HL-LHC Upgrade Project

Corfu Summer Institute 2022

Markus Zerlauth with acknowledgements to O.Brüning, M.Lamont, L.Rossi, J. Wenninger and many other CERN colleagues

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Outline

- LHC design performance and HL-LHC upgrade goals
- Completion of LIU, start of LHC Run 3 and lessons learnt for HL-LHC era
- Status of key (technological) deliverables towards the HL-LHC upgrade
  - Civil engineering
  - Final focusing magnets for lower beta*
  - Superconducting Link
  - Crab cavities
  - IT String
- HL-LHC as a truly international project (with recent challenges)
- Current Project planning and performance ramp-up

Introduction: LHC Performance Goals

- Collision energy: Higgs discovery requires E_{CM} > 1 TeV

  p collisions → E_{beam} > 5 TeV → LHC: E = 7 TeV [3.5/4TeV; 6.5TeV; 6.8TeV]

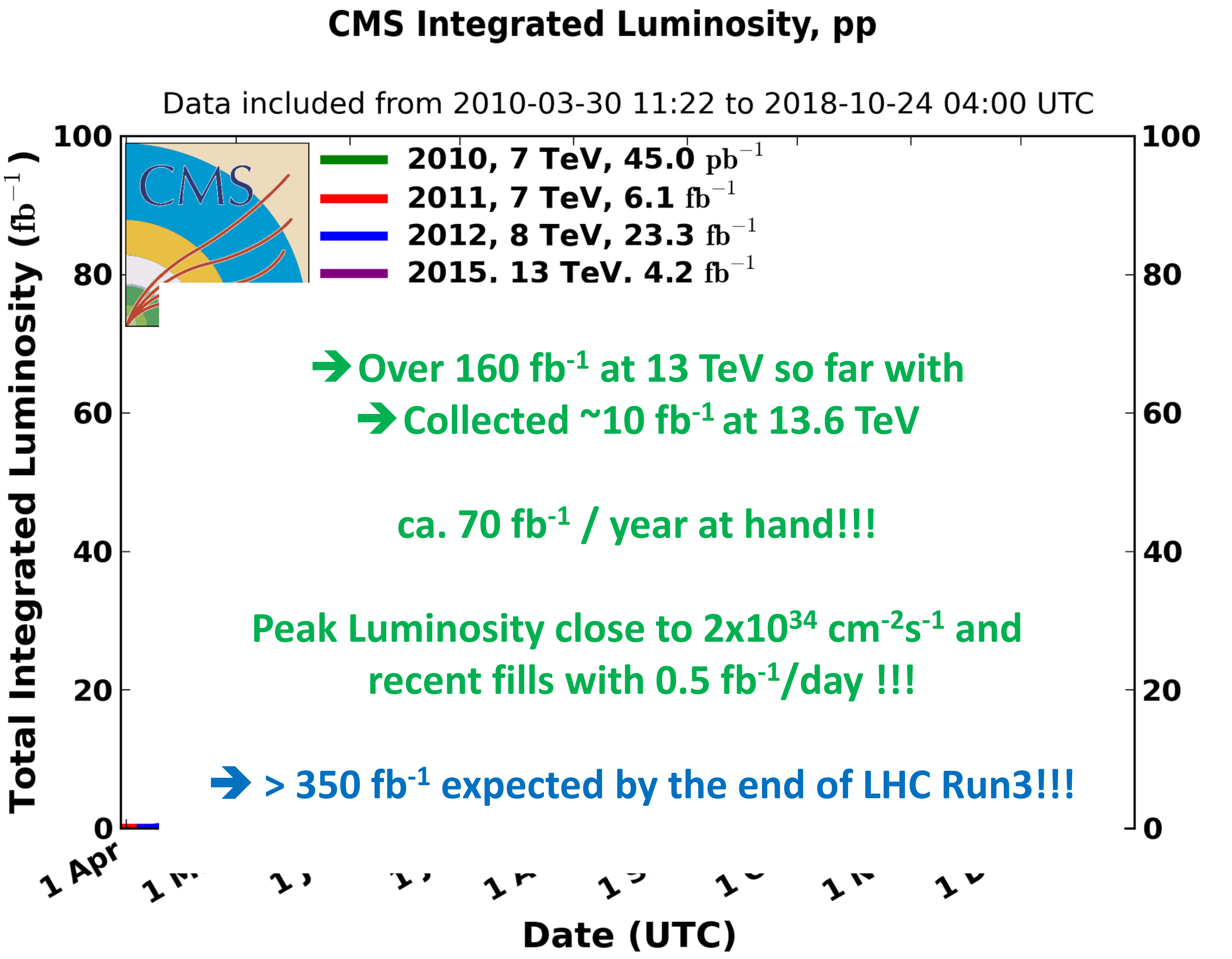
- Instantaneous luminosity: rate of events in detector $= L \times \sigma_{event}$

  rare events → L > 10^{33}cm^{-2}sec^{-1} → L = 10^{34}cm^{-2}sec^{-1} [2 10^{34}cm^{-2}sec^{-1}]

- Integrated luminosity: total number of events L $= \int L(t)dt$

  300 fb^{-1} with 1barn = 10^{-28}m^2 and femto = 10^{-15} [205 fb^{-1}]

  depends on the beam lifetime, the LHC cycle and 'turn around' time and overall accelerator efficiency



➔ Over 160 fb^{-1} at 13 TeV so far with

➔ Collected ~10 fb^{-1} at 13.6 TeV

ca. 70 fb^{-1} / year at hand!!!

Peak Luminosity close to $2x10^{34}$ $cm^{-2}s^{-1}$ and recent fills with 0.5 fb^{-1}/day !!!

➔ > 350 fb^{-1} expected by the end of LHC Run3!!!

Goal of High Luminosity LHC (HL-LHC):

The main objective of the HL-LHC is to determine and build a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

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

Devise beam parameters and operational scenarios for:

enabling at total integrated luminosity of **3000 fb^{-1}**

implying an integrated luminosity of **250 fb^{-1} per year**,

design oper. for **$\mu \leq 140$** (➔ peak luminosity **5×10^{34} cm^{-2} s^{-1}**)

➔ Operation with levelled luminosity!

➔ 10 x the integrated luminosity reach of first 10 years of LHC operation!!

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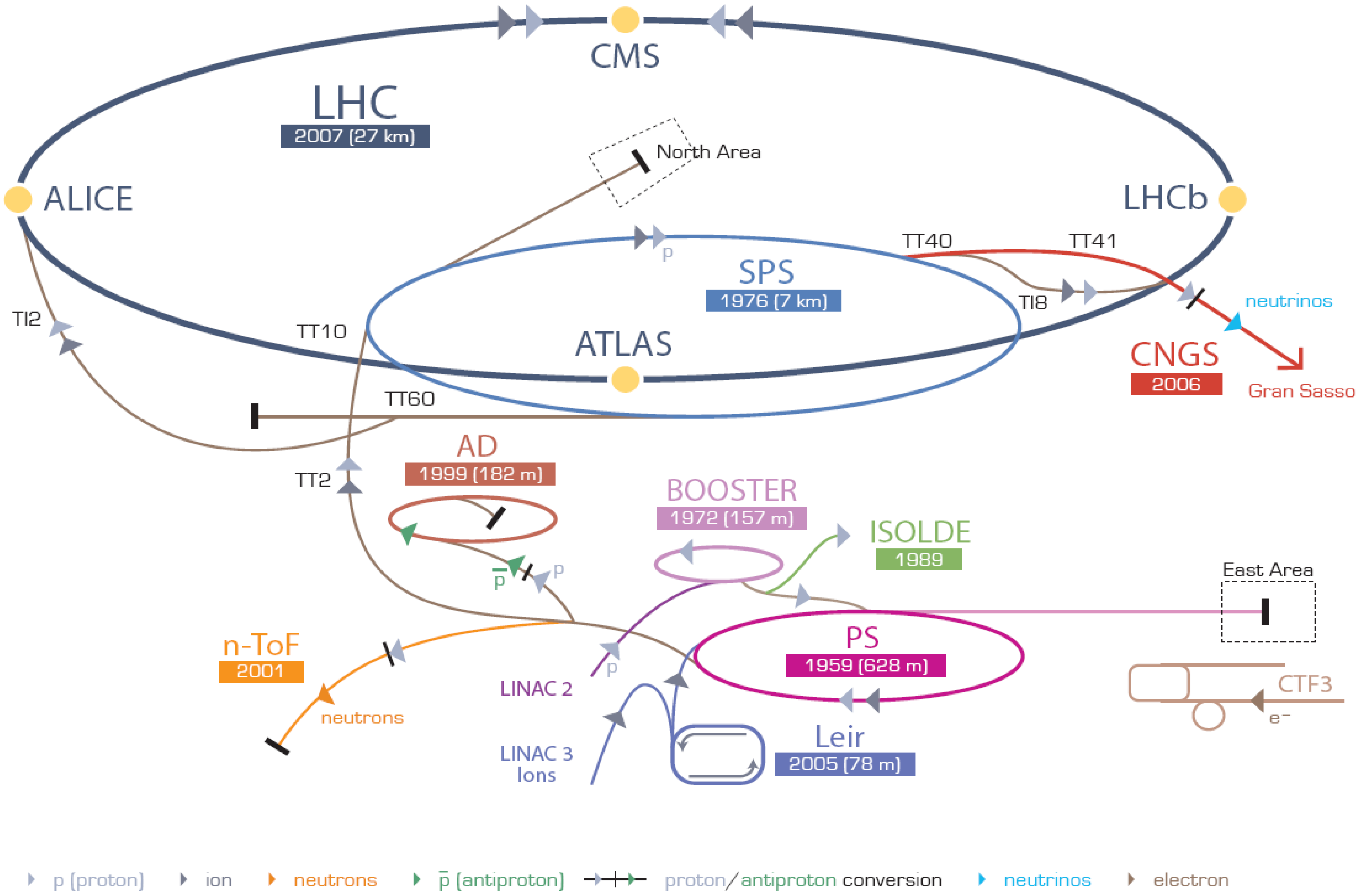
CERN accelerator complex



LHC Injector Upgrade Project (LIU)

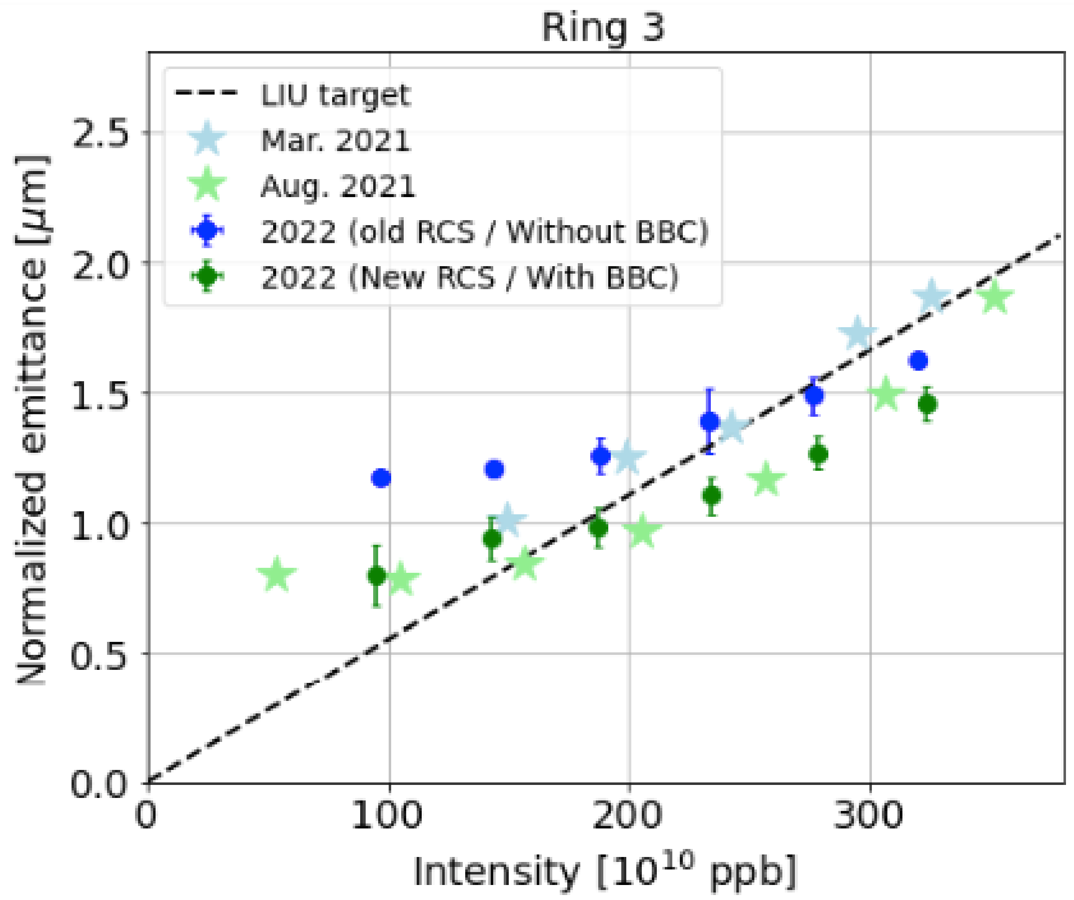
- HL-LHC performance relies on more intense and brighter bunche… …ctor complex (2.2E11p / 2um at SPS extraction wrt to LHC nominal of 1.15E… …n)
- 25ns beam limited by space charge in PS, PSB, SPS; SPS RF… …d SPS longitudinal instabilities
- 50ns beam limited by PS longitudinal instabilities… …e charge and SPS TMCI

Successfully deployed during LS2 in 2019/2020

Linac4 in for Linac2	• H^- injection into PSB at 1… • Expected double bri… … LHC beams out of the PSB
Booster	• Increase energy… • New RF syst… • New ma… …upply
PS	• Inje… …GeV • … …uction schemes • …ck systems: new wide-band longitudinal feedback; transverse …dback against head-tail and e-cloud instabilities
SPS	• Power upgrade of the main 200 MHz RF system • Electron cloud mitigation through a-C coating (baseline) or beam induced scrubbing

PS Booster : LHC Beam Production

- PSB managed to achieve the LIU target for the **LHC brightness already in 2021**
- **Performance re-established in 2022** after
- ✓ BCMS: operating on emittance plateau
- Flexibility for lowering the brightness

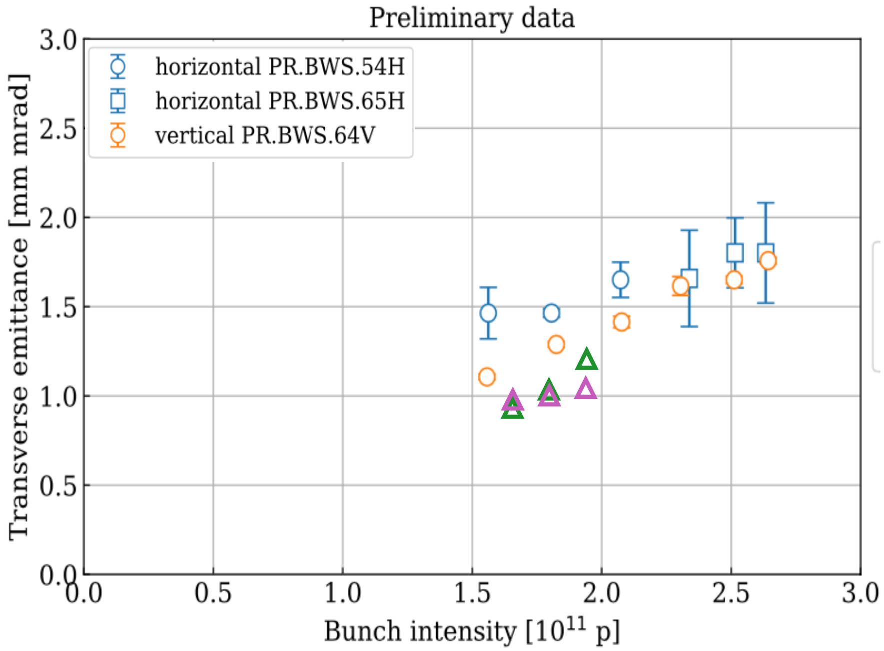


PS : LHC multi-bunch Beam Status - BCMS

- Measurements shown from 3rd of June in parallel with PSB and SPS
  - Values at c2843 (h84) before extraction (only 1 measurement)
  - Using PSB cycle with reduced tails

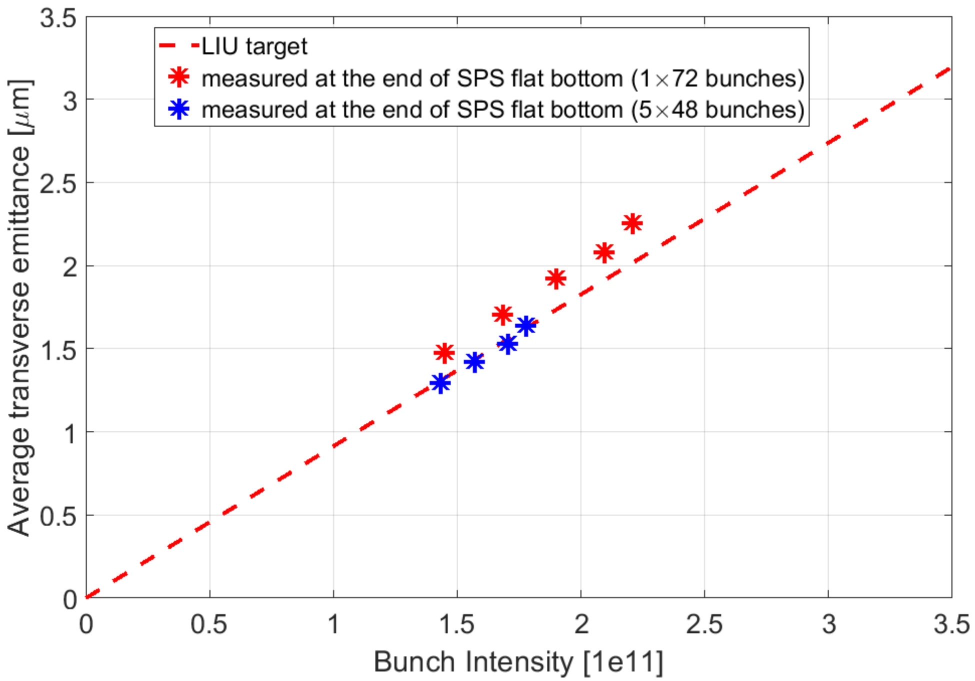
- **Both BCMS and LHC 25 ns cycles are ready**
- Target brightness demonstrated

Intensity	H emittance	V emittance
1.66e11 p/b	0.98 µm	0.90 µm
1.80e11 p/b	1.01 µm	0.98 µm
1.94e11 p/b	1.03 µm	1.19 µm



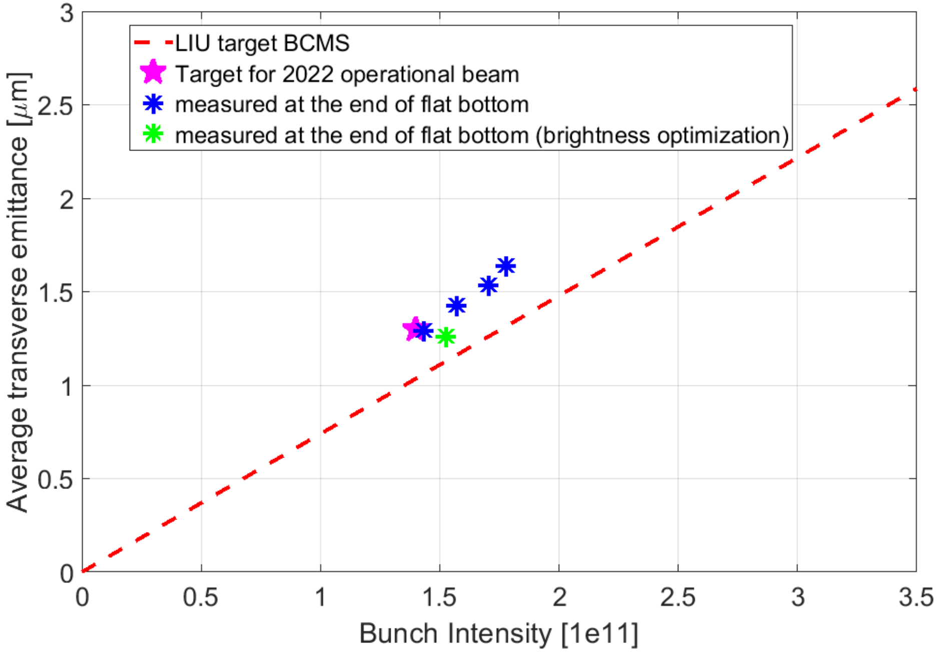
SPS : LHC multi-bunch Beam Status - BCMS

- Measurements shown from 3rd of June in parallel with PSB and SPS
  - Values at c2843 (h84) before extraction (only 1 measurement)
  - Using PSB cycle with reduced tails



Excellent brightness for both Standard and BCMS beams

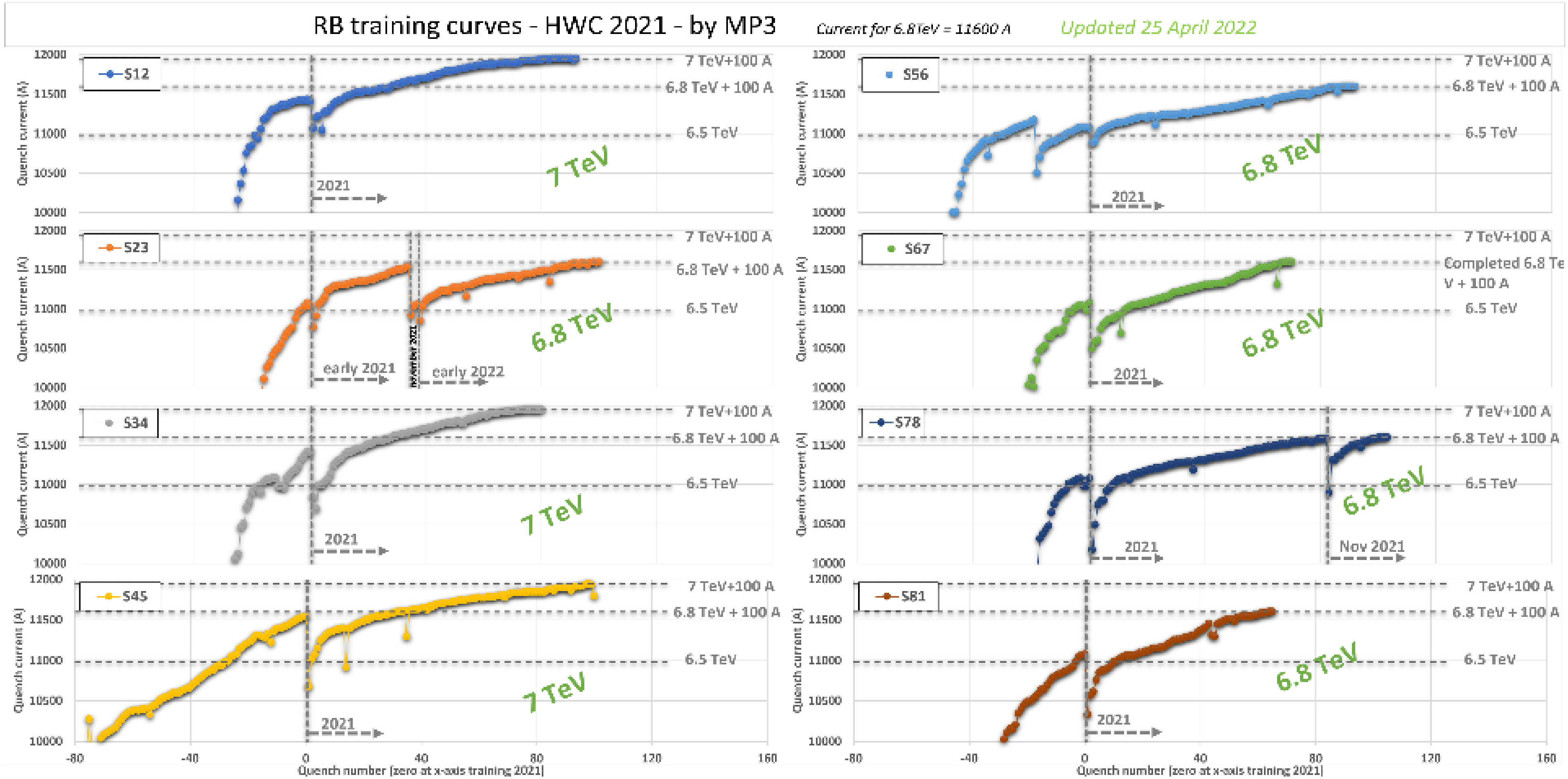
Beam for high intensity MDs: BCMS



Brightness can be slightly improved at the expense of transmission

LHC schedule coming out of Long Shutdown 2

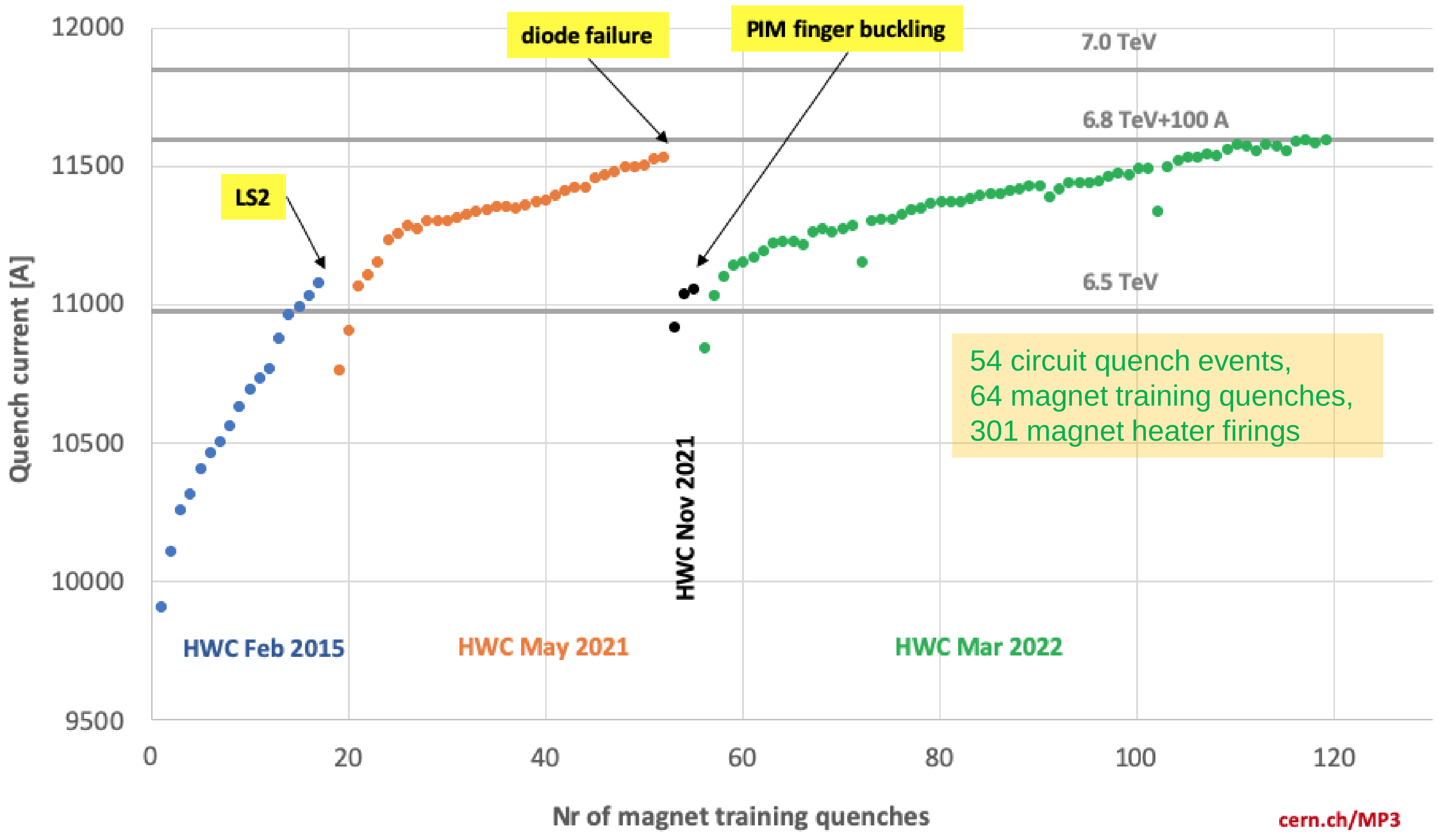
Training quenches RB Circuits



Collision energy of (HL-)LHC is strictly linked to achievable current of the 1232 (= 8 x 154) LHC main dipole magnets

- 5 sectors reached 6.8 TeV equivalent, 3 sectors reached 7 TeV
- No sign of permanent degradation.

Training history RB.A23



- The 64 quenches in S23 after the 2nd additional TC came as a surprise, as usually training goes faster after a TC
- Detailed analysis of the dipole training campaigns is ongoing, including results from reception tests in SM18.

Total nr of quenches in LHC main dipoles

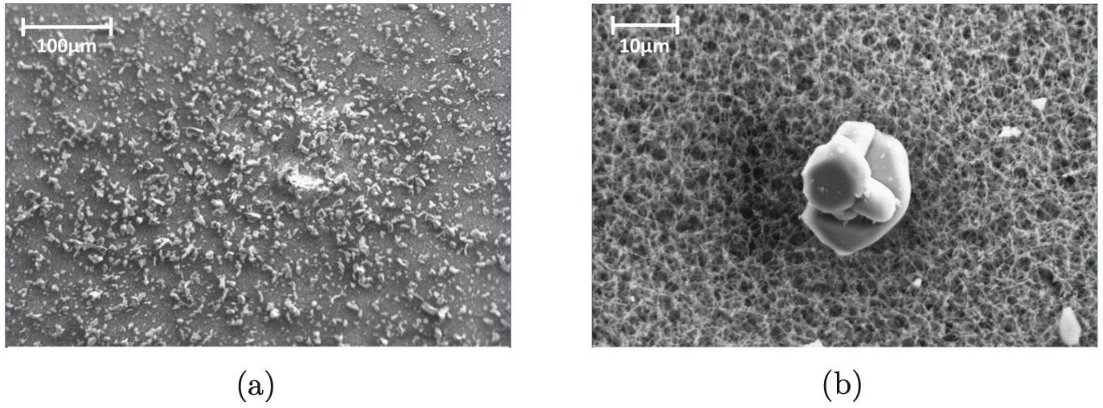
Nr of quenches in the same dipole magnet	Nr of dipole magnets
5	3
4	11
3	56
2	154
1	446
0	562

Conclusion:

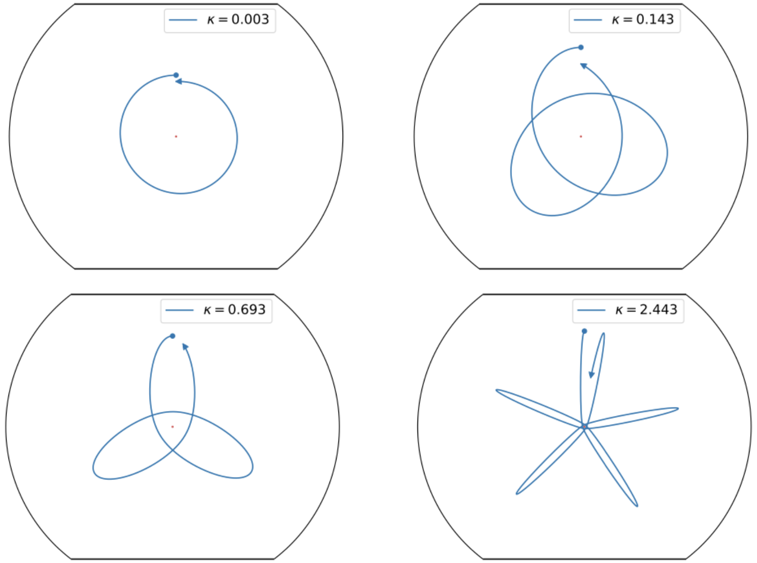
- Still 562 dipole magnets (45%) never experienced a training quench in the LHC since 2008.
- Some circuits (including corrector circuits) showed much longer training than in previous campaigns, and their behavior will be closely monitored in the coming years.
- Desired operating currents can still be reached (with only a few exceptions) 14 years after the start of the LHC, with several thermal cycles, numerous current cycles, radiation, and large number of quenches.
- a quench is a very violent process (especially in the high-current circuits), and that each quench implies a certain unavoidable risk (short-to-gnd, internal short, quench heater failure, etc).

UFOs and their interactions with the LHC beams

- Dust particles are inevitably present in the LHC vacuum chamber
- They get charged and can travel along the electric and magnetic fields of the beam and the surrounding magnets
- Interactions with the high intensity proton beams generate fast, localised beam losses that affect operation (and can generate magnet quenches)

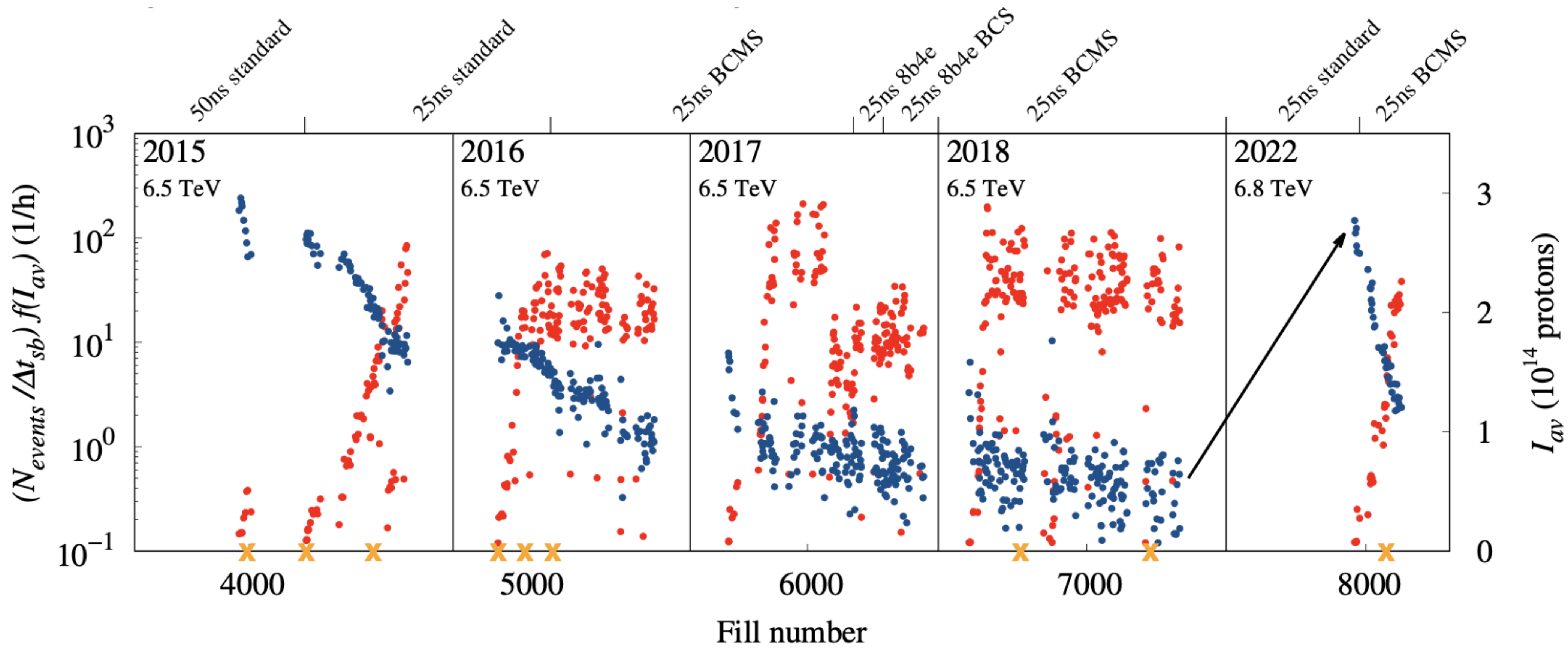


Dust samples from the ceramic tube of an injection kicker magnet. (b) shows an enlarged view of an Al_2O_3 particle with a radius of about 5 um



Examples of orbits of charged dust particulates around the LHC beam. Beam screen height is ~37 mm

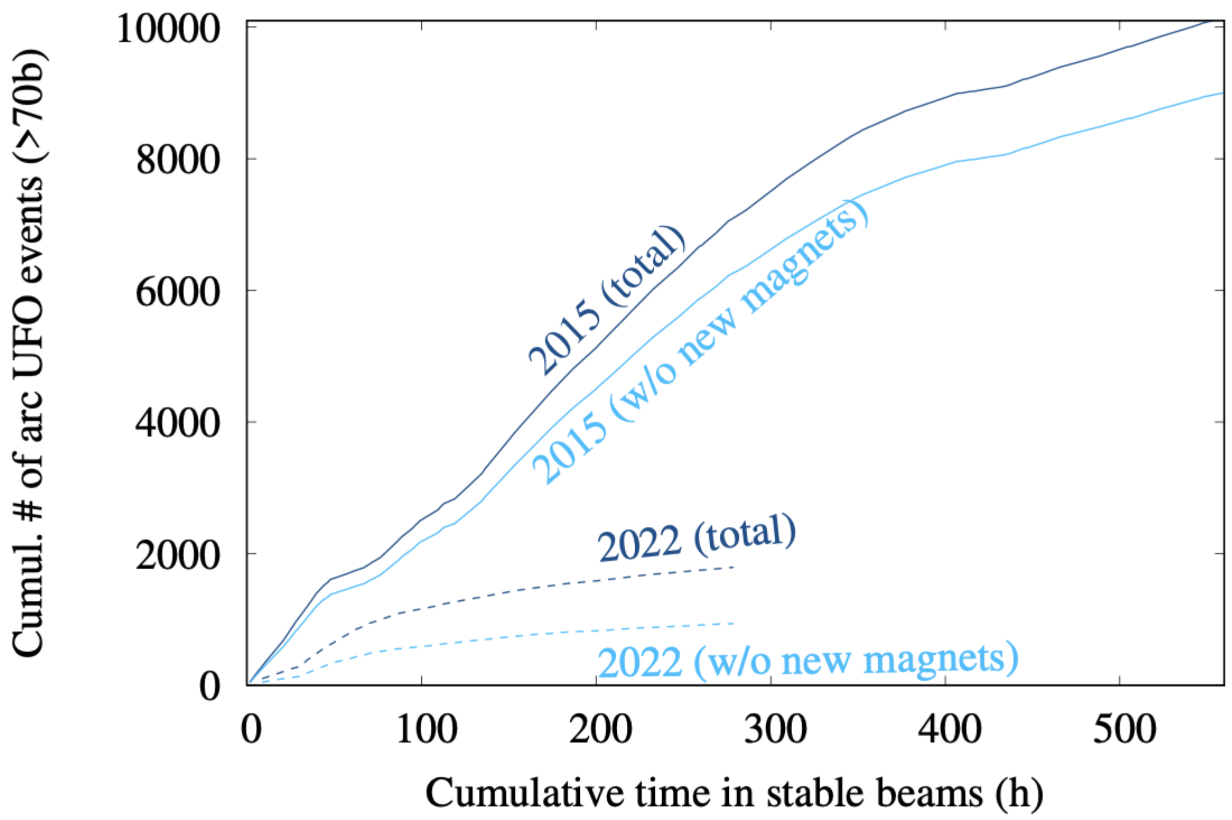
UFO conditioning in Run2 compared to 2022



Blue dots = **UFO rate**, red dots = **fill-averaged intensity**, orange crosses = **quench**

L. Mether

UFO rate 2015 vs 2022



- In general, situation much better than in Run 2 due to the very fast conditioning of the UFO rate
- But the impact of UFOs evidently depends on the BLM threshold strategy

Conclusion:

- Expected re-conditioning of UFOs at the start of Run3.
- Much lower quench margins at 7 TeV and with HL-LHC beam parameters
- (Part) of physics behind UFO mechanism still not fully understood

HiLumi HL-LHC PROJECT

L. Mether

Electron cloud and cryogenic heat load

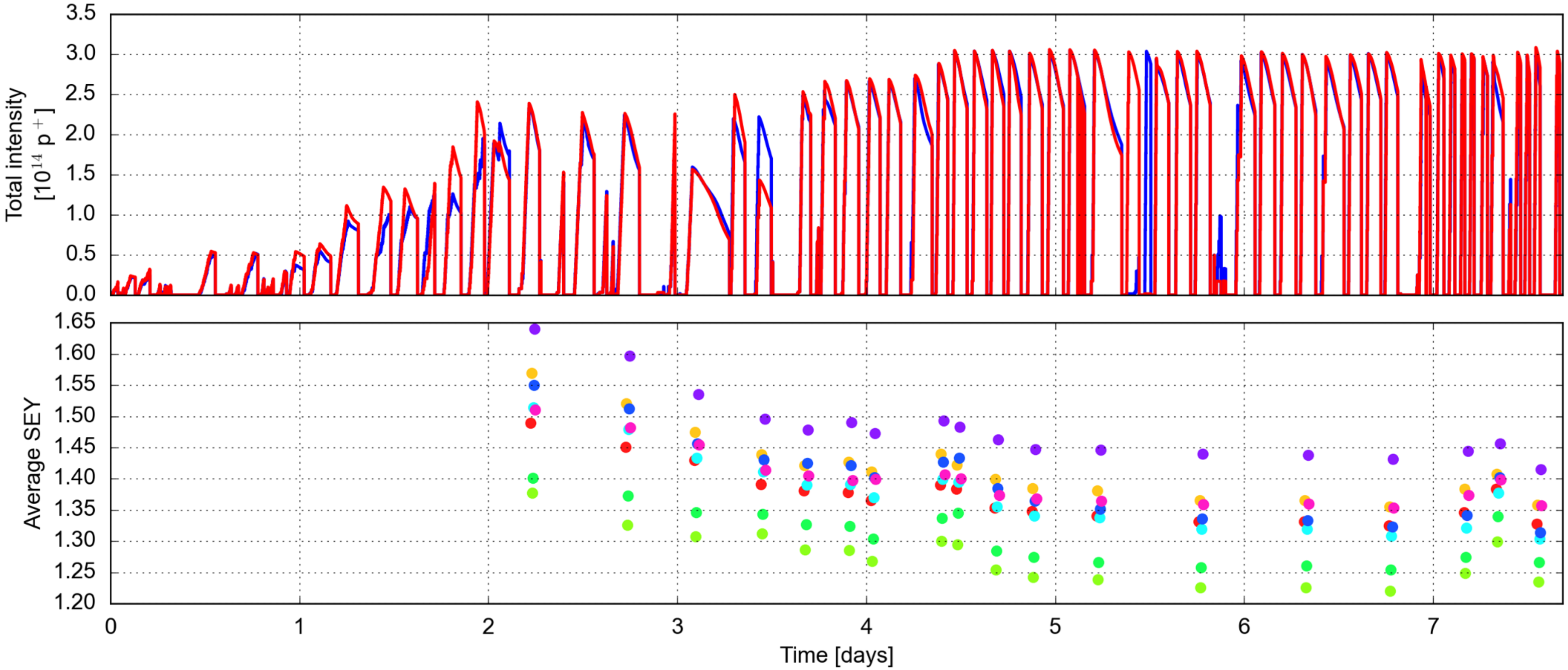
- Electrons are inevitably produced inside the LHC beam chamber. Seed electrons come e.g. from synchrotron radiation hitting the chamber's walls and ejecting electrons, or from the ionization of the residual gas.
- These electrons can subsequently be accelerated by the proton bunches. When they hit the vacuum chamber wall, they have a probability of ejecting more electrons, the cycle continues, and the electron cloud (e-cloud) is created.
- Parameter of interest is the Secondary Emission Yield (SEY), which is the average number of electrons produced per impact
- E-cloud both affects beam quality and considerable increases heat load on cryogenic system -> Potential limitation + electricity cost!
- Mitigation: 'Scrubbing' runs where increased bunch intensity and train lengths are injected to condition the beam screens

L. Mether

Electron cloud and cryogenic heat load

Evolution of the secondary emission yield (SEY) over the 2022 scrubbing run has shown a

- A clear reduction of the average SEY is observed in every sector
- Conditioning is initially fast and gets slower as the SEY decreases



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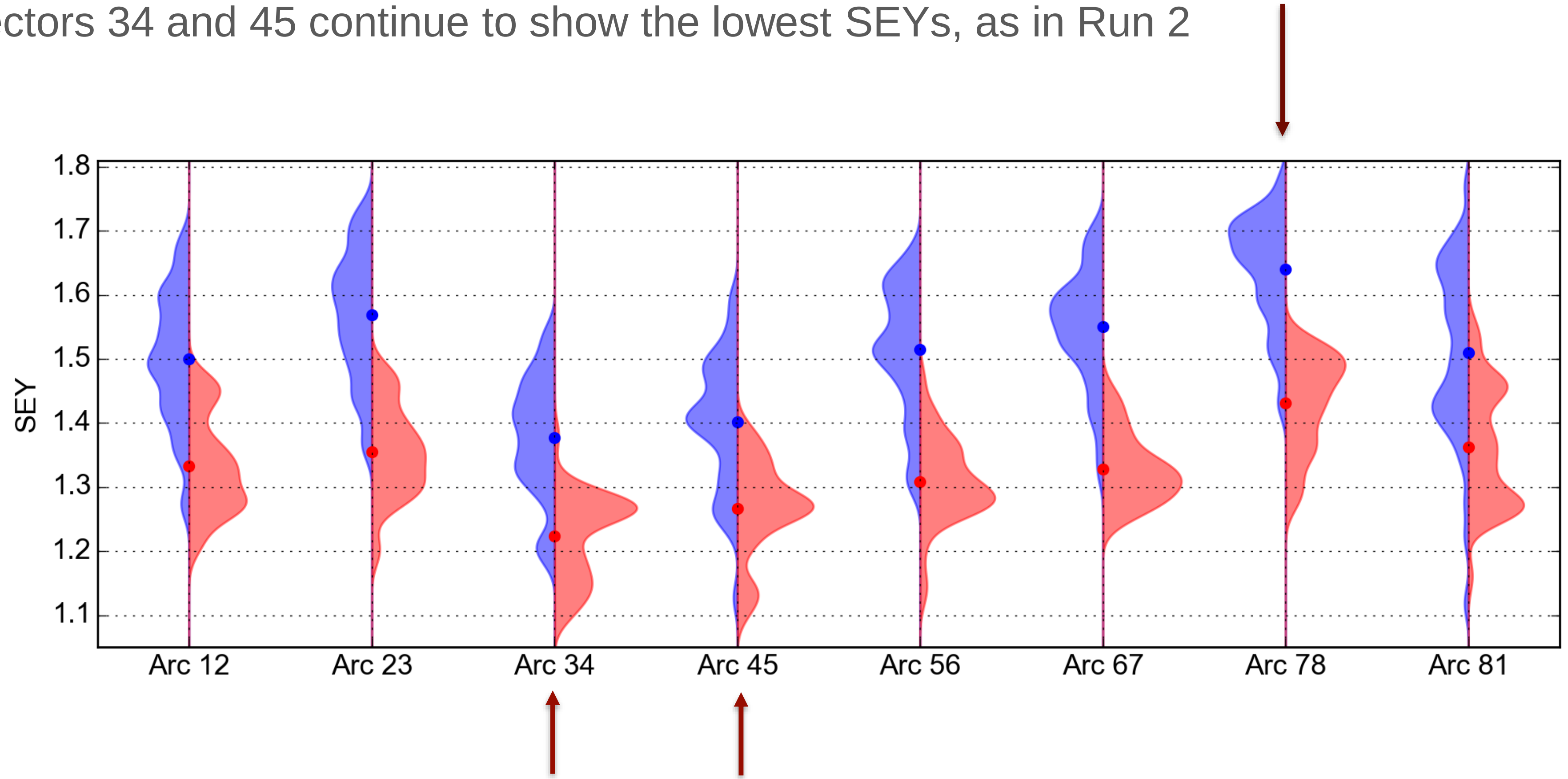
SEY evolution over scrubbing run

- Significant conditioning has taken place in every sector
  - Sector 78 showed significantly higher SEY than the other sectors from the beginning, and stays higher even after conditioning
  - Sectors 34 and 45 continue to show the lowest SEYs, as in Run 2



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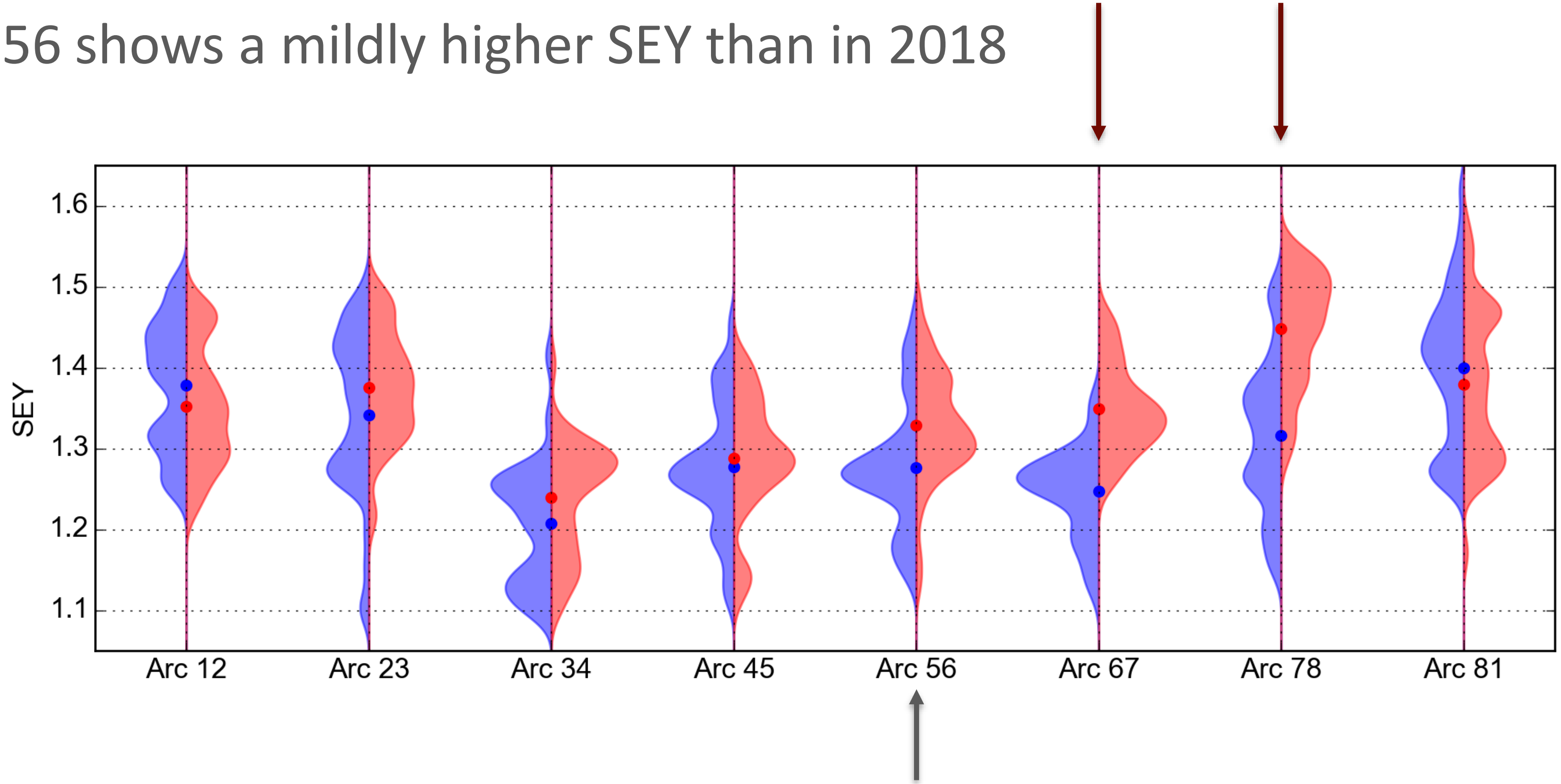
SEY comparison to 2018

A first analysis has been performed to compare the present cell-by-cell SEY to 2018

- In most sectors, the SEYs are currently very close to their 2018 values (at 450 GeV)
  - The differences are within the error bars of the analysis
- Sectors 67 and 78 still show much higher SEY than in 2018
- Sector 56 shows a mildly higher SEY than in 2018



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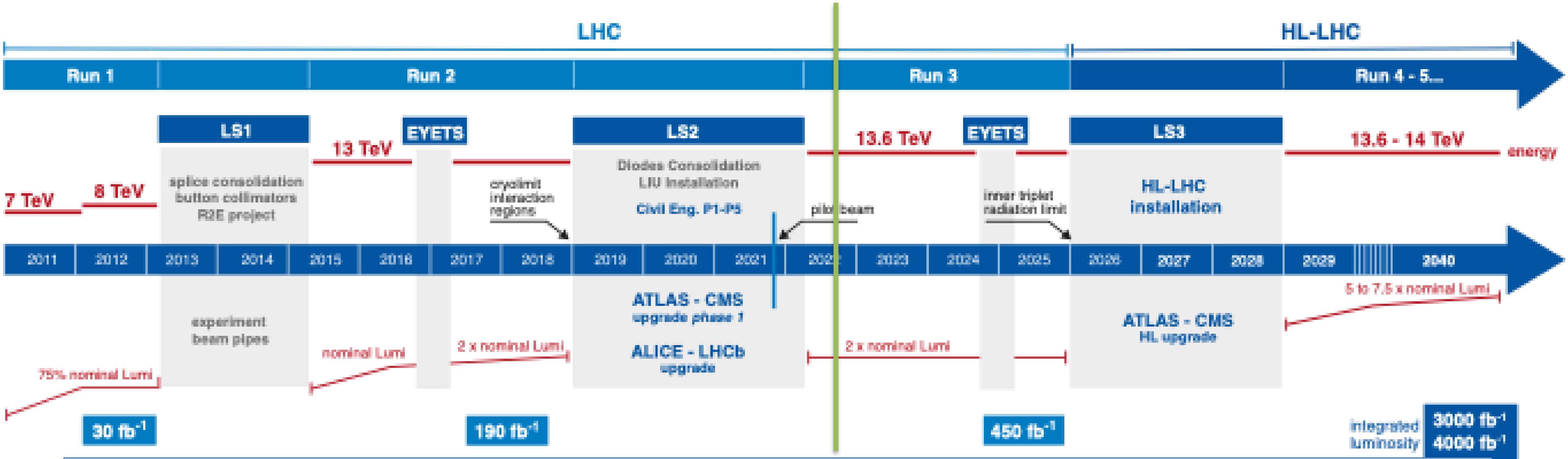
LHC / HL-LHC Plan



Run3 (physics production) started in July 2022!

Beam Energy for Run3 fixed @ 6.8 TeV

Long EYETS 2024-25

LS3 shifted by 1 year and extended to 3 years

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

➔ But shifts the IT String operation to 2025

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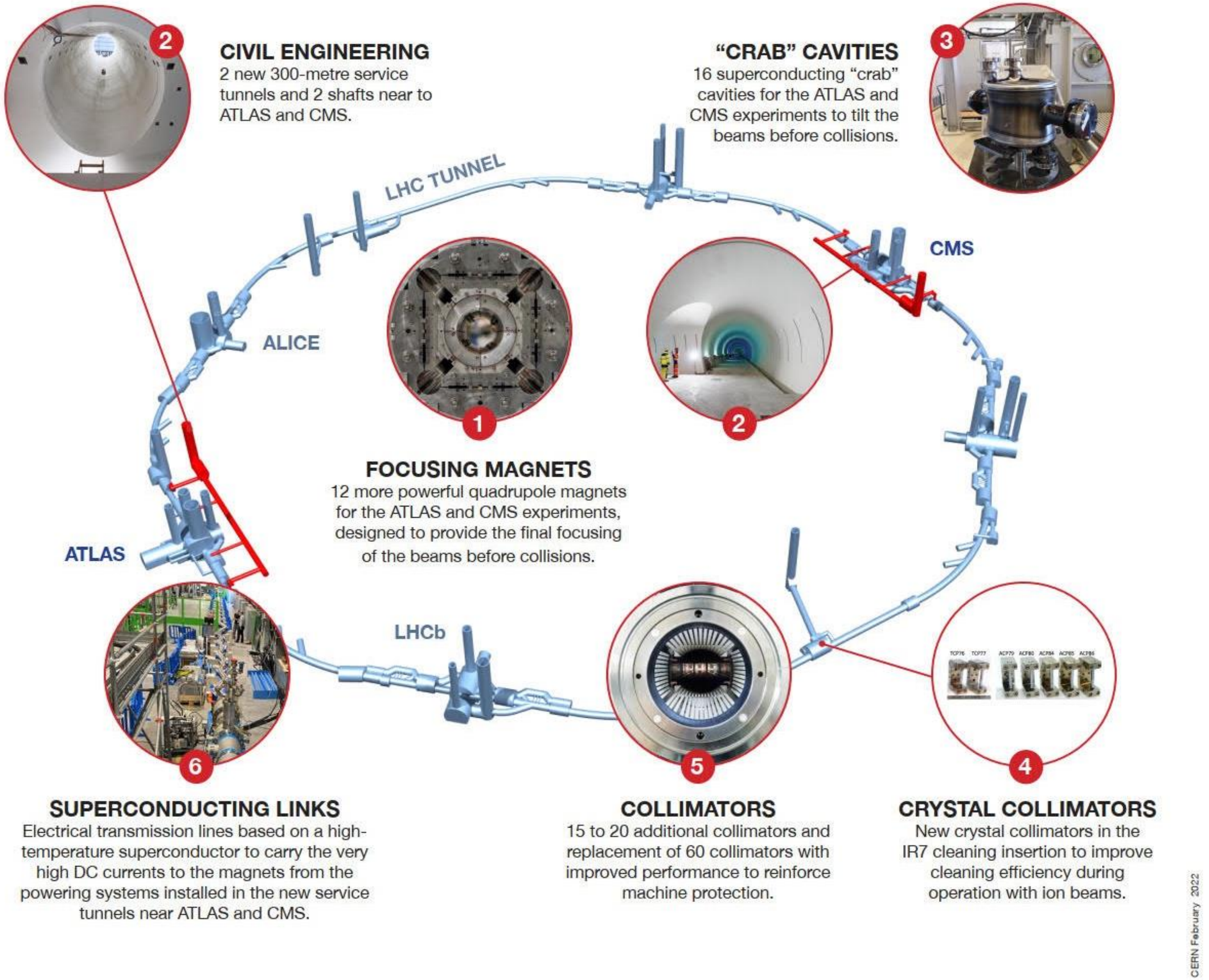
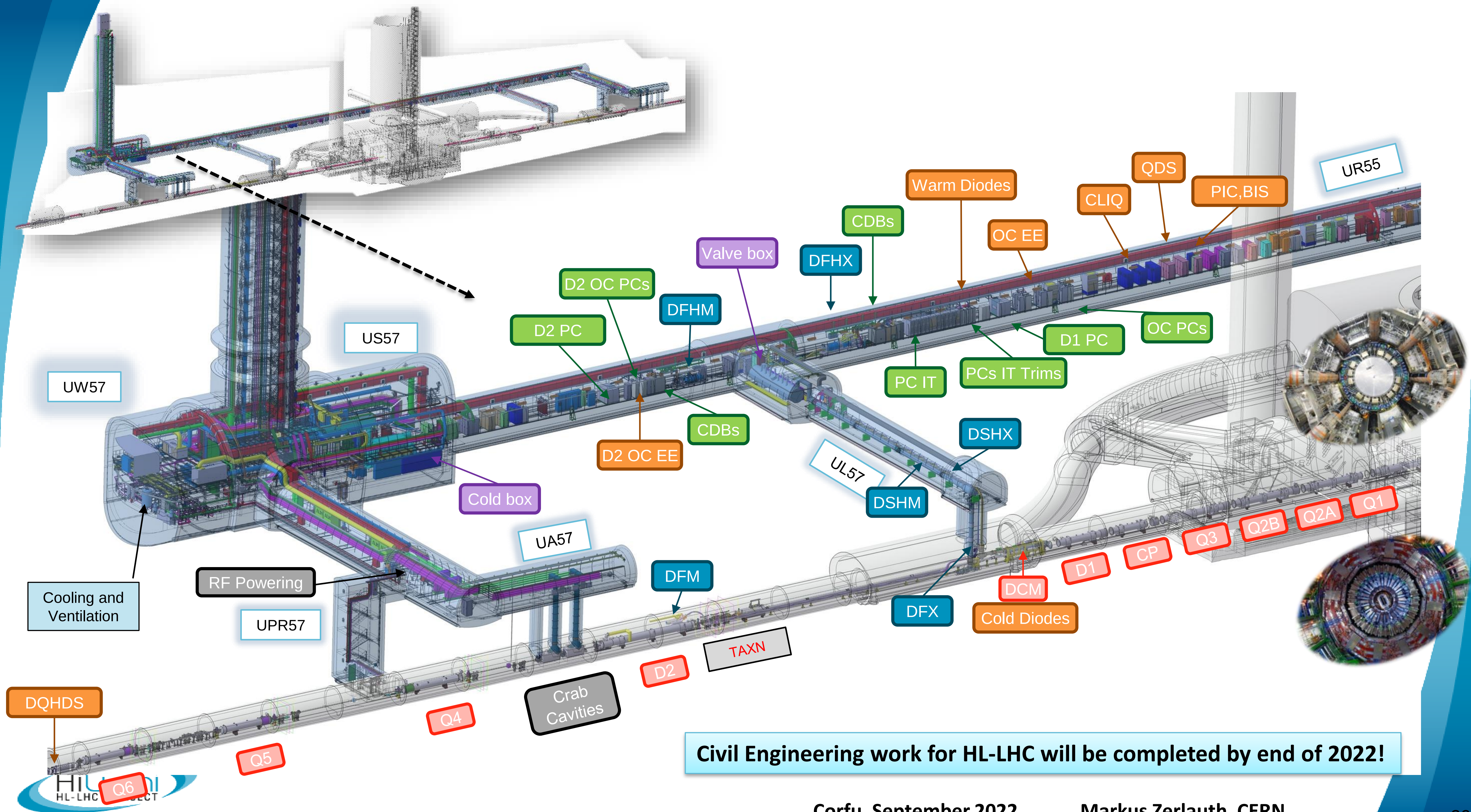
HL-LHC technology landmarks

No accelerator project has so many challenging novelties covering such a broad technology spectrum

Technology intensive project!



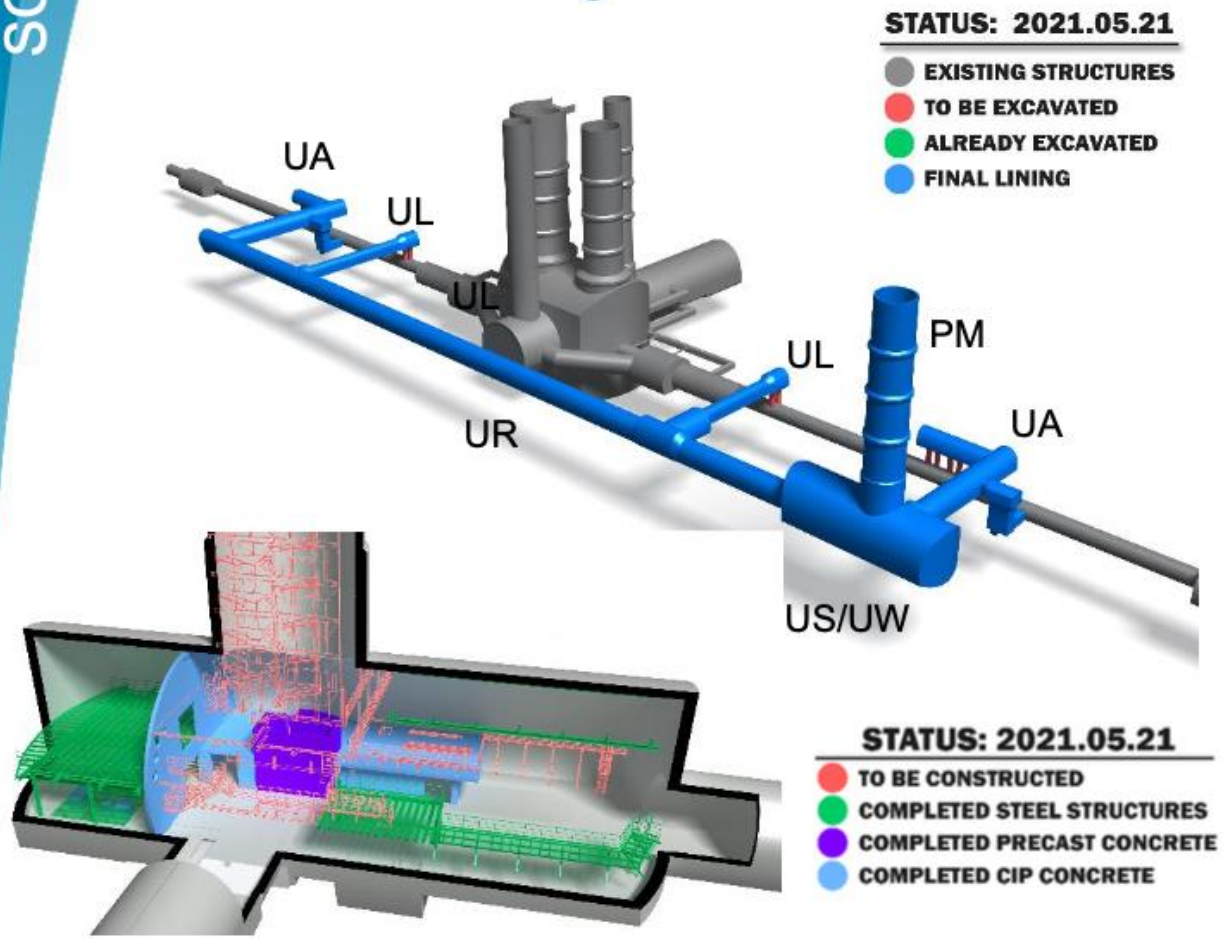


Civil Engineering work for HL-LHC will be completed by end of 2022!

HL-LHC civil engineering status (Point 1)

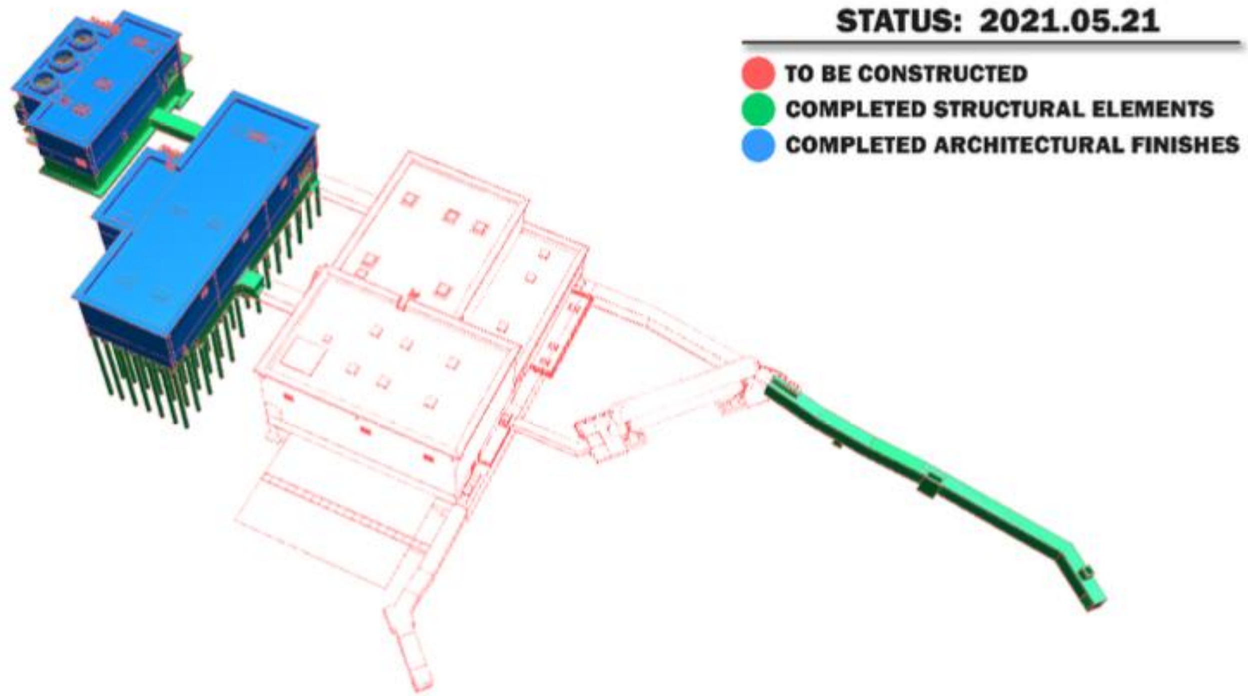
Overall progress Sep '21: 69%

Underground



Expected completion by October 2021 (including + ~1 month due to Covid-19)

Surface

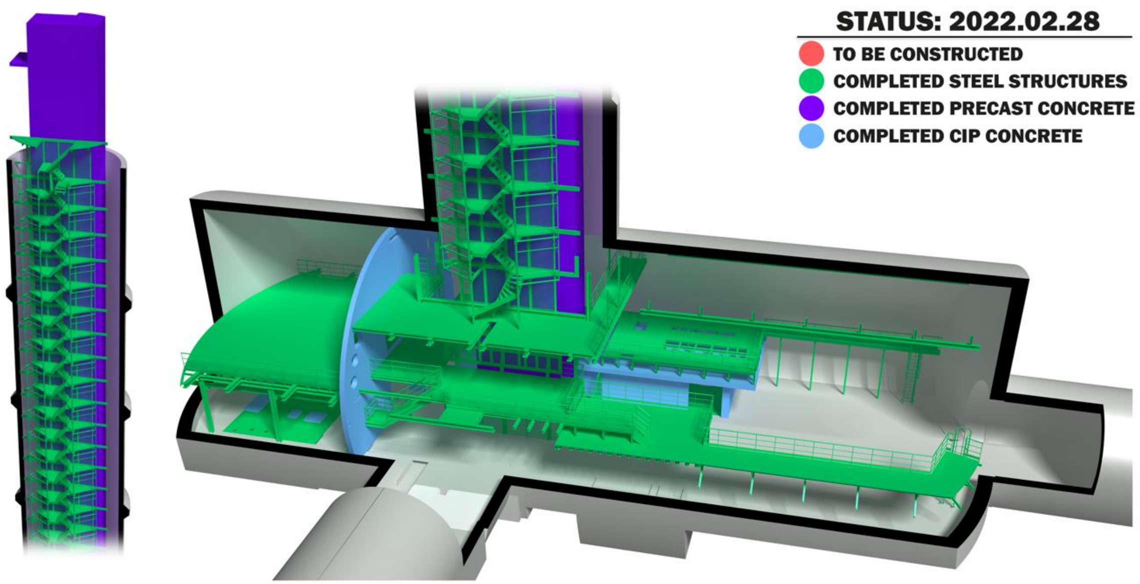


Expected completion by September 2022 (Including + ~1 month due to Covid-19)

HL-LHC civil engineering status (Point 1)

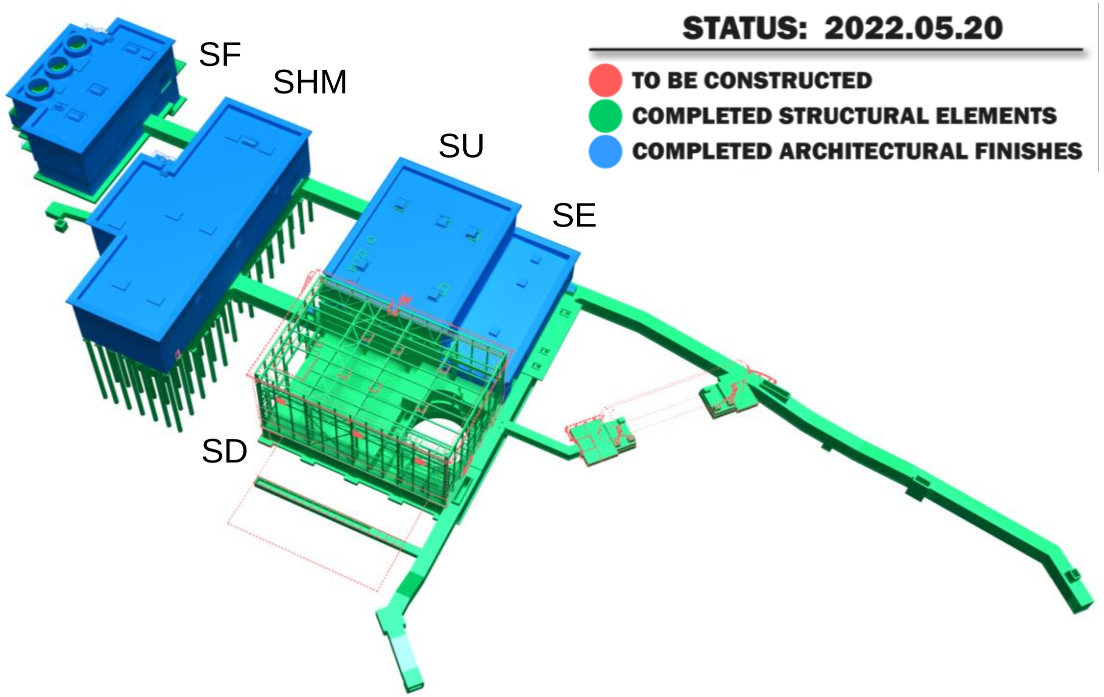
Overall progress today: 98%

Underground



Completed 2021
(including + ~1 month due to Covid-19)

Surface



Expected completion by September 2022
(Including + ~1 month due to Covid-19)

HL-LHC civil engineering status (Point 1)

SF (cooling tower) building

SF17

SF57

L. Tavian, HL-LHC TCC, WP17, 09 Jun'22

SHM (cryo-compressor) buildings

SHM17

SHM57

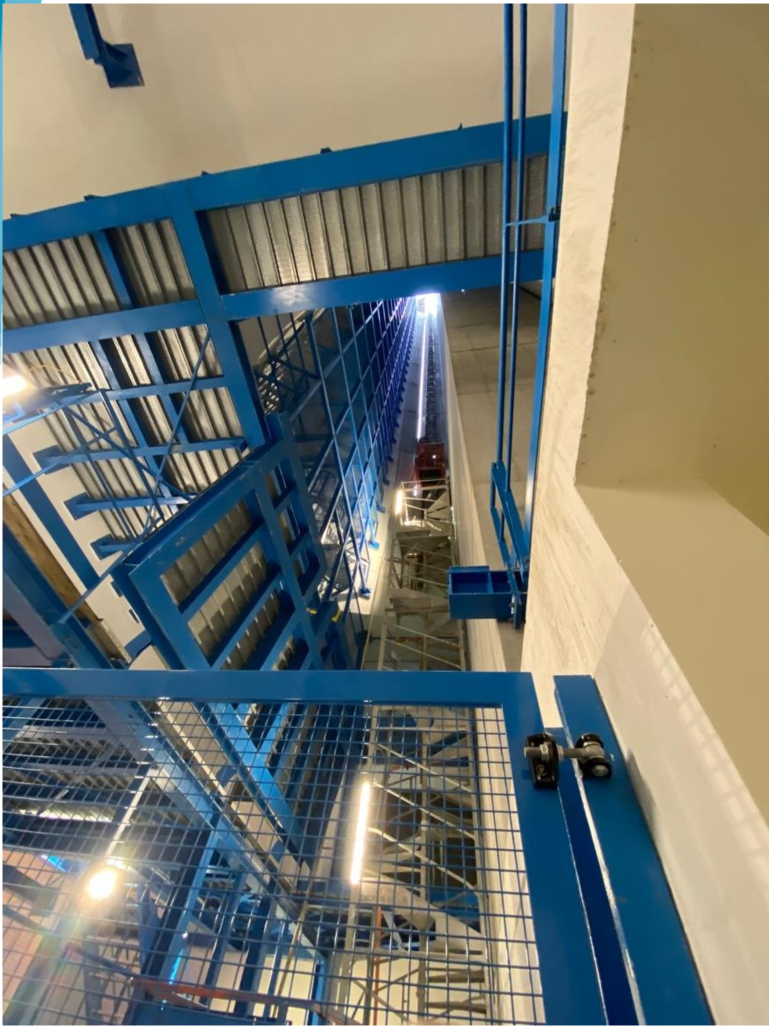
CV room
(plenum installation)

Inauguration Ceremony planned for December 2022

Markus Zerlauth, CERN

Underground works at P5

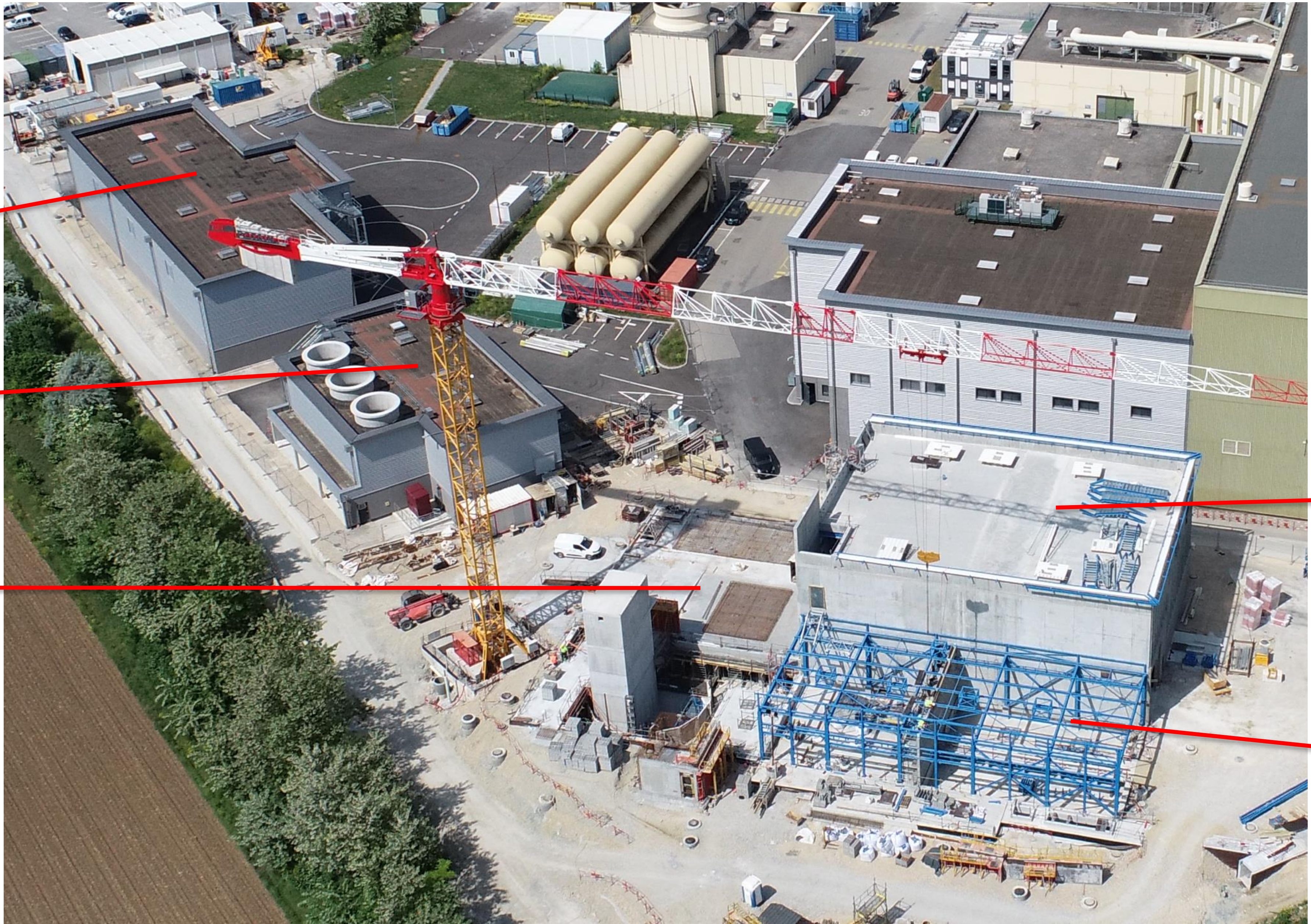
US57 cavern



PM57 shaft

UR55 gallery

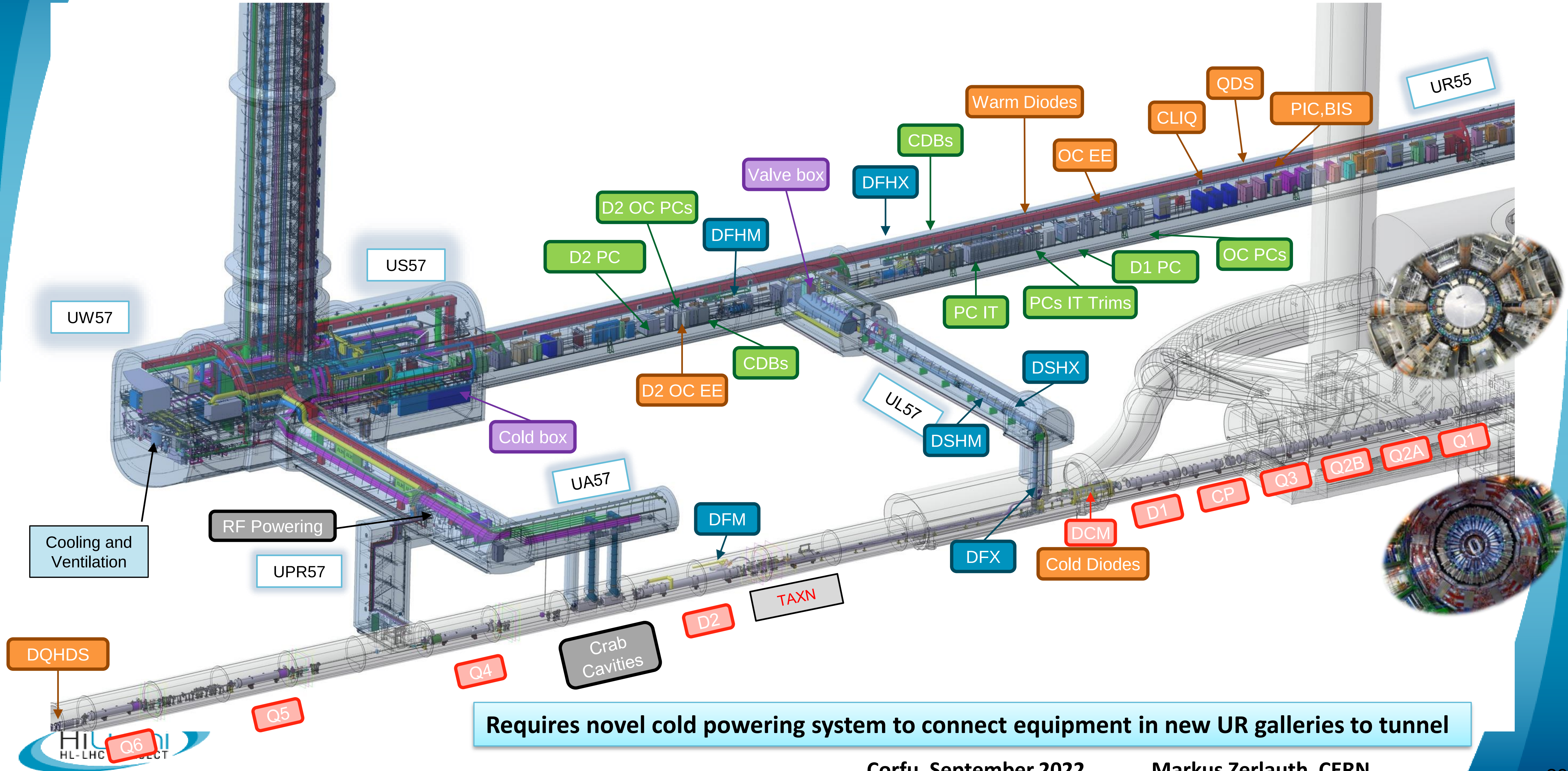
Delivery of the SF57 & SHM57 buildings



Technical galleries

Point 1

Point 5

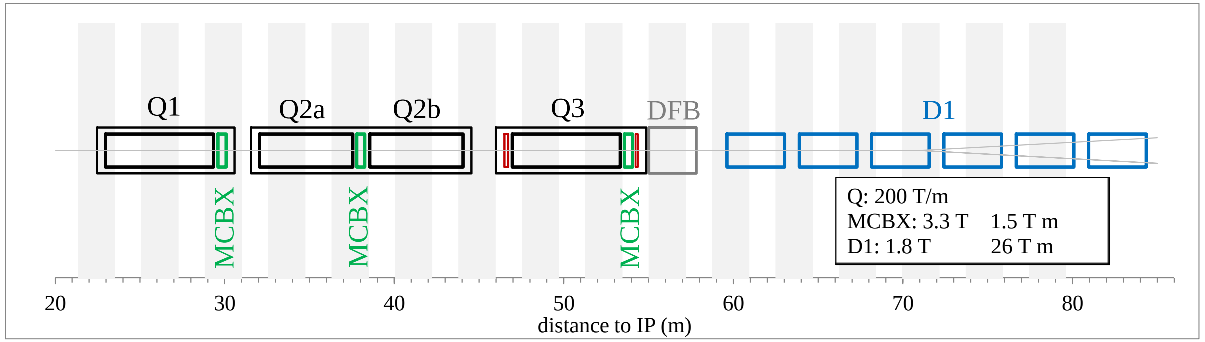


Requires novel cold powering system to connect equipment in new UR galleries to tunnel

New interaction region layout

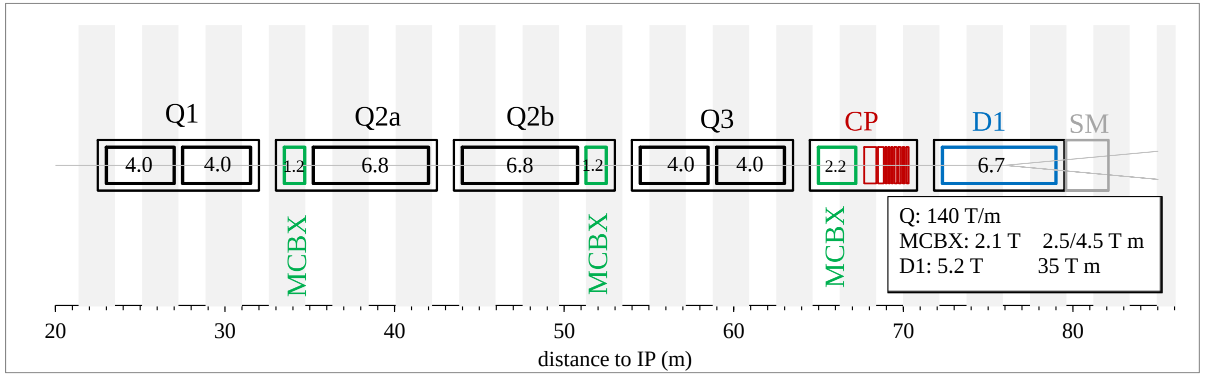
- New insertion and final focusing magnets
  - Main quadrupole magnets MQXFA (Q1, Q3) from AUP and MQXFB (Q2) from CERN
  - Superconducting separation and recombination dipoles, D1 from Japan and D2 from Italy
  - Higher Order Corrector package (CP) and orbit correctors (MCBX) from Italy and Spain

ATLAS CMS



LHC

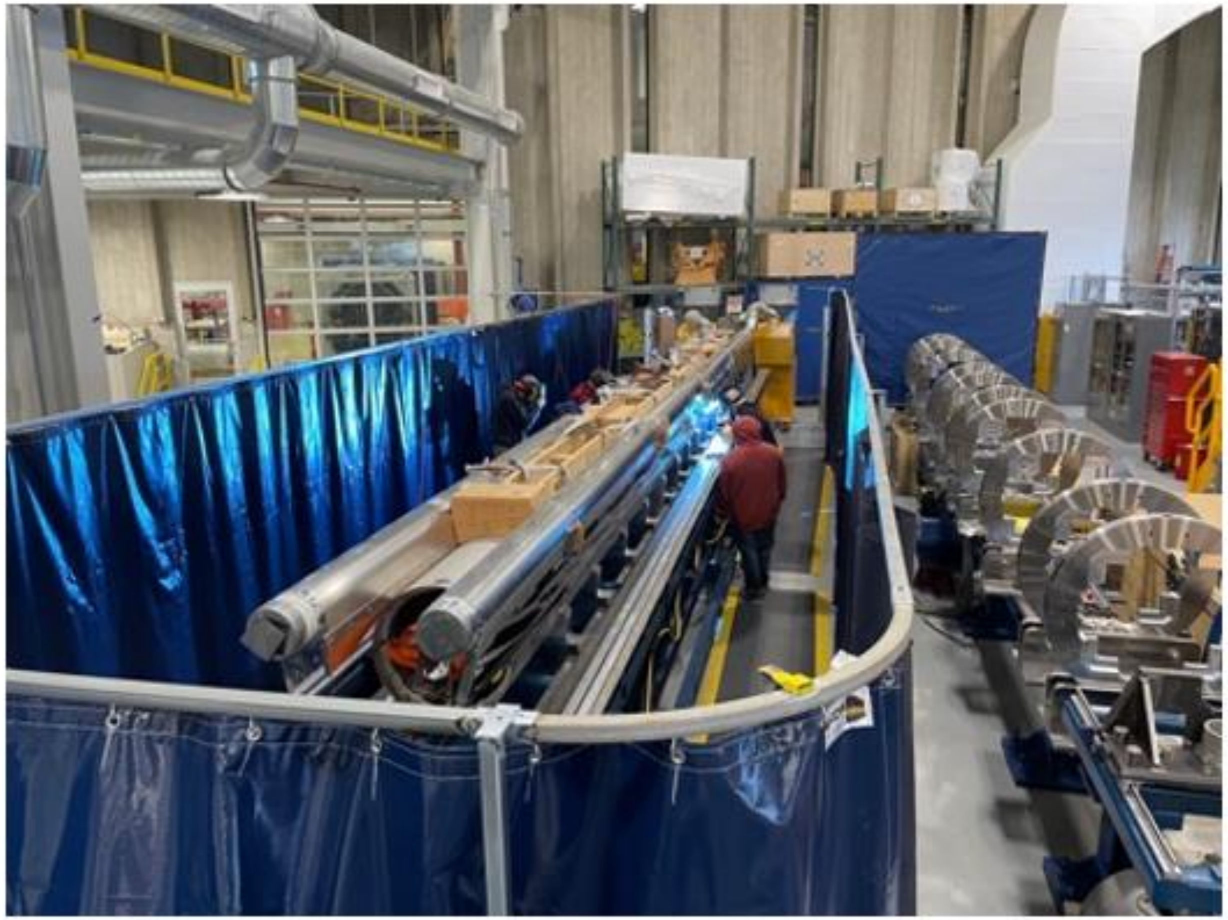
ATLAS CMS



HL-LHC

Update on MQXFA Cryo-Module Assembly

Fitting of bottom SS shell and longitudinal welding

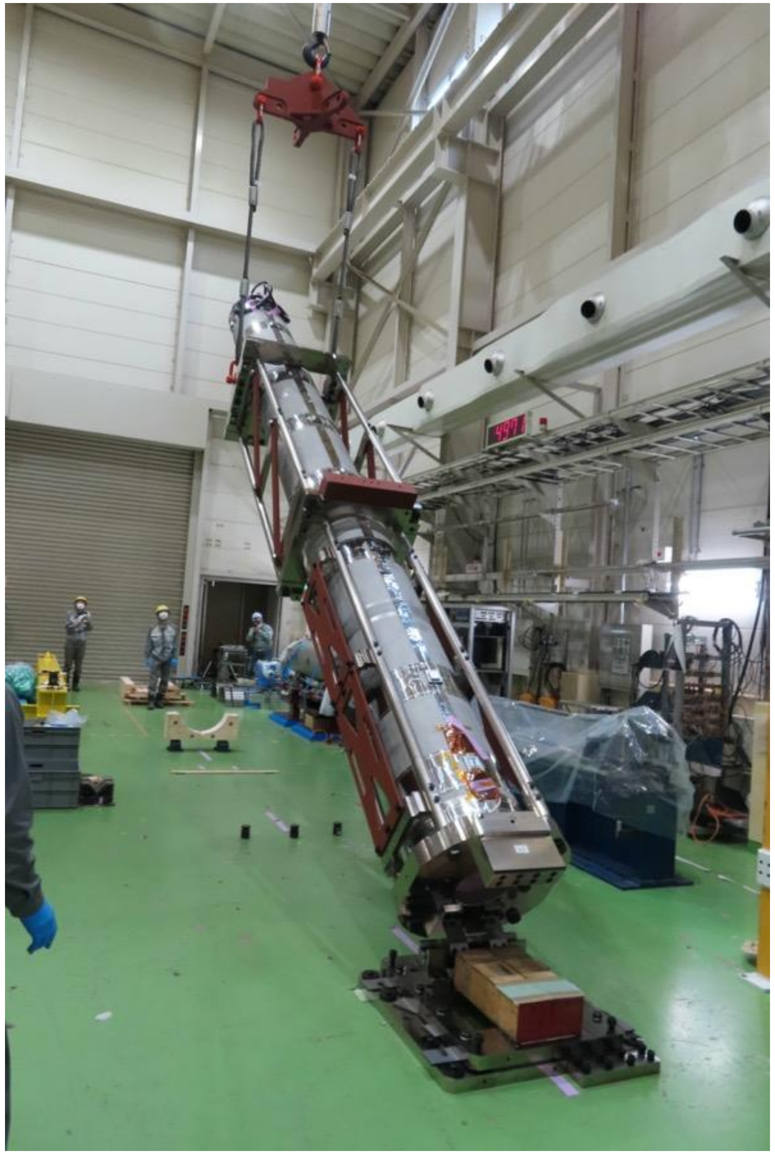


Update on MQXFB cold tests

- August 2022: MQXFBP3 test @ SM18:
  - Re-welded cold-mass from MQXFB01 with lower pre-stress of stainless-steel shell
  - But still using coils from initial production

Testing of D1 Prototype at KEK

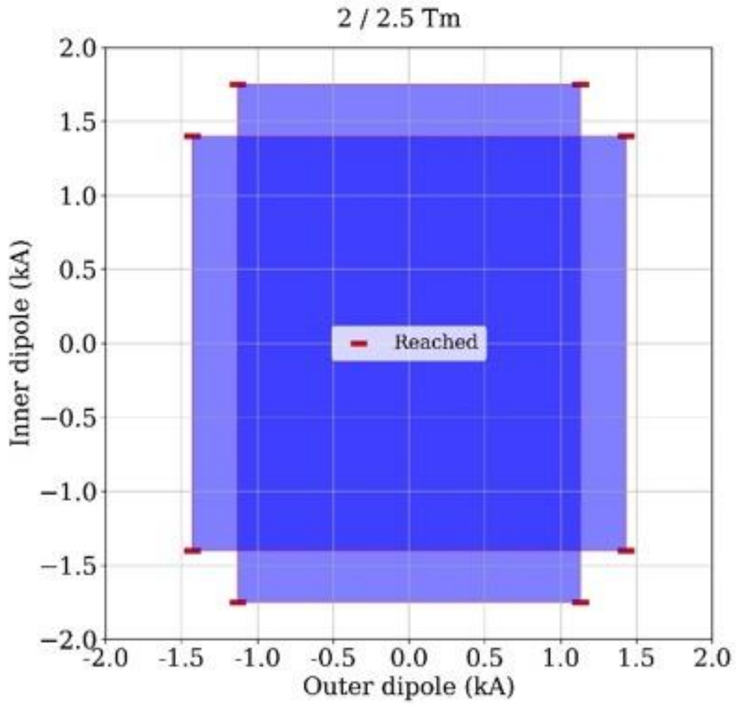
- Lifting up the D1 magnet



- Insertion into vertical cryostat

MCBXFBP2c: Cold Powering tests results

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



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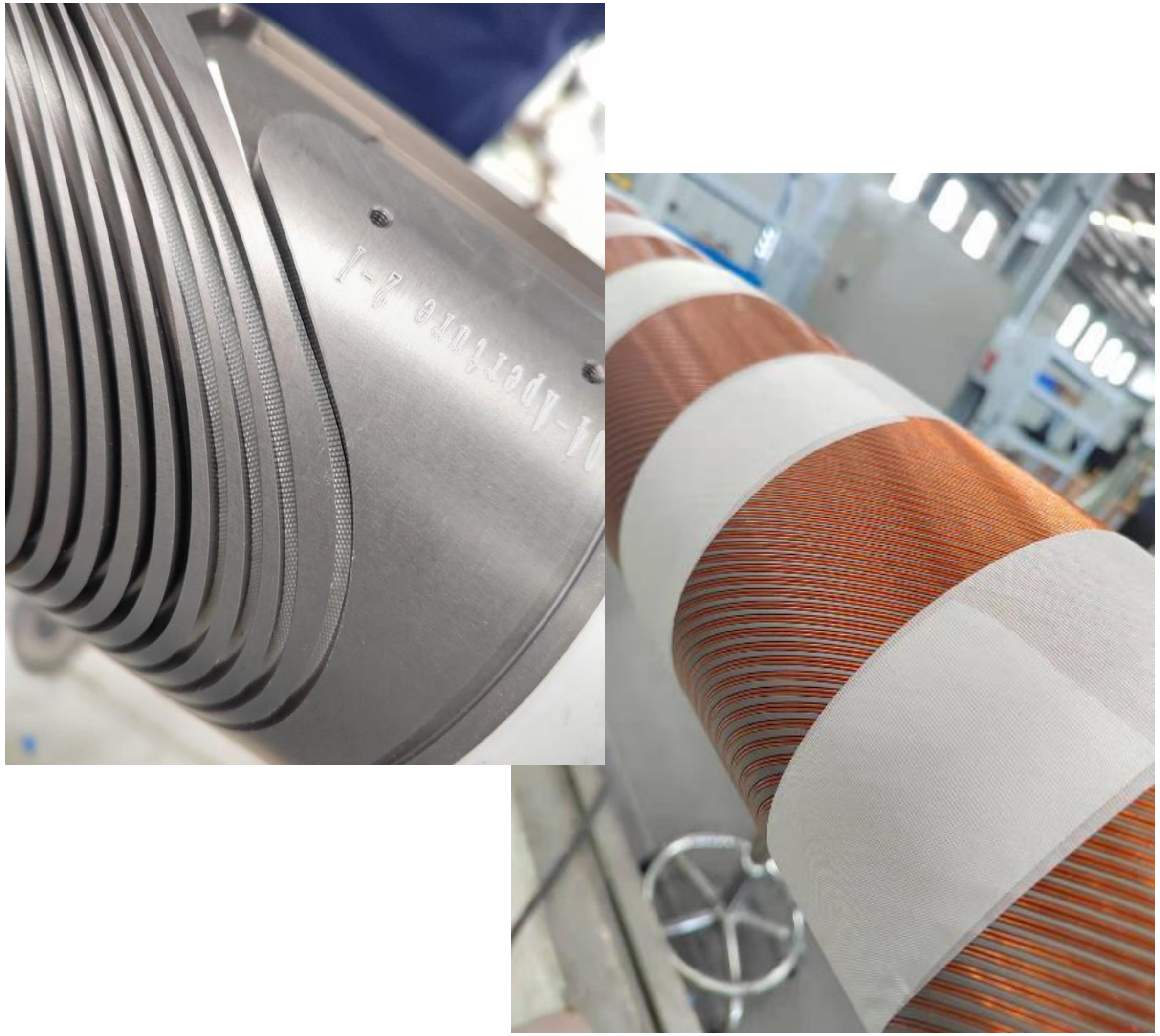
D2 Cold-Mass Assembly

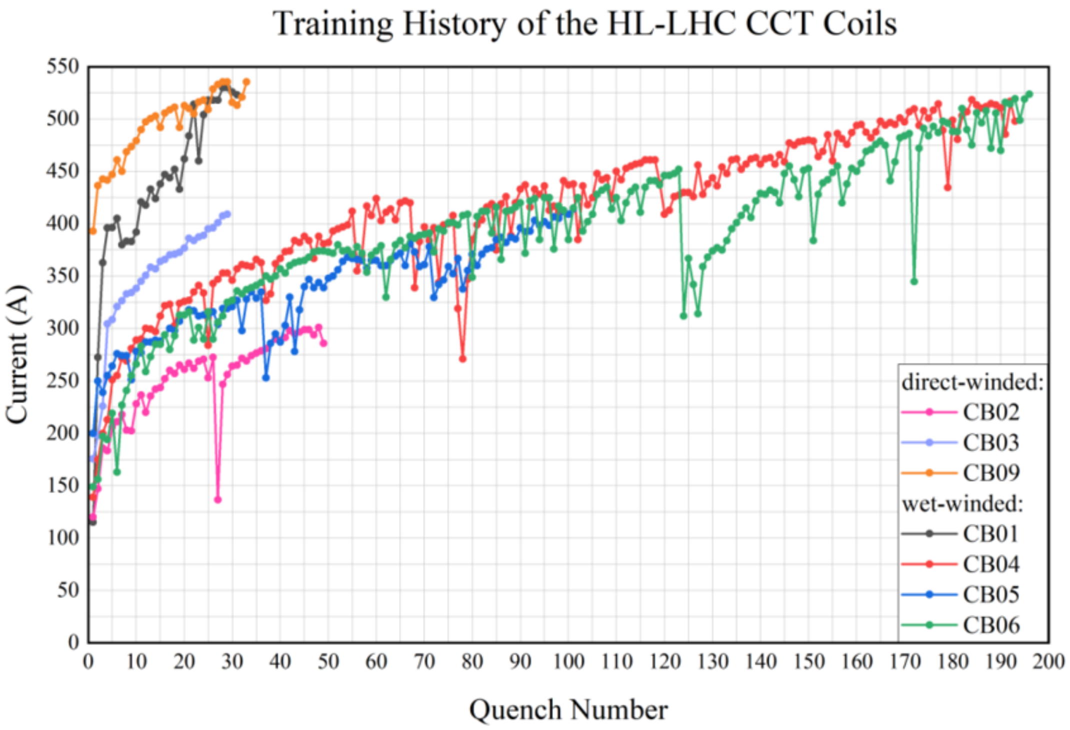
D2 Prototype on the test bench in SM18

D2 Prototype Cold-

Timeline: Main Milestones in 2022

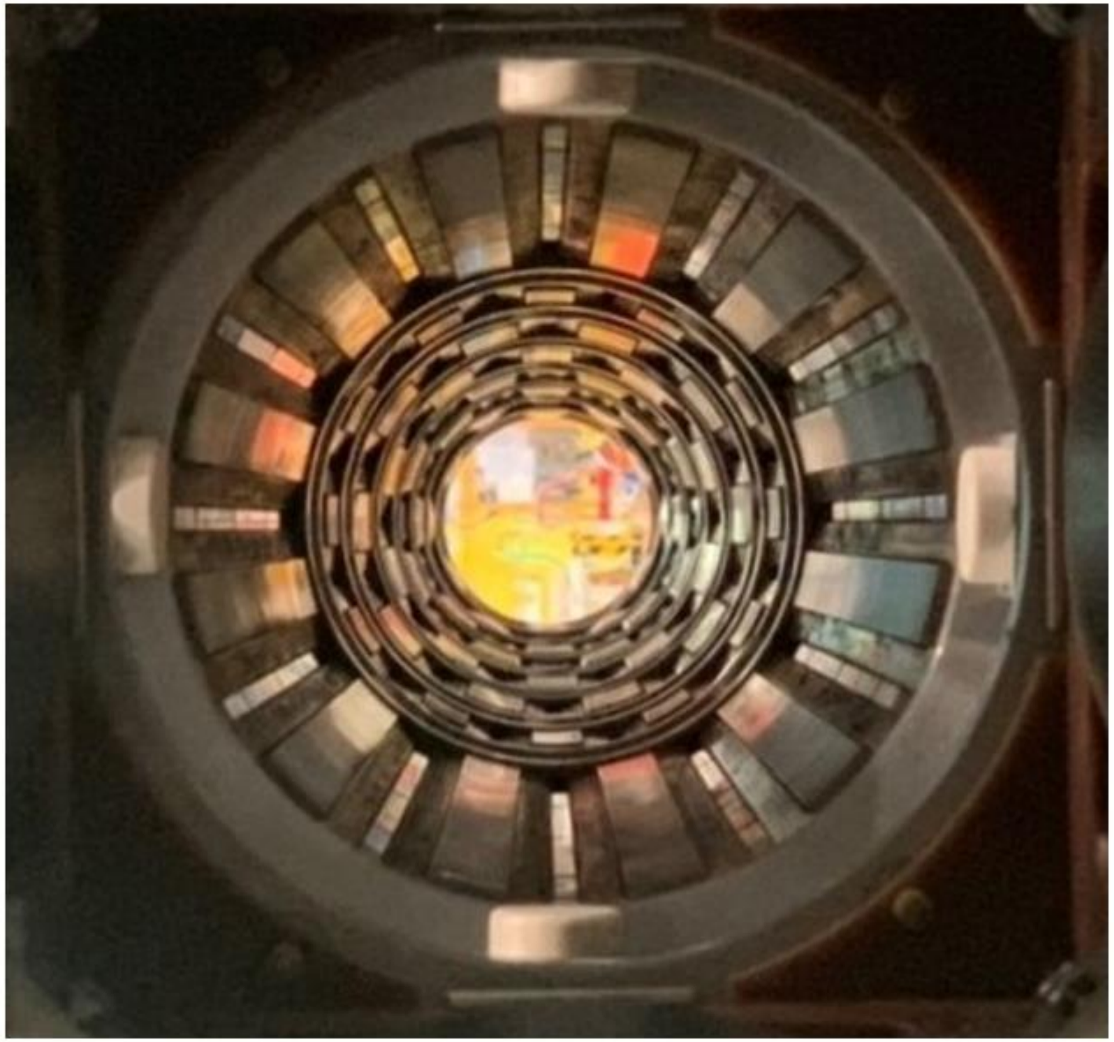
- July 2022: Canted Cosine Theta Corrector production at BAMA in China ➔ Iteration on former grooves and assembly procedure: CB09 and CB12 train faster ✓





Higher Order Corrector Package

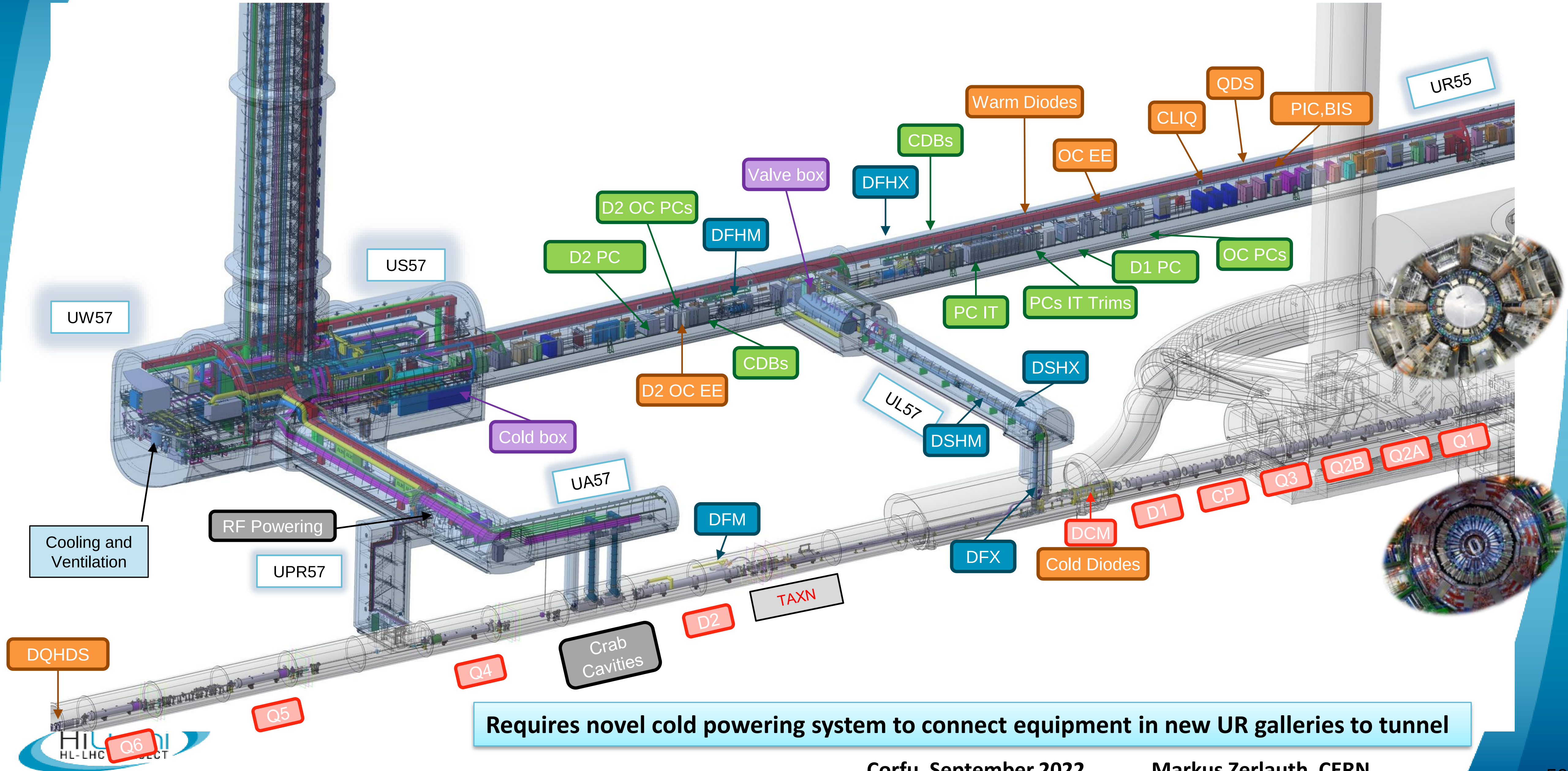
- November 2021: HO corrector manufacturing and assembly completed ✓



Sequence of corrector packages and preassembled cold mass

Timeline: Main Milestones still upcoming in 2022

- Fall 2022: cold test of first MQXFA horizontal Cold Mass
- Fall 2022: Cold test D2 Cryo Module
- End 2022: delivery of D1 Prototype to CERN
- End 2022: Cold test of MQXFB02 in SM18 [still using coils from initial production!]

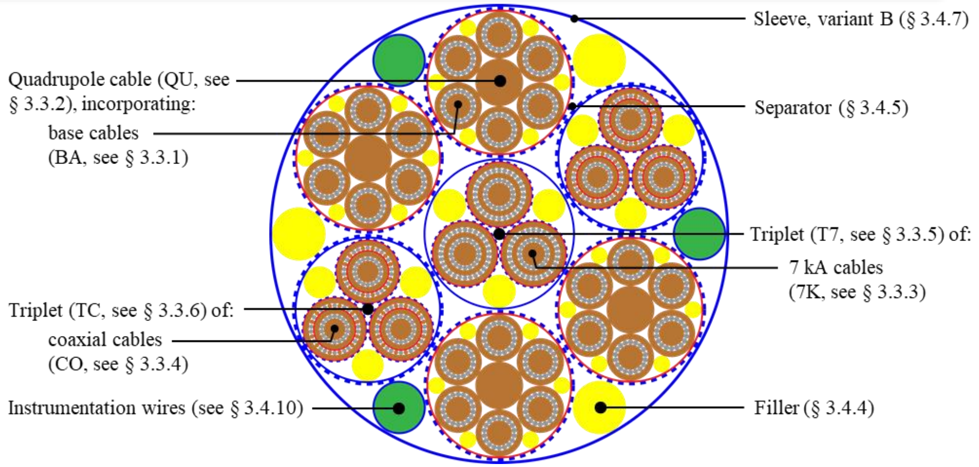


Requires novel cold powering system to connect equipment in new UR galleries to tunnel

MgB_2 Cable Assemblies (1/2)

Received from ICAS **2nd** (Triplets) and **3rd** (Matching Sections) MgB_2 series cables

Successfully HV tested both in industry and at CERN



$\Phi\sim$ 90 mm

- 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

To be produced: 5+5 Units

SC Link Cryostats

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

Leak/pressure tests at the company

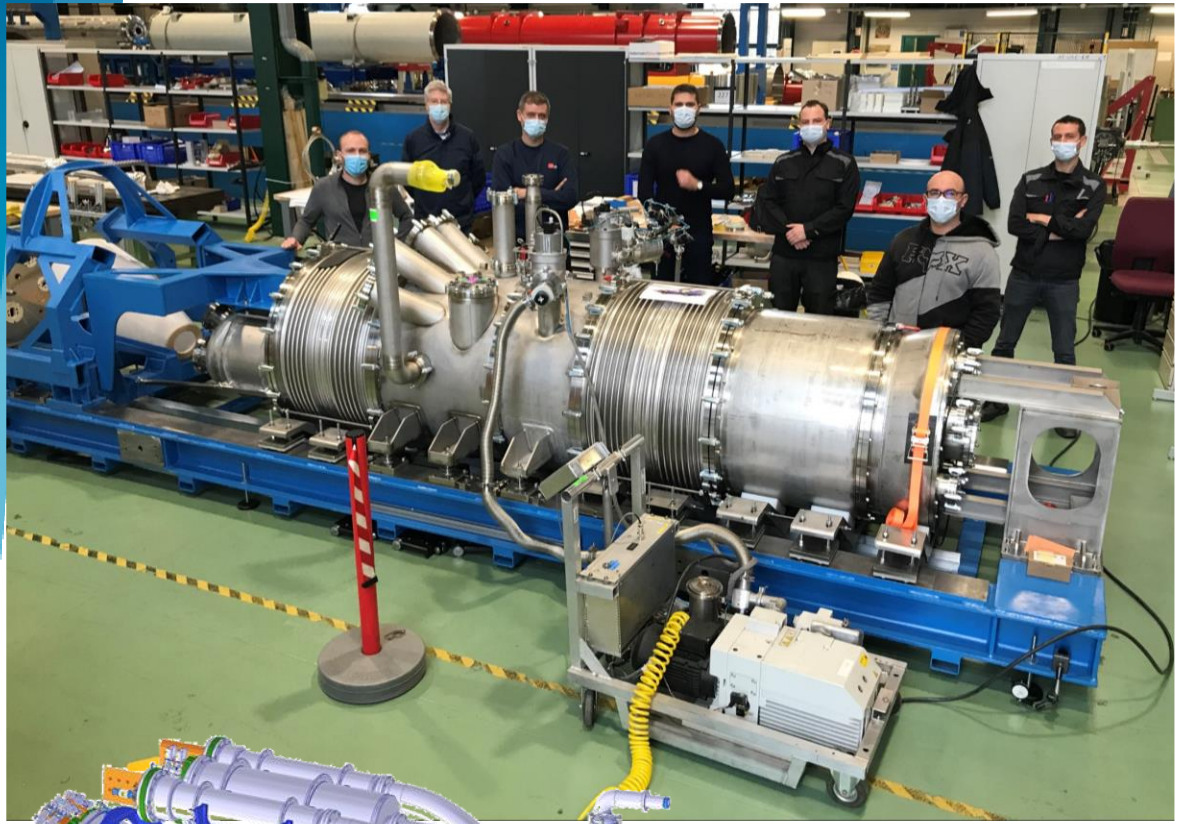
Delivery & Reception @ CERN

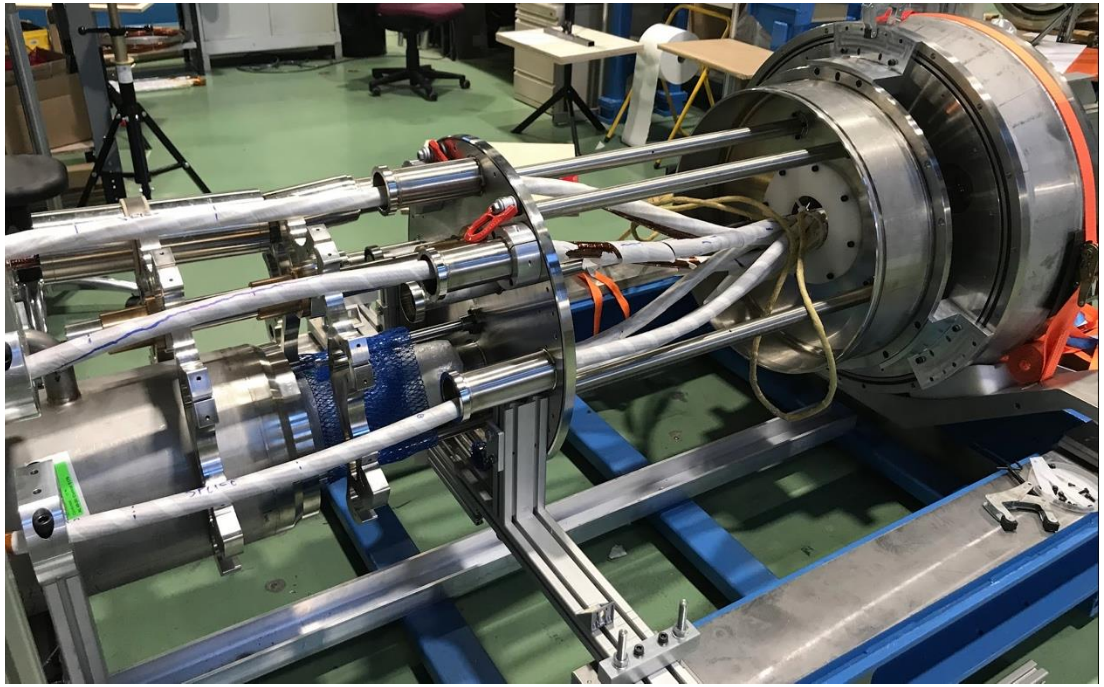
Final length for Triplets: 74.5 m

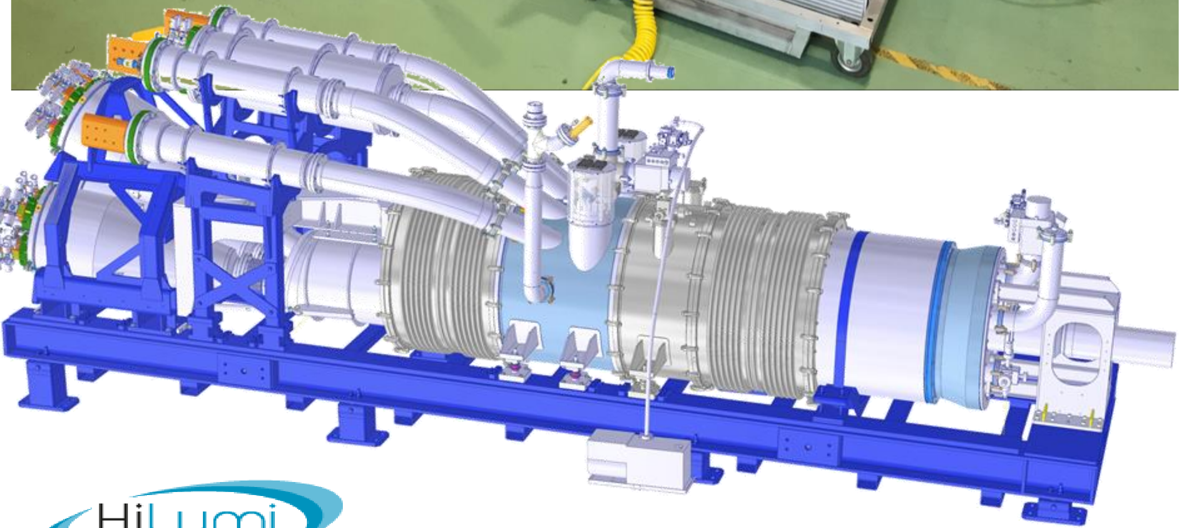
Optimization of leak test procedure

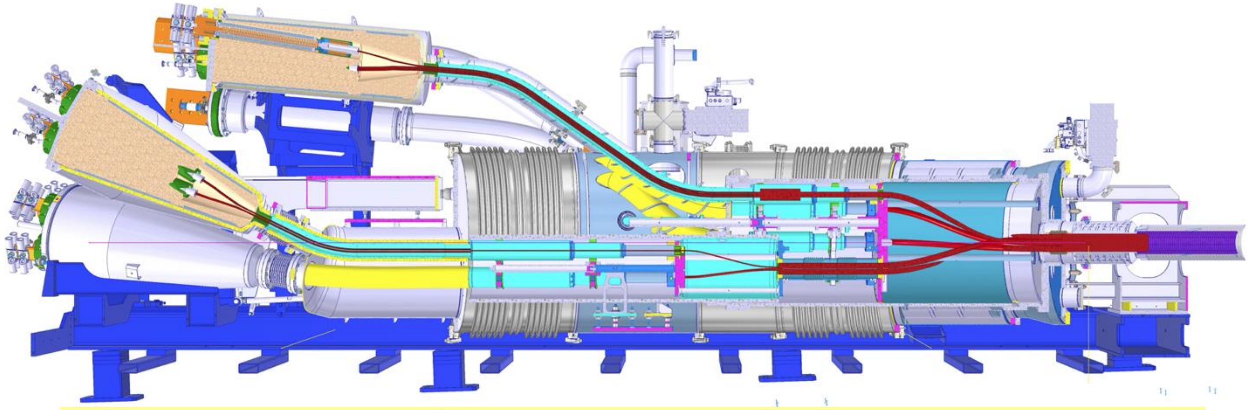
Visual and endoscopic inspections, dimension controls

First DFHX constructed @ CERN (2/3)





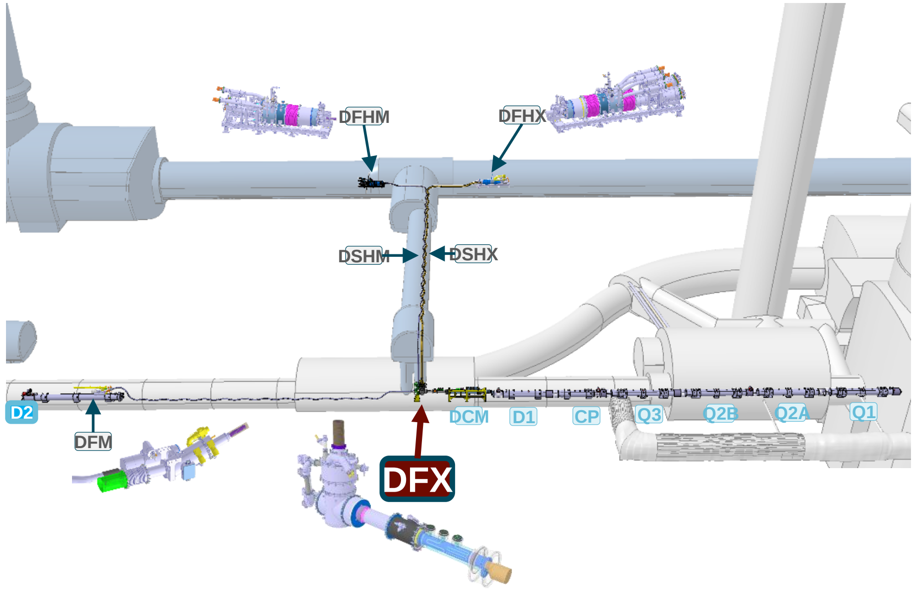




Completed **blank assembly of DFHX** and studied of MgB_2/HTS routing

DFX Cryostat

Completed **pre-series DFX** by SOTON (UK1) !

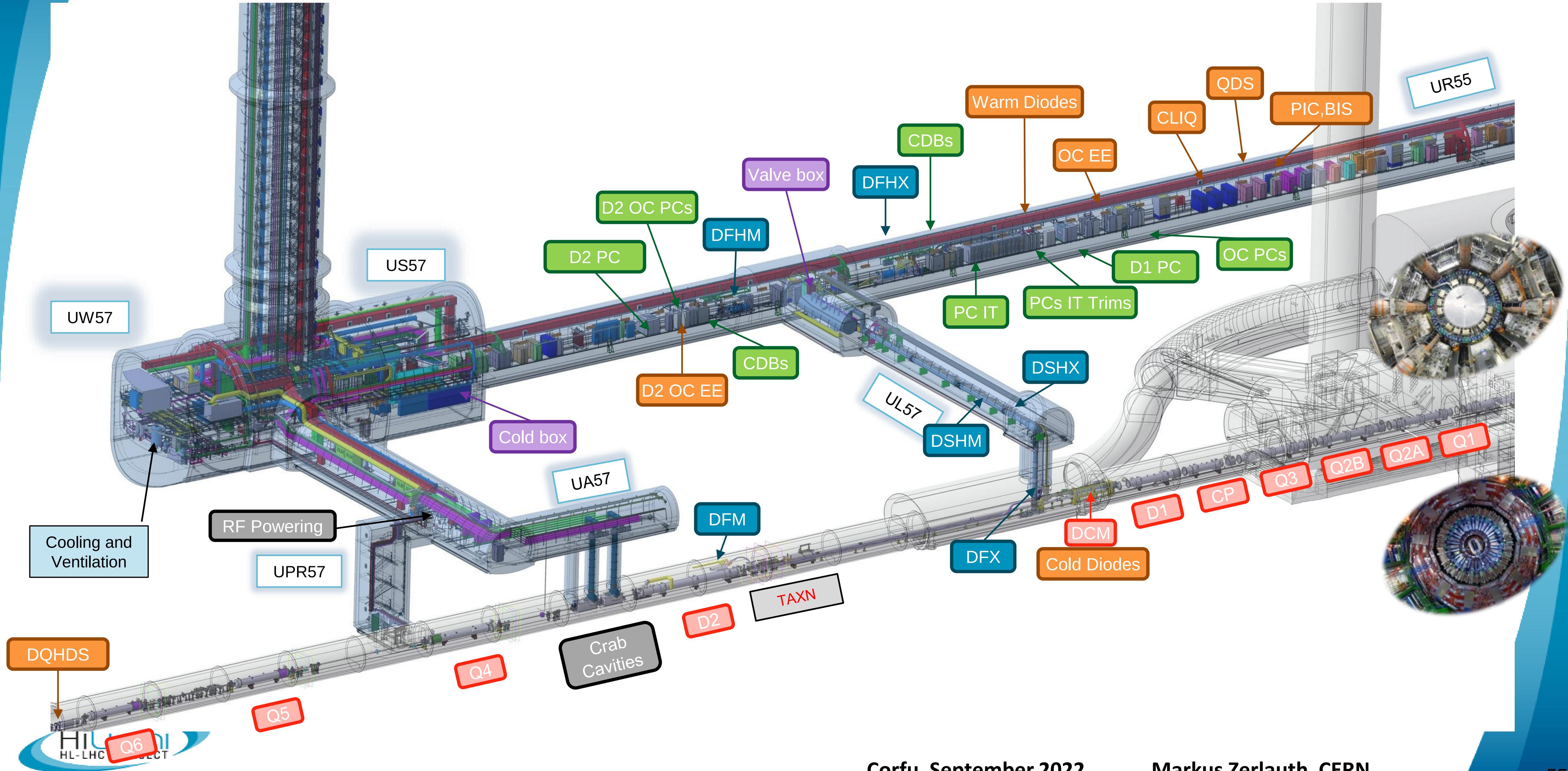


CERN-UK1 collaboration under addendum #4 of KE3299/TE/HL-LHC

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

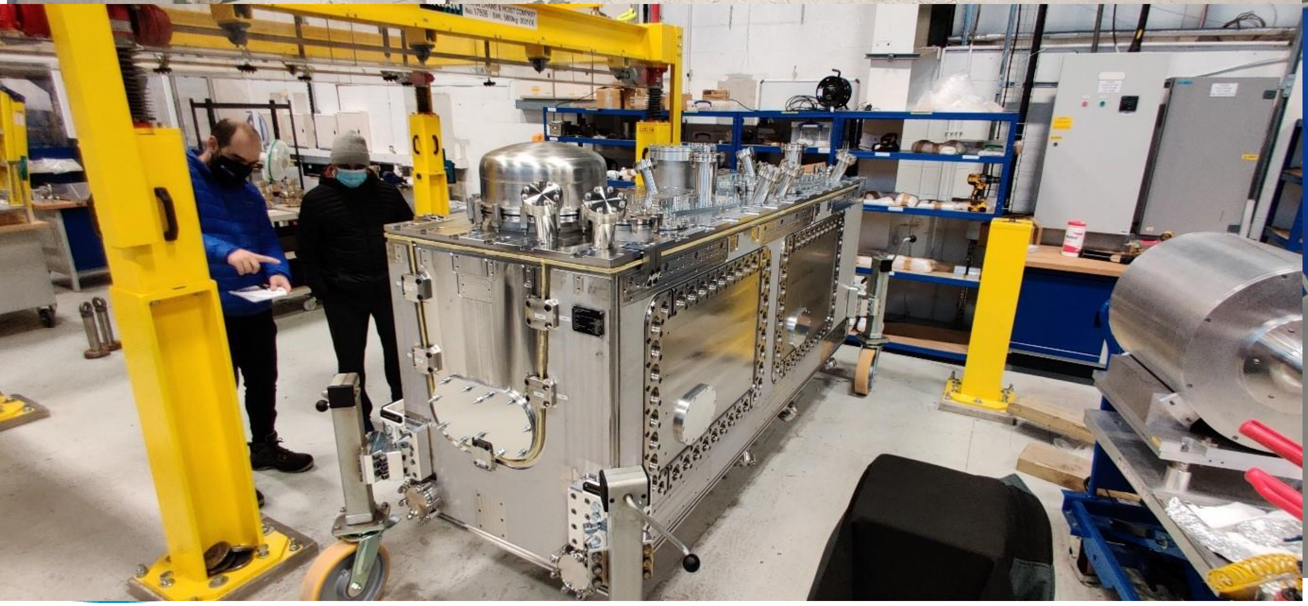
Completed in March 2022 at **LTI Metaltech** & **delivered to CERN**


UR55
QDS
Warm Diodes
CLIQ
PIC,BIS
CDBs
OC EE
Valve box
DFHX
D2 OC PCs
DFHM
D2 PC
US57
UW57
OC PCs
D1 PC
PC IT
PCs IT Trims
CDBs
D2 OC EE
DSHX
UL57
DSHM
Cold box
UA57
RF Powering
Cooling and Ventilation
UPR57
DFM
DFX
DCM
Cold Diodes
Q1
Q2A
Q2B
Q3
CP
D1
TAXN
D2
Crab Cavities
Q4
Q5
Q6
DQHDS

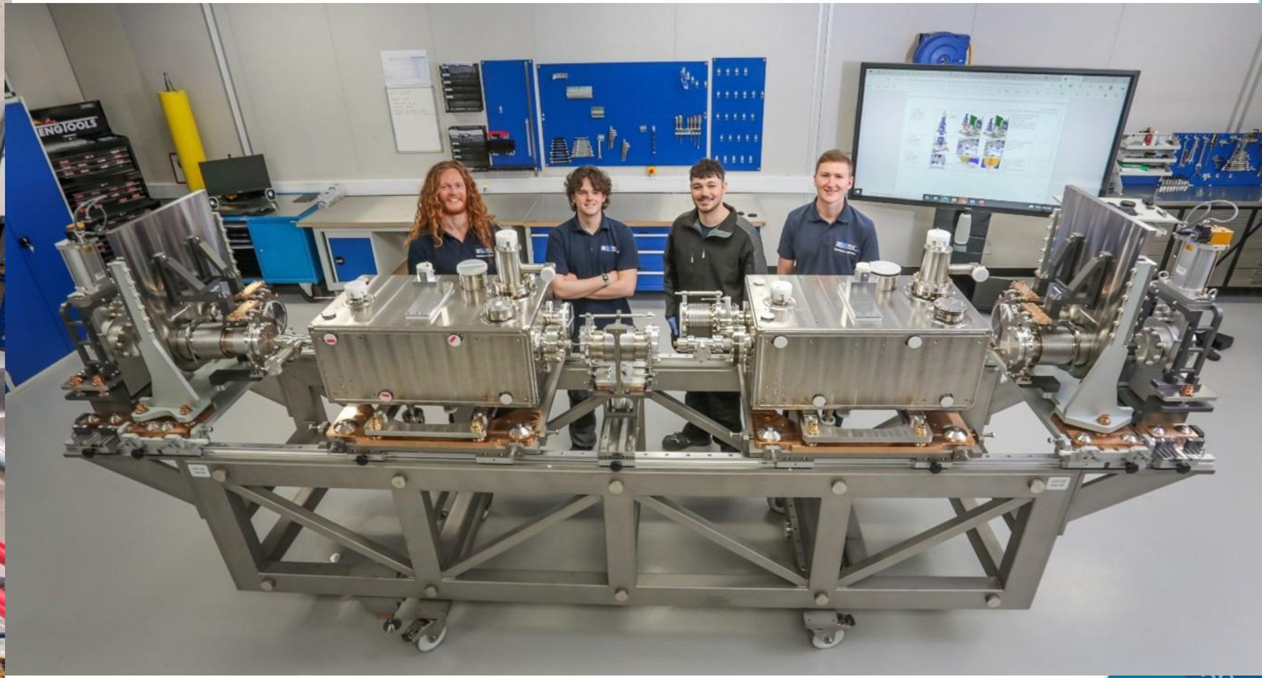
Update on RFD Cryo-Module

RFD Cavity in Transport Frame on arrival at Daresbury Laboratory

Completed RFD Cryo-Module to be installed in SPS for final beam validation in 2024



Outer vacuum Chamber

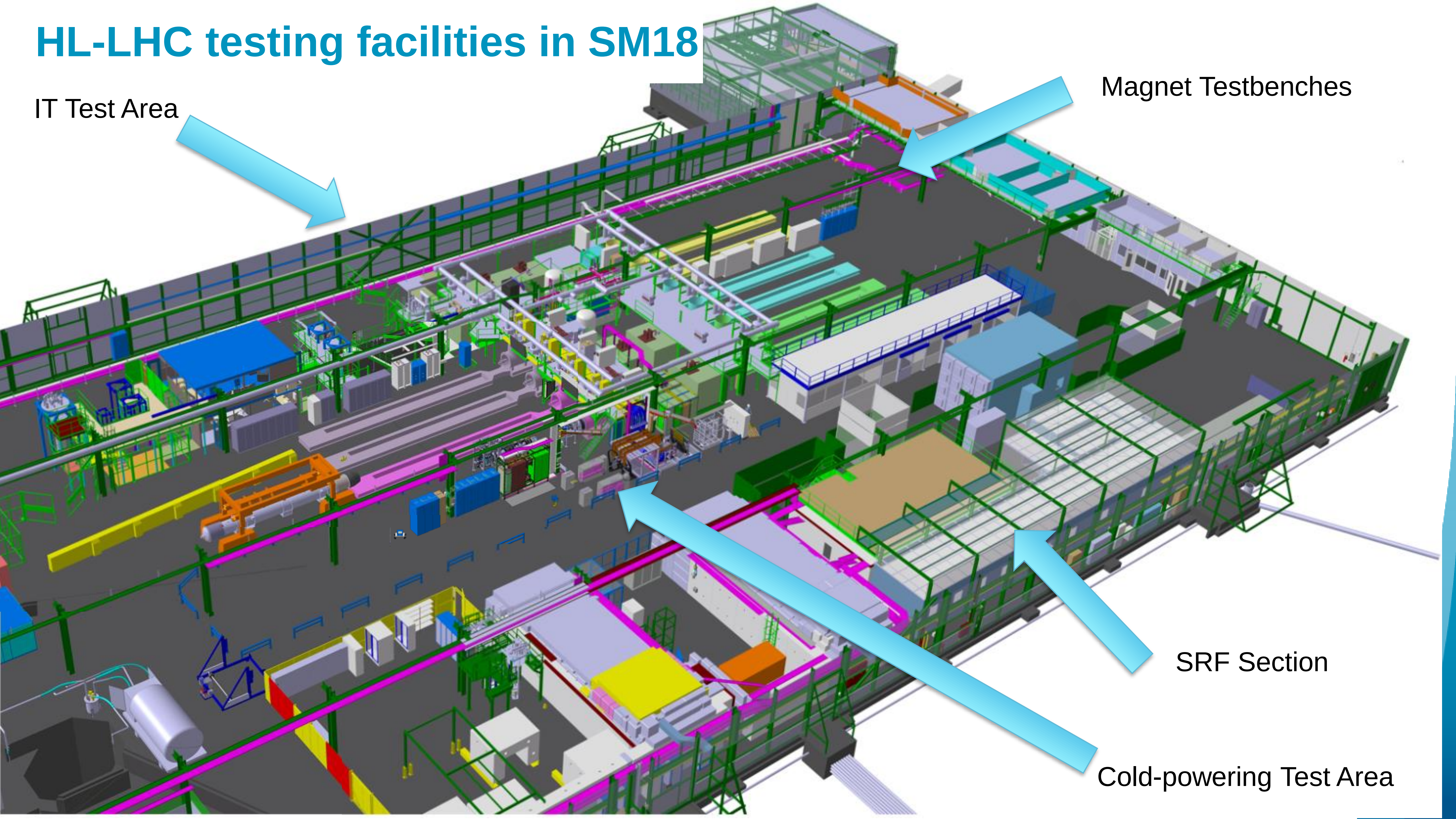


Cavity String prior to Cleanroom assembly

Outline

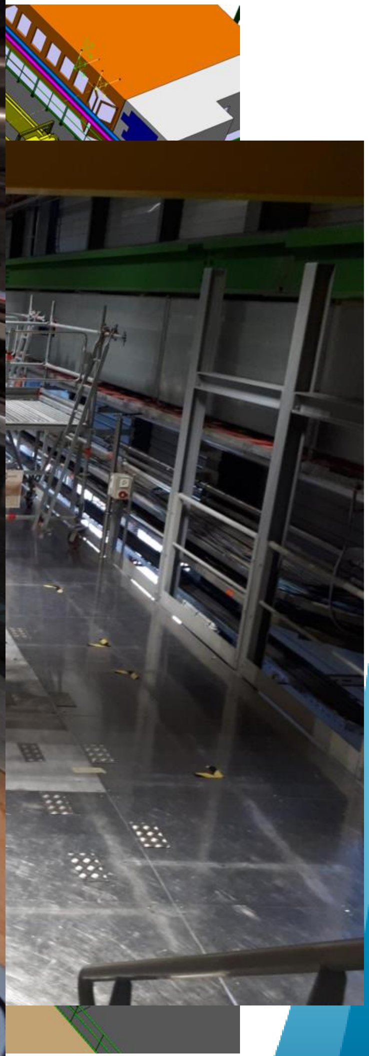
- LHC design performance and HL-LHC upgrade goals
- Completion of LIU, start of LHC Run 3 and lessons learnt for HL-LHC era
- **Status of key (technological) deliverables towards the HL-LHC upgrade**
  - Civil engineering
  - Final focusing magnets for lower beta*
  - Superconducting Link
  - Crab cavities
  - **IT String**
- HL-LHC as a truly international project (with recent challenges)
- Current Project planning and performance ramp-up

HL-LHC testing facilities in SM18



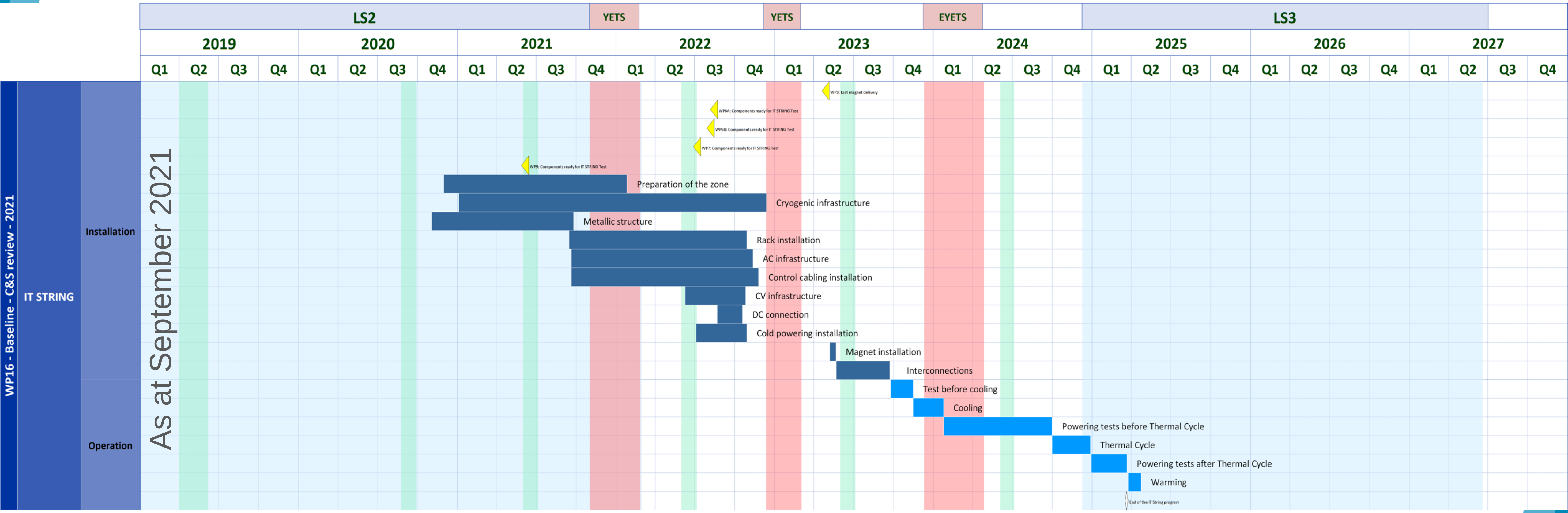
Important mil

- Overall inte
- Vacuum an
- Electrical s



New IT String Schedule

End of STRING test: April 2025



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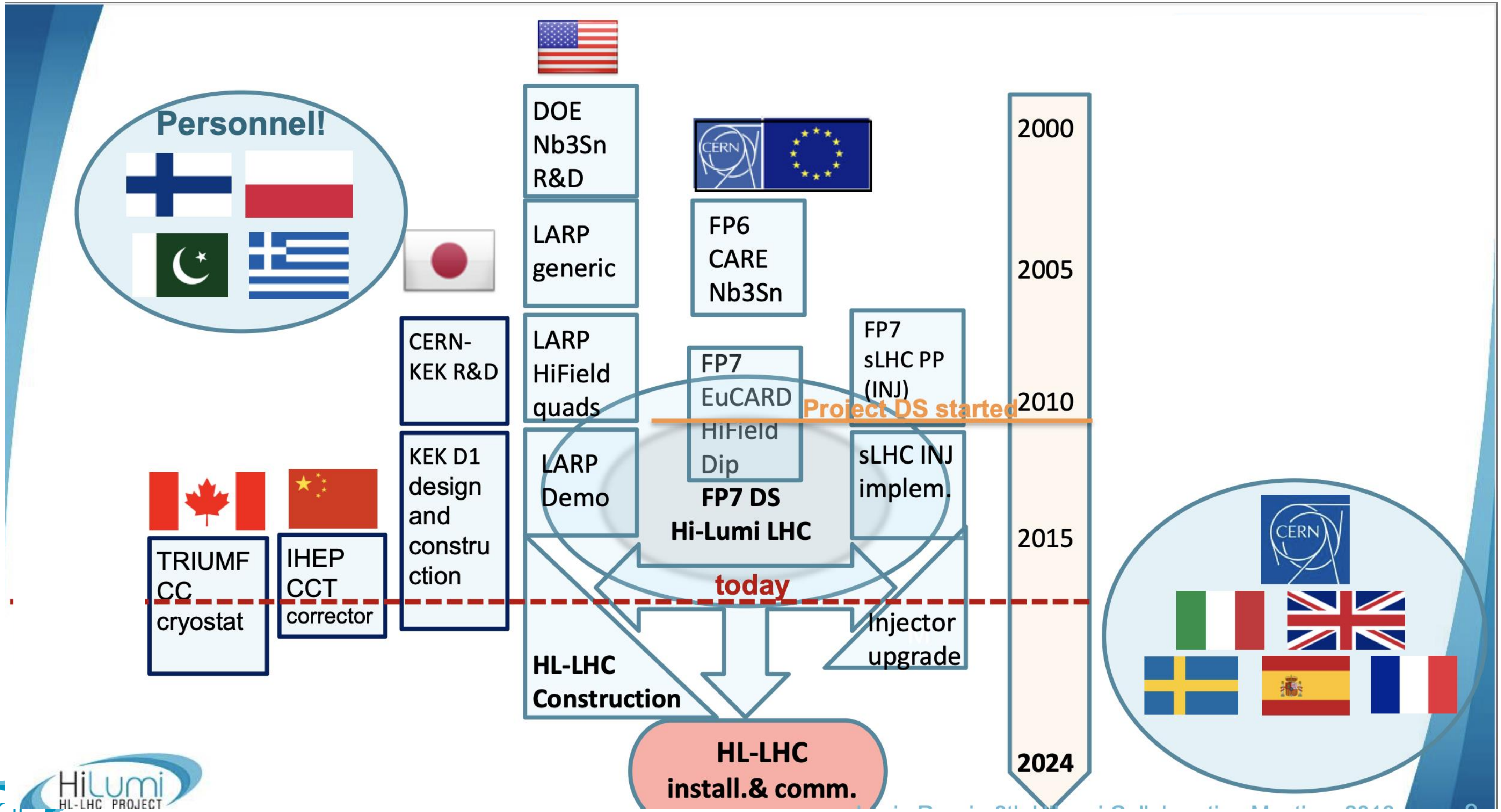
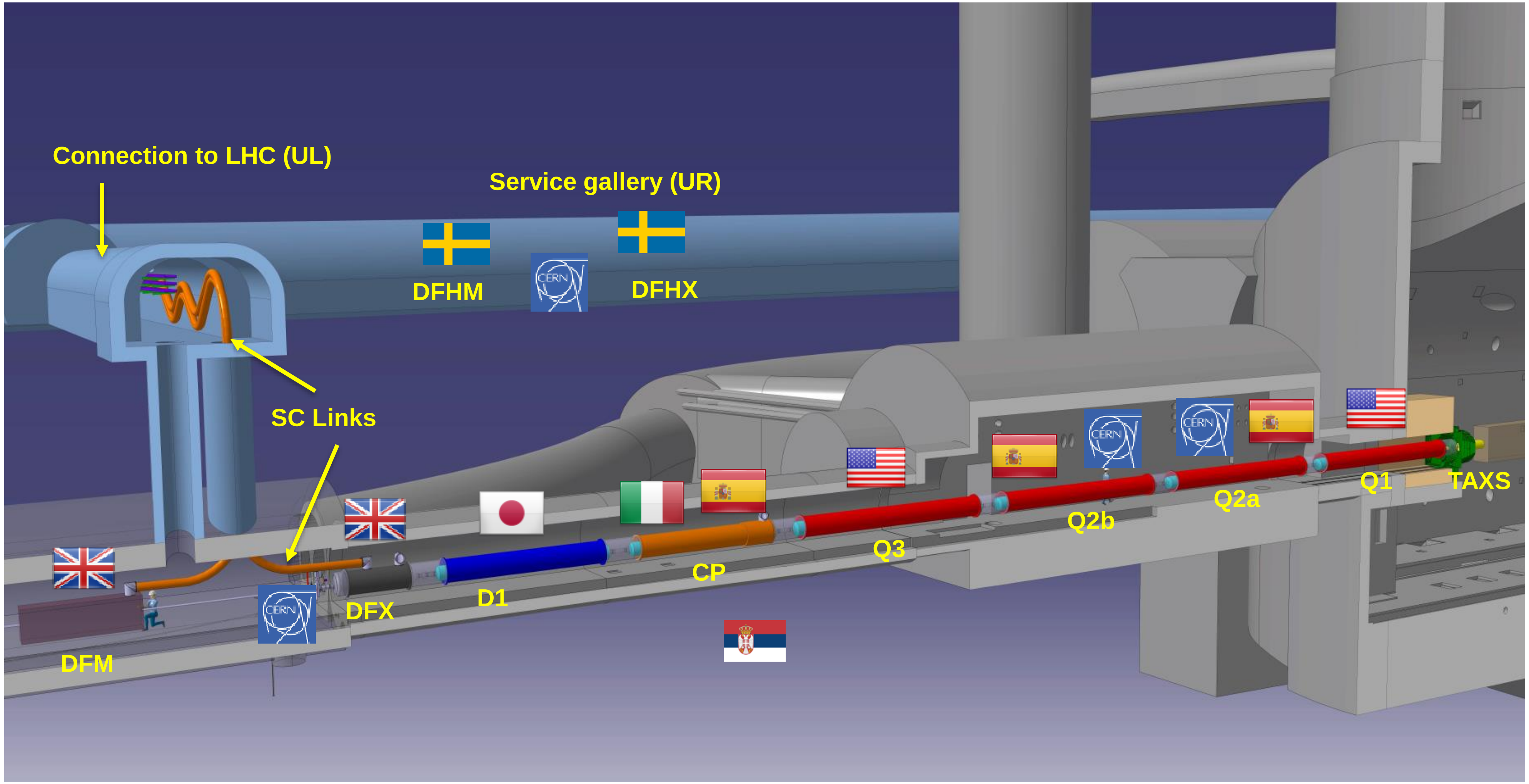
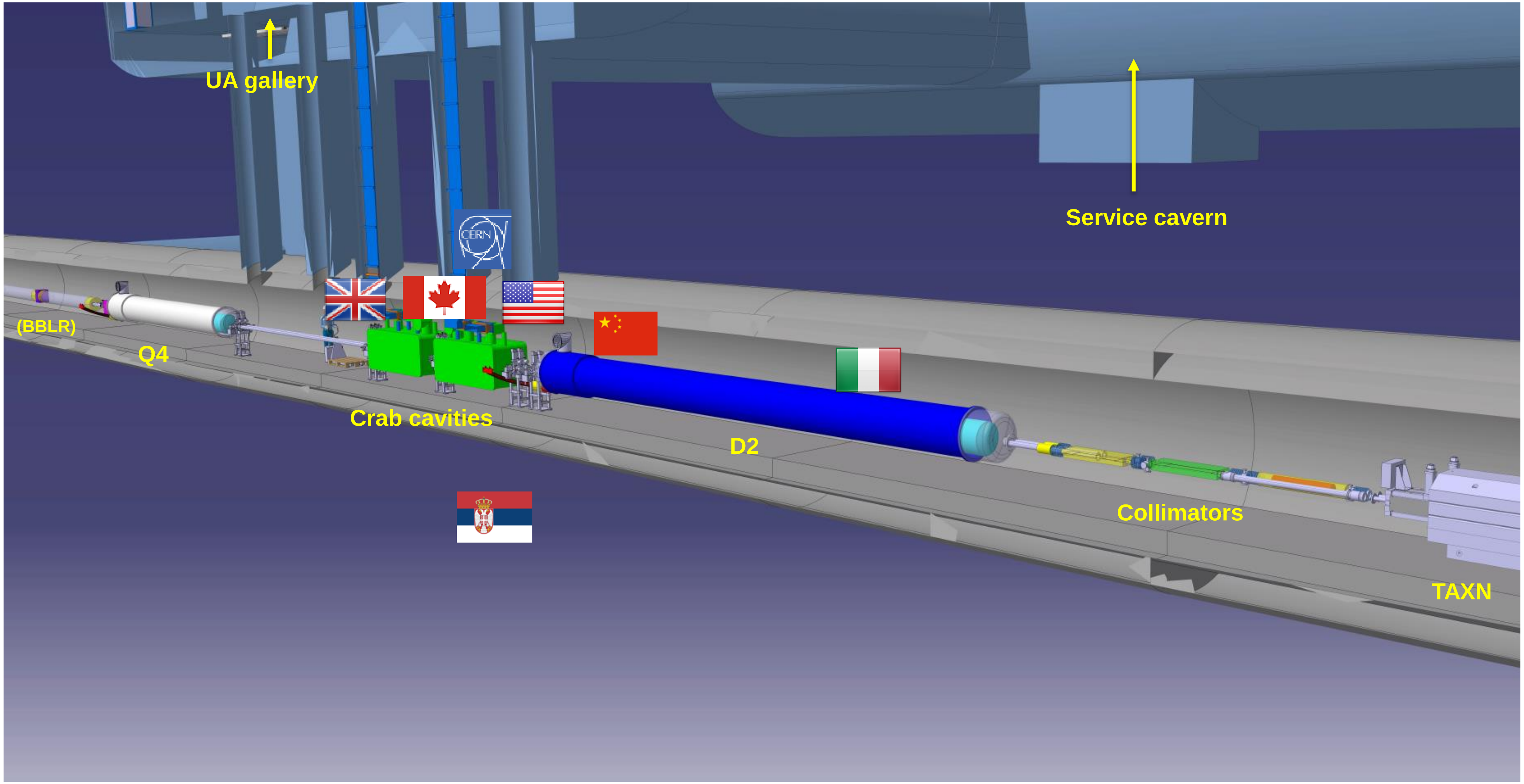
HL-LHC is a world-wide collaboration!



Truly International Collaboration offering exiting opportunities!



Truly International Collaboration offering exiting opportunities!



Russian in-kind contributions

- HL-LHC included a collaboration agreement with the Russian federation for the provision of
  - Construction of Low impedance collimators
  - Construction of crystal collimators
  - Copper part of HTS current leads
  - Upgrade of the HL-LHC beam dumping system (dilution kickers and dump cores)
  - Hollow electron leans for beam halo control
  - Beam Loss monitors
  - Construction of Beam position monitors
  - Experimental passive absorbers
  - Crab cavity powering system and distribution

- The agreement being left without funding from the Russian ministry, critical milestones could not be met for these deliverables, and CERN recently had to terminate the agreements for (the majority) of deliverables to avoid schedule risks for the project

- Despite partial descoping of some items and exploration of new in-kind contributions, this has a major impact on the CtC of project

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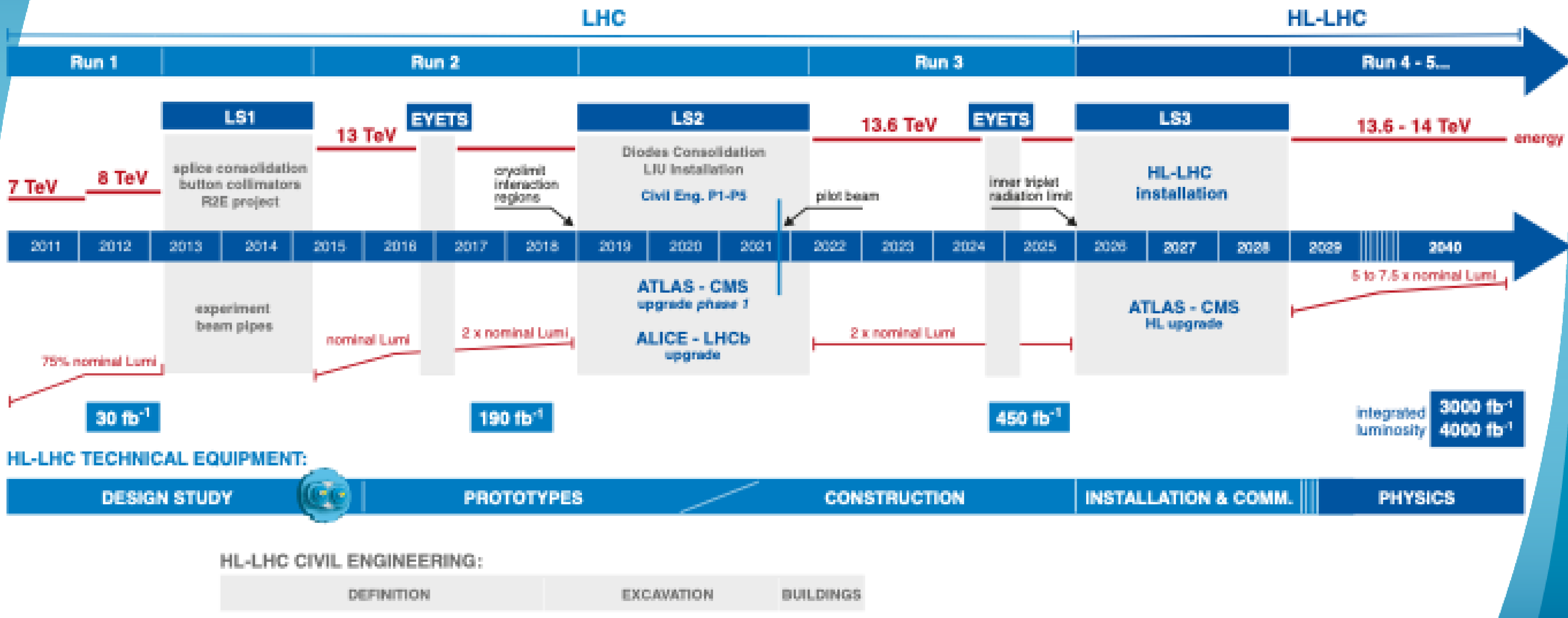
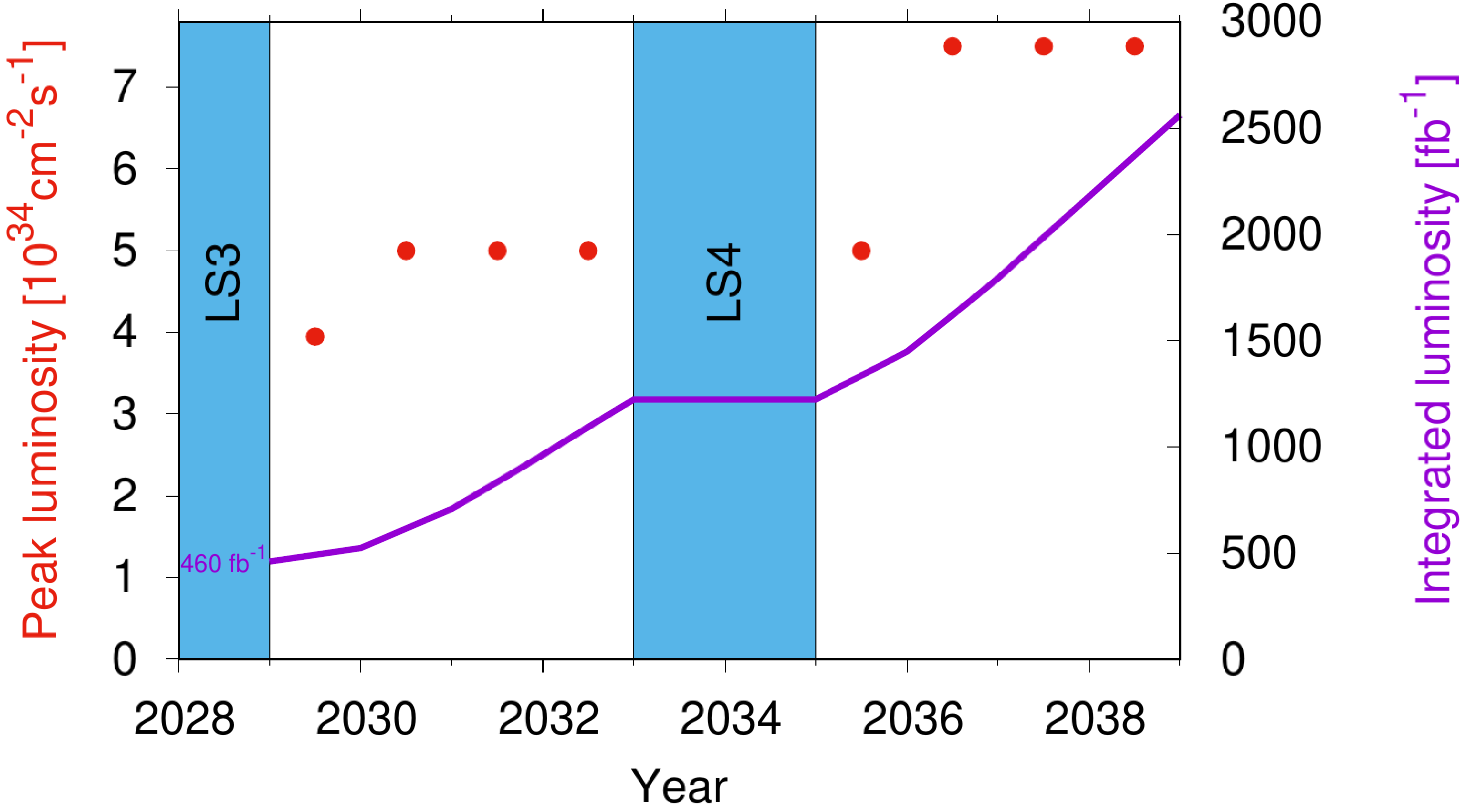
LHC / HL-LHC Plan



Expected HL-LHC performance

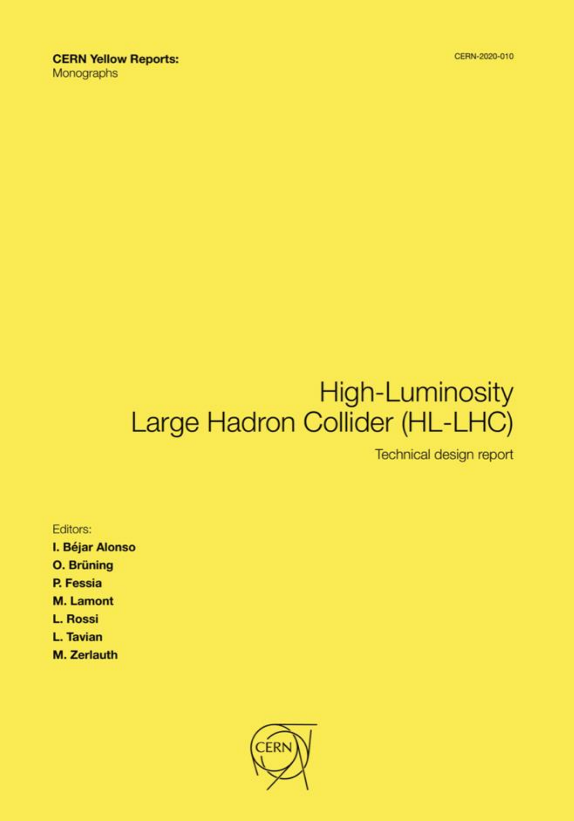


TDR V1.0 - The last version of the TDR including the added scope - 2020

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

EDMS: 1723851

and as CERN Yellow Book in October 2017



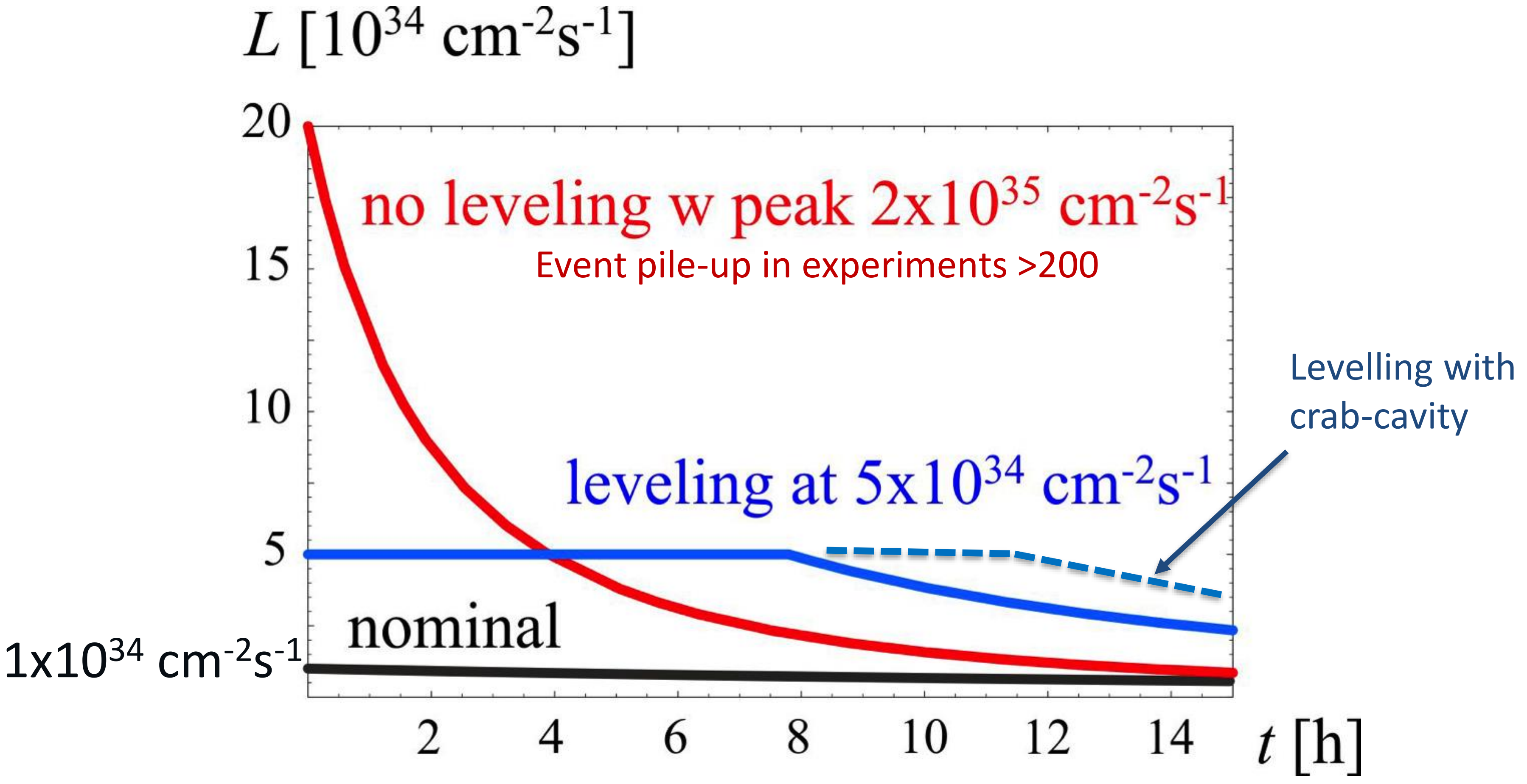
Updated Version V 1.0 published as

CERN Yellow Book in December 2020

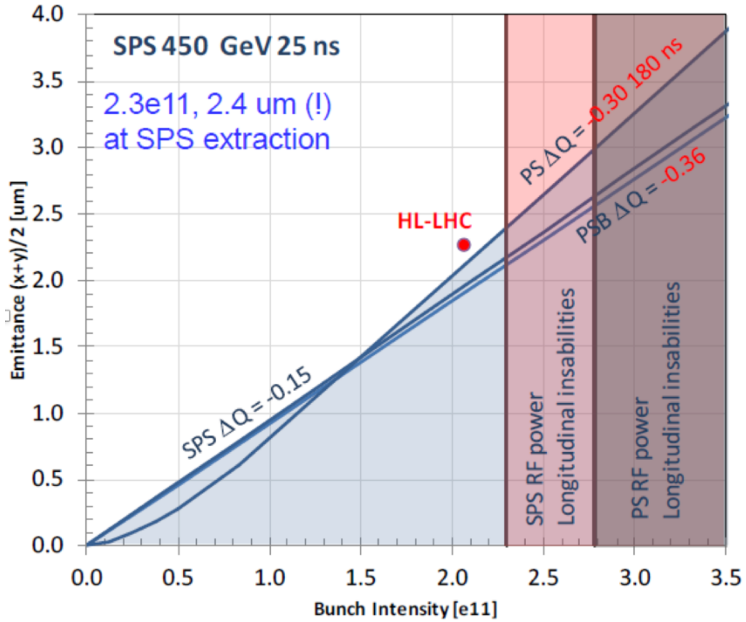
https://e-publishing.cern.ch/index.php/CYRM/issue/view/127

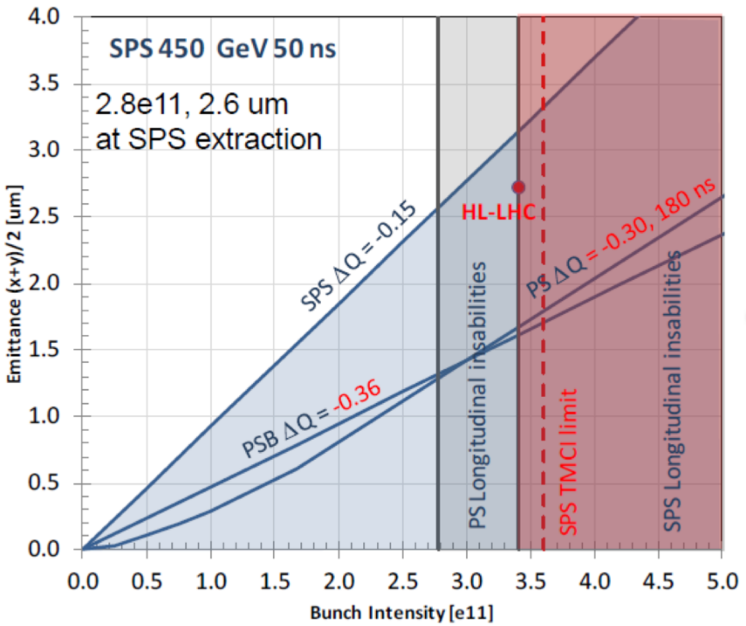
Thank you for your attention!
Question?

Operational Scenario for HL-LHC



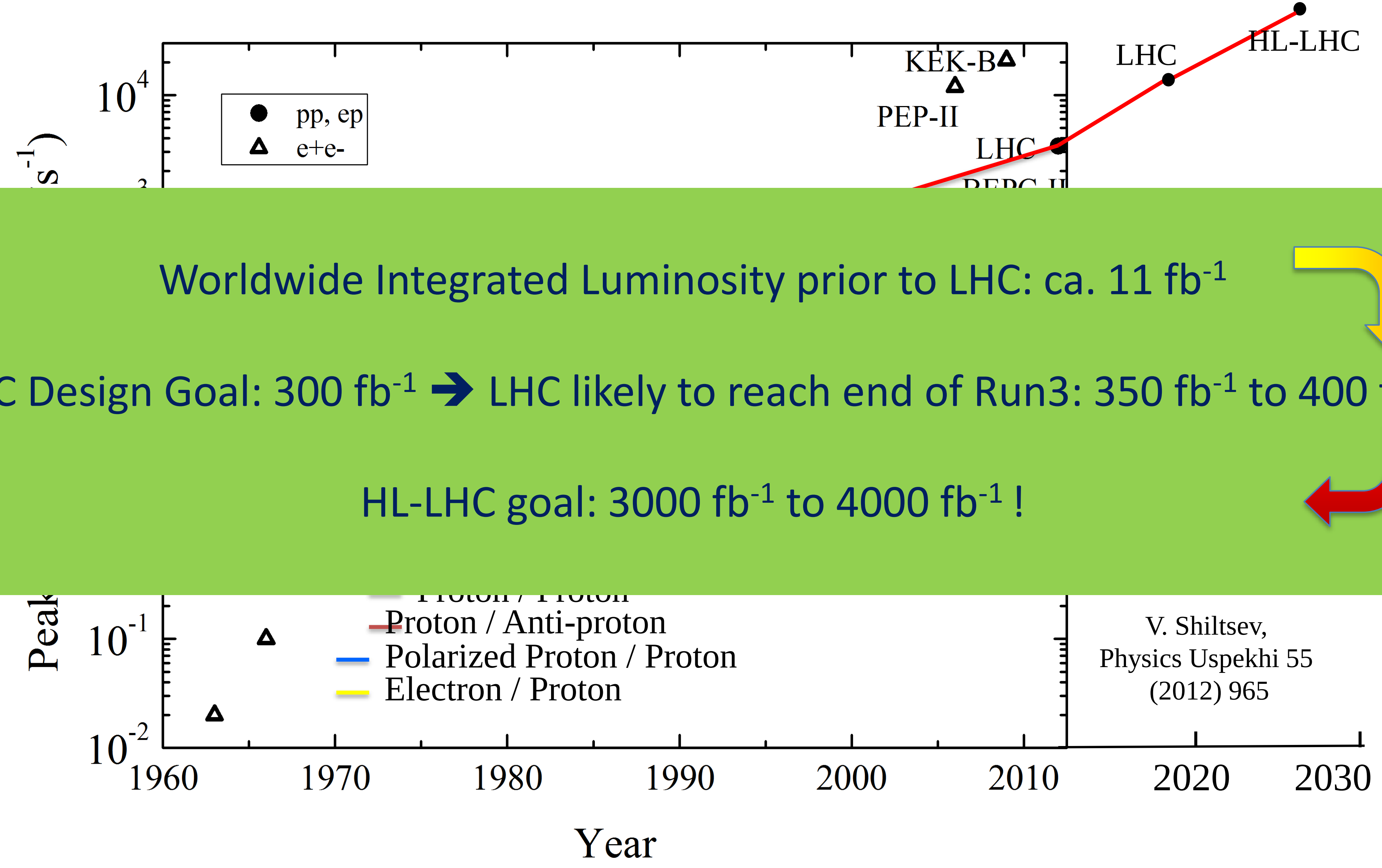
LHC Injector Upgra





- HL-LHC performance relies on more intense and brighter bunches from injector complex (2.2E11p / 2um at SPS extraction wrt to LHC nominal of 1.15E11p / 3.4um)
- 25ns beam limited by space charge in PS, PSB, SPS; SPS RF power and SPS longitudinal instabilities
- 50ns beam limited by PS longitudinal instabilities & SPS space charge and SPS TMCI

Peak luminosities of Hadron colliders



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

x 35

LHC Design Goal: 300 fb^{-1} ➔ LHC likely to reach end of Run3: 350 fb^{-1} to 400 fb^{-1}

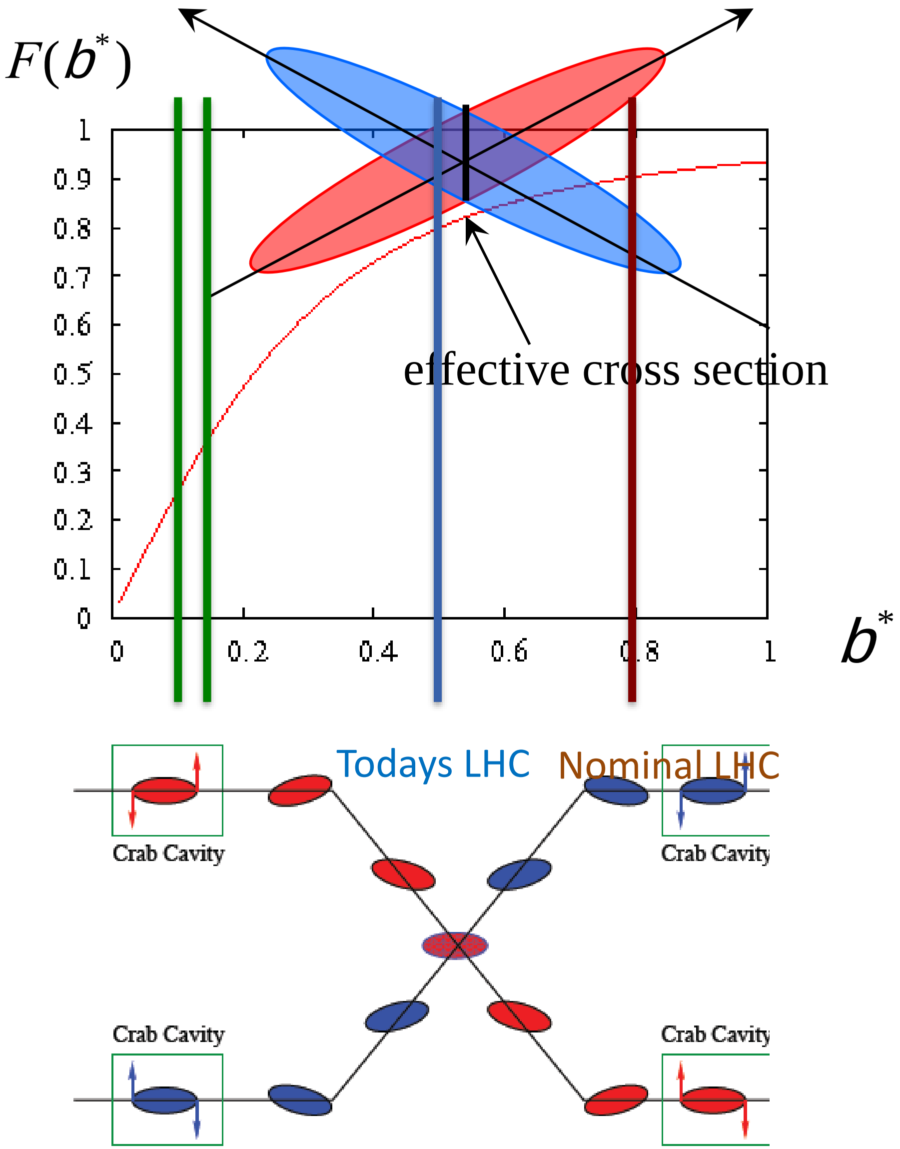
x 10

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

HL-LHC Upgrade Ingredients: Crab Cavities

- Attempt to claw back the very significant reduction in luminosity from the large crossing angle
- Create an oscillating transverse electric field that kicks head and tail of the bunches in opposite directions
- Serving to mitigate the effect of the crossing angle at the IP
- Challenging space constraints:

  ➔ requires novel compact cavity design



SPS Test Program for CCs

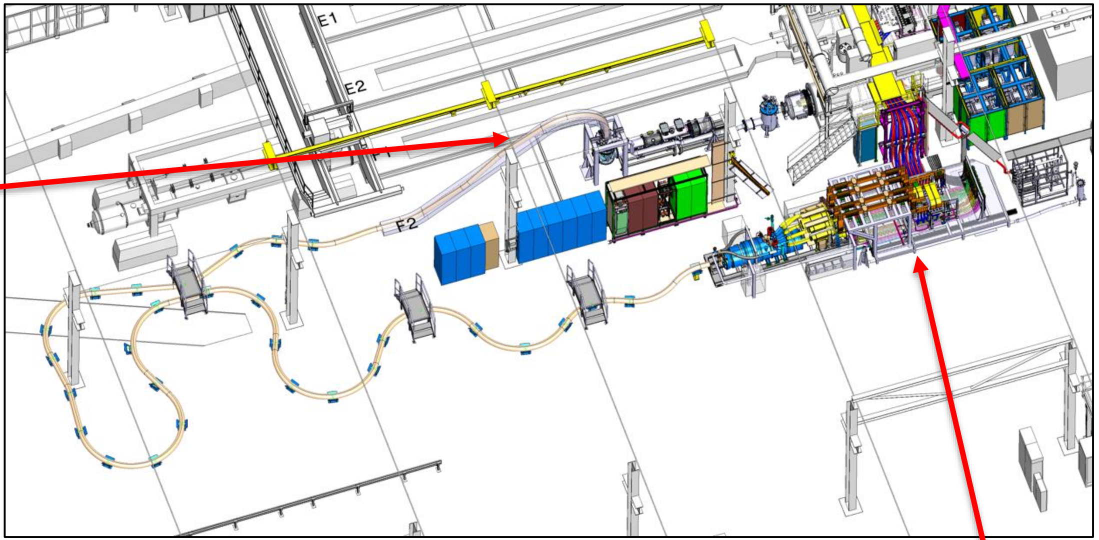
- The DQW module (2021 & 22) still to do
  - Demonstrate max stable voltage (nominal required 3.4 MV)
  - Intensity reach up to 4 batches of 72 bunches with LIU intensities – only possible in 2022 and beyond

- 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)

F2 Upgrade activities - May 2022

WP6a gratefully acknowledge the solid support of all teams involved

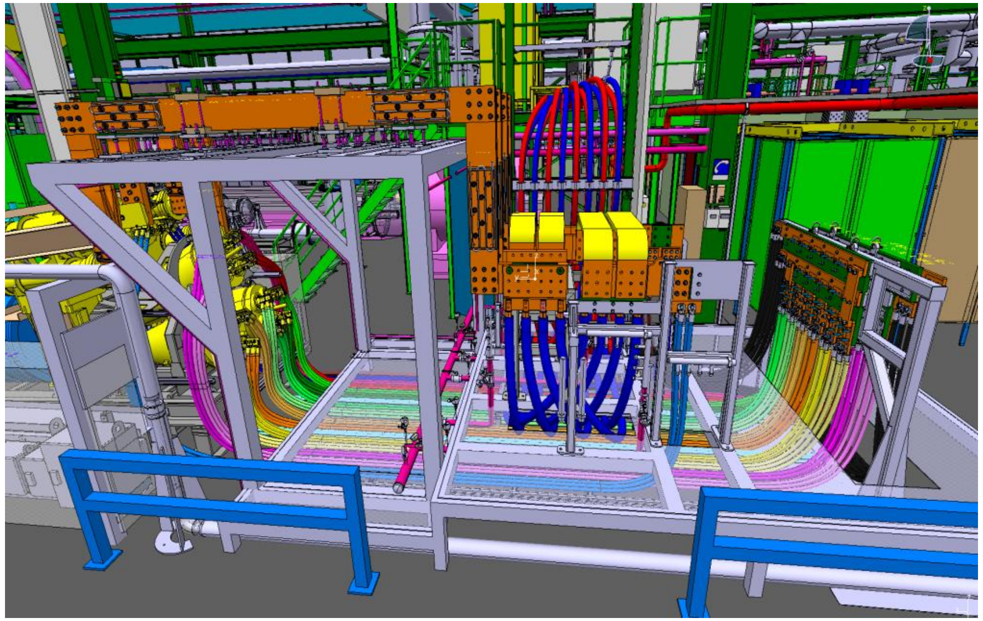
SC Link cable chain trials (SM18)



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….