LHC and HL-LHC

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Introduction: LHC Performance Goals

- Collis

  p col

A proton beam energy of 7TeV within the existing LEP tunnel with a circumference of 27km and an arc length of 22km
➔
Requires a peak magnet field in the dipoles of about 8.3Tesla!!!
[ca. 300000 times the earth magnetic field]

- 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}

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

  300fb^{-1} with 1barn = 10^{-28}m^{2} and fempto = 10^{-15}

  de
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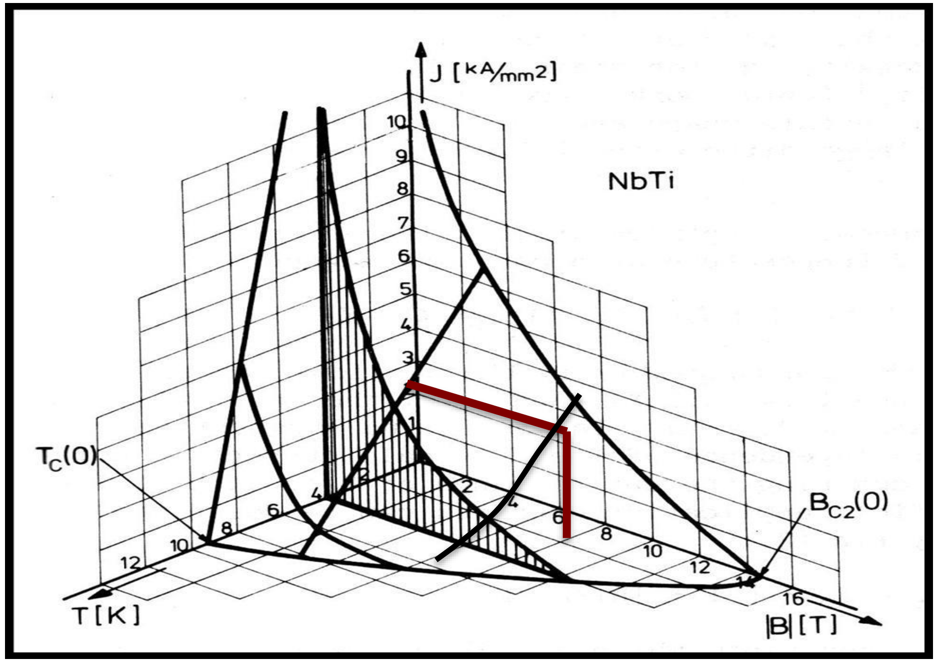
World hadronic luminosity production prior to the LHC: ca. 11fb^{-1}

Introduction: Magnet Technology

- LHC Dipole Magnets: 8.3T, with 11850A ➔ not possible with Cu
  ➔ superconductor, but with high ambient magnetic field > 8 T @ coil

Critical Surface for NbTi



➔ 1.9 K cooling with superfluid He (thermal conductivity)

➔ current density of 2.75 kA / mm^2

At the limit of NbTi technology (HERA & Tevatron ca. 5 T @ 2kA/mm^2)!!

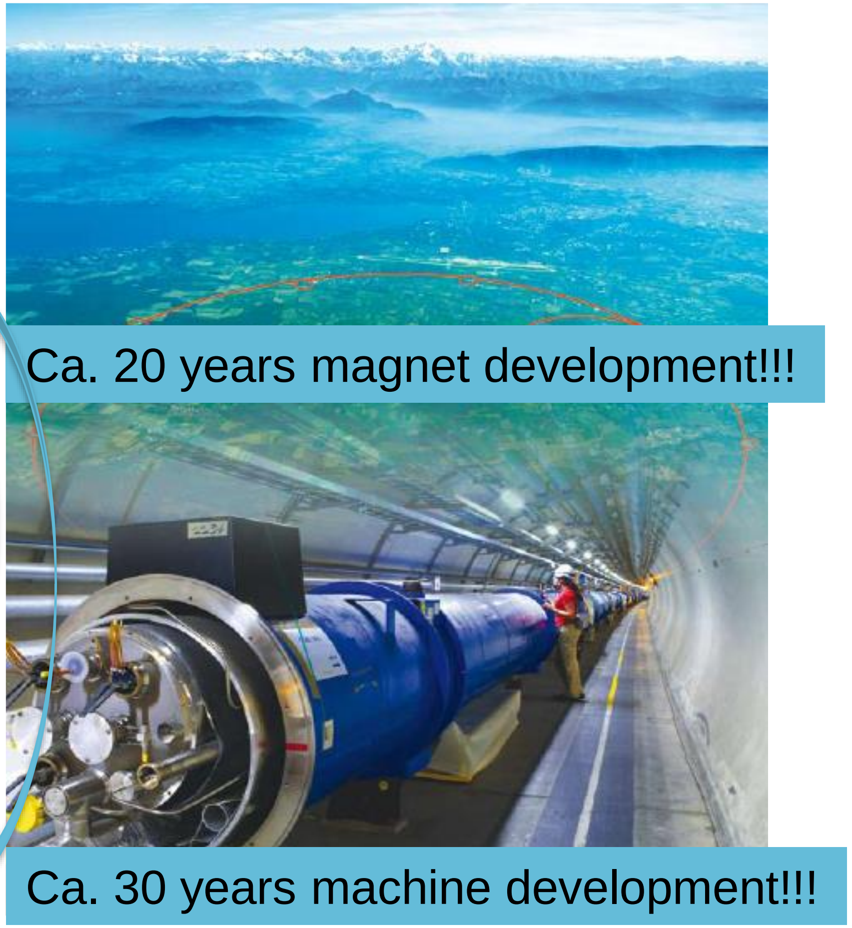
LHC (Large Hadron Collider)

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

2010-2037: Physics exploitation

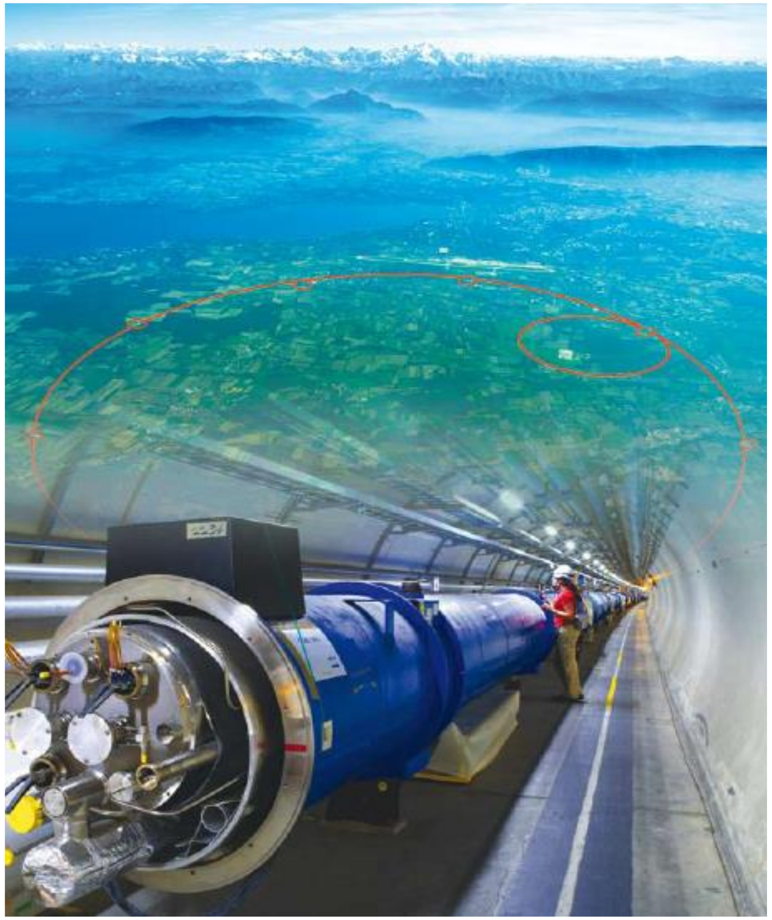


➔ Significant Time scale extending well beyond that of a physicist career!!!

LHC in the Geneva Basin and its Experiments

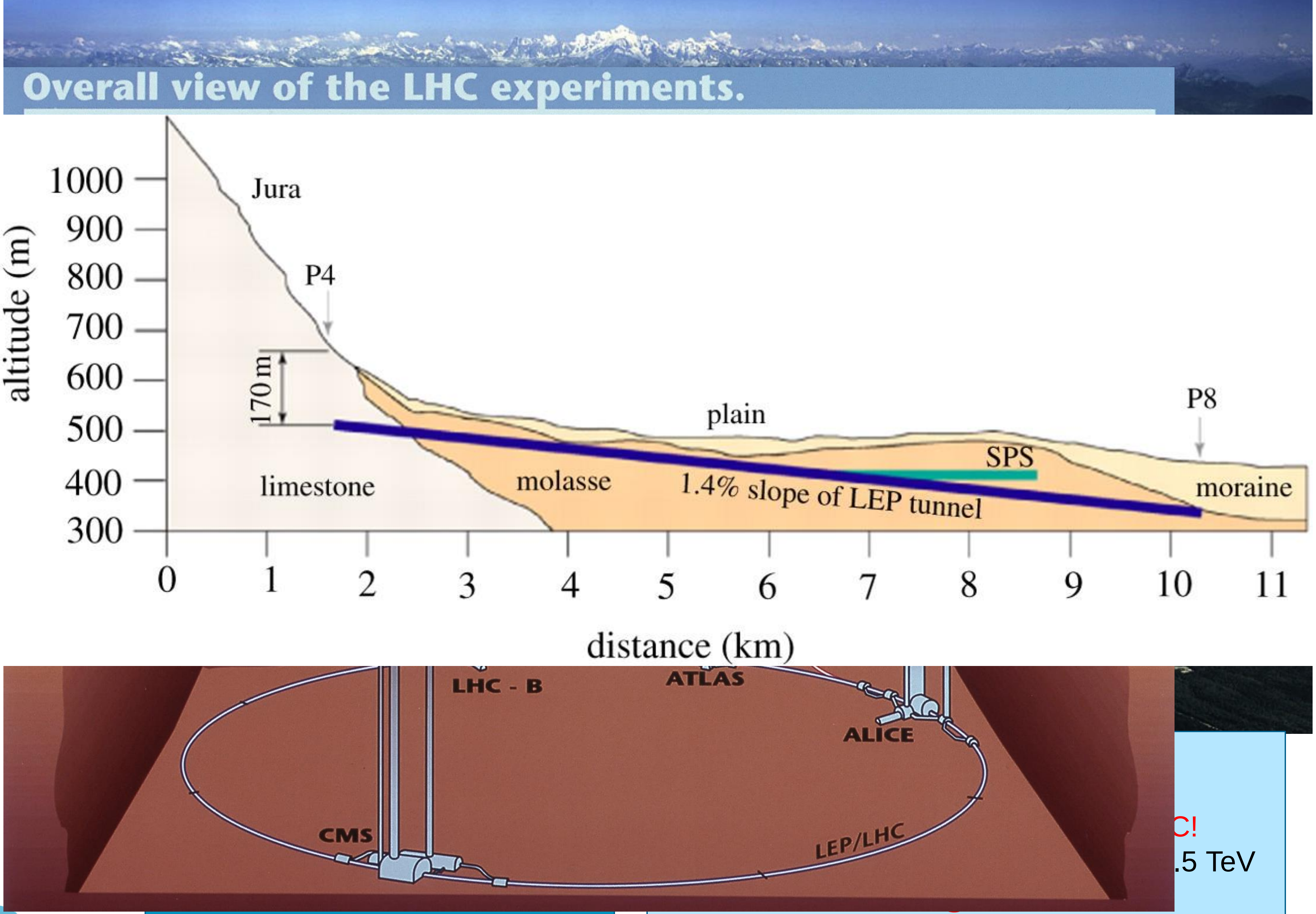
LHC (Large Hadron Collider): Magnet Technology

1983 1991 2000 2010



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

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

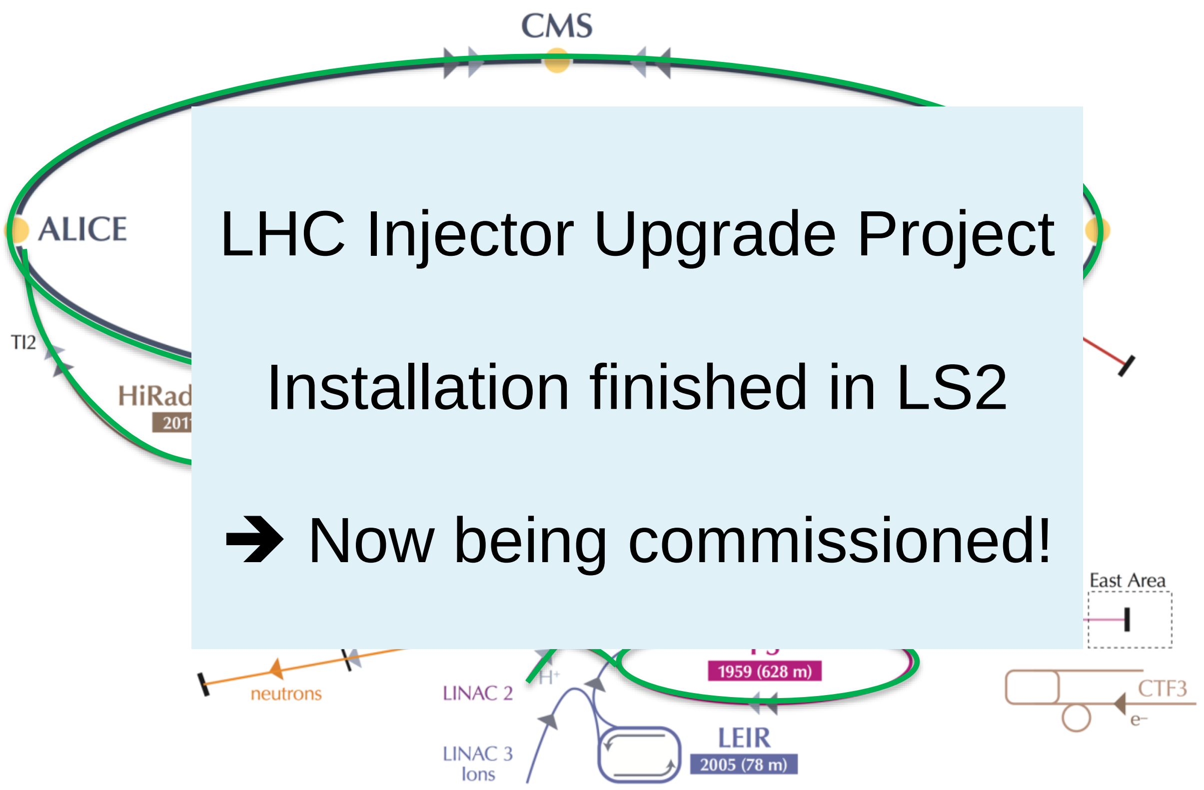

Overall view of the LHC experiments.
altitude (m)
1000
900
800
700
600
500
400
300
Jura
P4
170 m
plain
P8
SPS
limestone
molasse
1.4% slope of LEP tunnel
moraine
0 1 2 3 4 5 6 7 8 9 10 11
distance (km)
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

C!
.5 TeV

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^-

Energy management challenges: Example LHC

Energy stored in the LHC magnet system [8.3T]: ~10 GJoule

Worry about beam losses:

Failure Scenarios ➔ Local beam Impact

➔ Equipment damage

Lifetime & Loss Spikes ➔ Distributed losses

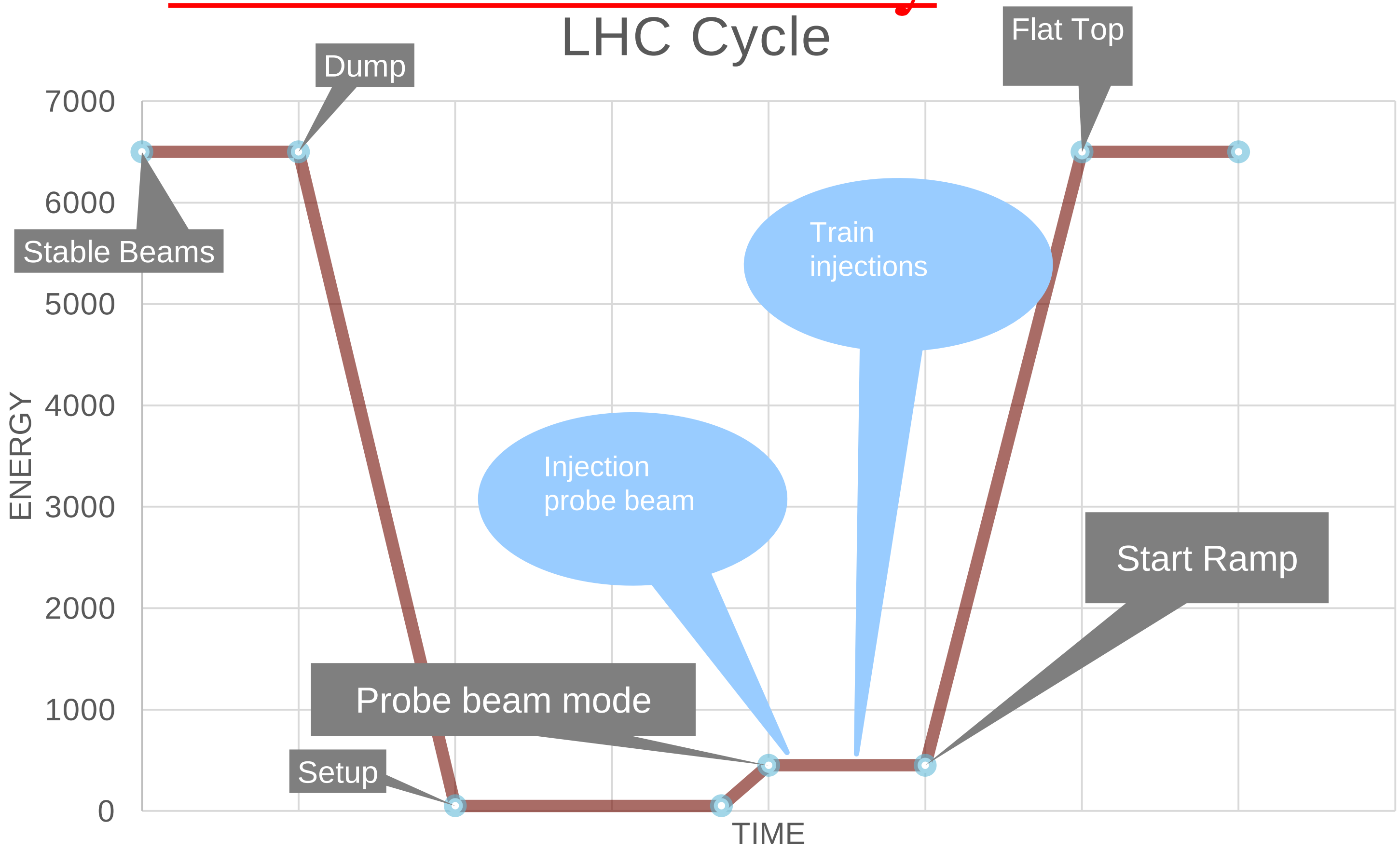
➔ Magnet Quench & QPS

➔ Machine efficiency

e.g. Cryo Sectors: 95% availability requires 99% with 8 sectors

8 Sectors ➔ [12 Sectors ➔ 20 Sectors]

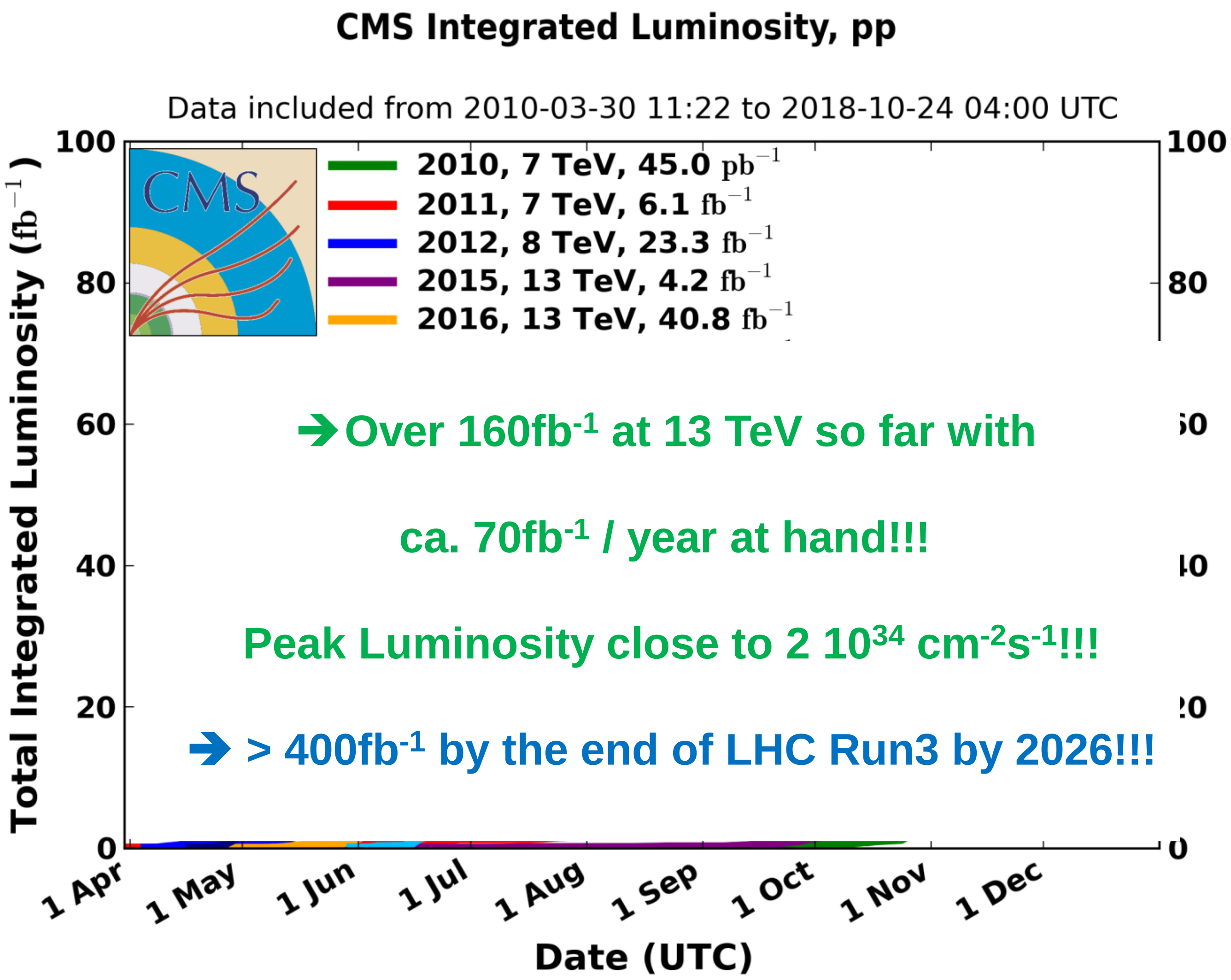
Machine Efficiency



This becomes more challenging with increased Collider size and Requires even more powerful injector complex!!!!

➔ ca. 50% in LHC operation including faults at best conditions!

LHC (Large Hadron Collider): Performance



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

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

Peak Luminosity close to 2 10^{34} cm^{-2}s^{-1}!!!

➔ > 400fb^{-1} by the end of LHC Run3 by 2026!!!

Higgs Discovery in July 2012 and 2013 Nobel Price for the Brout – Englert – Higgs mechanism

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But many questions remain and the search continues!!!

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

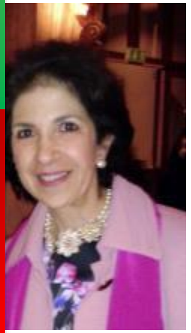
➔Need for more Data and Statistics!!
Doubling the Statistics requires 4 x more data!!!

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

Implies overcoming several limitations in the existing LHC!!!

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

➔ Need for an Upgrade!



Goal of High Luminosity LHC (HL-LHC):

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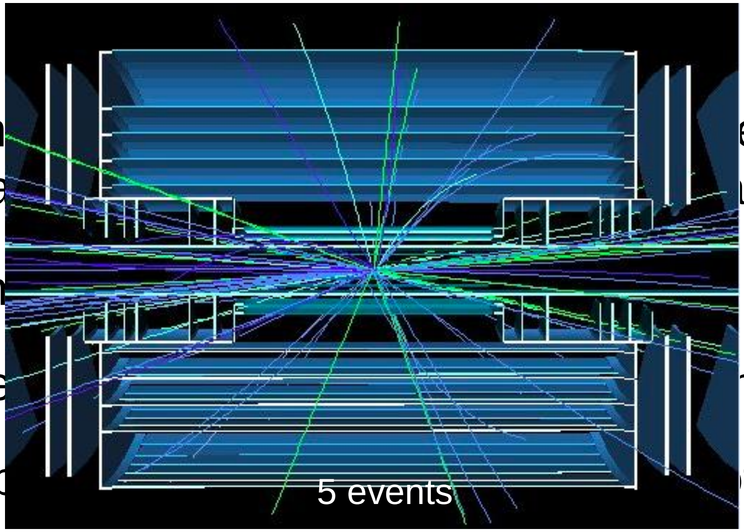

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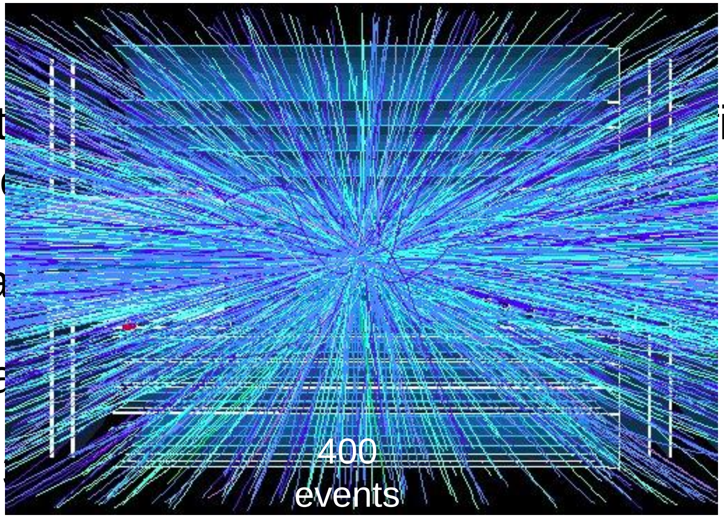

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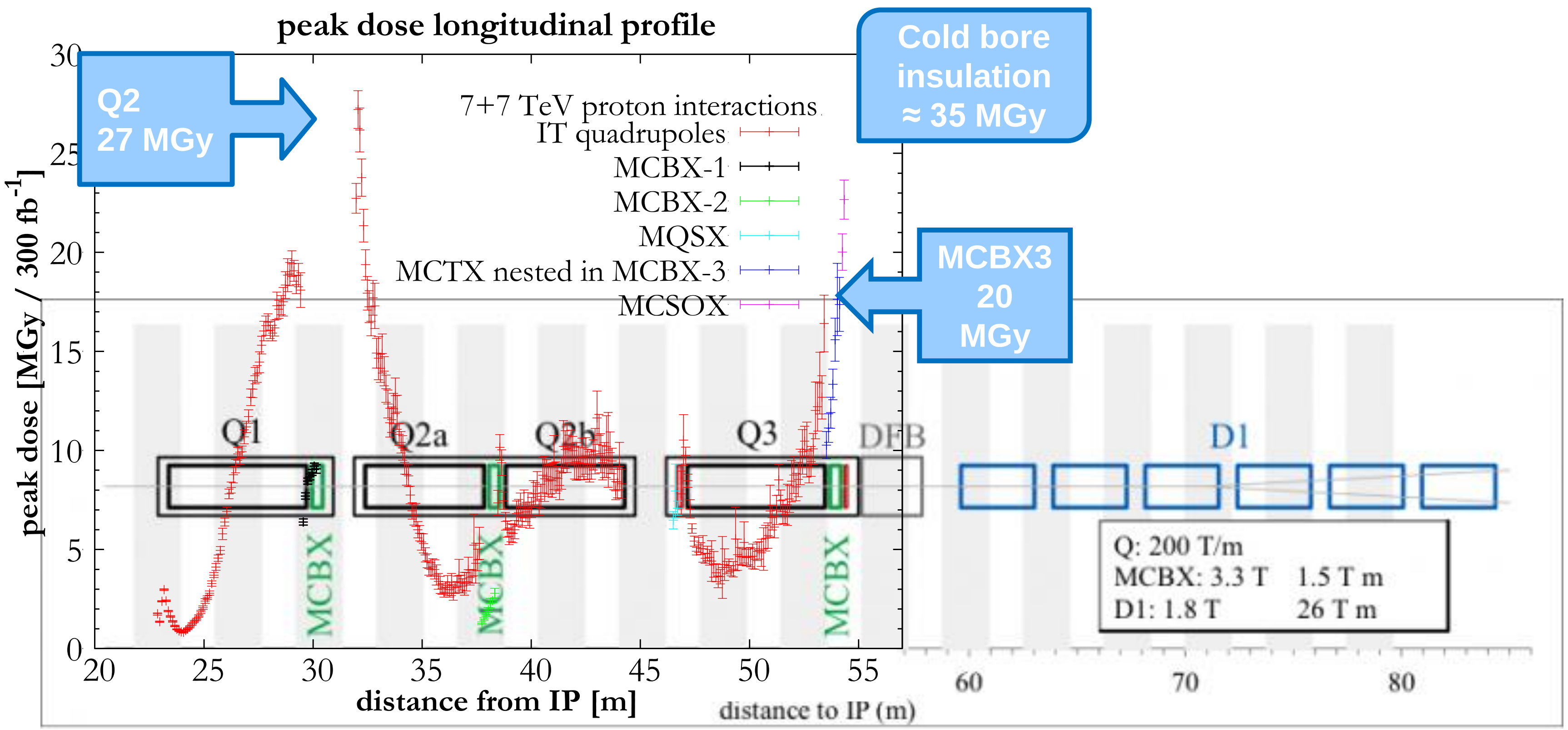
targets:

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

➔High machine efficiency and reliability are key upgrade ingredients!

LHC: Performance Limitation



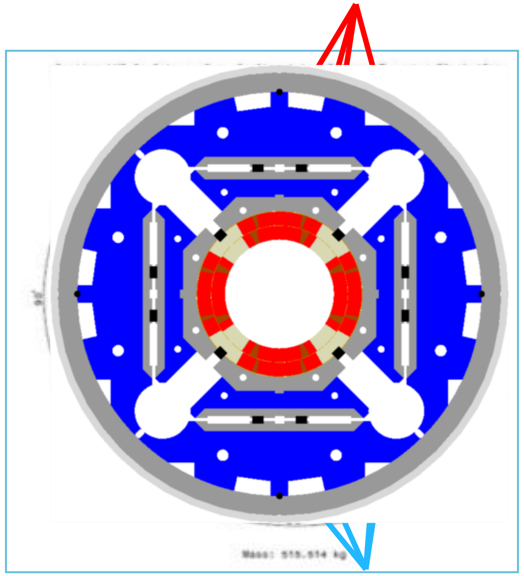
HL-LHC technical bottleneck: Radiation damage to triplet magnets

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

  8T peak field at coils ➔ 12T field at coils!!!

US-LARP MQXF magnet design Based on Nb_3Sn technology

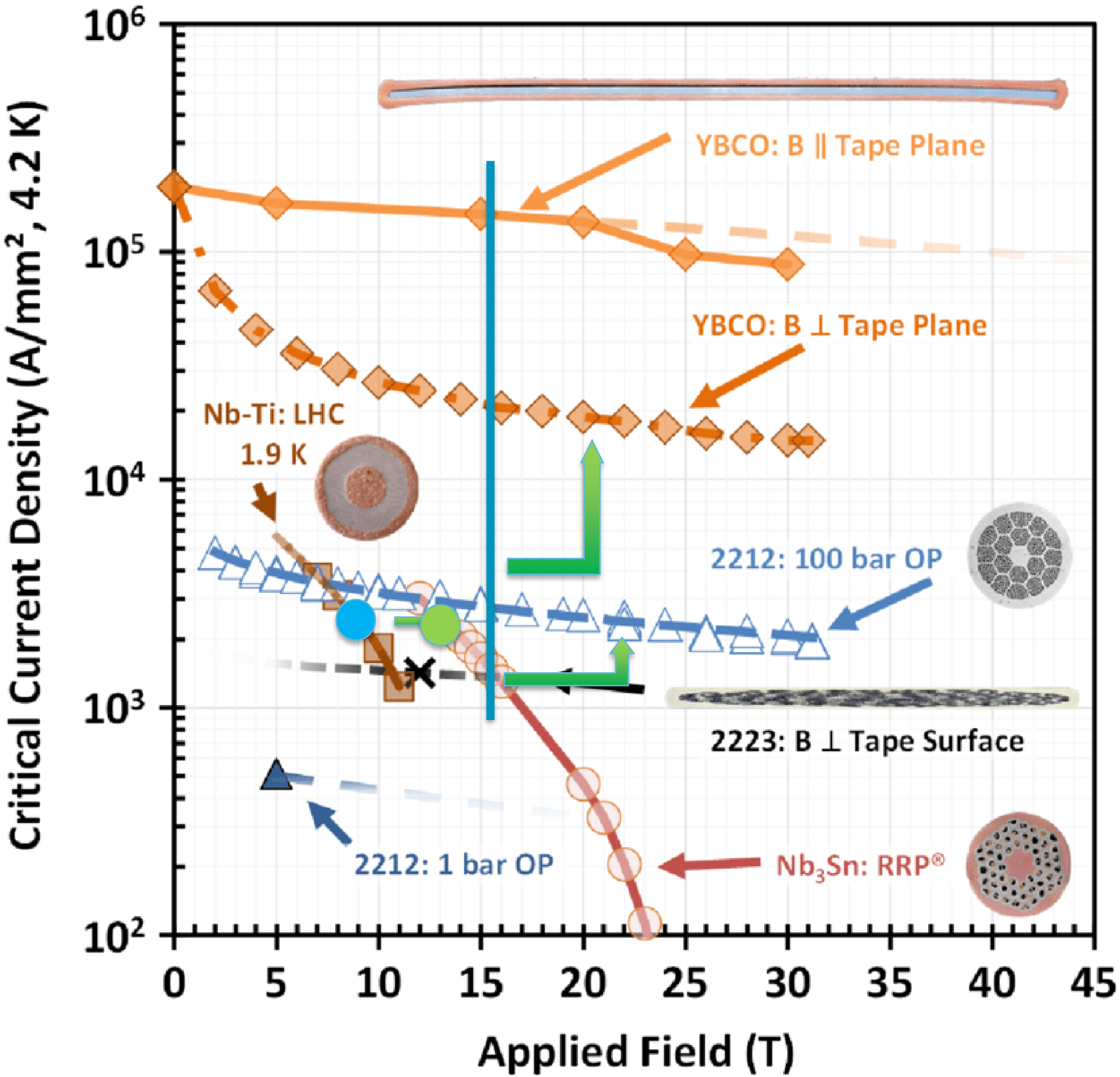


➔ Incompatible with Nb-Ti
➔ Nb_3Sn & Longer magnets

SC Magnet Technology

More SC for the same filed

→ Cost!



source:
D. C. Larbalestier @ Researchgate

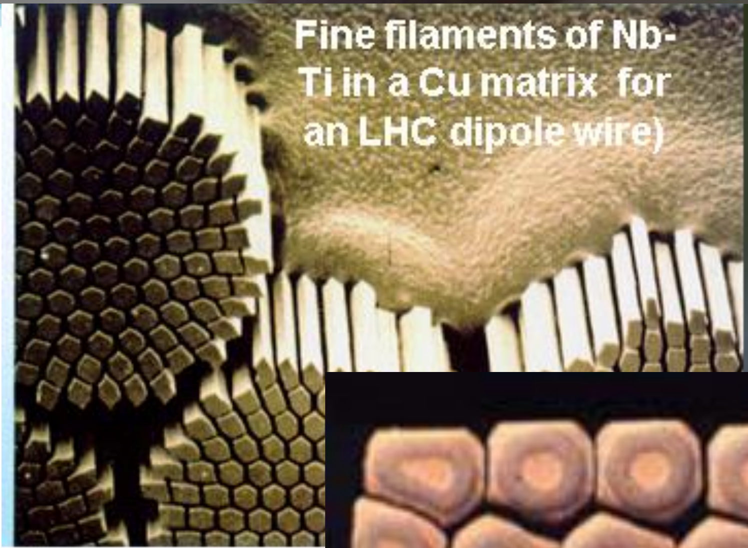
Nb_3Sn

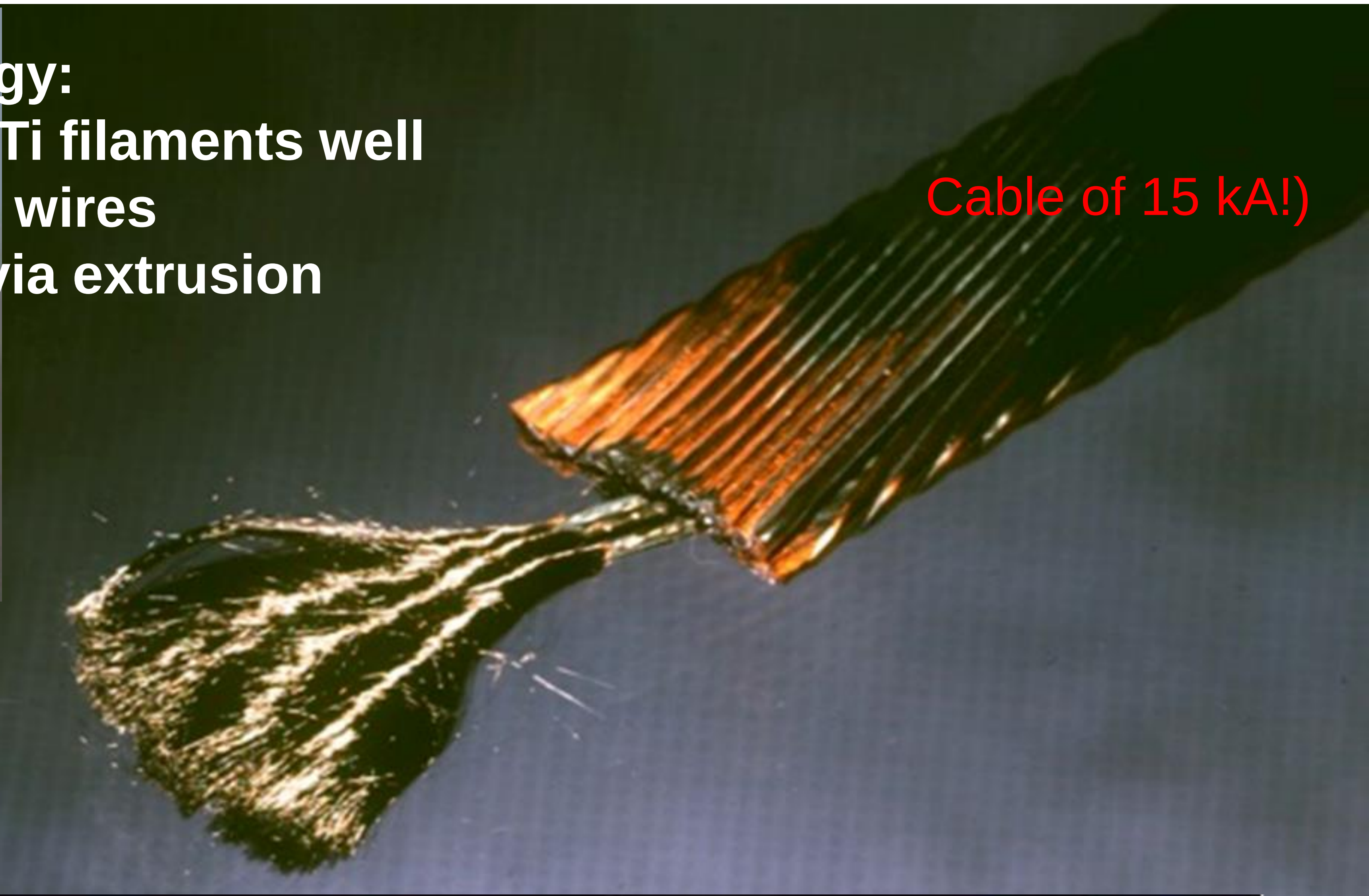
- HL-LHC with 11-12T
- 16 T for HEP?
- Almost a commodity!
  - 15-20 t per year for MRI
  - ITER needs 500 t
- ca 5 times cost of LHC Nb-Ti
- **Brittle material**

HTS (needed → 20 T)
→ on going R&D!

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

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

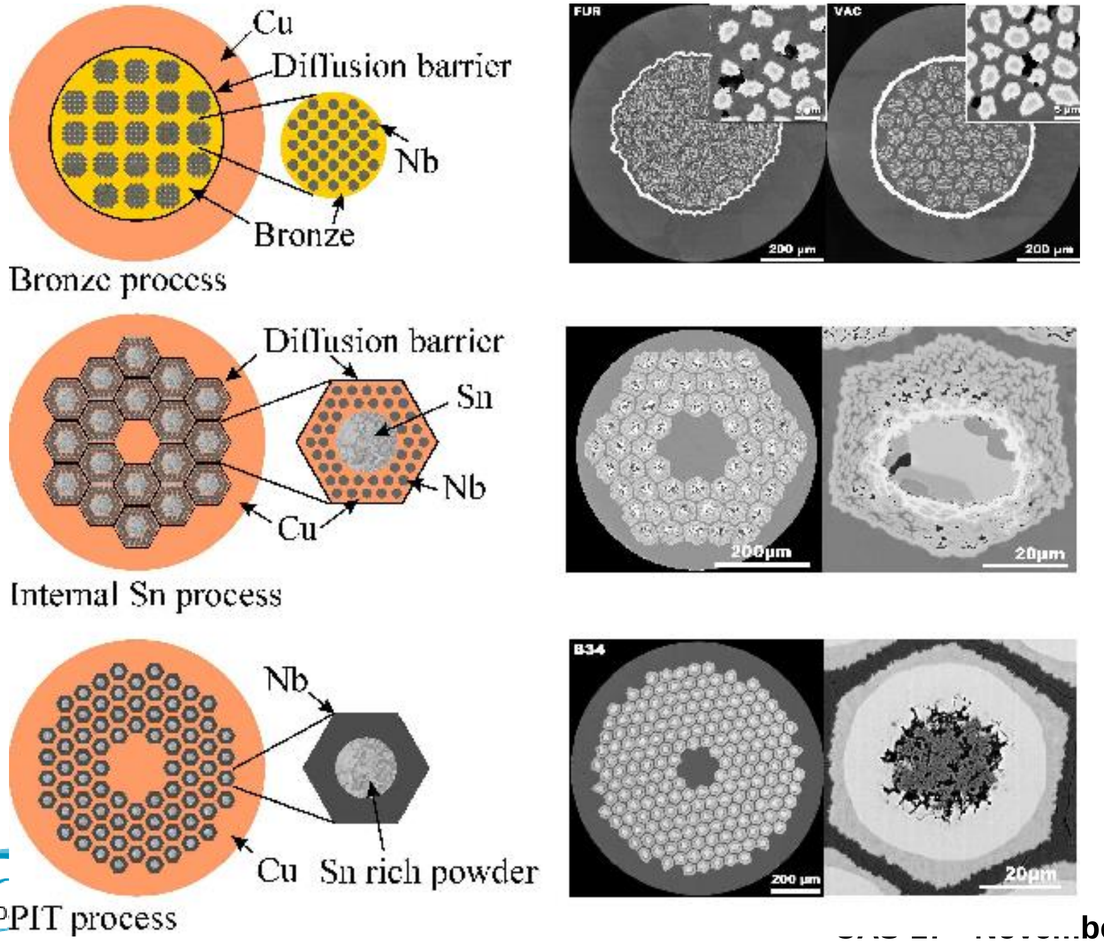


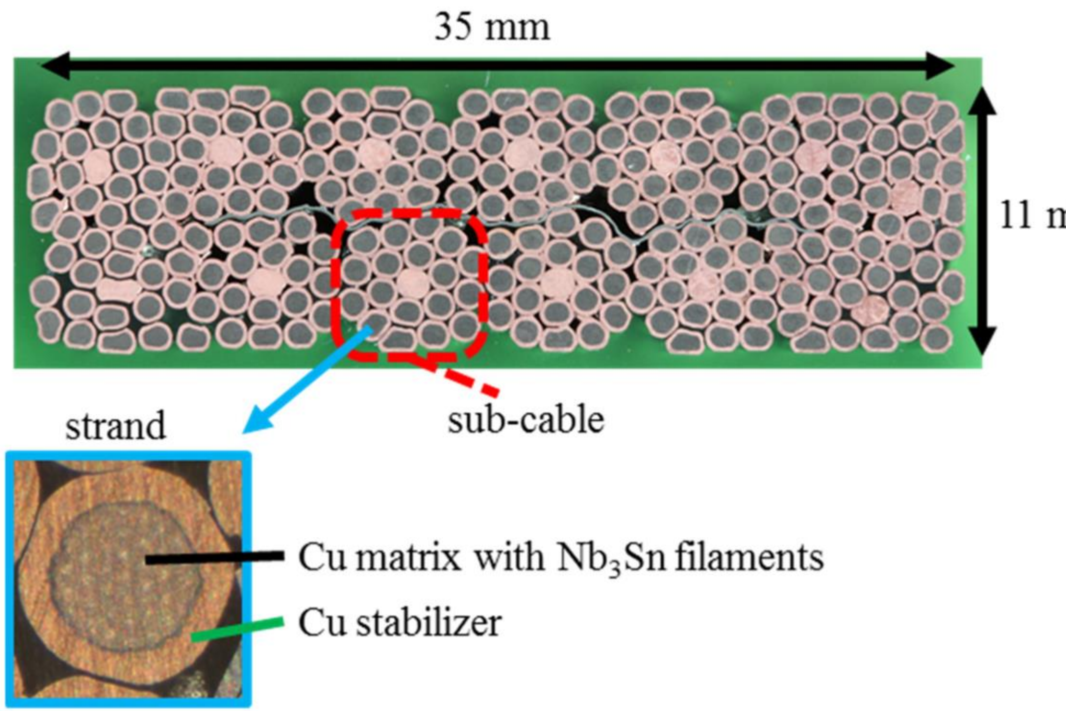


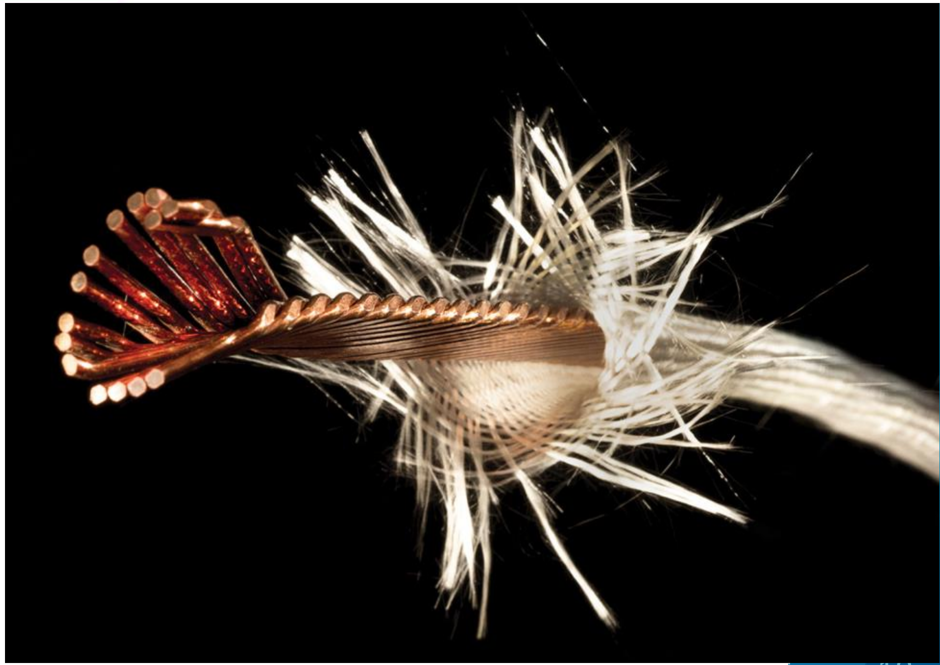
Cable of 15 kA!)

The Nb_3Sn SC Challenge:

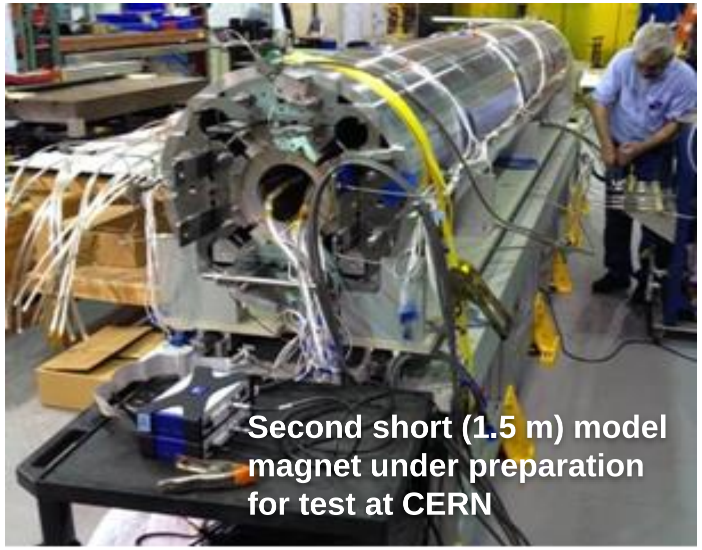
Nb_3Sn is brittle and cannot be drawn in final form – contrary to NbTi
Strand is drawn before cable is formed before the wire is heat-treated to form the Nb_3Sn superconductor!







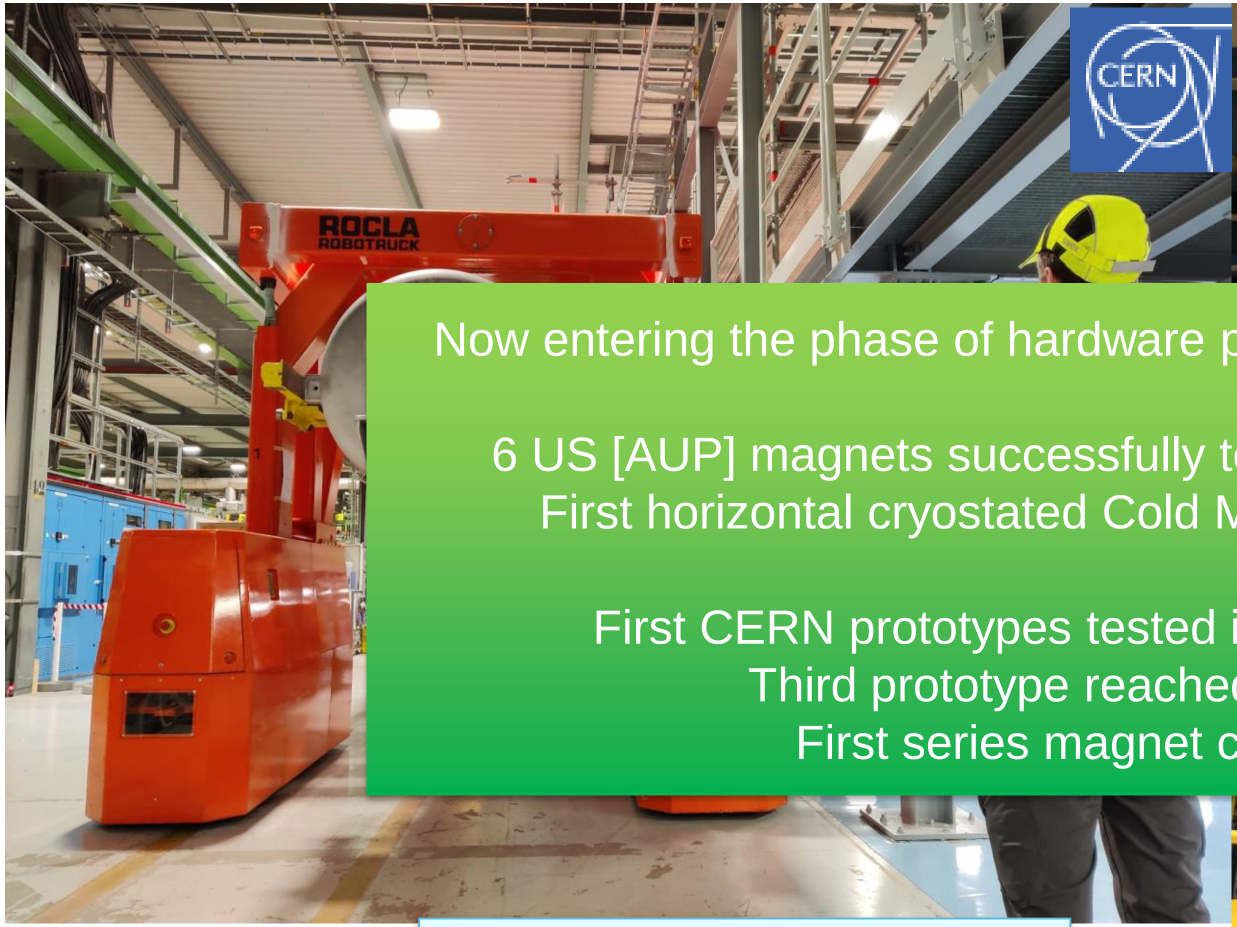
Nb_3Sn quadrupole: Transition from Prototype to Series production

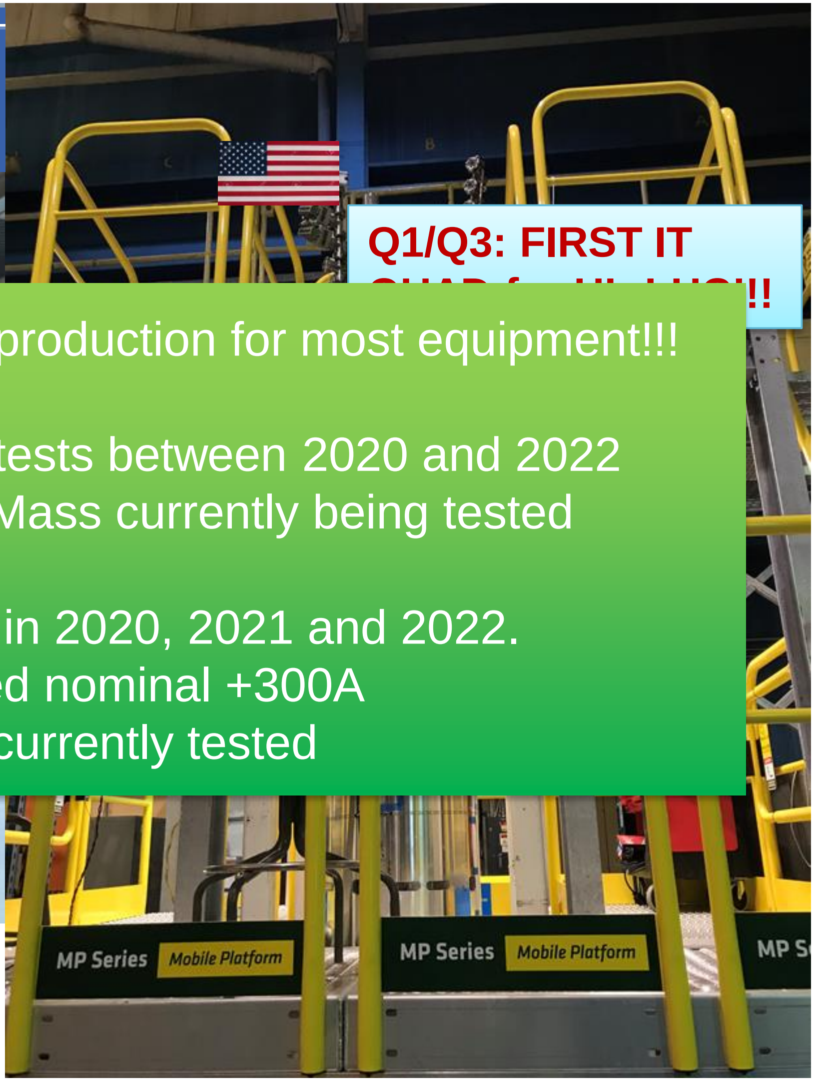


Second short (1.5 m) model magnet under preparation for test at CERN

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

Nb_3Sn quadrupole: Transition from Prototype to Series production





Q1/Q3: FIRST IT

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

6 US [AUP] magnets successfully tests between 2020 and 2022
First horizontal cryostated Cold Mass currently being tested

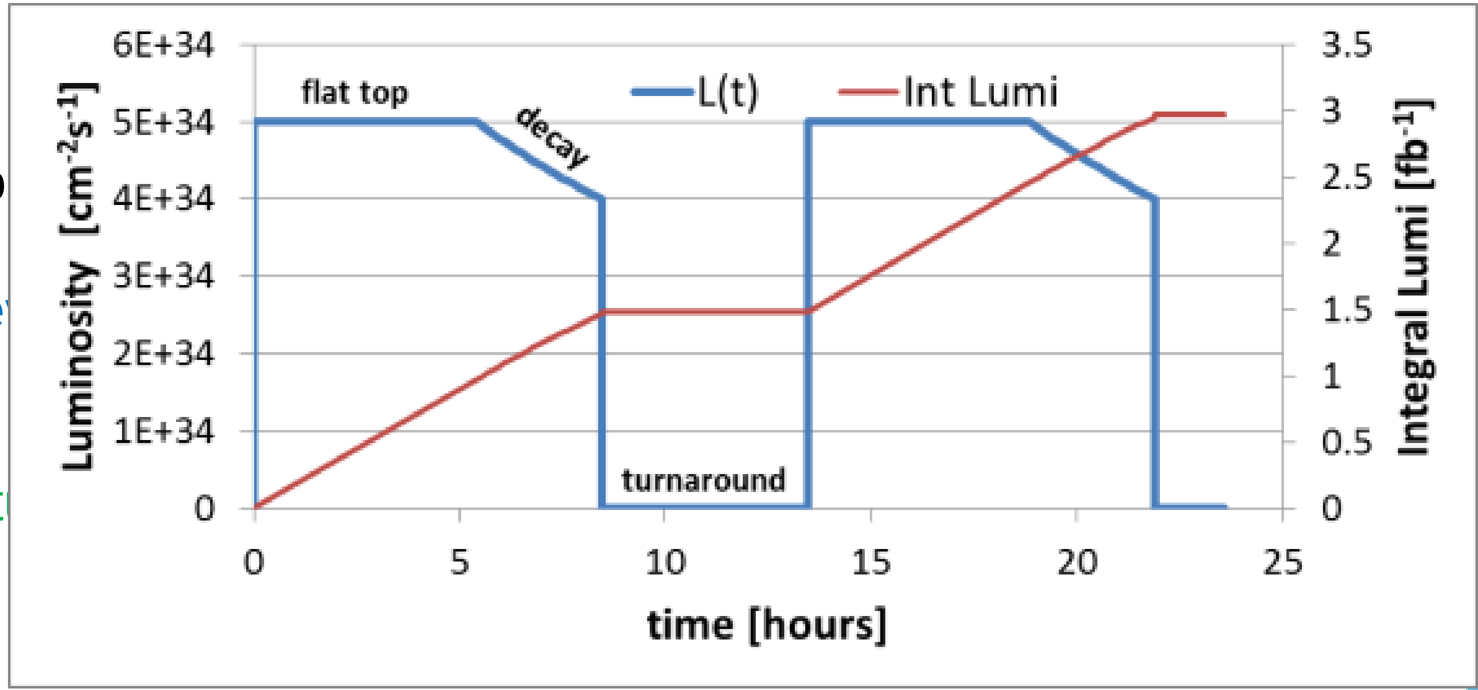
First CERN prototypes tested in 2020, 2021 and 2022.
Third prototype reached nominal +300A
First series magnet currently tested

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

Luminosity optimization:

- Luminosity Levelling at the lumino

All levelling methods have been successfully demonstrated in Machine Studies in the LHC!!!



- Lifetime proportional to total particles:

$$\tau_{eff} = \frac{N_{tot}}{n_{IP} \cdot \sigma_{tot} \cdot L_{leveled}}$$

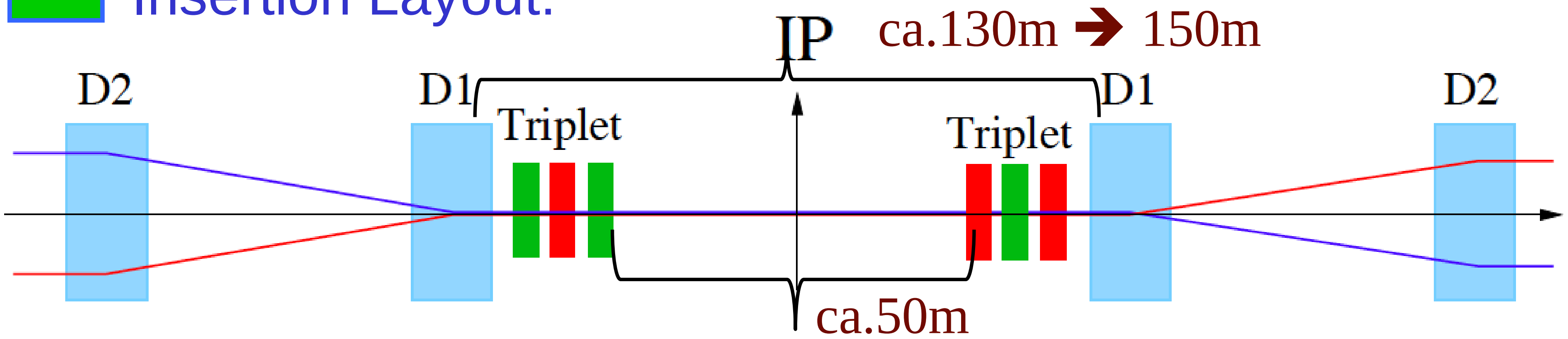
➔ Maximize the number of particles in the storage ring and the number of bunches!

➔ **Injector Complex Upgrade - LIU**

➔ **Stored Beam Power in the LHC!**

HL-LHC Challenges: Crossing Angle & Parasitic Collisions

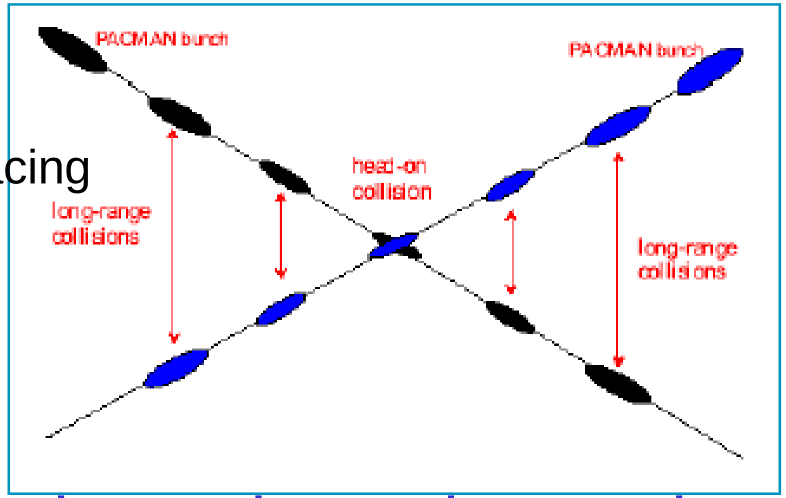
Insertion Layout:



Parasitic bunch encounters:

Operation with ca. 2800 bunches @ 25ns spacing
➔ approximately 50 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 triplet apertures for HL-LHC!!

HL-LHC Upgrade Ingredients: Crab Cavities

Geometric Luminosity Reduction Factor:

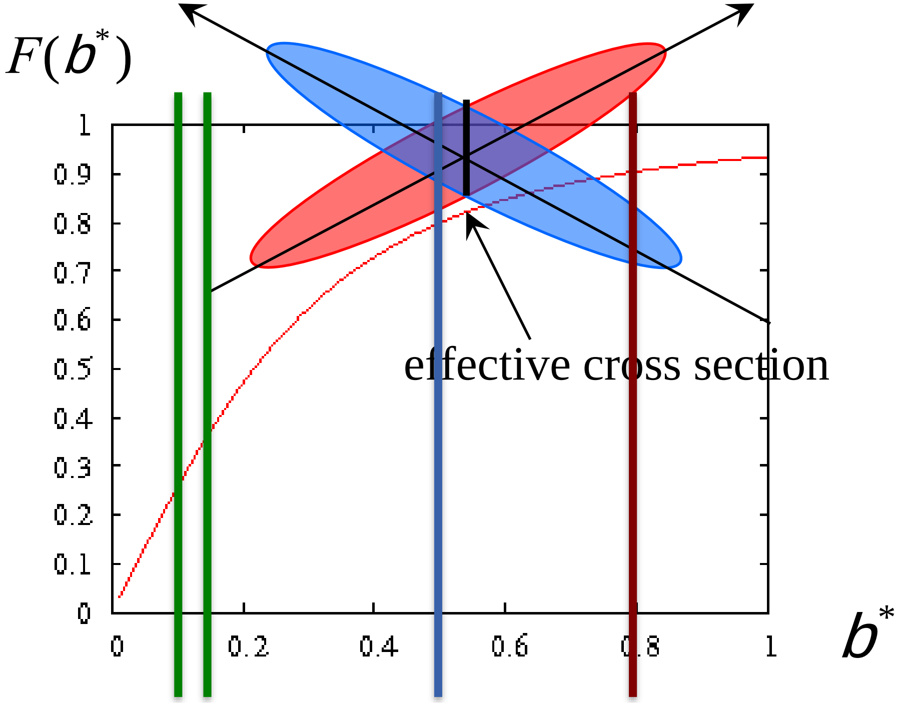
Crab Cavities:

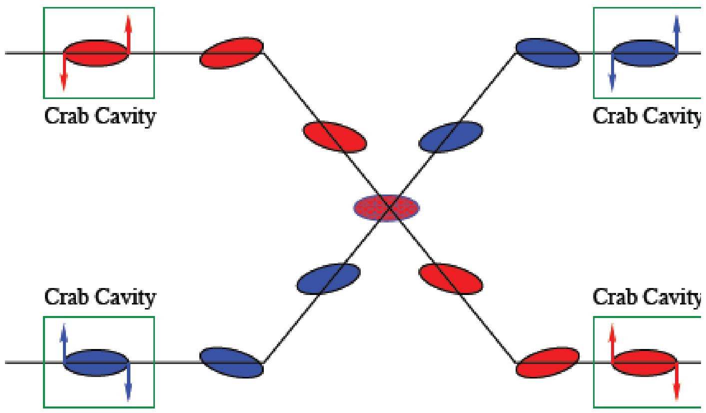
- Reduces the effect of geometrical reduction factor
- Independent for each IP

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

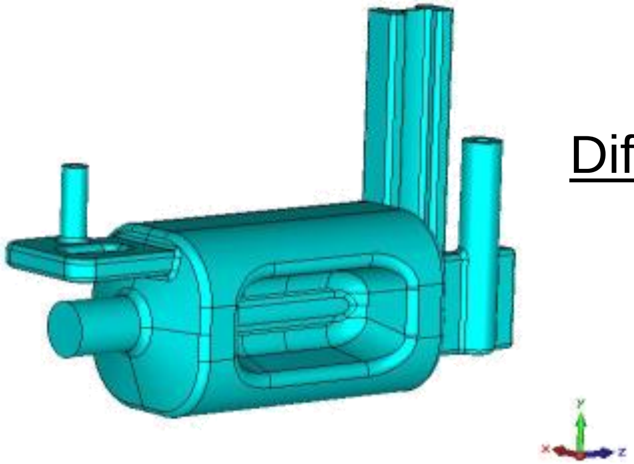
- Noise from cavities to beam Beam size and losses?!?
- Challenging space constraints:

  ➔ requires novel compact cavity design



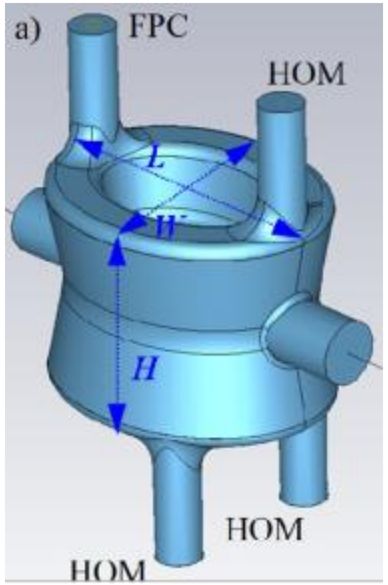


HL-LHC cavity designs



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

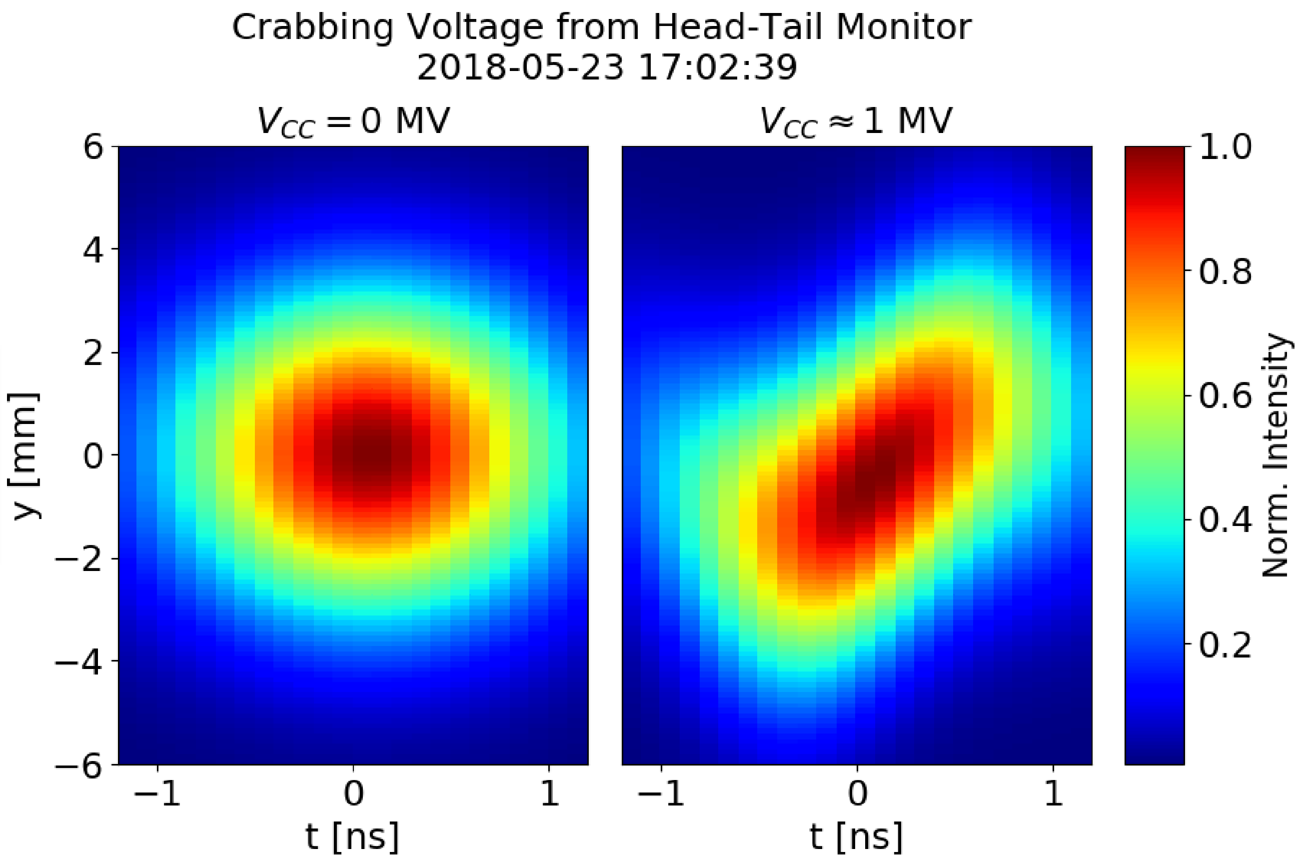
DQW crab-cavity
Cryomodule for
SPS tests

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

Crab cavity cryo-module for installation in the SPS

First proton crabbing ever!

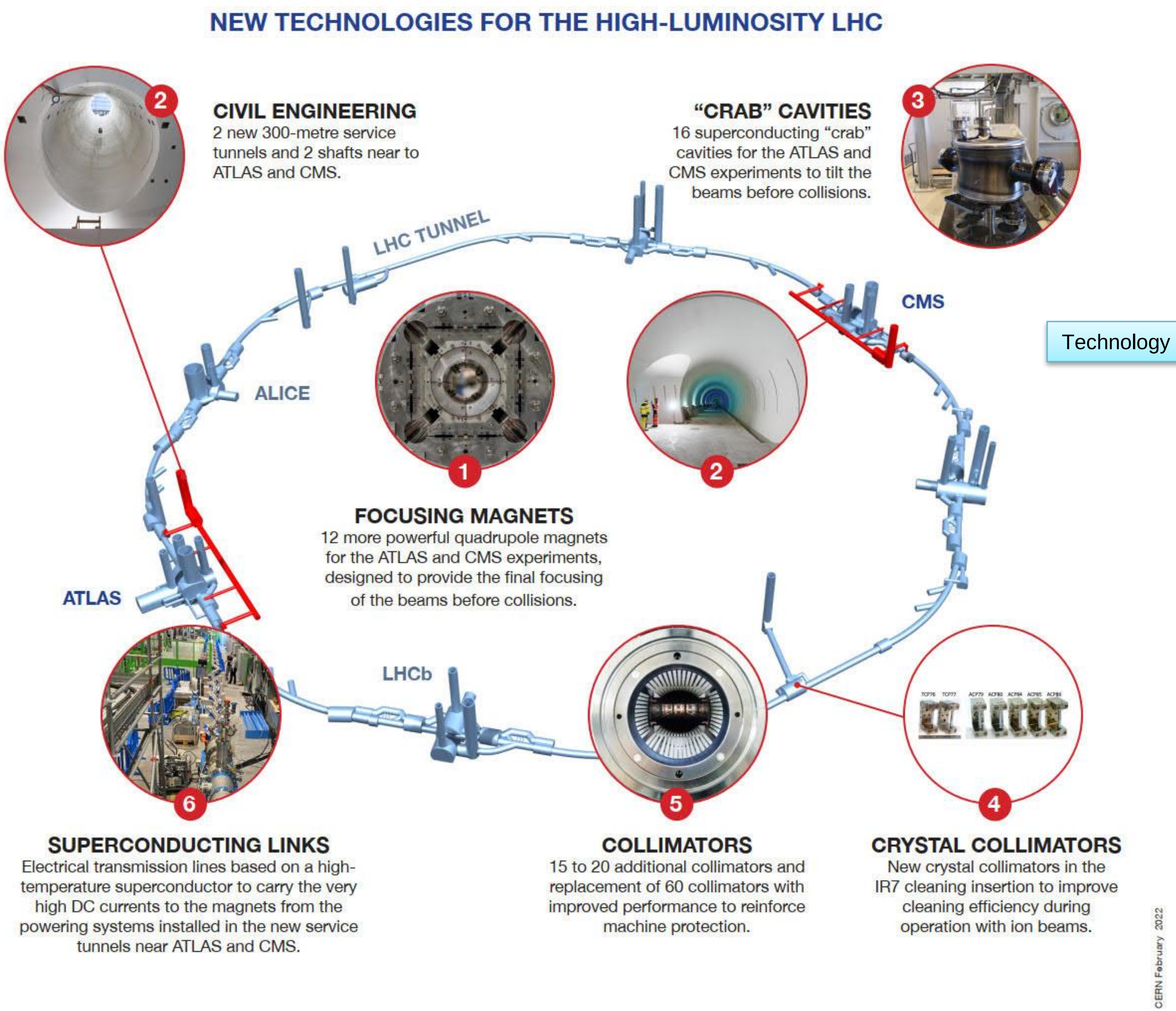
TEST in SPS ongoing since 2018



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

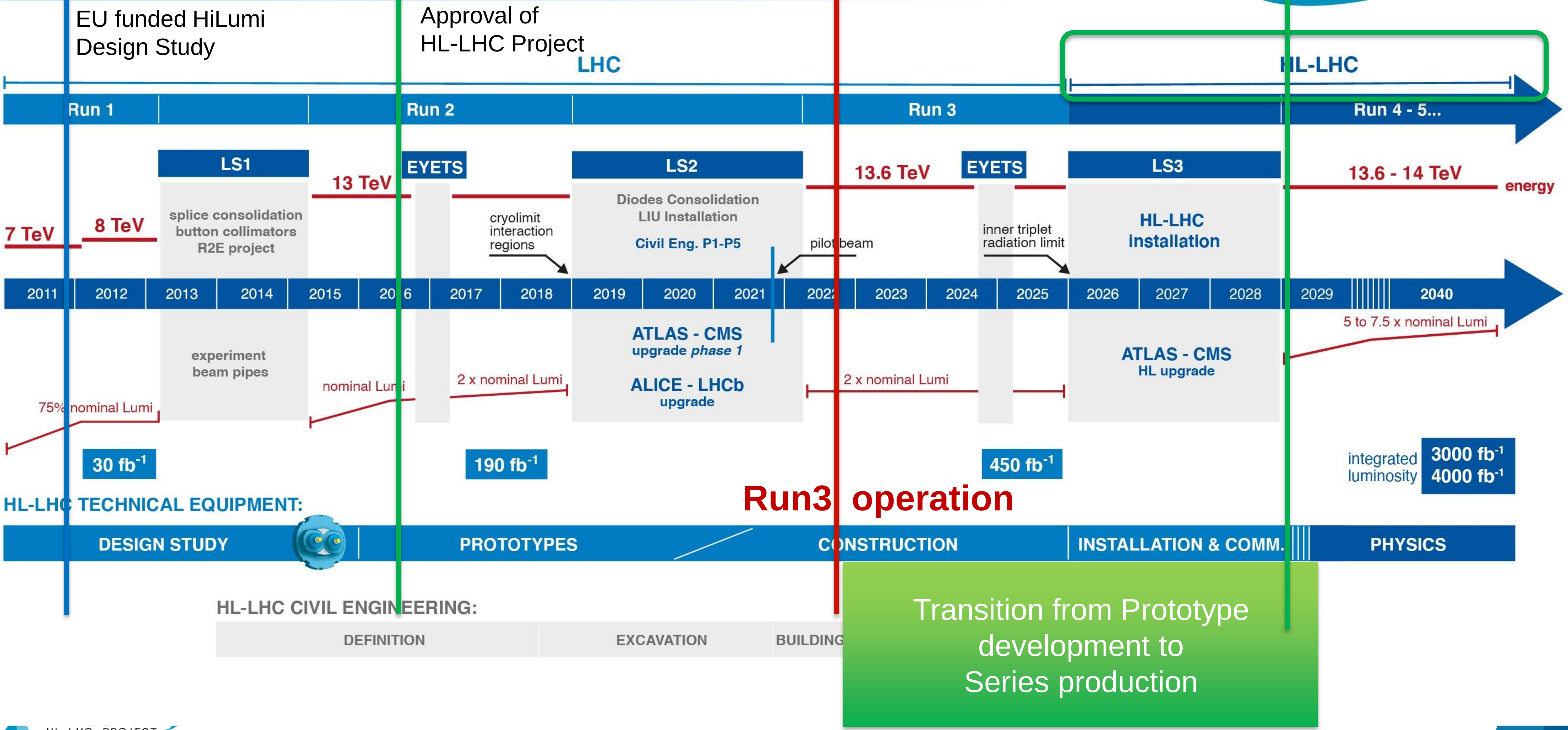
No accelerator project has so many challenging novelties covering such a broad technology spectrum

Technology intensive project!

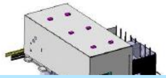


Technology landmarks

LHC / HL-LHC Plan



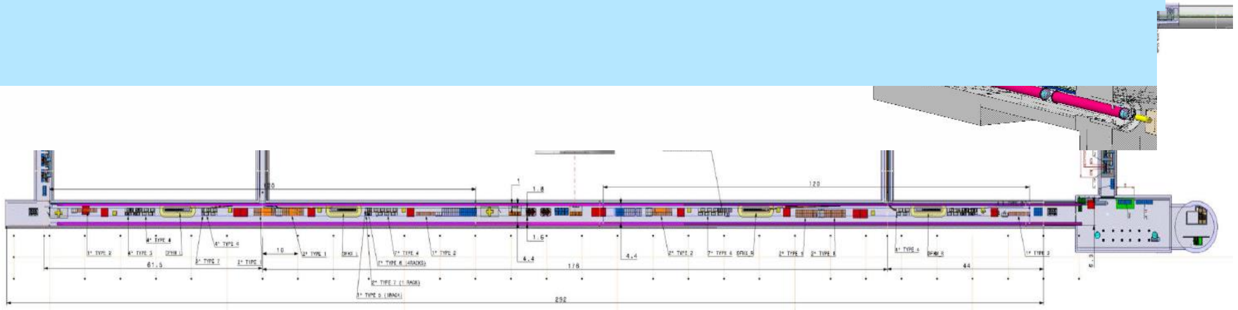
IR1 & IR5 Civil Engineering:



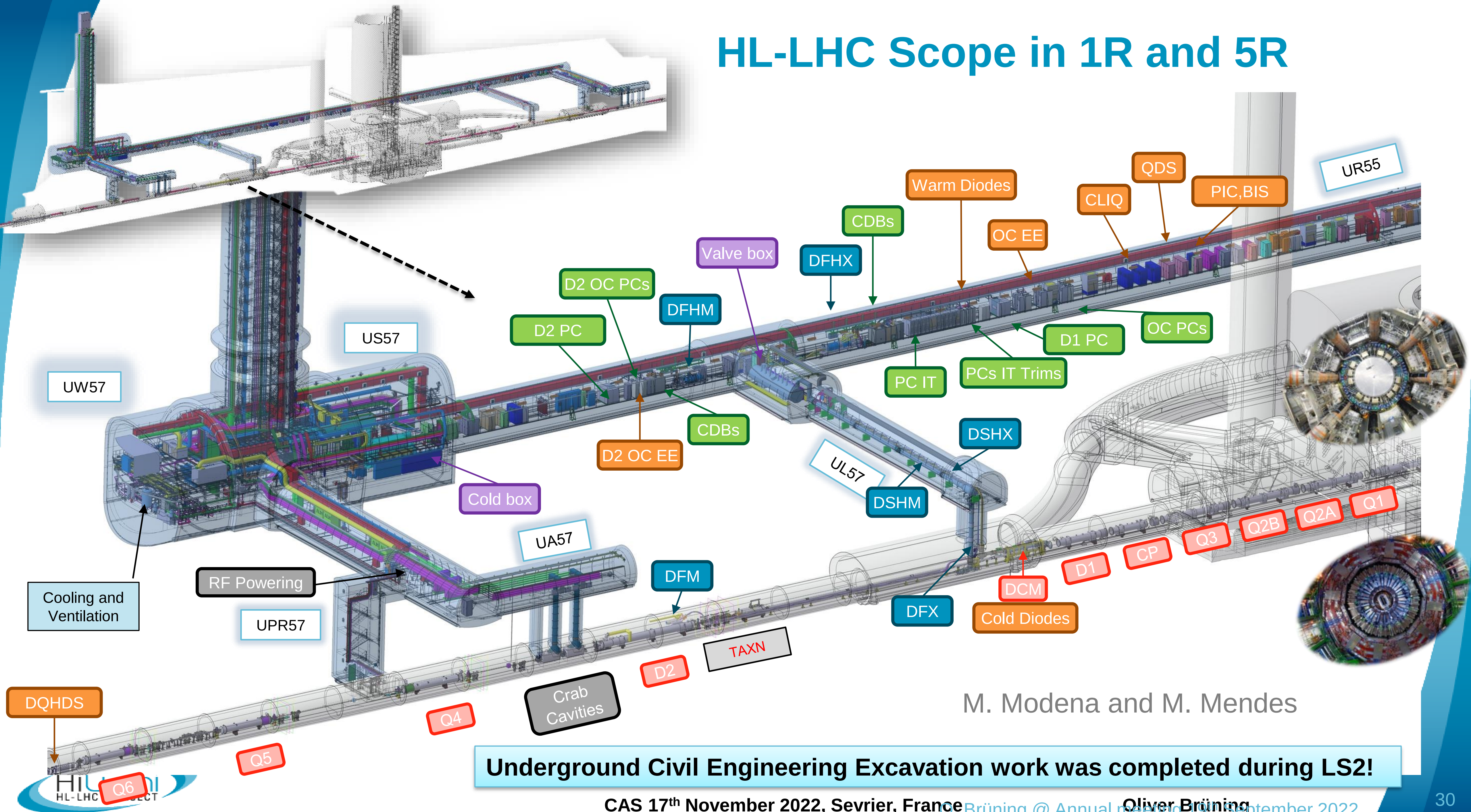
New Underground areas for the HL-LHC:

➔ Space for new HL-LHC equipment [e.g. cryo and power converter]

➔ Removal of all active components from the tunnel area [R2E and equipment failure due to radiation]



HL-LHC Scope in 1R and 5R



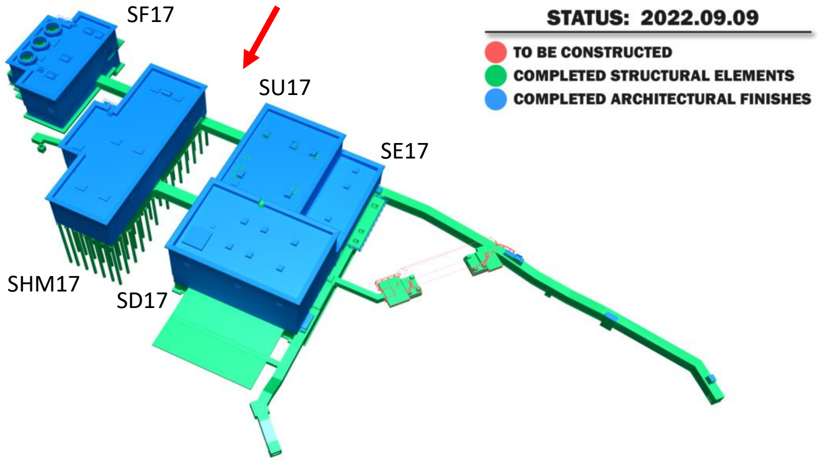
M. Modena and M. Mendes

Underground Civil Engineering Excavation work was completed during LS2!

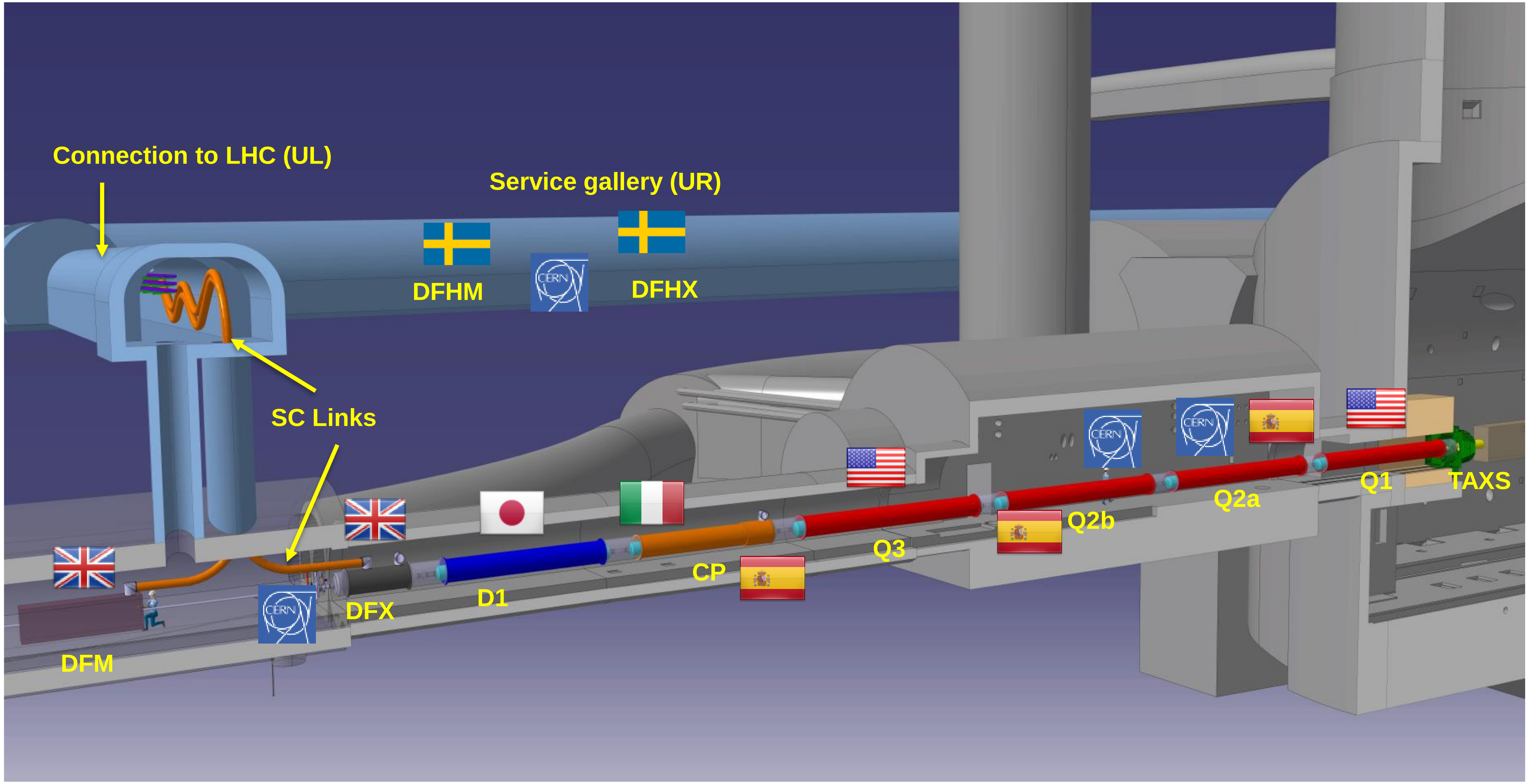
IR1 & IR5 Underground Civil Engineering: completed!

Surface Civil Engineering work to be finished in 2022!

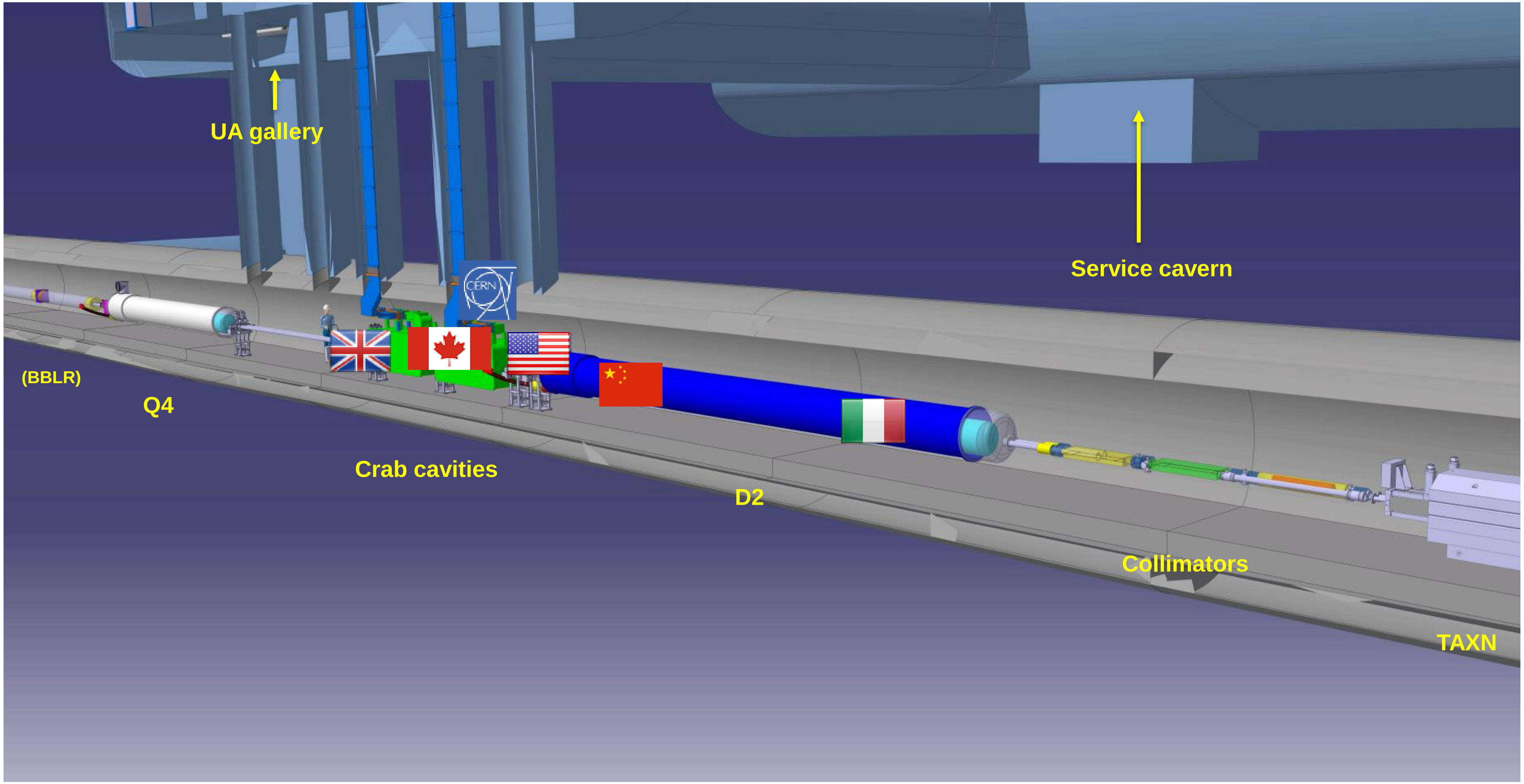
Main civil engineering work at Point 1 (ATLAS)



International Collaboration



The MS region with in-kind contributions



Thank you for your attention