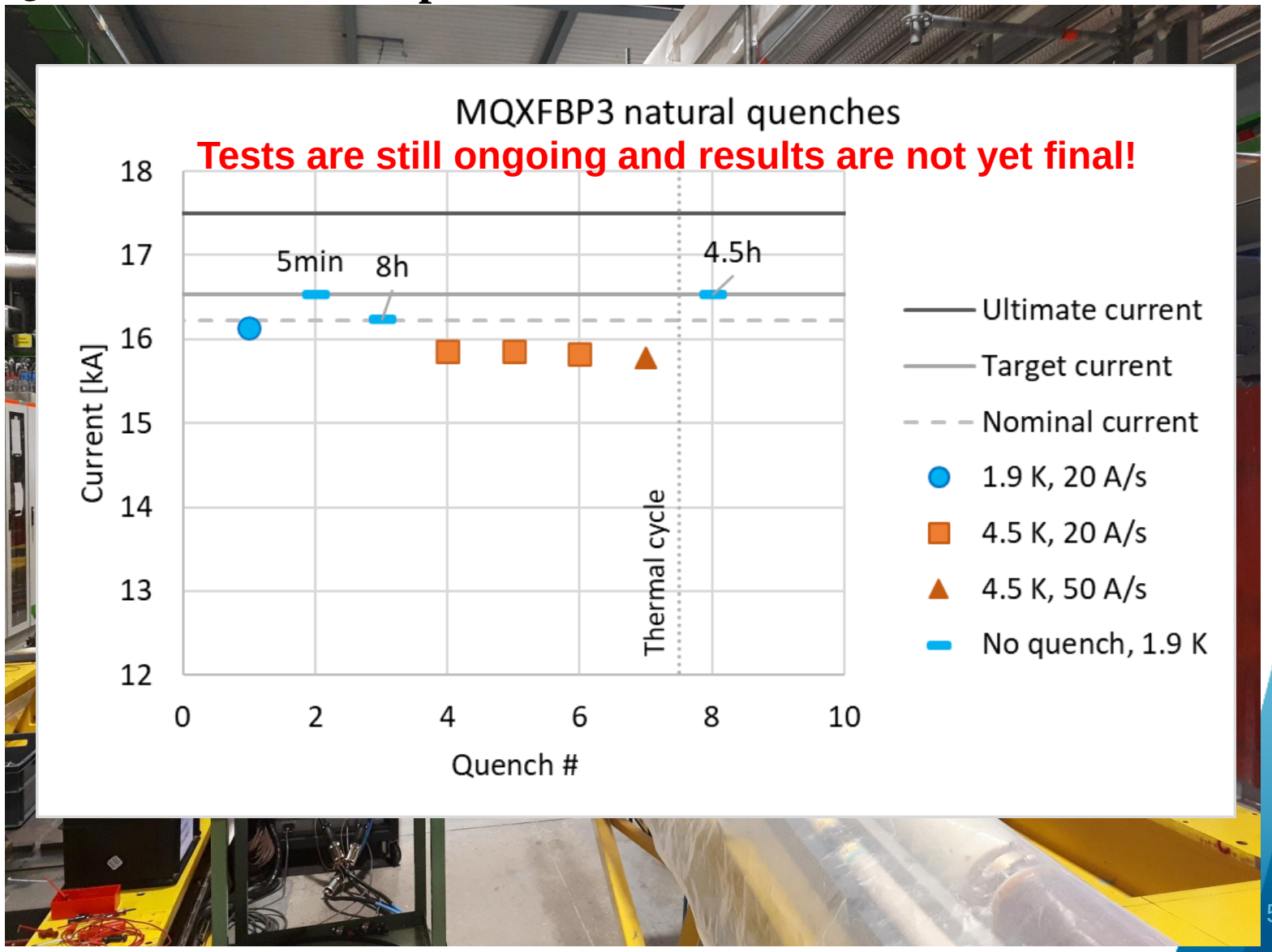
- **August 2022: MQXFBP3 test @ SM18:**

  Re-welded cold-mass from MQXFB01 with lower pre-stress of Stainless Steel shell

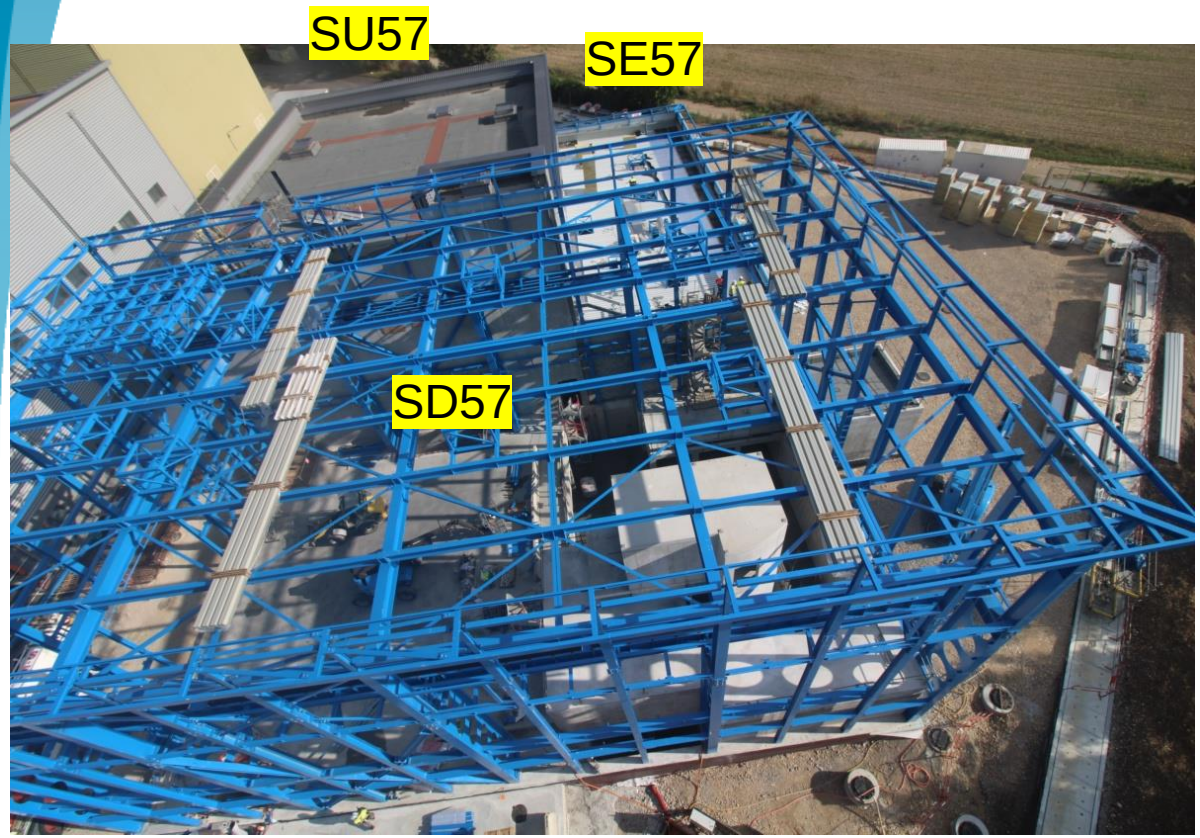
  But still using coils from early 2020!

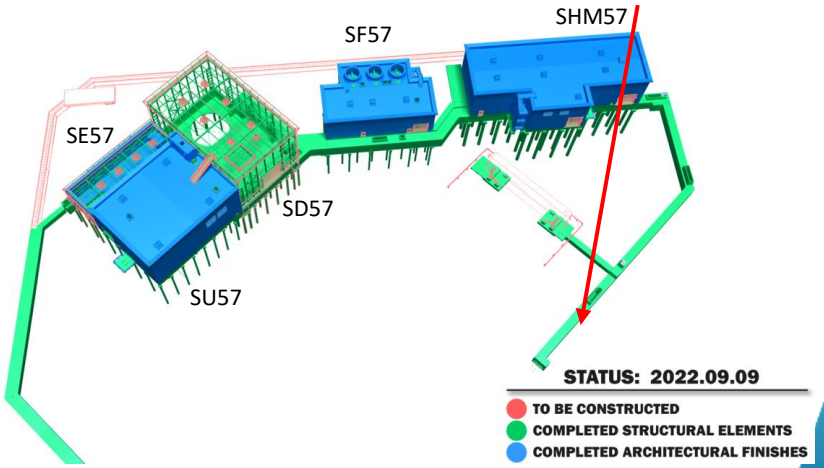
- ➔ **Reached nominal+300A after 1 quench ✓**
- ➔ **Held nominal +300A for 8h ✓**
- ➔ **Showed a limitation at 4.5K**
- ➔ **Returned to nominal+300A without quench after TC ✓**
- ➔ **Held nominal+300A for > 4.5h**

Ezio Todesco et al.



Main civil engineering work at Point 5 (CMS)





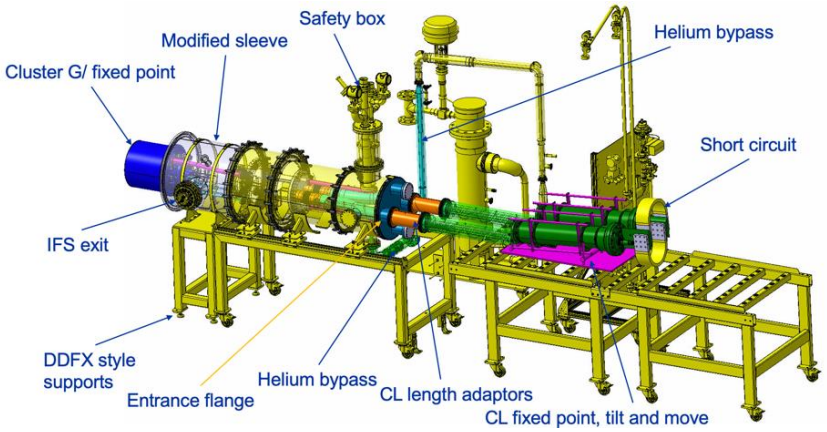
Pieter Mattelaer and Laurent Tavian

SM18 upgrade project – Scrutiny outcome

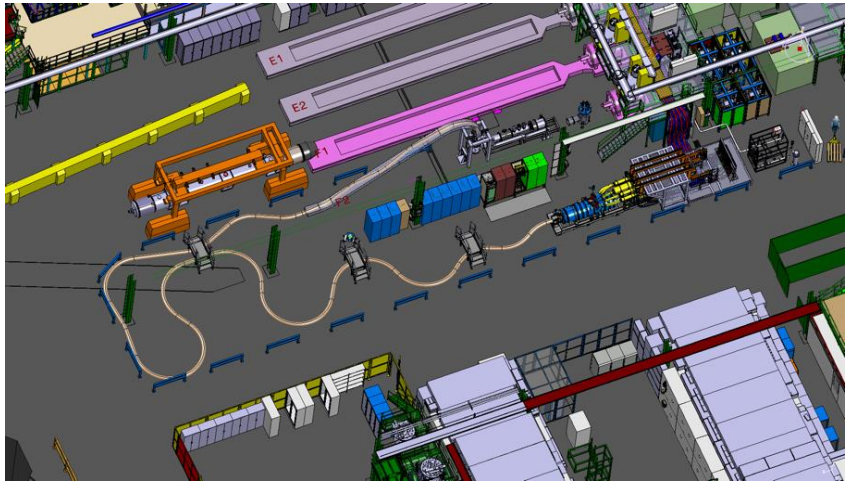
- Important upgrade of CERN's SM18 test facility is required to allow for the testing of (pre-)series magnets, current leads and cold powering systems (sc links and feedboxes) for the HL-LHC project
- A Scrutiny group v … equest, assure conformity with n … with needs beyond the HL project sco …
- Detailed report ar … ess of technical choices while mak … ality assurance and cost sharing
- DMR on the imple … 2637180/1.0

Updated schedule for magnet availability for IT String Test!

➔ Updated Schedule for String Test – operation now planned to extend well into 2025

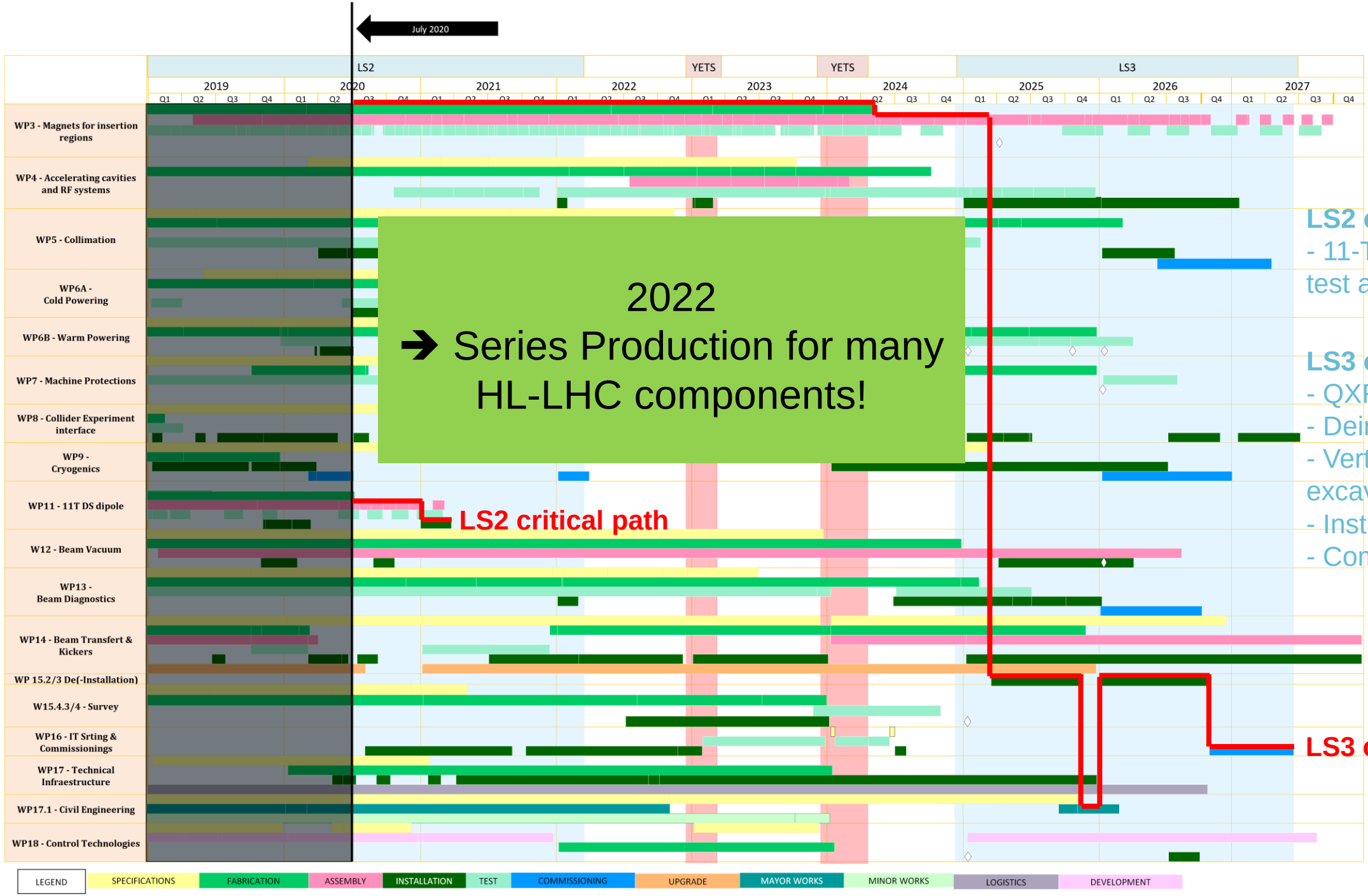


HTS current lead testing



Test station for sc link and feedboxes

Magnet test benches



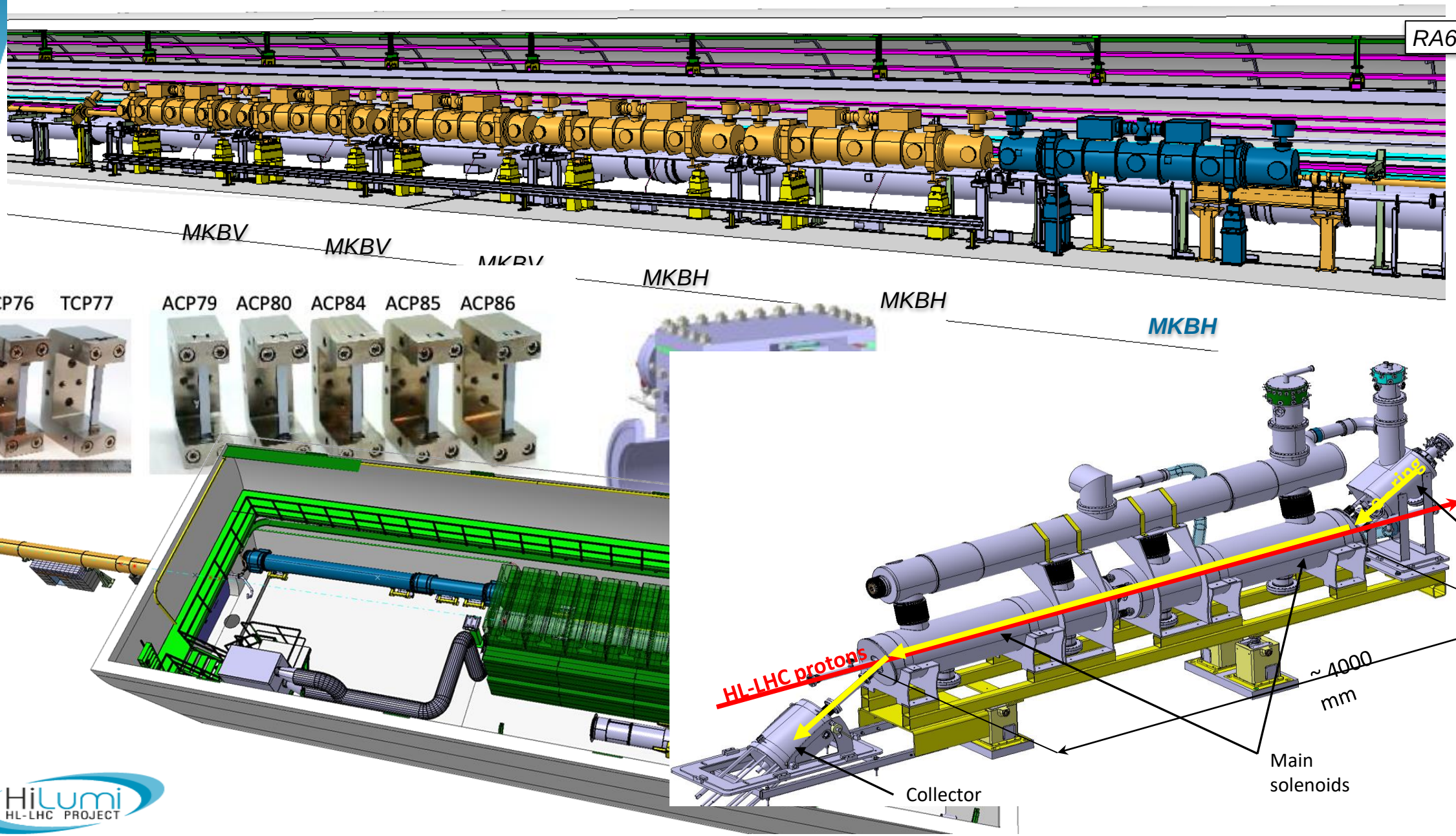
LS2 critical path:
- 11-T dipole assembly, test and installation

LS3 critical path:
- QXF assembly & test
- Deinstallation
- Vertical core excavation
- Installation
- Commissioning

LS3 critical path

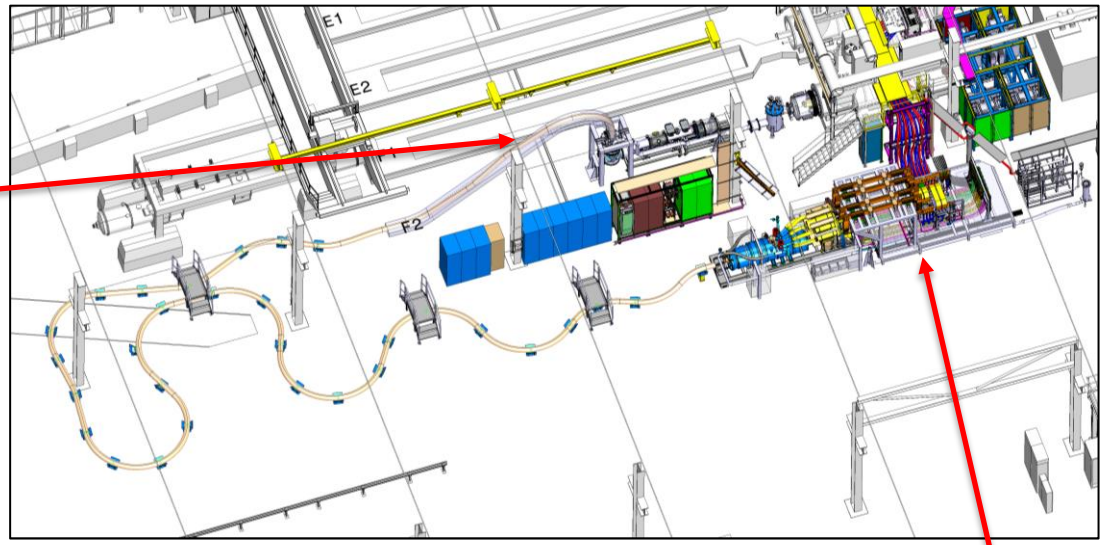
54

Added Scope since C&SR 2019



Upgrade activities: Cold Powering

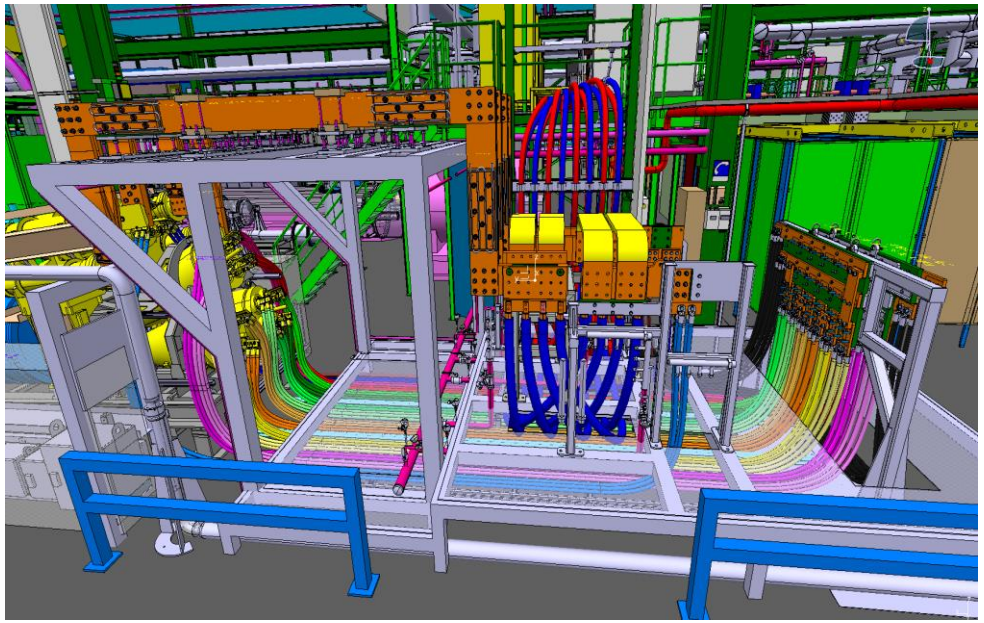
SC Link cable chain trials (SM18)



System test main equipment:

DFX – SM18 pre-assembly
DFHX – SMI2 pre-assembly
Cu current leads – Bld 100
HTS cable – in manufacture
Sc link cryostat – Flex building
Sc link cable – Bld 927
CL heater rack – SM18
QDS racks – SM18
CFB shuffling module – SM18

SM18 Cluster F2 Test Bench Safety Assessment, edms 2703683 by T.Otto.



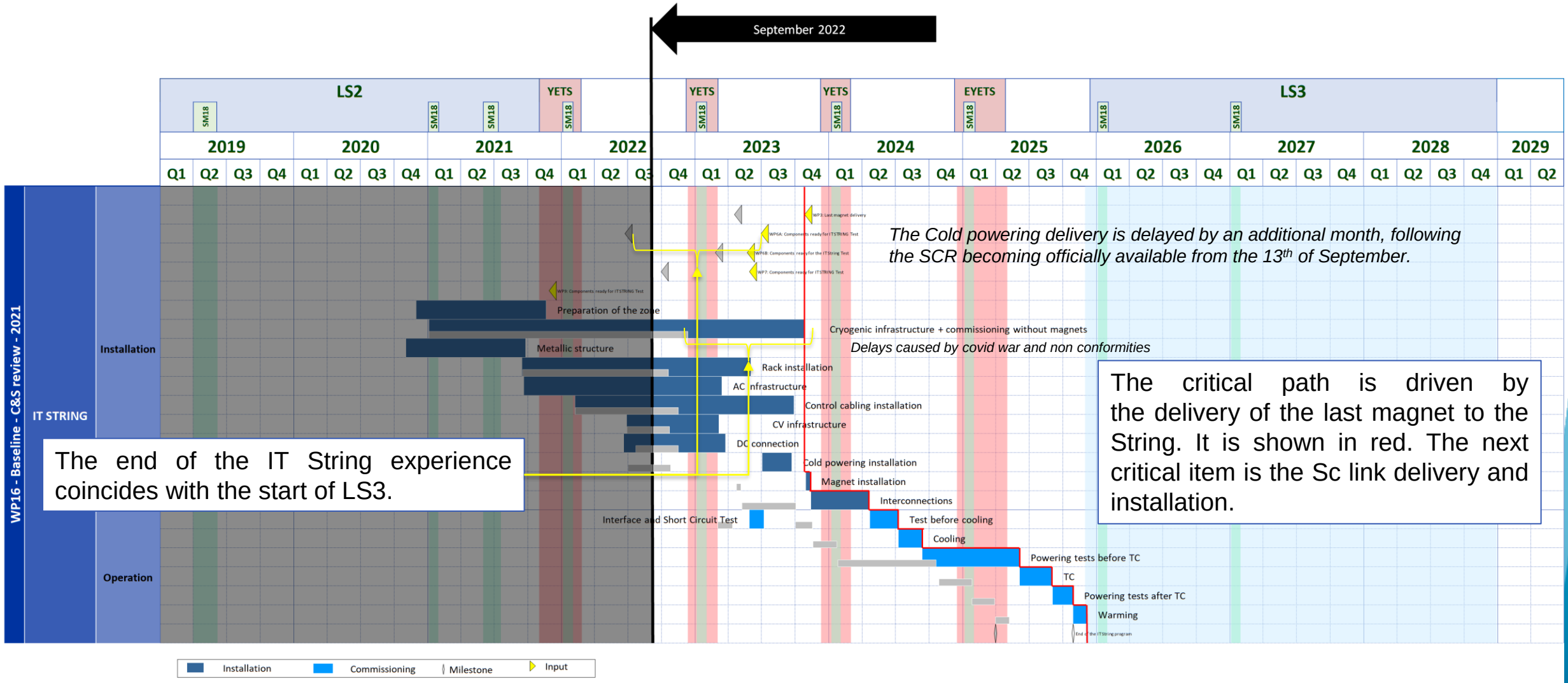
Patch Panel Assembly:

Support structures - installed
CRG helium panel - installed
WCC - installed,
WCC cooling - ongoing
ACC installed,
Signal cabling installed,
Cu parts PPI installed
Cu parts 18kA busbar - delay
IP2X cage - in manufacture

Patch Panel is taking shape….

New IT String Schedule

More details in Marta Bajko's presentation



The Cold powering delivery is delayed by an additional month, following the SCR becoming officially available from the 13th of September.

Delays caused by covid war and non conformities

The end of the IT String experience coincides with the start of LS3.

The critical path is driven by the delivery of the last magnet to the String. It is shown in red. The next critical item is the Sc link delivery and installation.

HL-LHC MDs in 2022

Despite limited MD time in 2022, beam time allocated for high priority studies in view of HL baseline

As part of beam commissioning/floating MDs

- Crystal collimators and Beam beam wire commissioning and setup

MD1 and MD2

- RF power limitations and instability thresholds (in addition to work on HE klystrons + fast reactive tuner system)
- Beam beam wire compensation (option, not in HL baseline today)
- HL-LHC BPM electronics
- e-cloud heat load scaling with bunch intensity
- Diffusion measurements of beam population with collimator scans
- Rematched/optimized IR7 optics for improved cleaning performance and impedance
- Dispersion Suppressor quench test with protons

Missing 11T + TCLD

2-day LHC Pb ion test on Nov 17th-18th