HL-LHC Upgrade Project

Horizons in Accelerators, Particle/Nuclear Physics and Laboratory-Based Quantum Sensors for HEP/NP, Nov 2022

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

Outline

- LHC design performance and HL-LHC upgrade goals
- Status of key (technological) deliverables towards the HL-LHC upgrade
  - Civil engineering
  - Final focusing magnets for lower beta*
  - Superconducting Link
  - Crab cavities
- HL-LHC as a truly international project
- 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]

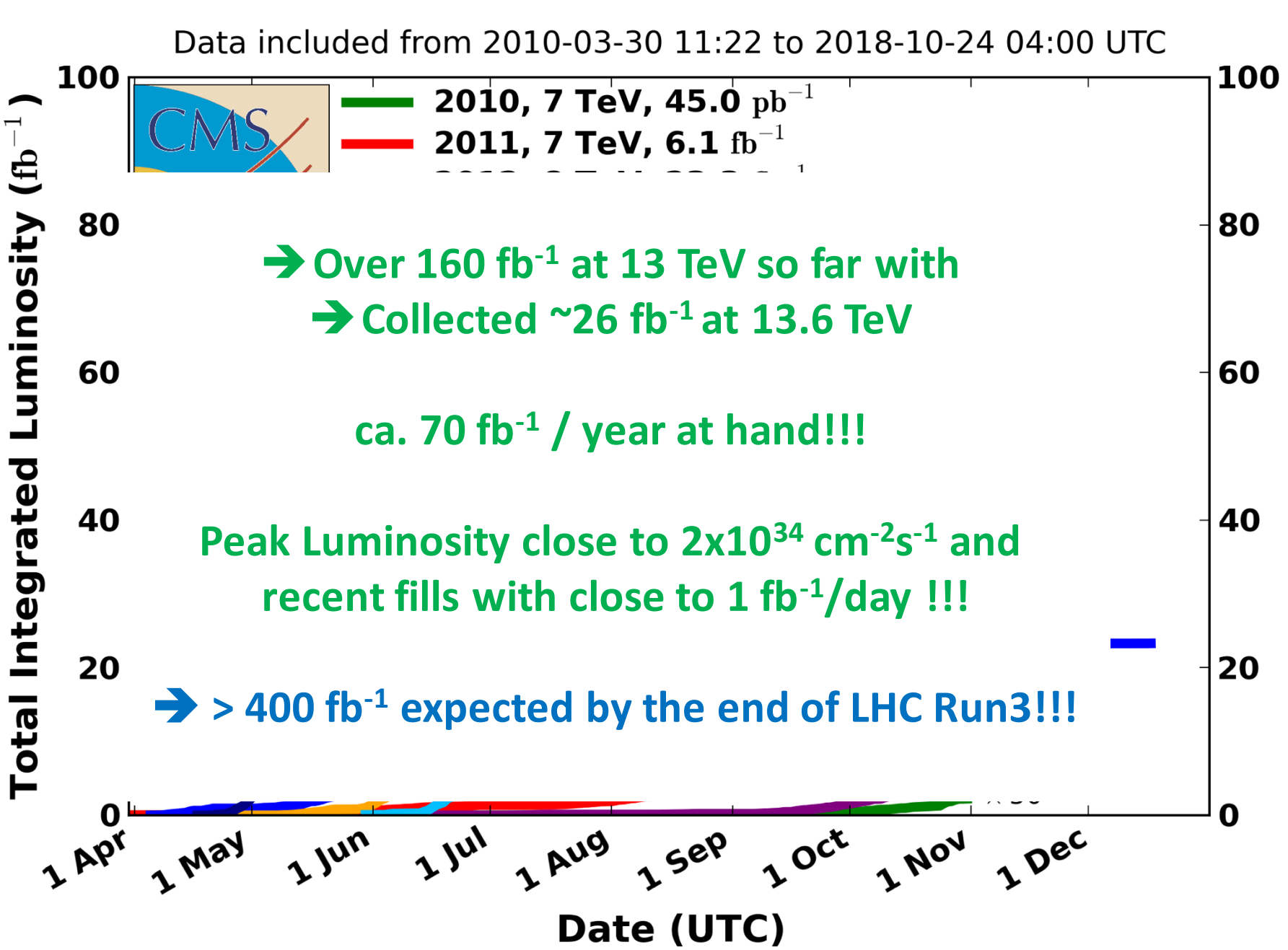
- Instantaneous luminosity: rate of events in detector $= L \times \sigma_{event}$

  rare events → $L > 10^{33}\text{cm}^{-2}\text{sec}^{-1}$ → $L = 10^{34}\text{cm}^{-2}\text{sec}^{-1}$ [$2\times10^{34}\text{cm}^{-2}\text{sec}^{-1}$]

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

  300 fb^{-1} with 1barn = 10^{-28}m^2 and femto = 10^{-15} [220 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 ~26 fb^{-1} at 13.6 TeV

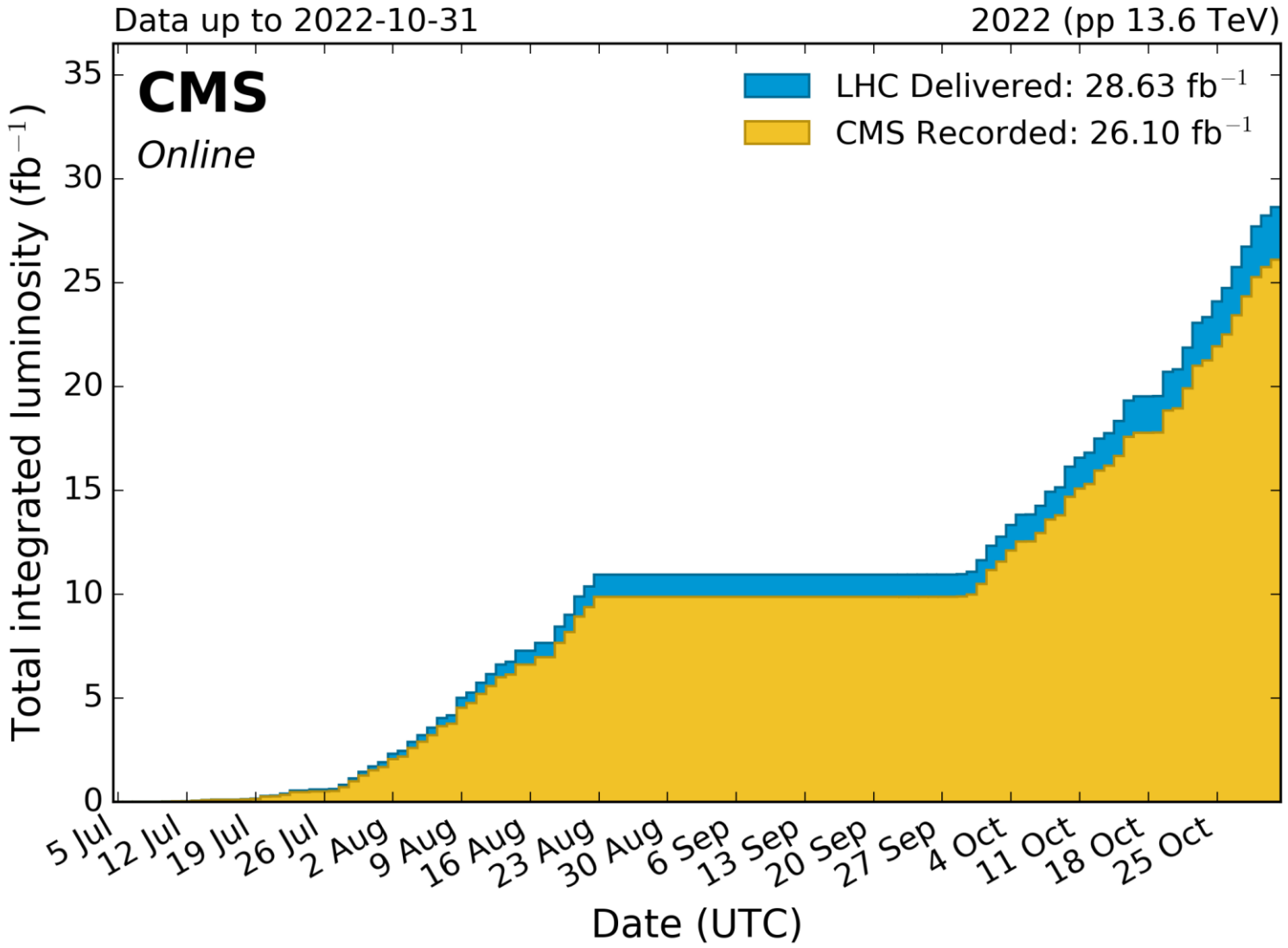
ca. 70 fb^{-1} / year at hand!!!

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

➔ > 400 fb^{-1} expected by the end of LHC Run3!!!

HiLumi HL-LHC PROJECT

CMS Integrated Luminosity, pp , 2022



Goal of HL-LHC upgrade project

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}**

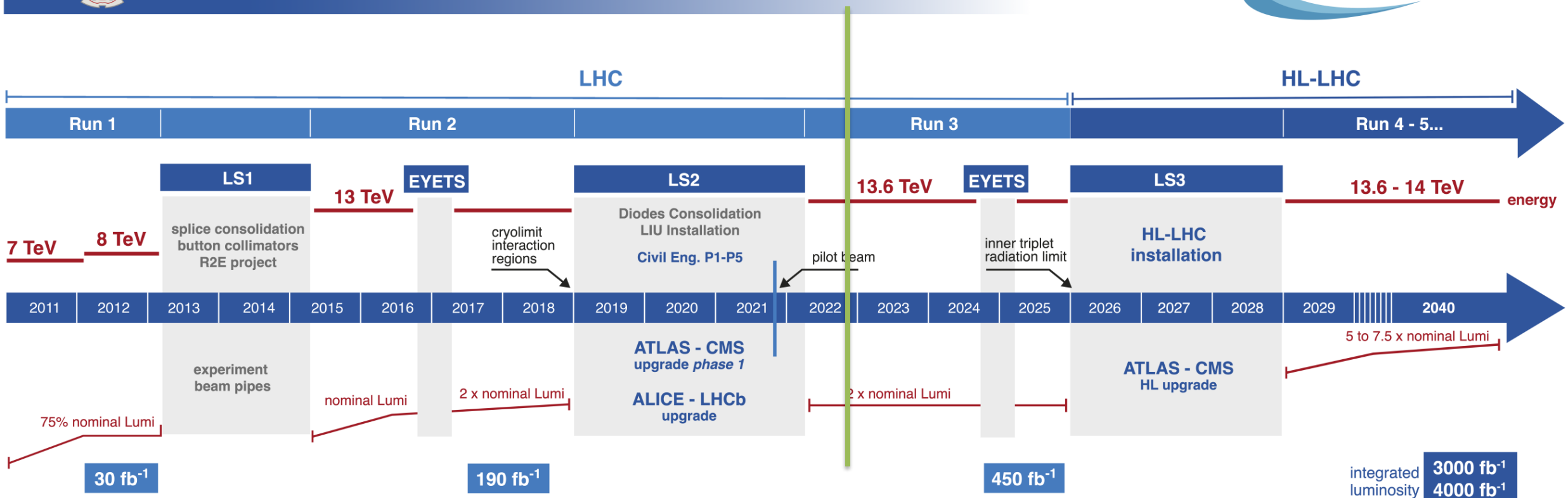
implying an integrated luminosity of **250 fb^{-1} per year**,

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

➔ Operation with levelled luminosity!

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

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

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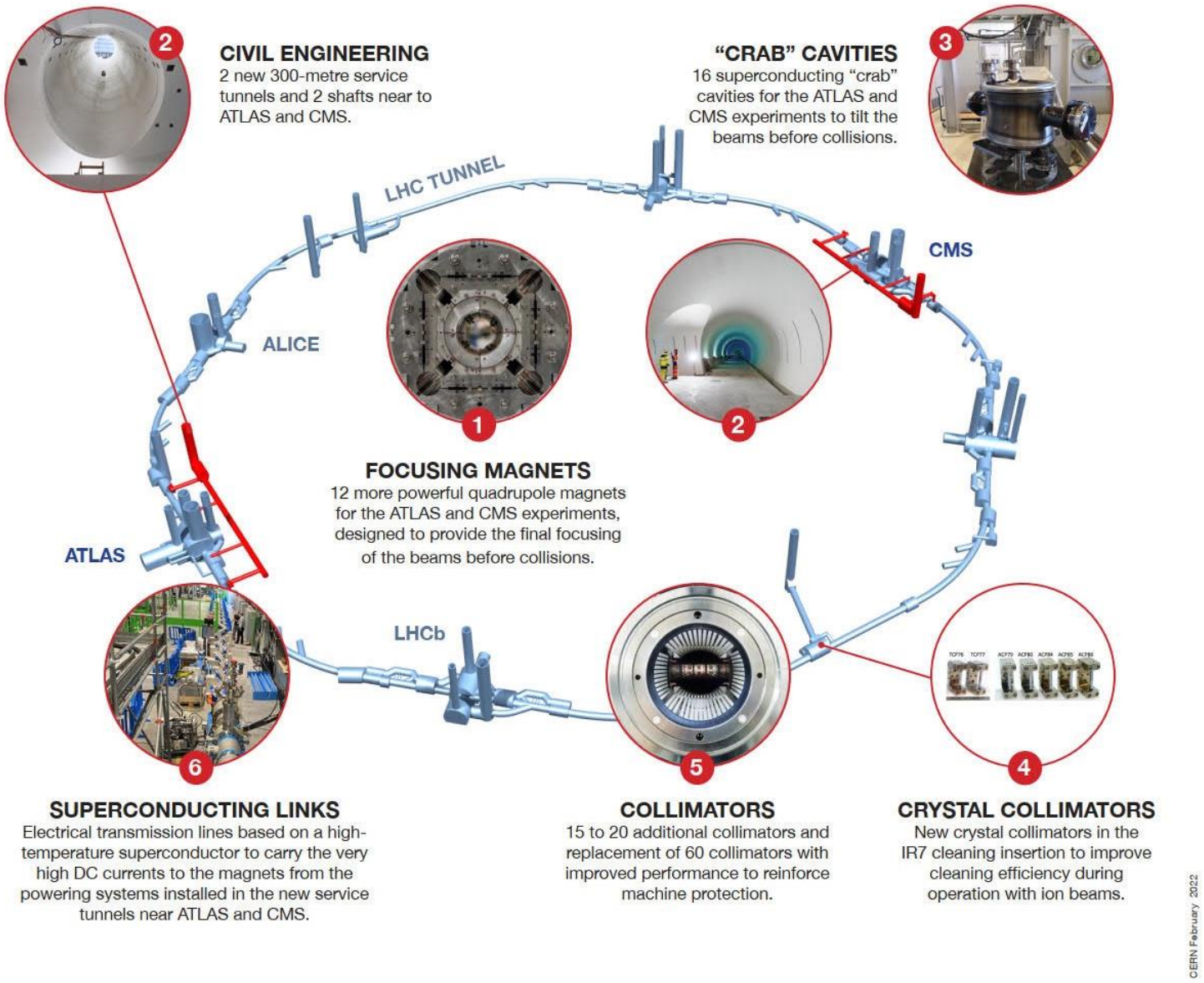
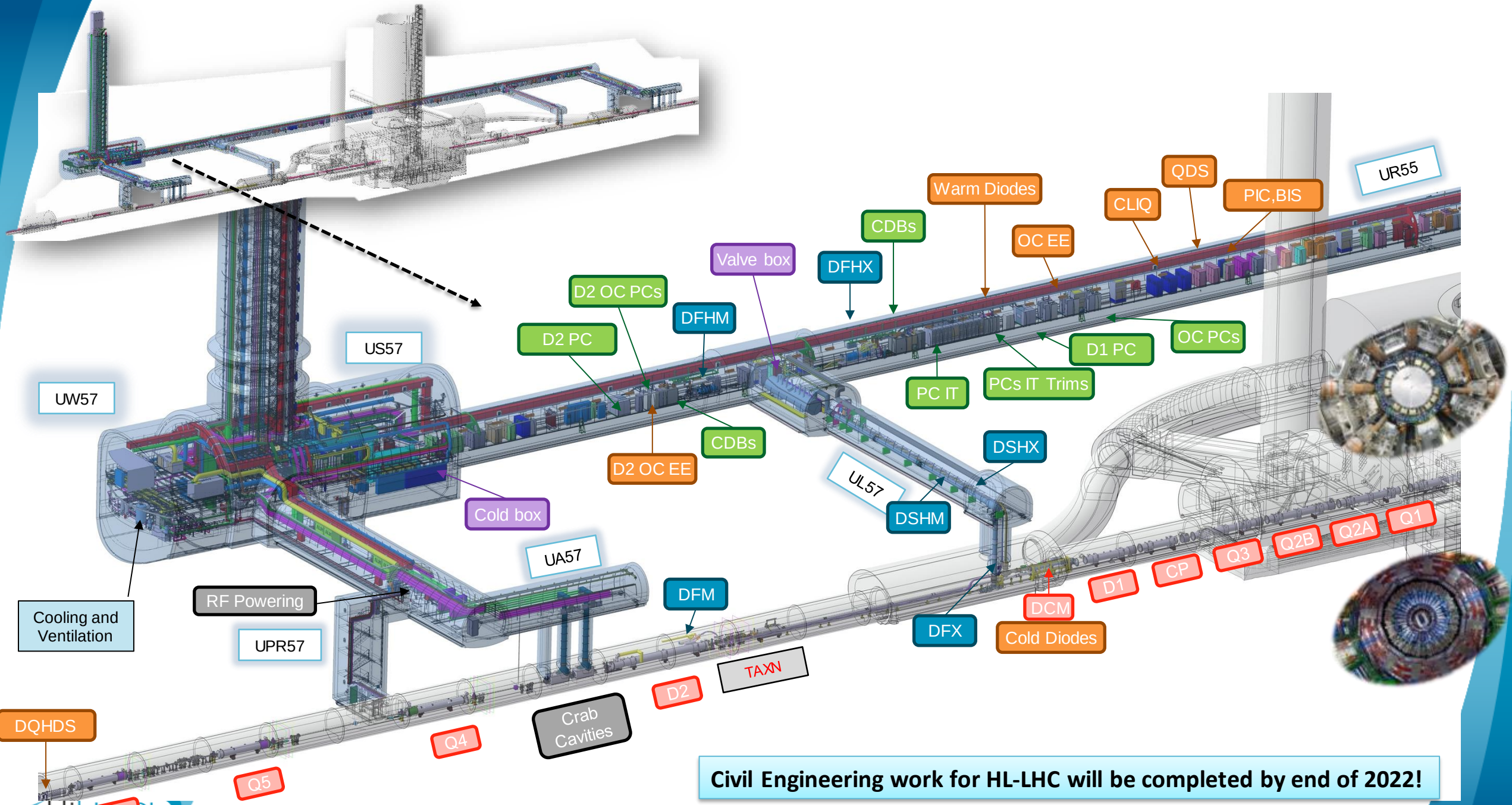
HL-LHC technology landmarks

HL-LHC is an accelerator upgrade project with many challenging novelties covering a broad technology spectrum

Technology intensive project!



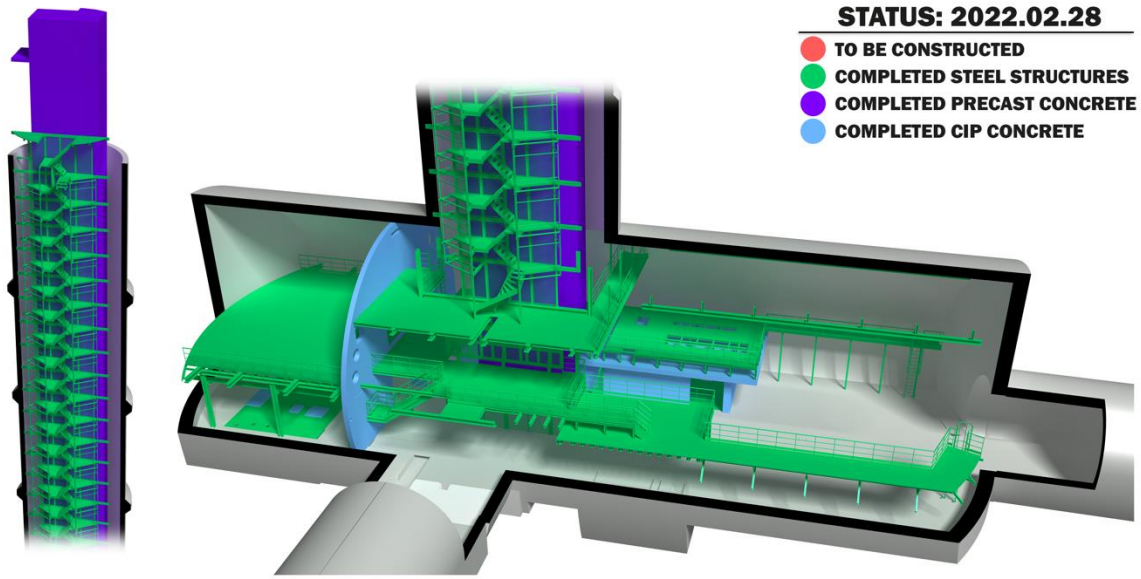


Civil Engineering work for HL-LHC will be completed by end of 2022!

HL-LHC civil engineering status (Point 1)

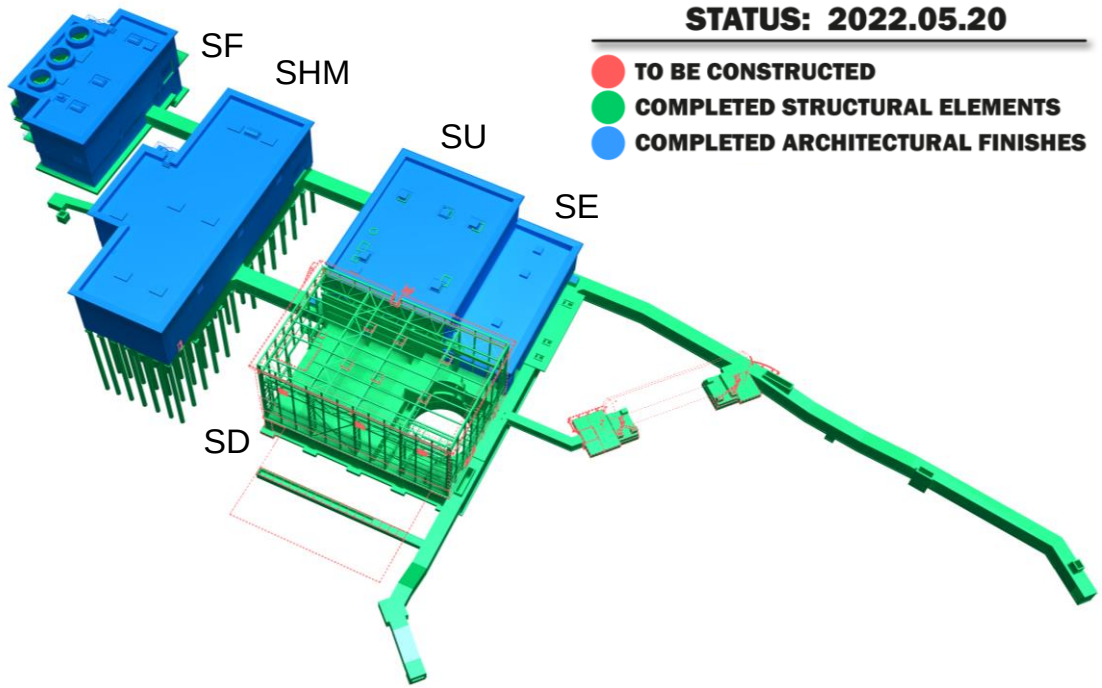
Overall progress today: 98%

Underground



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

Surface

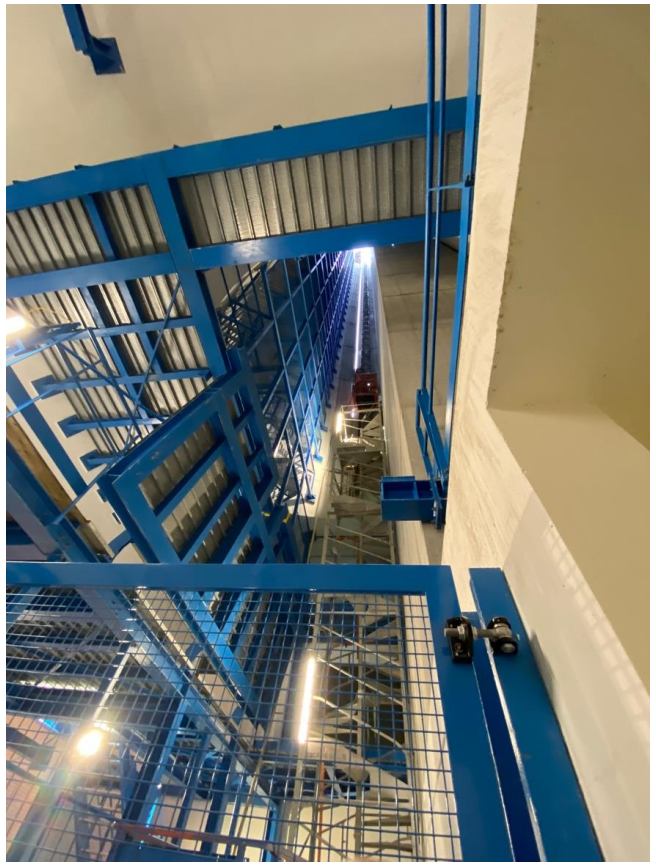


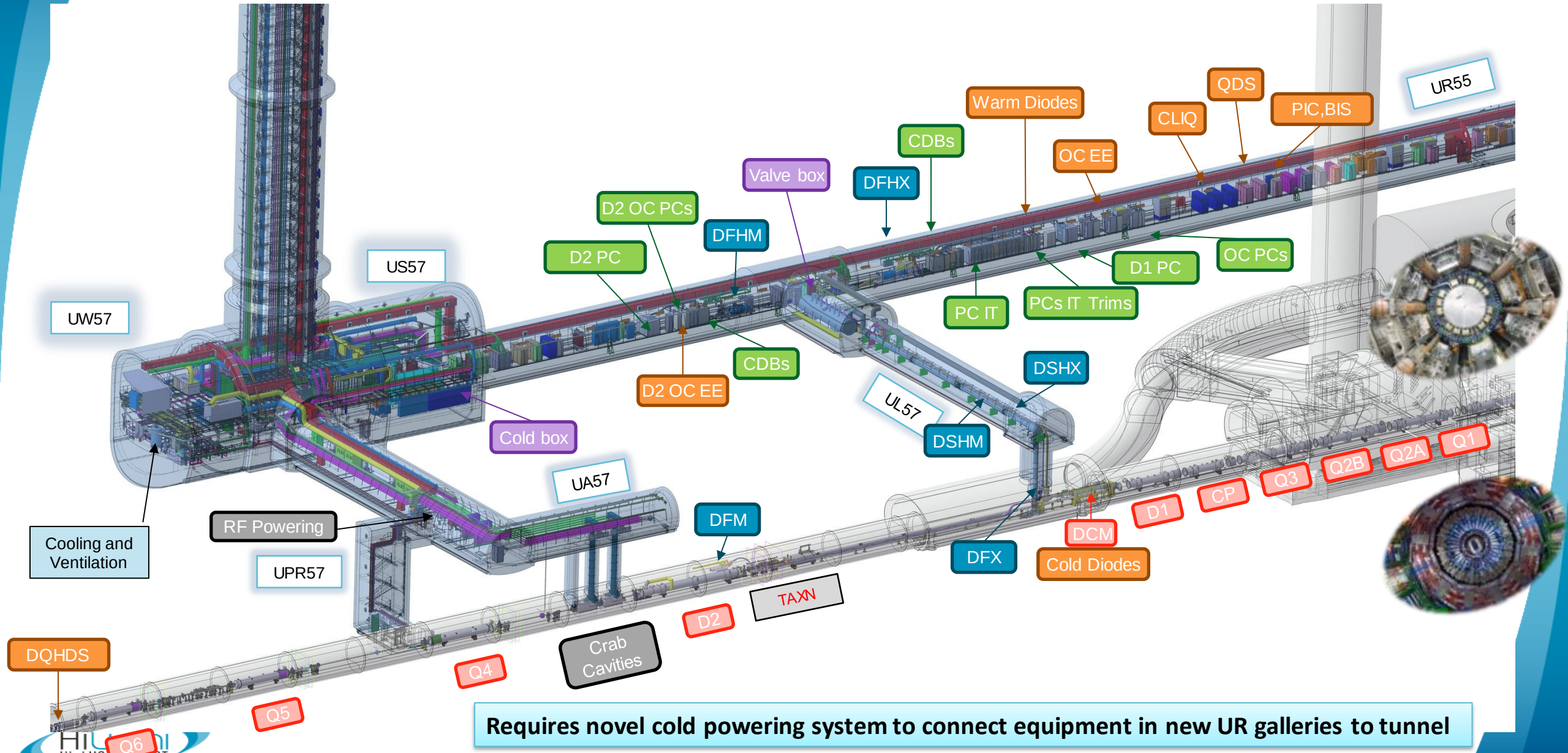
Point one works completed in September 2022 (Including + ~1 month due to Covid-19)

HL-LHC civil engineering status (Point 1)

HL-LHC civil engineering status (Point 5)

Inauguration Ceremony planned for December 2022



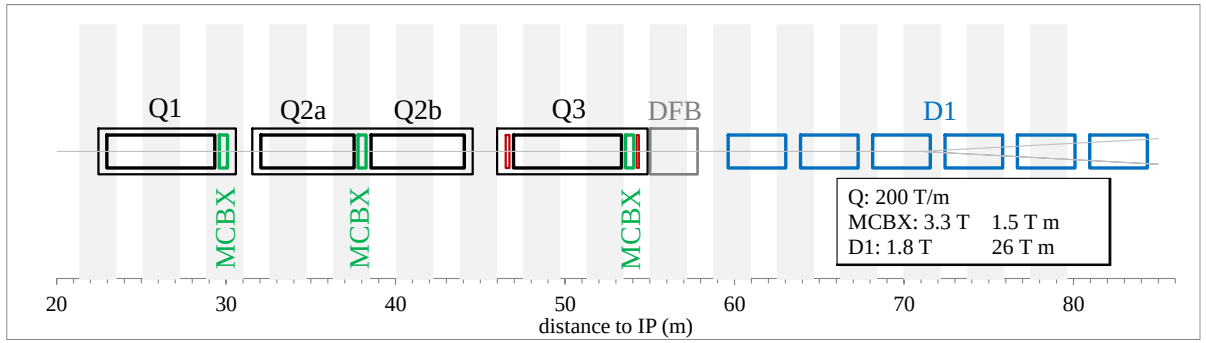


Requires novel cold powering system to connect equipment in new UR galleries to tunnel

New interaction region layout

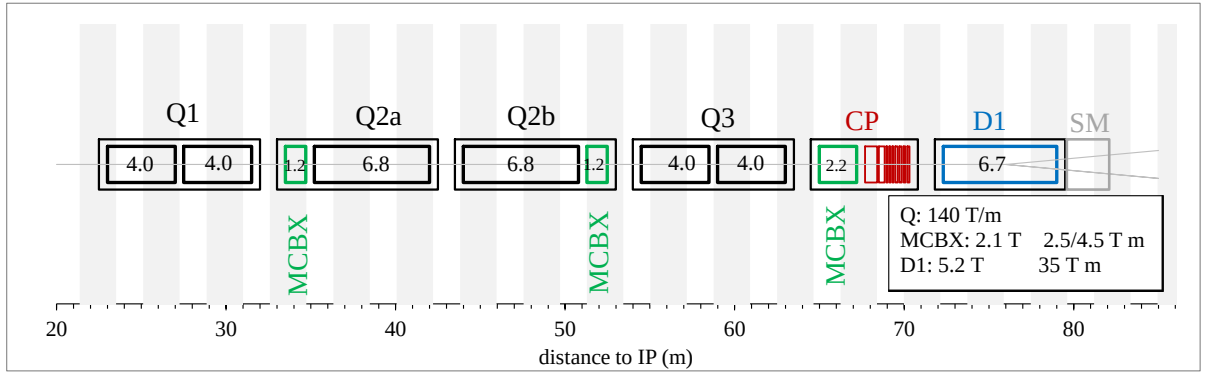
- New insertion and final focusing magnets
  - Main quadrupole magnets MQXFA (Q1, Q3) from AUP and MQXFB (Q2) from CERN
  - Superconducting separation and recombination dipoles, D1 from Japan and D2 from Italy
  - Higher Order Corrector package (CP) and orbit correctors (MCBX) from Italy and Spain

ATLAS CMS



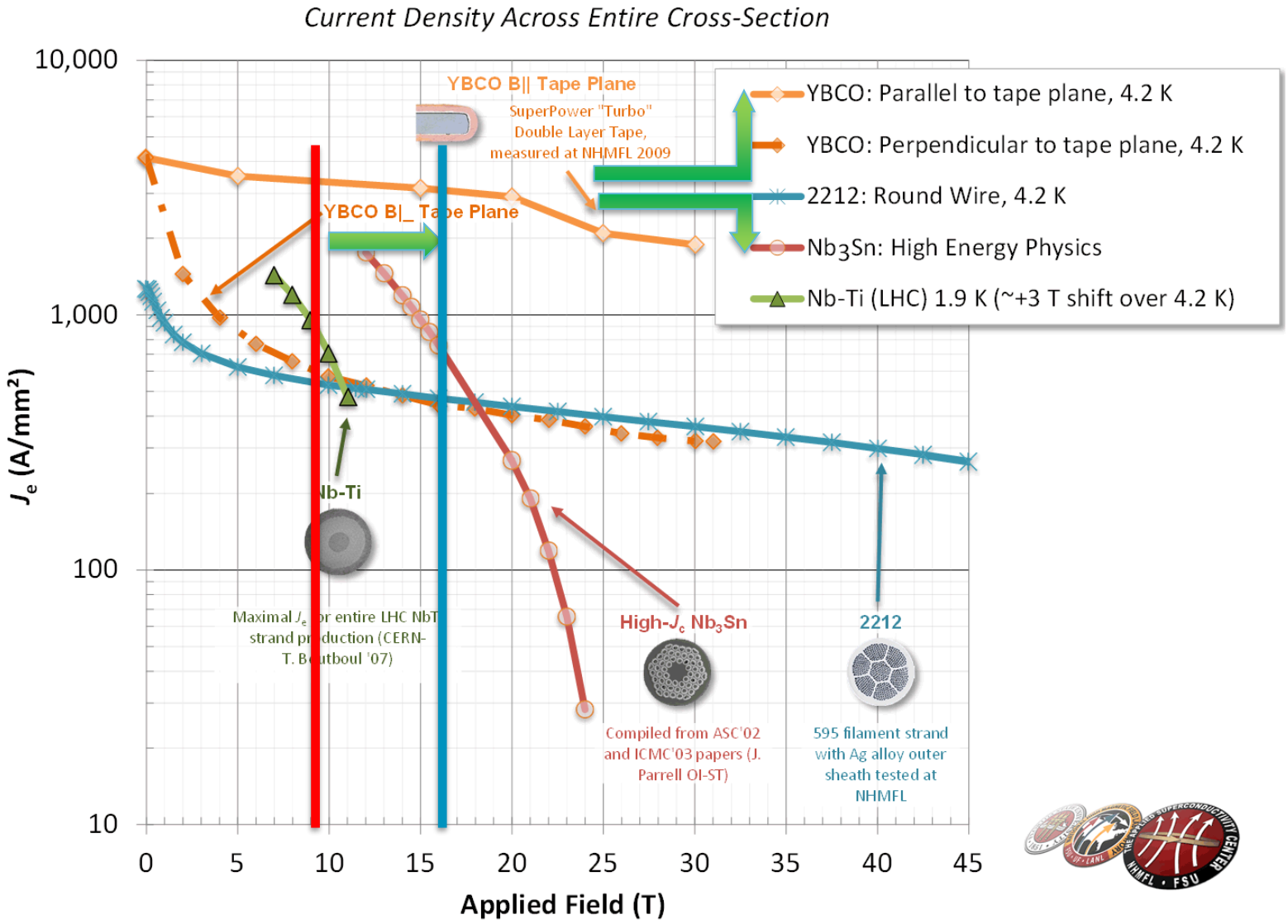
LHC

ATLAS CMS



HL-LHC

SC Magnet technology for HL-LHC



Nb_3Sn

- HL-LHC with 11-12T
- 16 T for HEP
- Almost a commodity!
  - 15-20 t per year for MRI
  - ITER needs 500 t
- ca x5 cost LHC Nb-Ti
- Brittle material

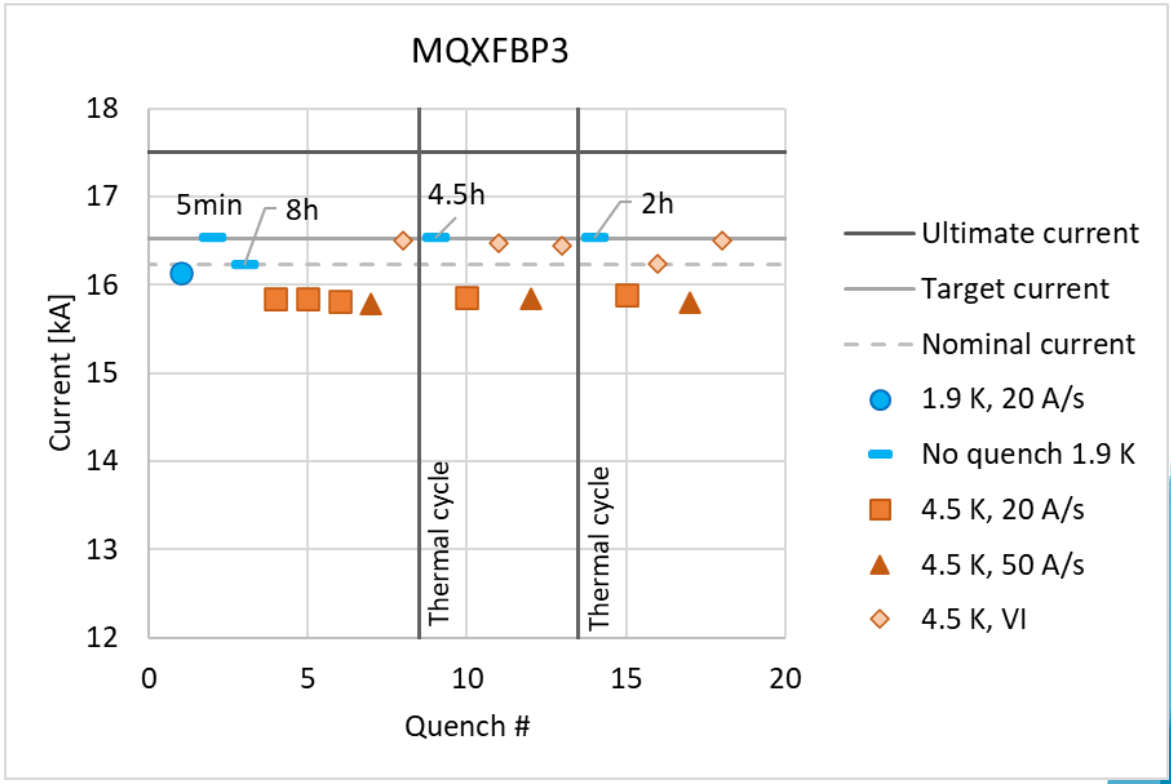
HTS (needed → 20 T)

→ on going R&D!

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

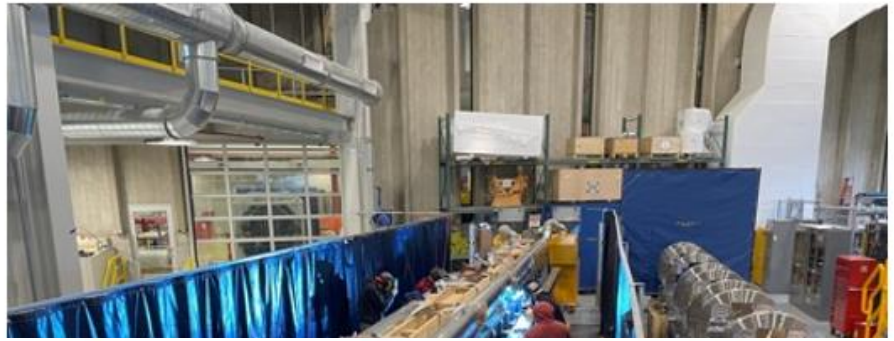
Main Quadrupole Magnets – Q2

- August 2022: Successful test of MQXFBP3 test @ SM18



Main Quadrupole Magnets – Q1/Q3

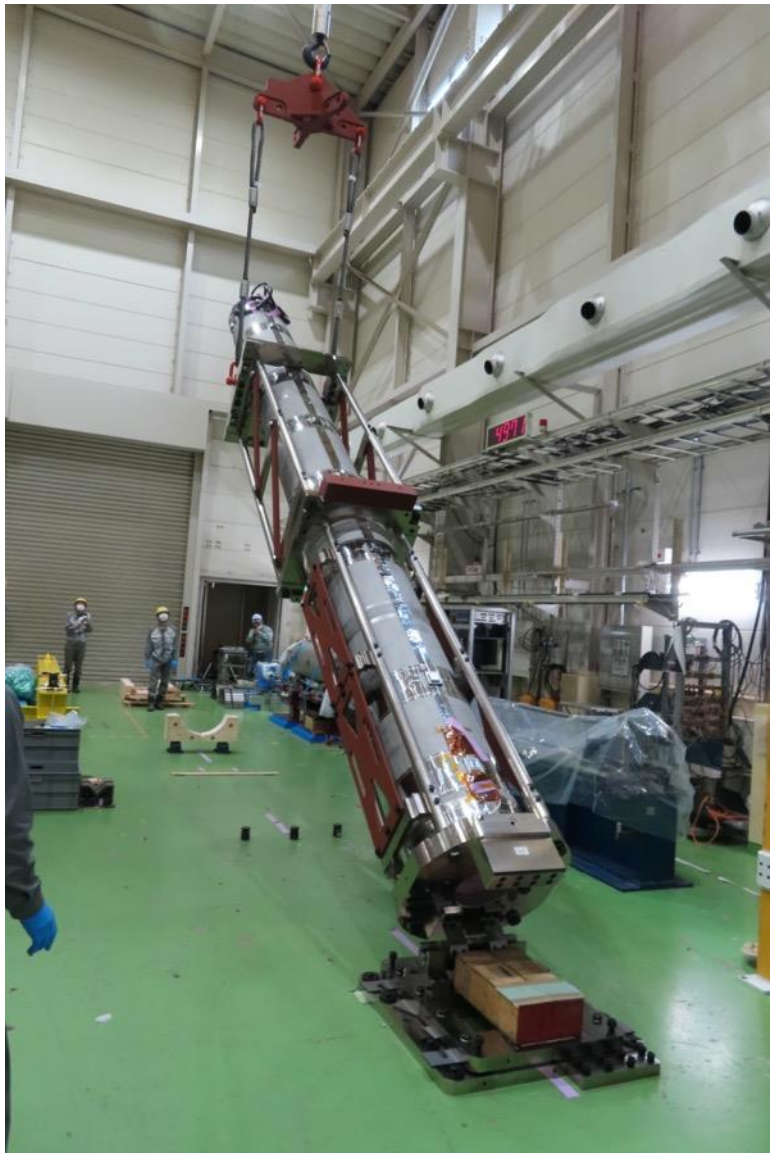
Fitting of bottom SS shell and longitudinal welding



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

Testing of D1 Prototype at KEK

- Lifting up the D1 magnet



- Insertion into vertical cryostat

D2 Cold-Mass Assembly

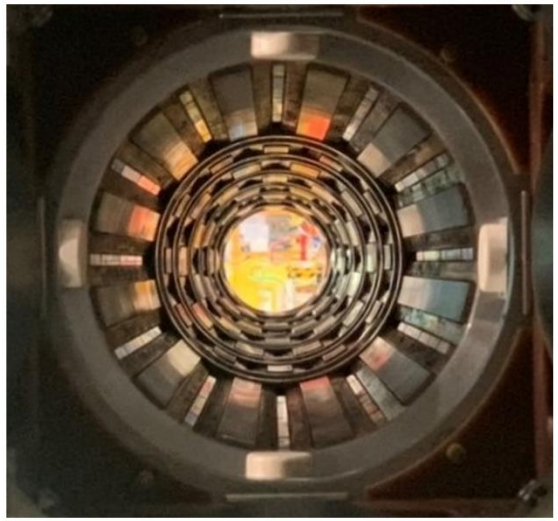
D2 Prototype Cold-M

D2 Prototype on the test bench in SM18

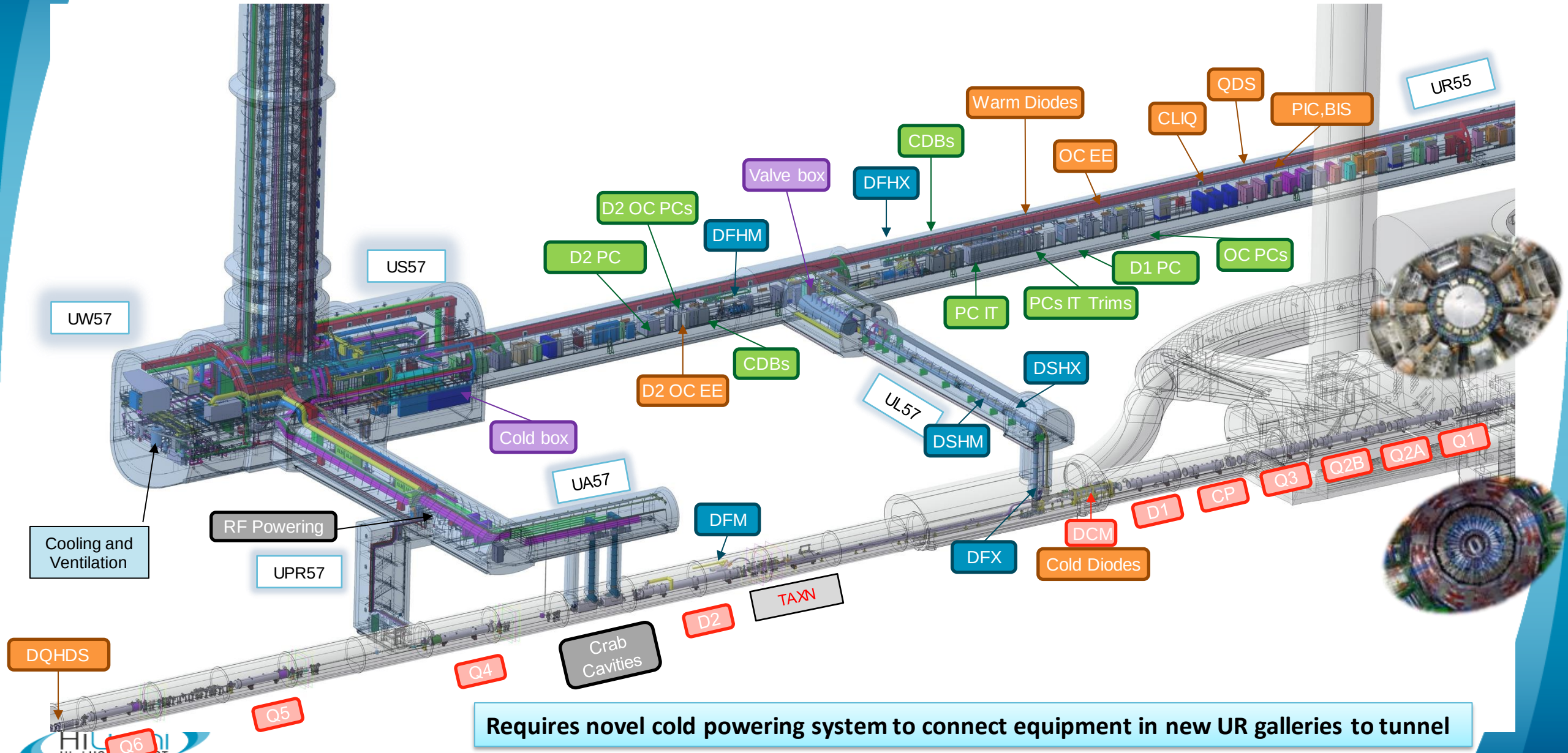
Dipole Orbit and Higher Oder corrector magnets

Nested dipole orbit correctors from Elytt in Spain

Canted Cosine Theta Corrector production at BAMA in China



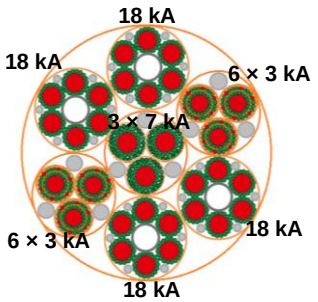
Higher Order Corrector Magnets from LASA in Italy

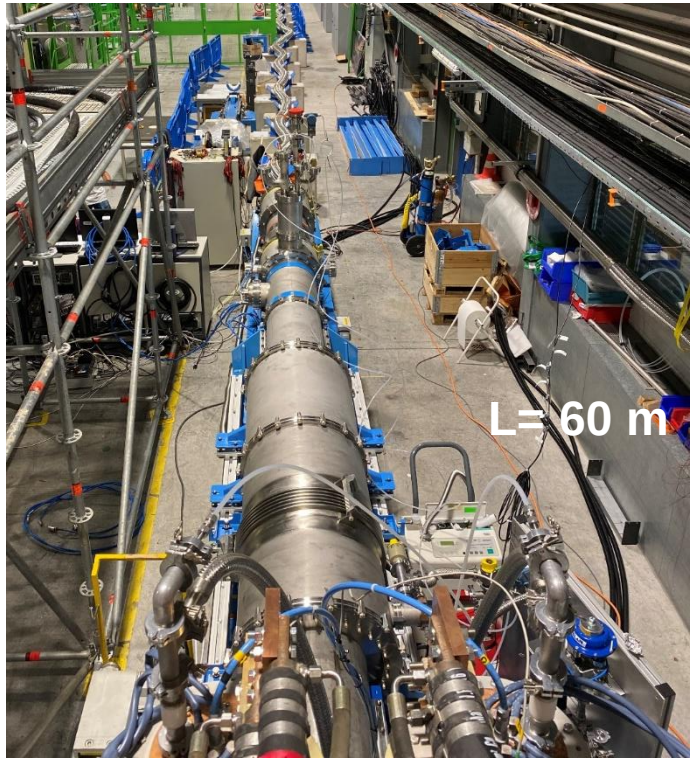


Requires novel cold powering system to connect equipment in new UR galleries to tunnel

Flexible MgB_2 superconducting links

MgB_2 cable:
$\Phi \sim 90$ mm
$|Itot| > 100$ kA @ 25 K



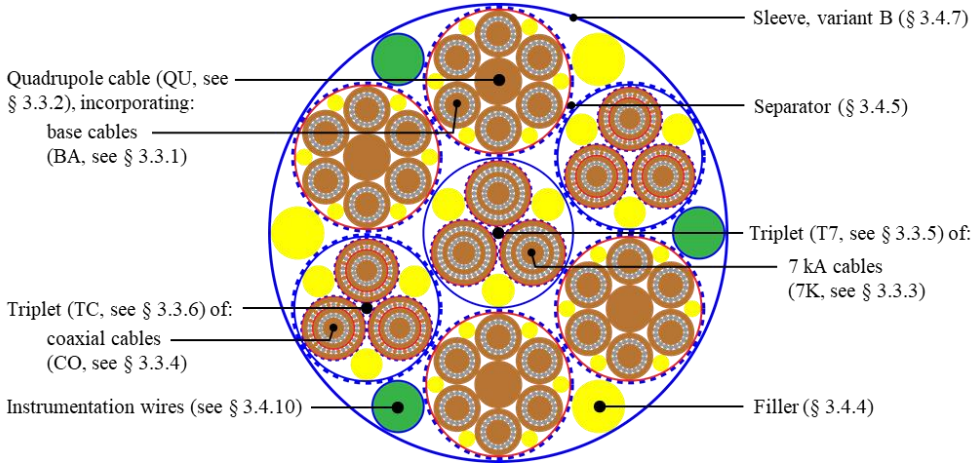


System demonstrator
in SM 18
DEMO2
Demonstration of **2 x 20kA +**
2 x 7kA in June'20
in MgB_2 @ 30K
in flexible cryostat
over 60m [54kA total]

Flexible MgB_2 superconducting links

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

Successfully HV tested both in industry and at CERN



Φ~ 90 mm

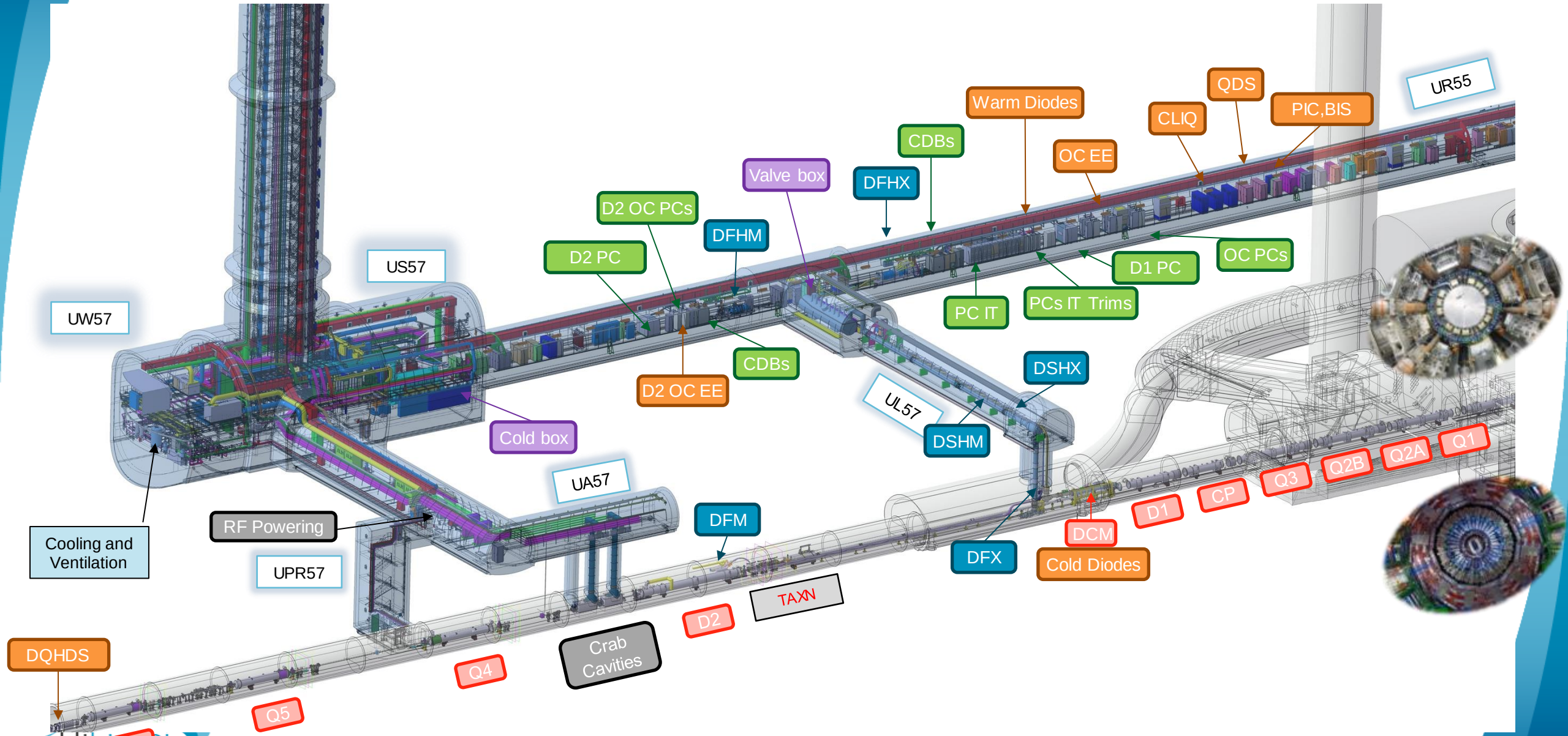
- Continuous tests at CERN of extracted strands from each constituent cable before approving further operations – 694 test pieces in 2021
- Production planned to be completed by end 2022

SC Link Cryostats

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

Leak/pressure tests at the company

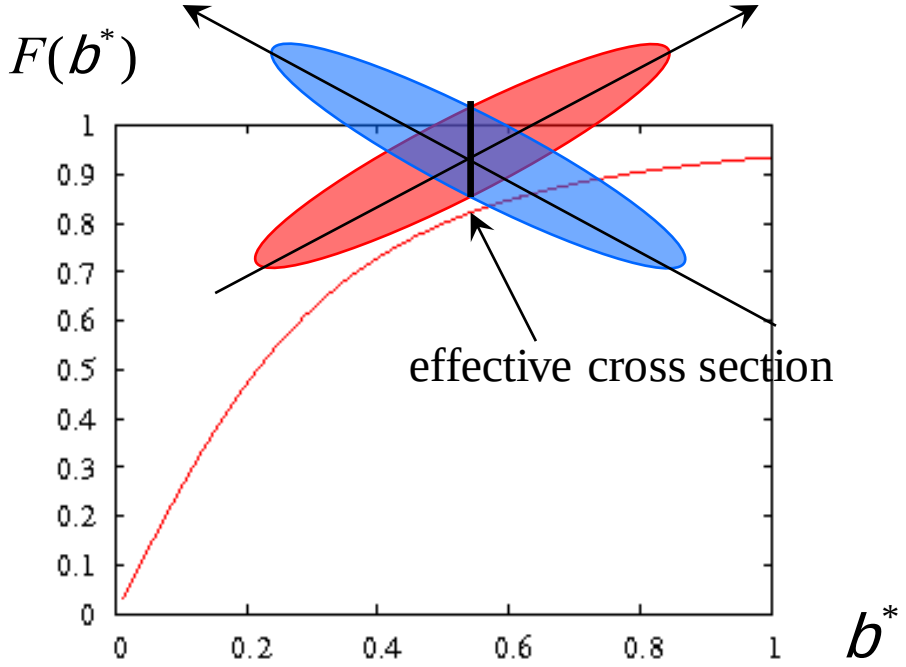
Delivery & Reception @ CERN

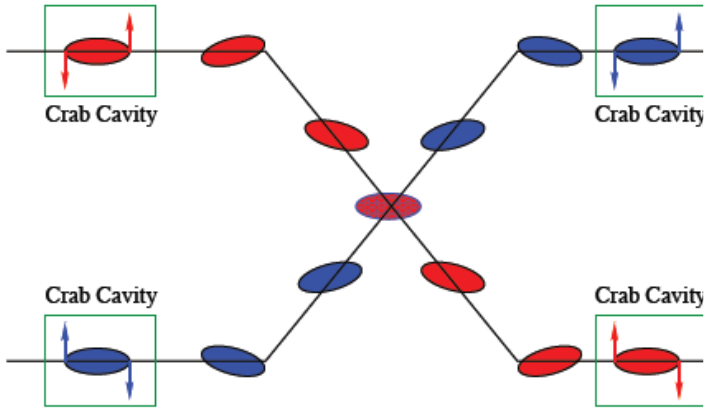

UR55
QDS
PIC,BIS
CLIQ
Warm Diodes
CDBs
OC EE
Valve box
DFHX
D2 OC PCs
DFHM
D2 PC
US57
UW57
OC PCs
D1 PC
PCs IT Trims
PC IT
CDBs
D2 OC EE
DSHX
UL57
DSHM
Cold box
UA57
Cooling and Ventilation
RF Powering
UPR57
DFM
DFX
DCM
Cold Diodes
D1
CP
Q3
Q2B
Q2A
Q1
TAXN
D2
Crab Cavities
Q4
Q5
Q6
DQHDS

Crab cavity development for the HL-LHC

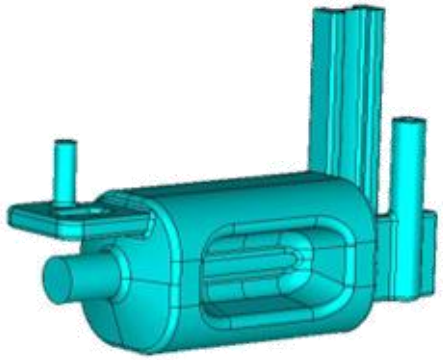
- Attempt to claw back the very significant reduction in luminosity from the large crossing angle
- Create an oscillating transverse electric field that kicks head and tail of the bunches in opposite directions
- Serving to mitigate the effect of the crossing angle at the IP
- Challenging space constraints:

  ➔ requires novel compact cavity design



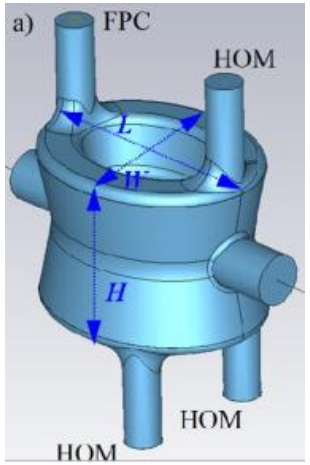


Crab cavity development



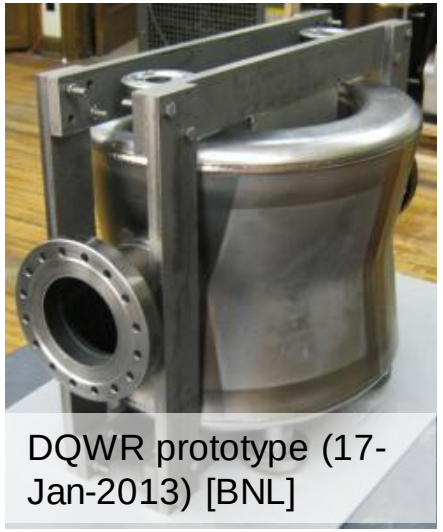
RF Dipole: waveguide or waveguide-coax couplers

Major R&D program
Concentrating on two designs for test installation and beam validation in SPS



Double ¼-wave (DQW): coaxial couplers with hook-type antenna

RF-Dipole Nb prototype [ODU-SLAC]

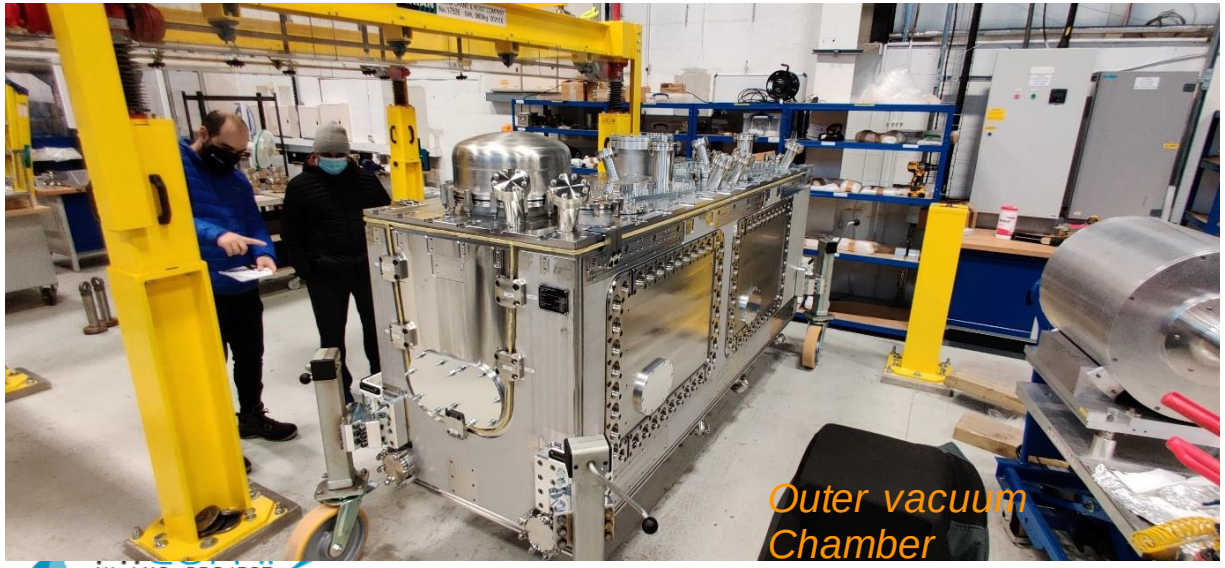


DQWR prototype (17-Jan-2013) [BNL]

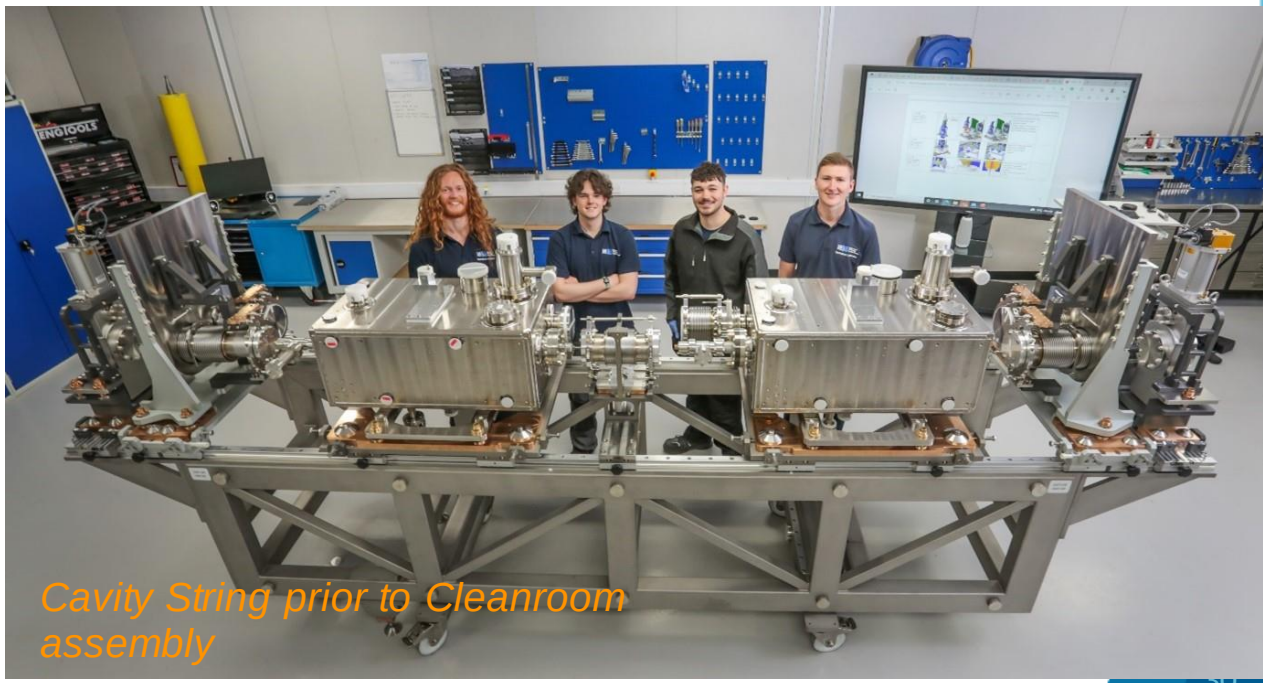
RFD Cryo-Module assembly in UK

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

Demonstration of crab cavities in hadron colliders

U.S. Particle Accelerator School
Education in Beam Physics and Accelerator Technology

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2022 USPAS Prize winners announced

Congratulations to the recipients of the 2022 USPAS Prize for Achievement in Accelerator Science and Technology:

USPAS Prize

- Prize Overview
- Past Prize Recipients and Citations
- Past Prize Committees
- Prize FAQs

Rama Calaga

For outstanding leadership bringing the crab cavities in hadron colliders from concept to reality and for the first demonstration of crabbing on a hadron beam.

Early-Career Award

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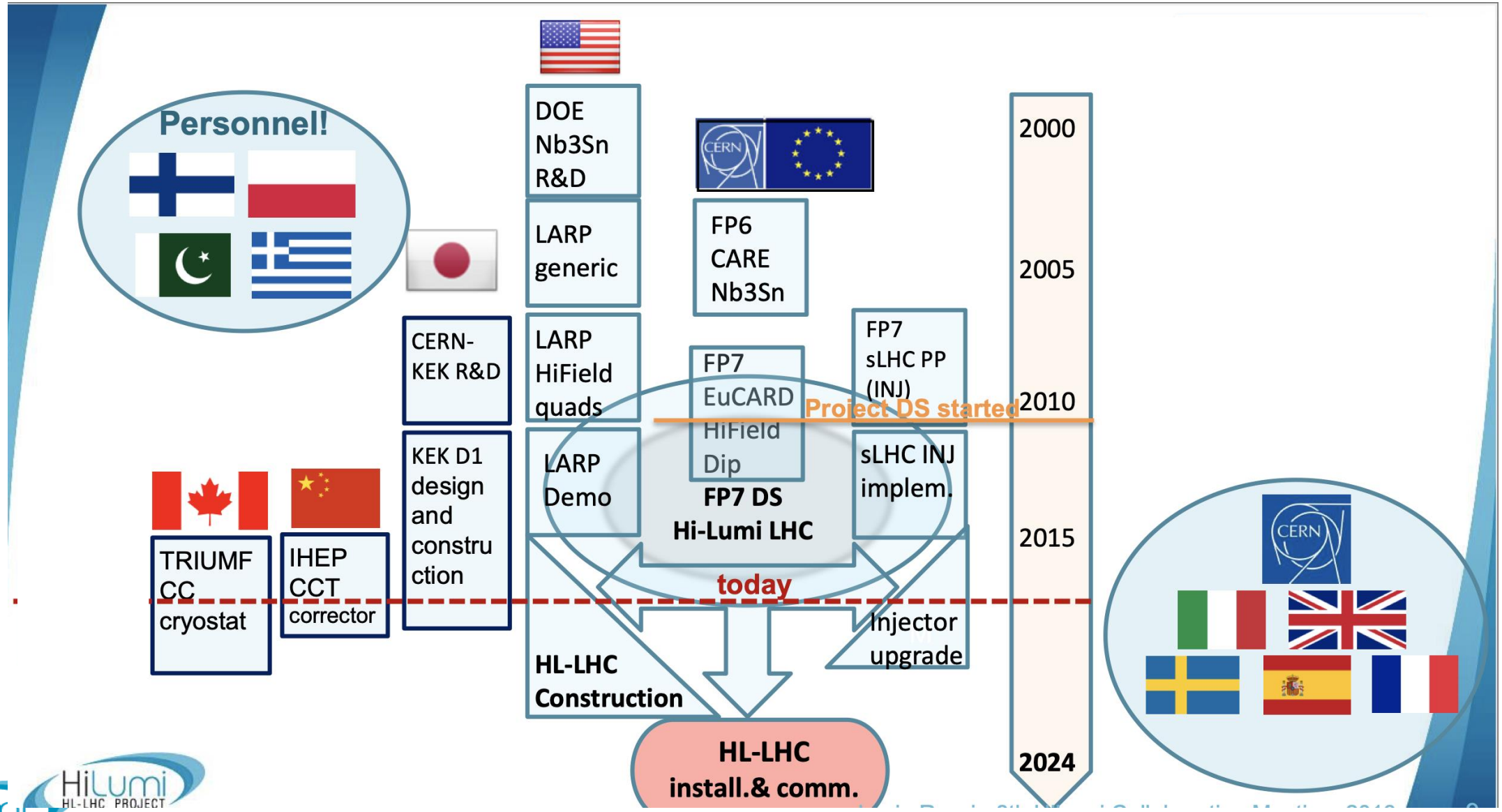
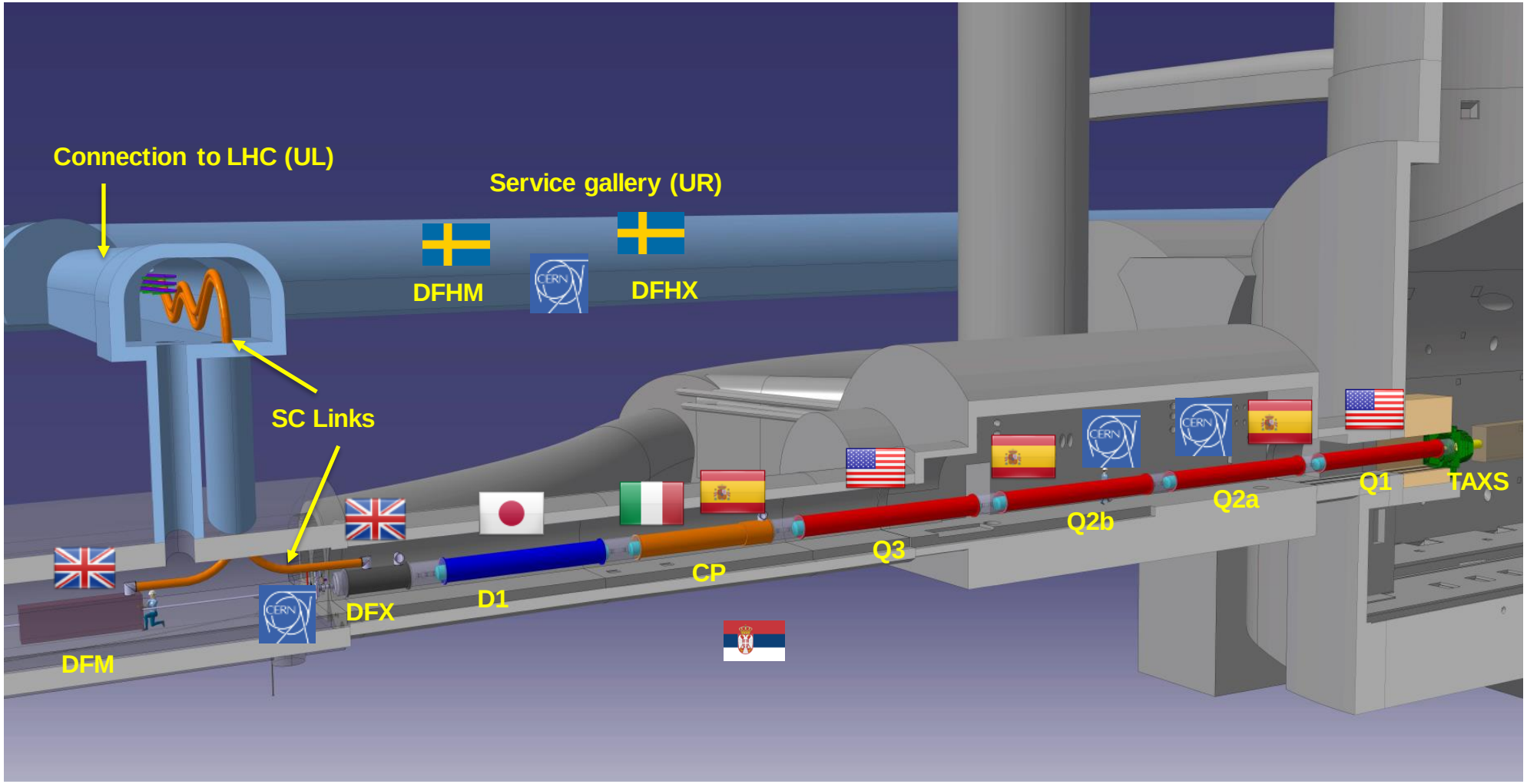
- HL-LHC as a truly international project
- Current Project planning and performance ramp-up

HL-LHC is a world-wide collaboration!



Truly International Collaboration offering exiting opportunities!



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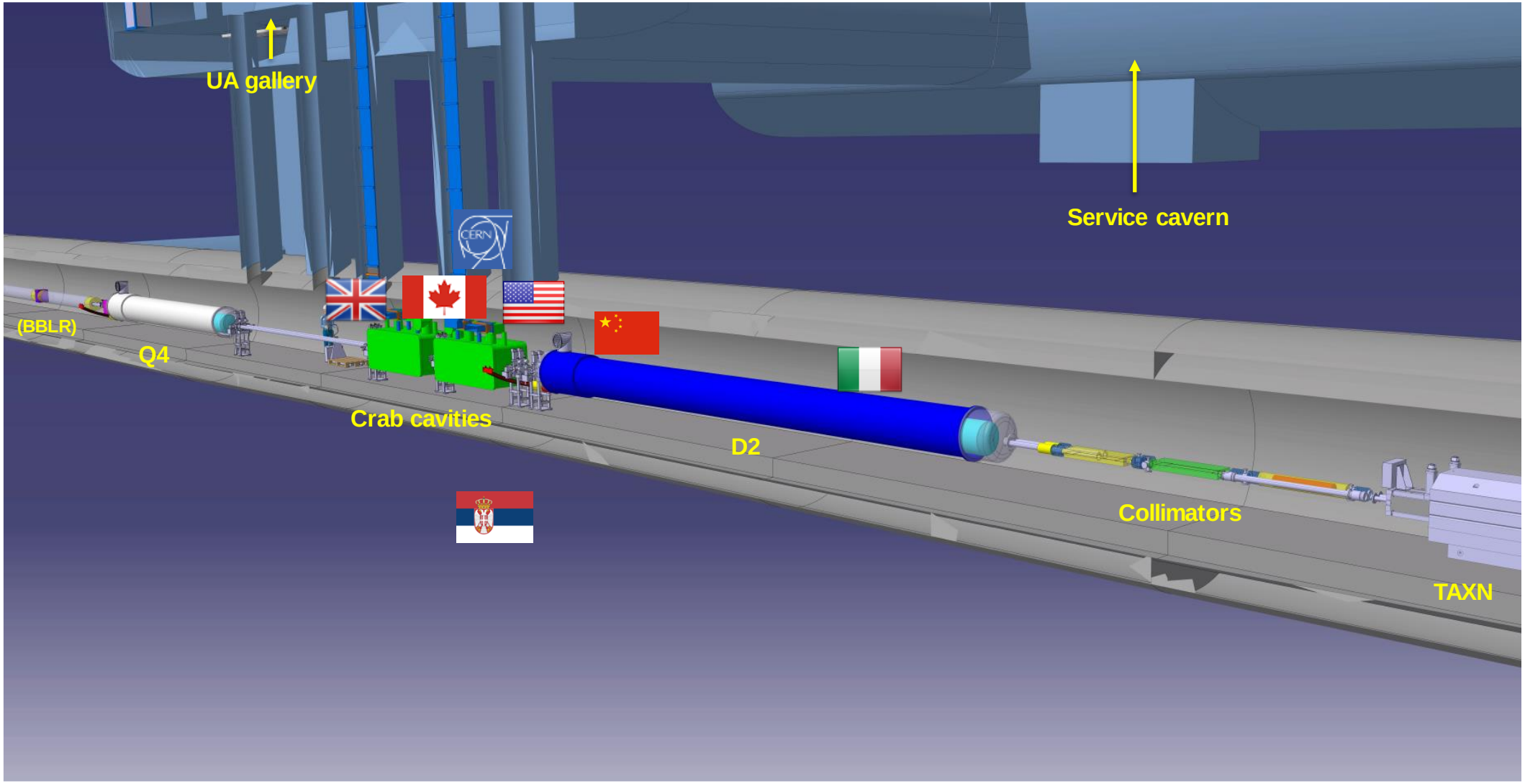

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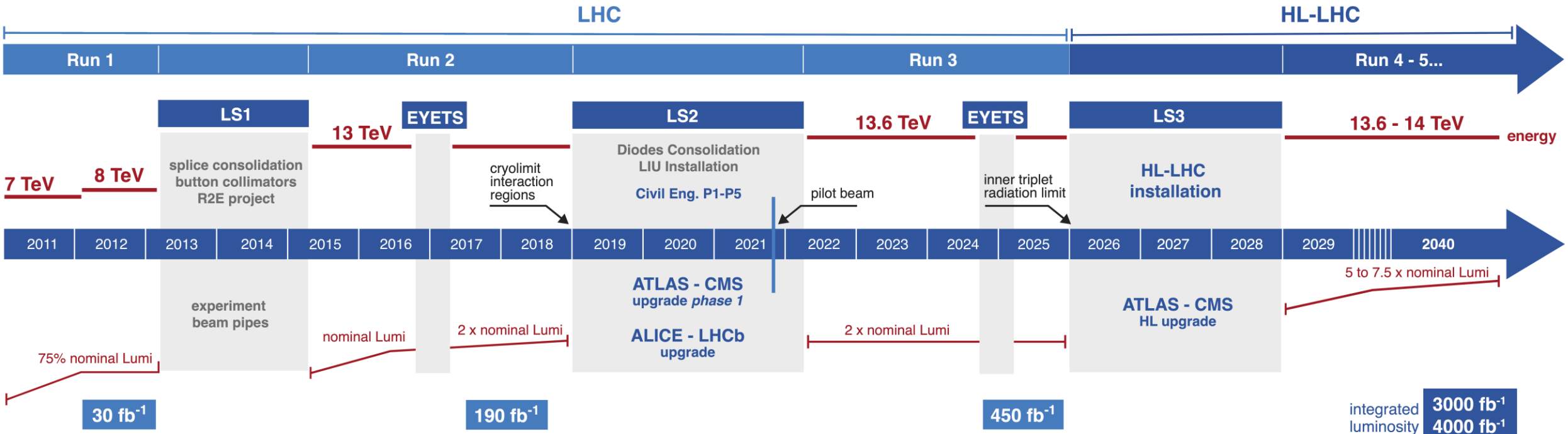
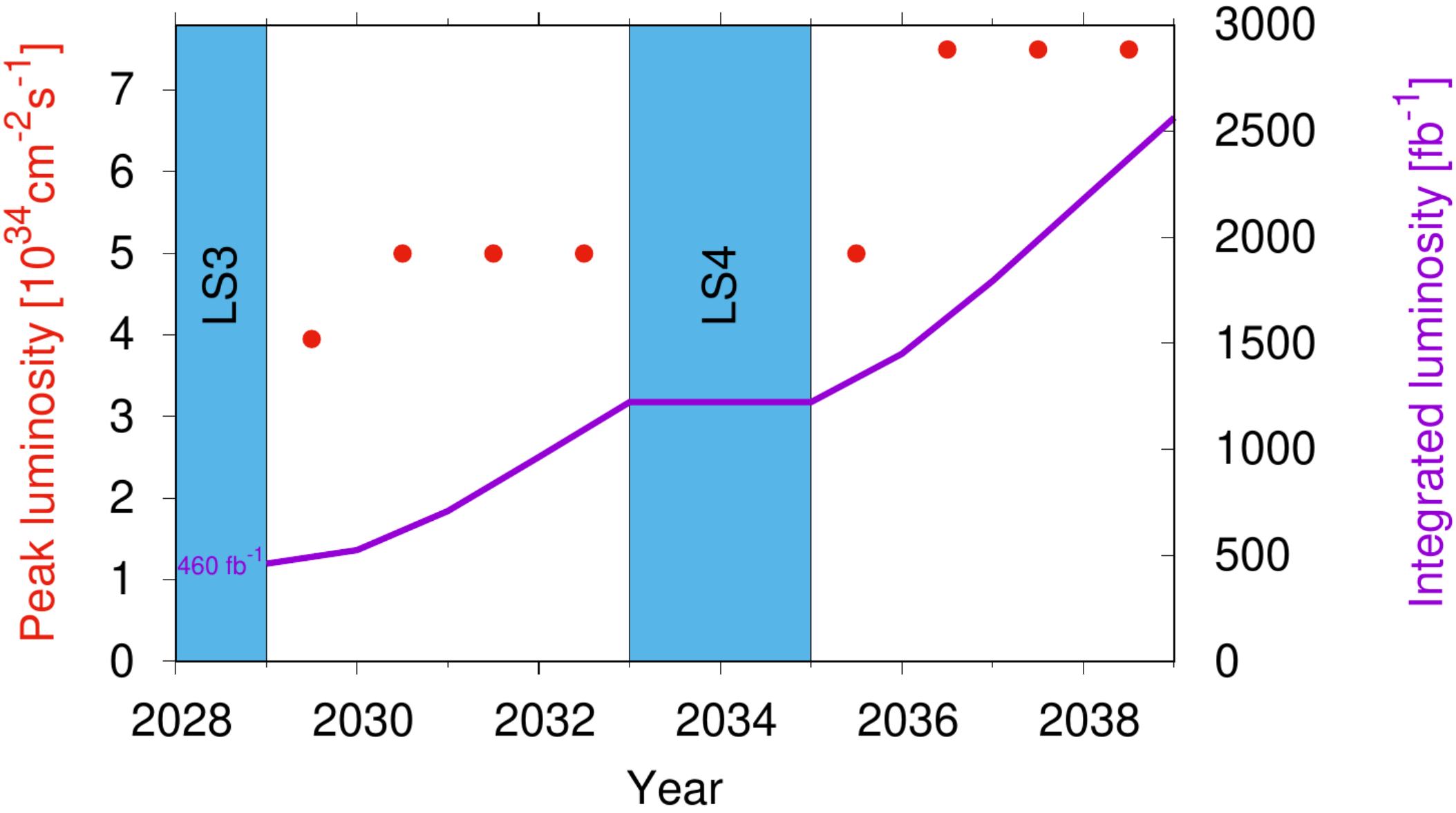
LHC / HL-LHC Plan



HL-LHC TECHNICAL EQUIPMENT:

HL-LHC CIVIL ENGINEERING:

Expected HL-LHC performance

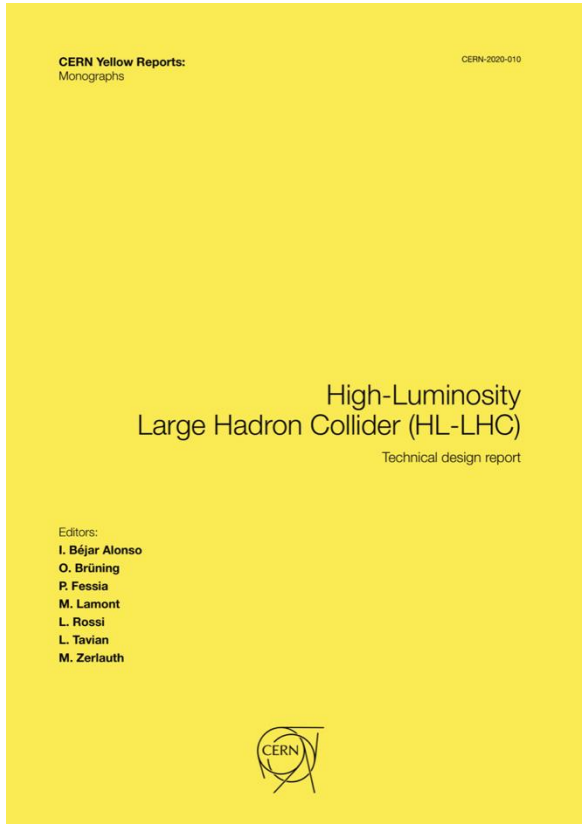


TDR V1.0 - The last version of the TDR including the added scope - 2020

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

EDMS: 1723851

and as CERN Yellow Book in October 2017



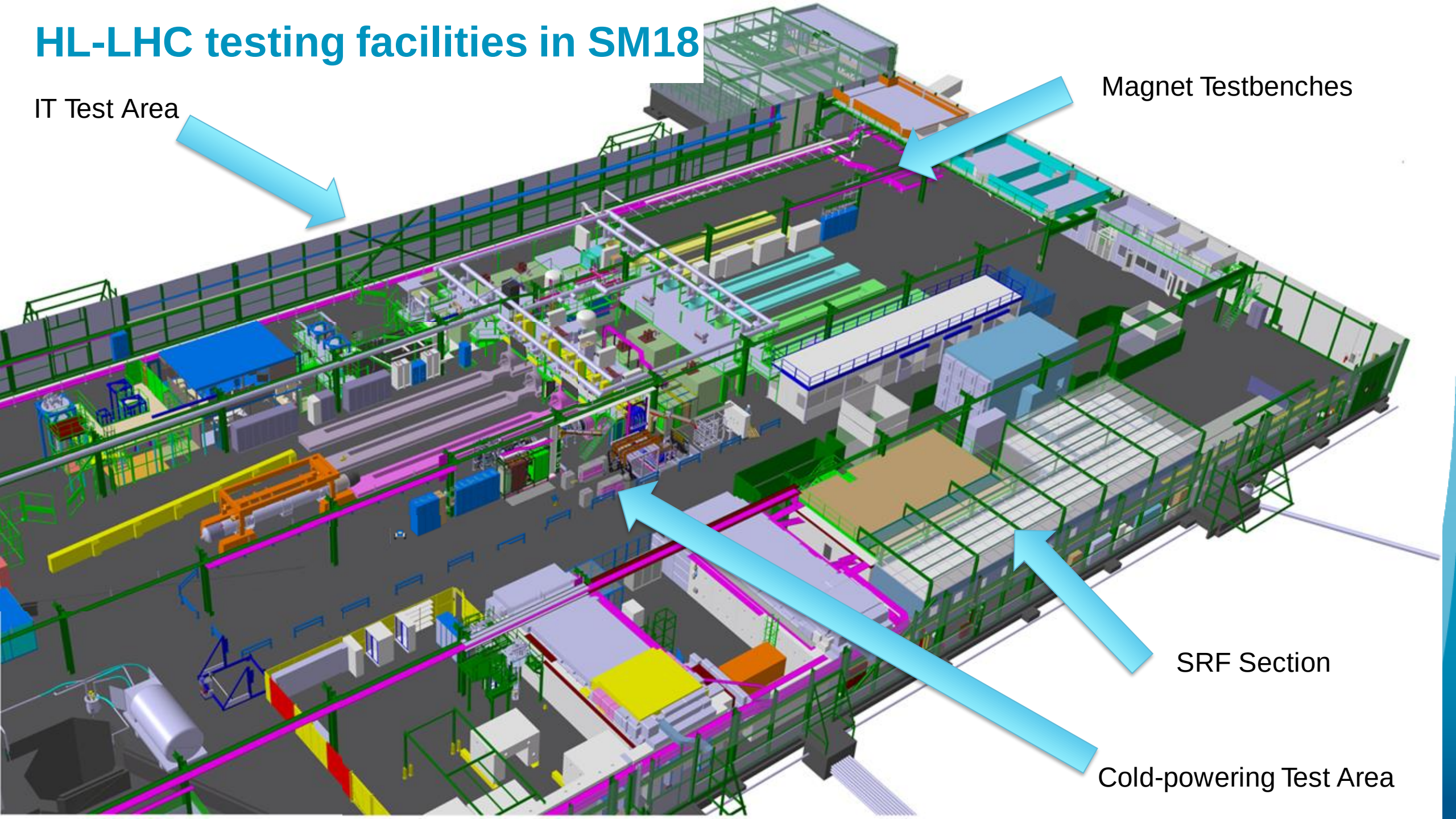
Updated Version V 1.0 published as CERN Yellow Book in December 2020

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

Thank you for your attention!
Question?

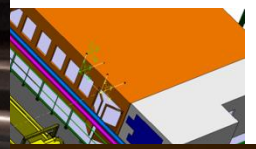
SPARE SLIDES

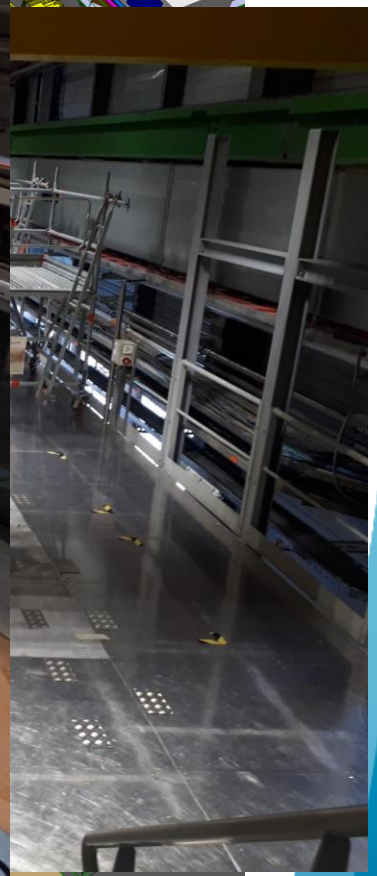
HL-LHC testing facilities in SM18



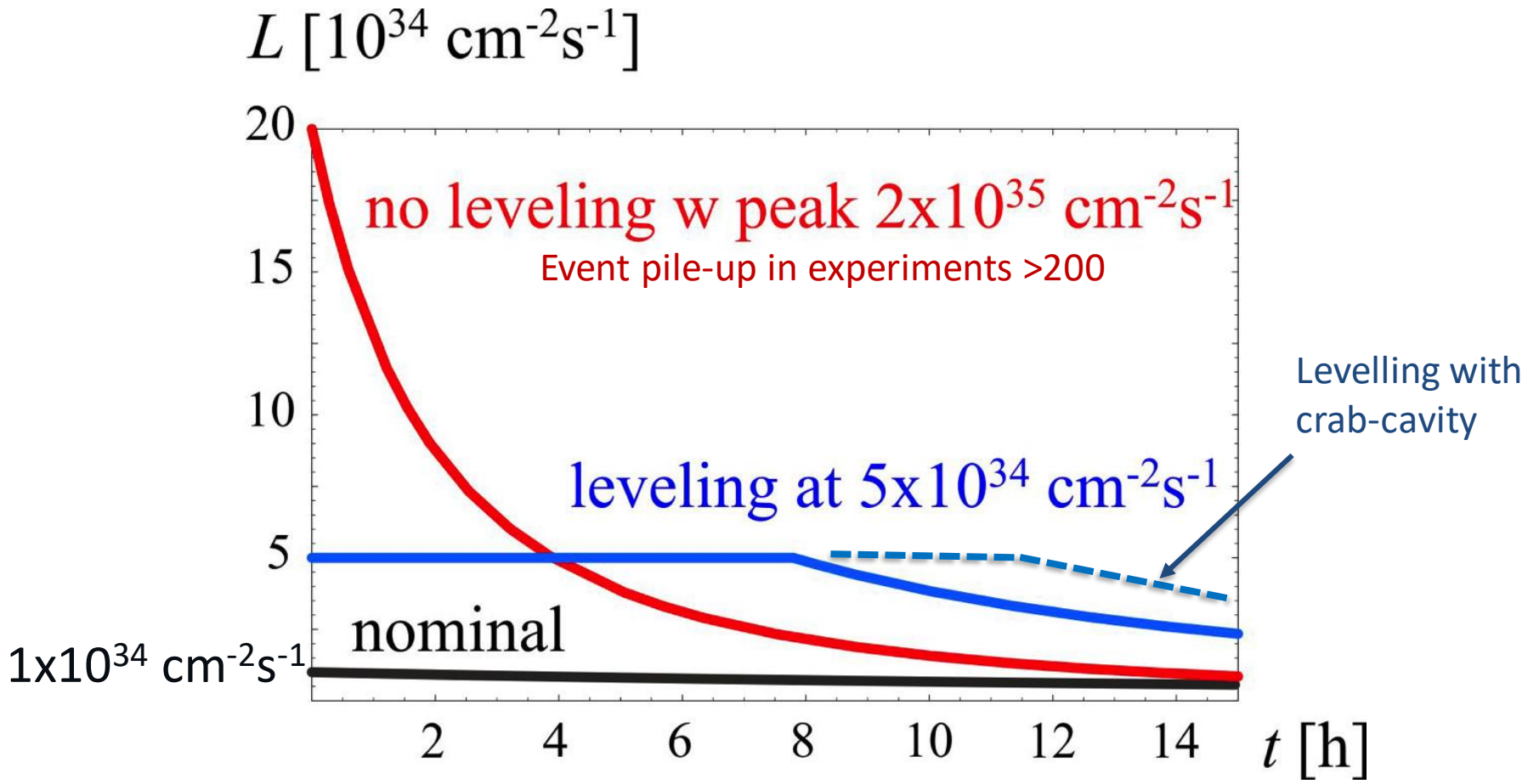
Important mil

- Overall inte
- Vacuum an
- Electrical s

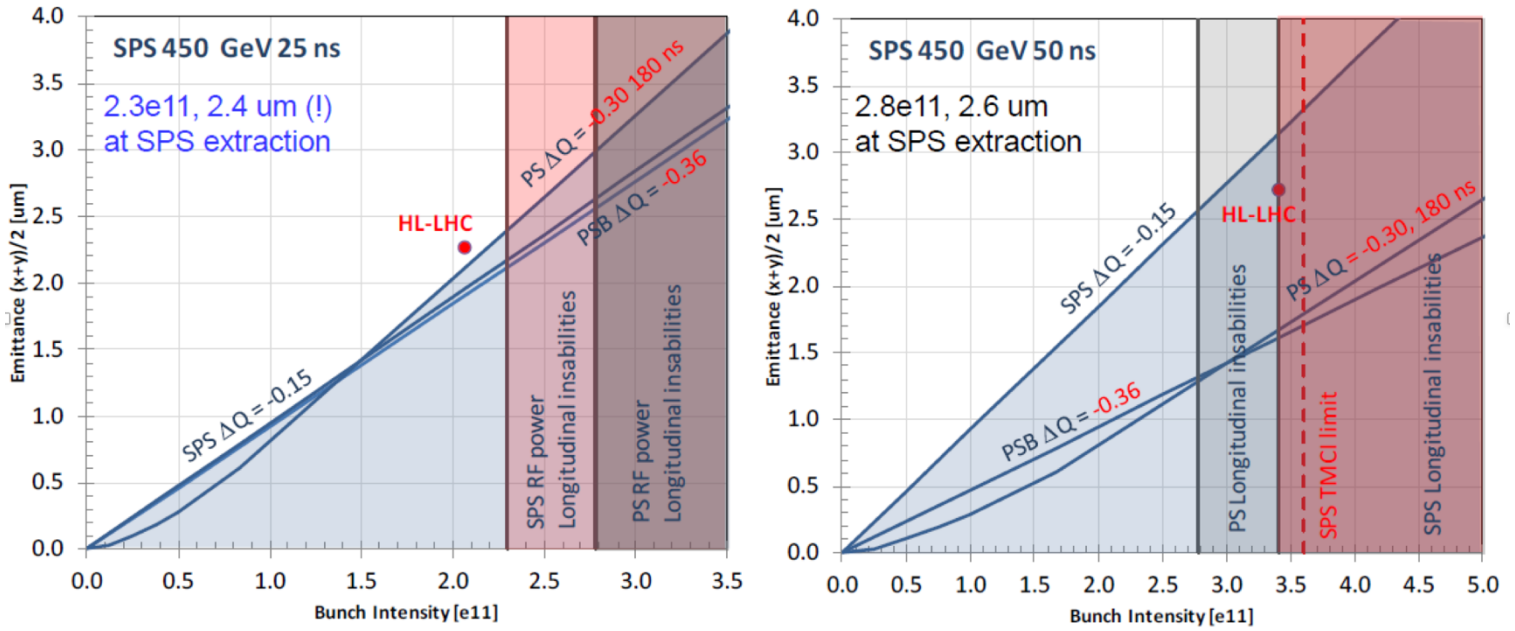




Operational Scenario for HL-LHC

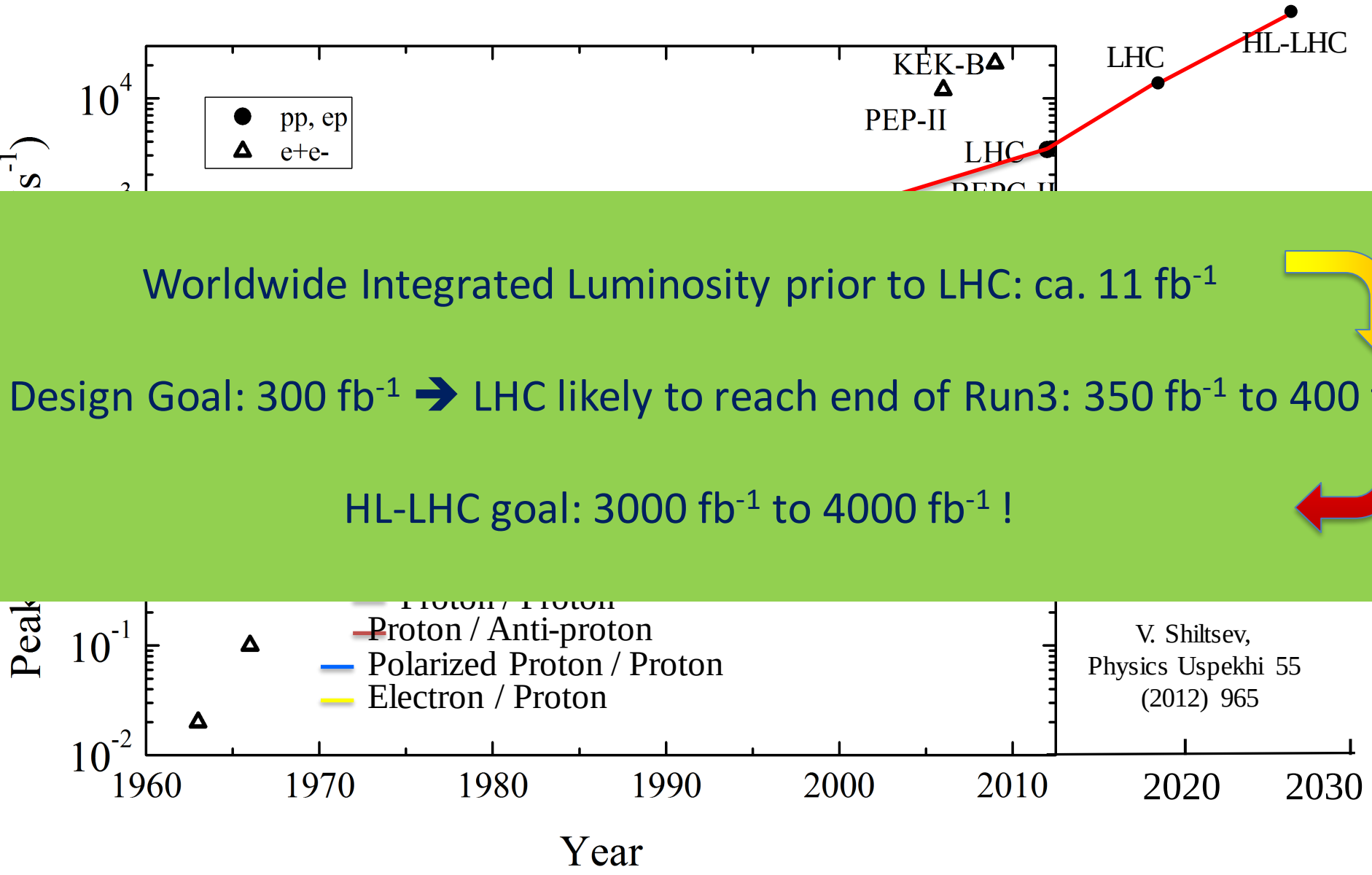


LHC Injector Upgra



- 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} !