The CERN Accelerator School

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HL-LHC Upgrade Project

CAS 2021

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

Introduction: LHC Performance Goals

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

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

- 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} [193 fb^{-1}]

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

LHC (Large Hadron Collider)

14 TeV proton-proton accelerator-collider built in the LEP tunnel

Lead-Lead (Lead-proton) collisions

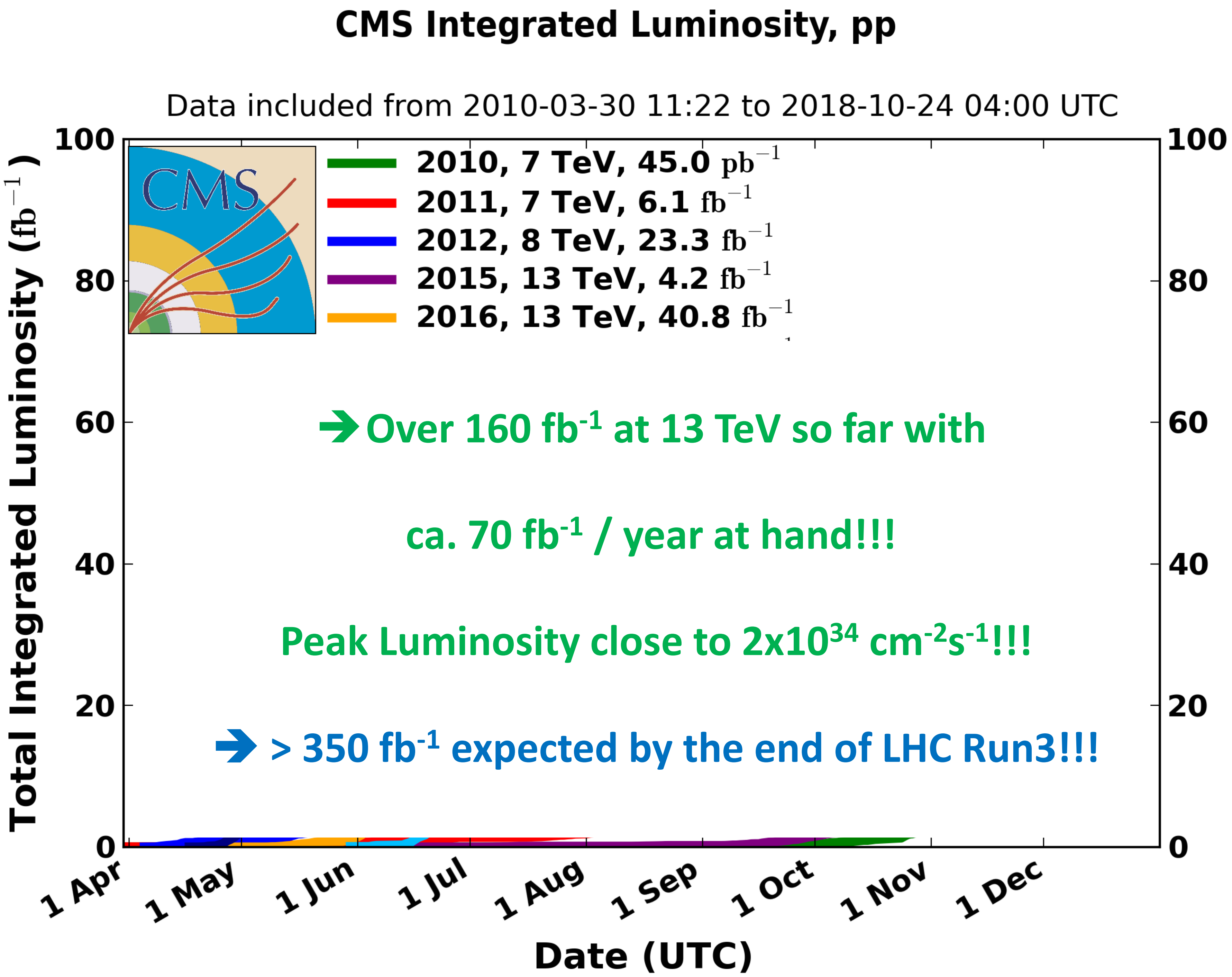
1983 : First studies for the LHC project
1988 : First magnet model (feasibility)
1994 : Approval by the CERN Council
1996-1999 : Series production industrialisation
1998 : Declaration of Public Utility & Start of civil engineering
1998-2000 : Placement of main production contracts
2004 : Start of the LHC installation
2005-2007 : Magnets Installation in the tunnel
2006-2008 : Hardware commissioning
2008-2009 : Beam commissioning and repair

2010-2025 : Physics exploitation

Ca. 20 years magnet development!!!

Ca. 30 years machine development!!!

➔ Significant Time scale extending well beyond that of a physicist's career!!!



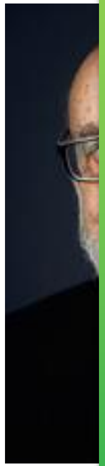
➔ Over 160 fb^{-1} at 13 TeV so far with

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

Peak Luminosity close to 2x10^{34} cm^{-2}s^{-1}!!!

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

Higgs Discovery in July 2012 and 2013 Nobel Price for the



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But many questions remain and the search continues!!!

➔ Higgs properties [coupling]
➔ More than one Higgs?
➔ Beyond SM Physics? Dark Matter & Dark Energy?

➔Need more Data and Statistics!!

Doubling the present Statistics requires 4 x more data!!!

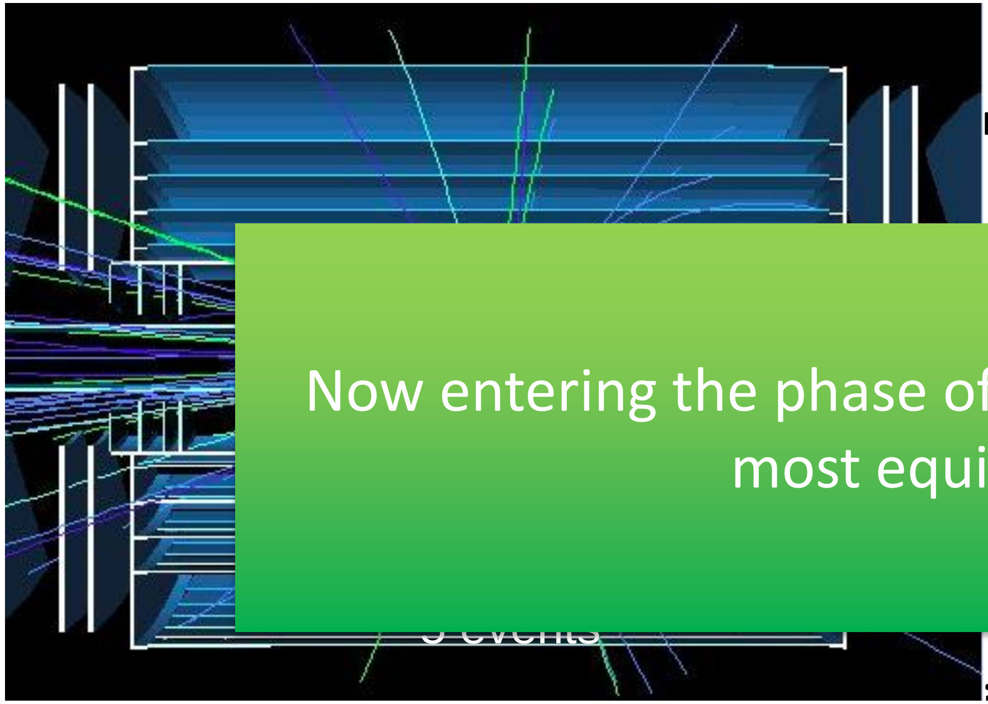
➔ HL-LHC goal: 10 times the LHC data Volume

Implies overcoming several limitations in the existing LHC!!!

Not only experiments: cryo <u>cooling</u> of triplet magnets & <u>radiation damage</u> in triplet magnets & <u>machine efficiency</u>!

➔ Need for an Upgrade!

Goal of High Luminosity LHC (HL-LHC):



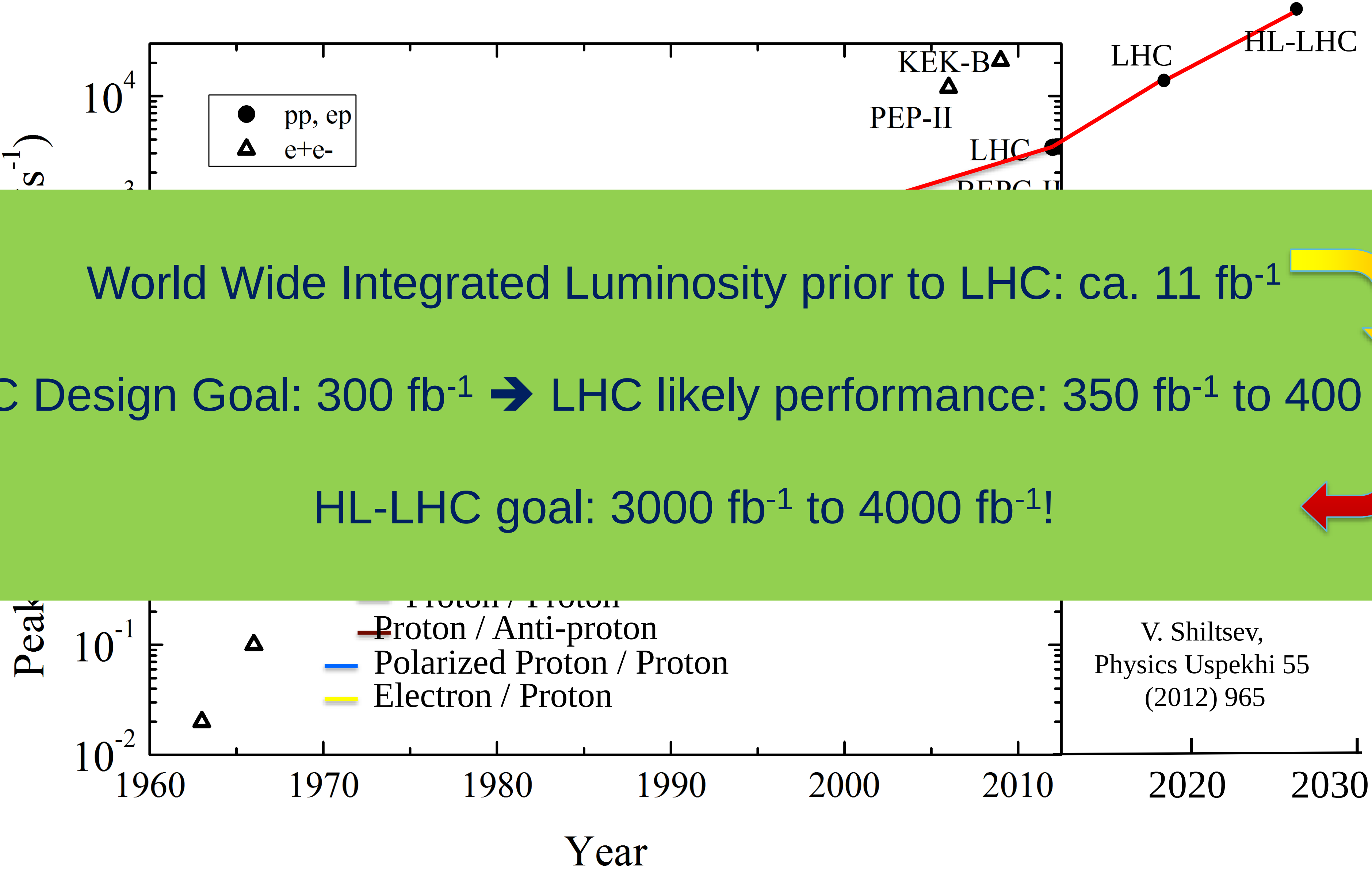

Now entering the phase of hardware production for most equipment!!!

Project approved by CERN Council in June 2016

➔ Operation with levelled luminosity!

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

Peak luminosities of Hadron colliders



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

x 35

LHC Design Goal: 300 fb^{-1} ➔ LHC likely performance: 350 fb^{-1} to 400 fb^{-1}

x 10

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

How to reach HL-LHC performance?

- **Lower beta* (~15 cm)**
  - New inner triplet magnets - wide aperture Nb_3Sn
  - Large aperture NbTi separator magnets and matching section quads
  - Novel optics solutions
- **Dealing with the regime**
  - Collision debris, high radiation
- **Crossing angle compensation**
  - Crab cavities
  - Long-range beam-beam compensation
- **Beam from injectors**
  - Major upgrade of complex (LIU)
  - High bunch population, low emittance, 25 ns beam

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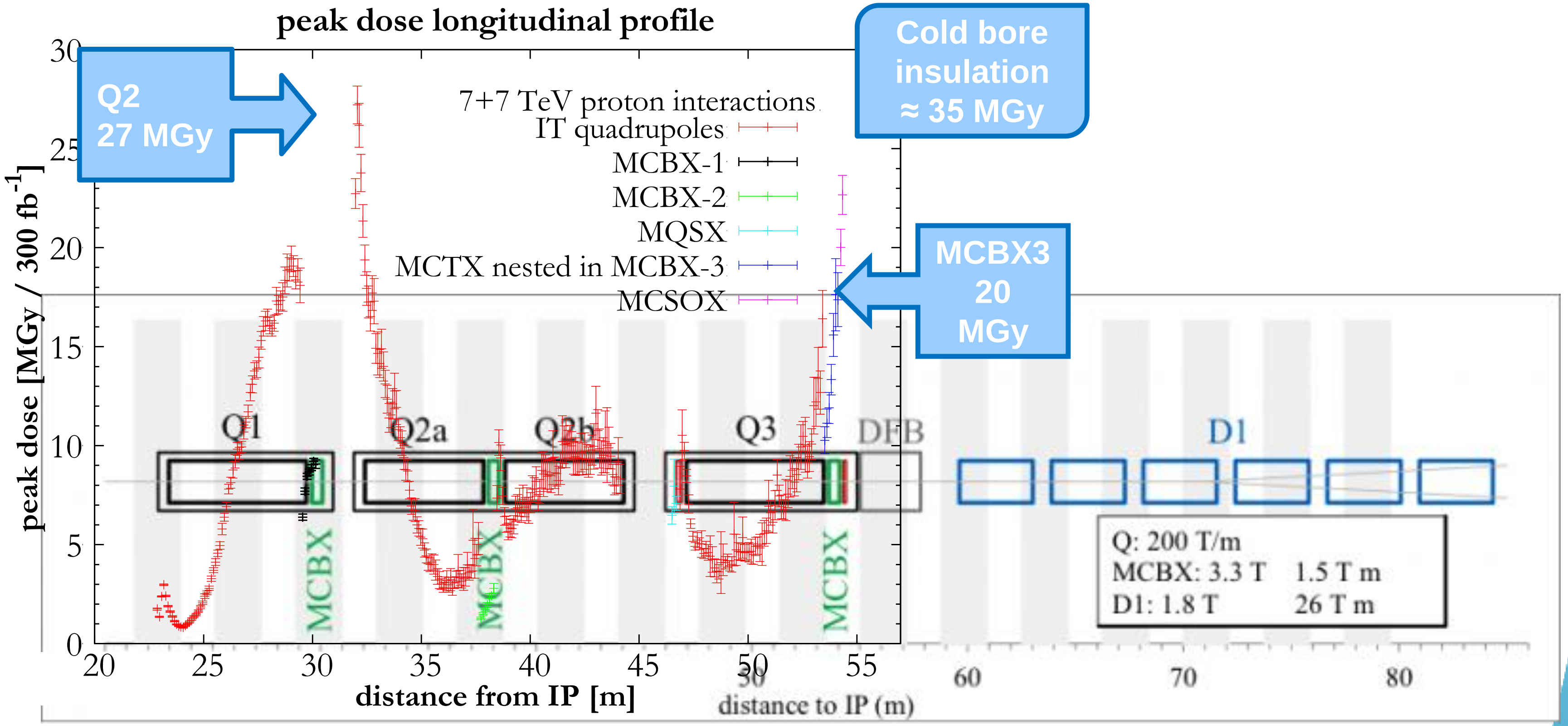
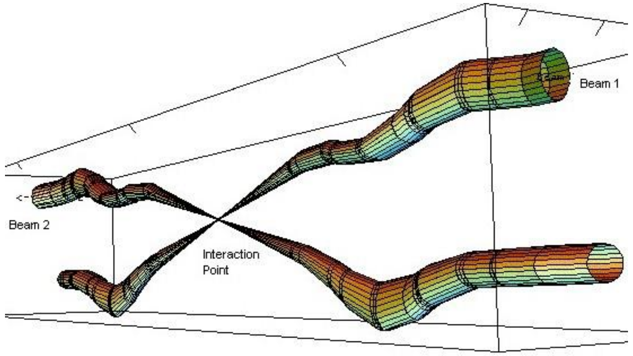
Luminosity Limitation: Debris from the IP

Radiation damage to magnets at 300 fb^{-1}





- Lower beta* implies larger beams in the triplet magnets
- Larger beams implies a larger crossing angle
- Aperture concerns dictate caution and radiation concerns due to physics debris

HL-LHC technical bottleneck: Radiation damage to triplet magnets

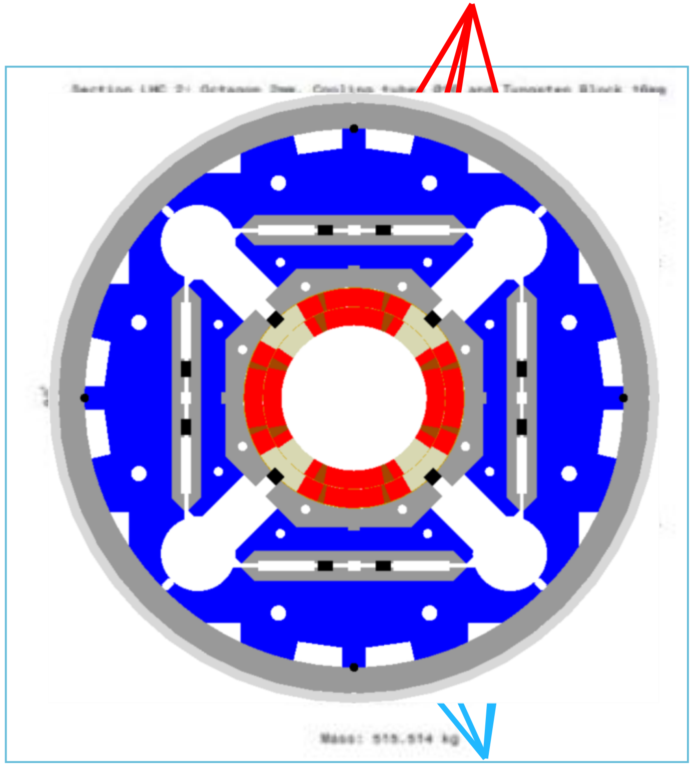
Need to replace existing triplet magnets with radiation hard system (shielding!) such that the new magnet coils receive a similar radiation dose @ 10 times higher integrated luminosity!!!!! ➔ Shielding!

➔ Requires larger aperture!

➔ New magnet technology!

➔ 70 mm at 210 T/m ➔150 mm diameter 140 T/m

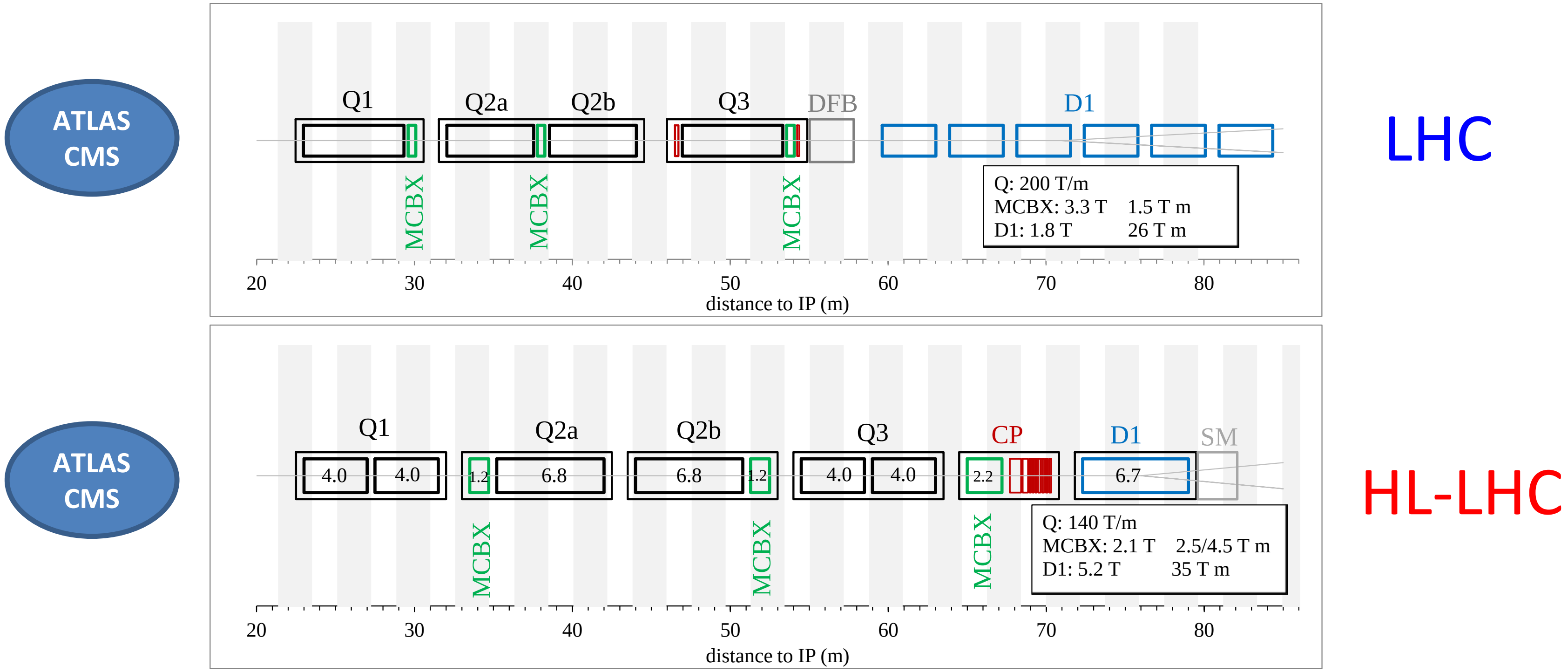
8 T peak field at coils ➔ 12 T field at coils (Nb_3Sn)!!!



US-LARP MQXF magnet design Based on Nb_3Sn technology

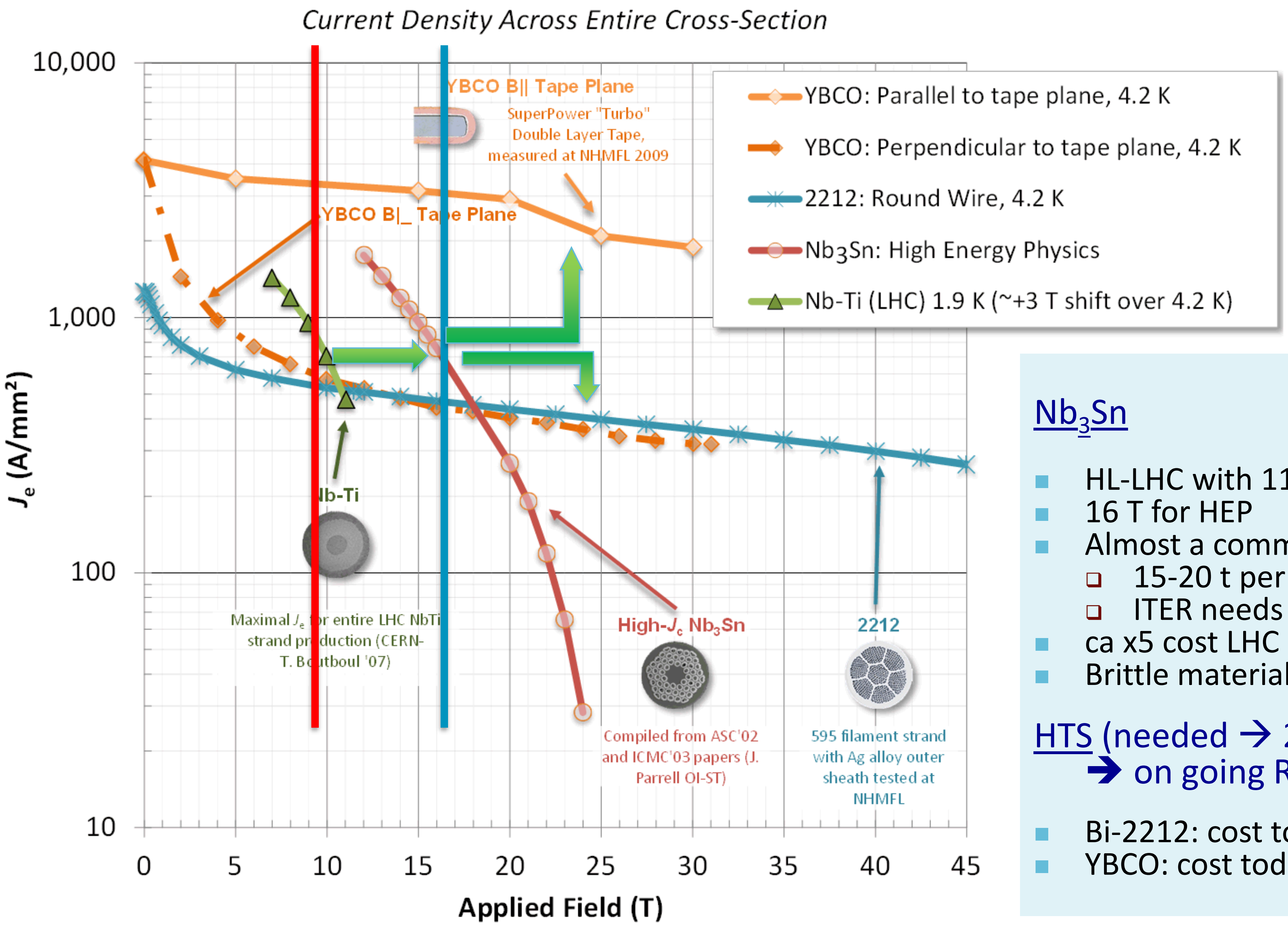
New interaction region layout

- New triplets are not enough by themselves
  - Superconducting separation dipoles (D1)
  - Corrector package
  - And beyond…



SC Magnet Technology

source: L. Rossi



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

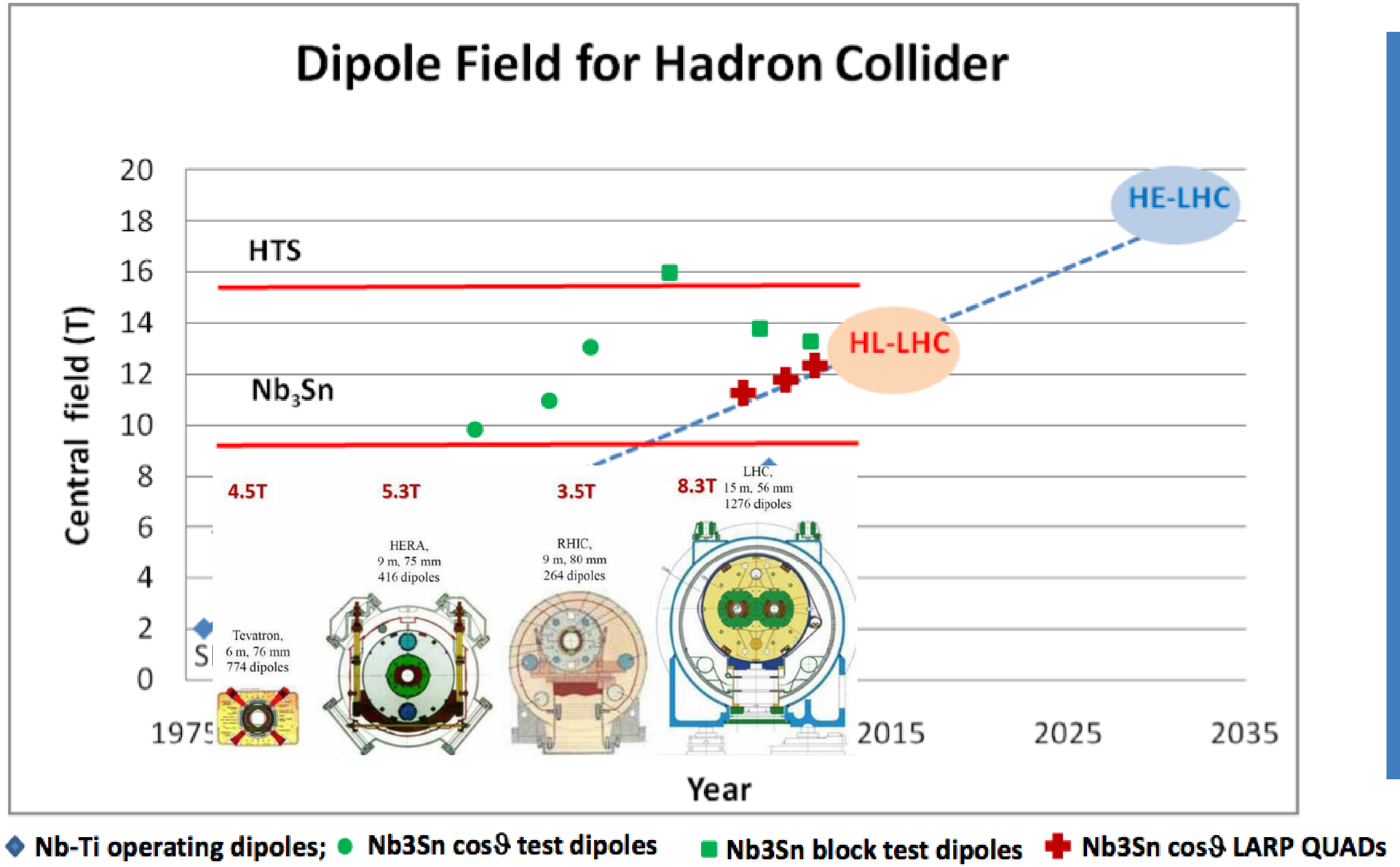
HTS (needed → 20 T)

→ on going R&D!

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

High Field SC Magnets

Magnet development requires substantial R&D effort!!!



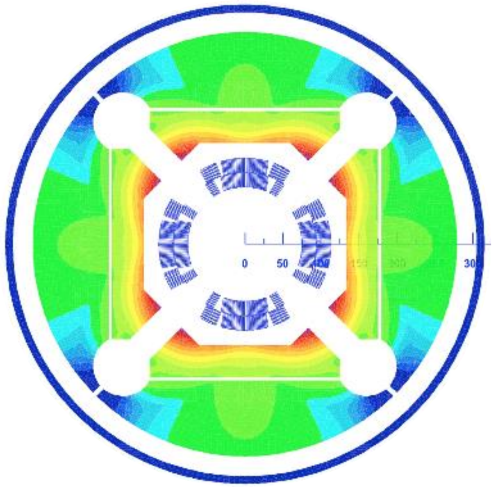
Transition from NbTi to Nb_3Sn: requires similar length of R&D!

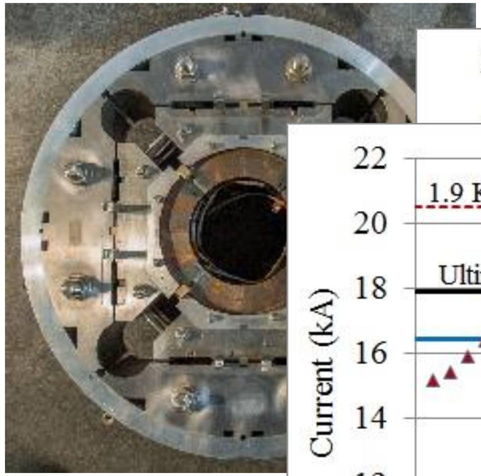
HL-LHC led the R&D for 11-15 T magnets based on Nb_3Sn technology:

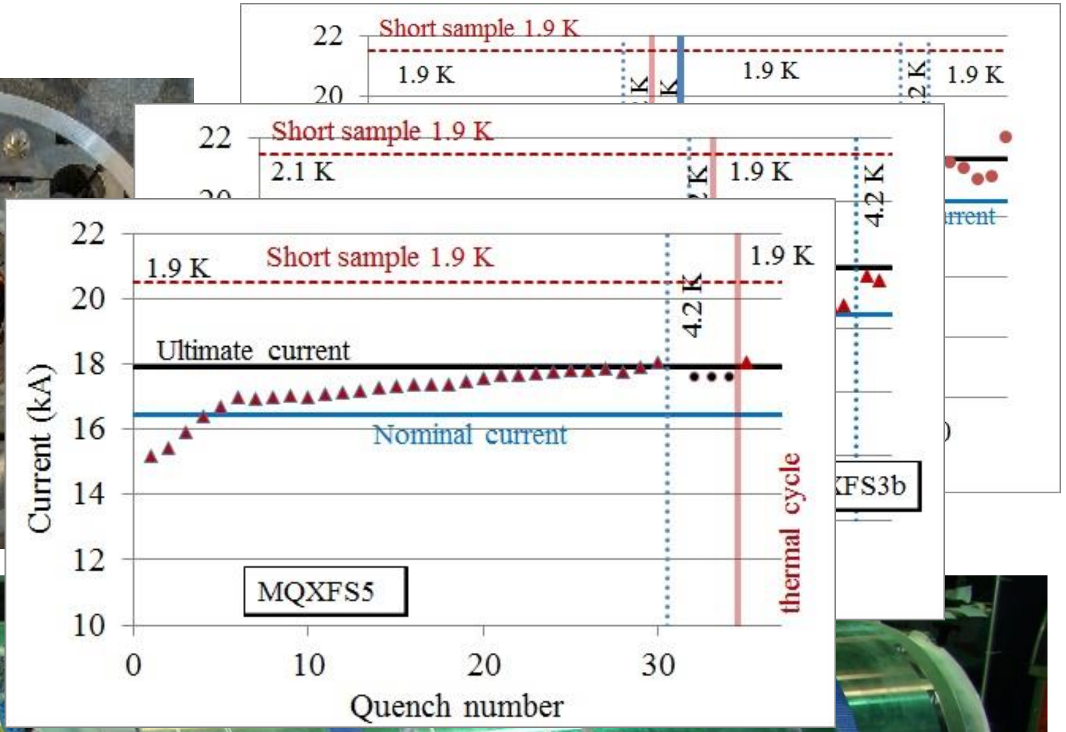
- ➔ Started in early 2000
- ➔ 15-20 years R&D program
- ➔ Ready by 2025

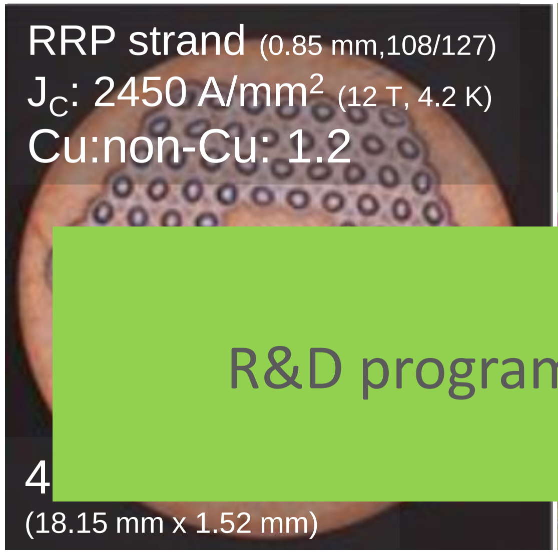
courtesy: L. Rossi (CERN)

HL-LHC quadrupole R&D



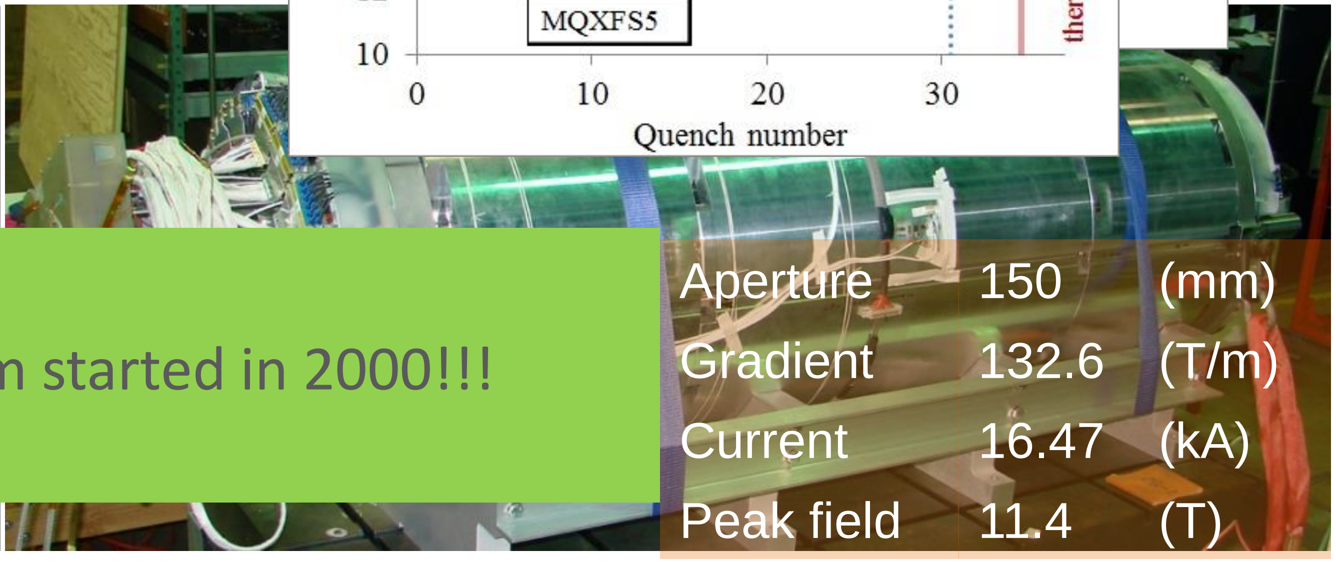






RRP strand (0.85 mm,108/127)
J_C: 2450 A/mm^2 (12 T, 4.2 K)
Cu:non-Cu: 1.2

4
(18.15 mm x 1.52 mm)



R&D program started in 2000!!!

Aperture	150	(mm)
Gradient	132.6	(T/m)
Current	16.47	(kA)
Peak field	11.4	(T)

Nb_3Sn quadrupole: 1st Long prototypes almost finished

Developments in 2020:

Q1/Q3: FIRST IT QUAD for HL-LHC Successfully tested!

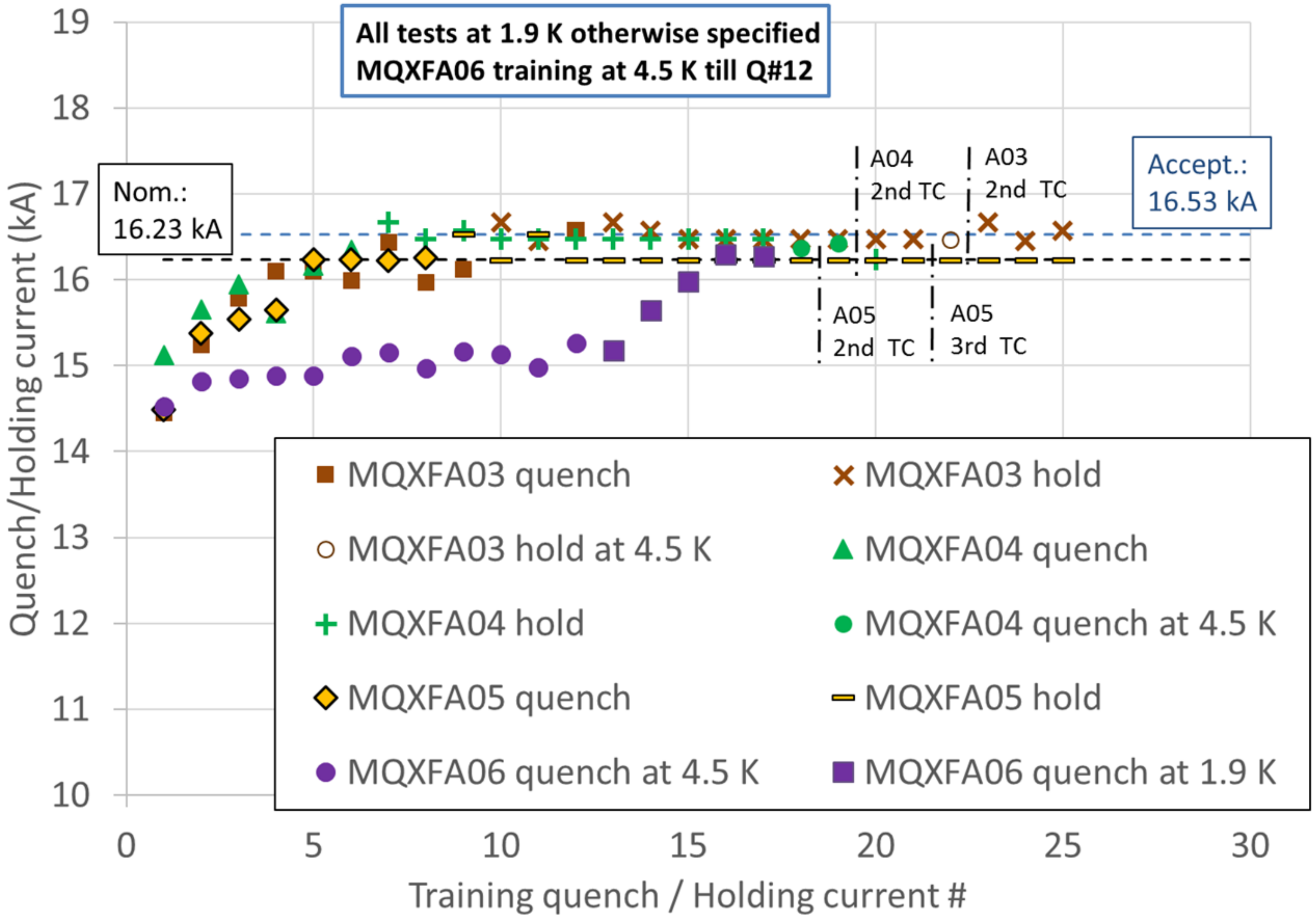
Now entering the phase of series production for most equipment!!!

2 US [AUP] magnets passed successfully tests in 2020 and received CD3 approval from DOE in 2020, ever since 2 additional magnets validated

First CERN prototypes tested in 2020 and 2021, first series magnet finished and to be cold tested towards end 2021

Q2: FIRST IT QUAD built and tested at CERN

Nb_3Sn quadrupole: 4th series magnet successfully tested at AUP



How to reach HL-LHC performance?

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- Dealing with the regime
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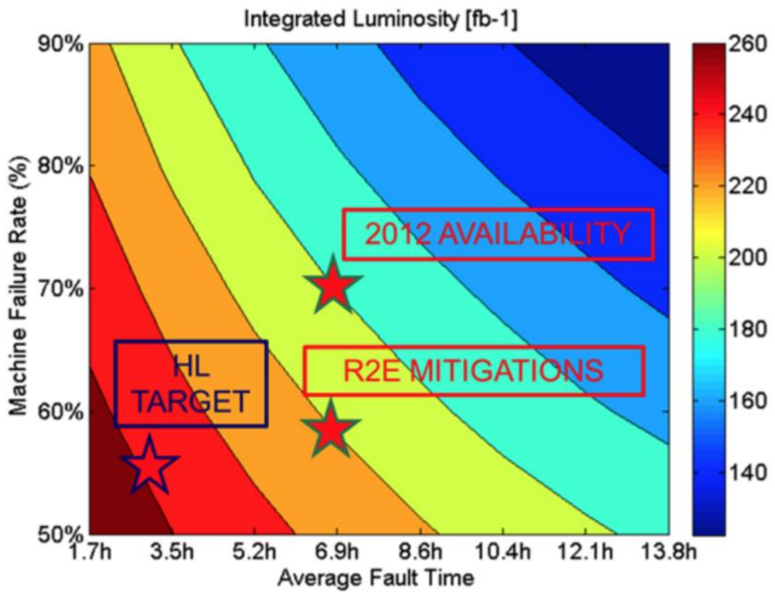
Dealing with the operation of a high energy high brightness machine

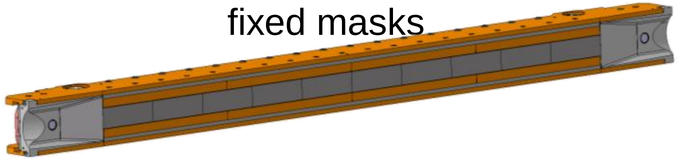
Very bright beams, very high bunch population, very high beam current

- Beam stability
  - New low impedance collimators
- Beam lifetime & loss spikes
  - Magnet quenches
- Machine protection
  - Failure scenarios - local beam impact - equipment damage
  - Quench protection
- Machine availability
  - Radiation to electronics (SEUs etc.)…



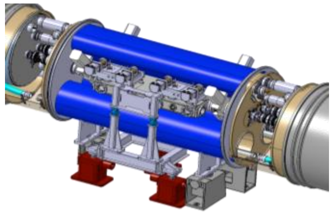
1) Shielding and Collimation upgrade:

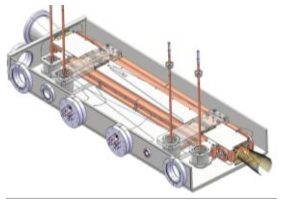
Completely new layouts
Novel materials.
IR1+IR5, per beam:
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks



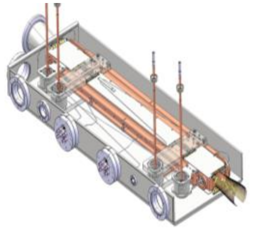
56 new collimators to be produced by LS3 in the present baseline!

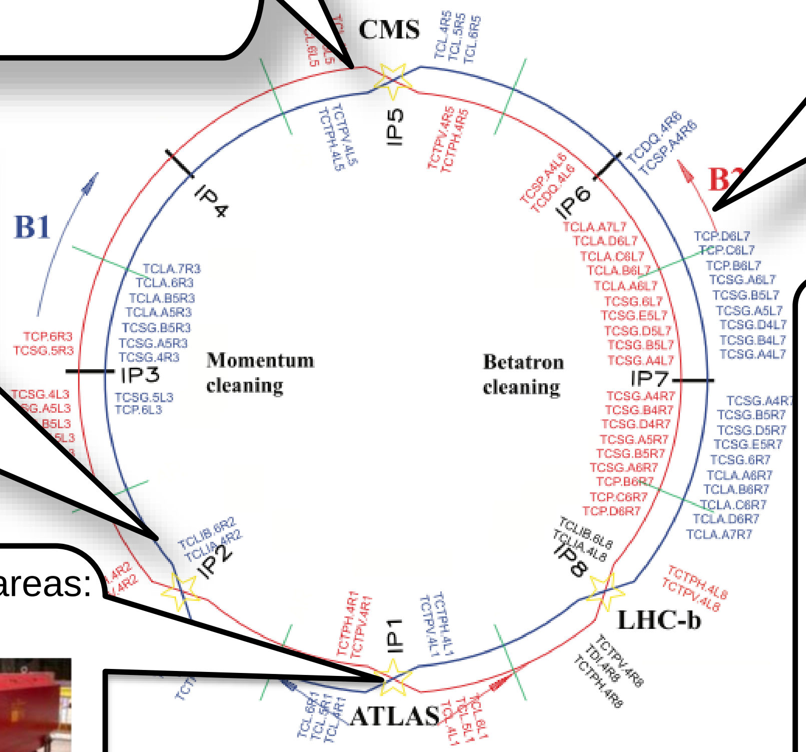
Cleaning: DS coll. + 11T dipoles, 2 units per beam



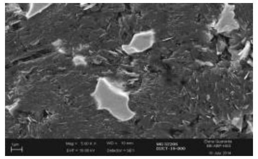


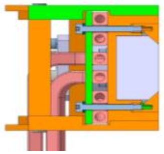
Ion physics debris: DS collimation

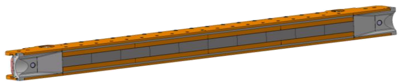




Low-impedance, high robustness secondary collimators

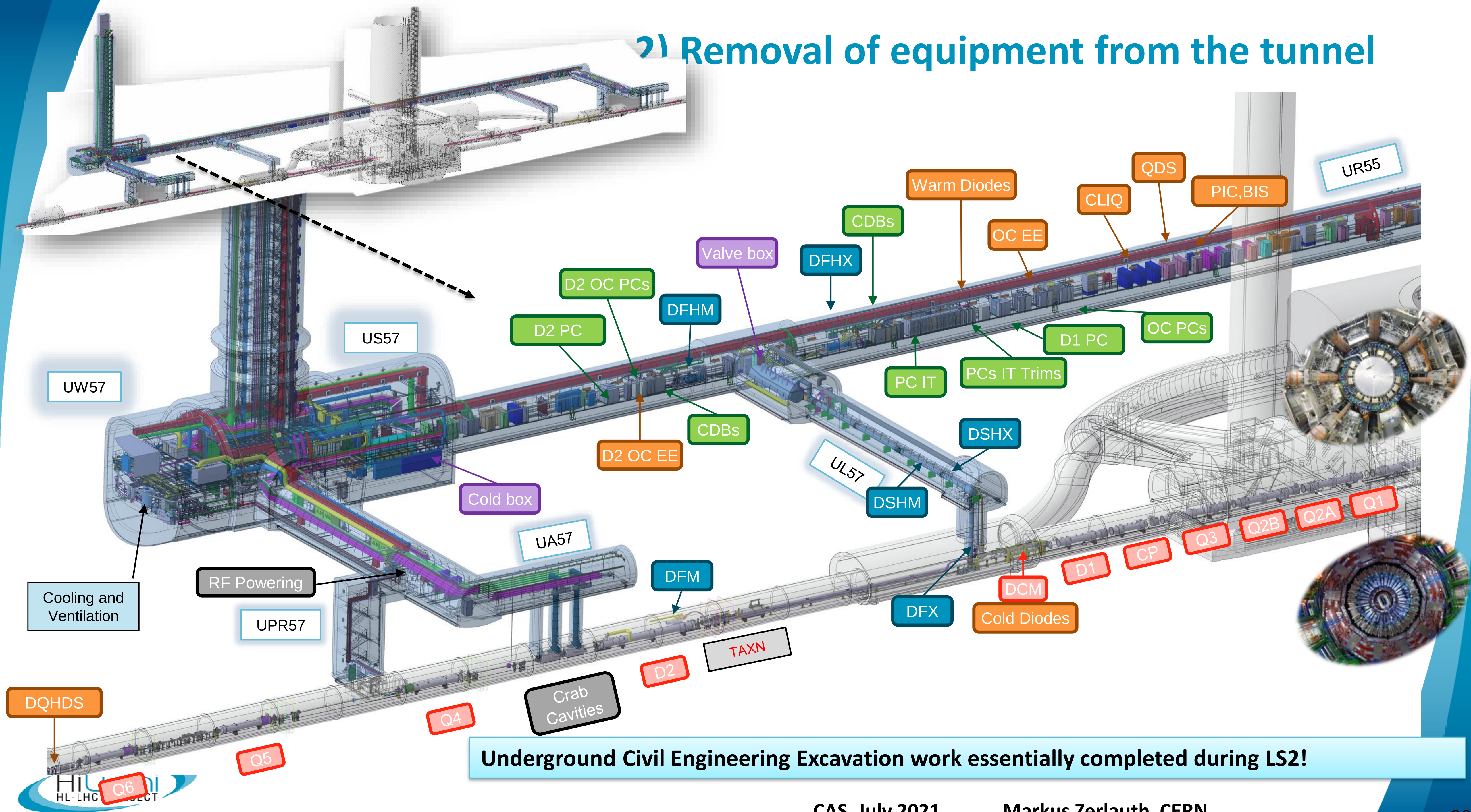






Shielding of the experimental areas: New TAXS and TAXN

2) Removal of equipment from the tunnel

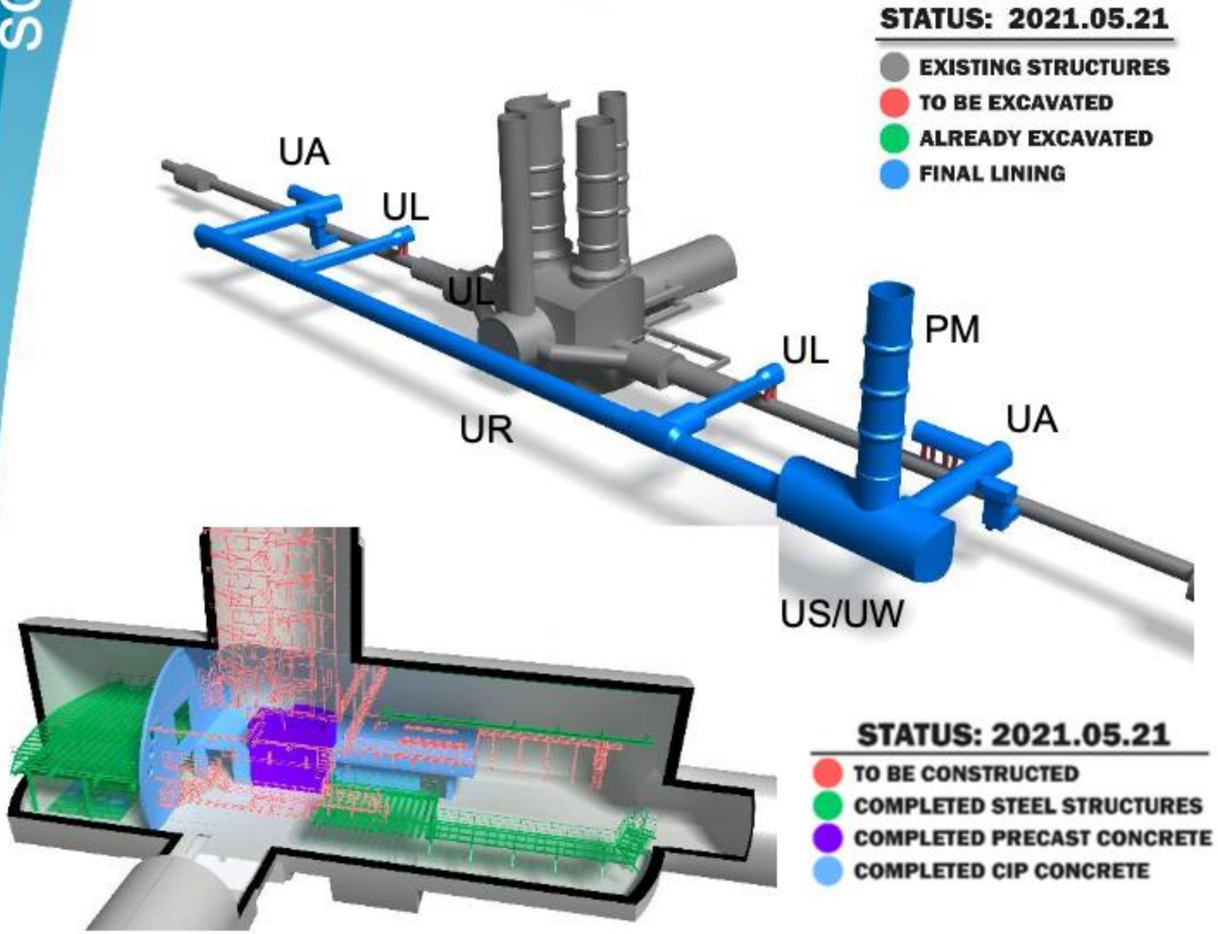


Underground Civil Engineering Excavation work essentially completed during LS2!

HL-LHC civil engineering status (Point 1)

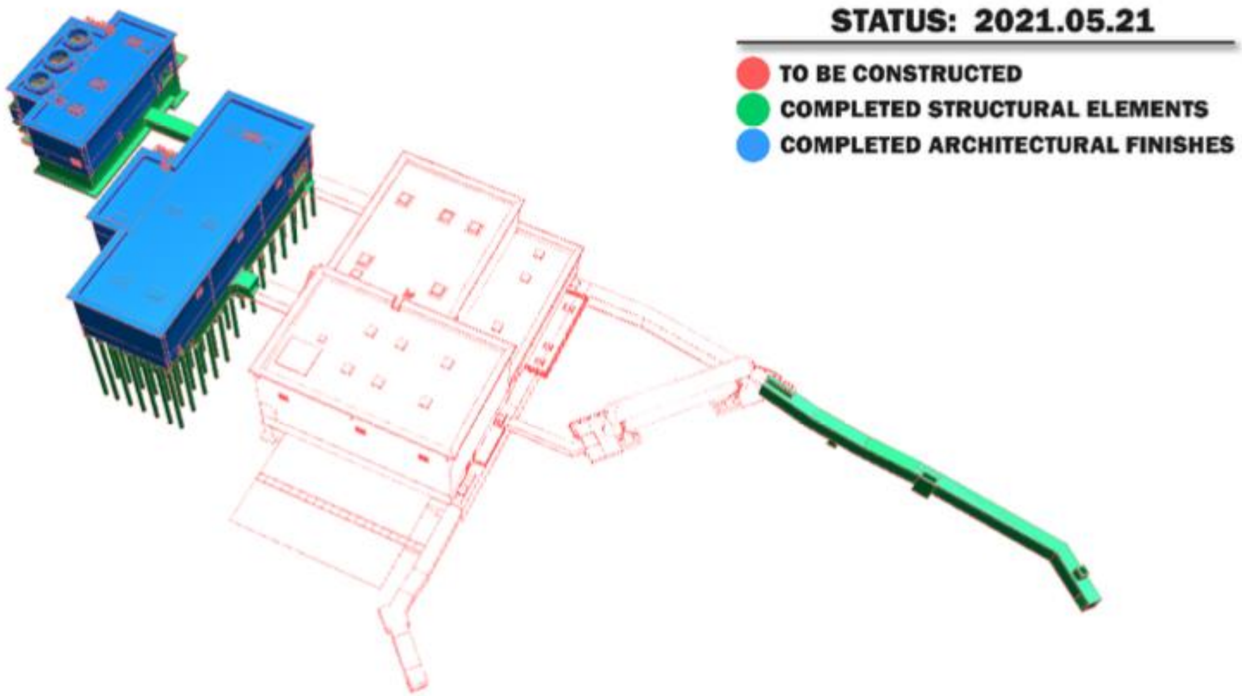
Overall progress: 69%

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 (early days)

HL-LHC civil engineering status (Point 1)

PM17 shaft
final lining

US/UW17 cavern

UA13/UR15 galleries

US17 cavern

IR1 & IR5 Surface Civil Engineering (early days)

SF57: Wall casting

SHM57: Ground slab casting

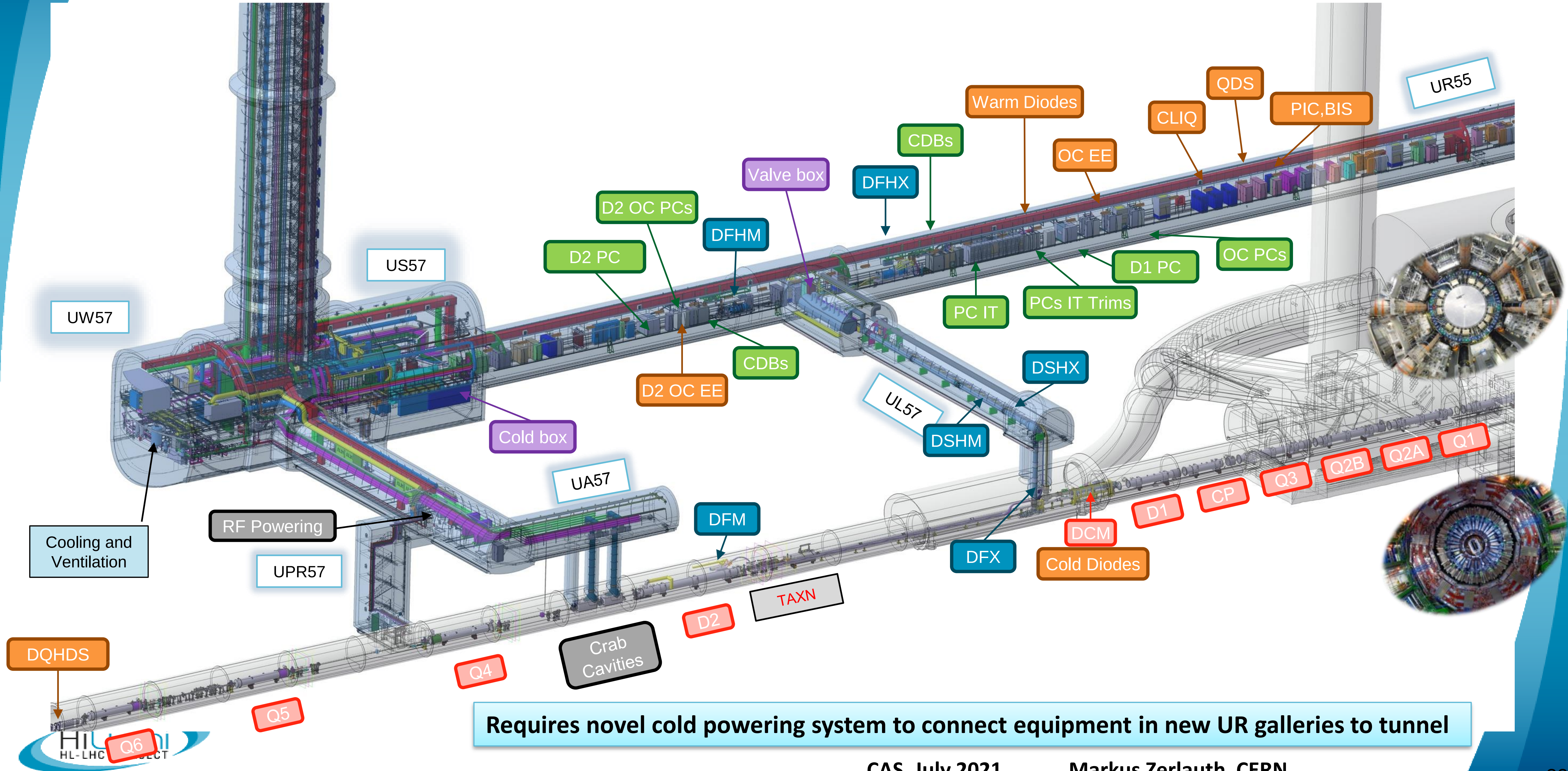
HL-LHC civil engineering status (Point 1)

SF17: Cooling tower building

SHM17: Cryogenic compressor building

Delivery expected on time (Aug’21)

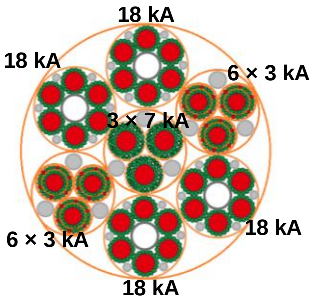
2) Removal of equipment from the tunnel



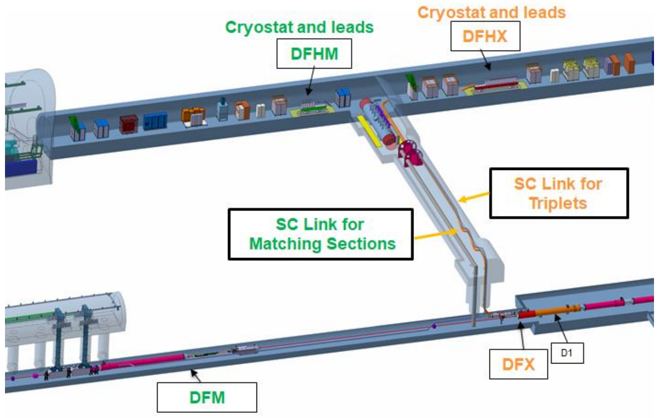
Requires novel cold powering system to connect equipment in new UR galleries to tunnel

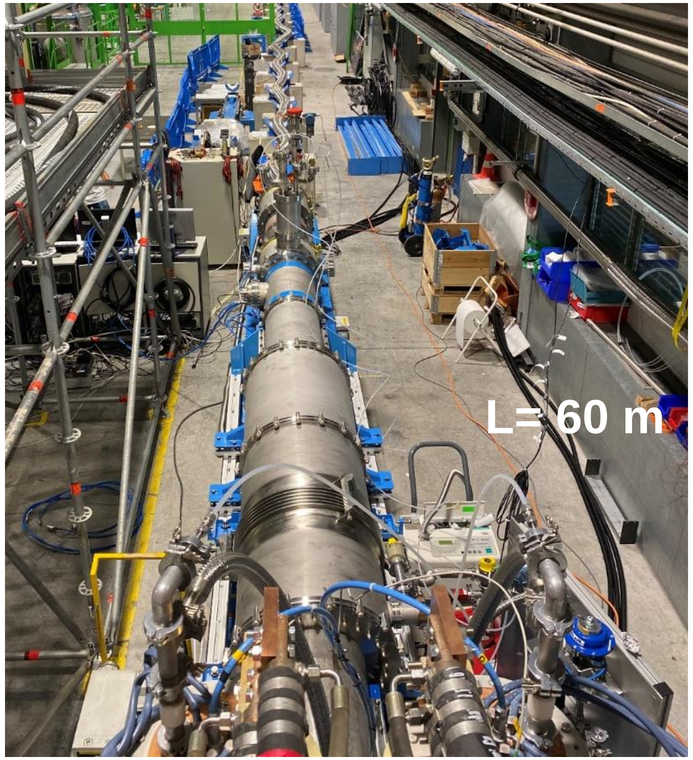
HL-LHC: Superconducting Link for HL-LHC Magnets

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



$\Phi\sim$ 90 mm



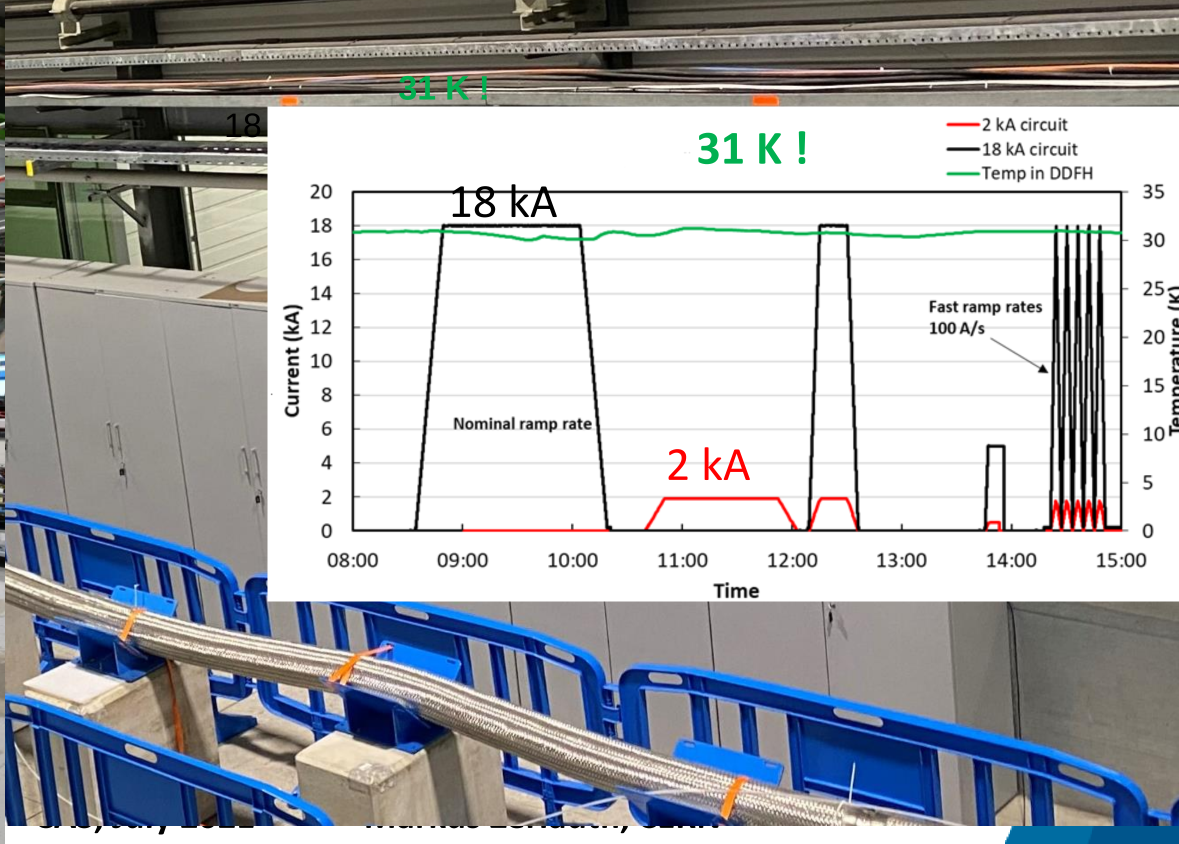


System demonstrator in SM 18
DEMO2
Demonstration of **2 x 20kA +**
2 x 7kA in June
in MgB_2 @ 30K
in flexible cryostat
over 60m [54kA total]

Courtesy of Amalia Ballarino

Superconducting Link: DEMO2 and DEMO3 completed!

- Successful qualification of SC Link for Triplets (Demo 2) – including EM compatibility 120 kA – Two cool-downs (June and September 2020). MgB_2 and HTS REBCO
- Assembled and successfully tested SC Link for Matching Section (Demo 3)
- Launching last large industrial procurement (long flexible cryostats for SC Links)



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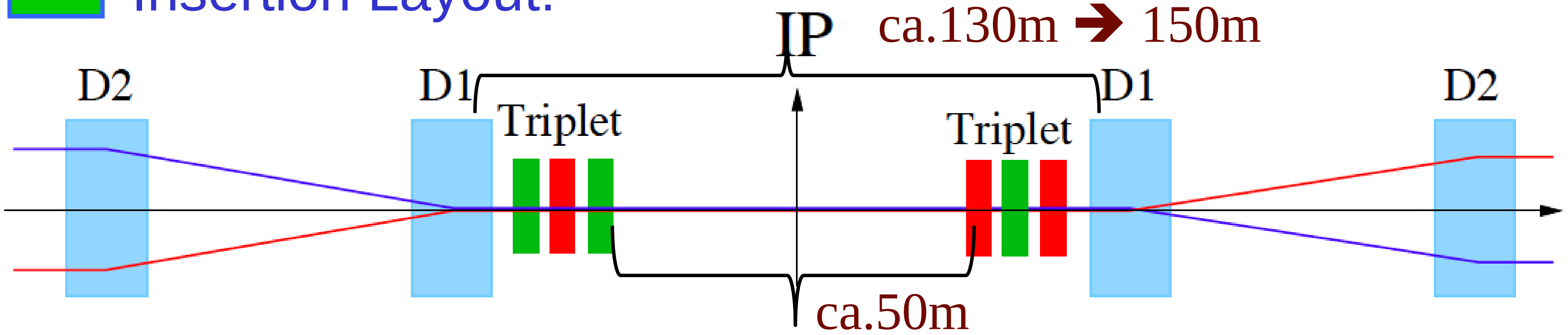
HL-LHC Challenges: Crossing Angle I

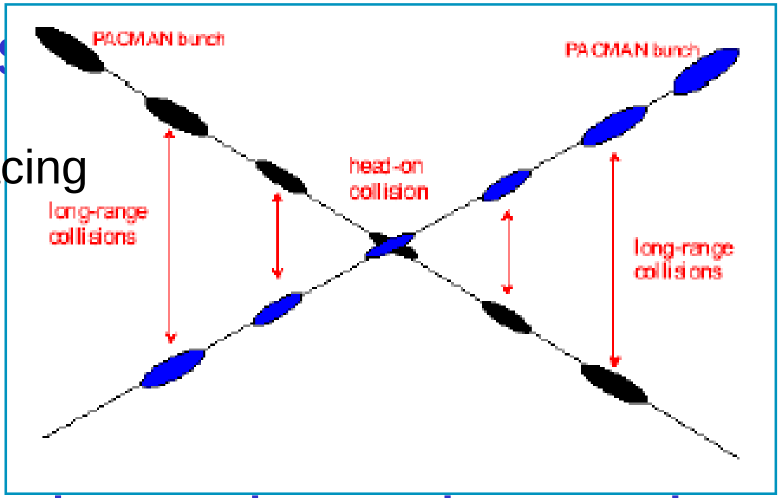
Insertion Layout:



Maximize the number of Protons

Operation with ca. 2800 bunches @ 25ns spacing
➔ approximately 30 unwanted collision per Interaction Region (IR).

➔ Operation requires crossing angle



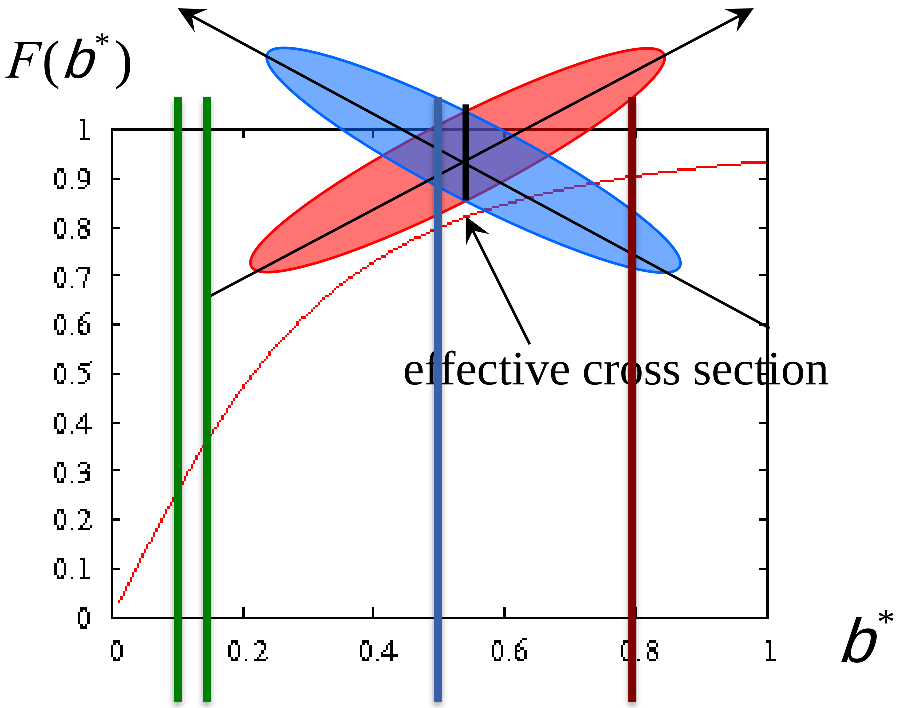
non-linear fields from long-range beam-beam interaction:

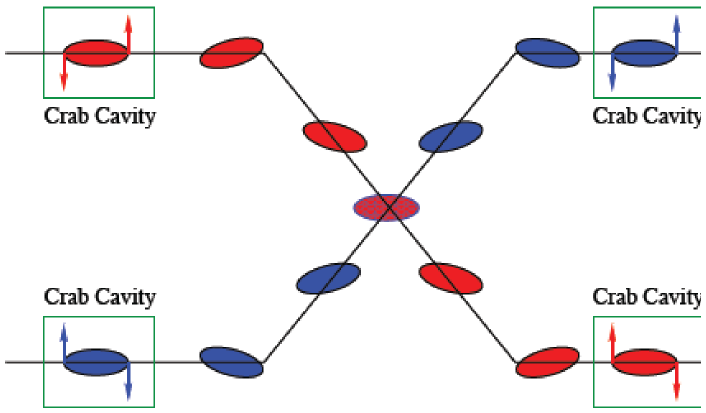
efficient operation requires large beam separation at unwanted collision points ➔ Separation of 10 -12 σ ➔ large crossing angle at Interaction Point!

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

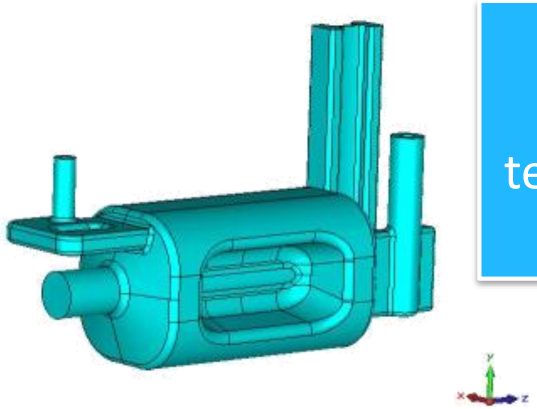




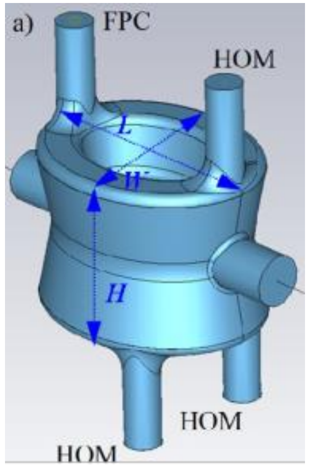
Crab cavity development

Major R&D program

Concentrating on two designs for test installation and beam valdiation in SPS



RF Dipole: waveguide or waveguide-coax couplers

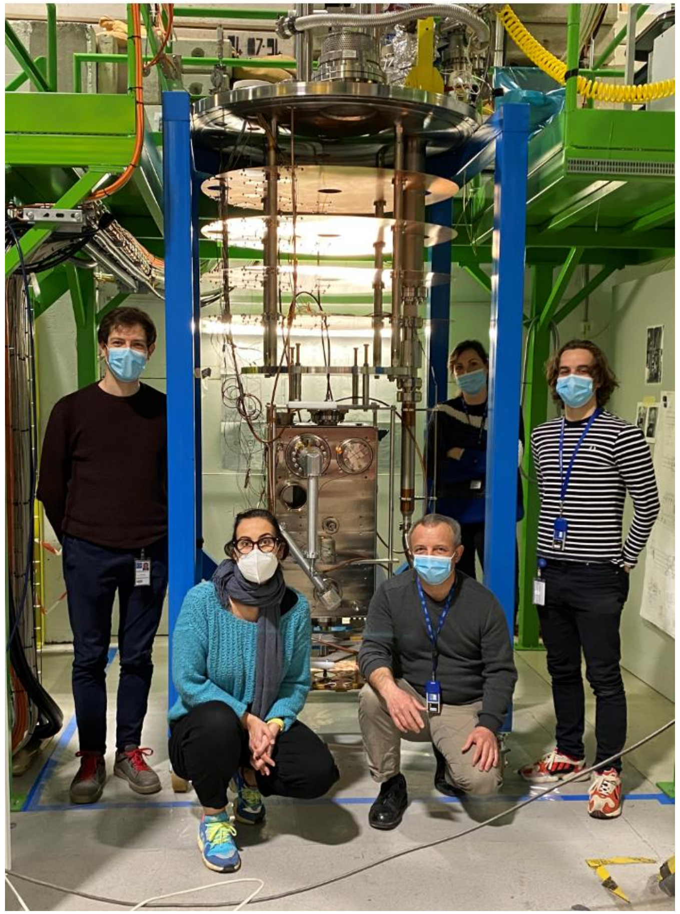


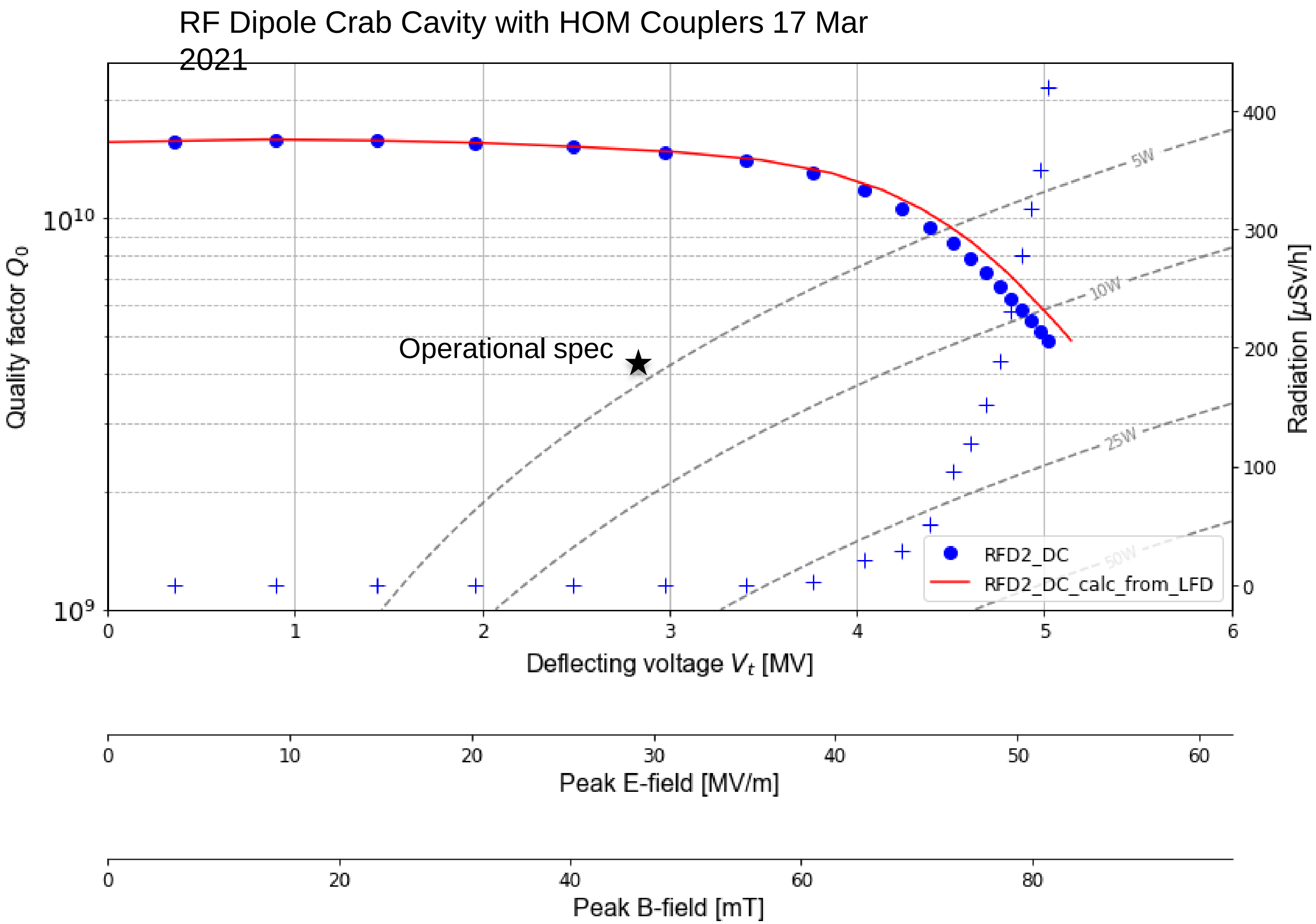
Double ¼-wave (DQW): coaxial couplers with hook-type antenna

RF-Dipole Nb prototype [ODU-SLAC]

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

RFD 2 Dressed Cavity with HOMs





CERN RFD 1 cavity under test @ CERN. Delays due to vacuum problems.

Crab cavity cryo-module for installation in the SPS

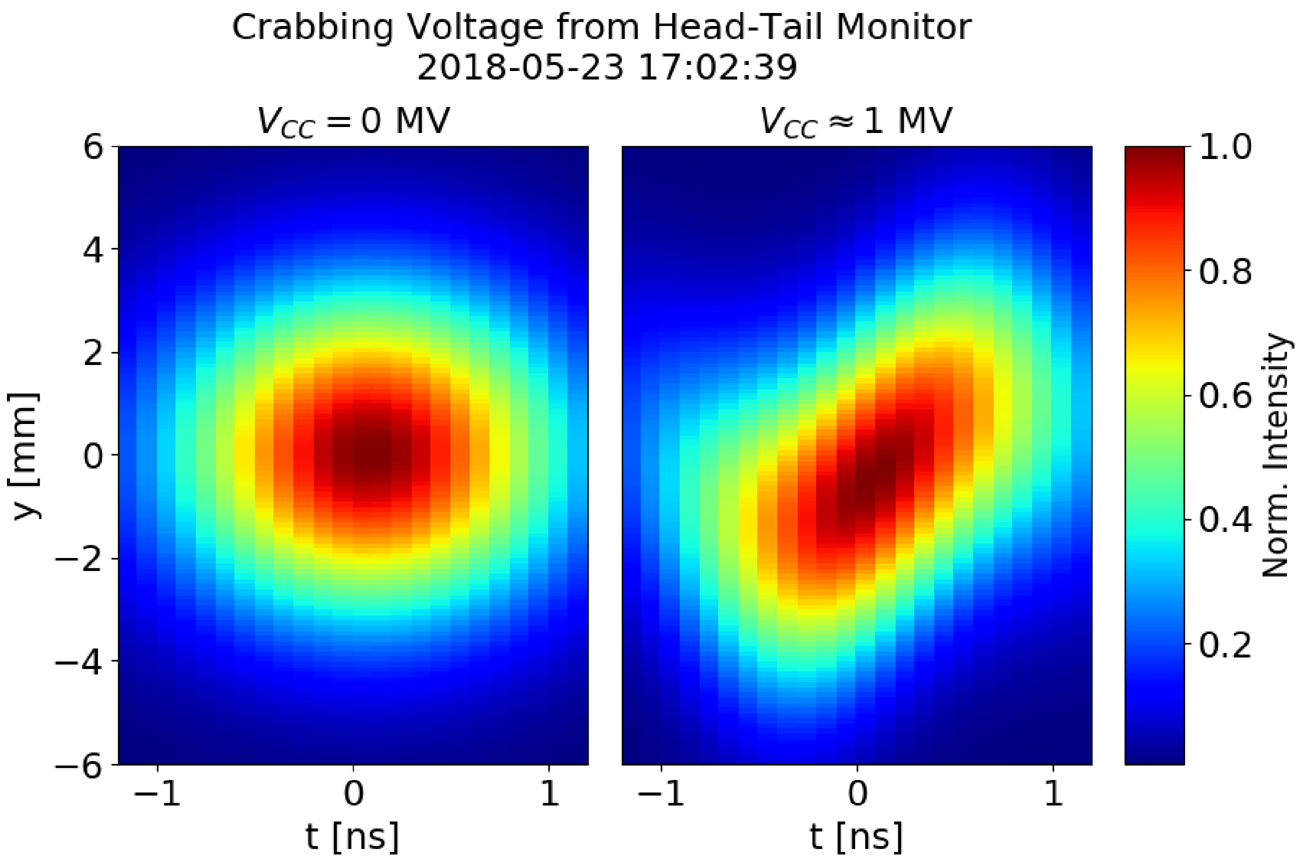
Compact Crab Cavity: SPS Installation

SRF test infrastructure operated with beam at end of Run 2 and planned to continue with DQW during Run 3

First proton crabbing ever!

TEST in SPS ongoing since 2018

Intensive Studies and R&D have been instrumental to obtain this result



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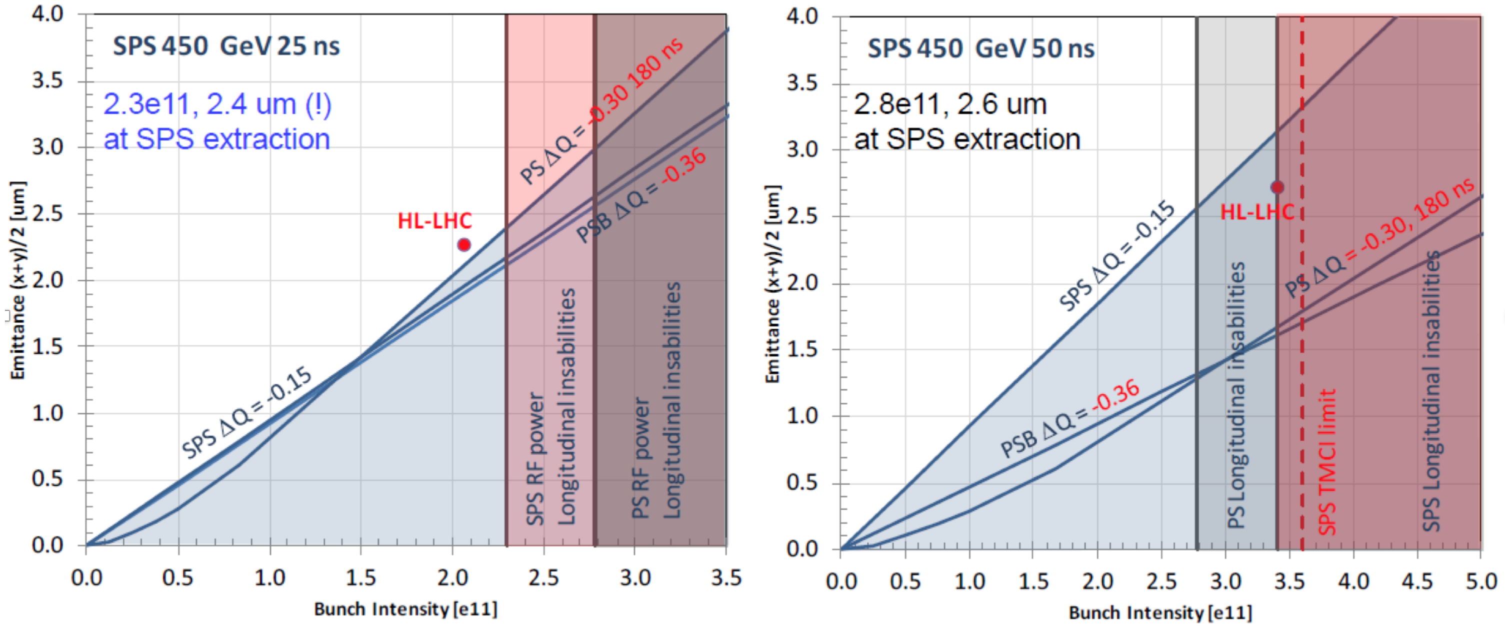
LHC Injector Upgrade



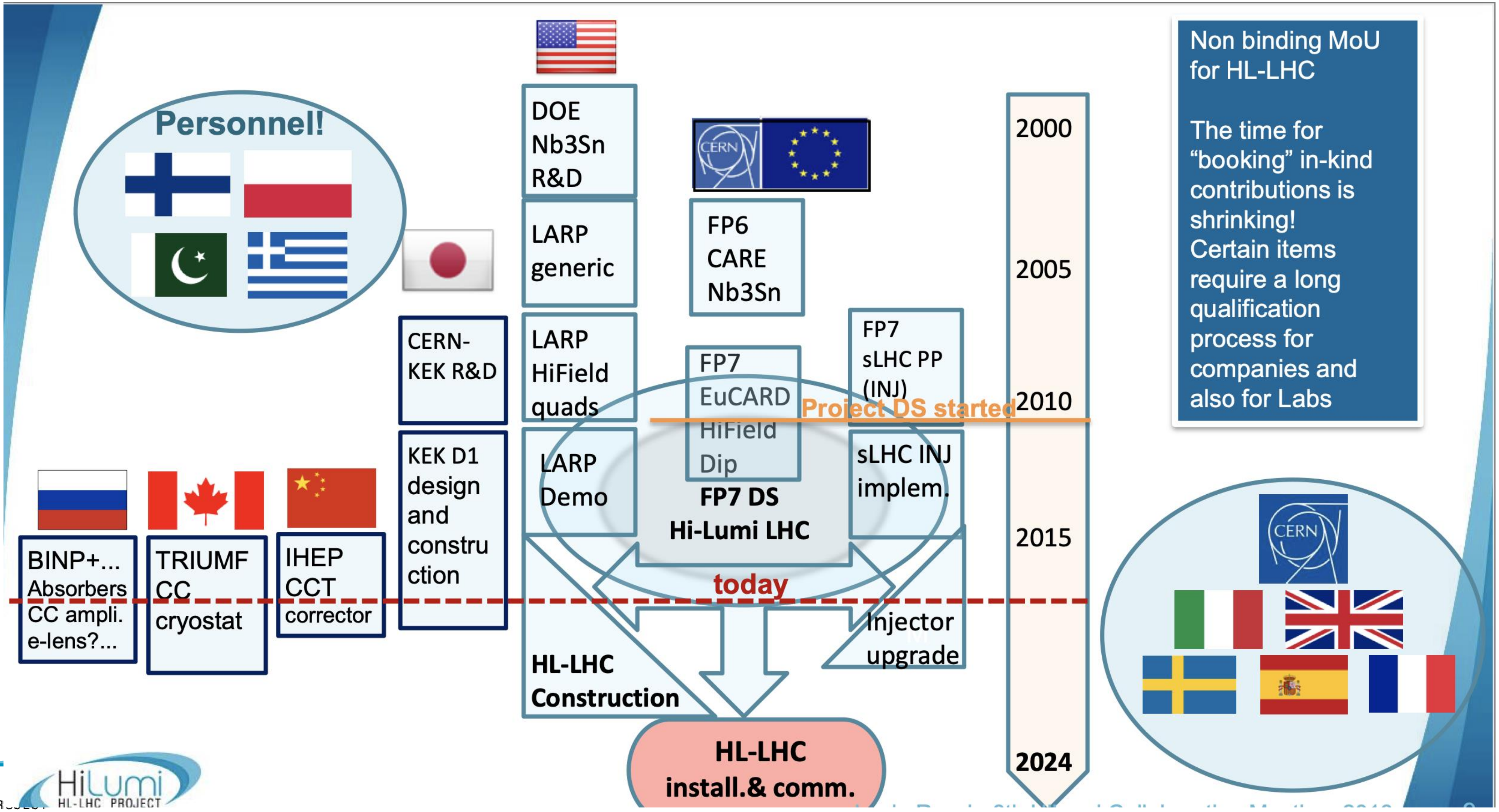
- HL-LHC performance relies on more intense and brighter bunches from injector complex (2.2E11p / 2um at SPS extraction wrt to LHC nominal of 1.15E11p / 3.4um)
- 25ns beam limited by space charge in PS, PSB, SPS; SPS RF power and SPS longitudinal instabilities
- 50ns beam limited by PS longitudinal instabilities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

LHC Injector Upgrade

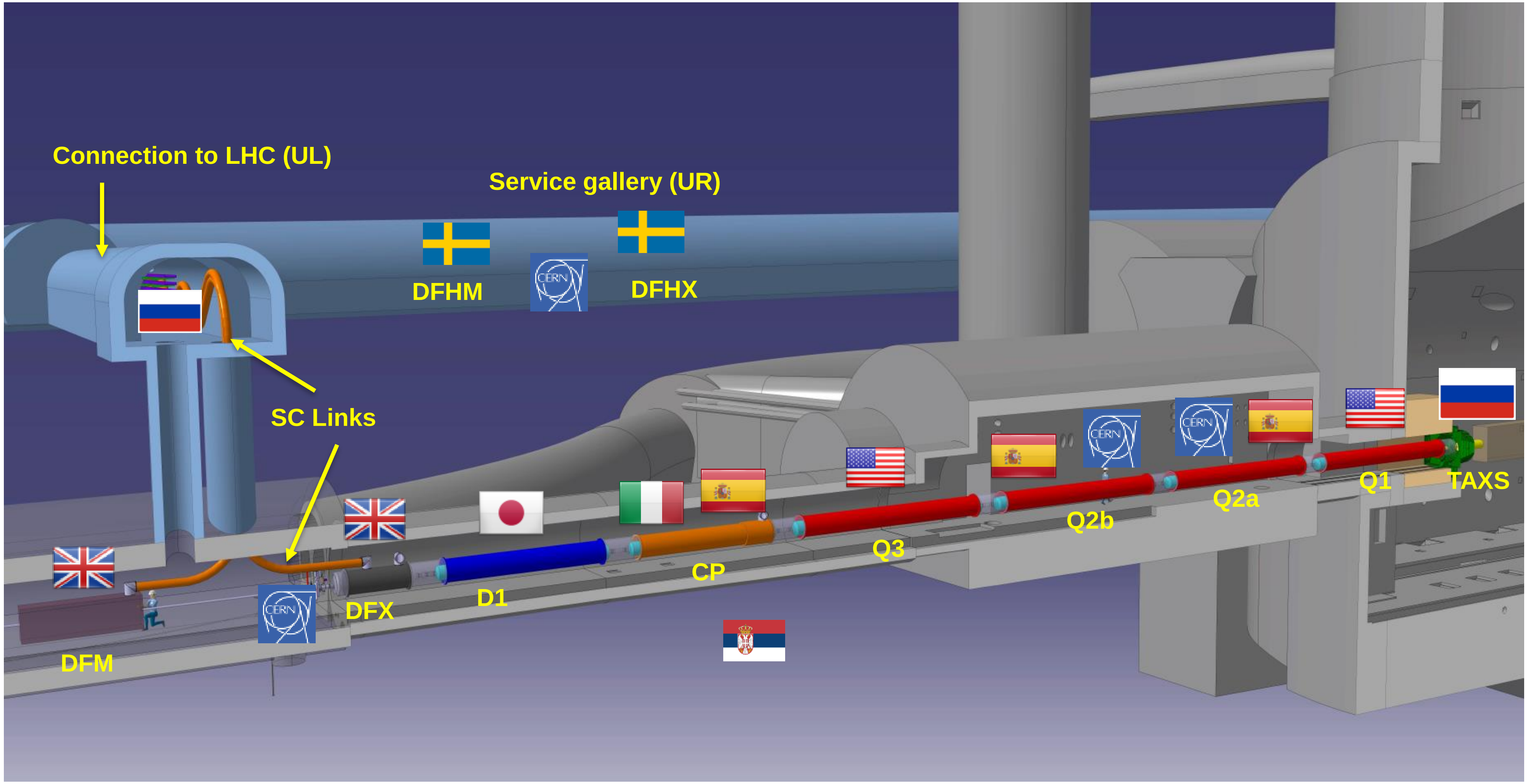
Linac4 in for Linac2	• H^- injection into PSB at 160 MeV • Expected double brightness for LHC beams out of the PSB
Booster	• Increase energy to 2 GeV • New RF system • New main power supply
PS	• Injection at 2 GeV • Beam production schemes • Feedback systems: new wide-band longitudinal feedback; transverse feedback 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

Many other options plus a full ion upgrade program

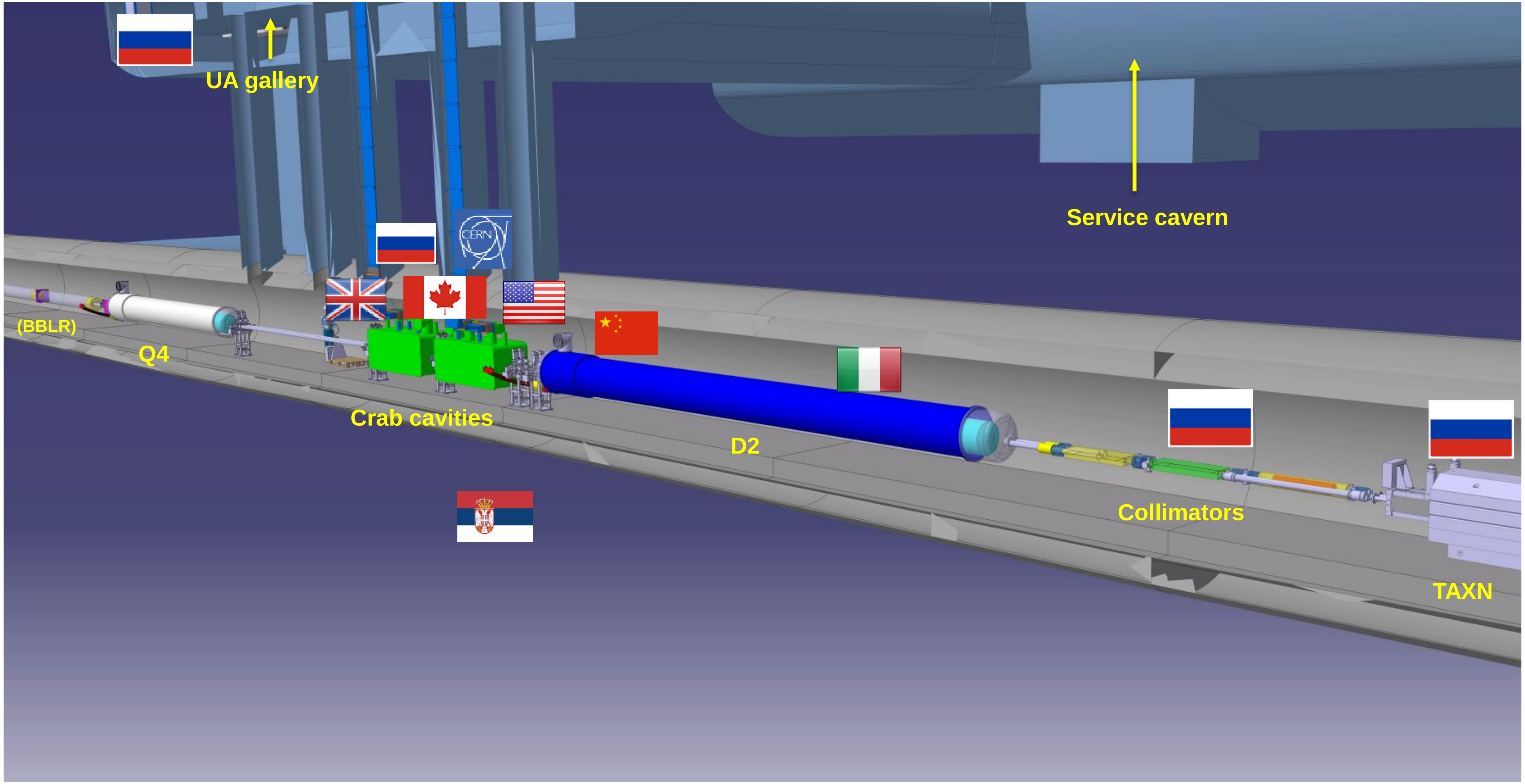
HL-LHC is not only a CERN project…



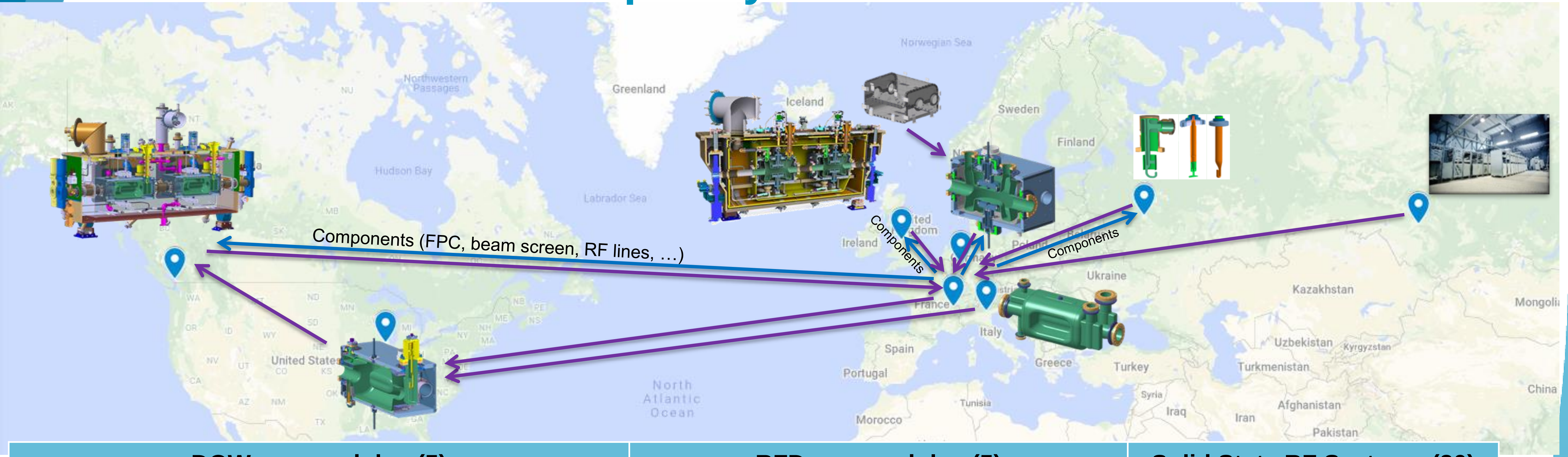
Truly International Collaboration



The MS region with in-kind contributions



Crab Cavity Series: CERN, Canada, Russia, UK, US-AUP the complexity of in-kind chain

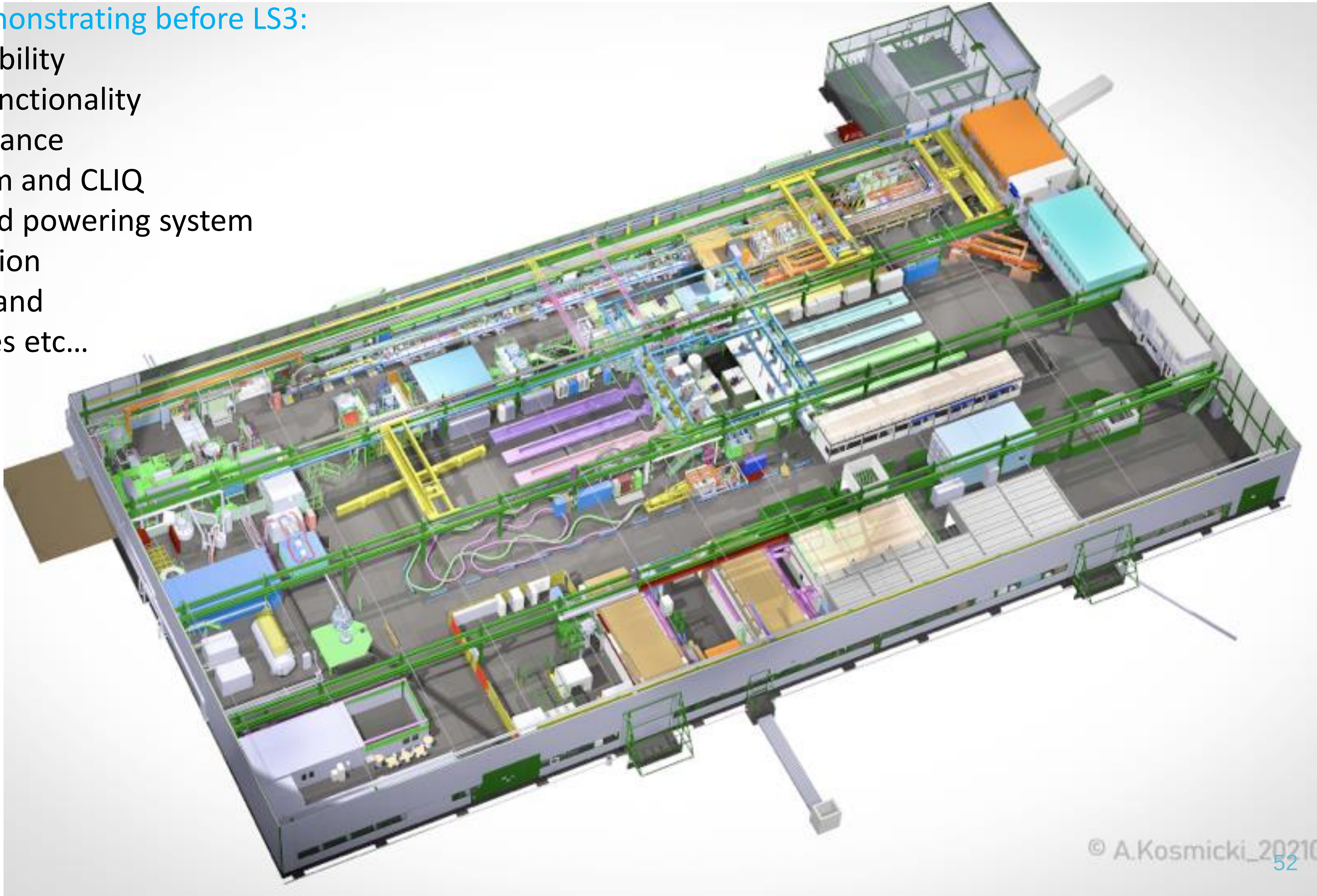


DQW cryomodules (5)	RFD cryomodules (5)	Solid State RF Systems (20)
• Cavities + processing + helium vessels by Research Instruments (**DE**) under **CERN** • Cold magnetic shields by **UK** • HOM couplers + antennas by **MEPHI-Russia & CERN** • 4 CM by **UK** (STFC) & 1 CM at CERN with some components by **CERN** • All cavities & CM cold validation tests at **CERN** (and a few at Uppsala-Sweden)	• Bare cavities by Zanon (**IT**) under **US-AUP** • Processing + cold magnetic shield + helium vessel + HOM couplers + antennas + cold tests by **US-AUP** • 5 CM by **TRIUMF-Canada** with some components by **CERN** • CM cold validation tests at **CERN**	• High power solid state amplifiers by **BINP-Russia** • First step, one amplifier prototype for qualification of SSPA technology

Next major milestone: IT String Installation in SM18

Important milestone for demonstrating before LS3:

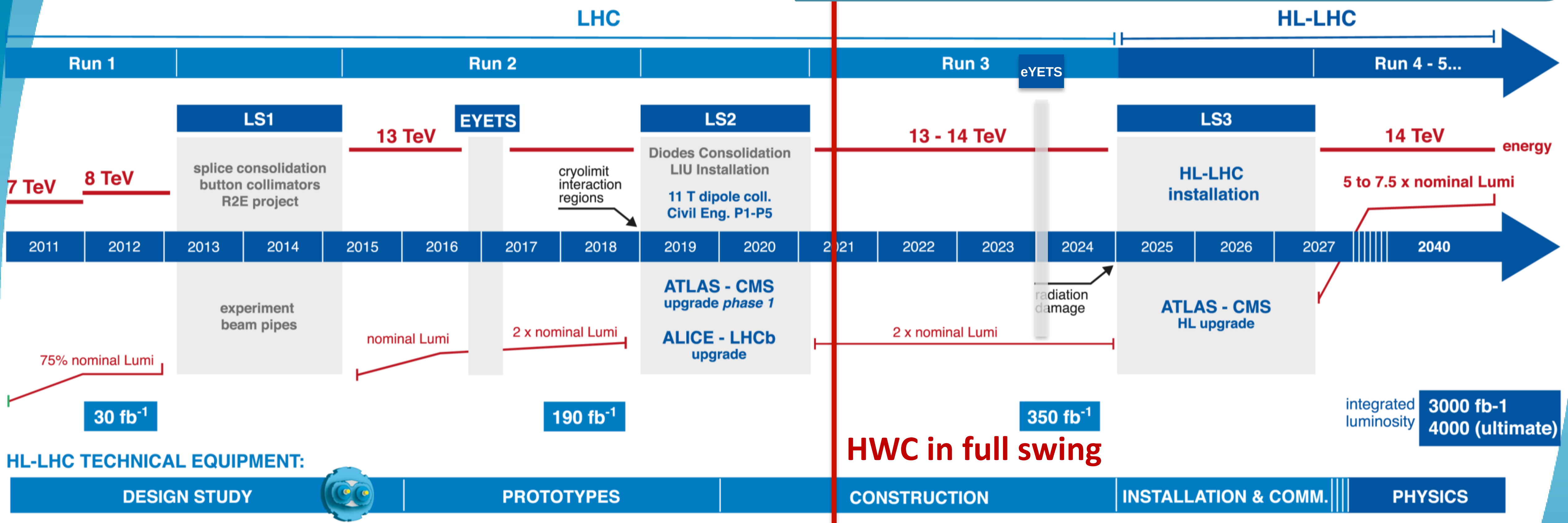
- Overall interface compatibility
- Vacuum and cryogenic functionality
- Electrical system performance
- Magnet protection system and CLIQ
- Final validation of the cold powering system
- Power Converter integration
- Validation of installation and commissioning procedures etc…



HiLumi HL-LHC PROJECT

LHC / HL-LHC Plan

After November 2019 retreat: CERN has decided, upon request of LHC Experiments Collaborations, to shift LS3 by 1 year, starting in 2025.

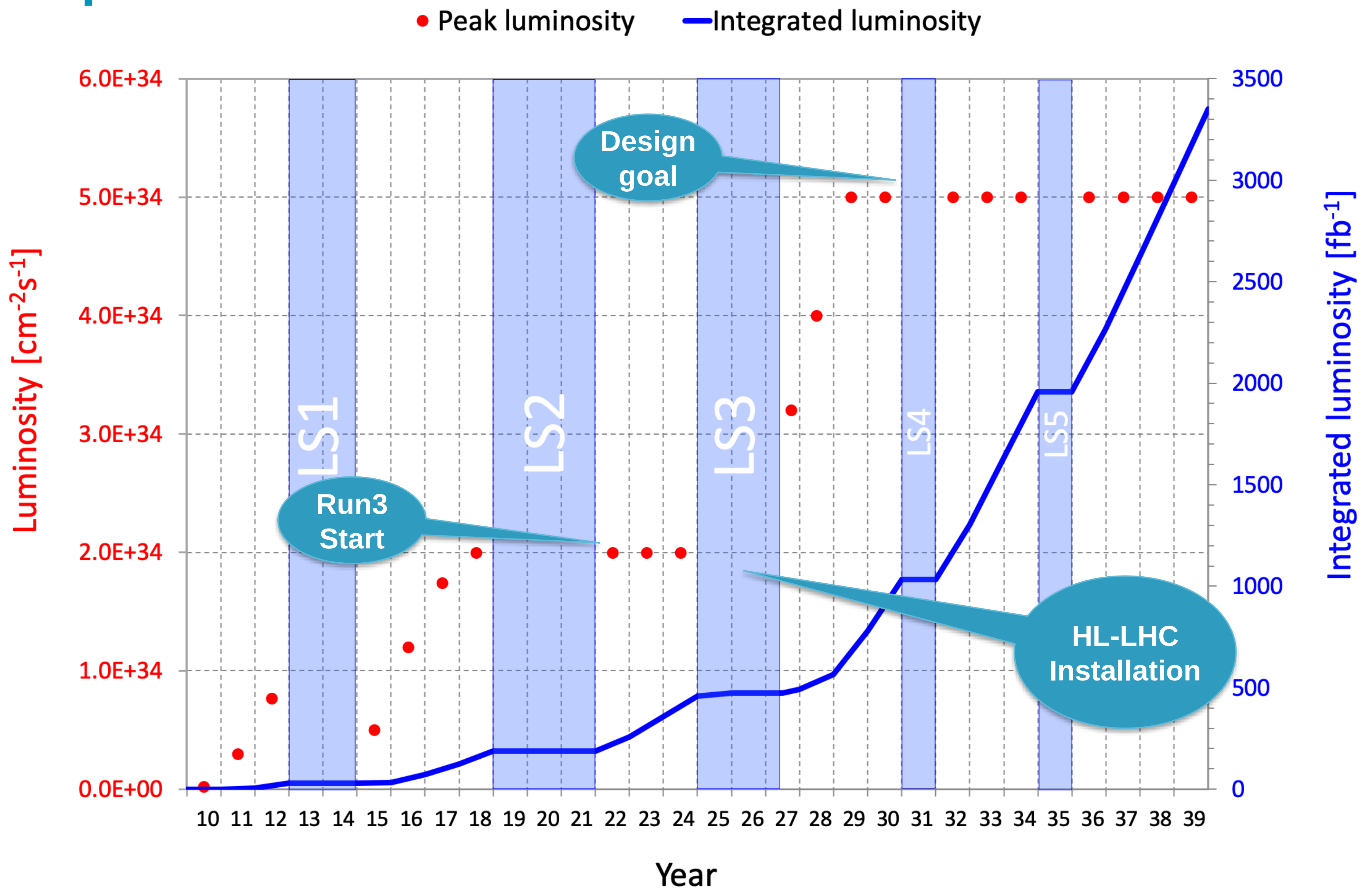


LS2 extended by 2 months; LS3 starts now in 2025

Meeting in June 2021 confirmed start of Run3 in Feb 2022 and need for eYETS 2023-24

However HL-LHC keeps the construction schedule unchanged to keep the momentum!

HL-LHC performance



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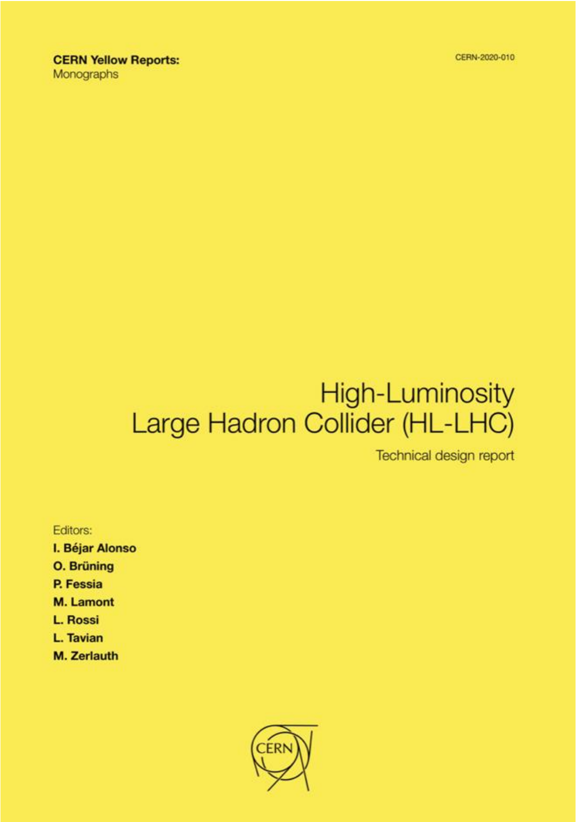
TDR V1.0 - The last version of the TDR including the added scope - 2020

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!
Questions ?