HL-LHC Introduction

O. Brüning
On behalf of the
HL-LHC Project

LHC in the Geneva Basin and its Experiments

LHC (Large Hadron Collider): Magnet Technology

14 TeV proton-proton accelerator-collider built in the LEP tunnel ➔ requires ca. 9T magnets!!!

➔ 200000 times the earth magnetic field!!

➔ Not feasible with Normal conducting magnets

Ca. 20 years magnet development!!!

Ca. 30 years machine development!!!

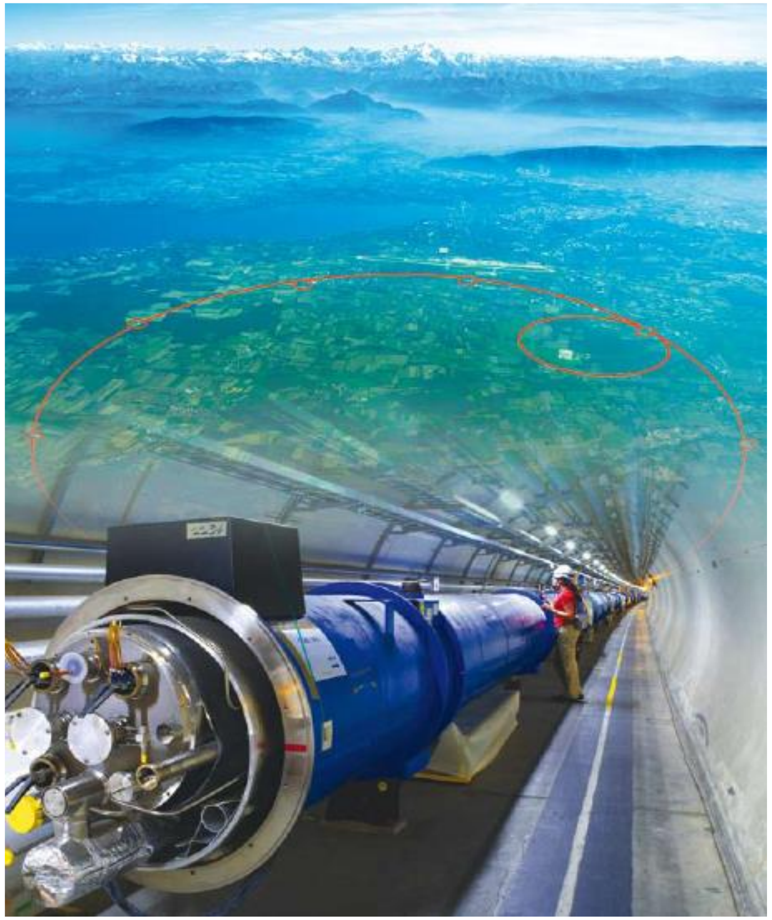
1983 : First studies for the LHC project
1988 : First magnet model (feasibility)
1994 : Approval by the CERN Council
1996-1999 : Series production industrialisation
1998 : Declaration of Public Utility & Start of civil engineering
1998-2000: Placement of main production contracts
2004 : Start of the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

As of 2010: Physics exploitation

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

LHC (Large Hadron Collider): Magnet Technology

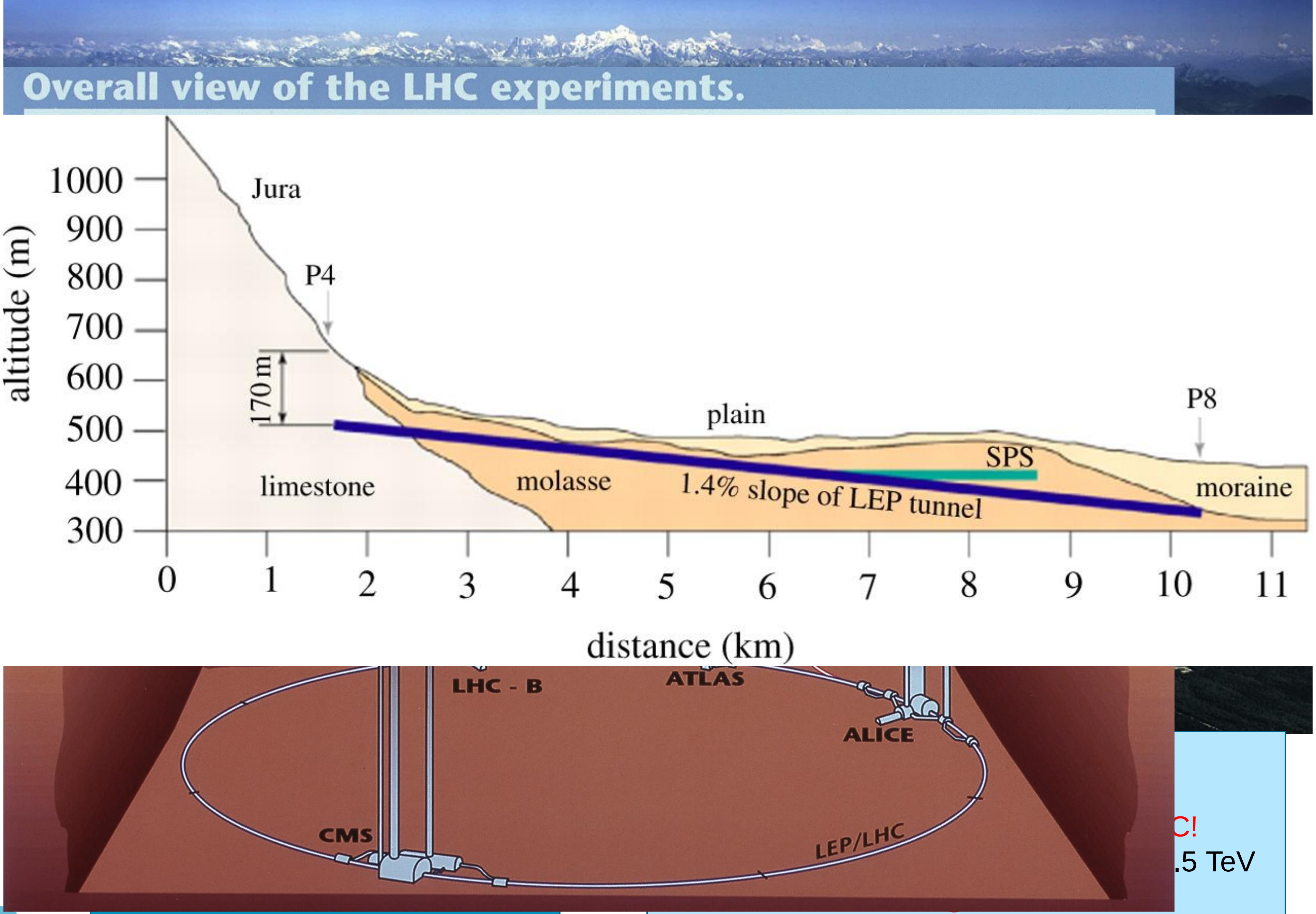
1983 1991 2000 2010



➔ The LHC dipole magnets mark the culmination of 30 years of superconducting magnet technology development!

➔ Requiring 1.9K [-271 degrees Celsius] operating temperature

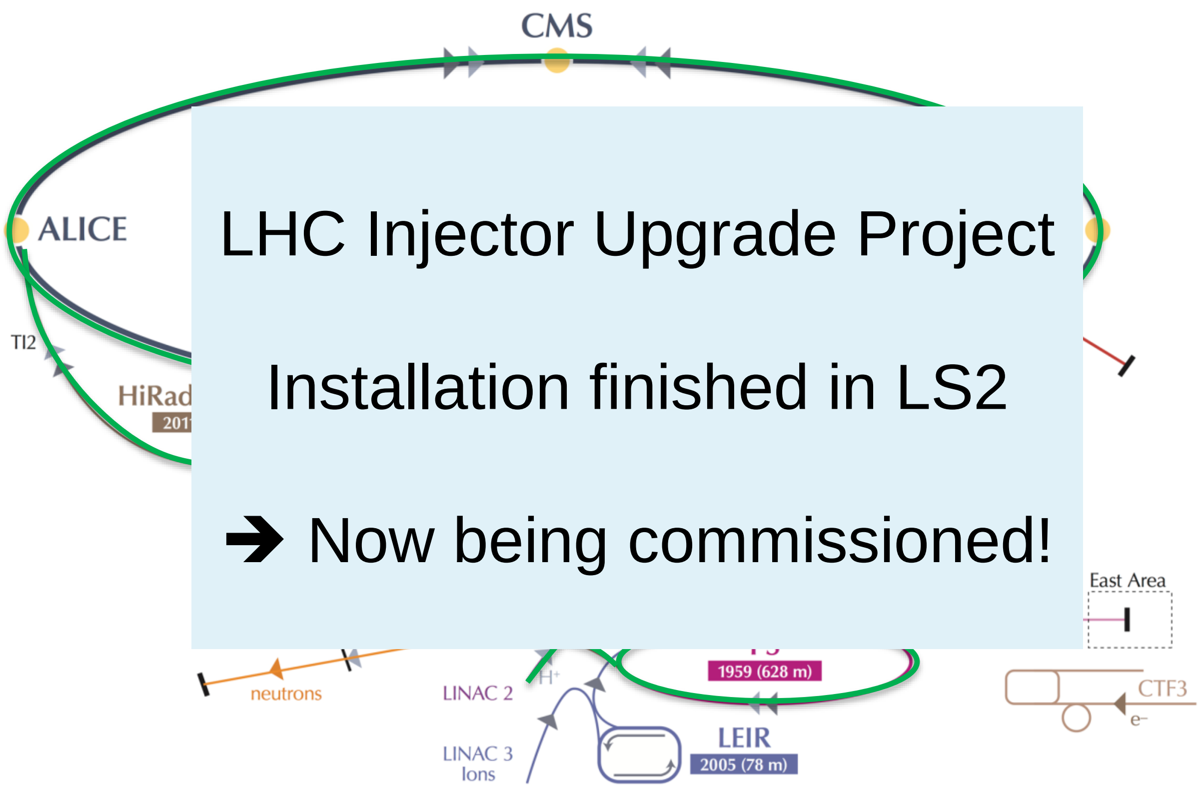
HiLumi HL-LHC PROJECT


Overall view of the LHC experiments.
altitude (m)
1000
900
800
700
600
500
400
300
Jura
P4
170 m
plain
P8
SPS
limestone
molasse
1.4% slope of LEP tunnel
moraine
0
1
2
3
4
5
6
7
8
9
10
11
distance (km)
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

The LHC is NOT a Standalone Machine

The LHC performance fully relies on the **performance of its injector complex**

- By itself **one of the largest accelerator facility in the world** with its own diverse and, for many aspects, unique physics program

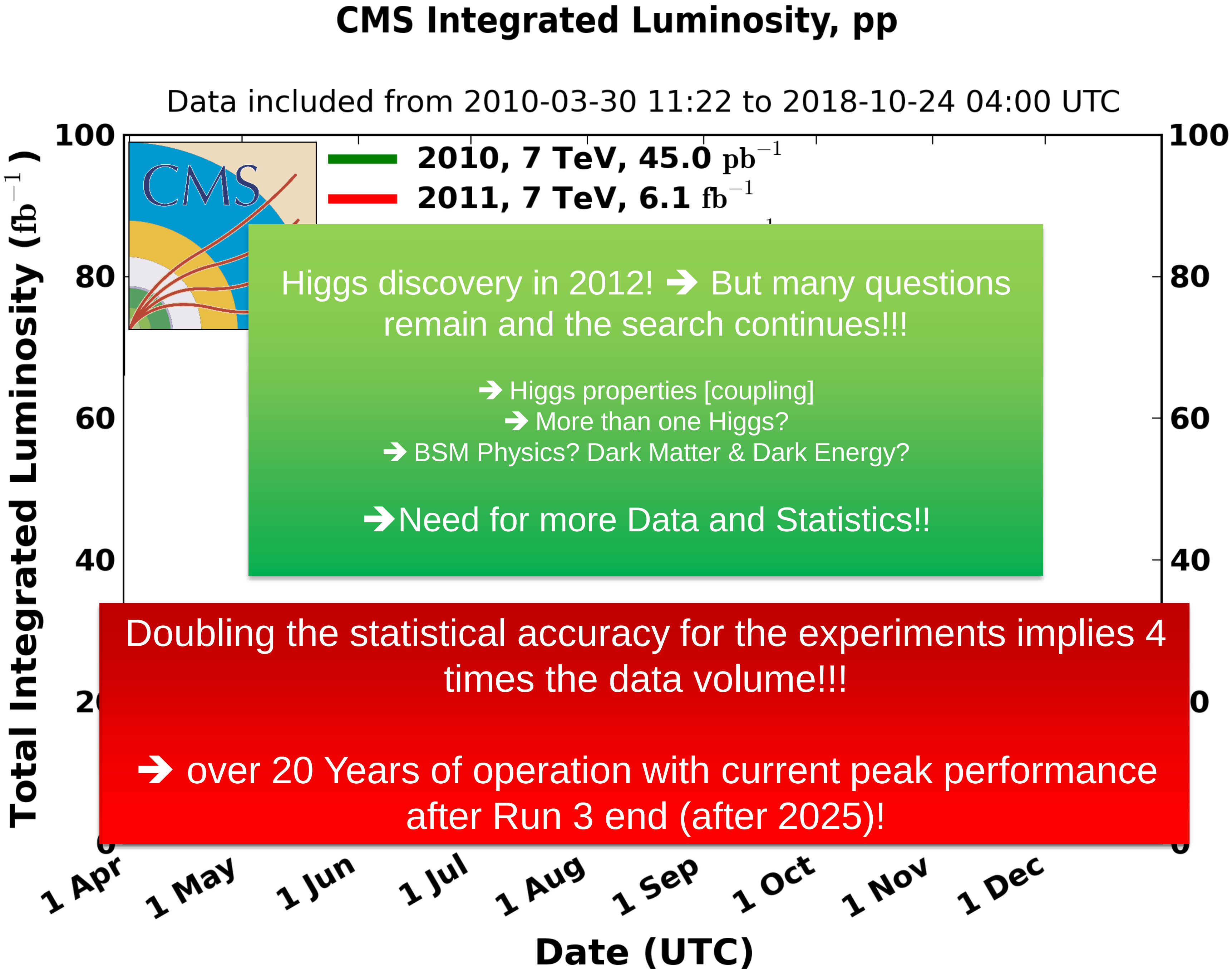


LHC Injector Upgrade Project

Installation finished in LS2

➔ Now being commissioned!

- LHC : 2x(0.45 – 7) TeV
- SPS : 26 – 450 GeV
- PS : 1.4 - 26 GeV / PS : 2 - 26 GeV
- PSB : 0.05 - 1.4 GeV / PSB : 0.16 - 2 GeV
- Linac 2: 0-50 MeV / Linac 4: 0-160 MeV H^-



Higgs discovery in 2012! ➔ But many questions remain and the search continues!!!

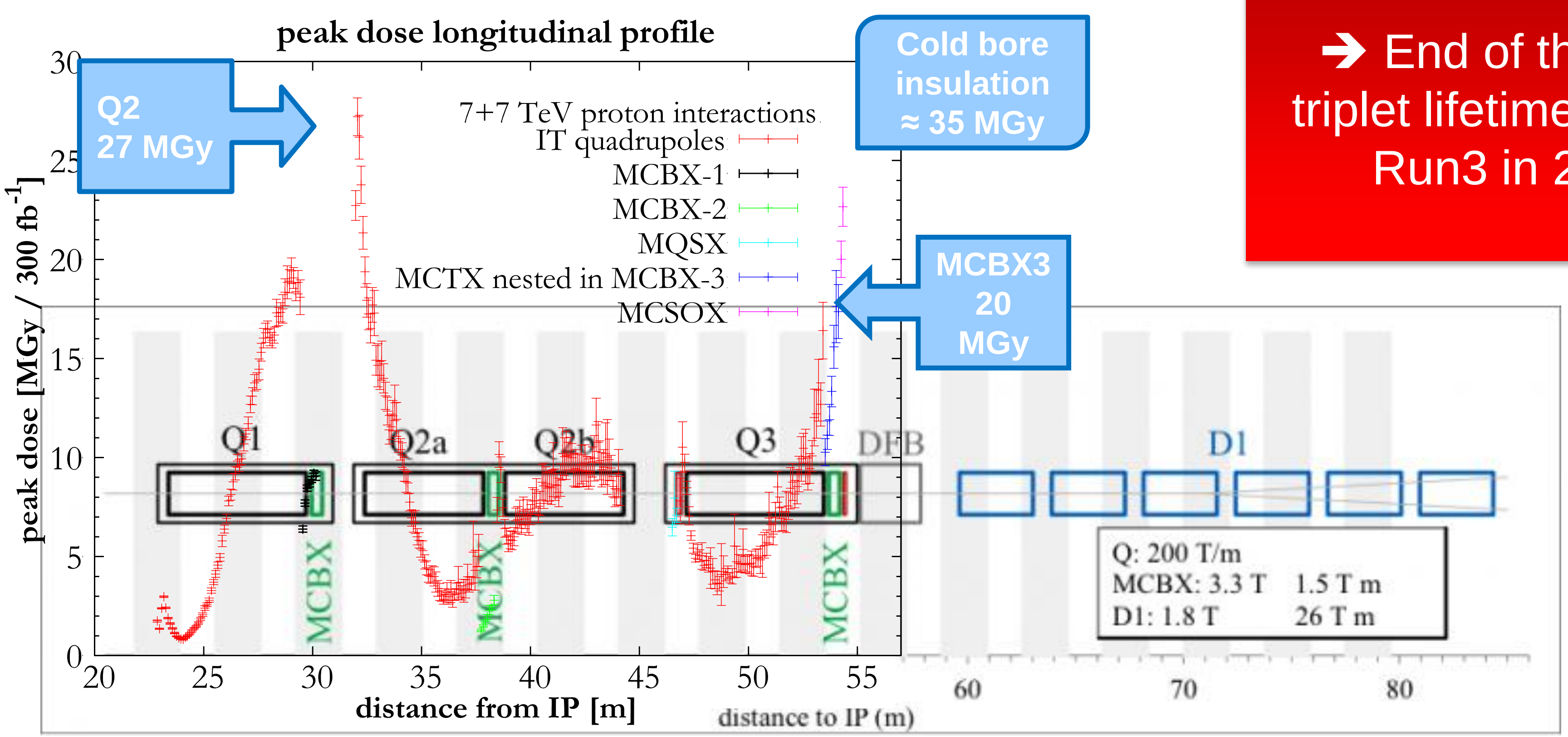
➔ Higgs properties [coupling]
➔ More than one Higgs?
➔ BSM Physics? Dark Matter & Dark Energy?

➔Need for more Data and Statistics!!

Doubling the statistical accuracy for the experiments implies 4 times the data volume!!!

➔ over 20 Years of operation with current peak performance after Run 3 end (after 2025)!

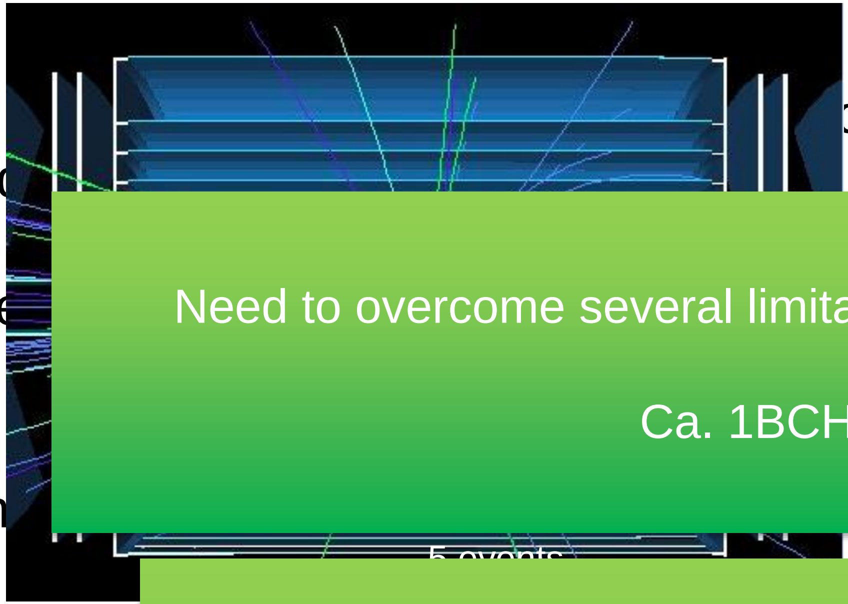
LHC Lifetime Limitation: Debris from the IP & Radiation damage to magnets!



➔ End of the LHC triplet lifetime by End Run3 in 2025

➔ HL-LHC goal: 10 times the LHC data Volume within 10 years of operation

Goal of High Luminosity LHC (HL-LHC):



The … nfiguration

and … g targets:

Prepare

Devise

en … design!

im

de … x the nominal value

… mode!

Need to overcome several limitations in the existing LHC machine!!!

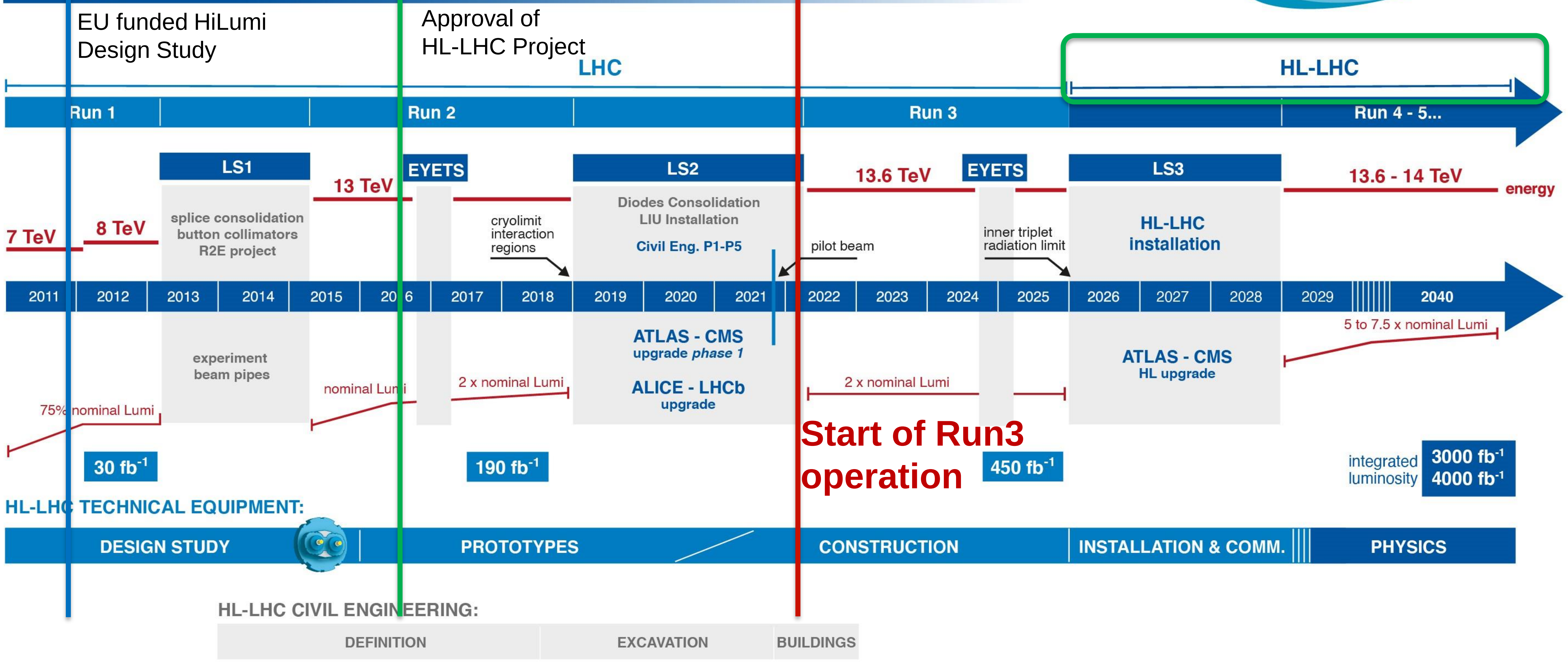
Ca. 1BCHF CtC Project

The HL-LHC Project is currently transitioning from

Prototype Validation to series production!!!

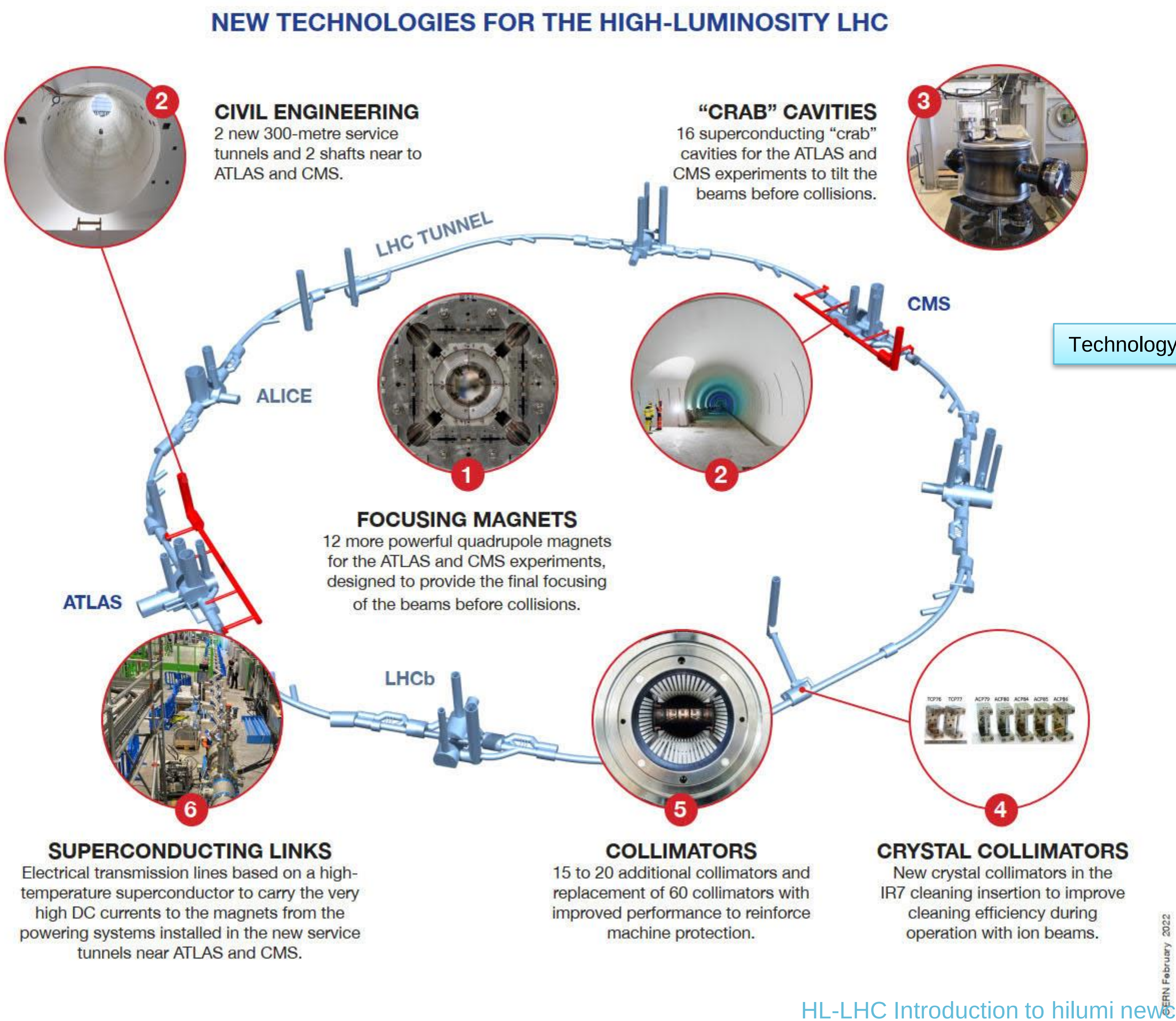
➔High machine efficiency and reliability are key upgrade ingredients!

LHC / HL-LHC Plan



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

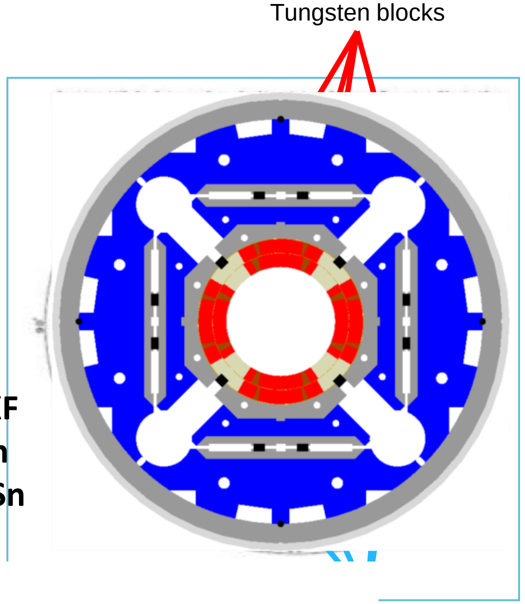
Technology intensive project!



Technology landmarks

HL-LHC technical bottleneck: Radiation damage to triplet magnets

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



US-LARP MQXF magnet design Based on Nb_3Sn technology

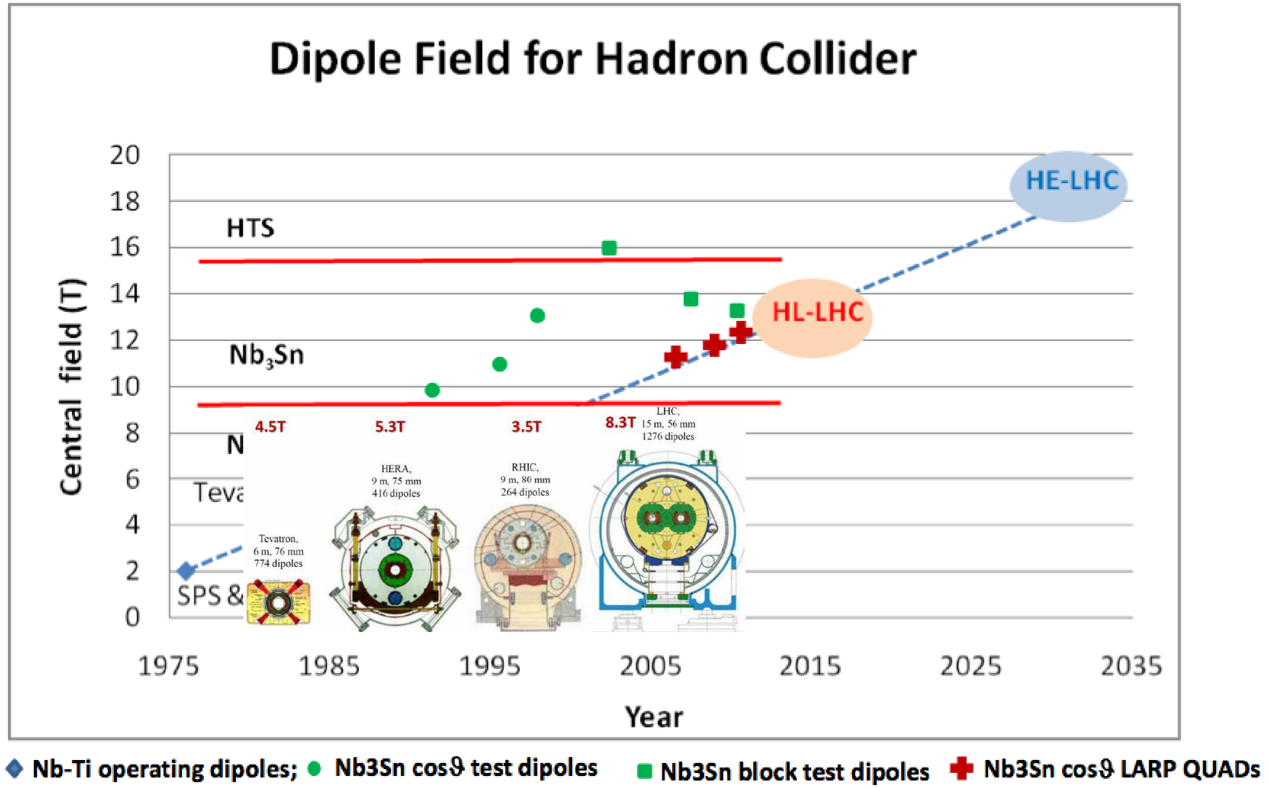
➔ Requires larger aperture!
➔ New magnet technology!

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

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

High Field SC Magnets

Magnet development requires substantial R&D effort!!!



courtesy: L. Rossi (CERN)

Ca. 30 years of NbTi magnet R&D leading up to the LHC dipole magnets!

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

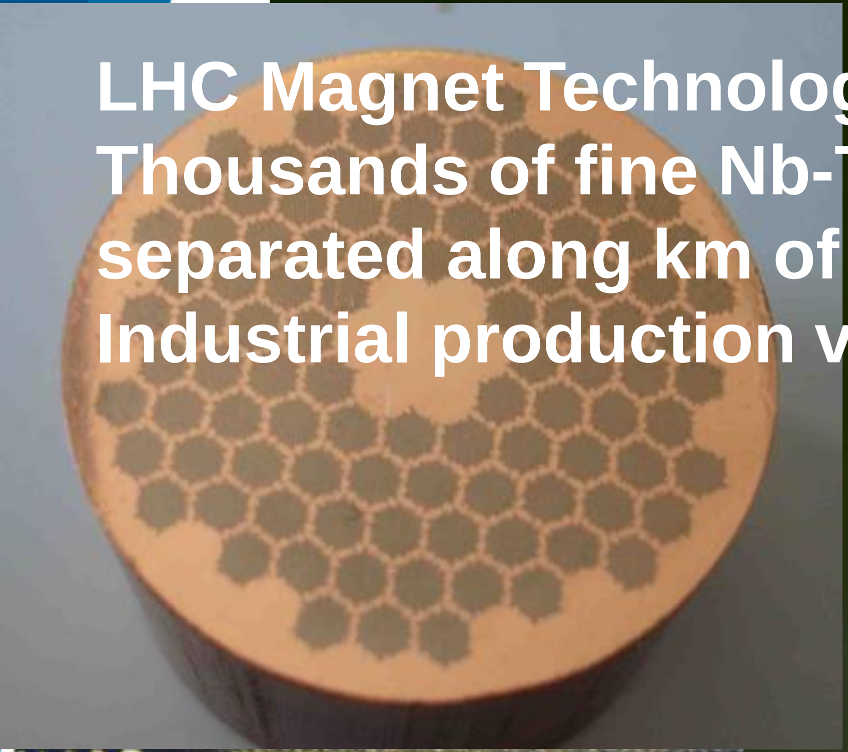
HL-LHC led the R&D for 11-15T magnets based on Nb_3Sn technology:

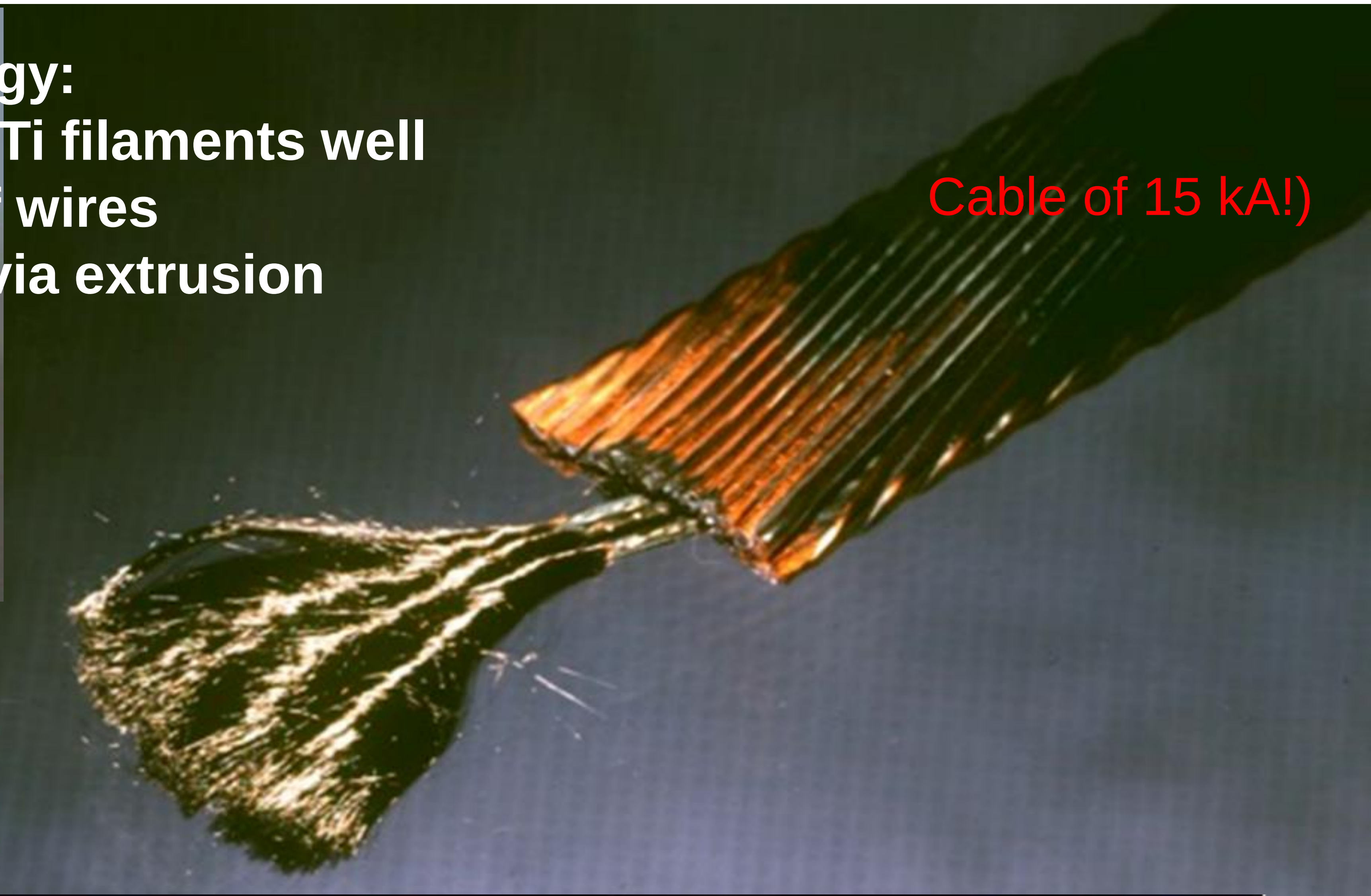
➔ Started in early 2000

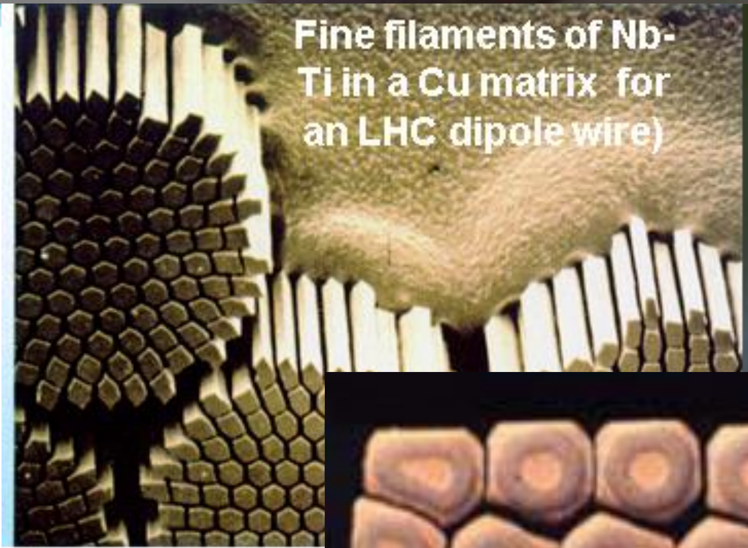
➔15-20 years R&D program

➔ Ready by 2025

LHC Magnet Technology:
Thousands of fine Nb-Ti filaments well separated along km of wires
Industrial production via extrusion

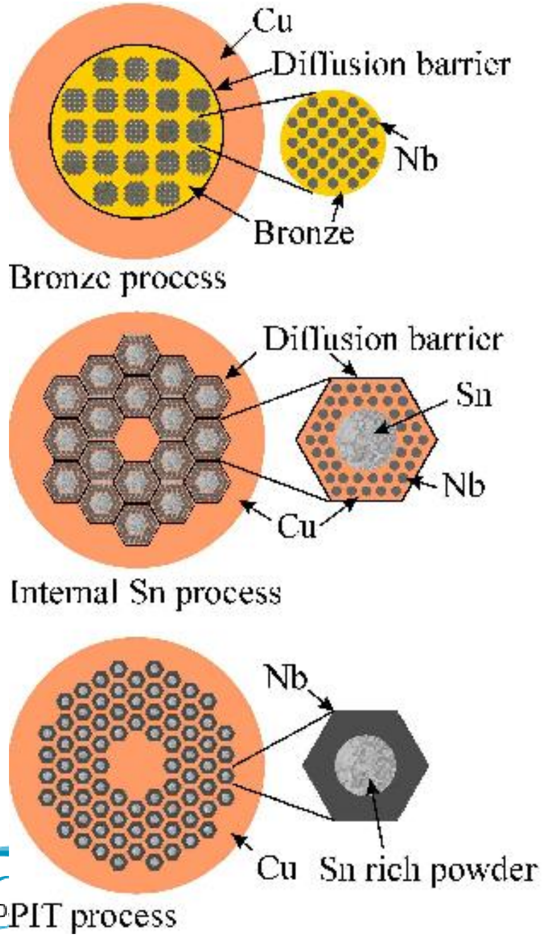


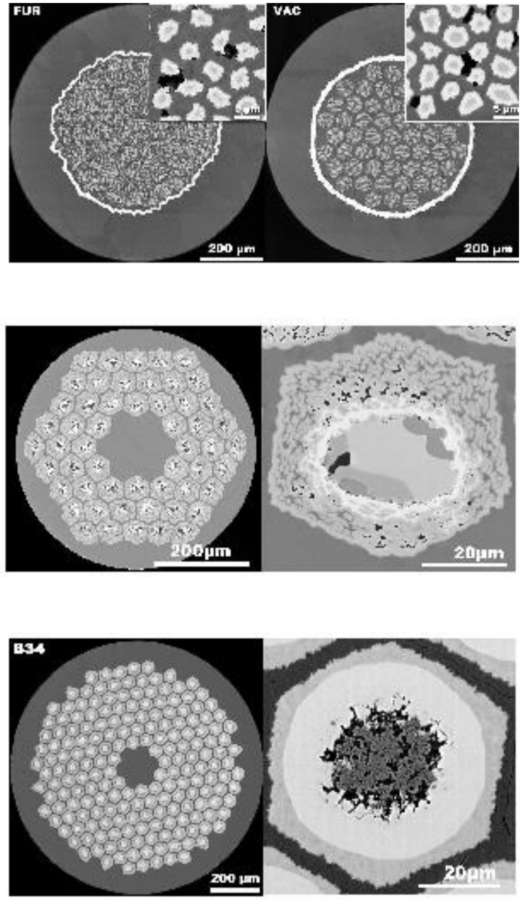


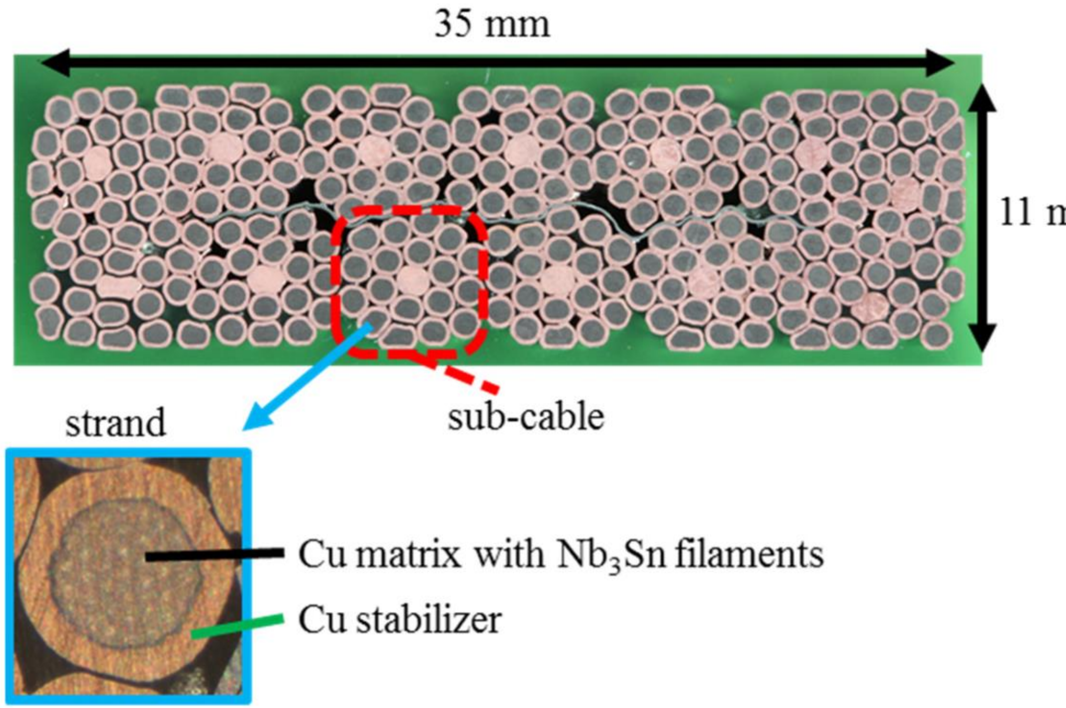


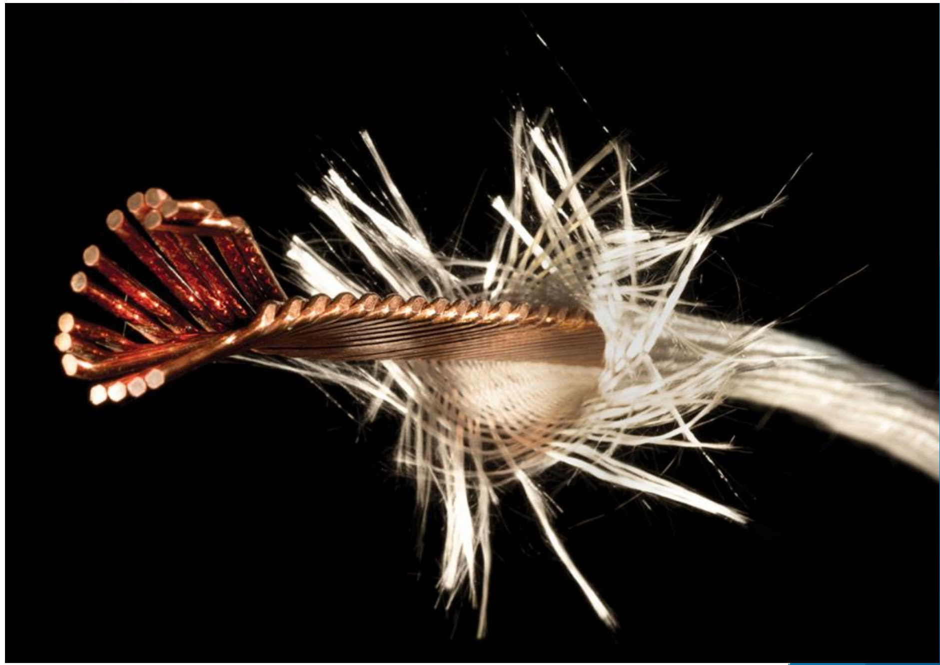
The Nb_3Sn SC Challenge:

Nb_3Sn is brittle and cannot be drawn in final form – contrary to NbTi
Strand is drawn before cable is formed before the wire is heat-treated to form the Nb_3Sn superconductor!

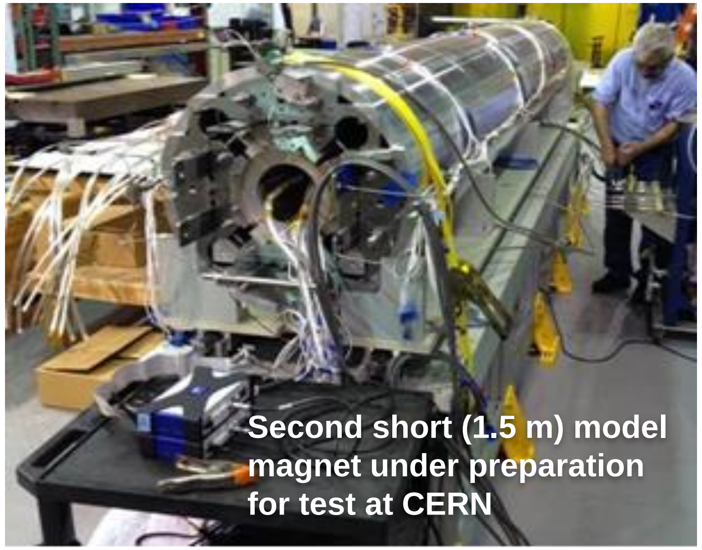








Nb_3Sn quadrupole: Transition from Prototype to Series production



Second short (1.5 m) model magnet under preparation for test at CERN

Insertion of coil package inside mechanical structure of the first IT quad prototypes (4.2 m long) in LBNL-USA

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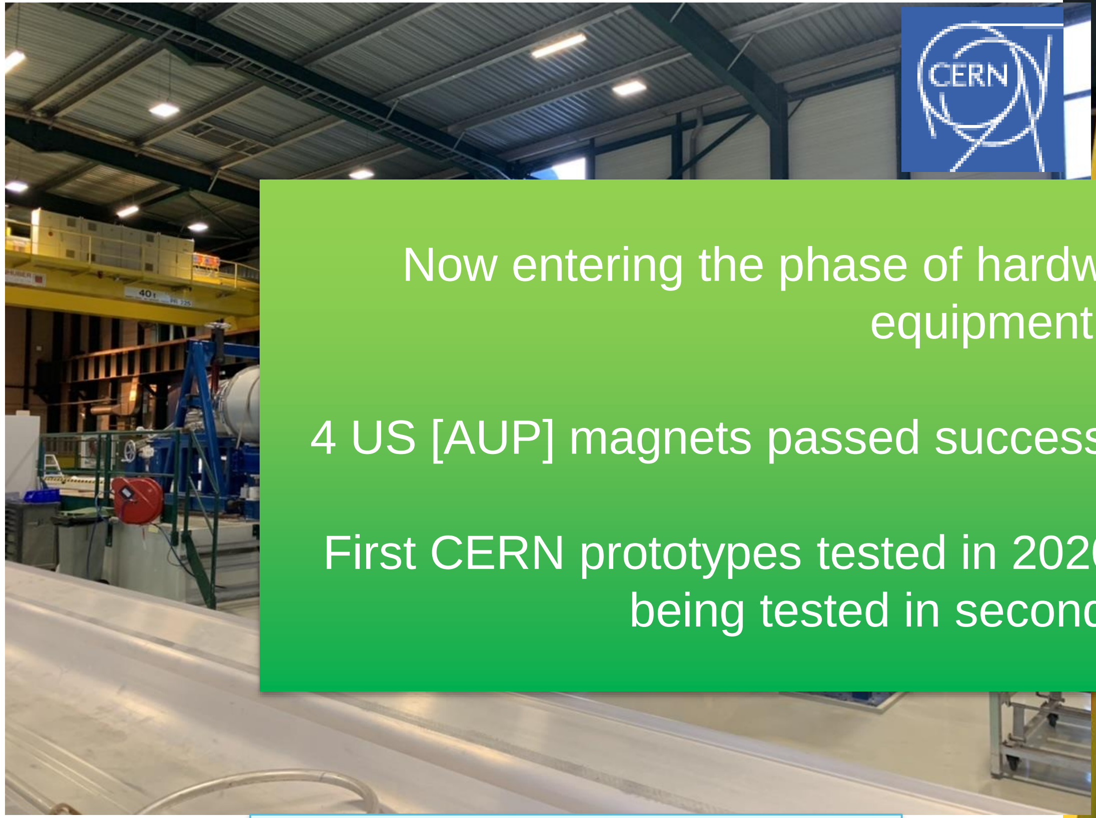
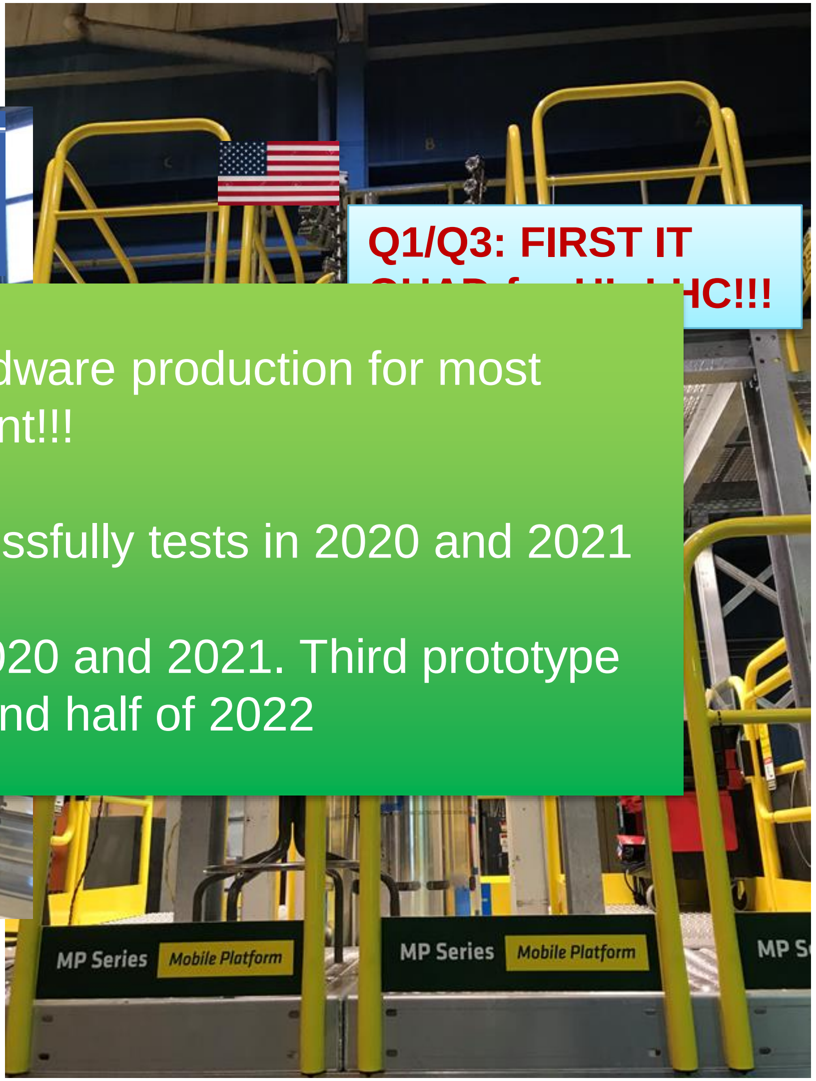
HL-LHC PROJECT

Nb_3Sn quadrupole: Transition from Prototype to Series production





Q1/Q3: FIRST IT
HC!!!

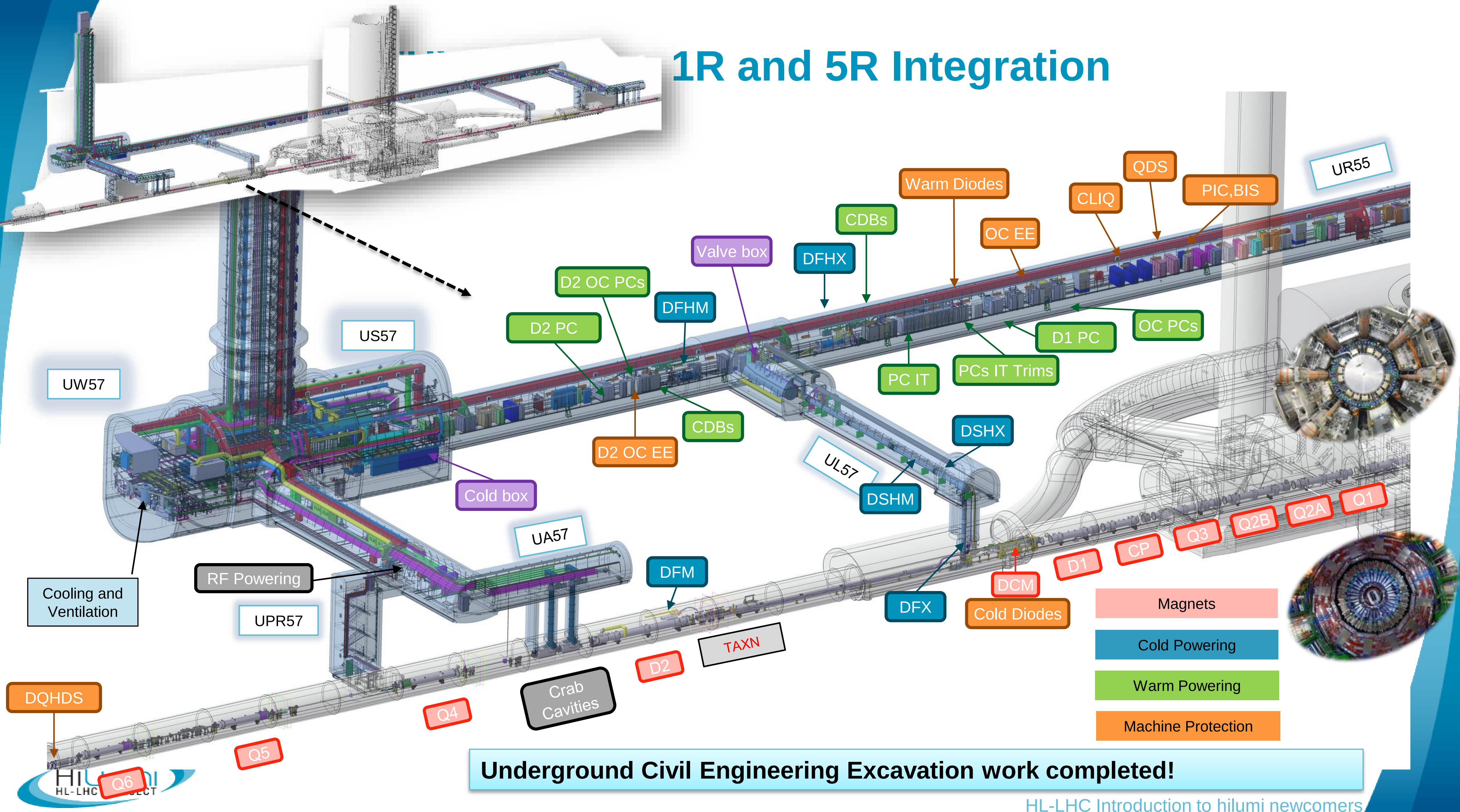
Now entering the phase of hardware production for most equipment!!!

4 US [AUP] magnets passed successfully tests in 2020 and 2021

First CERN prototypes tested in 2020 and 2021. Third prototype being tested in second half of 2022

Q2: IT QUAD prototype built and tested at CERN!!!

1R and 5R Integration



Underground Civil Engineering Excavation work completed!

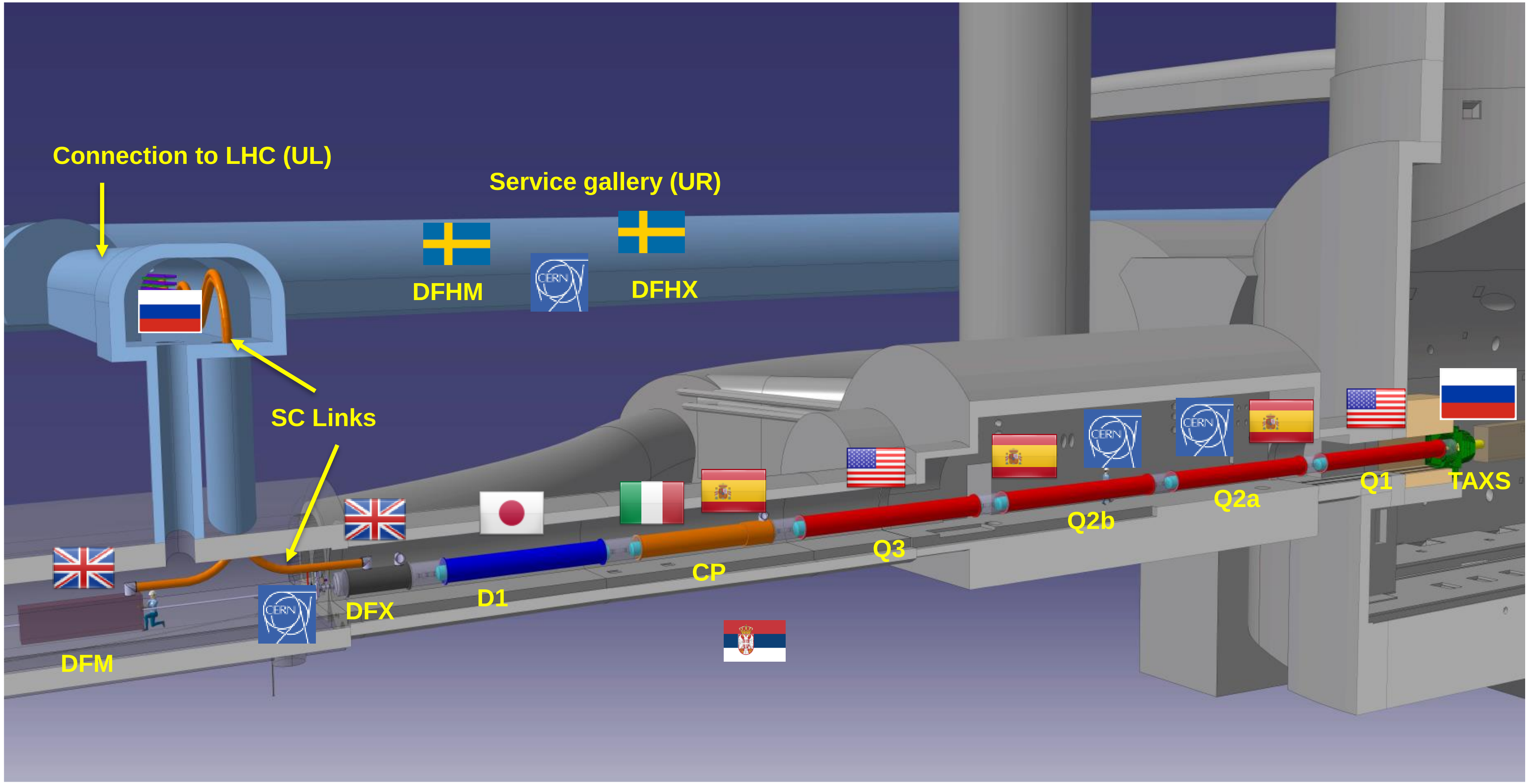
Visit of Council Delegates in September 2021

Underground Civil Engineering work finished in 2021!

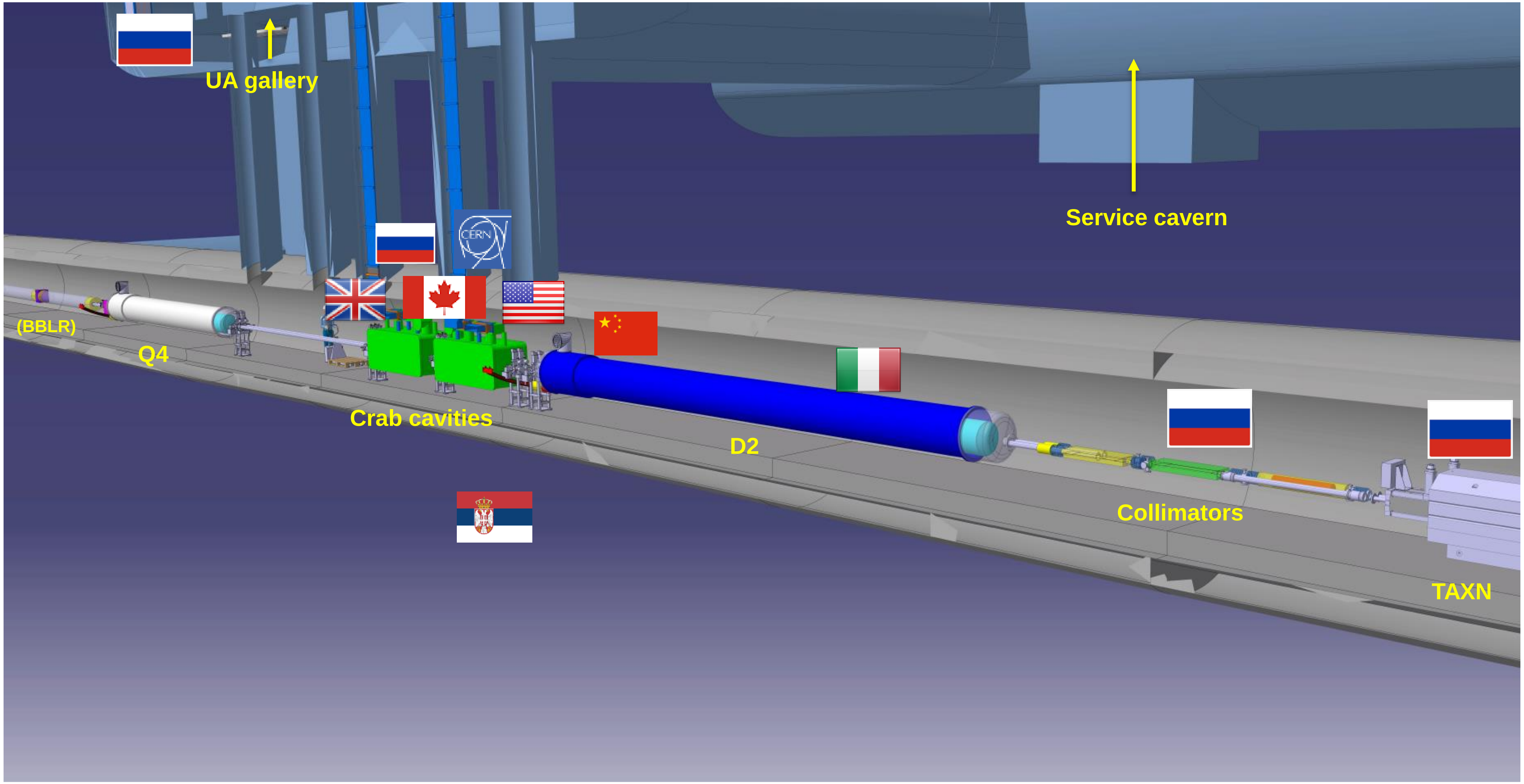
IR1 status April 2022

Surface Civil Engineering work to be finished in 2022!

HL-LHC is a truly International Collaboration



The MS region with in-kind contributions



HL-LHC PROJECT OFFICE

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Safety Coordinator: contractual support

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DSOs

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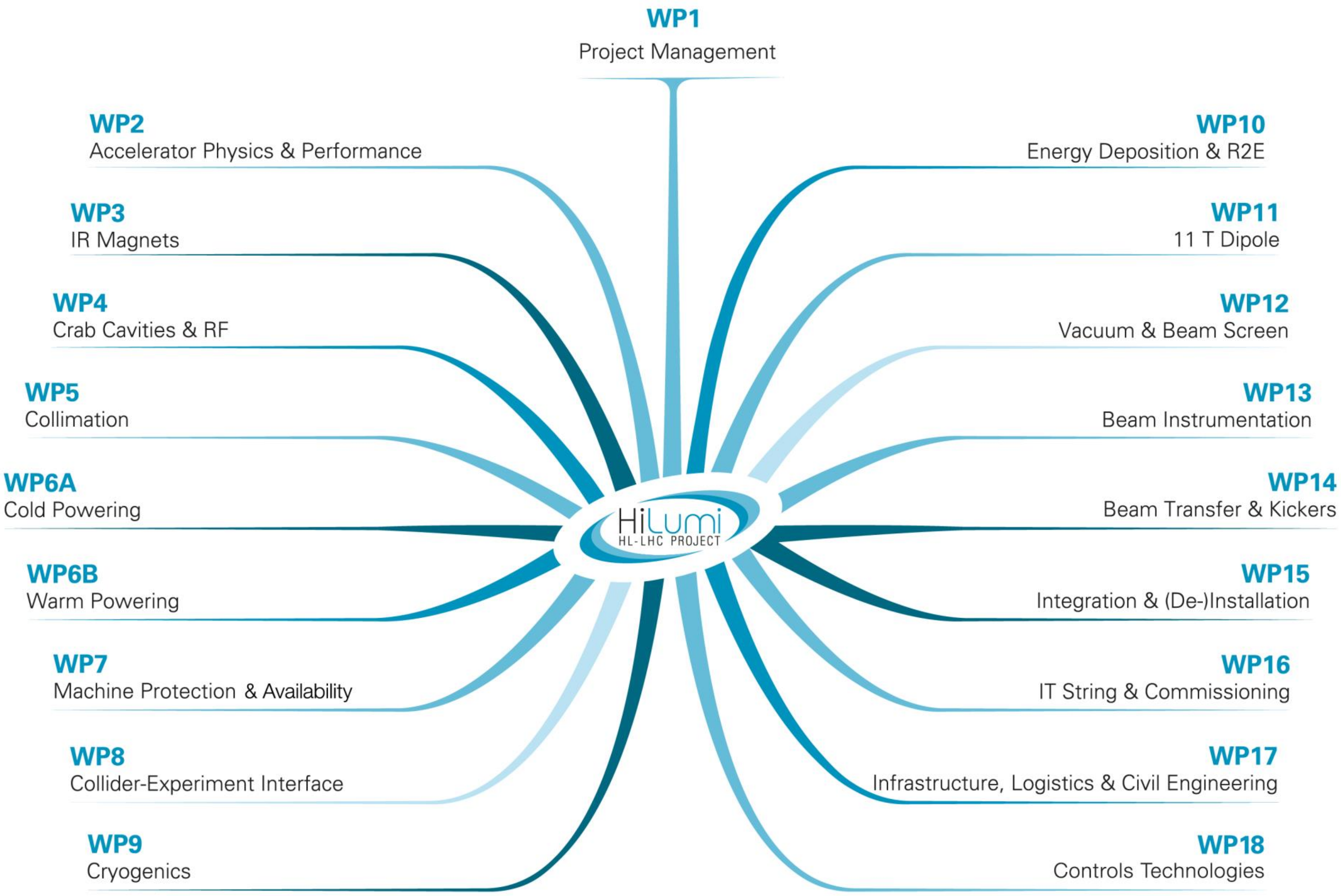
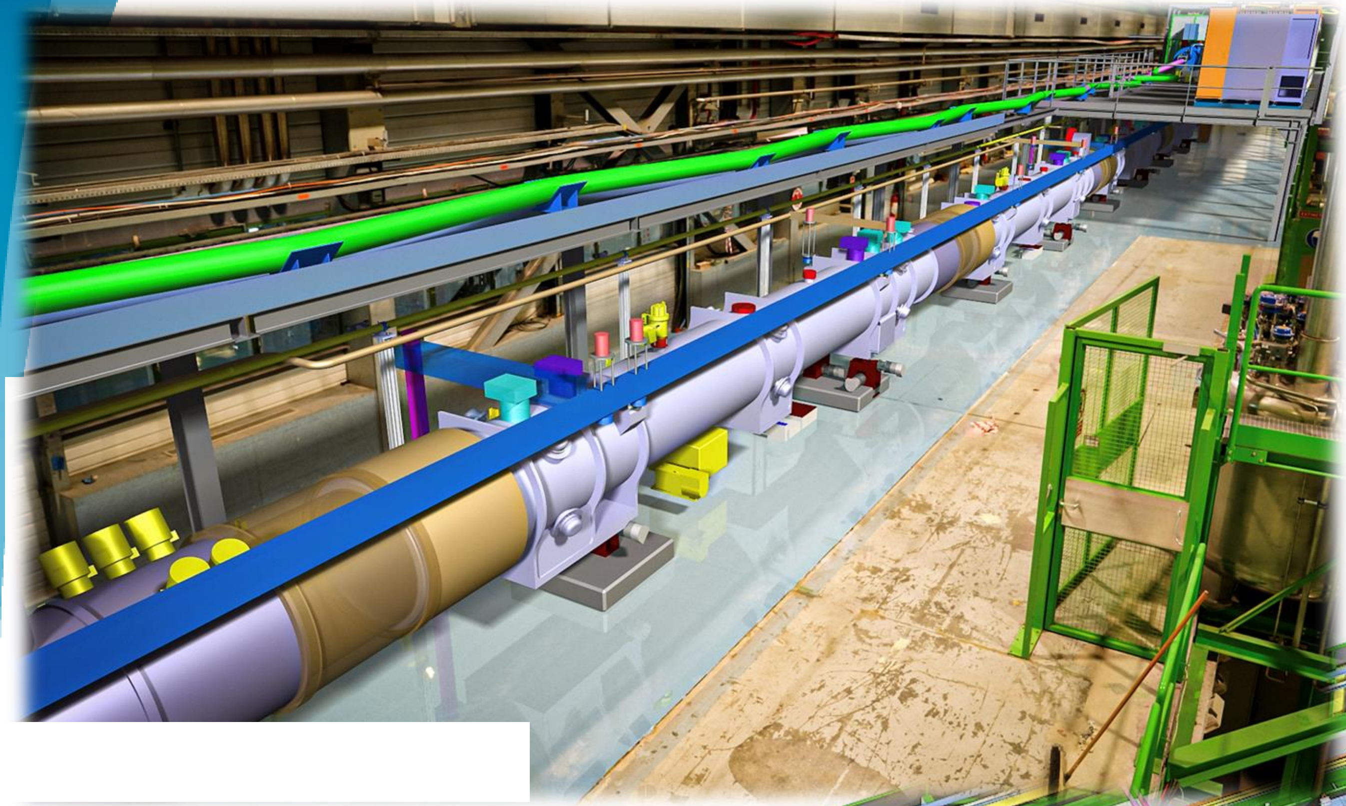
Michele Modena
Gema Aparicio Cantalapiedra
Joao Oliveira
Joao Pedro Pinheiro De Sousa

EN-ACE

Project Work Package Structure remains unchanged:

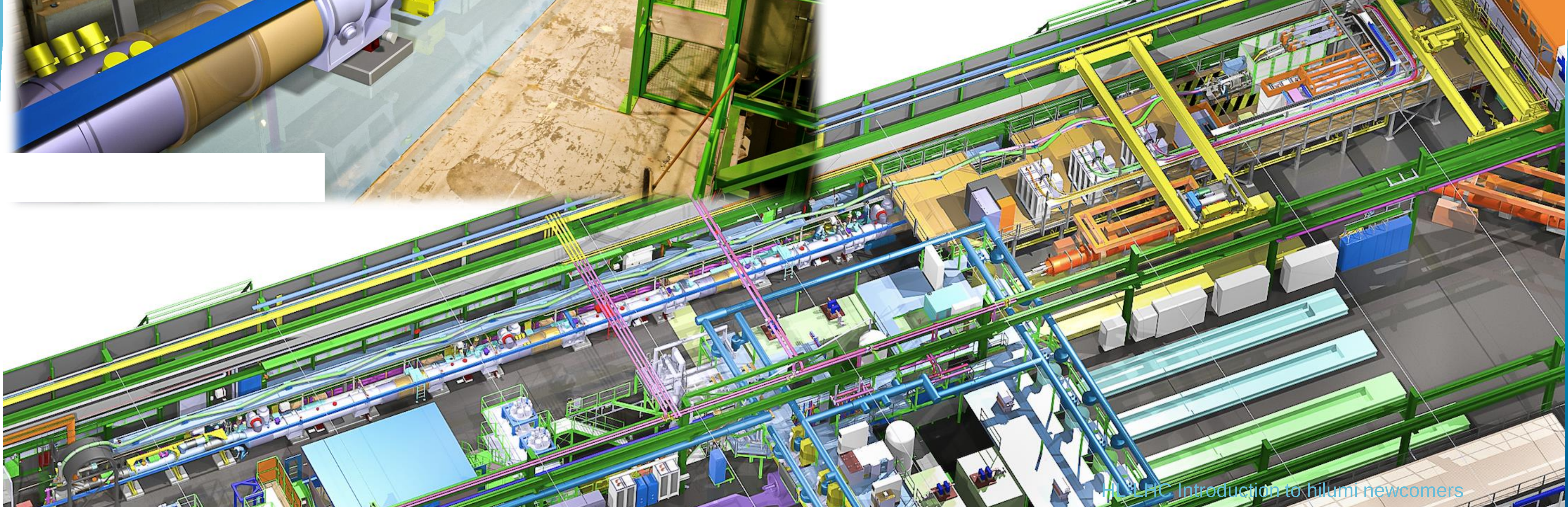


IT String Installation in SM18: Q1 up to D1 inclusive!



Installation started and foreseen until 2023

➔ Operation planned in 2024 and 2025

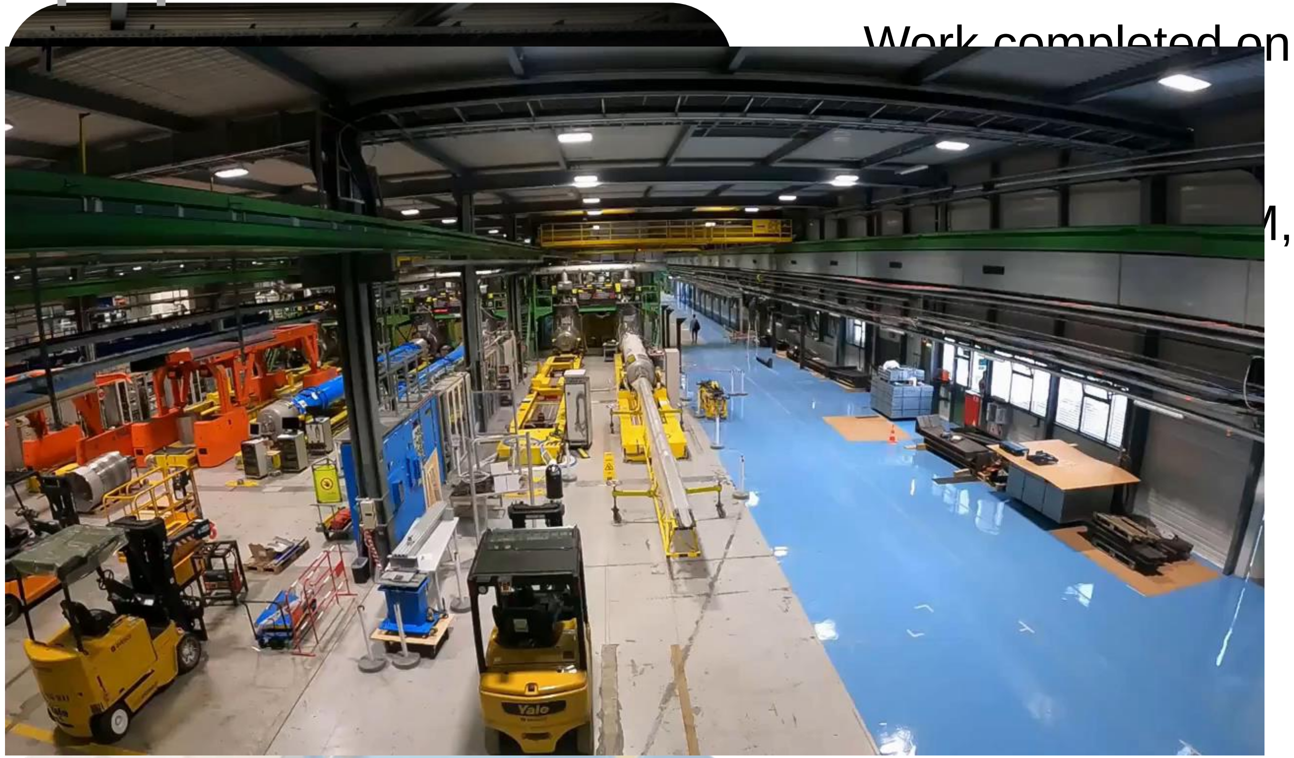


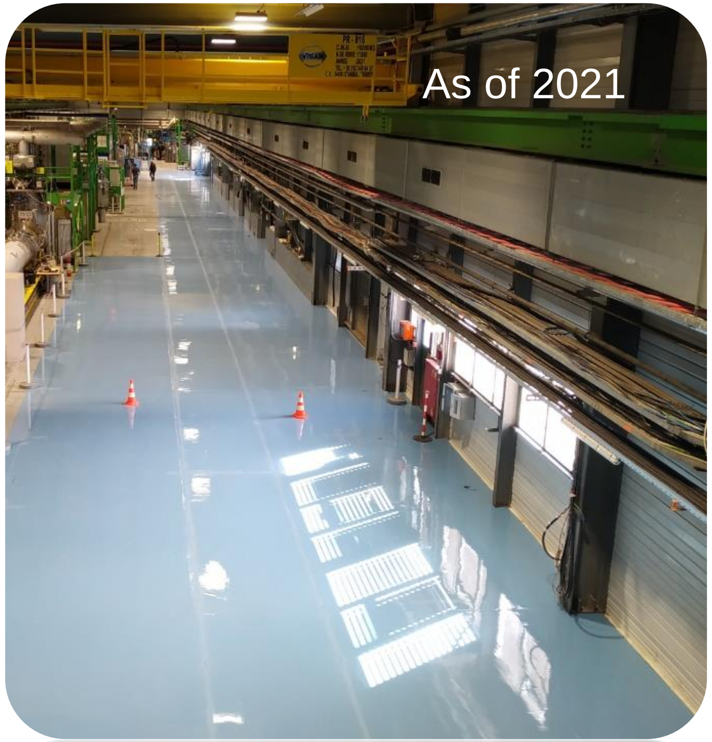
Main achievements since 10th Collaboration Meeting

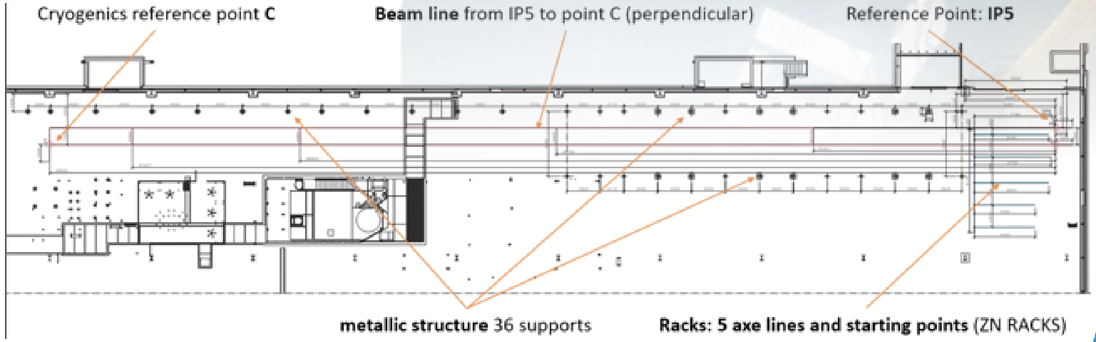
Zone preparation

The zone was **VACATED, CLEANED, PAINTED AND SURVEYED for** the major elements with regards to the machine references: IP5.

Work completed on

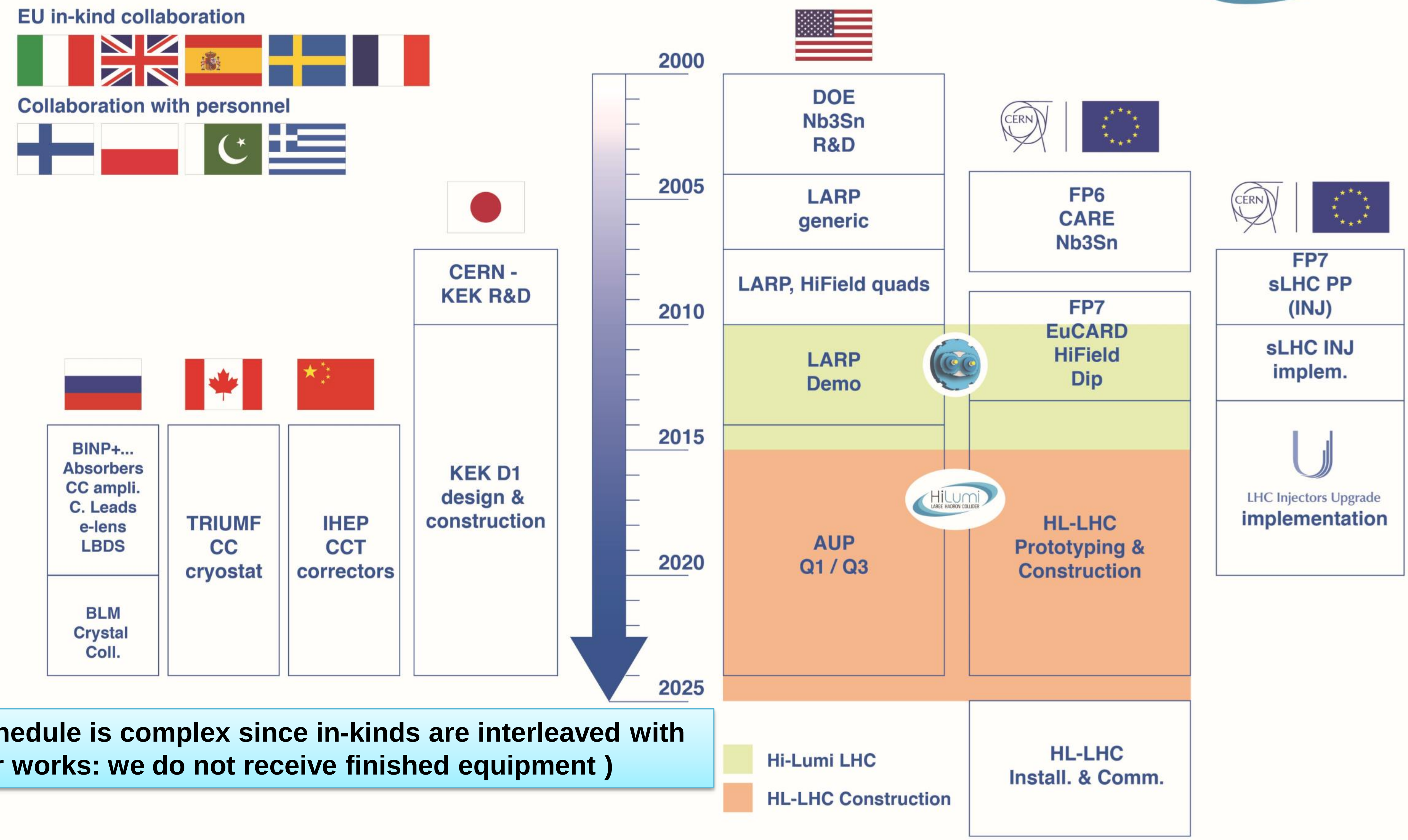






Questions?

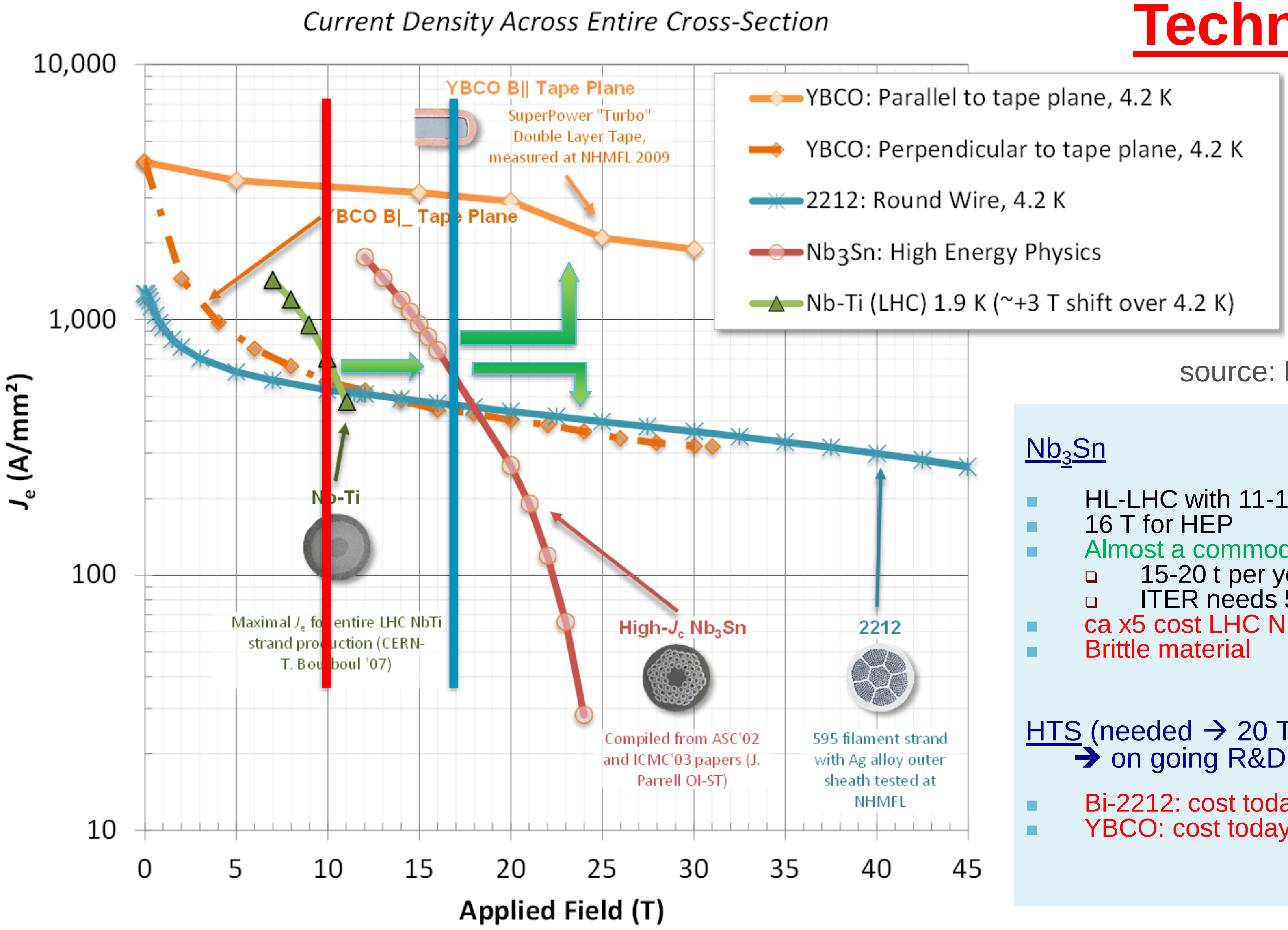
IN-KIND CONTRIBUTIONS



HiLumi: a global project since the start

Schedule is complex since in-kinds are interleaved with our works: we do not receive finished equipment)

SC Magnet Technology



source: L. Rossi

Nb_3Sn

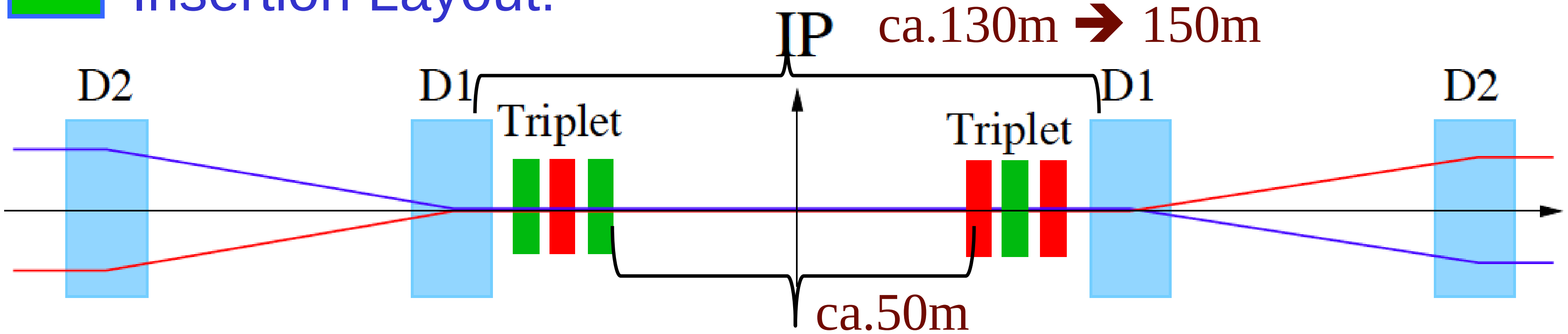
- HL-LHC with 11-12T
- 16 T for HEP
- Almost a commodity!
  - 15-20 t per year for MRI
  - ITER needs 500 t
- ca x5 cost LHC Nb-Ti
- Brittle material

HTS (needed → 20 T)
➔ on going R&D!

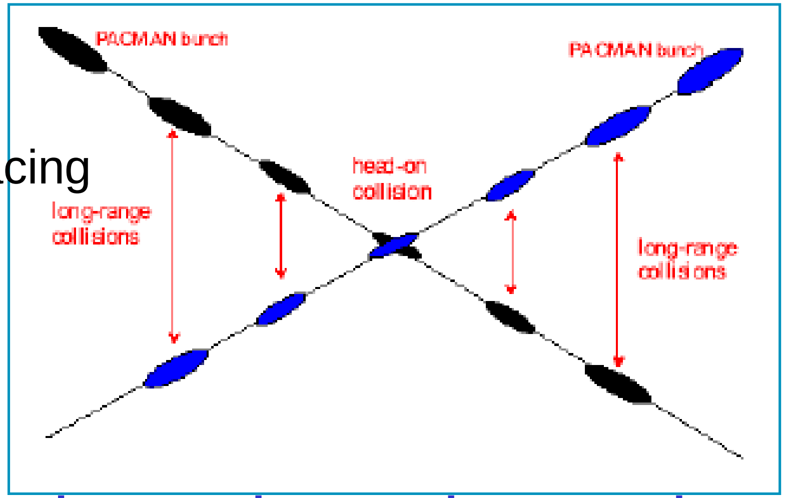
- Bi-2212: cost today 2-5x Nb_3Sn
- YBCO: cost today 10x Nb_3Sn

LHC Challenges: Interaction Region

- Insertion Layout:



- Parasitic bunch encounters:



Operation with ca. 2800 bunches @ 25ns spacing
➔ approximately 30 unwanted collisions 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 magnet apertures next to the experiments!!

➔ at the limit of magnet technology!!!

HL-LHC Upgrade Ingredients: Crab Cavities

Geometric Luminosity Reduction Factor:

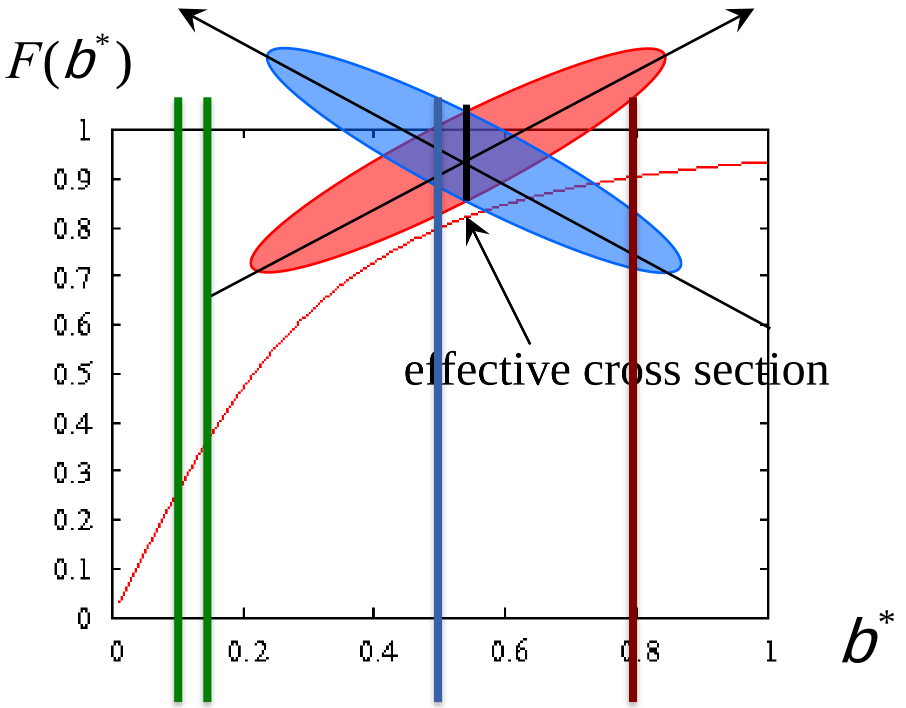
Crab Cavities:

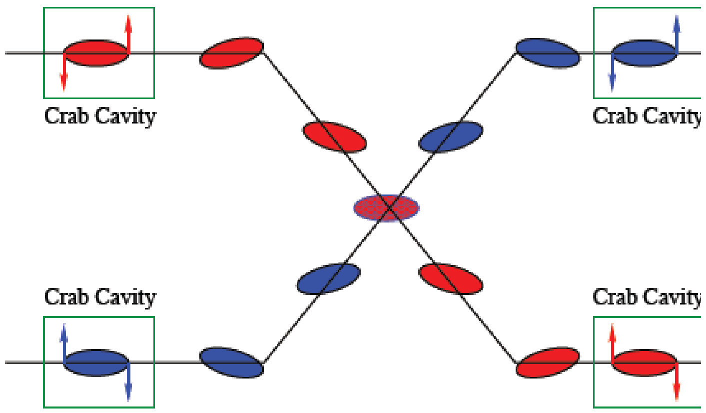
- Reduces the effect of geometrical reduction factor
- Independent for each IP

$$F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

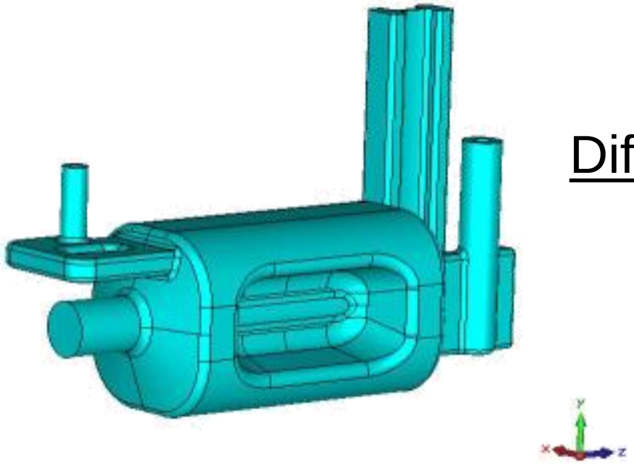
- Noise from cavities to beam Beam size and losses?!?
- Challenging space constraints:

  ➔ requires novel compact cavity design



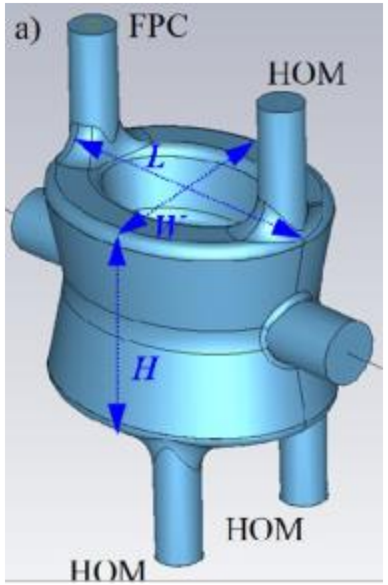


HL-LHC cavity designs



RF Dipole: Waveguide or waveguide-coax couplers

2 Designs with
Different Coupler concepts and
Deflection planes



Double ¼-wave:
Coaxial couplers with
hook-type antenna

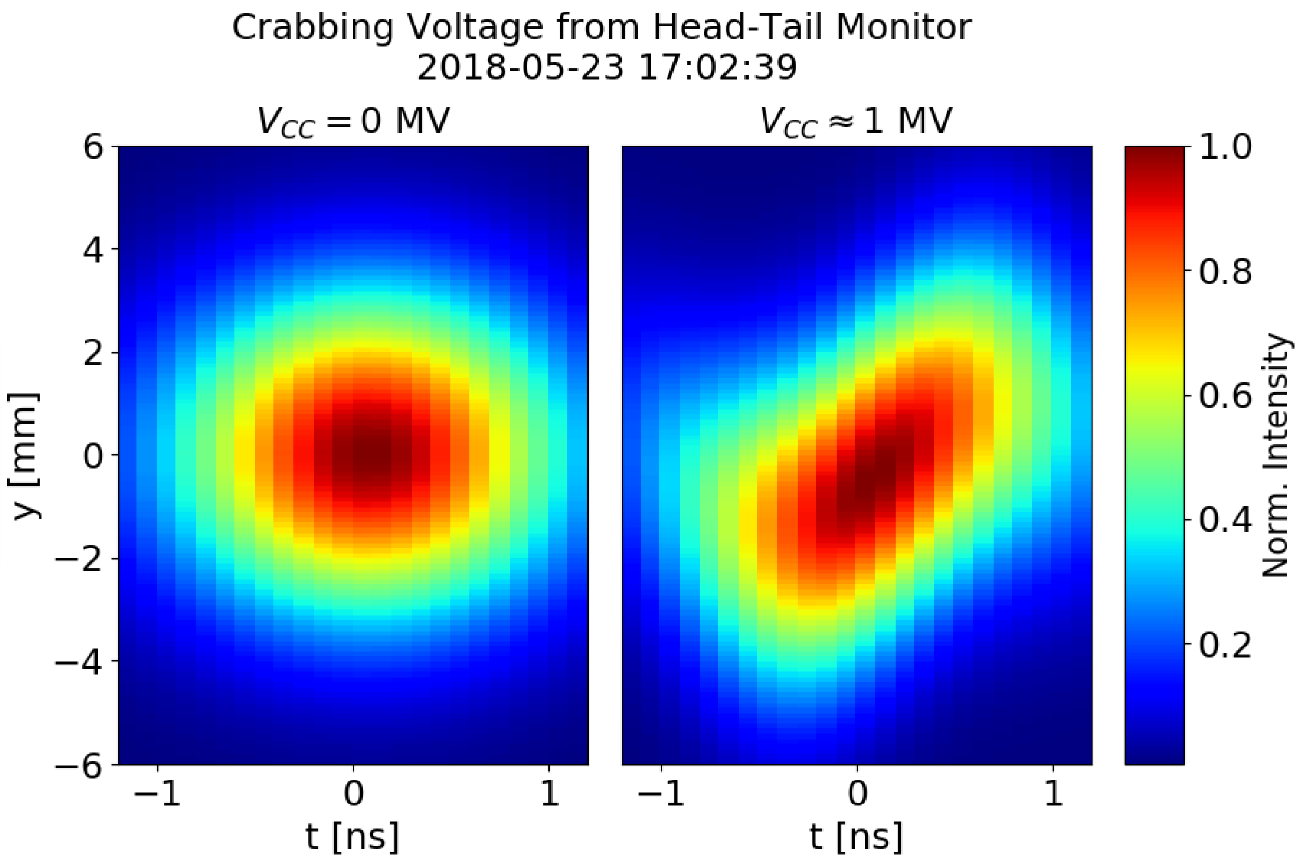
DQW crab-cavity Cryomodule for SPS tests

Present baseline: 4 cavities / IP / side → 16 total

Crab cavity cryo-module for installation in the SPS

First proton crabbing ever!

TEST in SPS ongoing since 2018



Study and R&D has been very useful to obtain this result

Industrial Contracts

By CERN

- Nb3Sn wire for SC Magnets
- Cryomagnets components (coil components, laminations, structure, shells, end covers, vacuum vessels, cold supports, IFS Flanges)
- 11T Collared Coil production
- LS2 Collimators production
- MoGr for LS2 Collimators (TCSPM, TCPPM)
- DQW Jacketed Cavities
- SC Link (MgB2 wire, MgB2 cable production and Flexible Cryostats)
- CLIQ units
- Civil Engineering Construction at P1 & P5
- Tungsten blocks for Beam Screens
- Cold Bores
- Cooling and Ventilation surface contracts
- Cryogenics for IT String (Proximity equipment and Cryolines) and Upgrade of Cryo-plant at P4

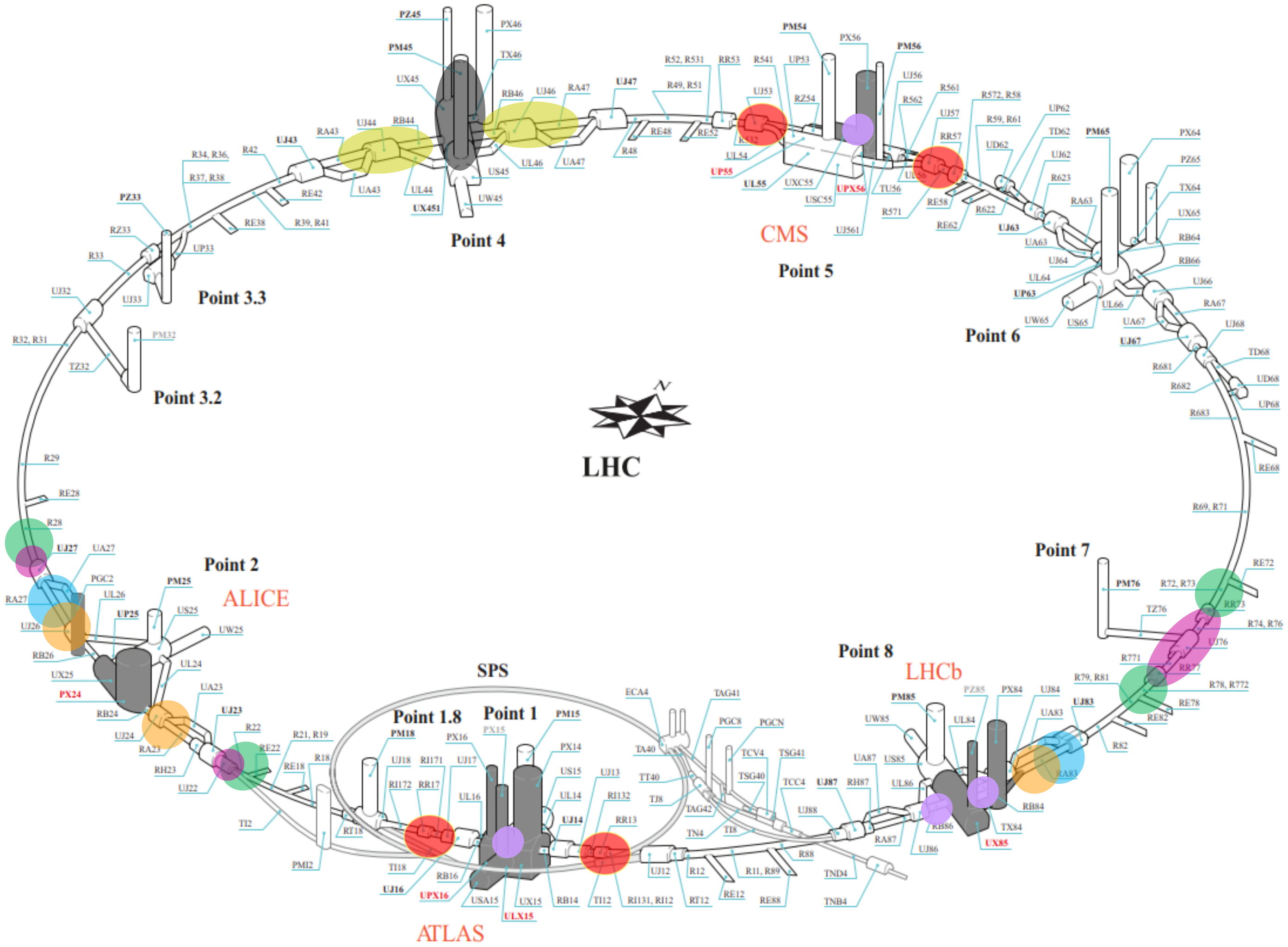
**Contracts already completed are underlined*

By Collaborations

- HO Correctors Production (by INFN-Lasa)
- D1 Production (by KEK)
- D2 Production (by INFN-Genova)
- Nested Correctors MCBXFA/B (by CIEMAT)
- MCBRD – CCT magnets (by IHEP)
- Cryomagnets components (by AUP)
- RFD Jacketed Cavities (by AUP)
- DFX/DFM (by HL-UK)
- DFHX/DFHM (by Uppsala University)
- Components for DQW/RFD Cryomodules (by HL-UK and Canada)

For more details related to **HL-LHC Procurement**, see presentation by H. Garcia Gavela

HL-LHC LS2 activities in the LHC tunnel



WP5 - Collimation

- 8 Target Secondary Collimators TCSPM in LSS7
- ~~*2 Dispersion Suppression Collimators TCLD in LSS7 (11T)*~~ *- postponed*
- 2 Dispersion Suppression Collimators TCLD LSS2 (CC)

WP8 - Collider & Experiment Interface

- TANB both sides LSS8
- ATLAS forward shielding modification and JTT installation
- CMS forward shielding modification and VAX support installation

WP9 - Cryogenics

- Cryogenics upgrade of refrigerator & cold Box

WP11 – 11T DS Dipole

- ~~*11T in A9R7 & A9L7*~~ *- postponed*
- CC in C11R2 & C11L2

WP12 – Beam Vacuum

- In-situ aC-coating Q5 at P8
- ~~*In-situ aC-coating Q6 at P8 and Q5-Q6 at P2*~~ *- postponed*

WP13 – Beam Diagnostics

- ~~*Wide-Band transverse pick-up BPW prototype at LSS4L*~~ *- postponed*
- Beam Gas Curtain BGC prototype at LSS4L
- BSRT (adding halo cleaning) at LSS4L/R

WP14 – Beam Transfer & Kickers

- Injection Dump TDIS at P2L & P8R
- ~~*Cooled MKI at P2*~~ *- postponed*
- Displacement of TCLIA in LSS2R (C4R2)

WP17 - Infrastructure Logistics and Civil Engineering

- Completion of the underground installation at P1 & P5
- UPR connections and general services installation at P1 & P5

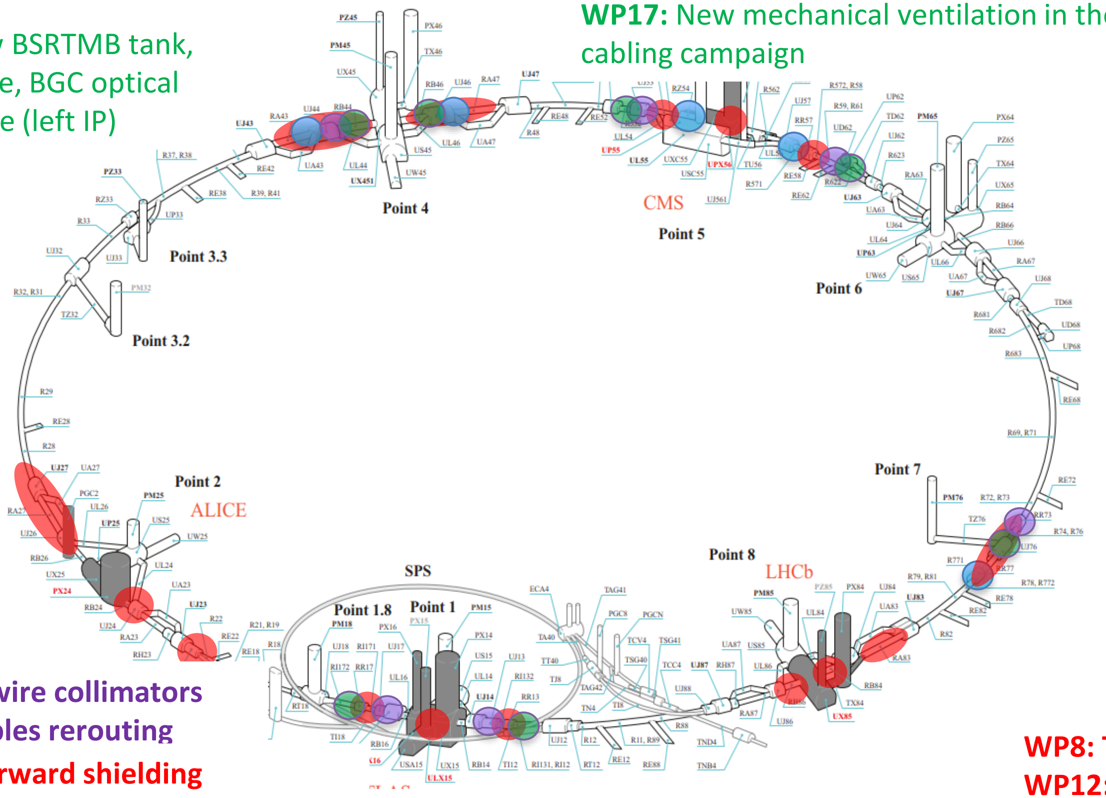
HL-LHC installation equipment in the LHC tunnel

1 EYETS 2016
2 YETS 2017
3 LS2
4 YETS 2021

WP13: BWS
WP13: Fluorescence Measurement Test Chamber Installation (BGC)
WP9: Cryogenics upgrade of refrigerator & Cold Box
WP13: *Wide-Band transverse pick-up BPW (postponed),* **Beam Gas Curtain BGC prototype & BSRT (adding halo cleaning)**

WP13: Installation of a **n**ew BSRTMB tank, new Coronagraph prototype, BGC optical system of the HEL prototype (left IP)

WP5: 2 TCTW wire collimators
WP17: UPR cables rerouting
WP8: CMS forward shielding modification & VAX support installation
WP17: Completion of the underground installation, UPR connections and general services installation campaign services installation
WP13: Remove of BRANA and replace by the new BRAND prototype (left IP)
WP17: New mechanical ventilation in the UA/UPRs and in the tunnel area new cabling campaign



WP5: 2 Dispersion Suppression Collimators TCLD
WP11: CC in C11R2 & C11L2
WP12: *In-situ aC-coating Q5-Q6 (postponed)*
WP14: Injection Dump TDIS, *Cooled MKI (postponed)* **& Displacement of TCLIA**

WP5: 1 TCSPM secondary proto collimator & 2 TCPC crystal collimators
WP5: Replace 1 TCPC crystal collimator
WP5: 8 Target Secondary Collimators TCSPM & *2 Dispersion Suppression Collimators TCLD (postponed)*
WP11: *11T in C9R7 & C9L7 (postponed)*
WP5: 2 TCPC crystal collimators

WP5: 2 TCTW wire collimators
WP17: UPR cables rerouting
WP8: ATLAS forward shielding modification and JTT installation
WP17: Completion of the underground installation, UPR connections and general services installation campaign

WP13: Remove of BRANA and replace by the new BRAND prototype (right IP)
WP17: New mechanical ventilation in the UA/UPRs and in the tunnel area new cabling

WP8: TANB both sides LSS8
WP12: In-situ aC-coating Q5-*Q6 (postponed)*
WP14: Injection Dump TDIS

An extra boost from the injectors

The LHC performance fully relies on the p

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A **new production scheme** – the **“BCMS”** - was put in place in the PS

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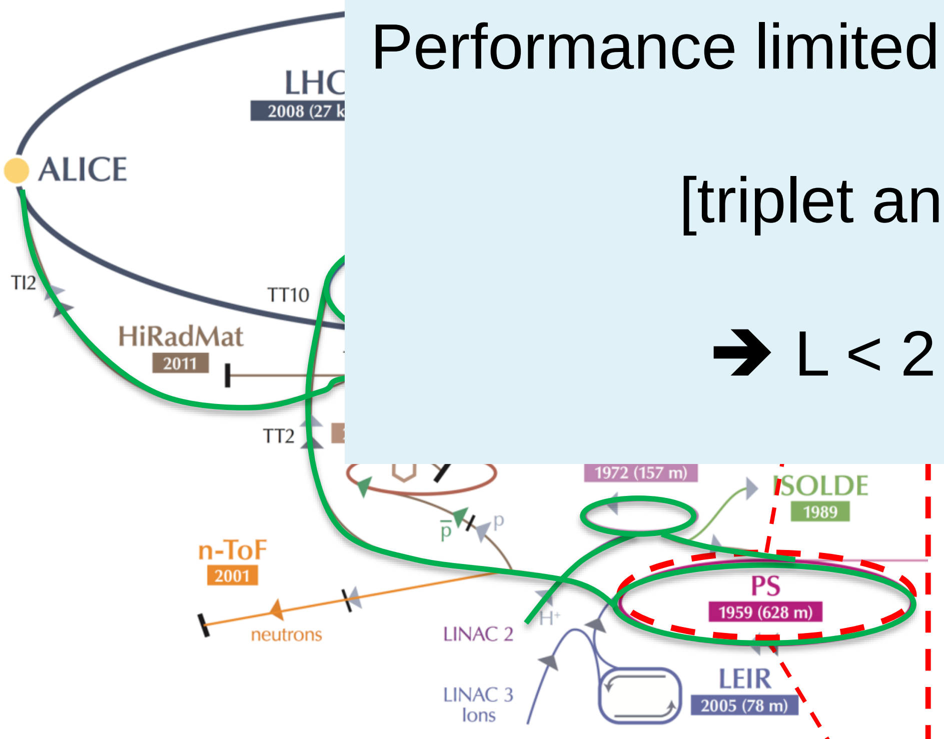
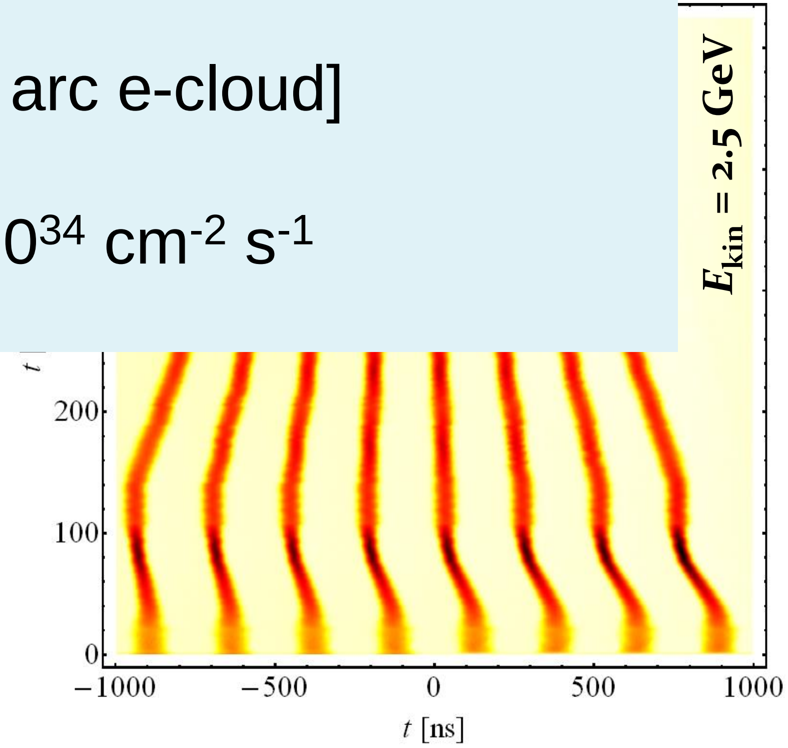
➔ Higher than nominal beam brightness!

Performance limited by LHC cooling power!!!

[triplet and arc e-cloud]

➔ L < 2 10^{34} cm^{-2} s^{-1}

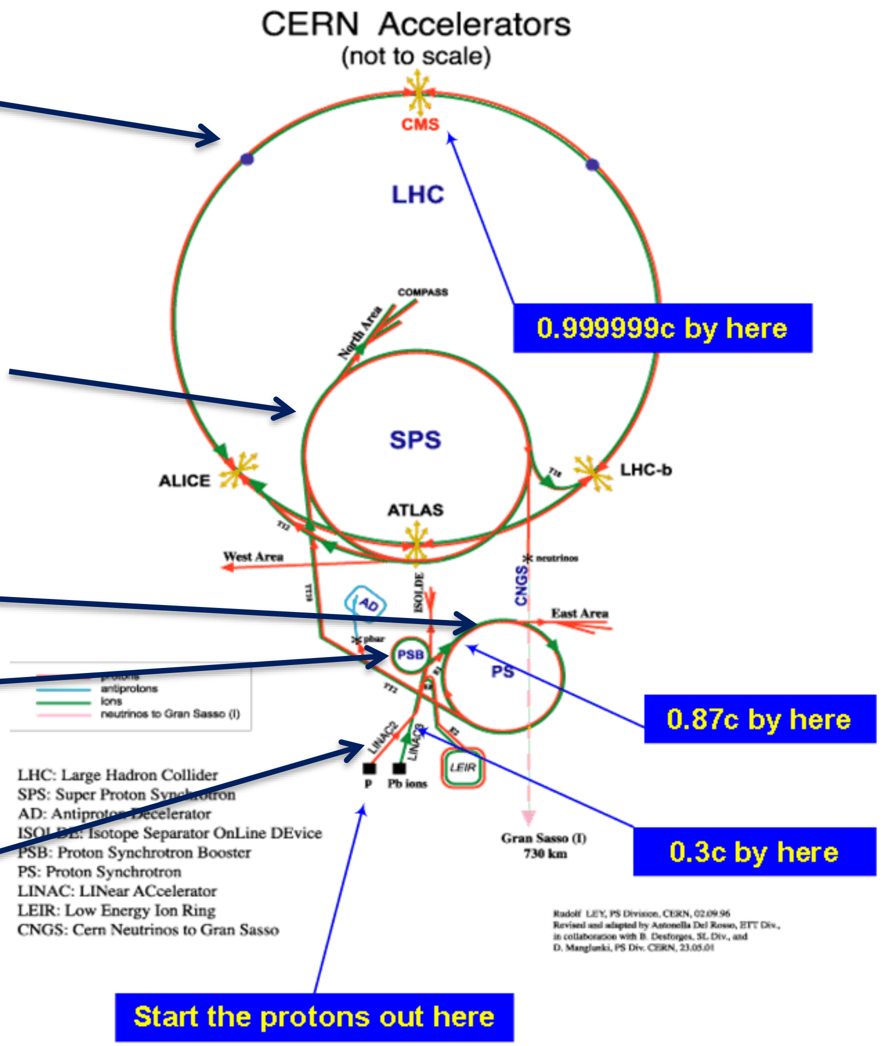




➔ L > 1.75 10^{34} $cm^{-2}s^{-1}$

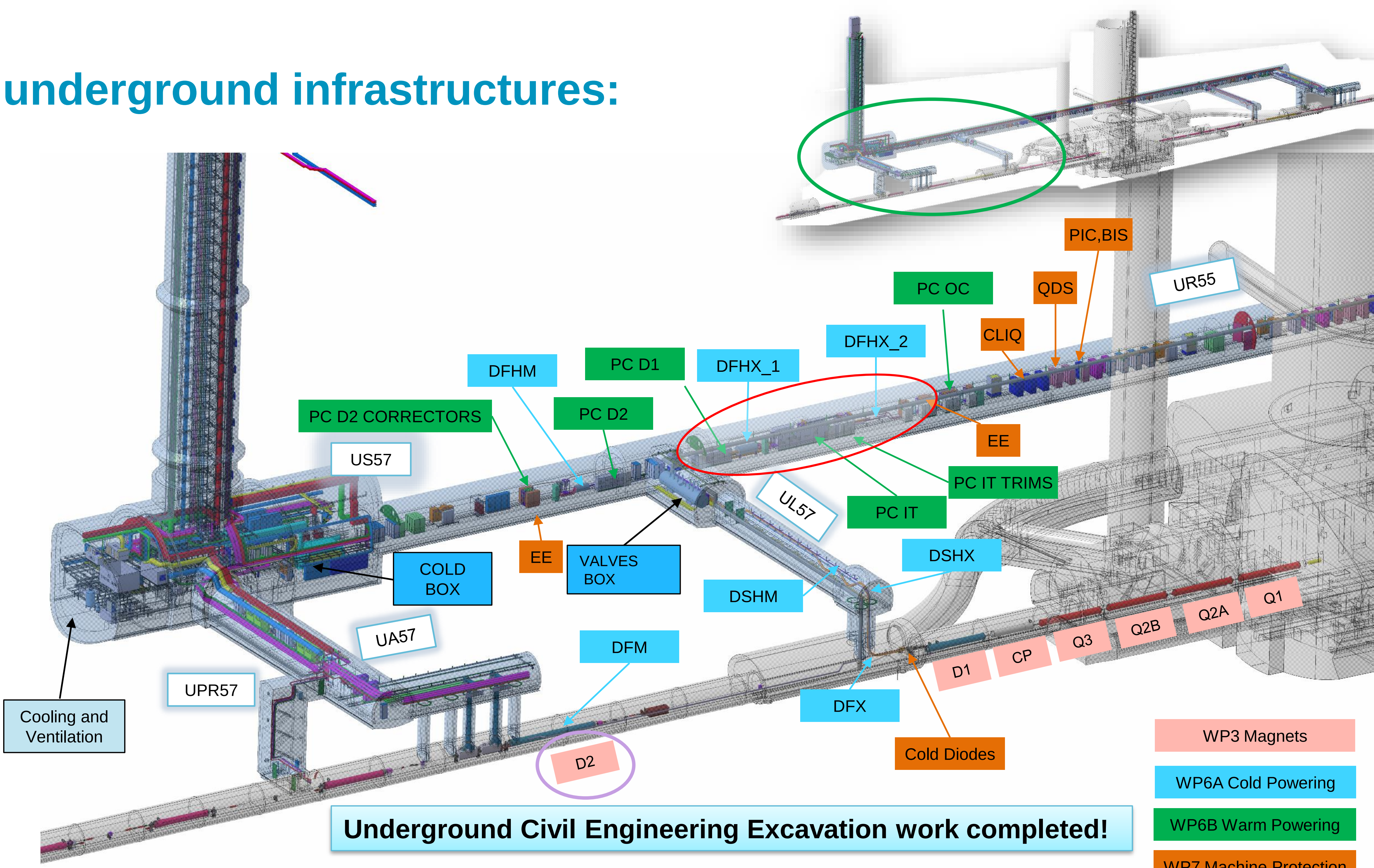
CERN proton accelerator chain: The LHC is NOT a Standalone machine

- LHC : 2x(0.45 – 7) TeV
- SPS : 26 – 450 GeV
- PS : 1.4 - 26 GeV
- PSB : 0.05 -1.4 GeV
- Linac: 0-50 MeV



LHC Injector Upgrade Project completed in LS2 ➔ recommissioning injectors now!

New underground infrastructures:



Underground Civil Engineering Excavation work completed!