HL-LHC Upgrade Project

Joint KEK - CERN Committee, Dec 2022

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

Outline

- HL-LHC design parameters and project planning
- Status of key technologies towards the HL upgrade
  - Civil engineering
  - Final focusing magnets for lower beta*
  - Superconducting Link
- Inner Triplet String
- Ongoing (and potential future) collaborations KEK – CERN
- Conclusions

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HL Project Management and Organisation

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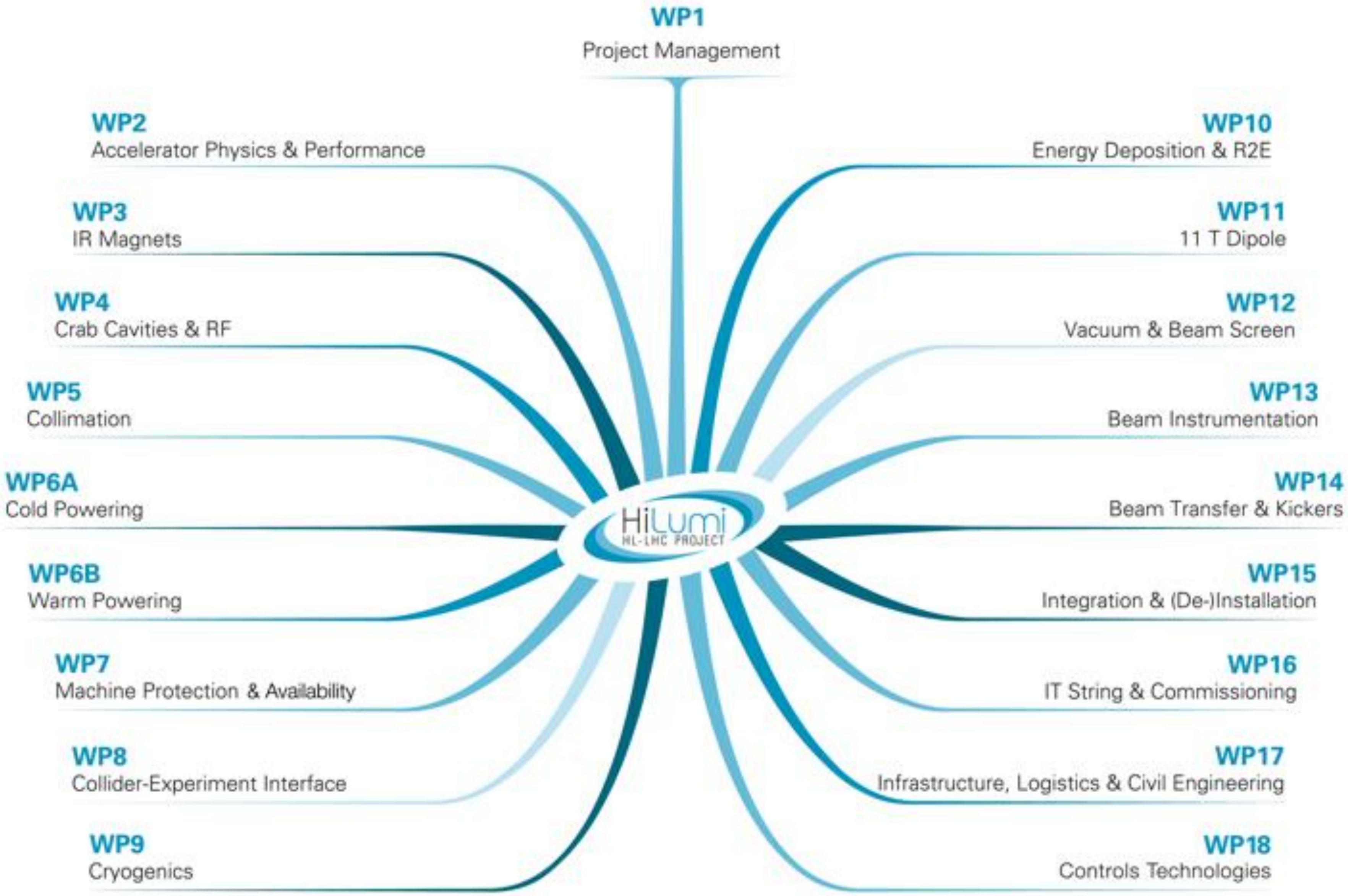


Goal of HL-LHC upgrade project

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:

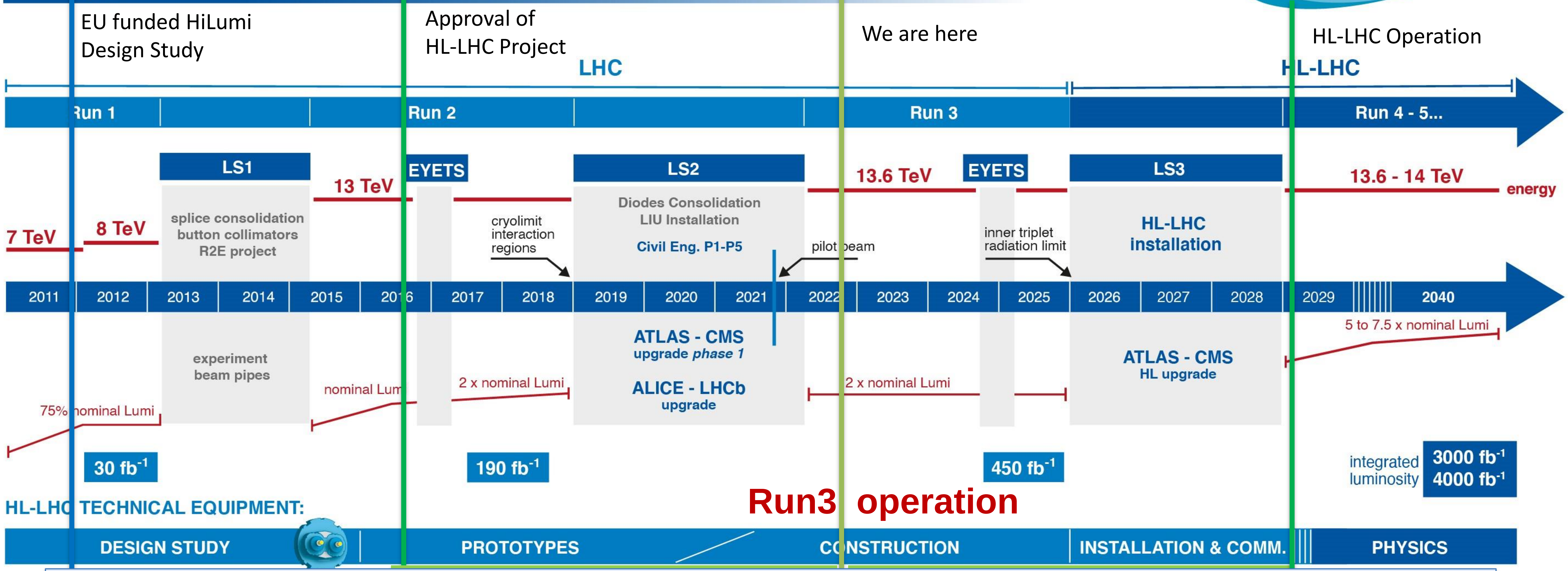
enabling at total integrated luminosity of **3000 fb^{-1}**

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

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

-> A challenge as well for the experiments!
Operation with levelled luminosity!

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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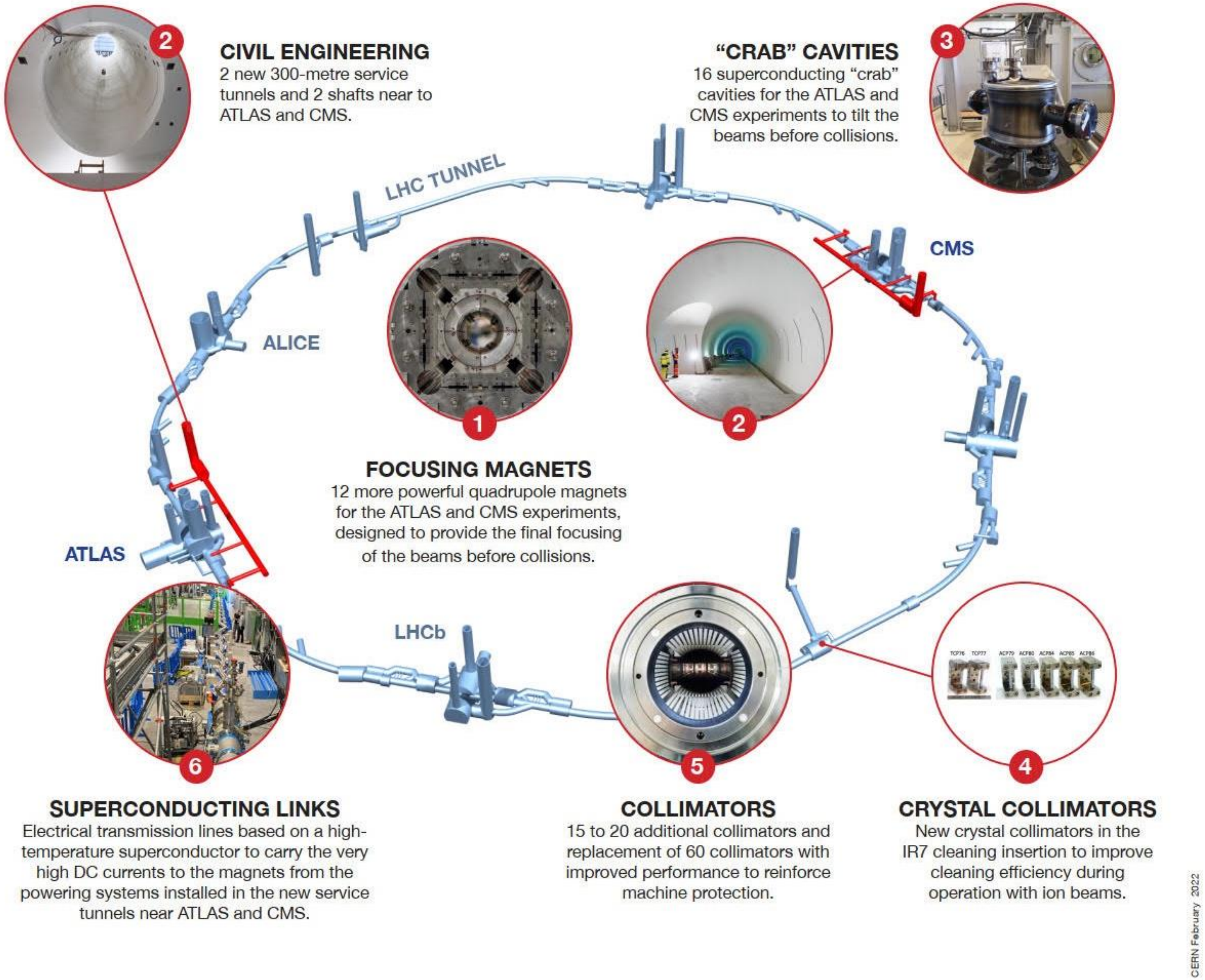
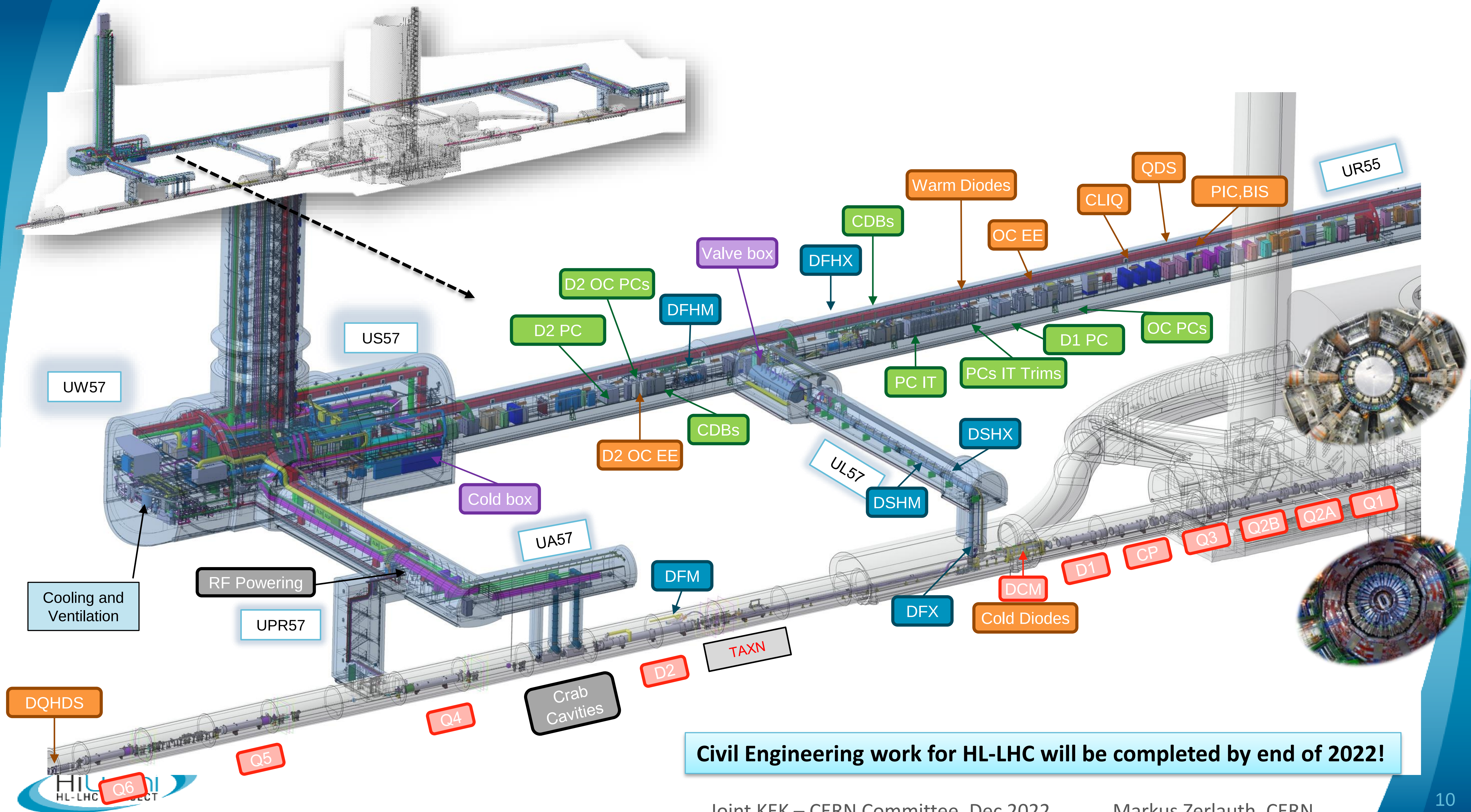
HL-LHC technology landmarks

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

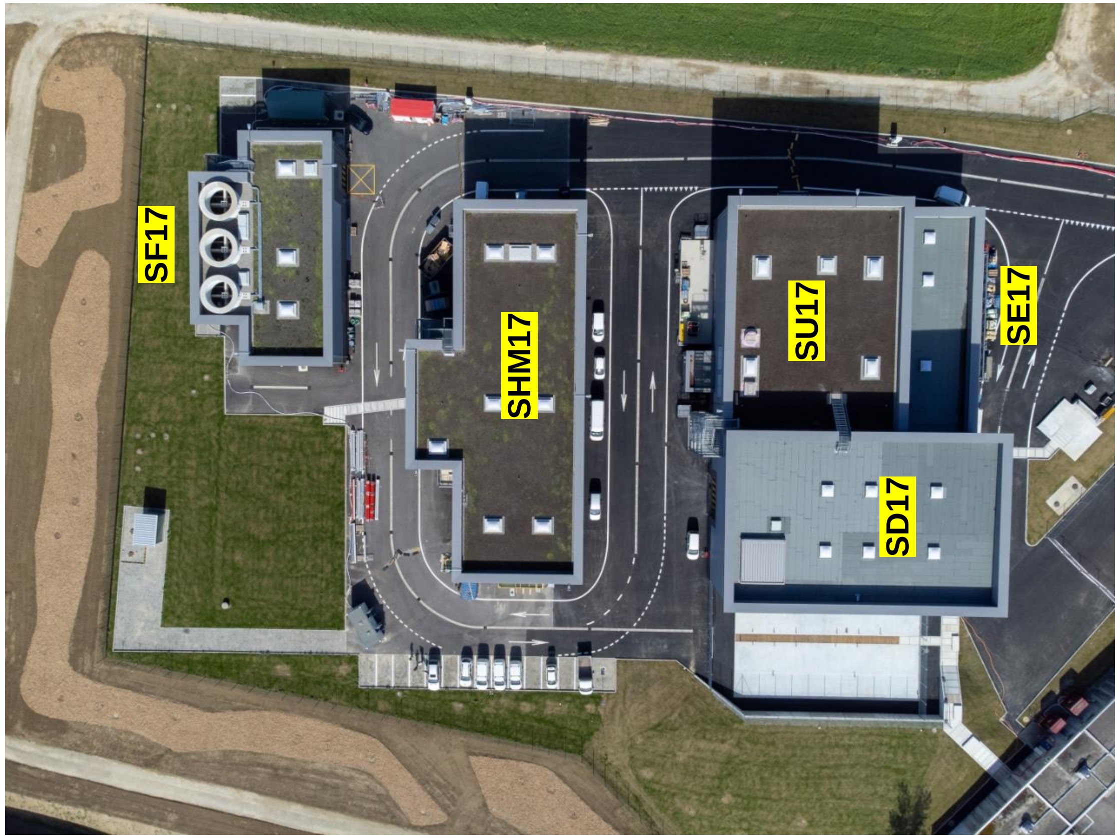
Technology intensive project!



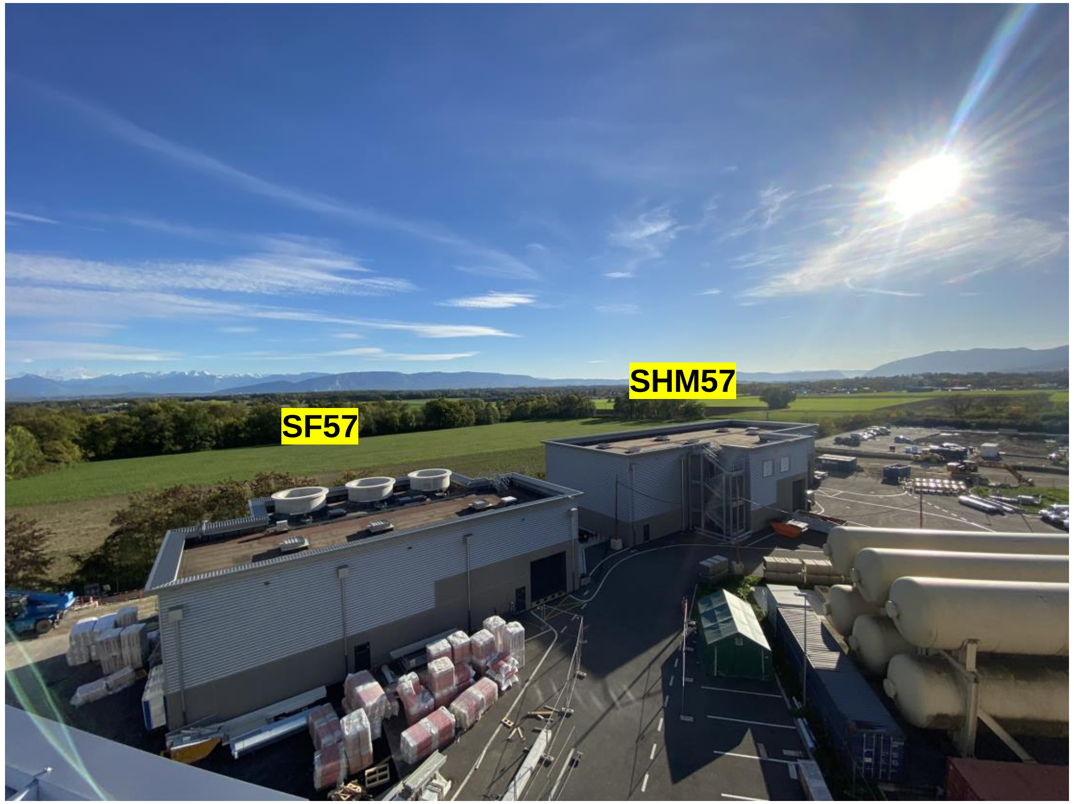


Civil Engineering work for HL-LHC will be completed by end of 2022!

Completion of the civil engineering works at Point 1



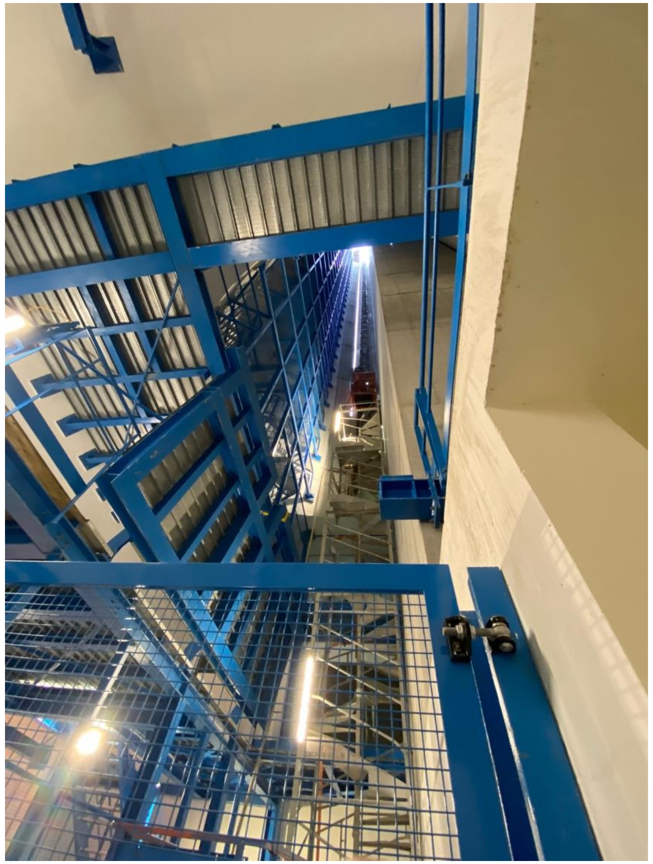
Progress of surface buildings at P5

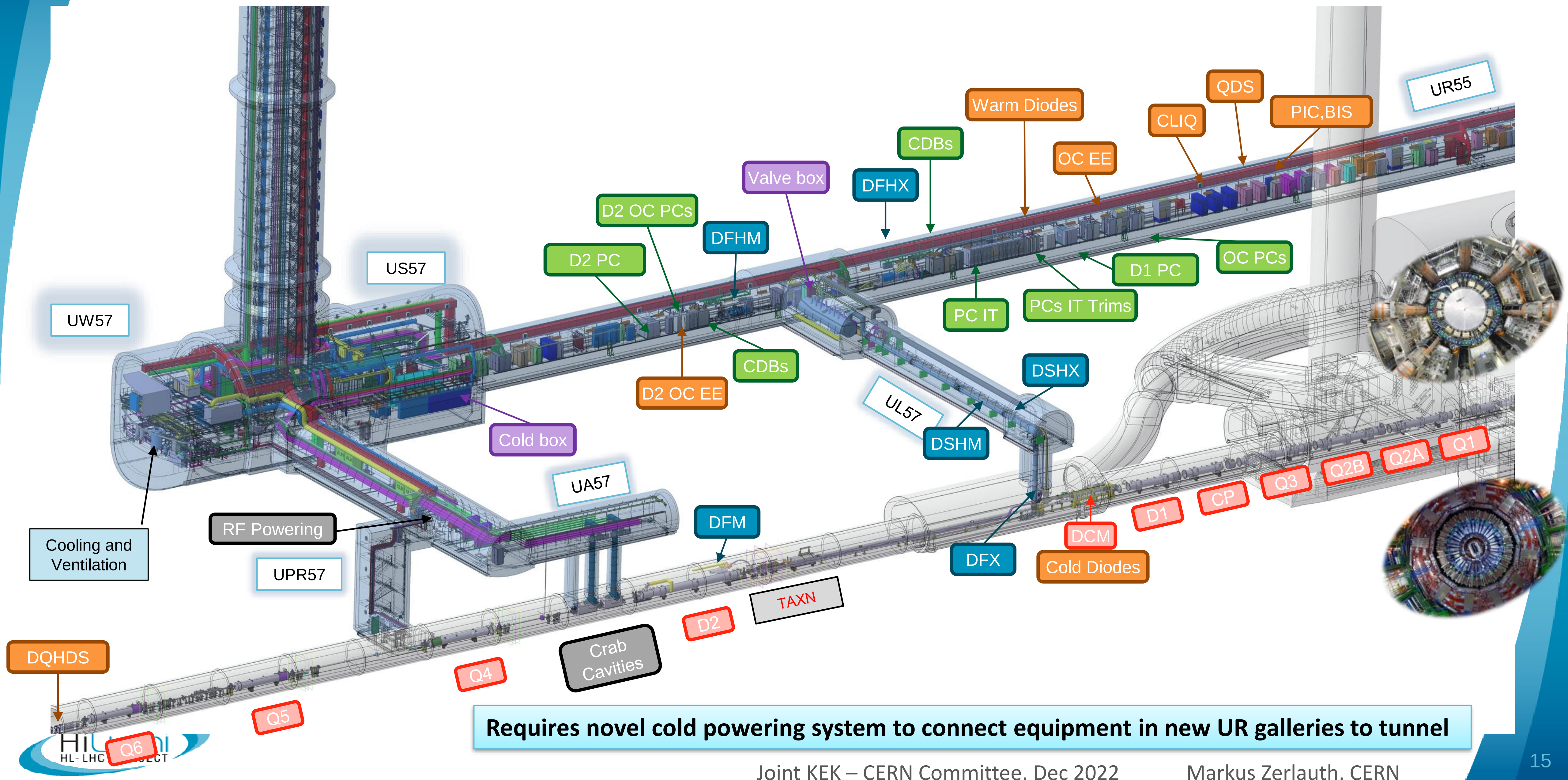


HL-LHC civil engineering status (Point 1)

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

Ceremony for completion of CE on January 20th 2023

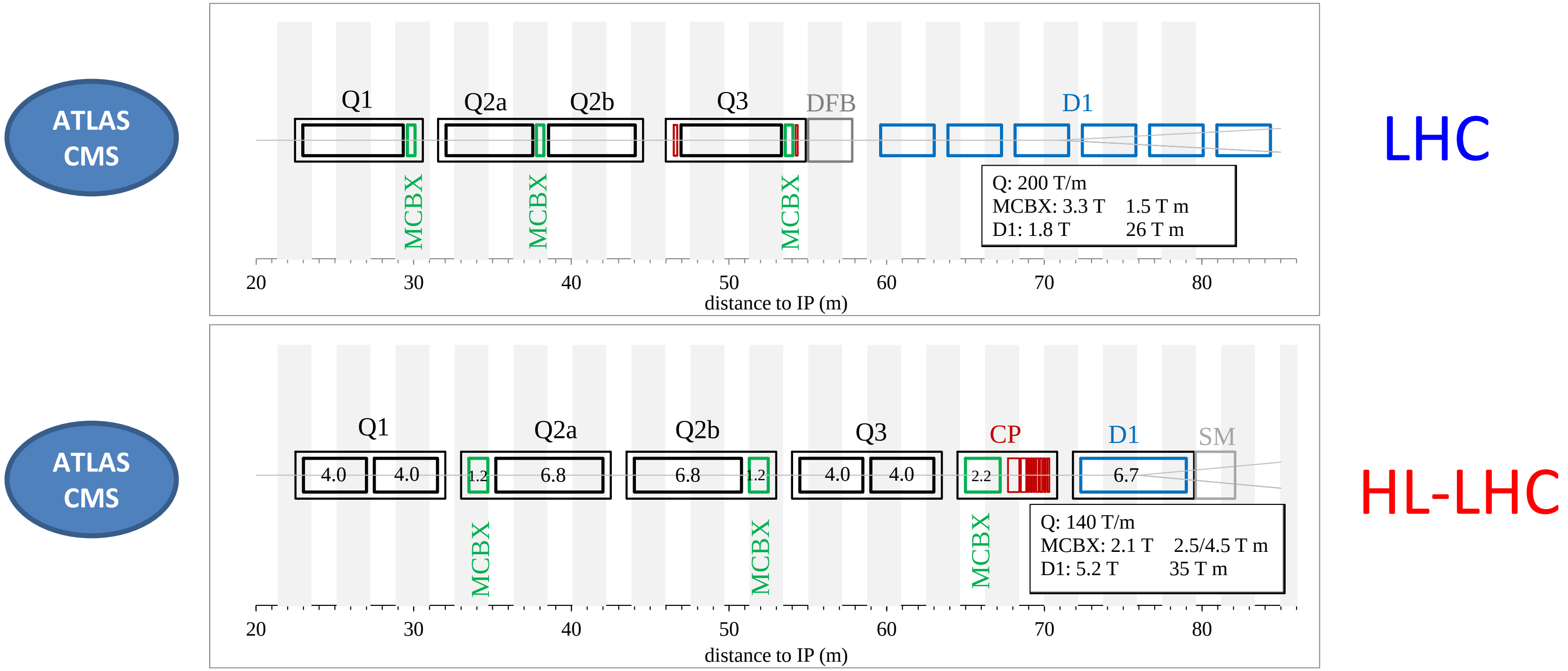




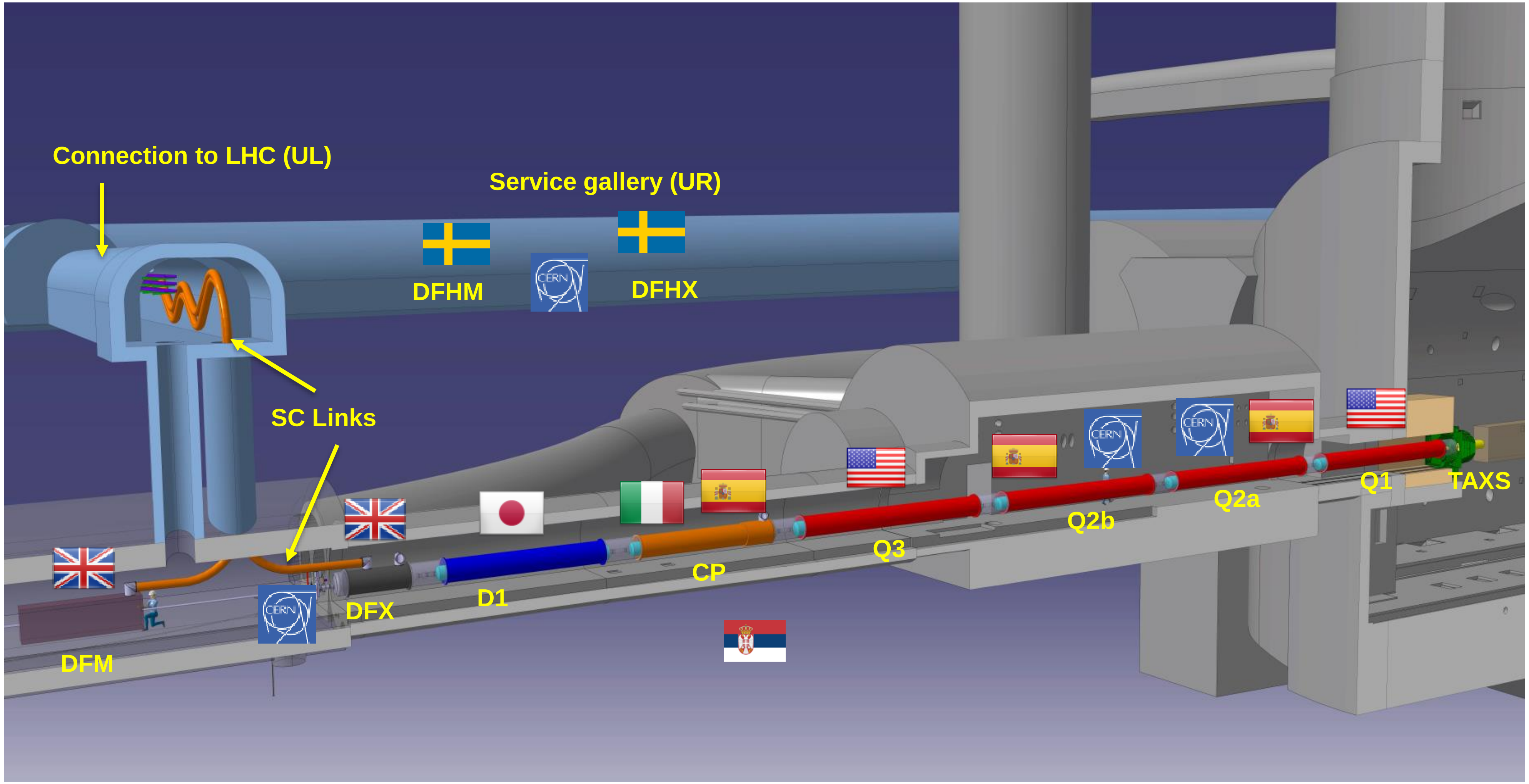
Requires novel cold powering system to connect equipment in new UR galleries to tunnel

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

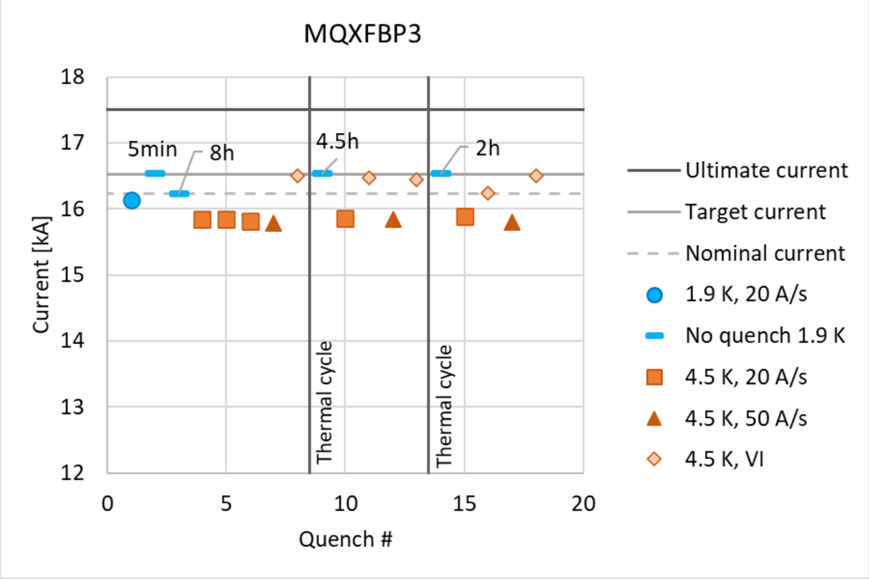


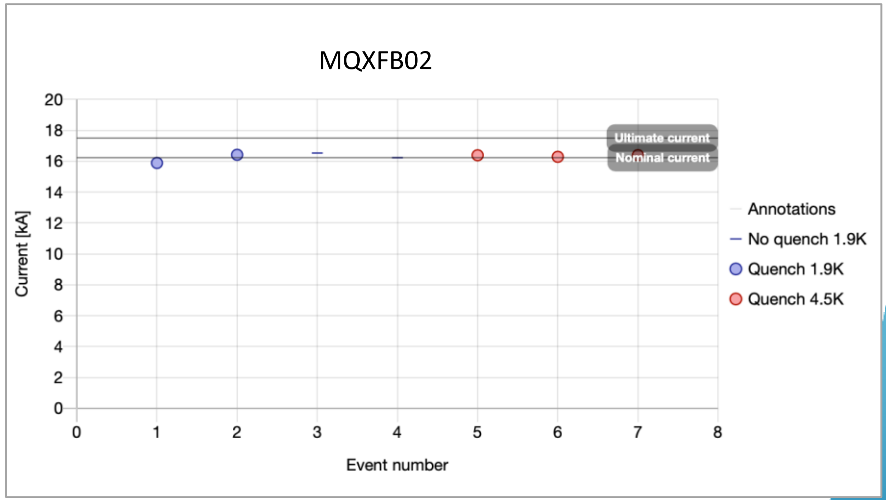
Truly International Collaboration offering exiting opportunities!



Main Quadrupole Magnets – Q2

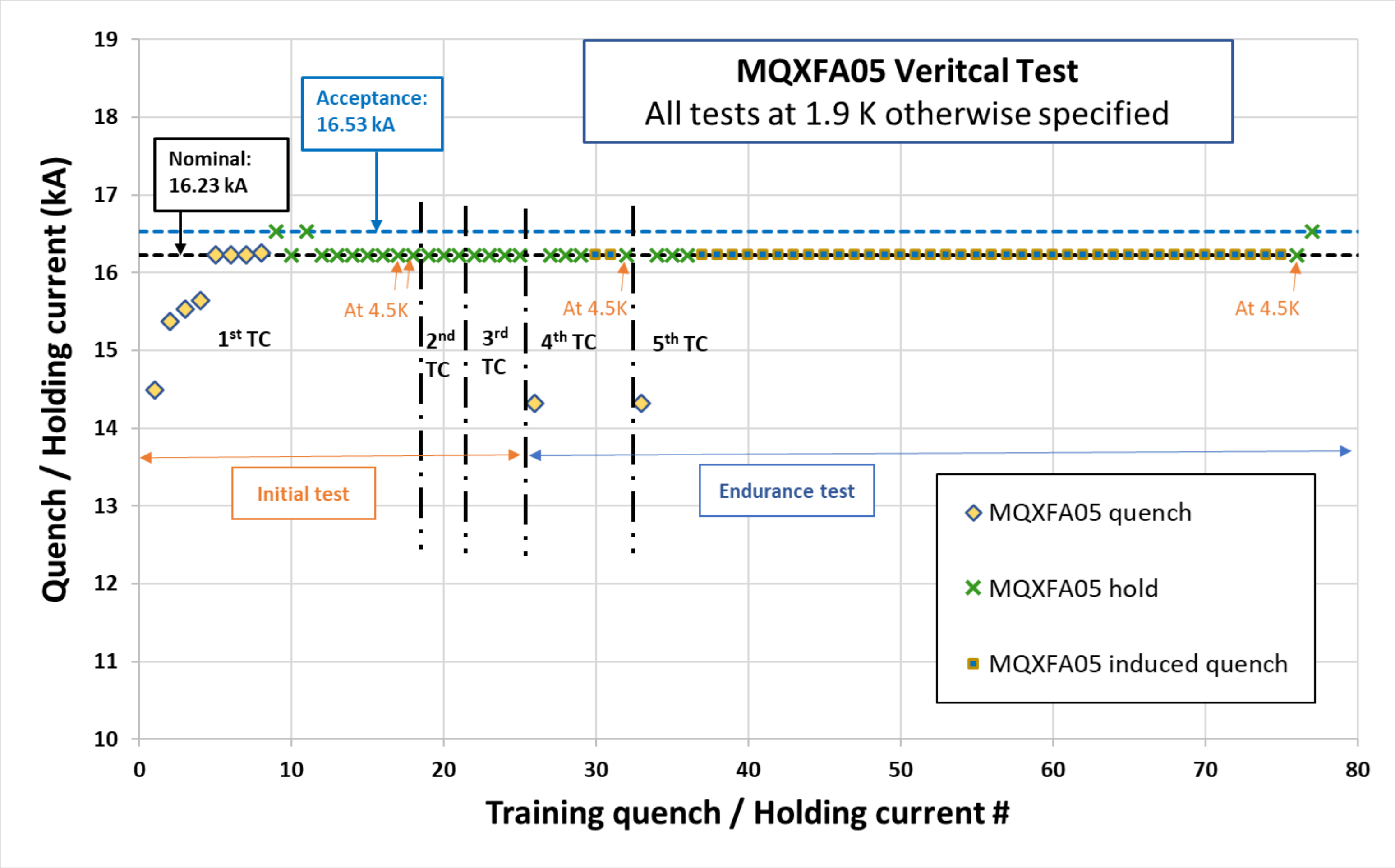
- August 2022: Successful test of MQXFBP3 test @ SM18
- November-December 2022: Ongoing tests of MQXFB02





Main Quadrupole Magnets – Q1/Q3

Fitting of bottom SS shell and longitudinal welding



Cold-test of first series cryostat assembly LQXFA01 imminent

Testing of D1 Prototype at KEK

- Lifting up the D1 magnet

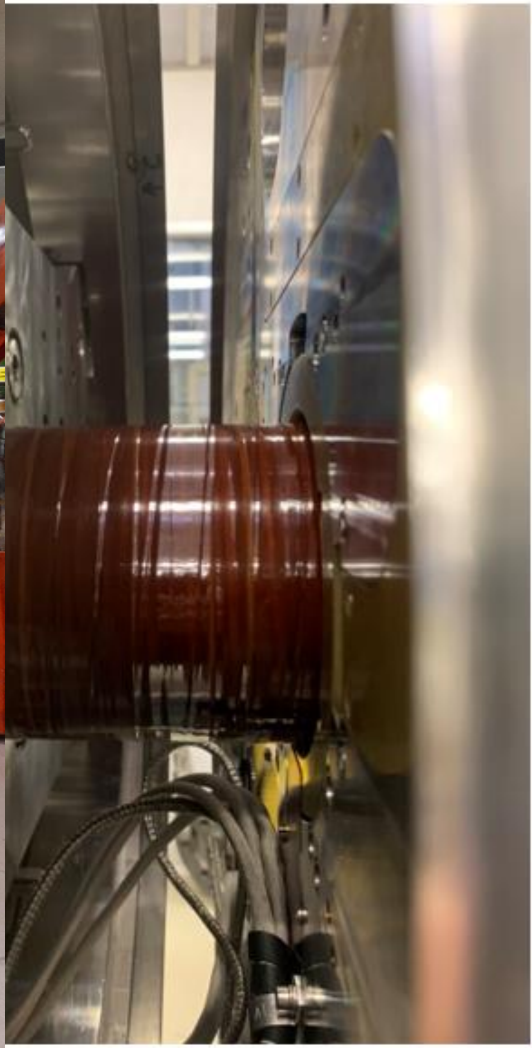
- Insertion into vertical cryostat

See following presentation for more details!
Looking forward to reception of magnet at CERN in March'23
for final preparations and integration in IT String

D2 Cold-Mass Assembly

D2 Prototype on the test bench in SM18

D2 Prototype Cold-



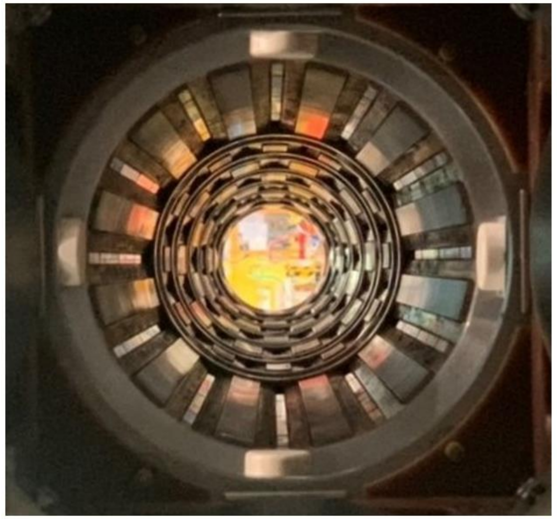
Dipole Orbit and Higher Oder corrector magnets

Nested dipole
orbit correctors
from Elytt in Spain

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Canted Cosine Theta Corrector
production from IHEP/Bama in China

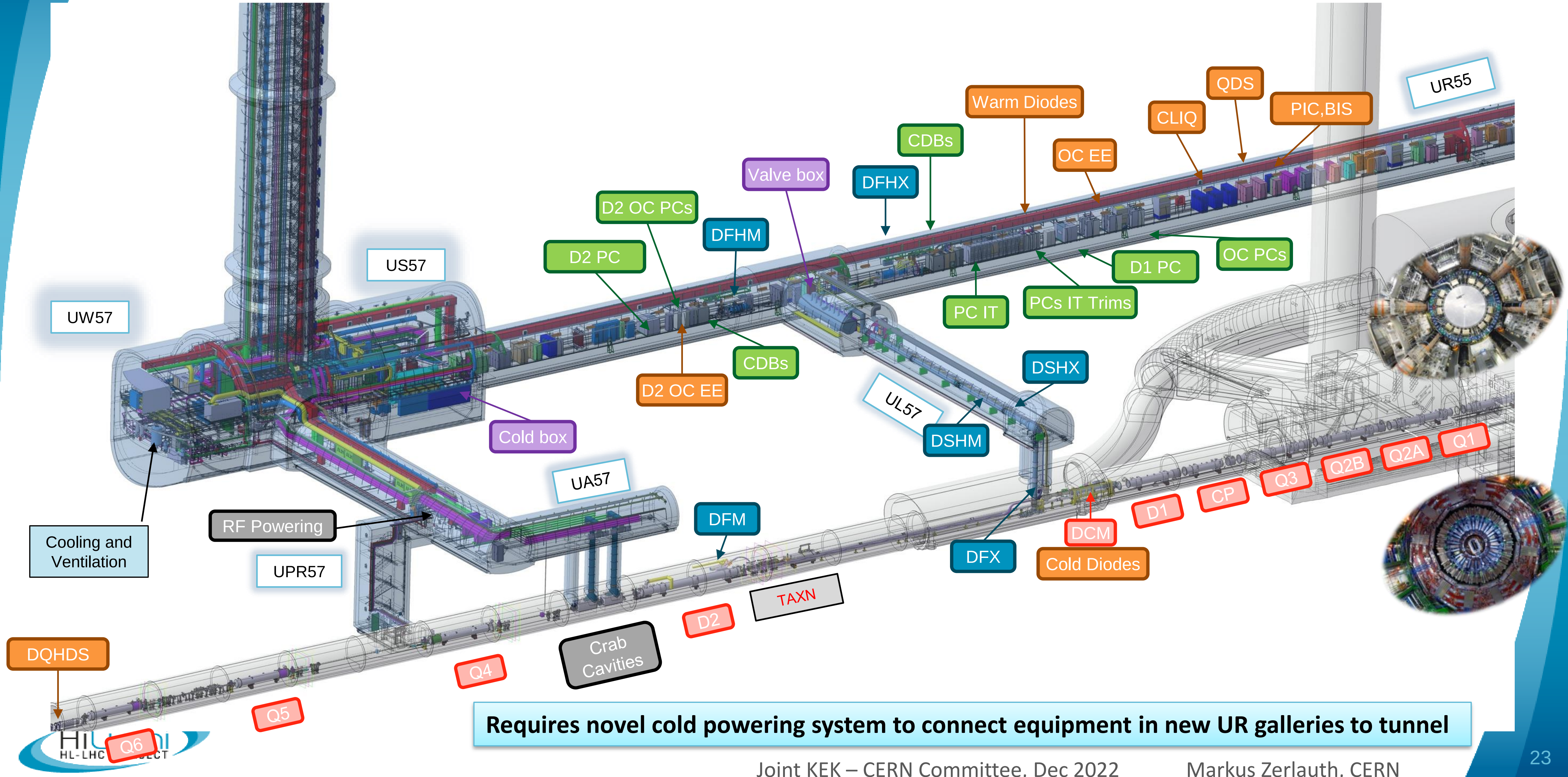
Institute of High Energy Physics
Chinese Academy of Sciences



Higher Order Corrector
Magnets from LASA in Italy

INFN

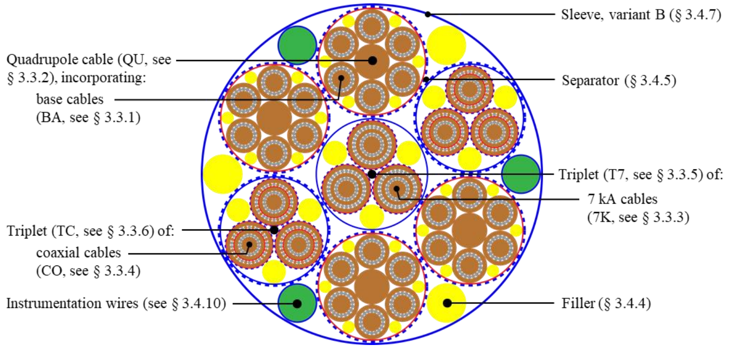
HiLumi HL-LHC PROJECT



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

Flexible MgB_2 superconducting links

Demonstration of **2 x 20kA + 2 x 7kA** in June’20
in MgB_2 @ 30K
in flexible cryostat
over 60m [54kA total]



$\Phi\sim$ 90 mm

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

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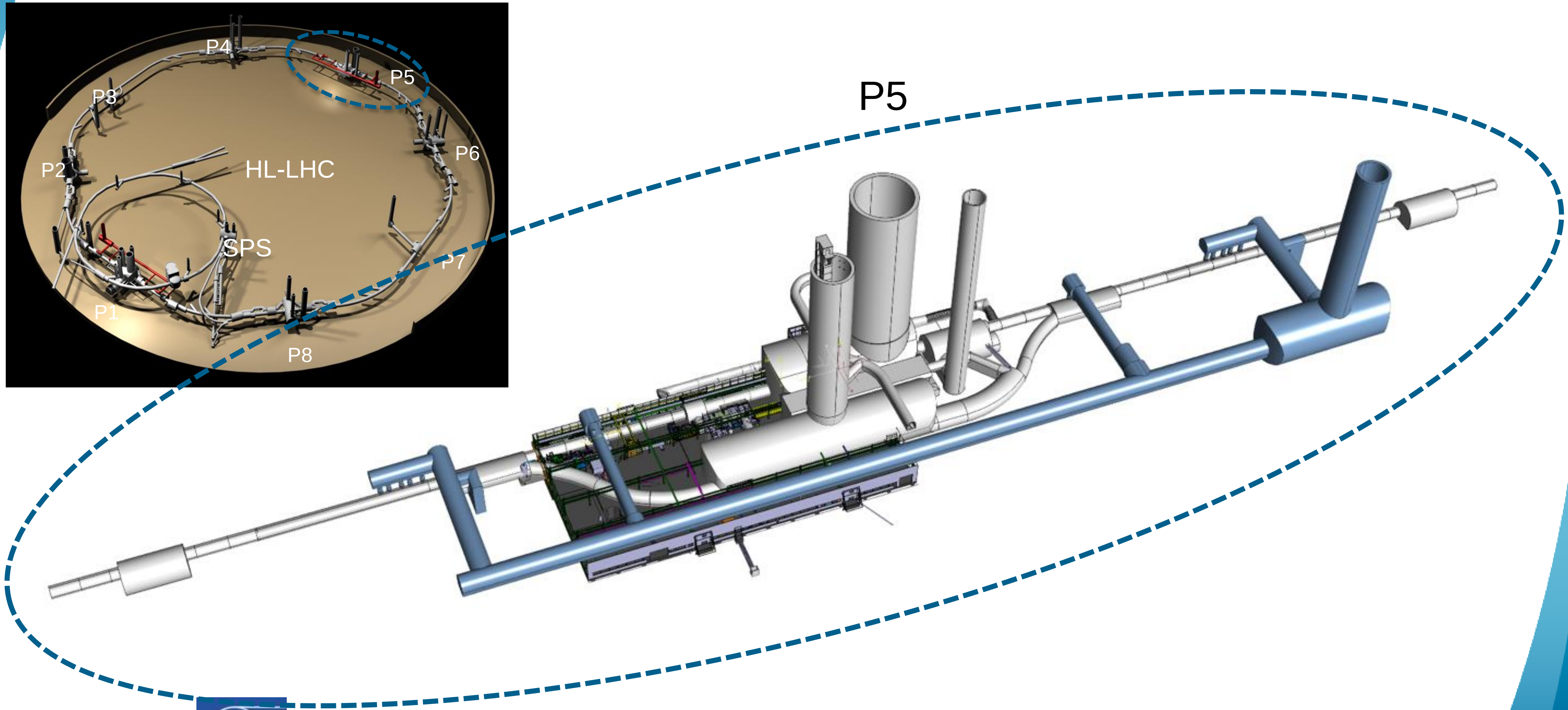
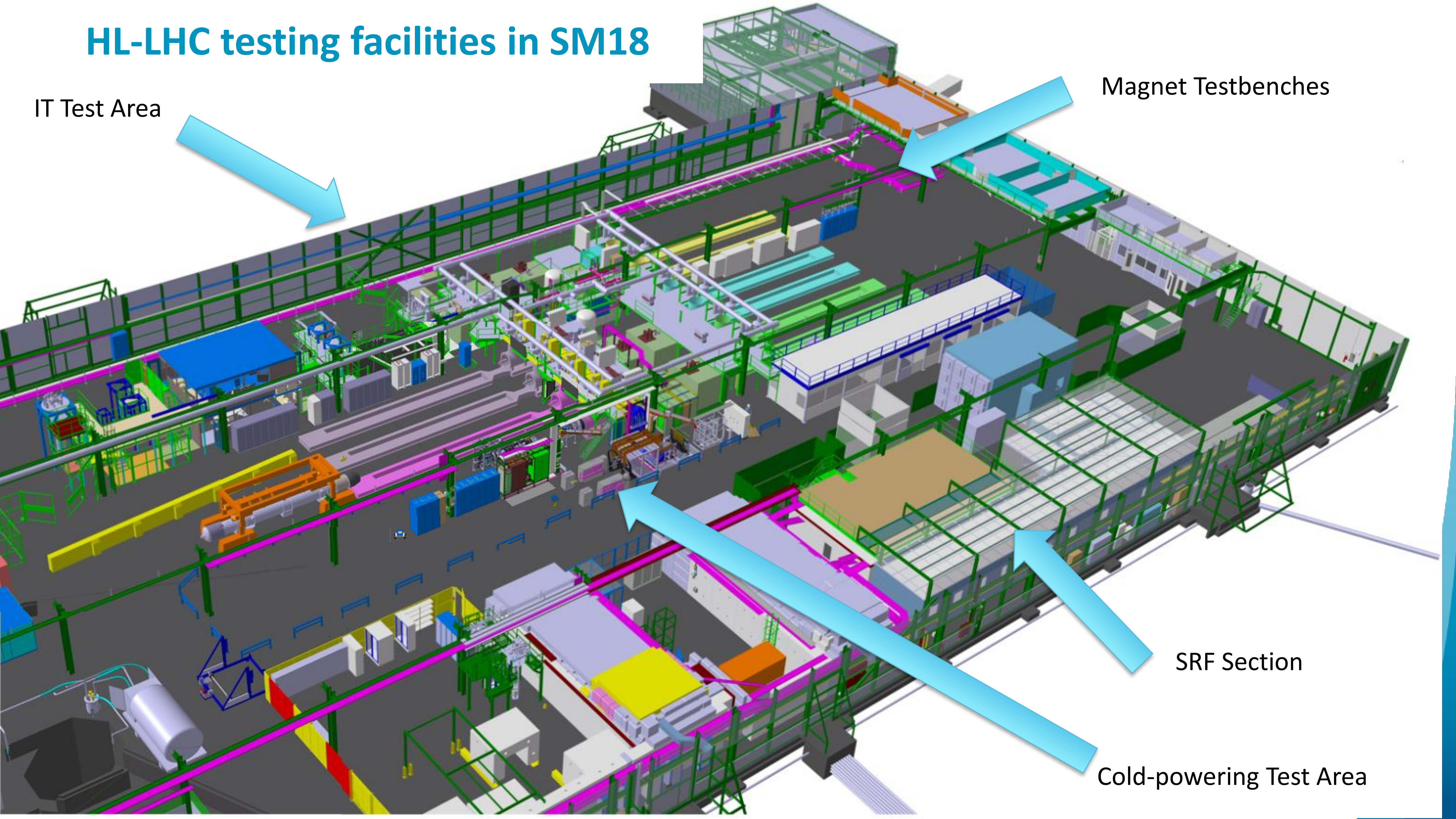
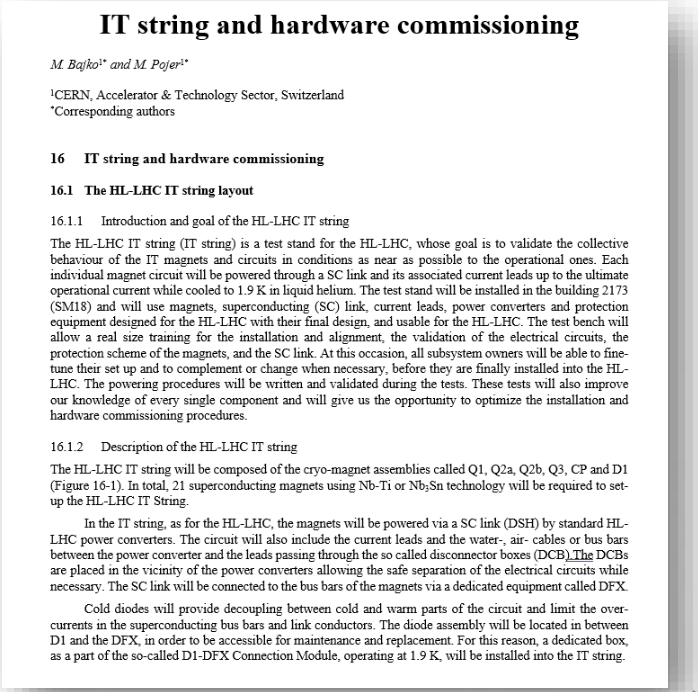
HL-LHC IT STRING: P5L



HL-LHC testing facilities in SM18



The IT STRING Scope



IT string and hardware commissioning

M. Bajko[1*] and M. Pojer[1*]

[1]CERN, Accelerator & Technology Sector, Switzerland
*Corresponding authors

16 IT string and hardware commissioning

16.1 The HL-LHC IT string layout

16.1.1 Introduction and goal of the HL-LHC IT string

The HL-LHC IT string (IT string) is a test stand for the HL-LHC, whose goal is to validate the collective behaviour of the IT magnets and circuits in conditions as near as possible to the operational ones. Each individual magnet circuit will be powered through a SC link and its associated current leads up to the ultimate operational current while cooled to 1.9 K in liquid helium. The test stand will be installed in the building 2173 (SM18) and will use magnets, superconducting (SC) link, current leads, power converters and protection equipment designed for the HL-LHC with their final design, and usable for the HL-LHC. The test bench will allow a real size training for the installation and alignment, the validation of the electrical circuits, the protection scheme of the magnets, and the SC link. At this occasion, all subsystem owners will be able to fine-tune their set up and to complement or change when necessary, before they are finally installed into the HL-LHC. The powering procedures will be written and validated during the tests. These tests will also improve our knowledge of every single component and will give us the opportunity to optimize the installation and hardware commissioning procedures.

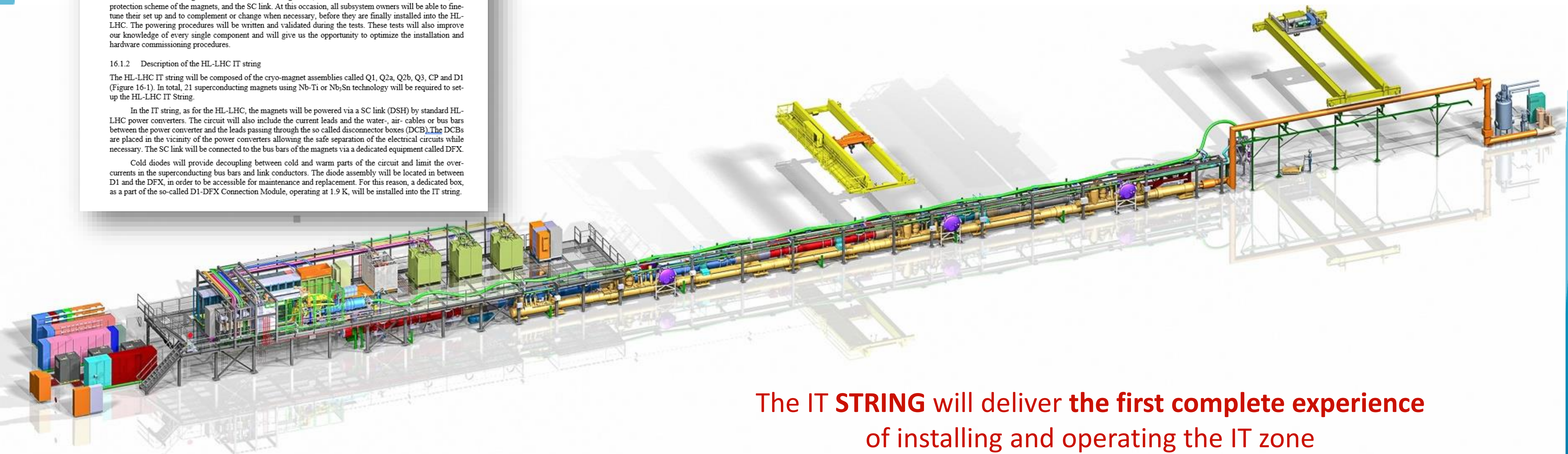
16.1.2 Description of the HL-LHC IT string

The HL-LHC IT string will be composed of the cryo-magnet assemblies called Q1, Q2a, Q2b, Q3, CP and D1 (Figure 16-1). In total, 21 superconducting magnets using Nb-Ti or Nb_3Sn technology will be required to set-up the HL-LHC IT String.

In the IT string, as for the HL-LHC, the magnets will be powered via a SC link (DSH) by standard HL-LHC power converters. The circuit will also include the current leads and the water-, air- cables or bus bars between the power converter and the leads passing through the so called disconnector boxes (DCB). The DCBs are placed in the vicinity of the power converters allowing the safe separation of the electrical circuits while necessary. The SC link will be connected to the bus bars of the magnets via a dedicated equipment called DFX.

Cold diodes will provide decoupling between cold and warm parts of the circuit and limit the over-currents in the superconducting bus bars and link conductors. The diode assembly will be located in between D1 and the DFX, in order to be accessible for maintenance and replacement. For this reason, a dedicated box, as a part of the so-called D1-DFX Connection Module, operating at 1.9 K, will be installed into the IT string.

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).

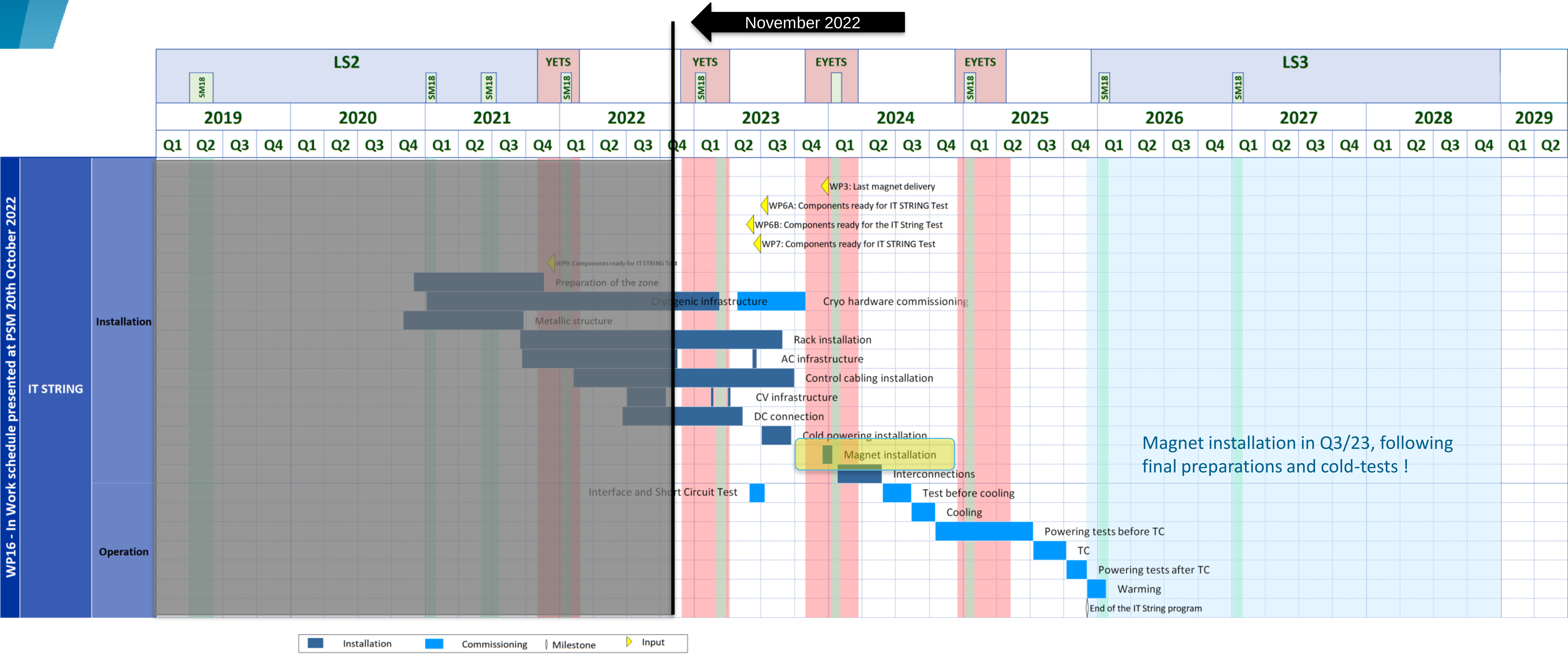


The IT **STRING** will deliver **the first complete experience** of installing and operating the IT zone

Ref. HL-LHC IT STRING Scope https://edms.cern.ch/document/1693312/1

Status in pictures

WP16 – The String



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Other ongoing collaborations/exchanges with HL

- Separation/recombination dipole D1 (WP3)
  - New addendum is under preparation (Add #2) for additional material to be supplied by CERN but paid by Hitachi (mainly laminations for QPH)
  - Finalisation of welding qualifications being discussed this week
- Beam Instrumentation (WP13)
  - Halo monitoring important for HL-era due to higher beam intensity and (likely) overpopulated tails
  - Coronagraph prototype developed and ready for installation in LHC, simulations show challenges to reach expected performance down to 5.5 sigma
  - Following LHC beam measurements, workshop planned in June 2023 to review results and explore eventual other options
  - For Electro Optical BPMs, there might still be an interest in the acquisition of a streak camera
- Machine Protection (WP7)
  - First delivery of capacitors for QHPS received and being used for IT String pre-series
  - Recent proposal of full HL-LHC QHPS series to MEXT
- Crab cavities (WP4)
  - Encouraging discussions towards potential additional in-kind contributions to HL project for IOTs and power transmission chain for CCs. MS being launched in parallel in-line with master schedule

13th HL-LHC collaboration meeting 2023 in Vancouver, BC, Canada

Conclusions

- HL-LHC project has entered full series-production phase
- Tunnel installation will start in 3 years from now, with IT String as very important intermediate validation milestone starting operation in Q4’24
- Excellent and very pro-active collaboration with KEK, with promising discussions on further enlargement of within the scope of HL project

Thank you for your attention!
Question?

SPARE SLIDES

Additional in-kind contributions under discussion

Additional contribution to the current program which is a package of D1 and ATLAS upgrade

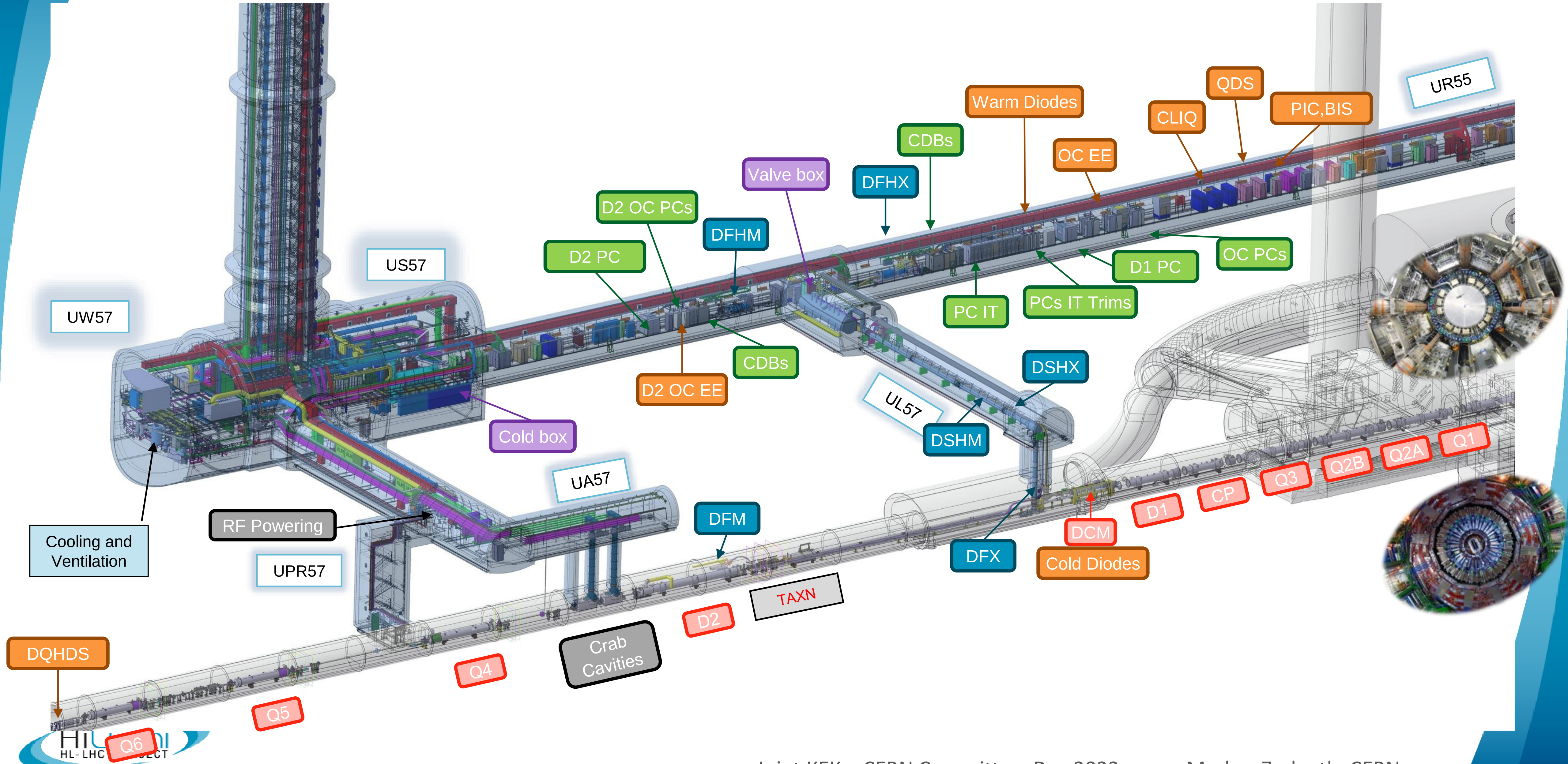
- Discussion at KEK with HEP community
  - HL-LHC additional contribution endorsed as high priority project

- June
  Budget request
  from KEK to MEXT
- August
  Request
  from MEXT to MOF
- December
  Decision at MOF
- April next year
  Start funding

KEK to MEXT	Quench heater	RF source	RF distributor	D1-D2 beam pipe	Robot	HTS tape
MEXT judgement	○	○	○	○	no	no
MEXT to MOF	○	Request next fiscal year or Supplemental Budget			N/A	N/A
MOF decision	?	?	?	?	N/A	N/A

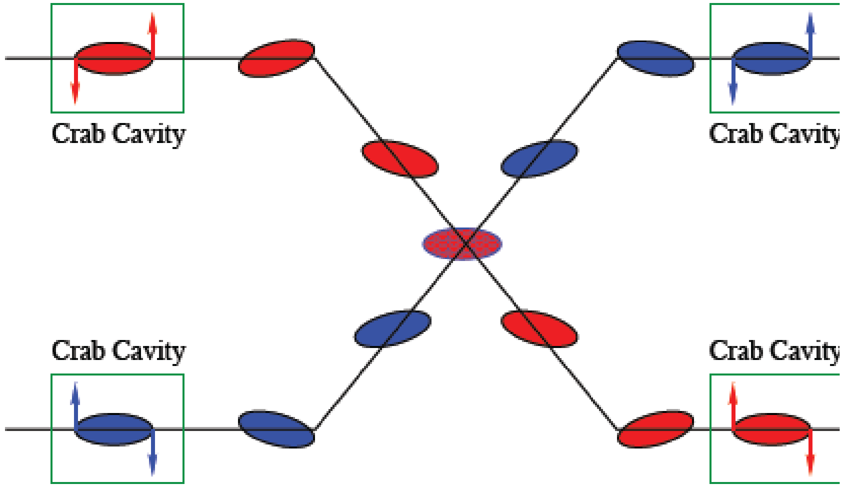
- Budget size of RF source and distributor is too large to simply "add" to the current program
  → Progress evaluation for the whole program next year.
  With good assessment, MEXT will request to MOF
- Small hope for Supplemental Budget within this fiscal year

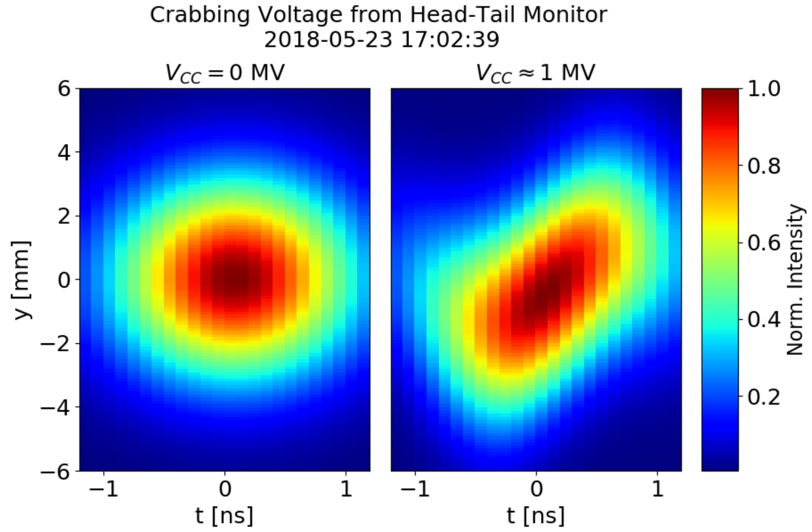
Ordinary Budget : Budget well planned for a fiscal year (April to March next year) ← Baseline
Supplemental Budget : Irregular budget, for example, to recover from a disaster, to stimulate economy··· ← Lucky addition


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

Crab cavity development

- Serving to mitigate the effect of the crossing angle at the IP
- Create an oscillating transverse electric field that kicks head and tail of the bunches in opposite directions



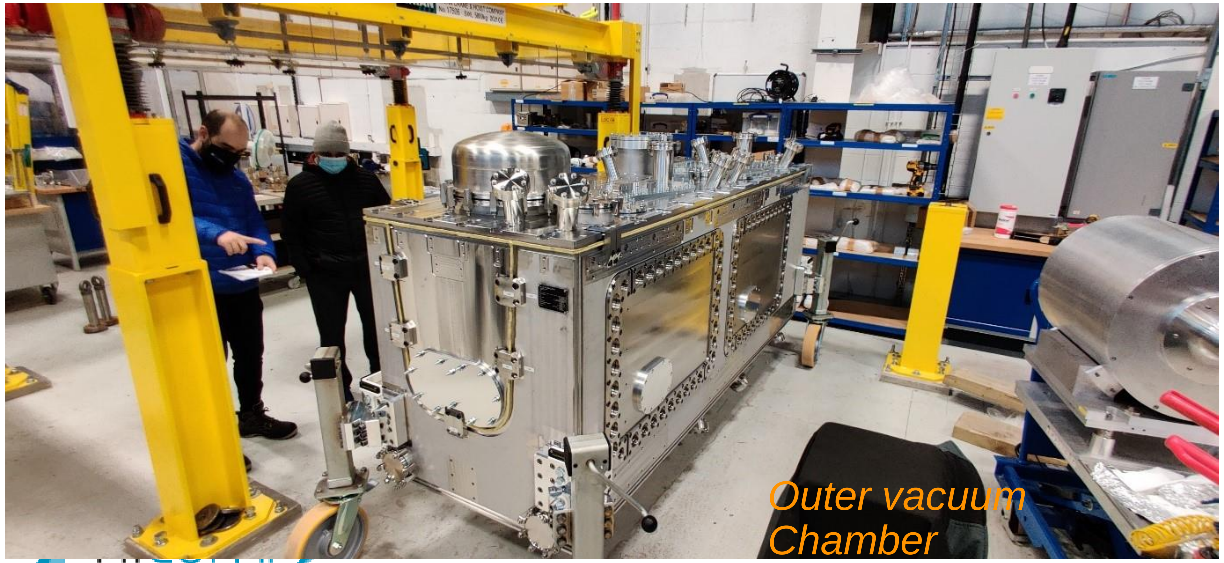


Double ¼-wave (DQW)　　RF Dipole

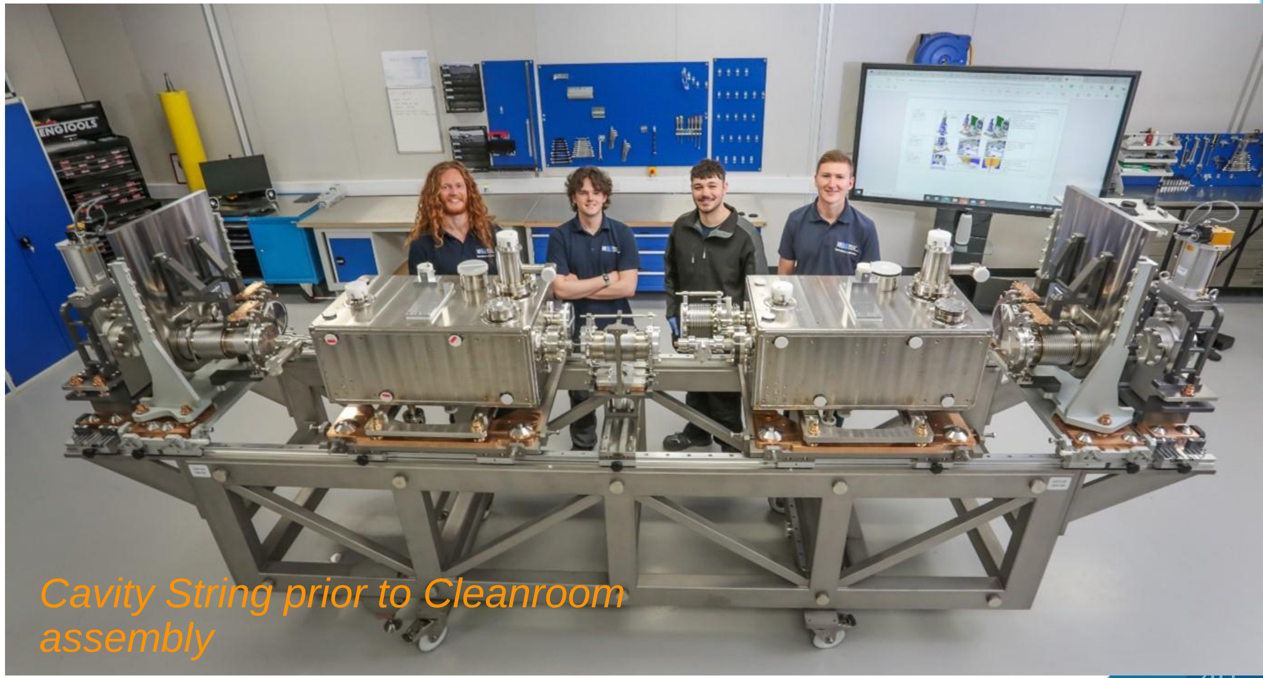
RFD Cryo-Module assembly in UK

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



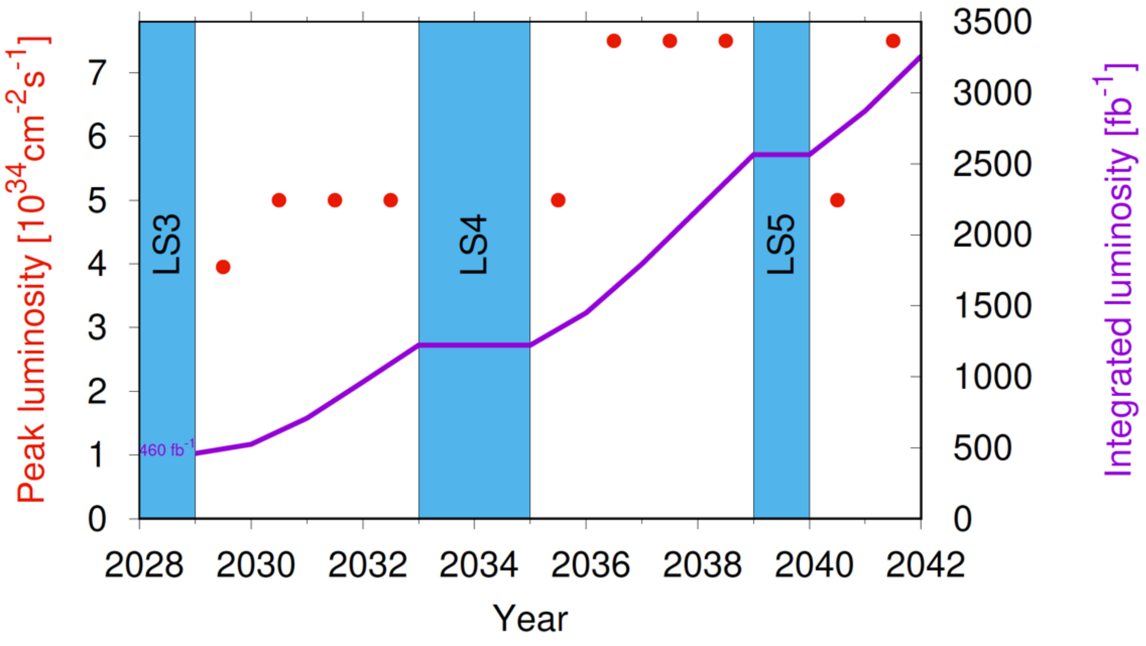
Outer vacuum Chamber



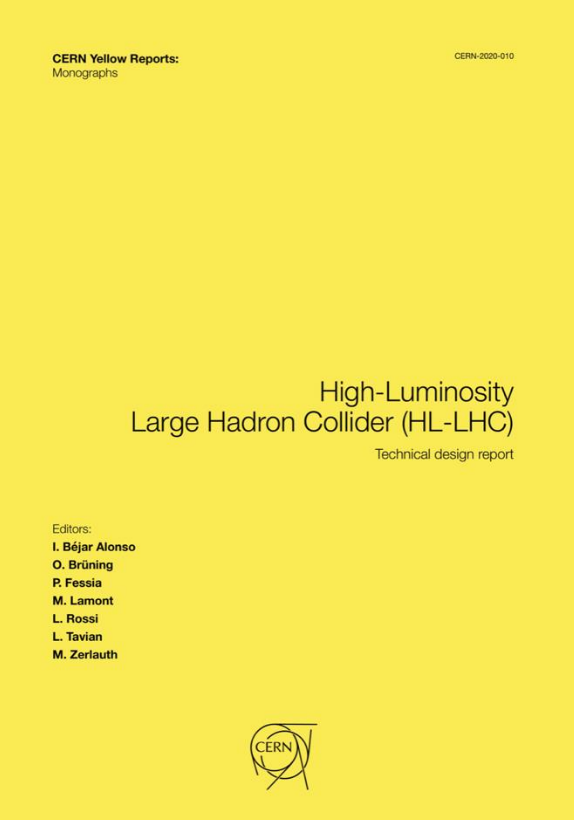
Cavity String prior to Cleanroom assembly

Start of HL-LHC exploitation and performance ramp-up

Year	ppb $[10^{11}]$	Virtual lumi. $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Days in physics	θ $[\mu\mathrm{rad}]$	β^*_{start} [cm]	β^*_{end} [cm]	CC	Max. PU
2029	1.8	4.4	90	380	70	30	exp	116
2030	2.2	9.7	120	500	100	30	on	132
2031	2.2	11.3	160	500	100	25	on	132
2032	2.2	13.5	160	500	100	20	on	132
2033-34	Long shutdown 4							
2035	2.2	13.5	140	500	100	20	on	132
2036	2.2	16.9	170	500	100	15	on	132
2036	2.2	16.9	200	500	100	15	on	200



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

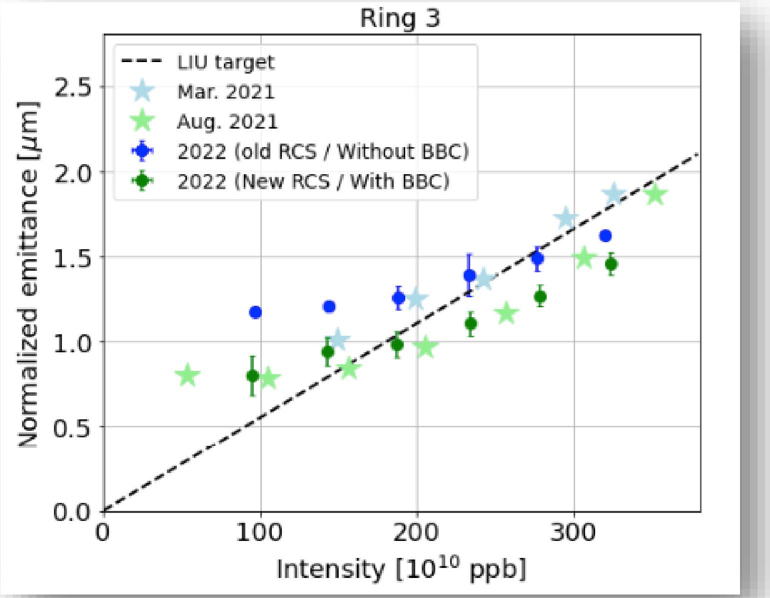
https://e-publishing.cern.ch/index.php/CYRM/issue/view/127

Recall

Injector complex started again in 2021 following deployment of the **LHC Injectors Upgrade** in LS2. Excellent progress since in achieving the HL-LHC beam characteristics.

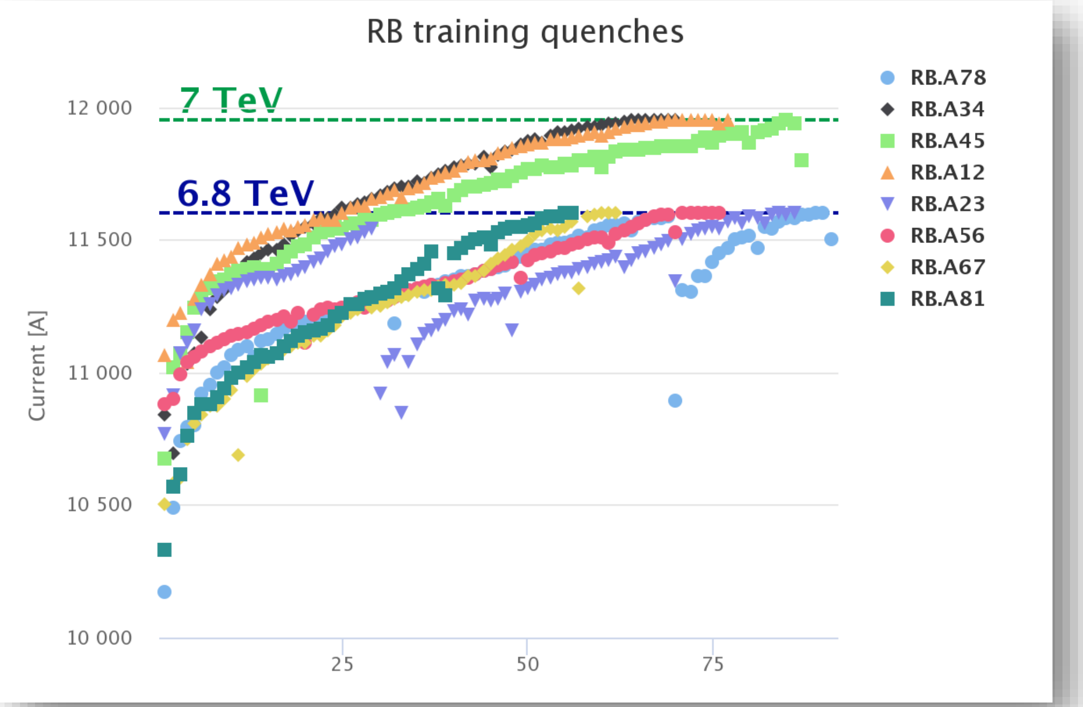
LHC in 2021 - hardware commissioning and a long dipole magnet training campaign opening the way to operation at 6.8 TeV (via 3 sector WU-CDs).

Booster



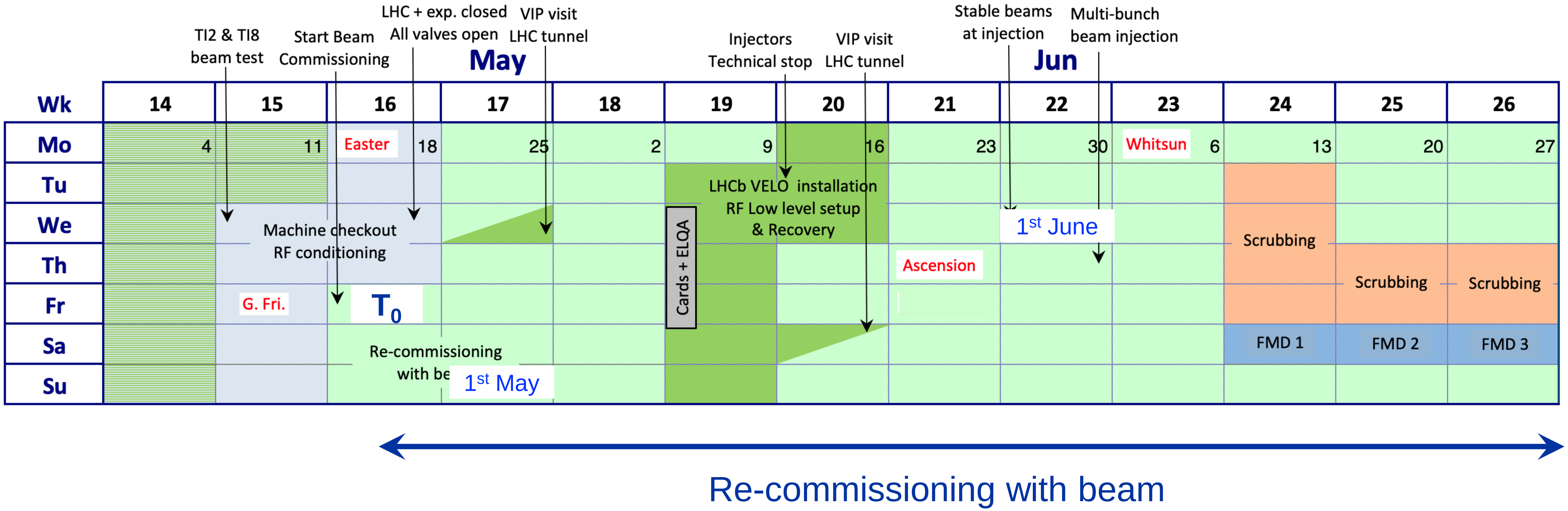
"Beam Size"

Protons per bunch

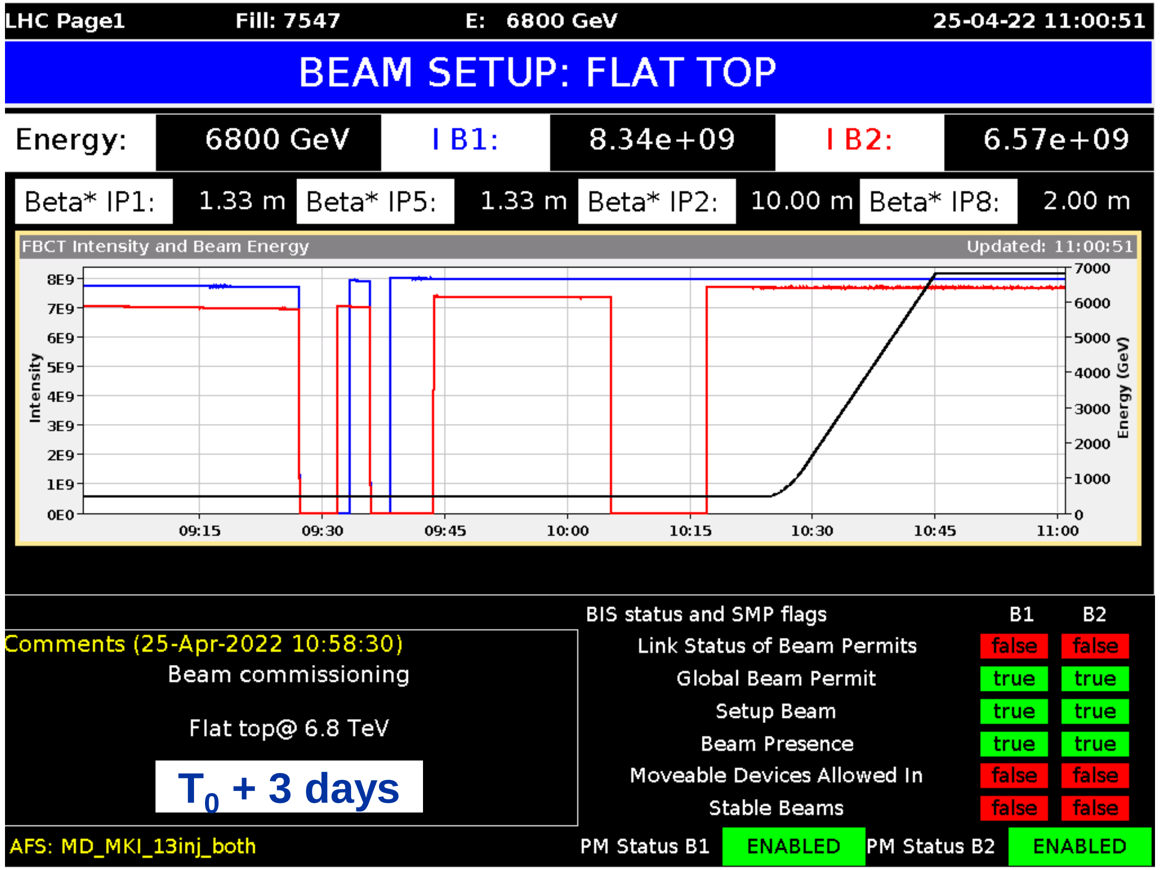


2022 – Q2

- Started Beam Commissioning Friday 22 April
- Week's stop for LHCb VELO side A installation mid-May

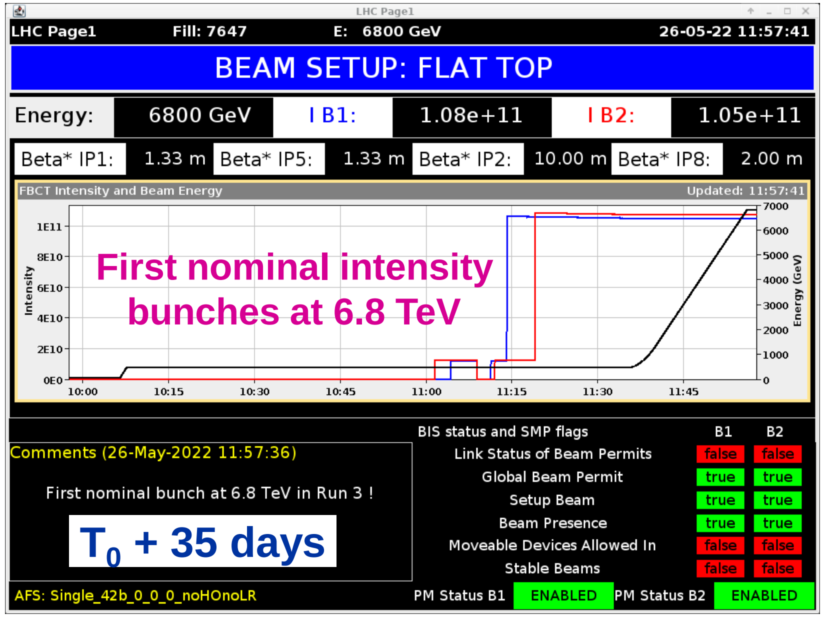


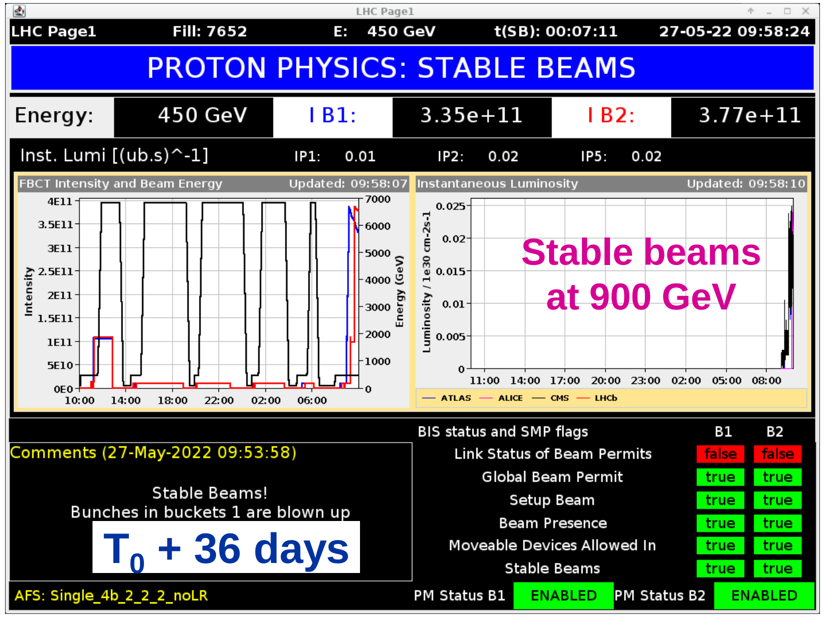
25^{th} April - First beams at 6.8 TeV

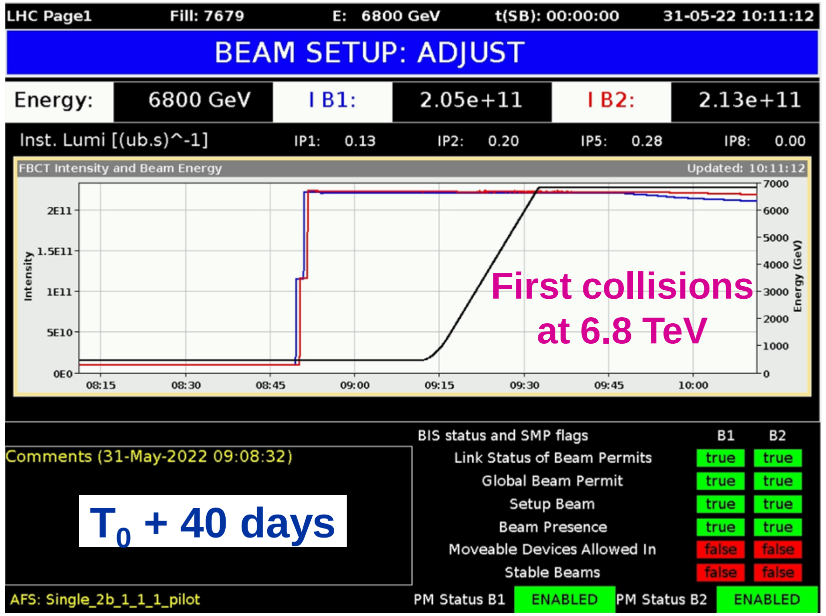


No big deal on the day but on the back of a long training and powering test campaign

Commissioning progress







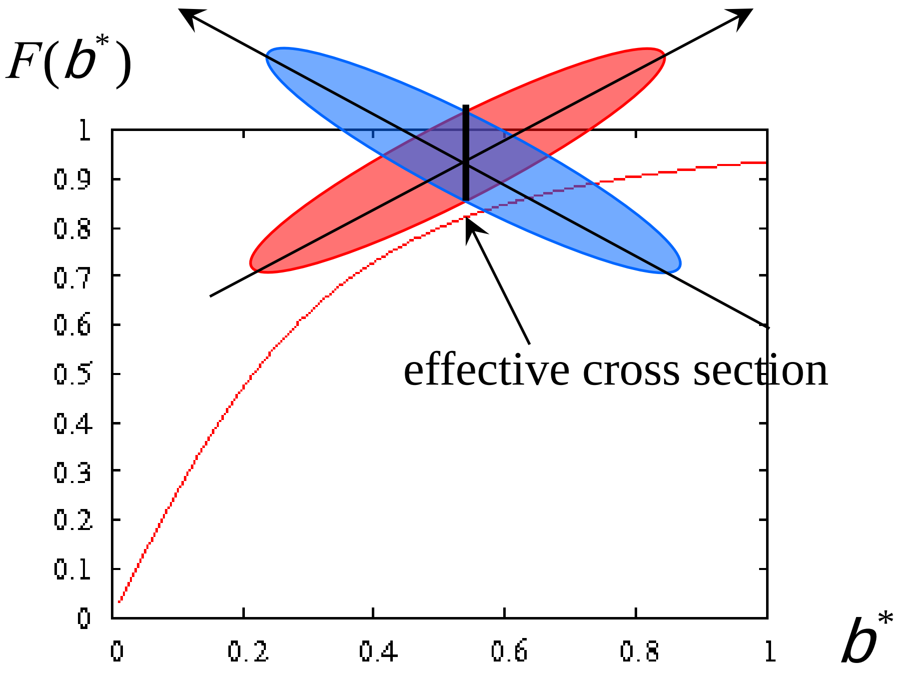
President of the Swiss Confederation

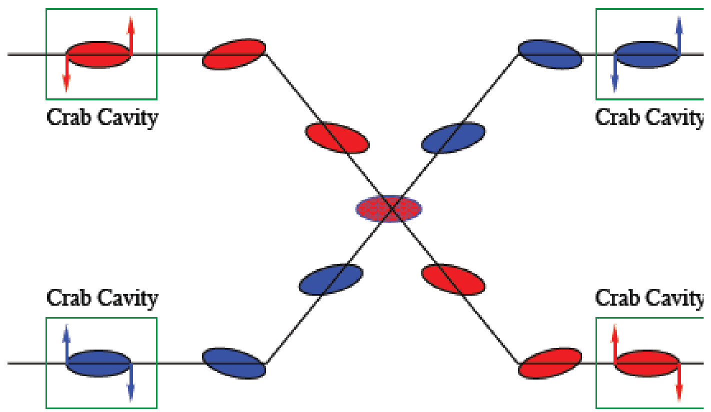
President of Slovakia

Crab cavity development for the HL-LHC

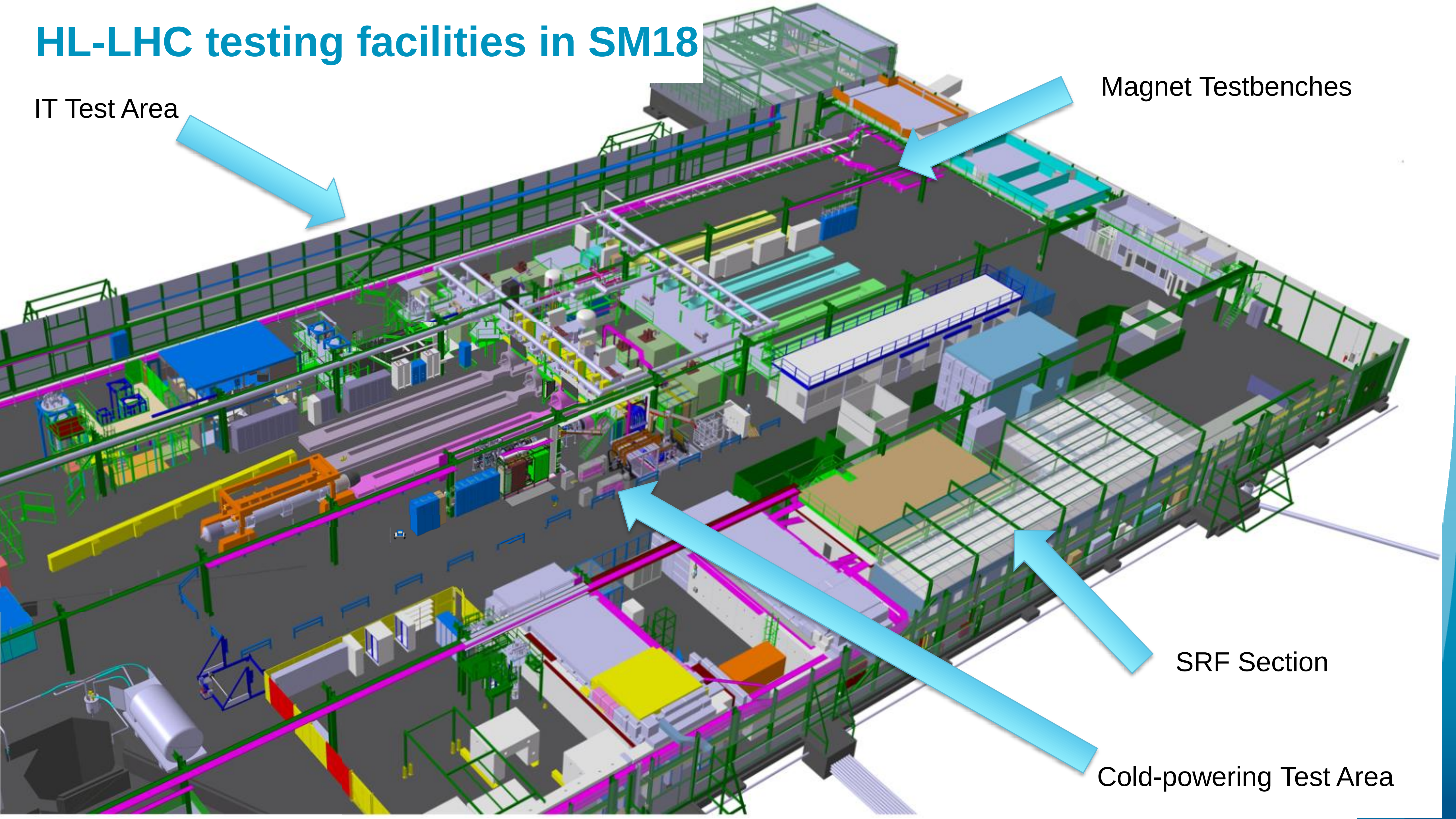
- Attempt to claw back the very significant reduction in luminosity from the large crossing angle
- Create an oscillating transverse electric field that kicks head and tail of the bunches in opposite directions
- Serving to mitigate the effect of the crossing angle at the IP
- Challenging space constraints:

  ➔ requires novel compact cavity design



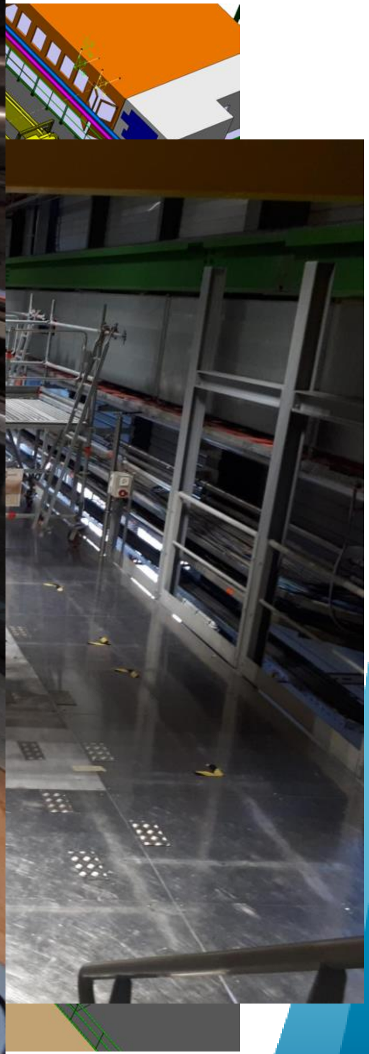


HL-LHC testing facilities in SM18

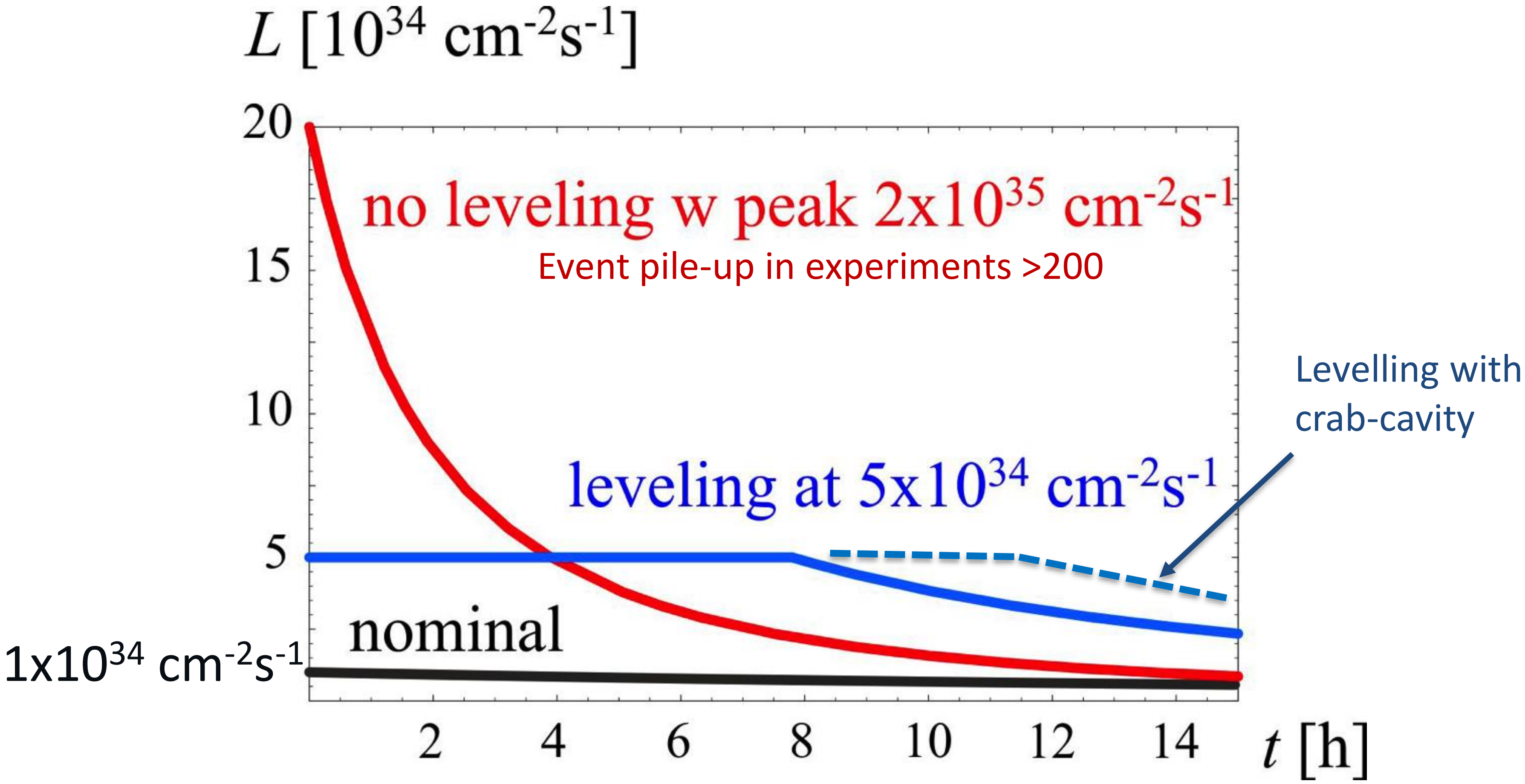


Important mil

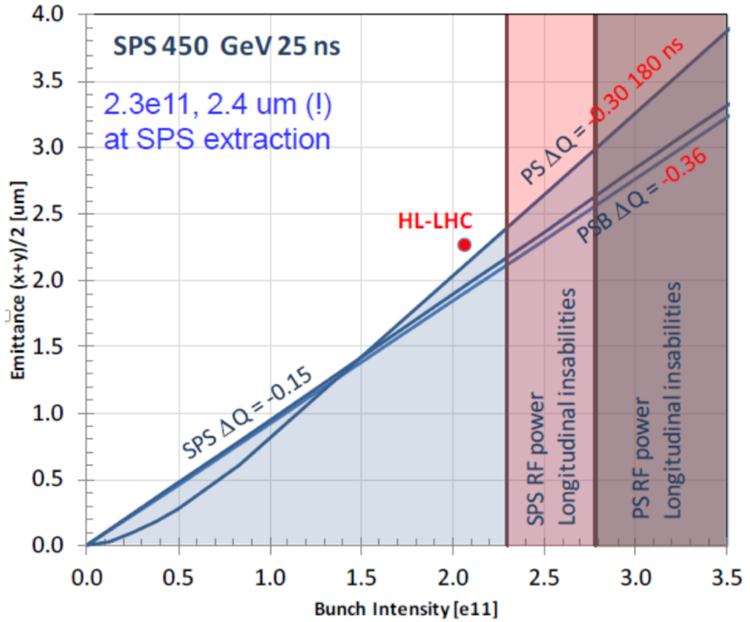
- Overall inte
- Vacuum an
- Electrical sy

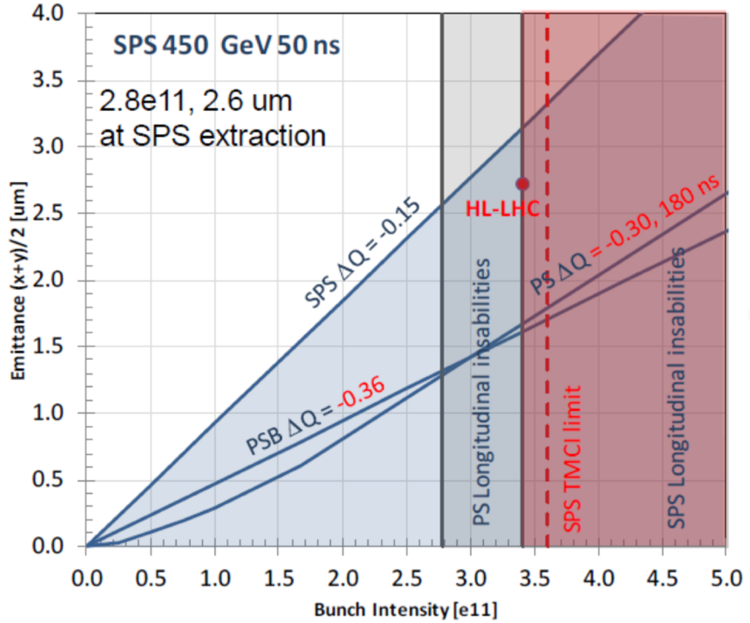


Operational Scenario for HL-LHC



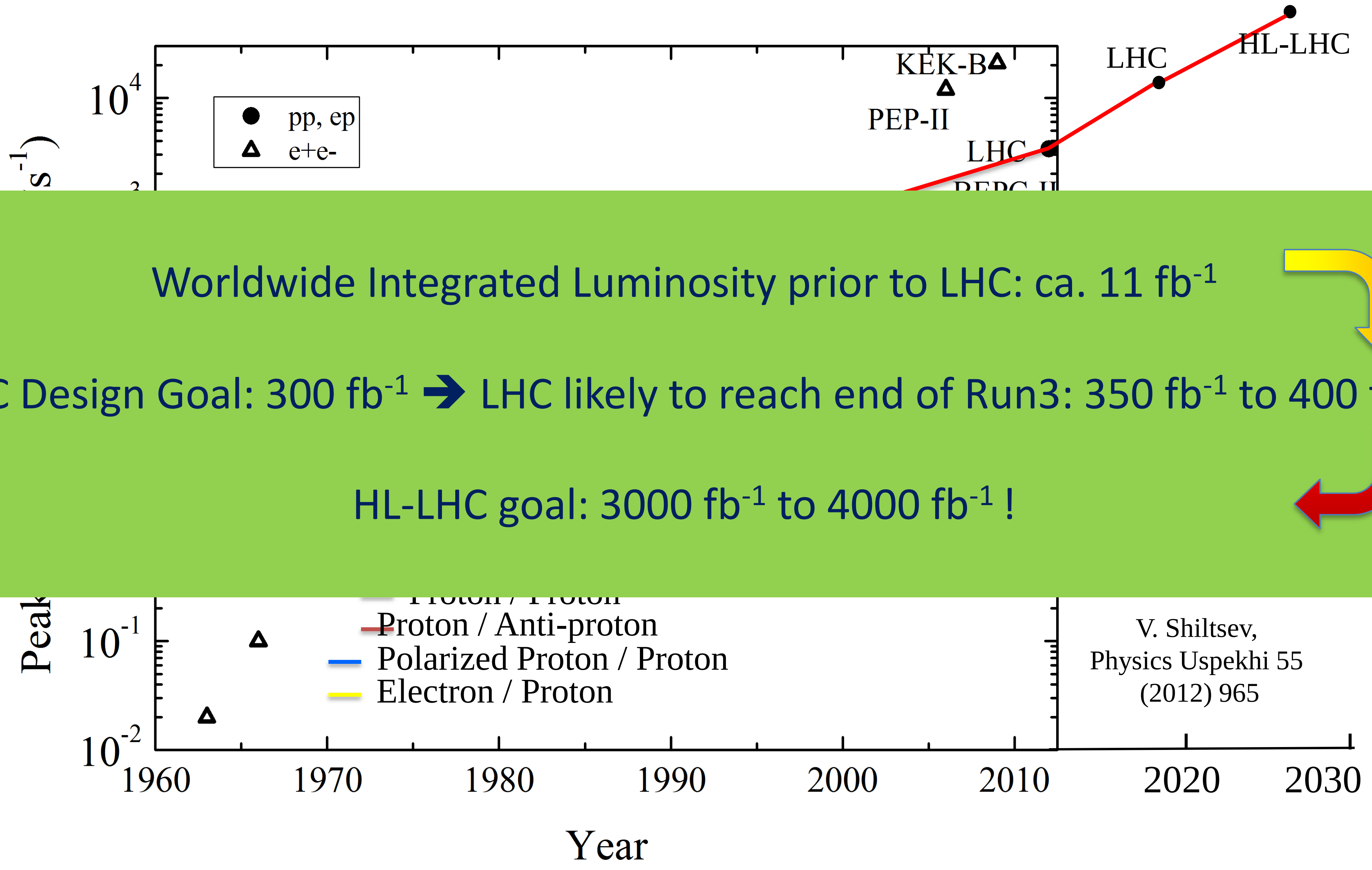
LHC Injector Upgra





- 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} !

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} [220 fb^{-1}]

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