The CERN Accelerator School

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# High Luminosity LHC – Status and Prospects

CAS November 2024

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

# Outline

- LHC design performance and HL-LHC upgrade goals
- (Main) Technical challenges of the HL-LHC upgrade
- Inner Triplet String
- Preparing HL-LHC operation and performance ramp-up
- Conclusions

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# 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$^{-1}$ [$2 \times 10^{34}$cm$^{-2}$sec$^{-1}$]

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

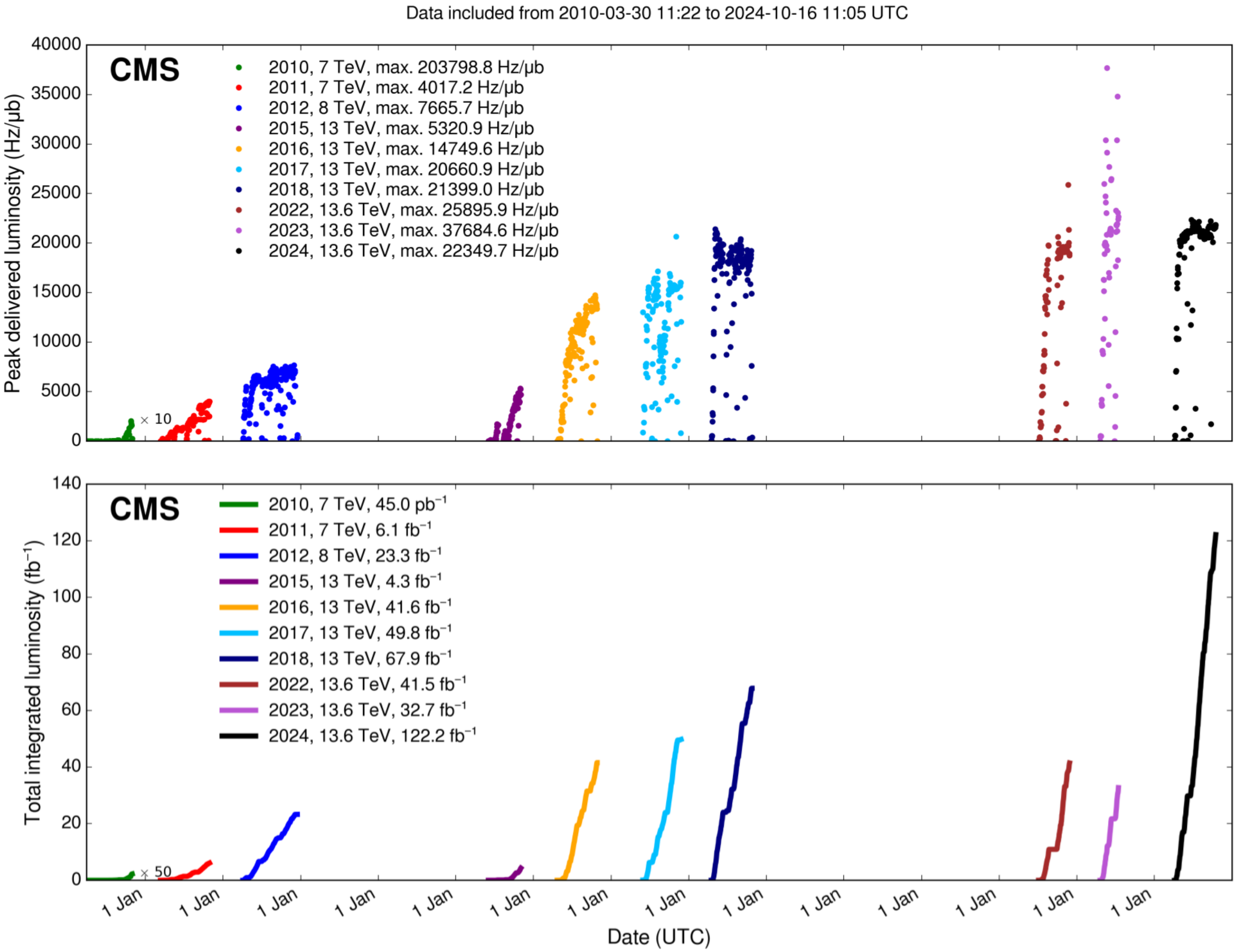
  300 fb$^{-1}$ with 1barn = $10^{-28}$m$^2$ and femto = $10^{-15}$ [360 fb$^{-1}$]

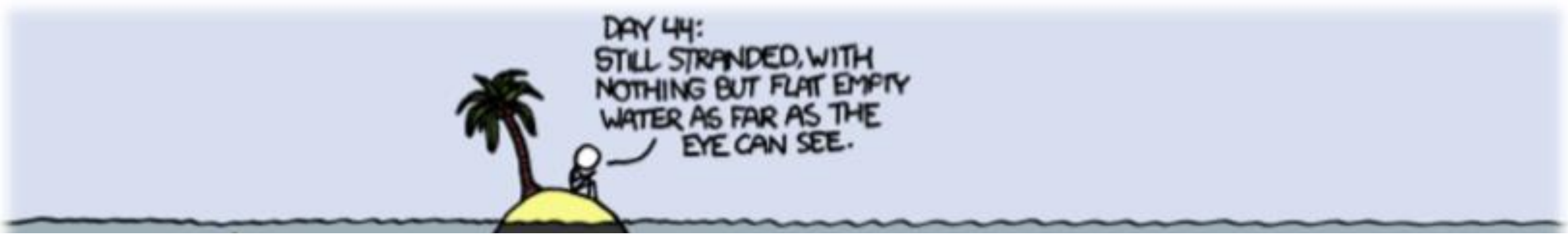
  depends on the beam lifetime, the LHC cycle and 'turn around' time and overall accelerator efficiency

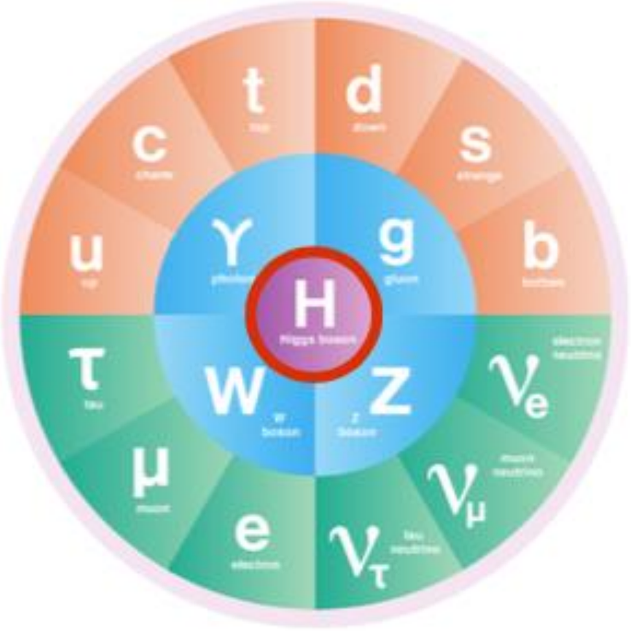
HiLumi HL-LHC PROJECT


WE FOUND A NEW PARTICLE

# After that it’s been quite a ride






**the standard-model particle set is complete**

**but we have been lucky with the Higgs boson's 125 GeV mass**

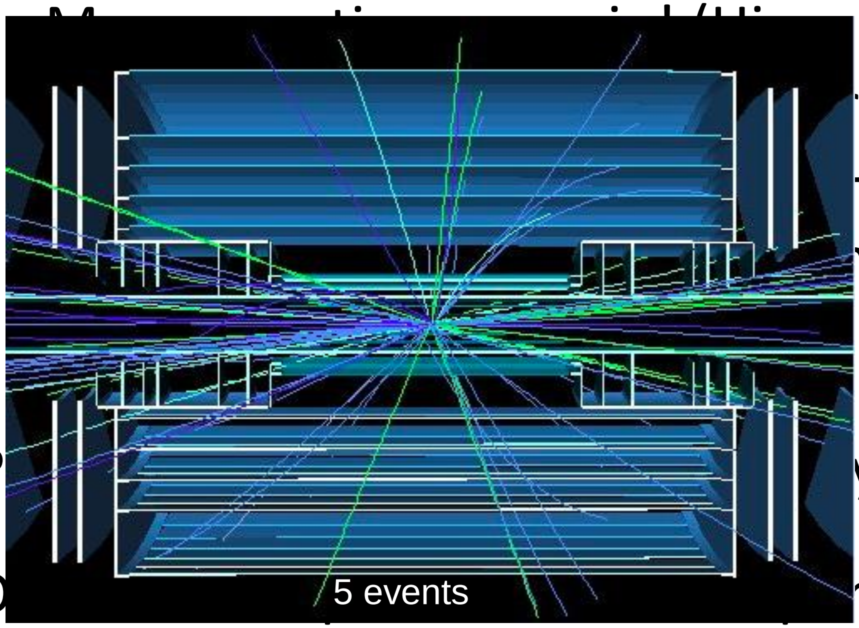
**it opens a door to the most mysterious part of the Standard Model**

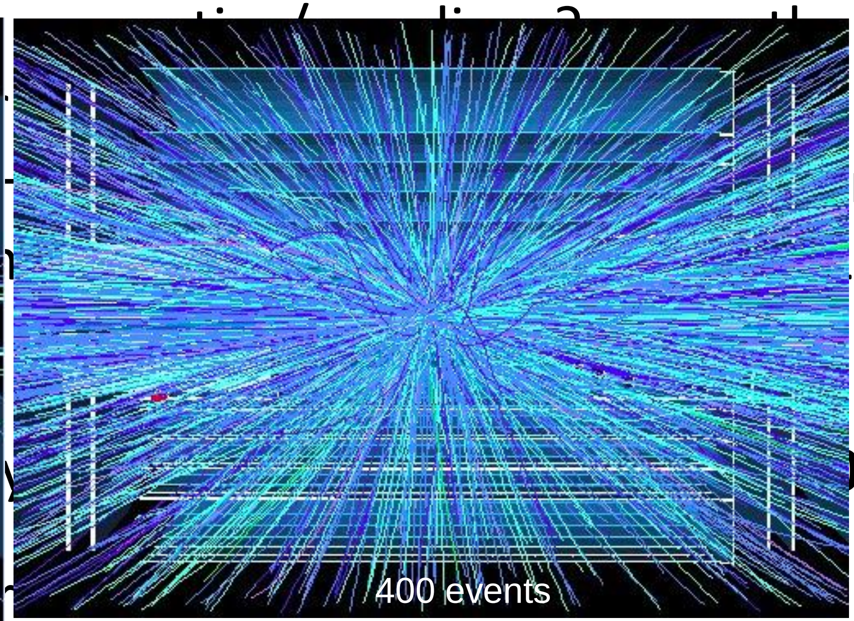
*Almost every problem of the Standard Model originates from Higgs interactions*

$$\mathscr{L} = y H \psi \bar{\psi} + \mu^2 |H|^2 - \lambda |H|^4 - V_0$$

*flavour* ($y H \psi \bar{\psi}$) — *naturalness* ($\mu^2 |H|^2$) — *stability* ($\lambda |H|^4$) — *cosmological constant* ($V_0$)

# Goal of HL-LHC upgrade project




Implies overcoming several limitations in the existing LHC!!!
Cryo cooling of triplet magnets & radiation damage in triplet magnets & machine efficiency!

But also for the experiments!!

➔ Need for an Upgrade!

## Higher Intensity

Increase bunch population

$$\mathcal{L} = \frac{N^2 f_{rev} k_c}{4\pi\beta^* \epsilon_{xy}} F$$

Smaller $\beta^*$

Reduced emittance

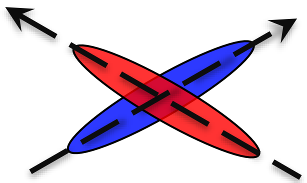
Smaller beam size at IP

Increase F

**Crossing angle reduction factor**

$$\frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2}\right)^2}}$$

**Shorter bunches, smaller crossing angle, crab cavities**



# HL-LHC Design Parameters

| Parameter | Nominal LHC (design report) | HL-LHC 25ns (standard) |
|---|---|---|
| Beam energy in collision [TeV] | 7 | 7 |
| $N_b$ | 1,15E+11 | 2,2E+11 |
| $n_b$ [12] | 2808 | 2760 |
| $N_{tot}$ | 3,2E+14 | 6,1E+14 |
| Beam current [A] | 0,58 | 1,1 |
| Half Crossing angle [μrad] | 142,5 | 250 |
| Minimum $\beta^*$ [m] | 0,55 | 0,15 |
| $\varepsilon_n$ [μm] | 3,75 | 2,50 |
| $\varepsilon_L$ [eVs] | 2,5 | 3,03 |
| Piwinski parameter | 0,65 | 2,66 |
| Peak Luminosity without crab-cavity [$cm^{-2}$ $s^{-1}$] | 1,00E+34 | 8,1E+34 |
| Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [$cm^{-2}$ $s^{-1}$] | - | 1,70E+35 |
| Events / crossing without levelling and without crab-cavity | 27 | 212 |
| Levelled Luminosity [$cm^{-2}$ $s^{-1}$] | - | 5,0E+34 [4] |
| Events / crossing (with leveling and crab-cavities for HL-LHC) [7] | 27 | 131 |
| Leveling time [h] (assuming no emittance growth) [7] | - | 7,2 |
| $n_b$ / injection | 288 | 288 |
| $\varepsilon_n$ at SPS extraction [μm] [3] | 3,5 | 2,1 |

LHC Magnet system

LHC injector complex

HL-LHC triplet magnets

HL-LHC crab cavities

Machine operation & availability

LHC injector complex

HiLumi HL-LHC PROJECT

# LHC / HL-LHC Plan


➔ ~1.5 years until start of Long Shutdown 3

➔ 80% of the project budget of ~1.1 BCHF already committed

➔ The project is ready for installation start in 2026! ➔ endorsed by 2023 C&SR

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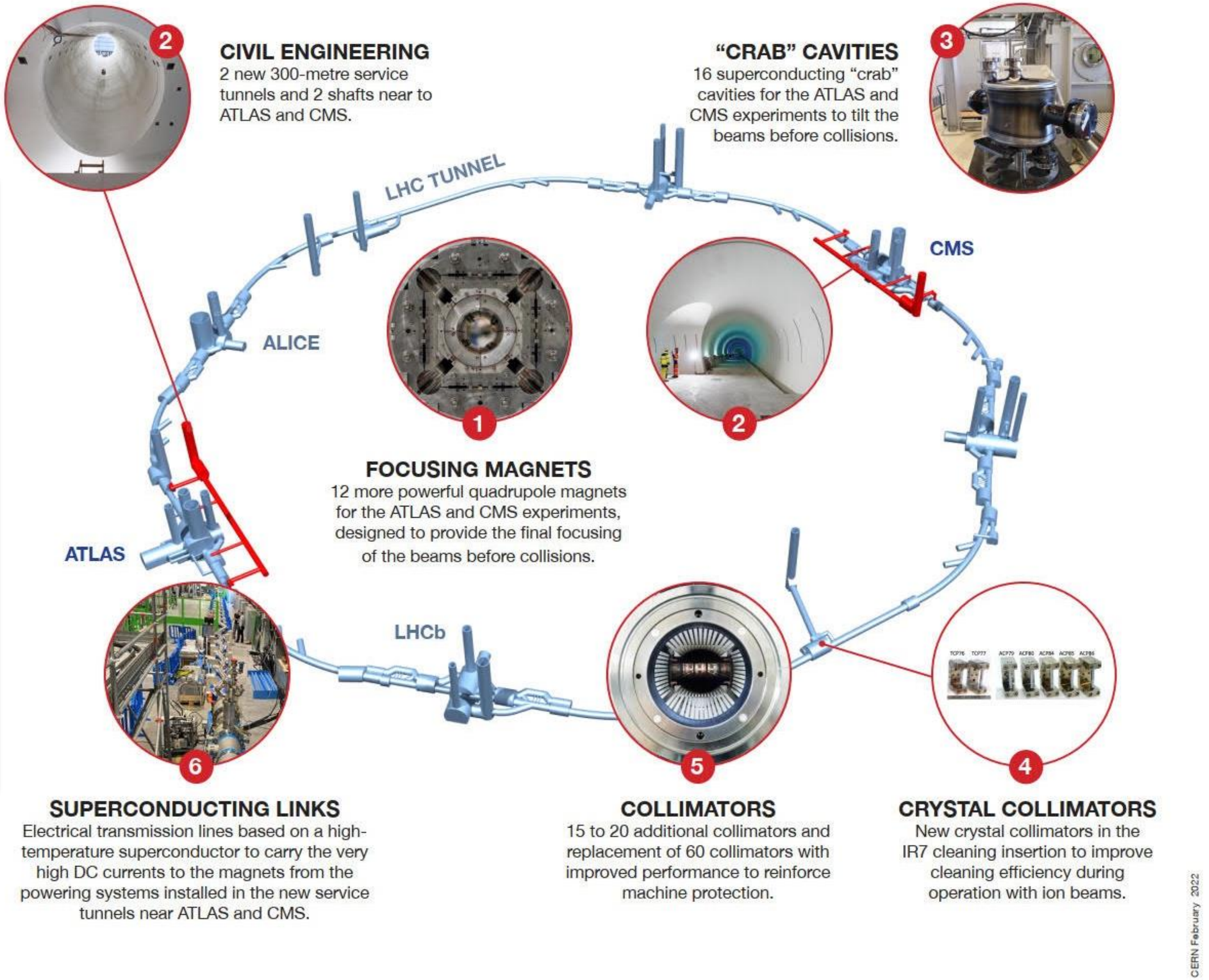
# HL-LHC technology landmarks

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

*Technology intensive project!*

*Major upgrades in P1 and P5, large fraction of LHC will remain unchanged*



# HL-LHC Technical Challenges: Triplet Magnets

Operation beyond 2026:

Requires replacement of LHC Triplet magnets

**10 x the luminosity** ➔ Requires new, more radiation resistant triplet magnets

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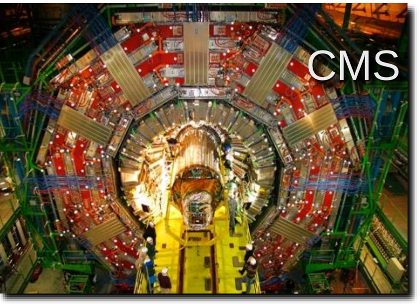
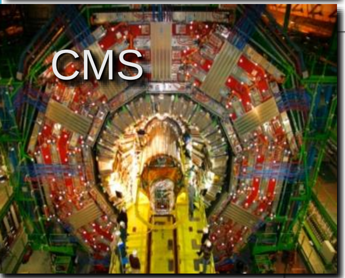
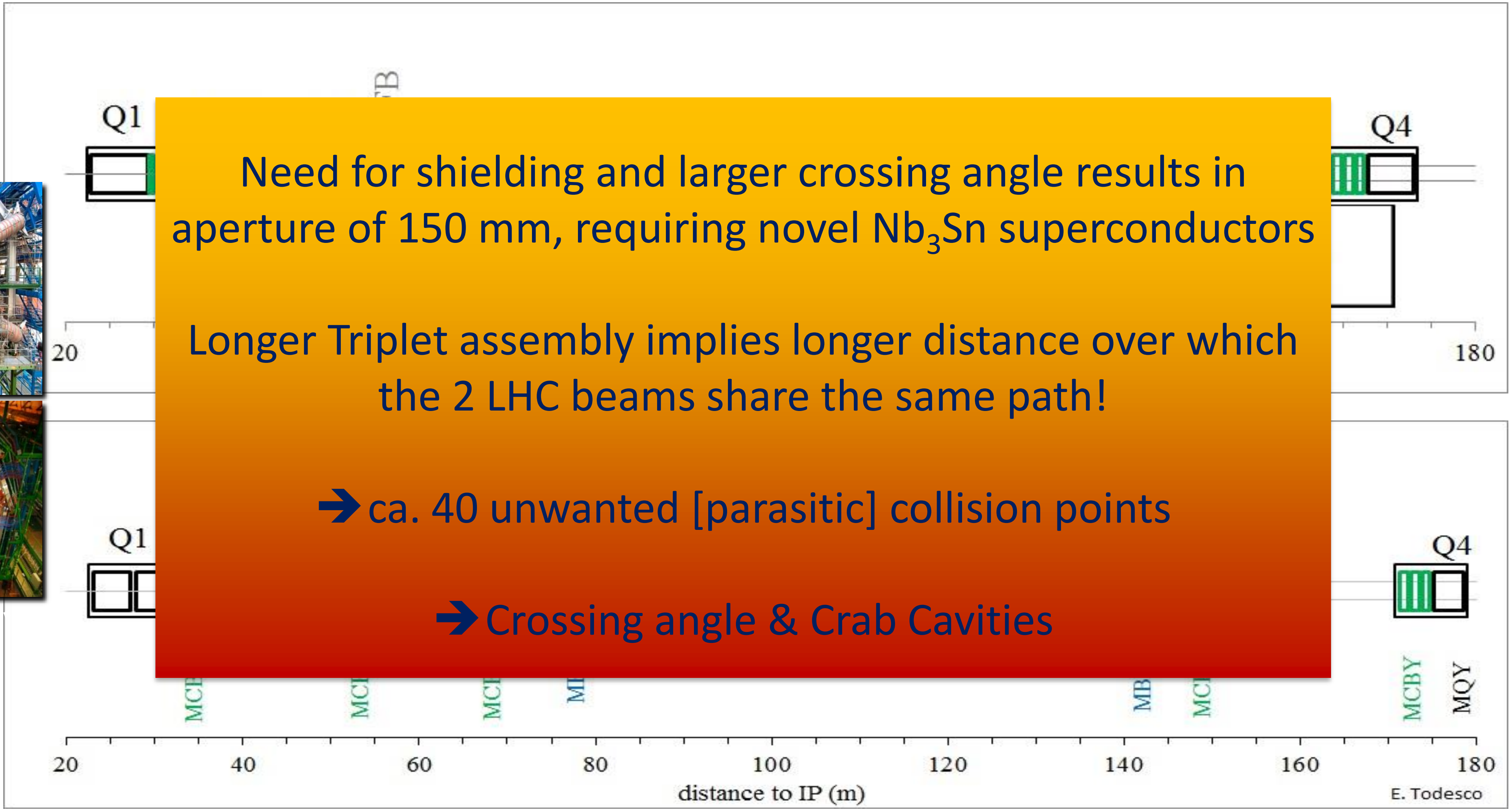


# New HL-LHC Triplet Layout


Need for shielding and larger crossing angle results in aperture of 150 mm, requiring novel $Nb_3Sn$ superconductors

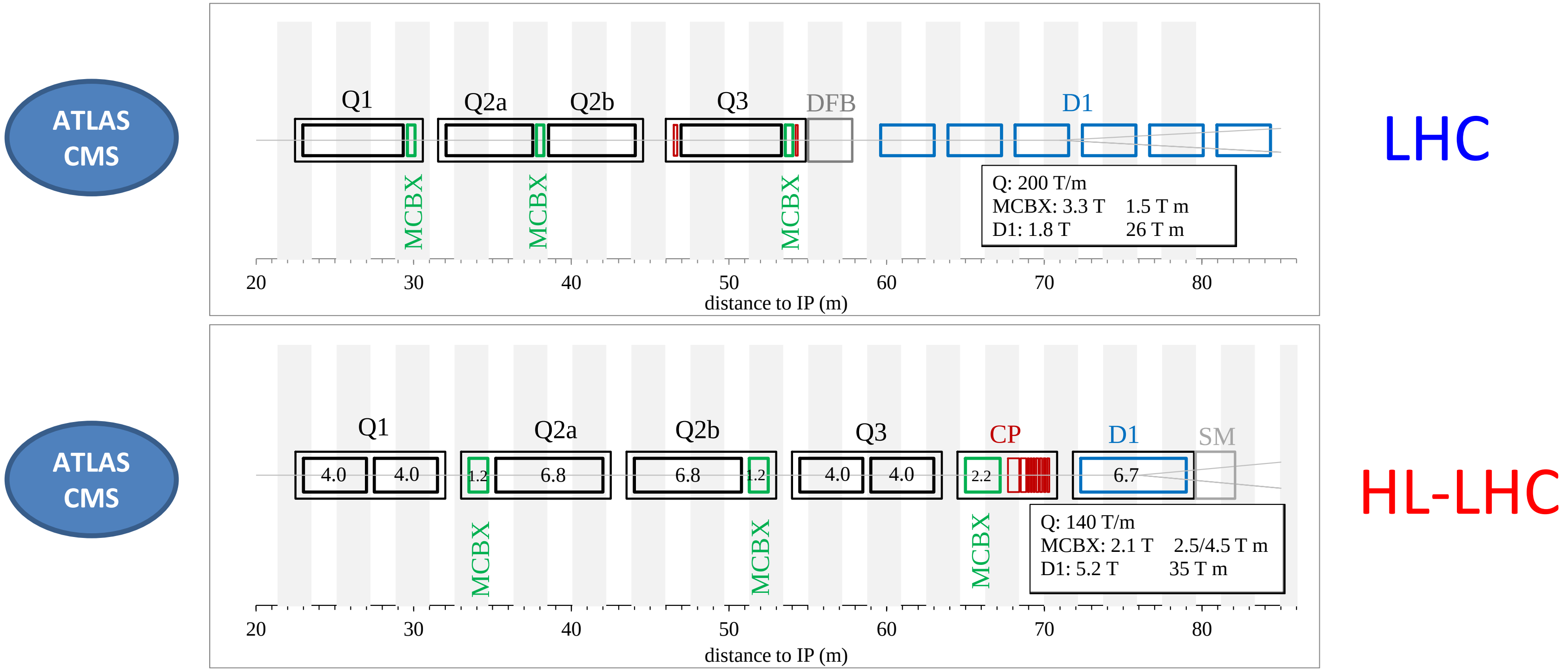
Longer Triplet assembly implies longer distance over which the 2 LHC beams share the same path!

➔ ca. 40 unwanted [parasitic] collision points

➔ Crossing angle & Crab Cavities

# 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



# HL-LHC technical bottleneck:
# Radiation damage to inner triplet magnets

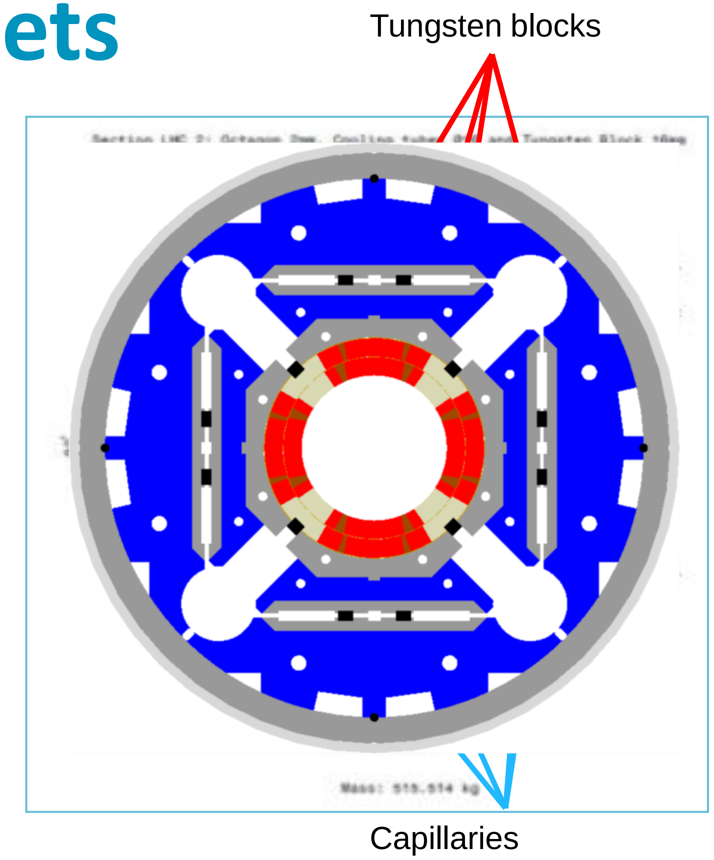
Need to replace existing triplet magnets with radiation hard system (shielding!) such that the new magnet coils receive a similar radiation dose @ 10 times higher integrated luminosity!!!!! ➔ Shielding!

➔ Requires larger aperture!

➔ New magnet technology!

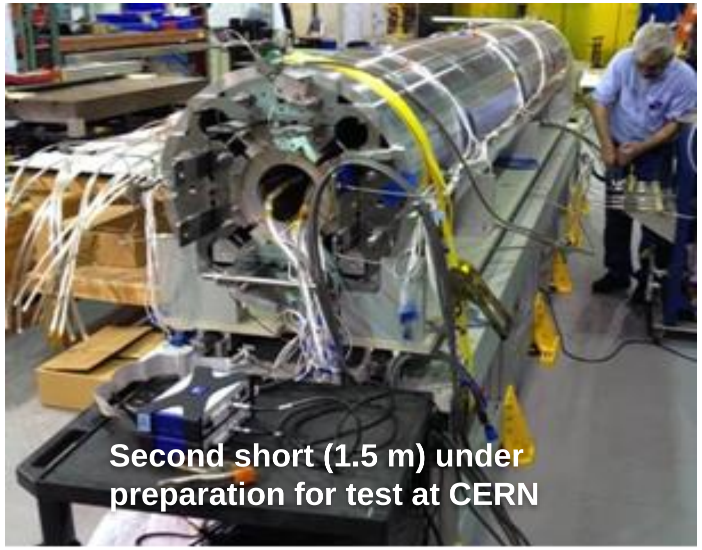
➔ 70 mm at 210 T/m ➔150 mm diameter 140 T/m

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




**US-LARP MQXF magnet design Based on $Nb_3Sn$ technology**

# $Nb_3Sn$ quadrupole: Transition from Prototype to Series production

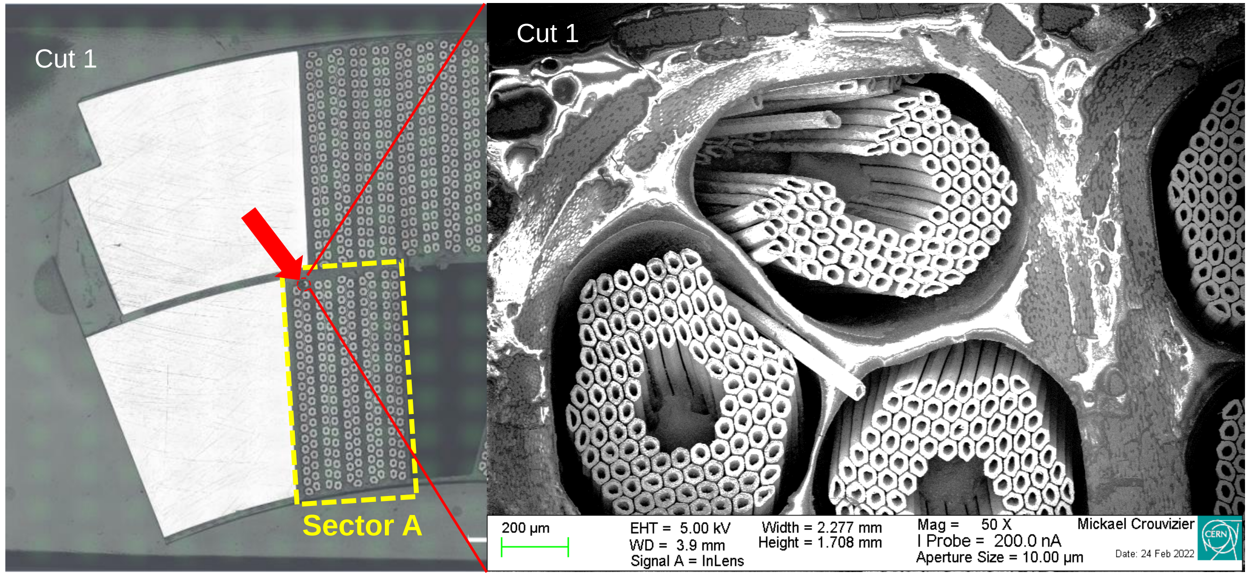


Second short (1.5 m) under preparation for test at CERN

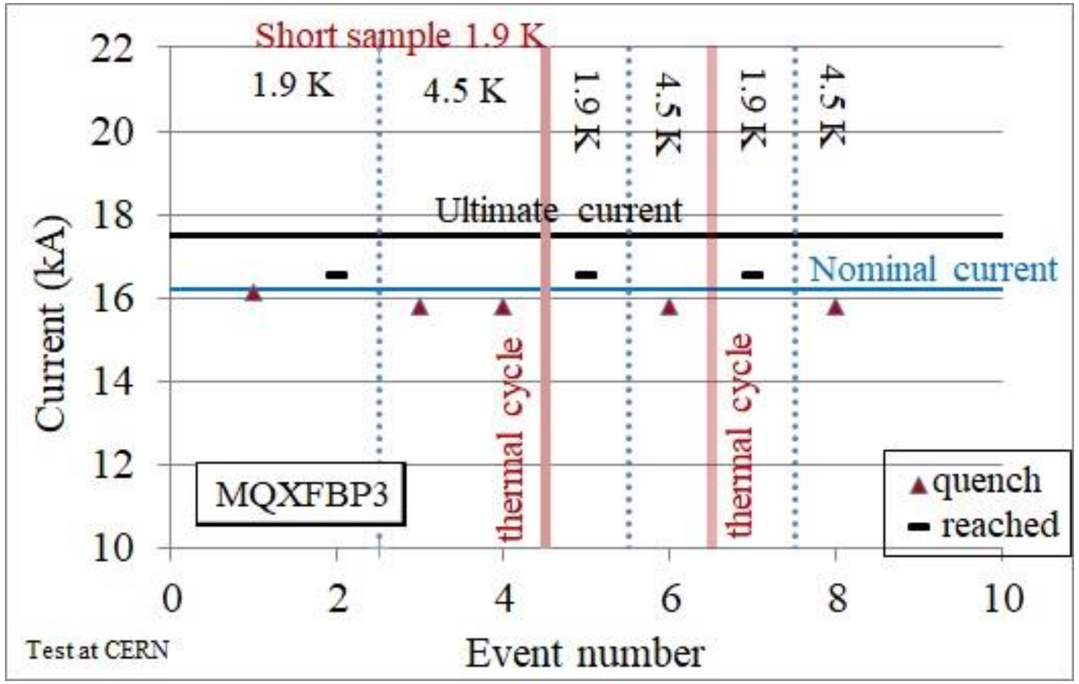

Insertion of coil package inside mechanical structure of the first IT quad prototypes (4.2 m long) in LBNL-USA

# MQXFB: From prototypes to series

- MQXFBP2: limited at 15 kA (~6.5 TeV)
- MQXFBP2: limited at 16 kA (~6.8 TeV)
- MQXFBP3 (previously called MQXFB01): tested in August 2022, nominal +300 A reached with one training quench, three thermal cycles without degradation
  - Old coils, old magnet assembly procedure, first magnet with optimized welding of SS shells (cause 1)
  - Performance limitation still visible at 4.5 K, above operational levels (2 K margin, 0.3 K needed)



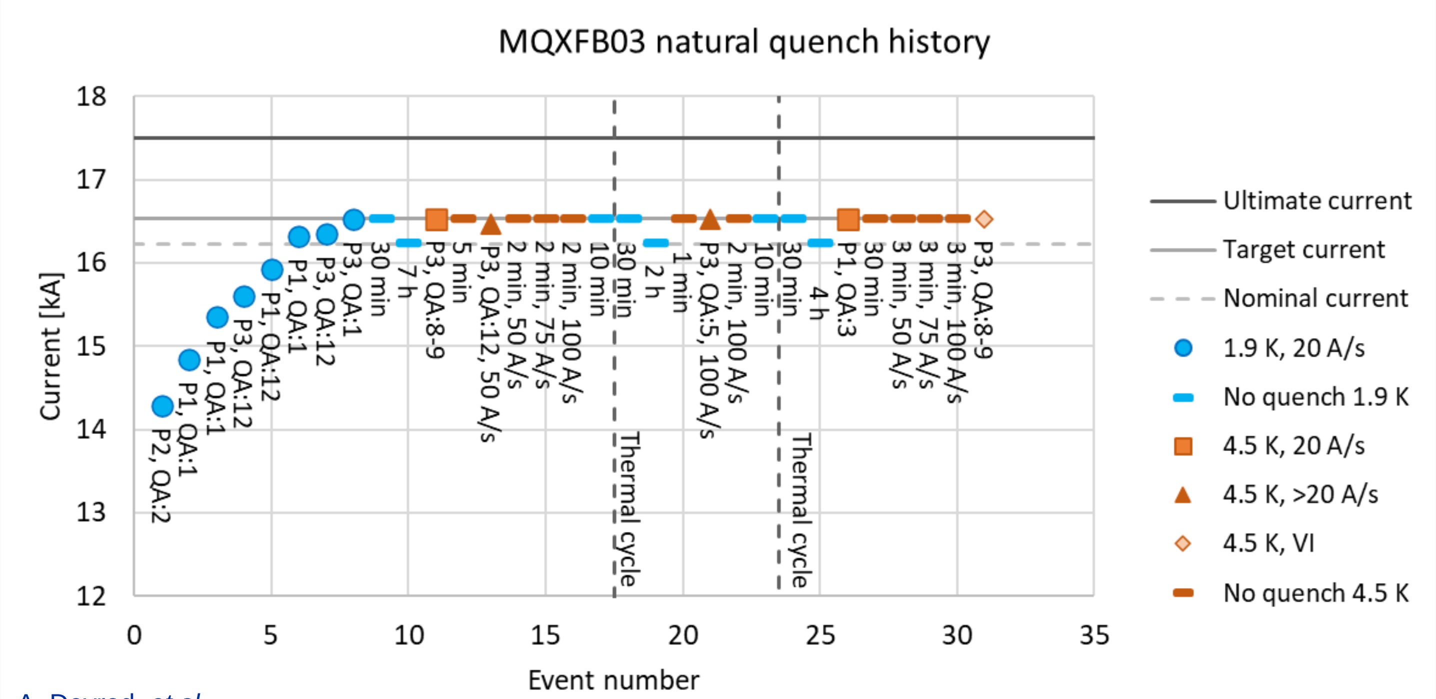

Broken filaments in coil 108, limiting MQXFBP1 (M. Crouvizier, A. Moros, S. Sgobba, et al.)




MQXFBP3 training [F. Mangiarotti, S. Izquierdo Bermudez, et al.]

# Improvement Plan for MQXFB

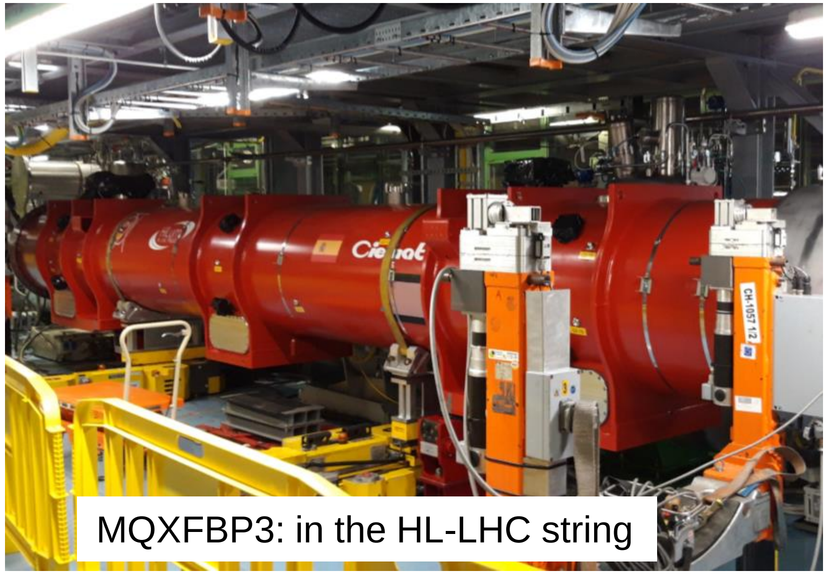
- After steady progress with prototypes and first of series which already reached acceptance criteria at 1.9K, MQXFB03 is the 3rd **magnet of 3-stage strategy,** integrating full set of improvements for *cold mass assembly*, *magnet loading* and *coil manufacturing*
- It was tested in **Q3/Q4 2023** and is the first 7.2-m-long MQXFB magnet to achieve target current of 16.53 kA at both **1.9 K and 4.5 K.**
- It shows good endurance after **2 warm-up/ cooldown cycles** with no retraining at 1.9 K; no ramp rate degradation up to **100 A/s;** initial **training quenches at 1.9 K** are all in coil ends



A. Devred, *et al.*

Acknowledgement: Susana Izquierdo Bermudez

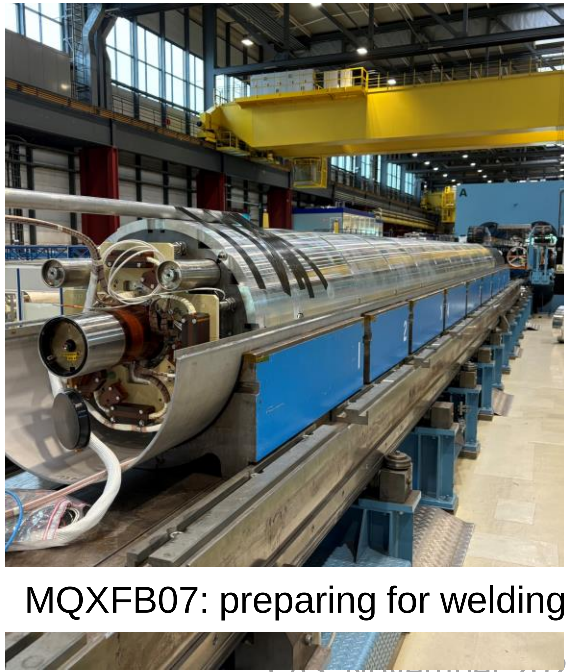

MQXFBP2: being prepared for the HL-LHC string


MQXFBP3: in the HL-LHC string


MQXFB03: ready to be tested in Q2 conf
MQXFB05: fully qualified for HL-LHC ✓

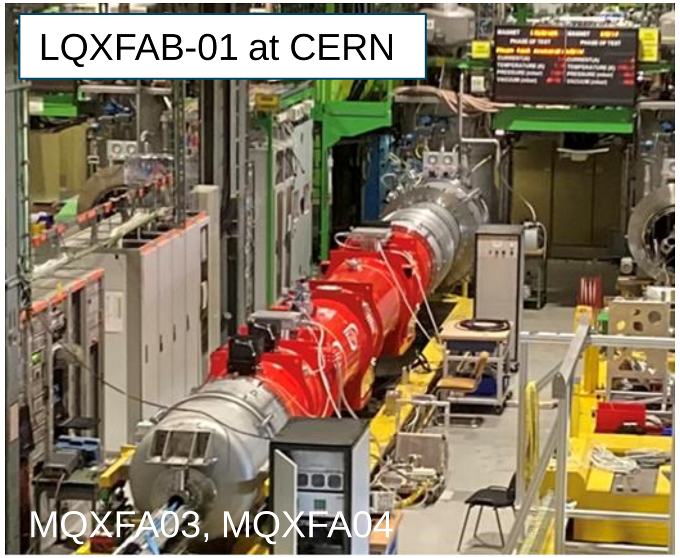

MQXFB04: fully qualified for HL-LHC ✓

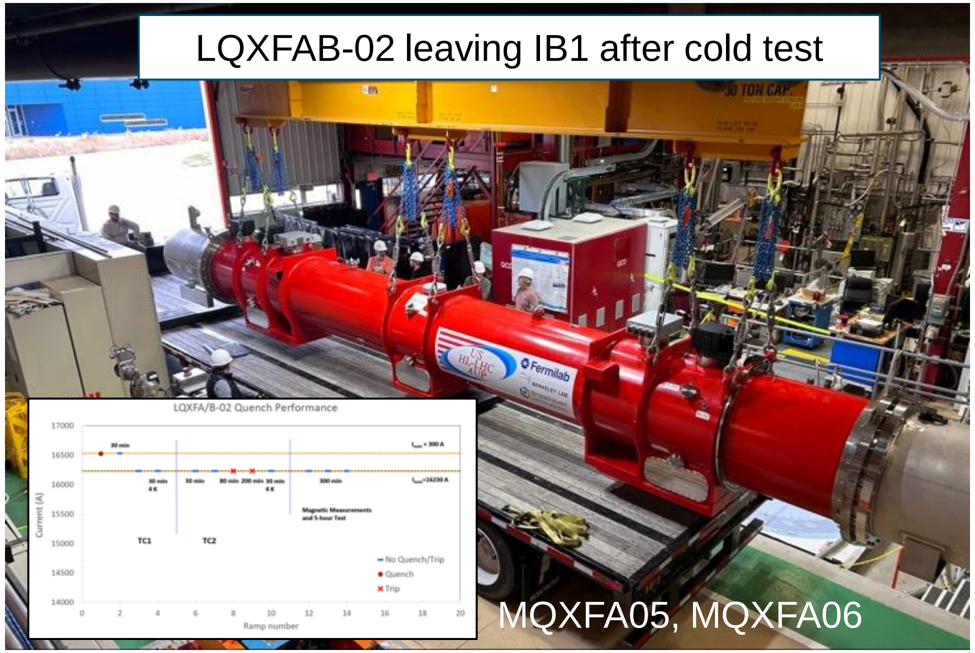

MQXFB06: cold mas finishing


MQXFB07: preparing for welding


MQXFB08: magnet assembly

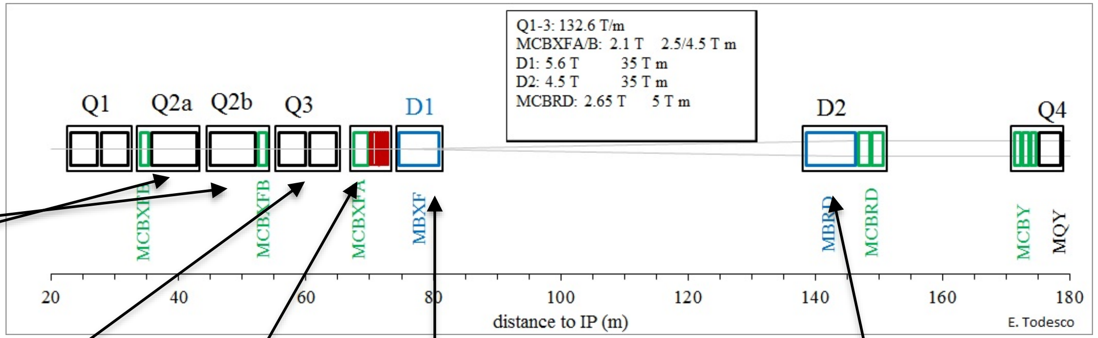
# Cold Masses and CryoAssemblies Technical Progress






# Magnets

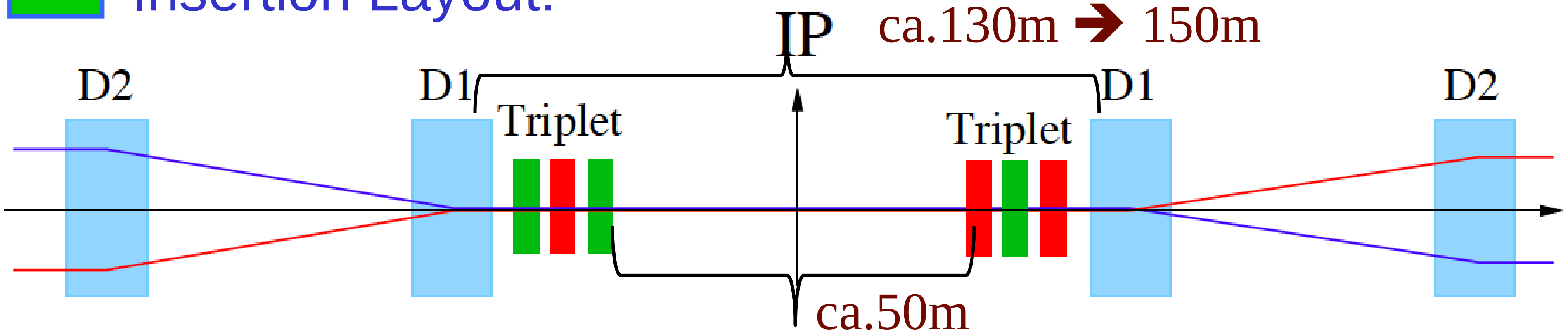




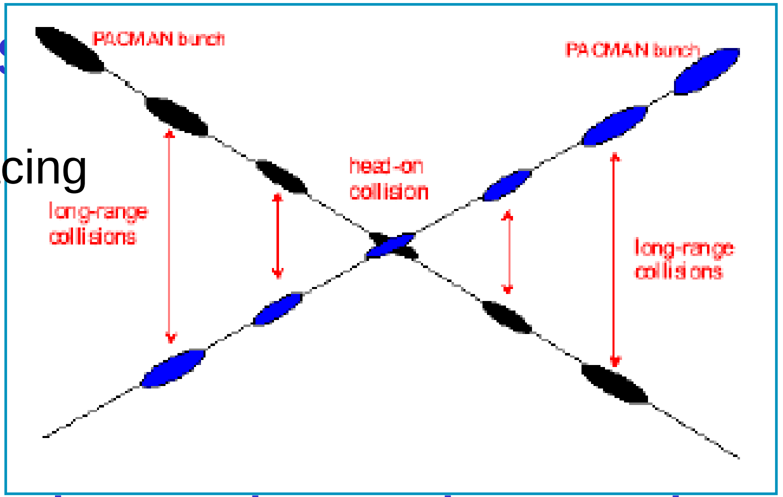

[Arrival of AUP magnet @ CERN]

# 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

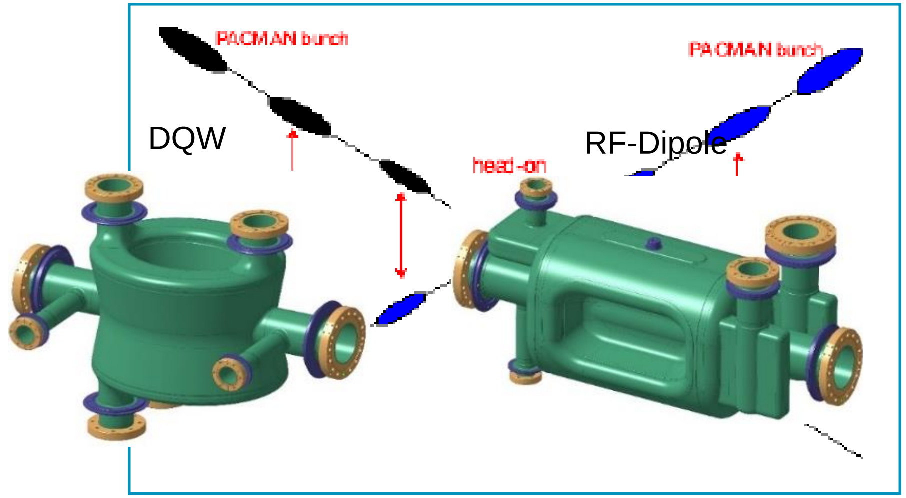
- non-linear fields from long-range beam-beam interaction:

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

# HL-LHC Technical Challenges: Crab Cavities

## Geometric Luminosity Reduction Factor:

## Crab Cavities:

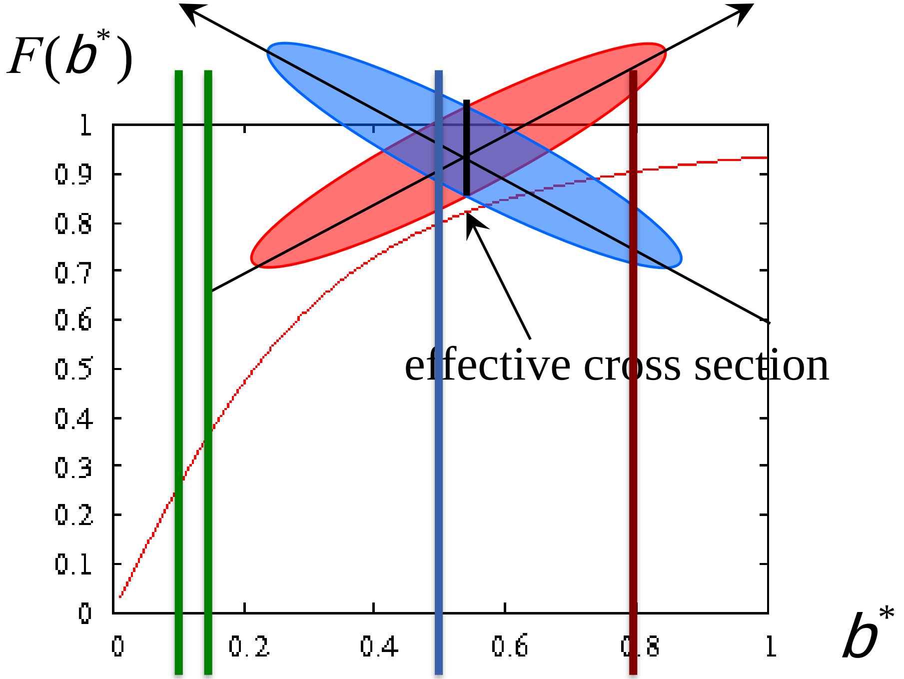


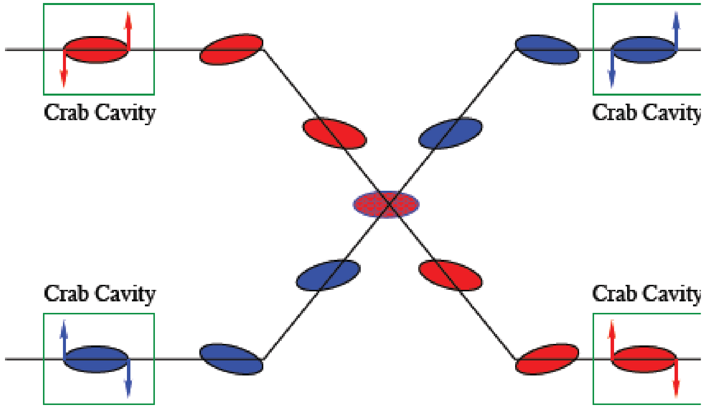

Full Crossing angle:

285 mrad LHC TDR

-> 329 mrad in LHC op

-> 500 mrad HL TDR



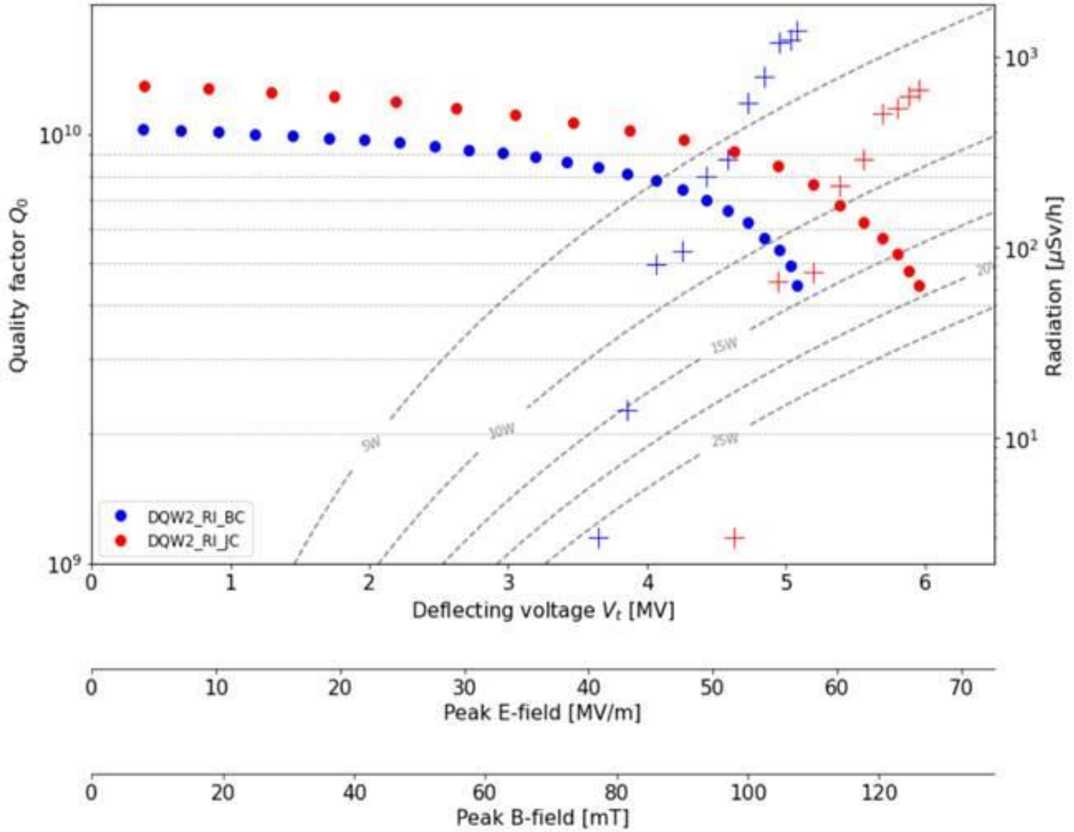




- Challenging space constraints – 194 mm separation between the 2 beams

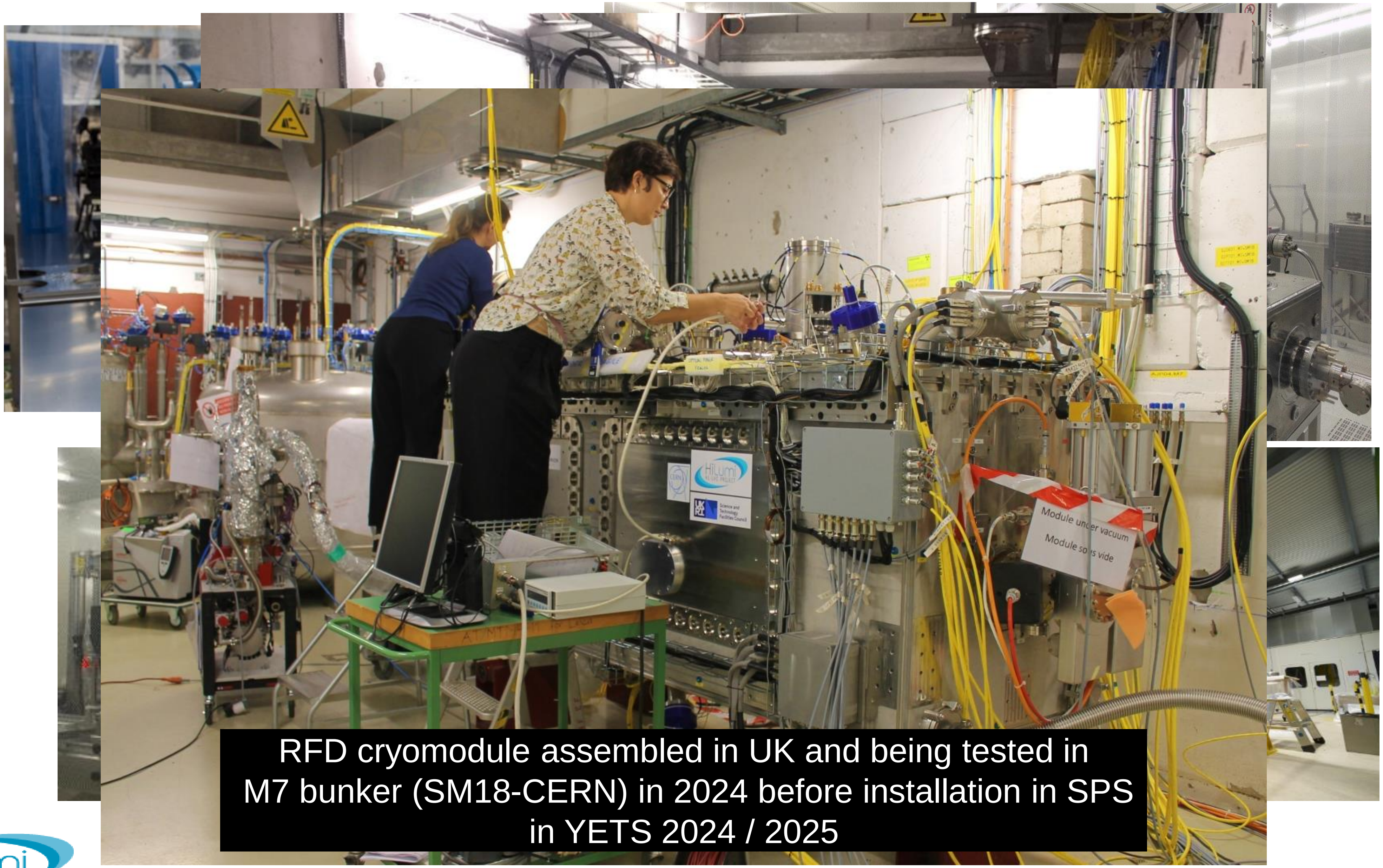
  ➔ requires compact cavity design

# Industrial DQW Series (RI)

- 1st pre-series jacketed cavity with excellent results, metrology to be finalized before acceptance
- 2nd cavity in metrology and cold tests soon

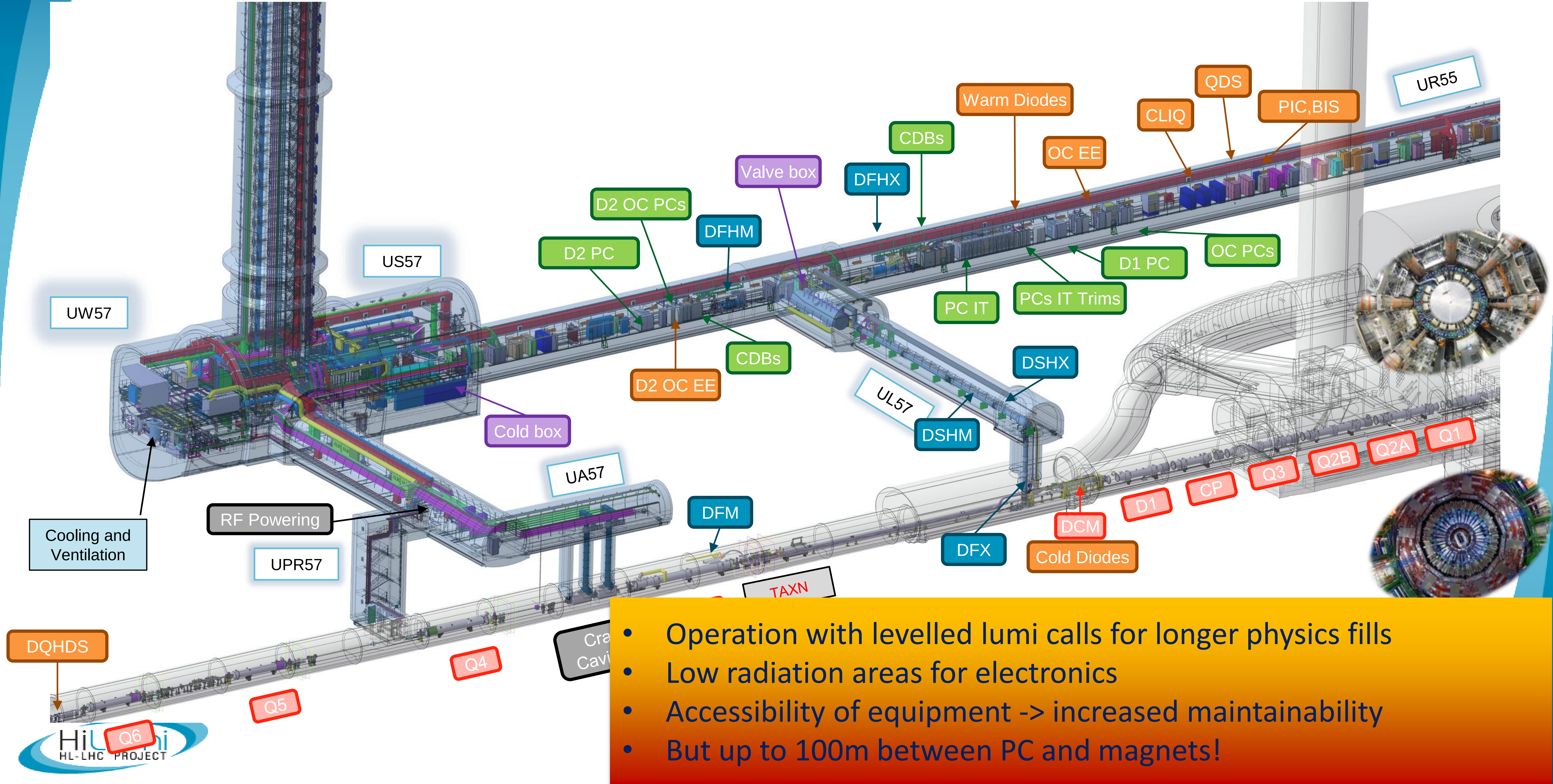


# Crab cavity cryo-modules for installation in the SPS




RFD cryomodule assembled in UK and being tested in M7 bunker (SM18-CERN) in 2024 before installation in SPS in YETS 2024 / 2025

# HL-LHC Technical Challenges: Machine Efficiency




- Operation with levelled lumi calls for longer physics fills
- Low radiation areas for electronics
- Accessibility of equipment -> increased maintainability
- But up to 100m between PC and magnets!

# IR1/5 underground civil engineering completed in 2022

Construction Finished End 2022

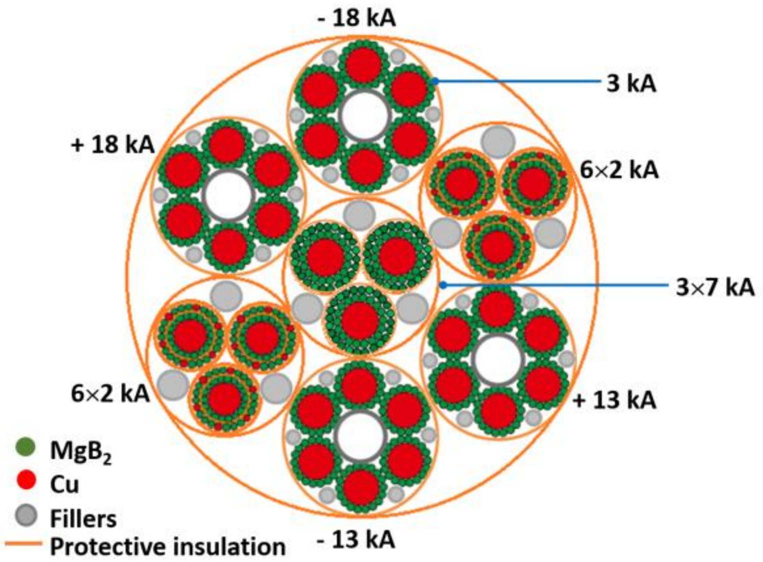
work was conducted during LS2 ➔ vibration impact

# Completion of Surface buildings in 2023

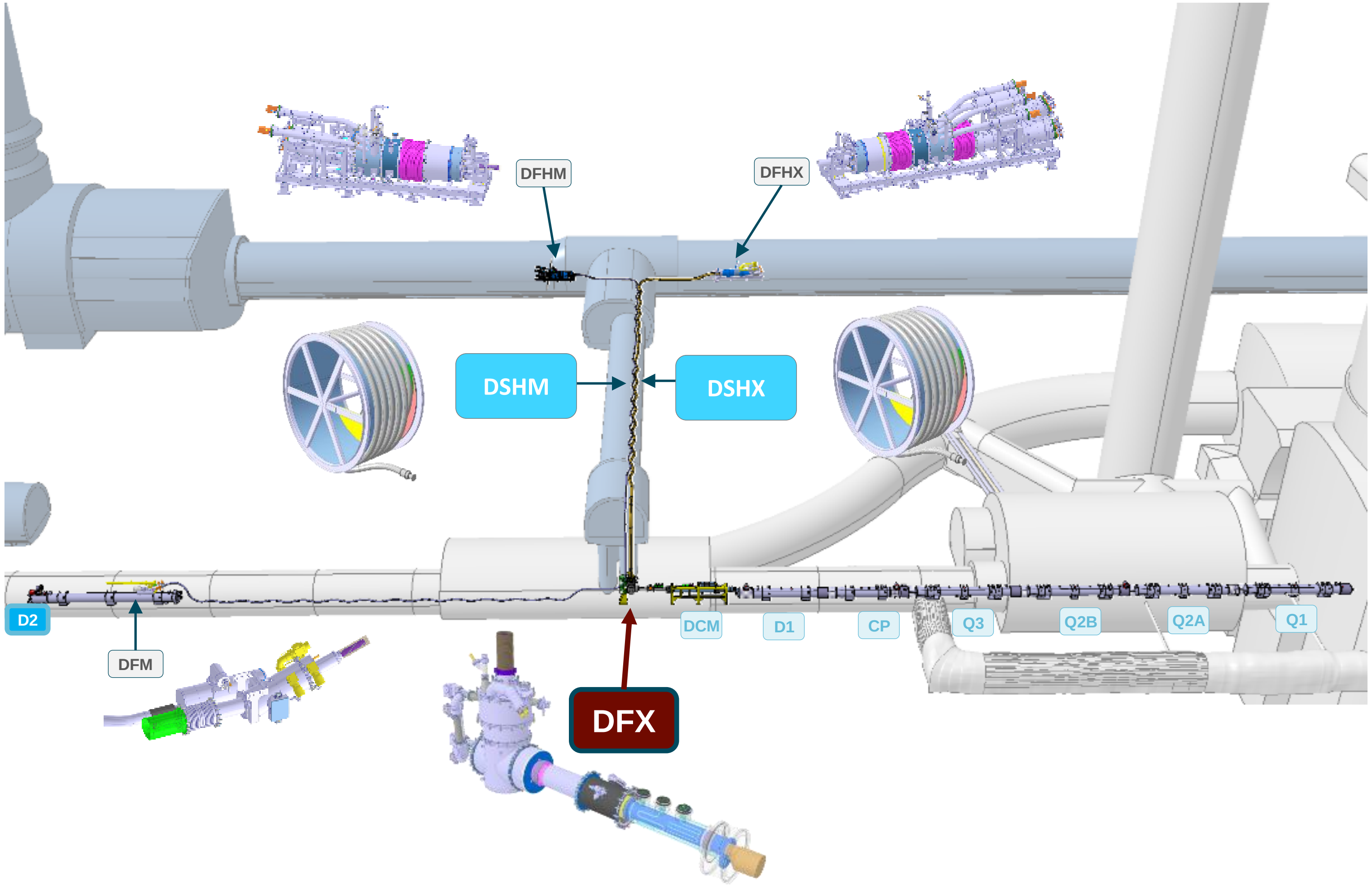

Work Ended Spring 2023


20th January 2023
Celebration Ceremony: Point 5

# HL-LHC Technical Challenges: Cold powering systems based on flexible sc link using $MgB_2$ superconductor




Diam ca. 90mm
> 100kA @ 25K

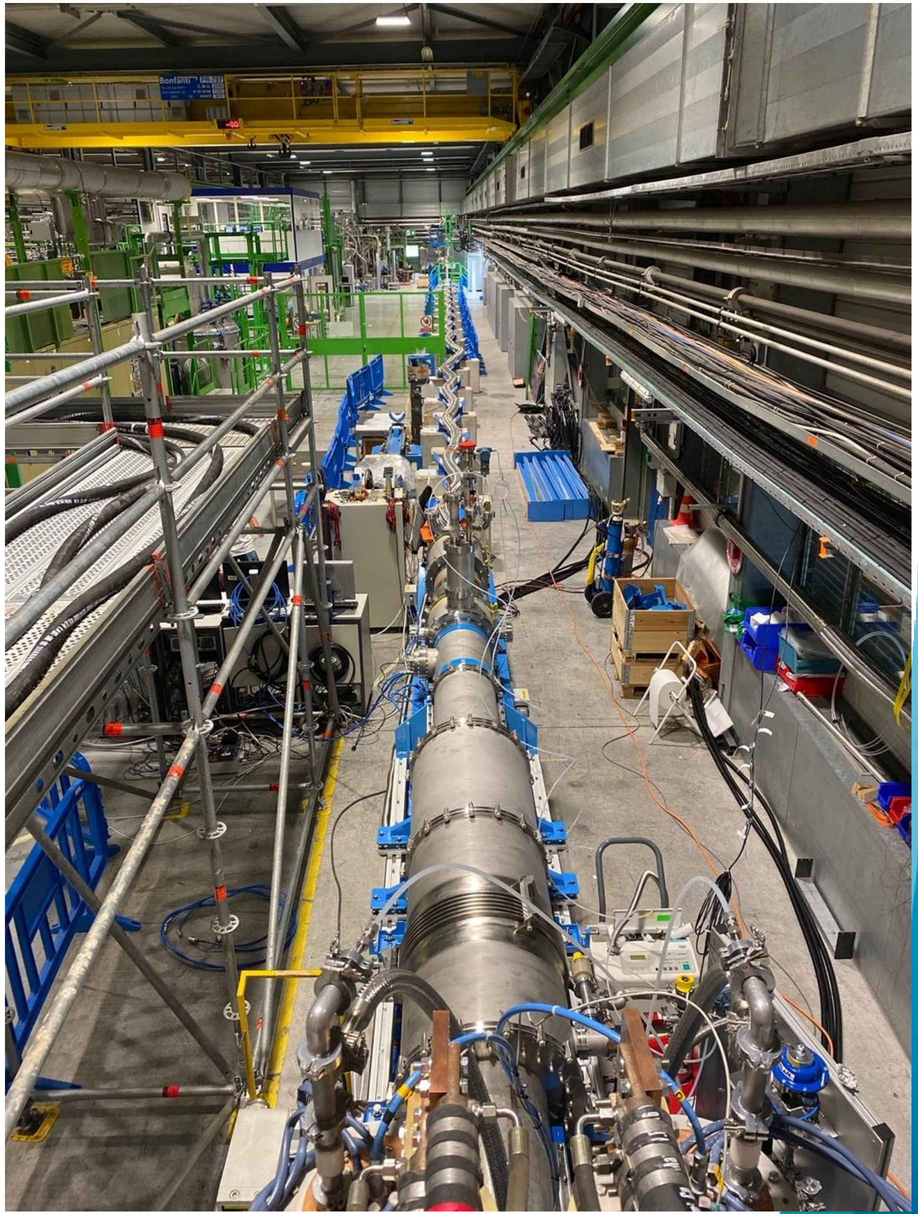


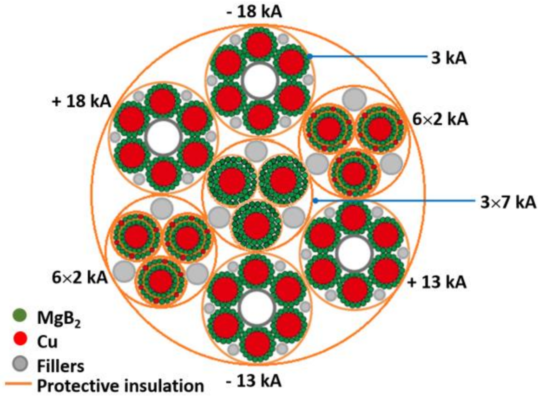
# Mg2B Superconductor and Superconducting link

Cable production complete !

More than half of flexible cryostats at CERN

Assembly of the first complete
system incl. flexible cryostats is ongoing

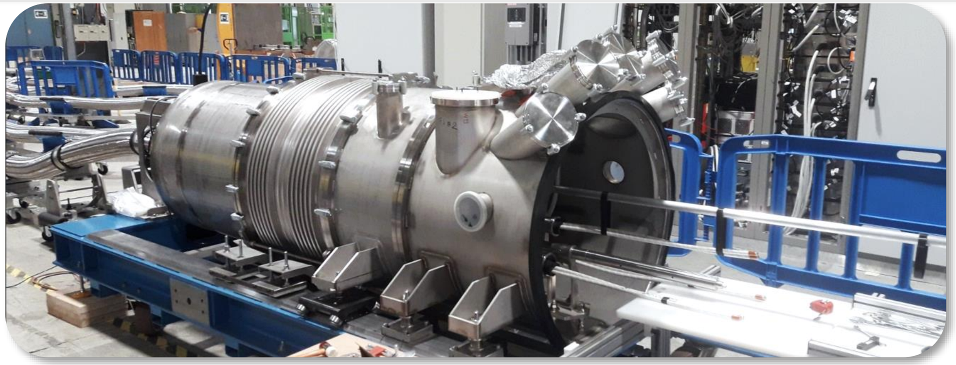





Demo-3 in SM18

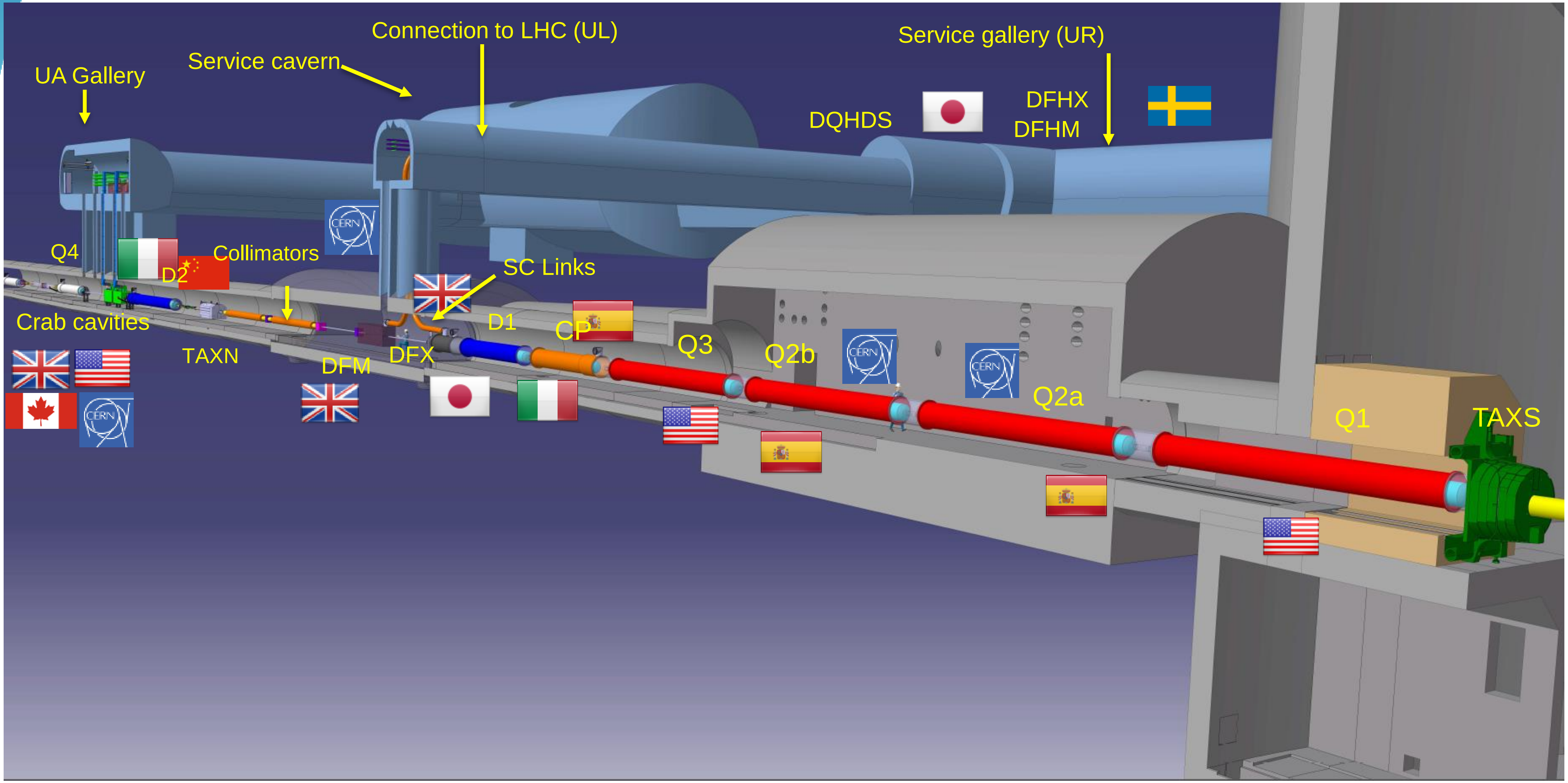
Successfully Demonstrated Concept between 2020 / 22 with > 120kA @ 30K


## Complete System Test ongoing in SM18



SC-Link-DFHX assembly in pictures

# The realization of HL-LHC is a truly international collaboration

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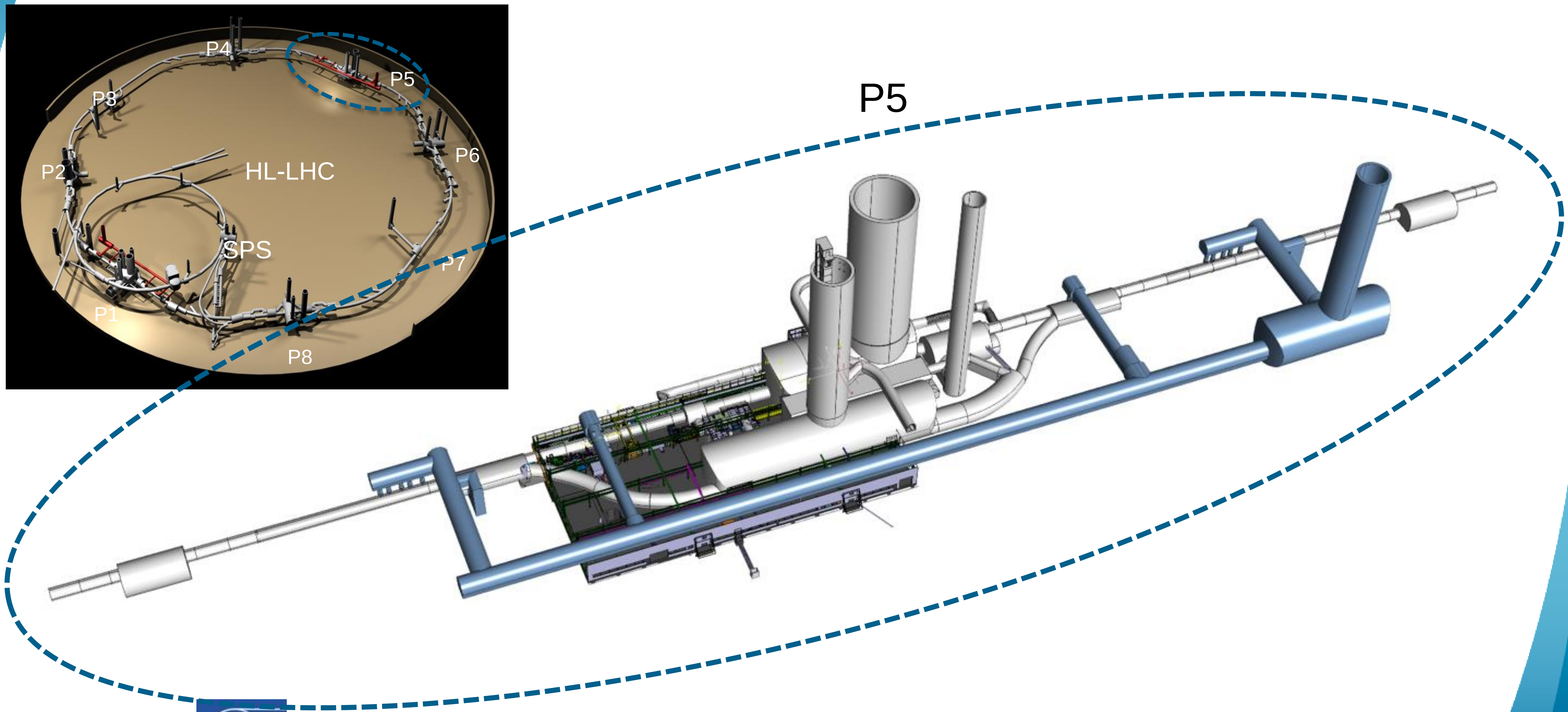
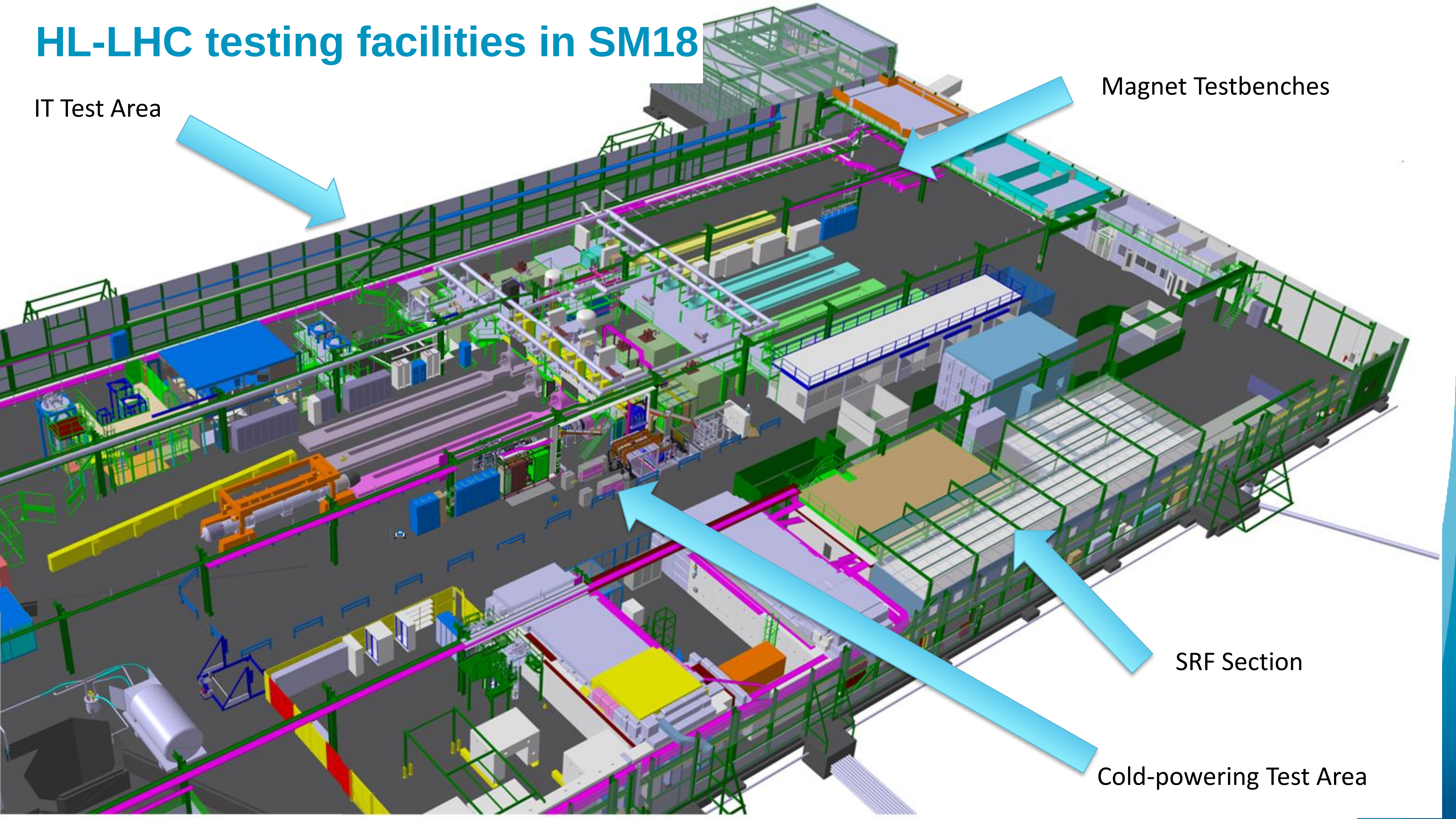
# HL-LHC IT STRING: P5L



# 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.

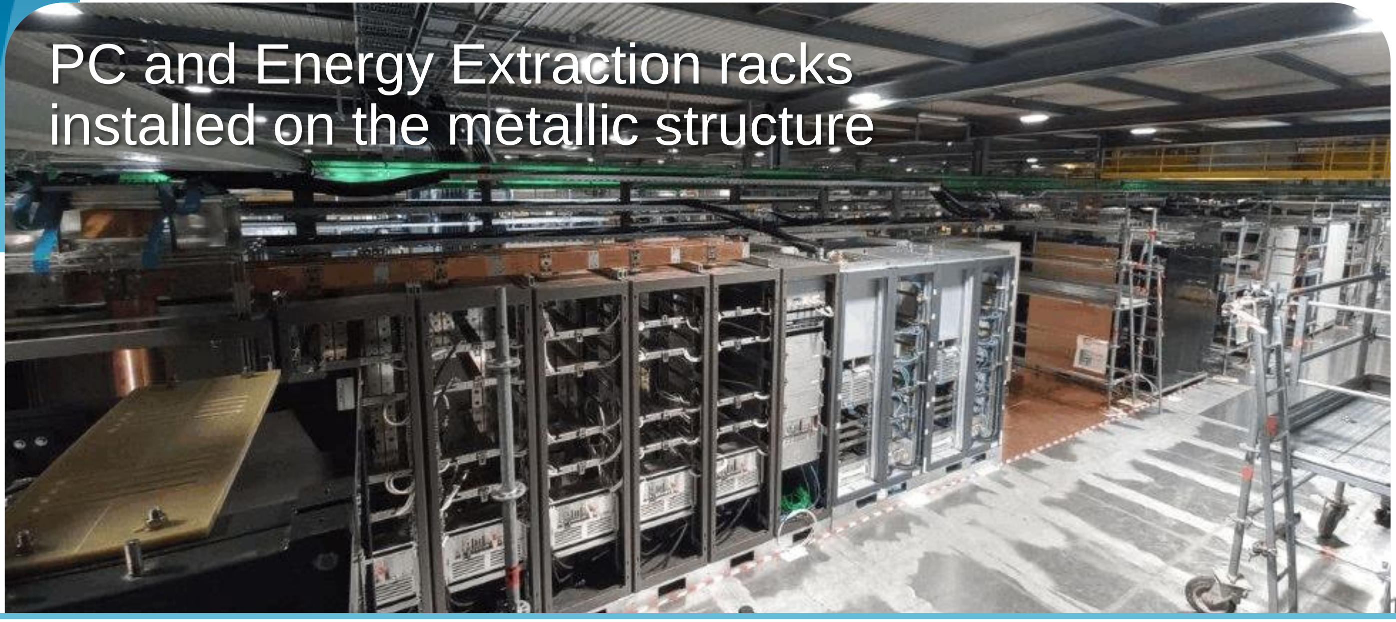
The ***scope*** of the IT STRING is to represent, as best as reasonably achievable in a surface building, the various operation modes to **STUDY and VALIDATE the COLLECTIVE BEHAVIOUR** of the different systems of the HL-LHC's IT zone (magnets, magnet protection, cryogenics of the magnets and of the superconducting link, magnet powering, vacuum, alignment, interconnections between magnets, and the superconducting link itself).

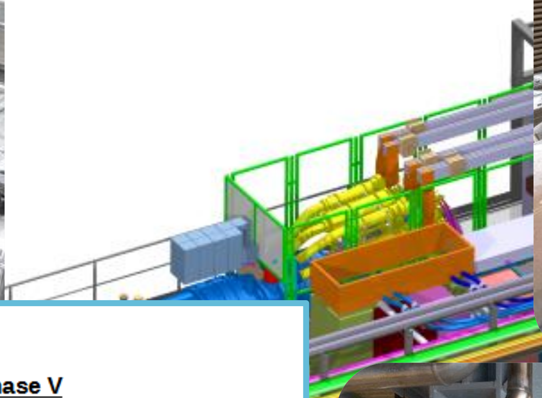
The IT **STRING** will deliver **the first complete experience** of installing and operating the IT zone

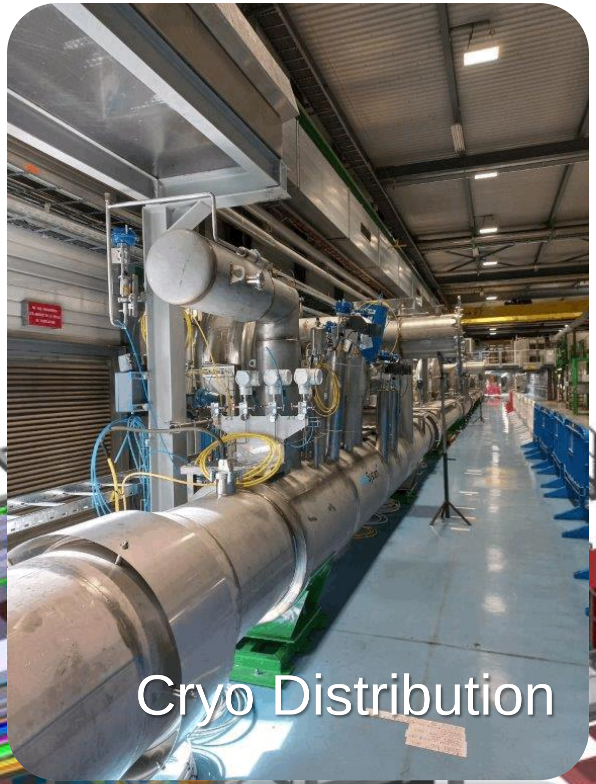
Early involvement of OP would be extremely important and beneficial for later commissioning in machine

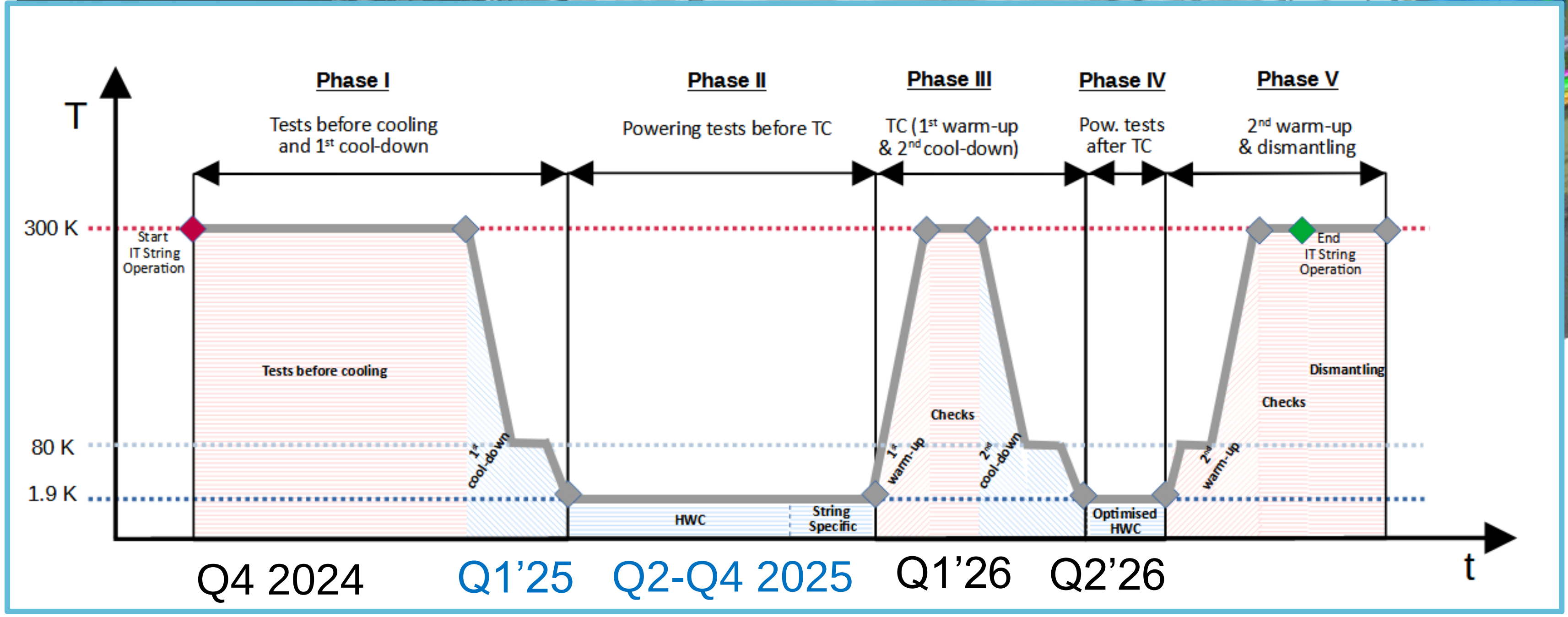
Ref. HL-LHC IT STRING Scope https://edms.cern.ch/document/1693312/1

# IT String Status in pictures



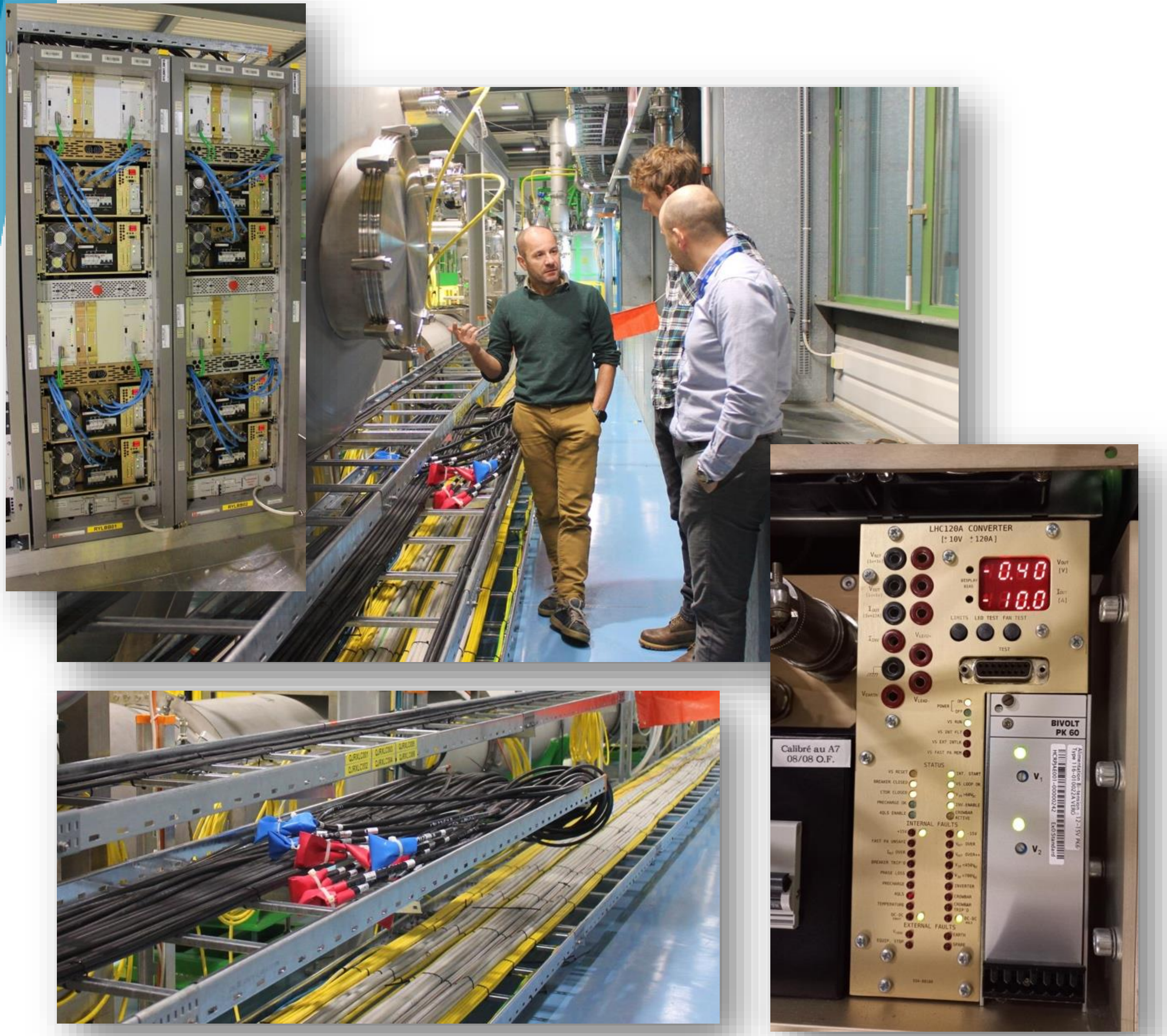



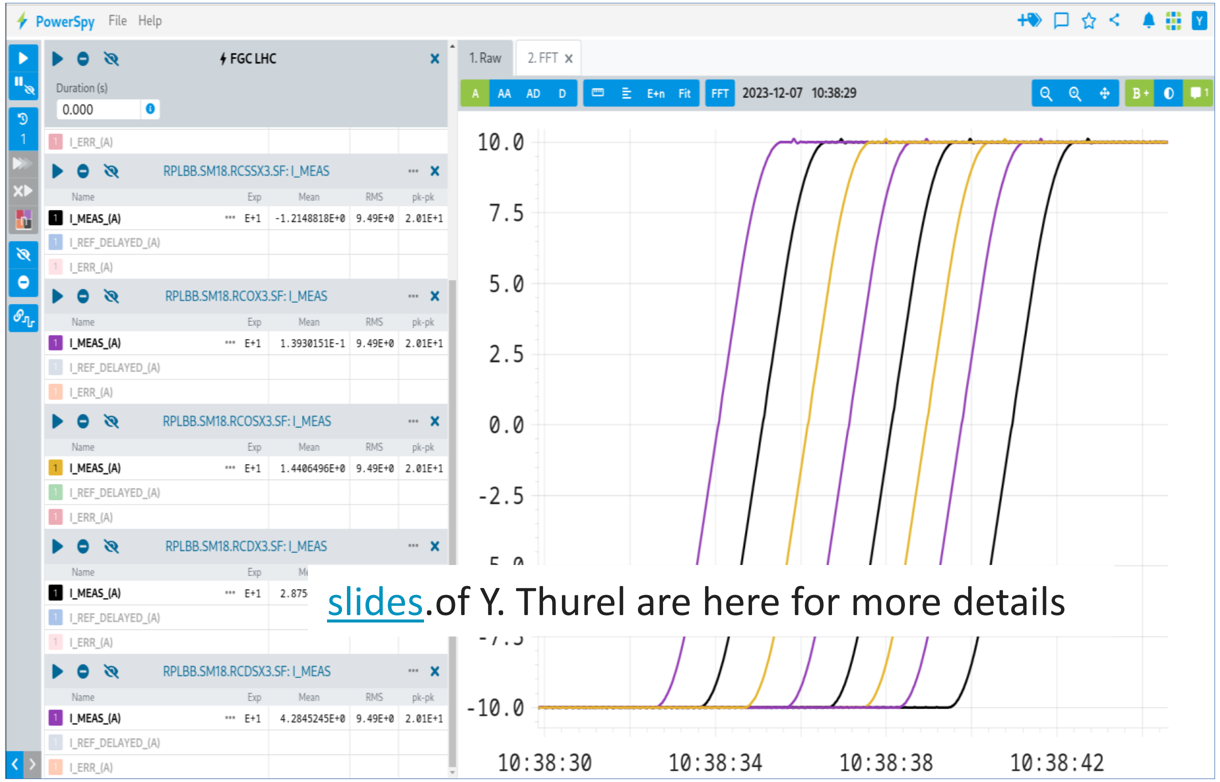



# FIRST 10 Ampers in the HL-LHC IT STRING

The 120 A circuits are with the smallest current ratings among all STRING circuits. They rely on known LHC technology.



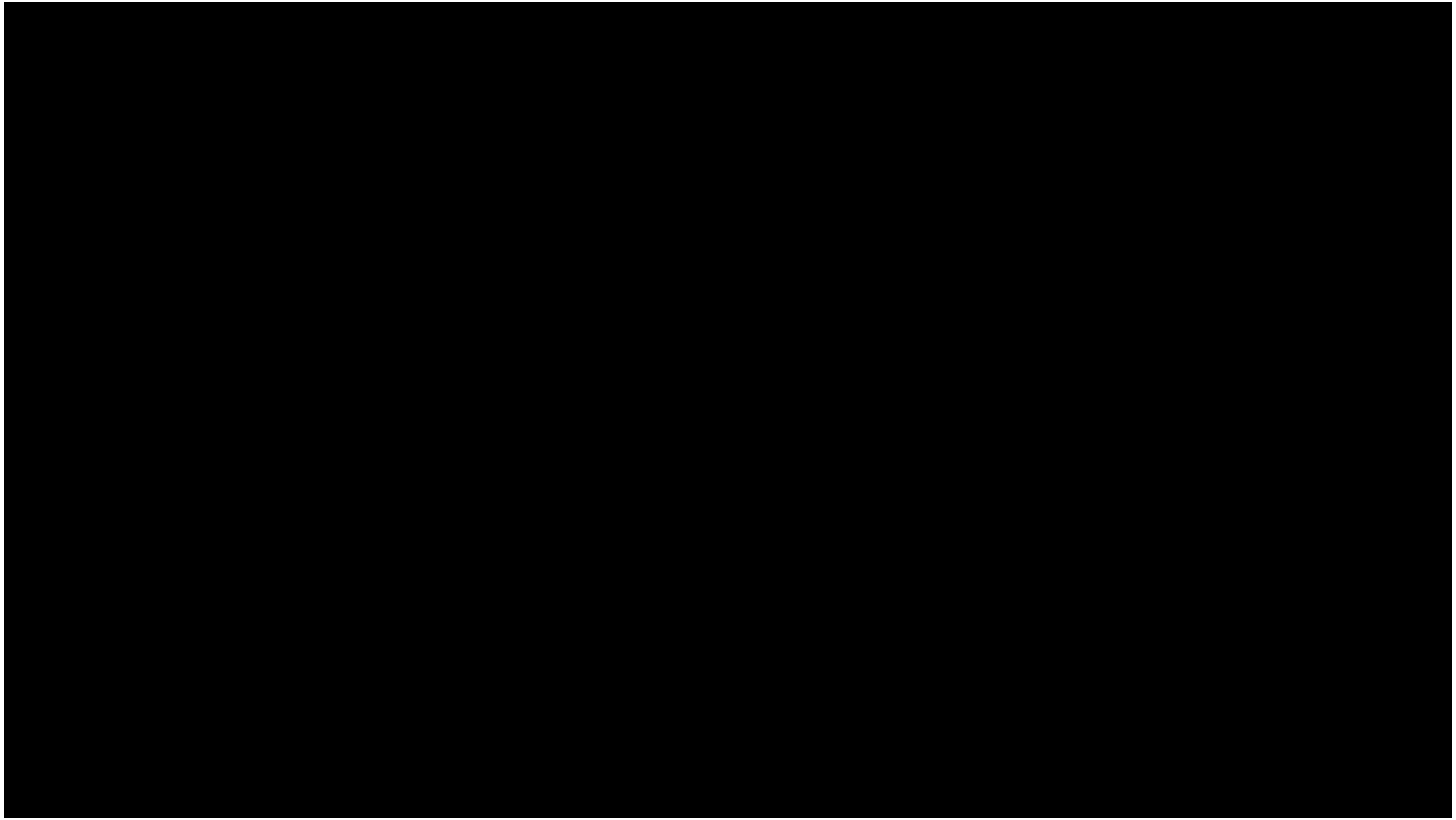




[slides](#).of Y. Thurel are here for more details

All eight converters ramping from -10A to +10A | Imeas [A]

# IT String as a testbed for LS3 installation

# IT String as a testbed for LS3 installation

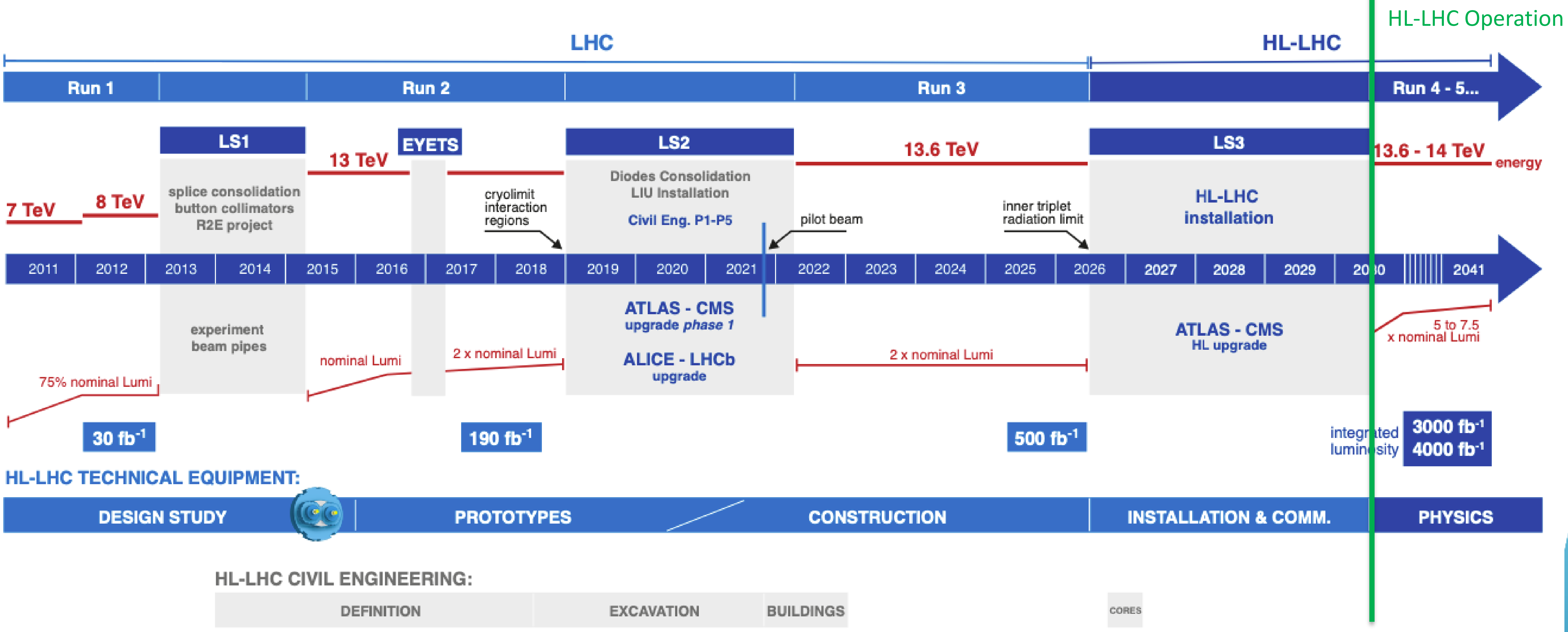


HiLumi HL-LHC PROJECT

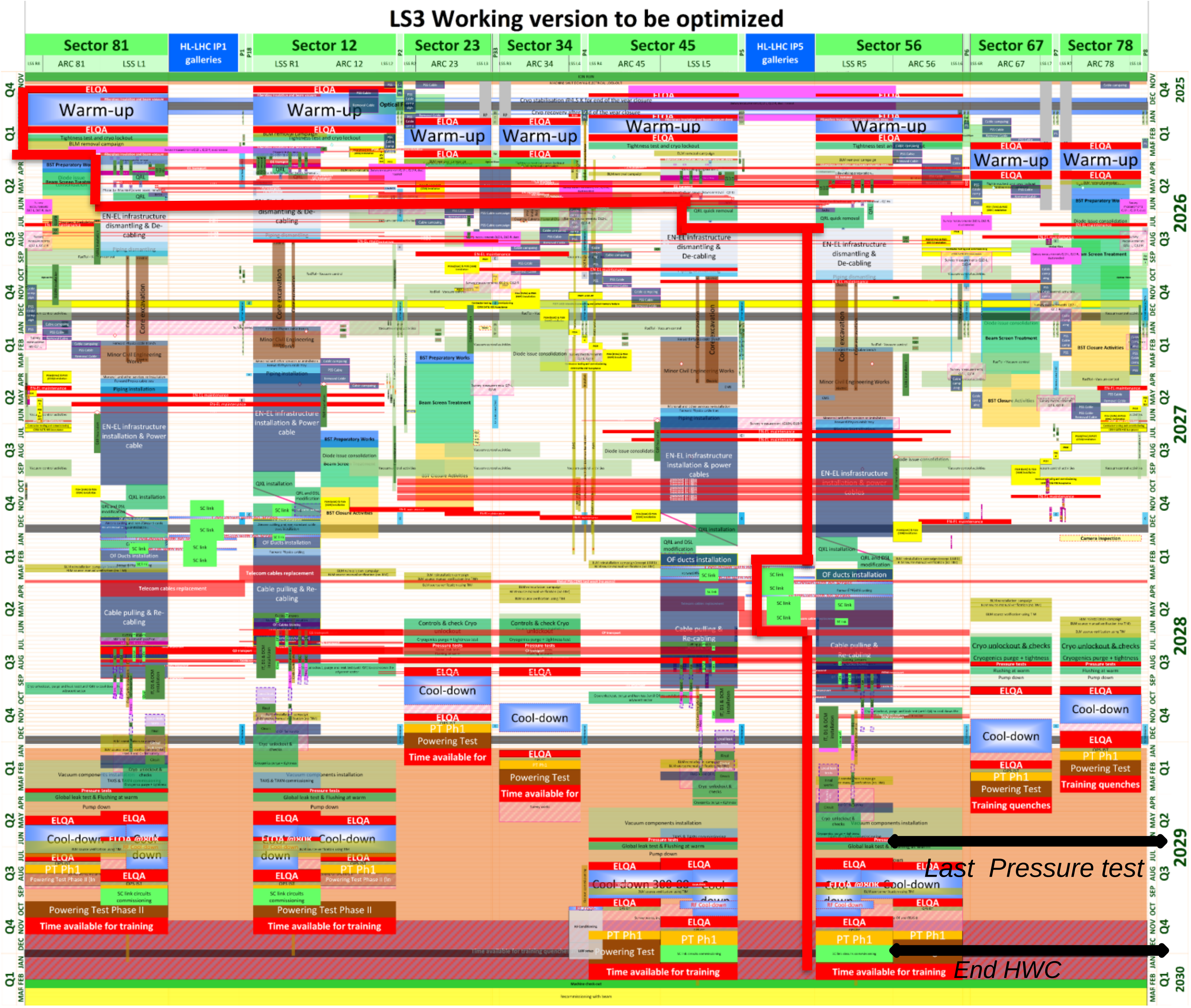
# Outline

- LHC design performance and HL-LHC upgrade goals
- (Main) Technical challenges of the HL-LHC upgrade
- Inner Triplet String
- Preparing HL-LHC operation and performance ramp-up
- Conclusions

# LHC / HL-LHC Plan



# HL Installation in the LHC during LS3 @ P1&P5




Acknowledgement: Estrella Vergara, HL-LHC C&S Review

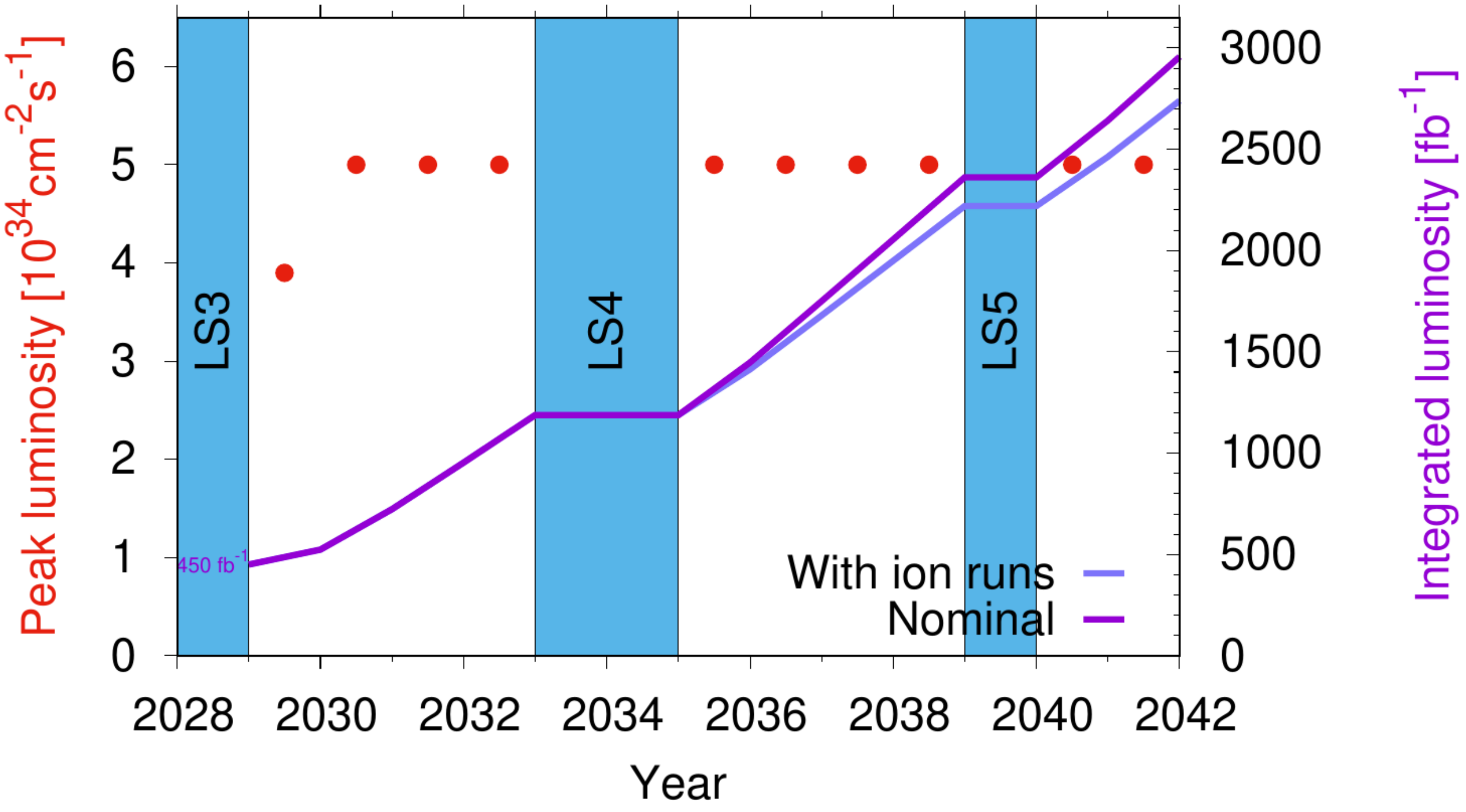
# HL-LHC hardware commissioning to start already in mid 2029, machine checkout as of Q1 2030!

# Start of HL-LHC exploitation and performance ramp-up

| Year* | ppb $[10^{11}]$ | Virtual lumi. $[10^{34}\text{cm}^{-2}\text{s}^{-1}]$ | Days in physics | $\theta$ $[\mu\text{rad}]$ | $\beta^*_{\text{start}}$ [cm] | $\beta^*_{\text{end}}$ [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 |

* Nota bene: To be updated with new long-term schedule

# Then another miracle happens…




Extension of the ALICE run beyond LS4 and the planned LHCb upgrade in LS4, both will have an impact on LHC operation and on the performance reach of HL-LHC.

# Outline

- LHC design performance and HL-LHC upgrade goals
- (Main) Technical challenges of the HL-LHC upgrade
- Inner Triplet String
- Preparing HL-LHC operation and performance ramp-up
- Conclusions

*Dear Santa Claus,*

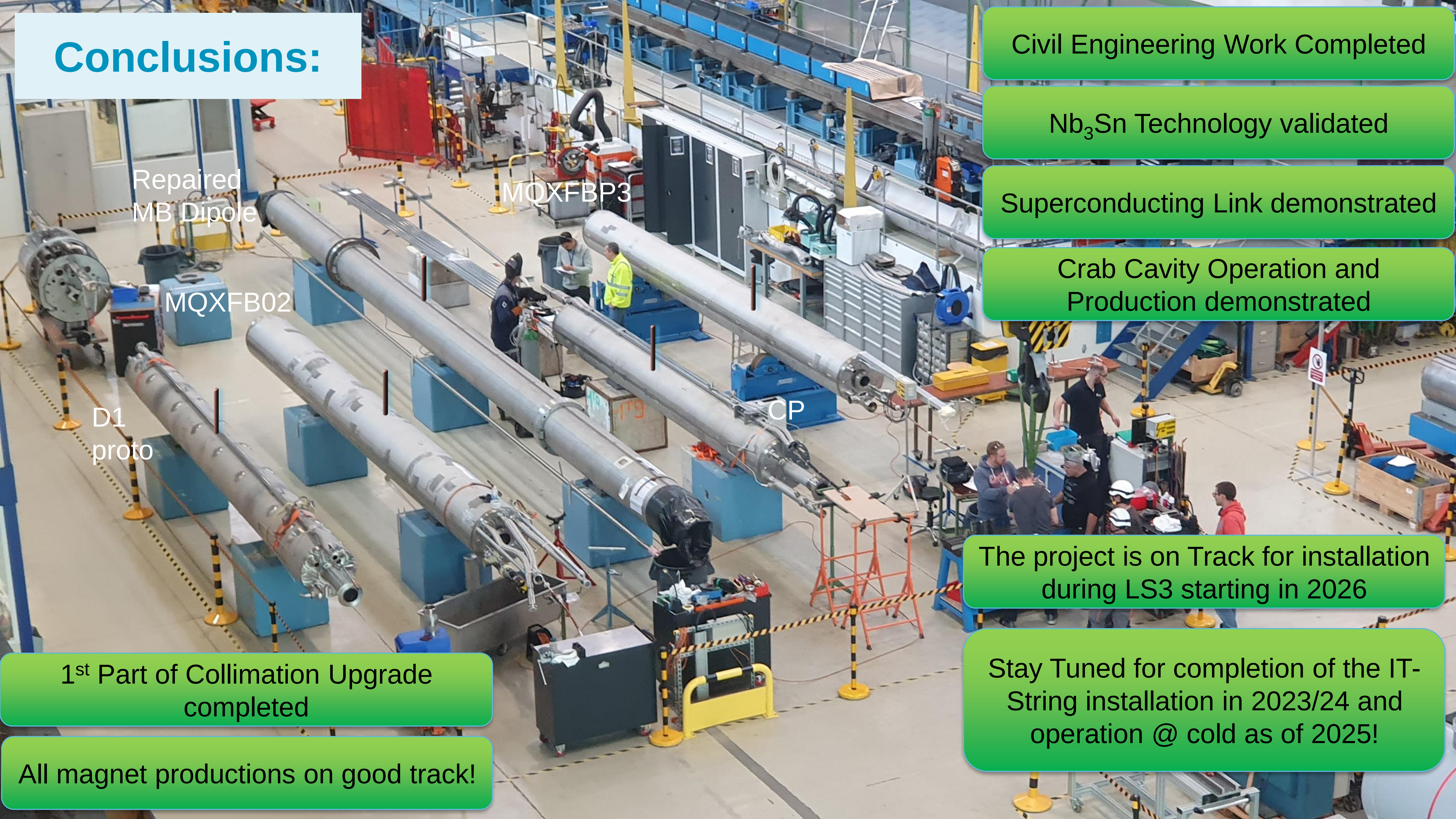
*We have been good these past decades. Please could you now bring us*

- *a dark matter candidate*
- *an explanation for the fermion masses*
- *an explanation of matter-antimatter asymmetry*
- *an axion, to solve the strong CP problem*
- *a solution to fine tuning the EW scale*
- *a solution to fine tuning the cosmological constant*

*Thank you, Particle Physicists*

*ps: please, no anthropics*

# Conclusions:




Civil Engineering Work Completed

$Nb_3Sn$ Technology validated

Superconducting Link demonstrated

Crab Cavity Operation and Production demonstrated

The project is on Track for installation during LS3 starting in 2026

Stay Tuned for completion of the IT-String installation in 2023/24 and operation @ cold as of 2025!

1st Part of Collimation Upgrade completed

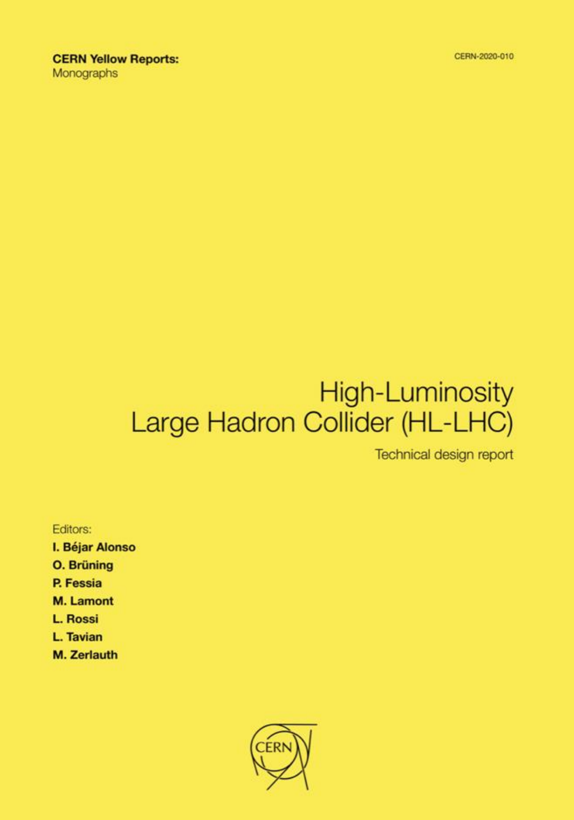
All magnet productions on good track!

# 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



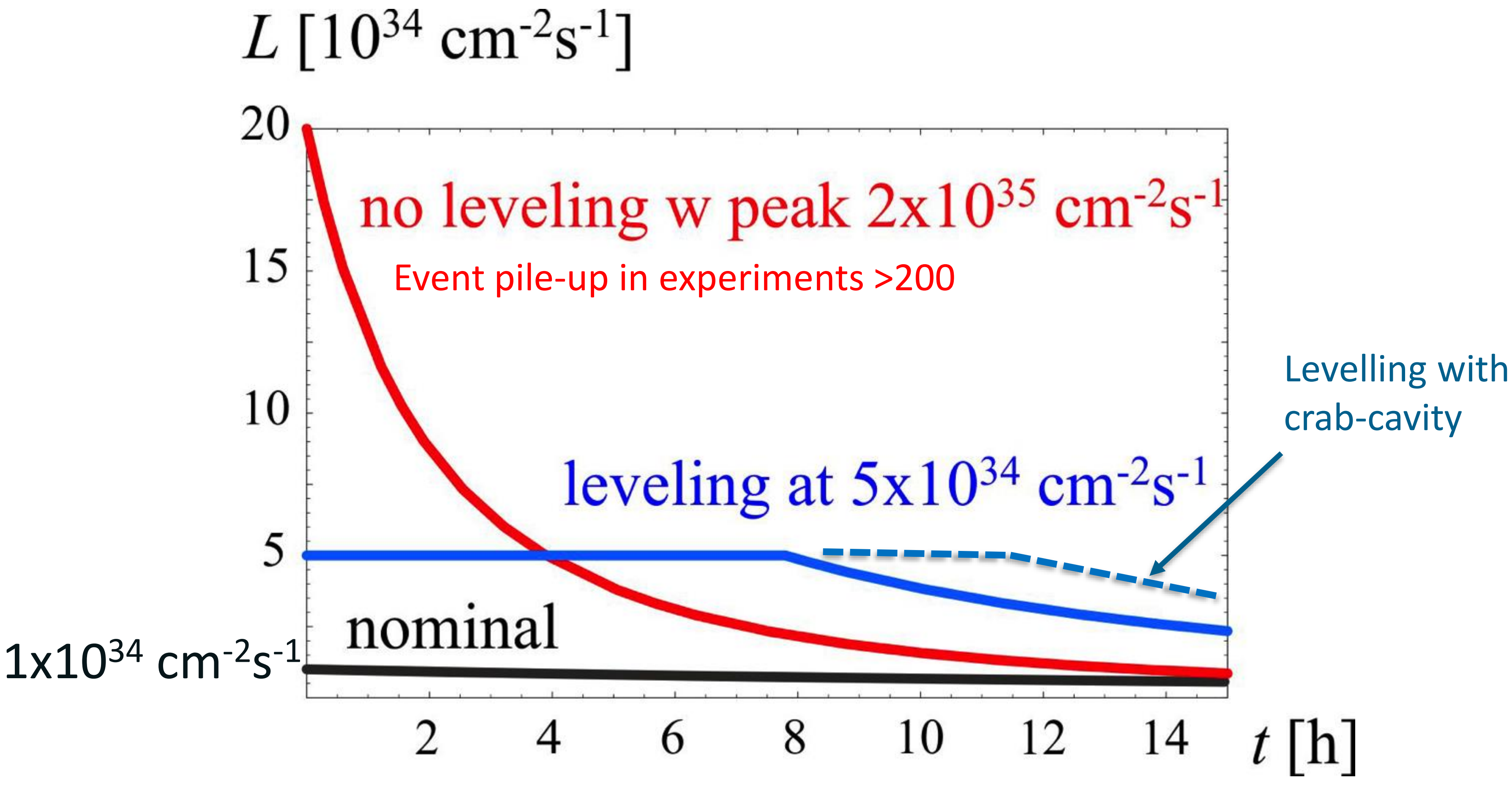

Updated Version V 1.0 published as

CERN Yellow Book in December 2020

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

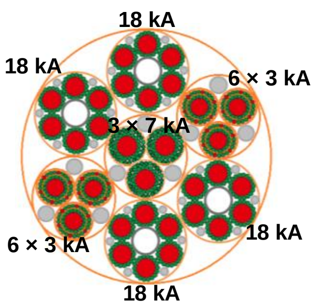

High
Luminosity
LHC

# Ideal (HL-)LHC operation

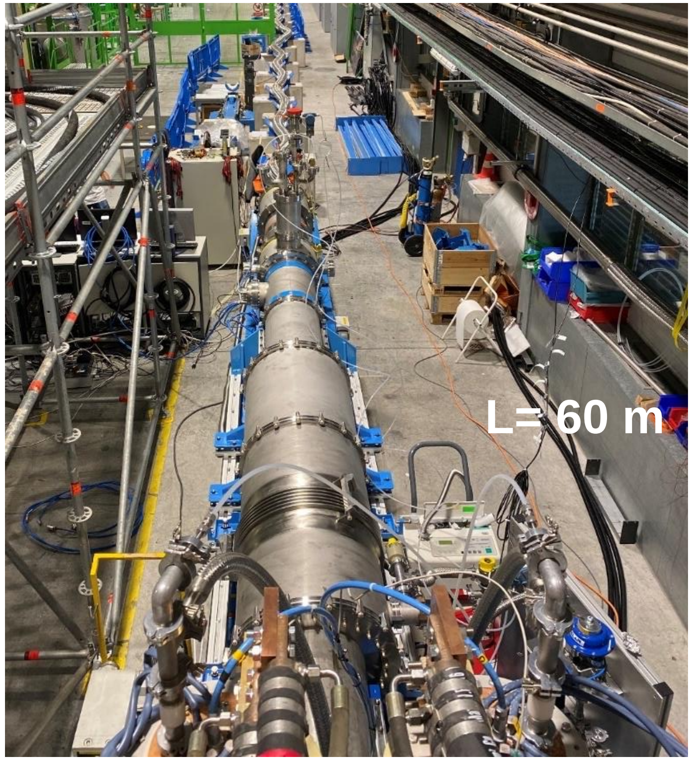


# Flexible $MgB_2$ superconducting links

$MgB_2$ cable:
Φ ~ 90 mm
|Itot| > 100 kA @ 25 K




Φ~ 90 mm

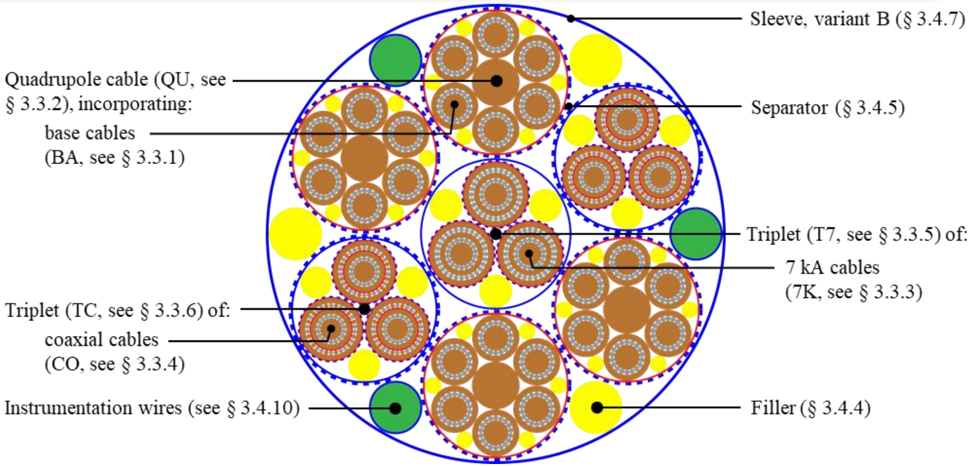




System demonstrator in SM 18
DEMO2
Demonstration of **2 x 20kA +**
**2 x 7kA** in June
in $MgB_2$ @ 30K
in flexible cryostat
over 60m [54kA total]

# $MgB_2$ Cable Assemblies (1/2)

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

- Wire grading and cable map approval procedures established
- 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

To be produced: 5+5 Units

# SC Link Cryostats

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

Leak/pressure tests at the company

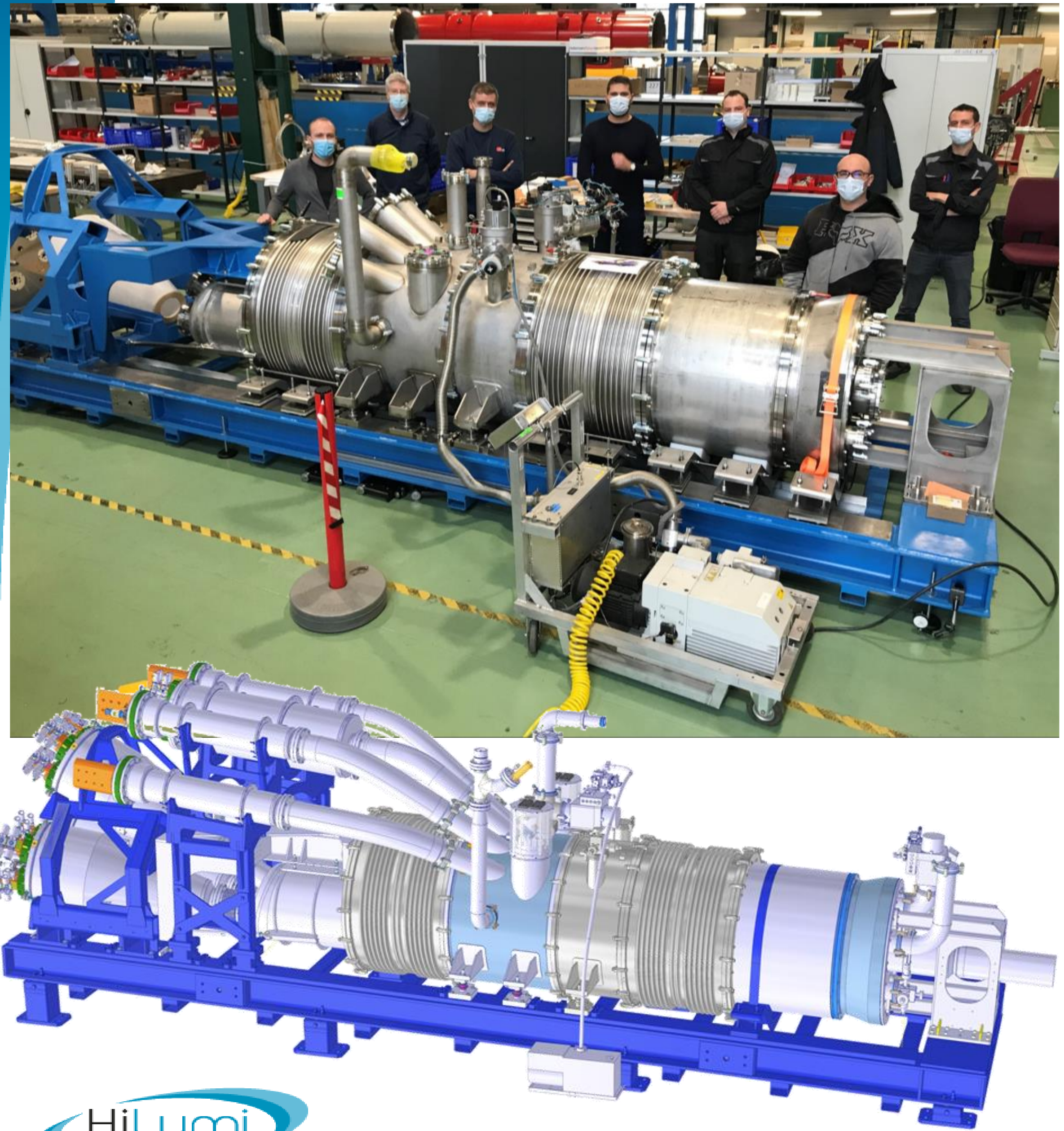

Delivery & Reception @ CERN

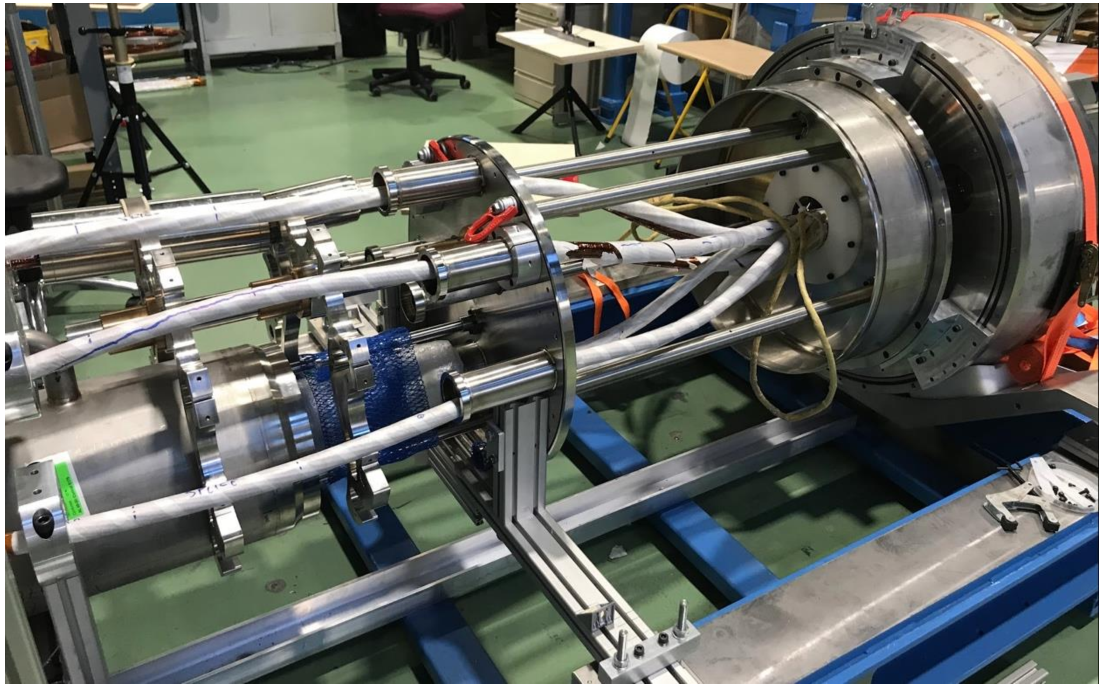
**Final length for Triplets: 74.5 m**

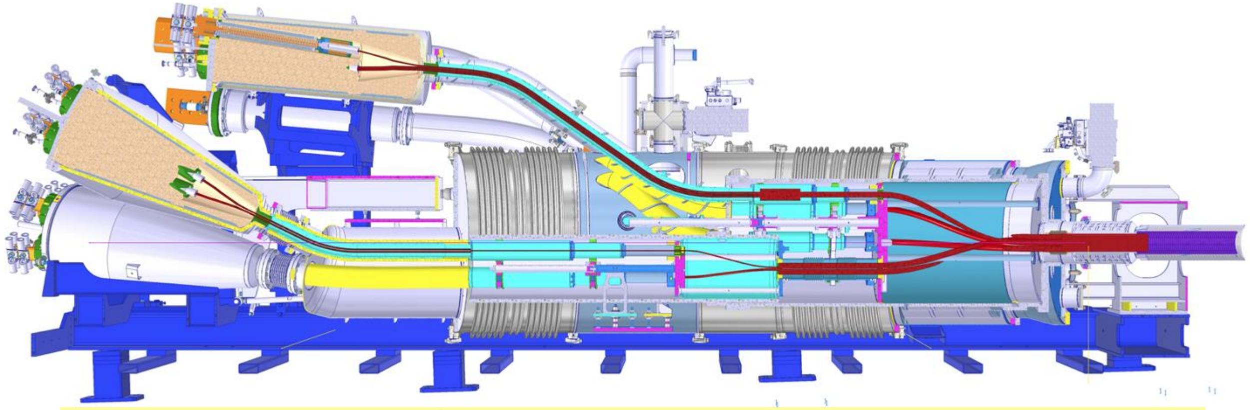
Optimization of leak test procedure

Visual and endoscopic inspections, dimension controls

# First DFHX constructed @ CERN (2/3)





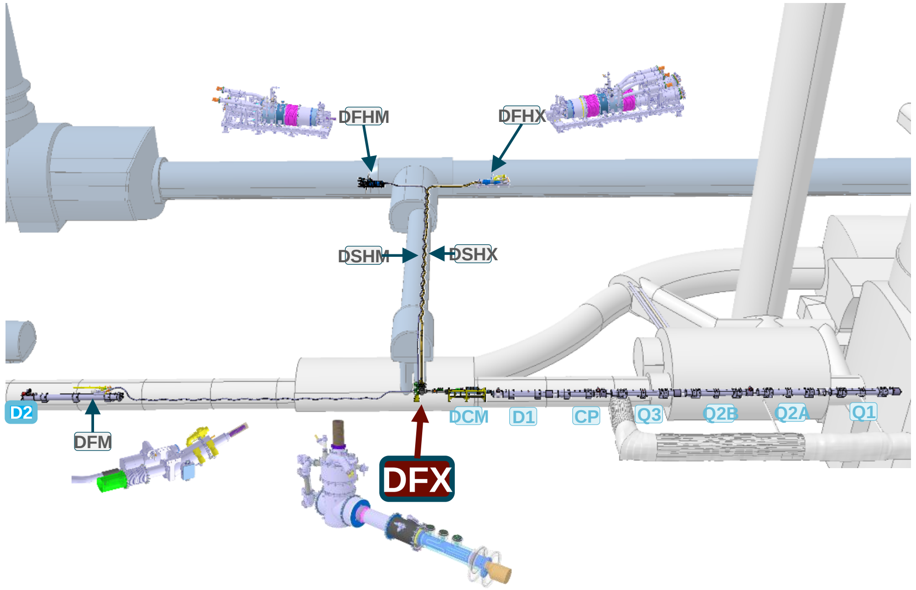


Completed **blank assembly of DFHX** and studied of $MgB_2$/HTS routing

HiLumi HL-LHC PROJECT

# DFX Cryostat

Completed **pre-series DFX** by SOTON (UK1 ) !


**CERN-UK1 collaboration** under addendum #4 of KE3299/TE/HL-LHC

Design, Manufacturing, QC & CE certification under the responsibility of **Southampton University**

**PRR** 3 March 2020. **1.5 intense years** from raw material procurement to completion of qualification and CE certification by notified body

**Completed in March 2022** at **LTI Metaltech** & **delivered to CERN**

# HL-LHC Project Office

HiLumi HL-LHC PROJECT

Communications & Outreach Office

Cécile Noels

Proj

Irene Garcia Obrero

Michela Lan

PROJECT MANAGEMENT

Thomas Otto

Christelle Gaignant

Michel Bonnet

The HL-LHC Project is in the process of

Strengthening the liaison with the CERN central support team and

Safety Units for the

LS3 Organization

PLAN

Monitoring & Control Offi

OORDINATION

Integration & Installation Office

Giovanna Vandoni

Lars Jensen

Laurent Tavian

Hector Garcia Gavela

Paolo Fessia

Maria Barberan, Thomas Bauler, Lidia Brozda, Sarah Fleury

Cécile Noels

Henry de Maynard

Victor Guillen Humbria, Gorana Prica

Michele Modena

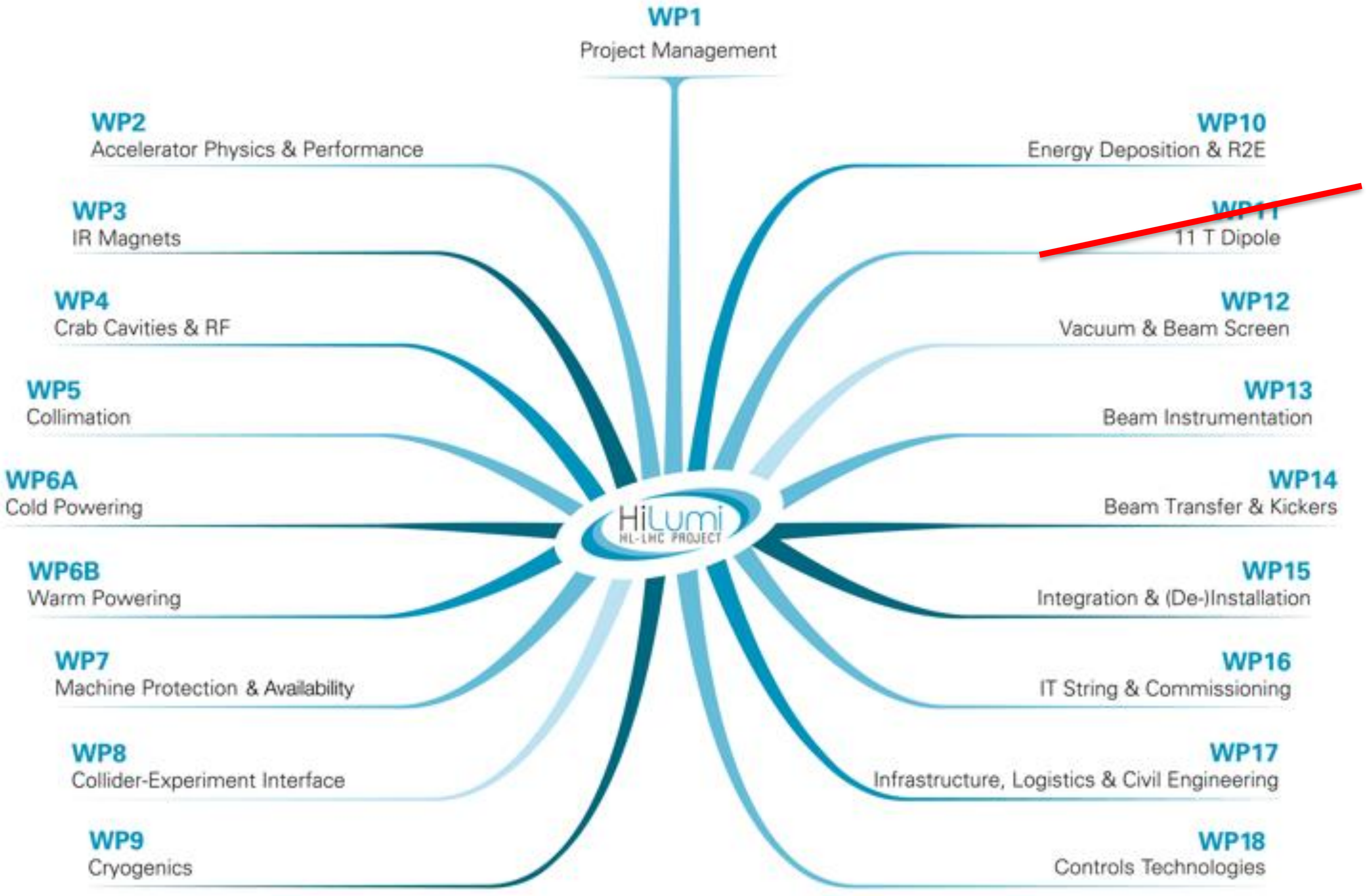
Lars Jensen, Laura Martins, Evan Vedsessou, Estrella Vergara

Laura Martins

Thomas Bauler, Lidia Brozda

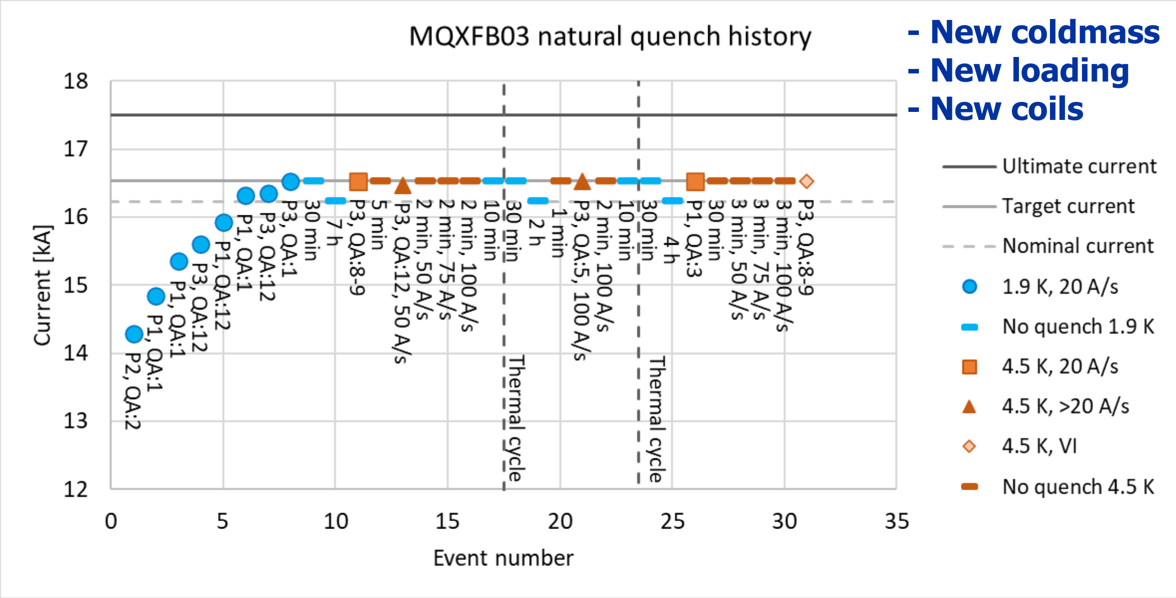
Miguel Navarro, Francesca Nicoletti

# HL Project Management and Organsiation



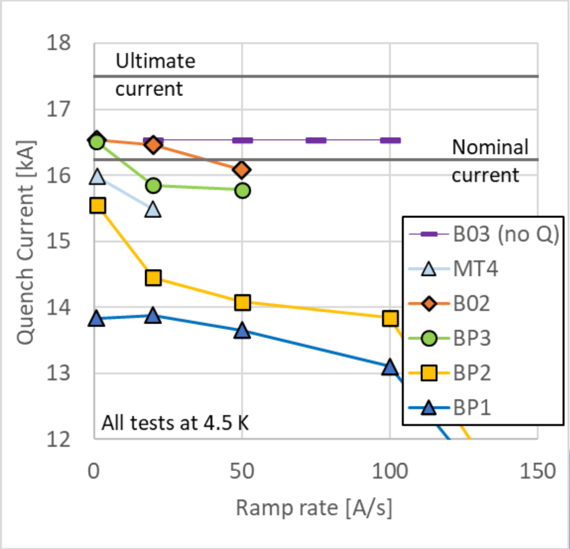
# Recovery Plan for MQXFB

- MQXFB03 is the 3rd **magnet of 3-stage strategy,** integrating all recovery actions
  - **(1) improved** *cold mass assembly* and fixed point;
  - **(2) improved** *magnet loading* to avoid overshoot;
  - **(3) improved** *coil manufacturing* to remove hump & belly.
- It was tested in **Q3/Q4 2023** and is the first 7.2-m-long MQXFB magnet to **achieve target current of 16.53 kA** at both **1.9 K and 4.5 K.**
- It shows **good endurance** after **2 warm-up/ cooldown cycles** with no retraining at 1.9 K; **no ramp rate degradation** up to **100 A/s;** initial **training quenches at 1.9 K** are all in **coil ends** (2 training quenches at 4.5 K upon reaching target current plateau under investigation).
- **Performance limitation** and **phenomenology** observed on previous, full-length, MQXFB magnet straight sections (near apex of hump & belly) have been **overcome** and **root cause** has been **eliminated.**
- **Series production** has been **launched** (next magnet, MQXFB04, already loaded).




Quench Performance of 7.2-m-Long MQXFB03 Quadrupole Magnet at CERN

Ramp rate sensitivity of 7.2-m-Long MQXFB03 Quadrupole Magnet at CERN

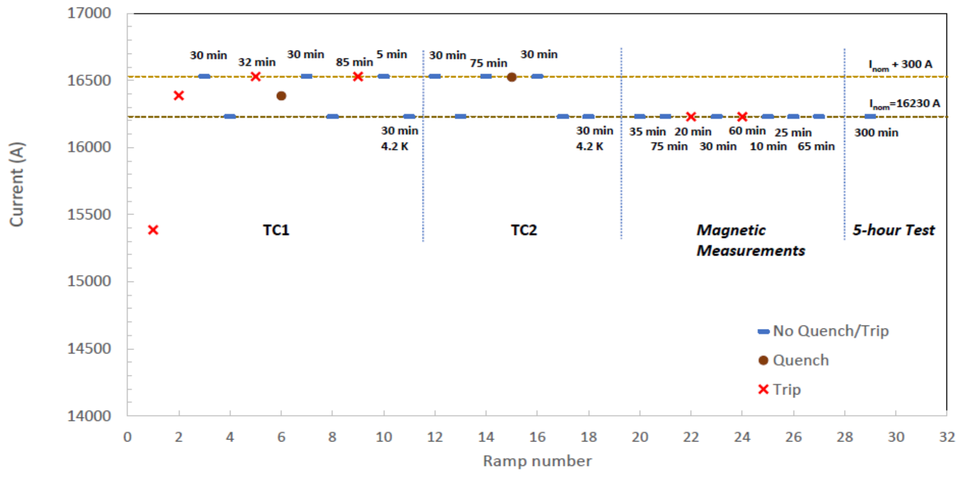



A. Devred, *et al.*

# Highlights on MQXFA (US Contribution)

- **AUP** has completed the assembly and has successfully tested on an horizontal bench at Fermilab the first **Q1/Q3 cryo-magnet (LQXFA01).**
- **LQXFA01** includes 2 4.2-m-long quadrupole magnets: **MQXFA03** and **MQXFA04,** which were previously tested in vertical station; neither of them exhibited **any retraining.**
- **LQXFA01** was **shipped to CERN** and arrived in SMI2 on **28 November 2022.**
- It will be retested at CERN on **upgraded test bench A2** in **Spring 2024** prior to installation in the string (but cannot be used as is for tunnel installation).

⇒ *Warm thanks to all of those in **LMF, EN-MME** and **HSE** who contributed to resolve the issue of weld procedure qualification and paved the way for use of this cryomagnet in the string.*




Quench summary of LQXFA01 tested horizontally at Fermilab

**Courtesy of S. Feher and G. Ambrosio** (Fermilab)

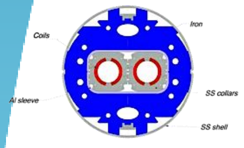
First AUP LQXFA01 cryomagnet mounted on Cryostat Tooling in SMI2 at CERN

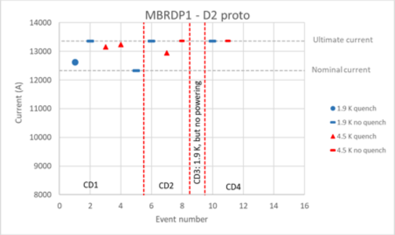
**Courtesy of D. Duarte Ramos** (CERN TE-MSC)

# Nb–Ti Magnets for HL-LHC

**After E. Todesco** (CERN TE-MSC)

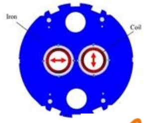
- Good progress on industrial productions of Nb–Ti magnets for HL-LHC, thanks to efficient collaborations with partner institutes; production of remaining MCBXF correctors to be internalized by CIEMAT and CERN.



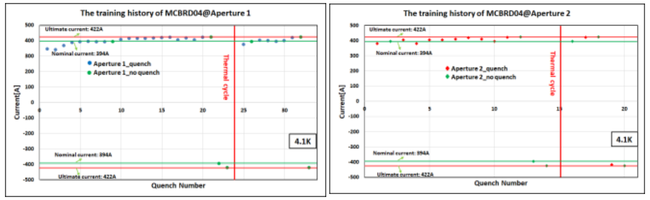

8-m-long, 105-mm-double aperture **D2 dipole magnet** prototype (4.5/5.3 T bore/peak field @12.23 kA)

**Courtesy of S. Farinon** (INFN-Genova)
**and A. Foussat** (CERN TE-MSC)



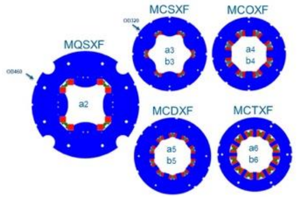

苏州八匹马超导科技有限公司

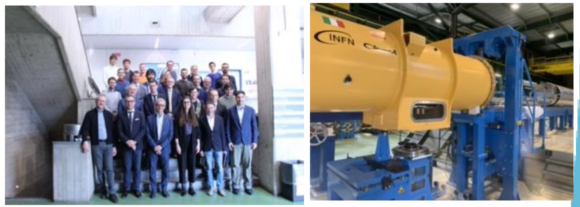
**MCBRD04**




2-m-long, 105-mm-double aperture, **CCT orbit corrector magnet** (2.6/2.94 T bore/peak field @394 A)

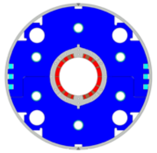
**Courtesy of Q. Xu** (IHEP)
**and A. Foussat** (CERN TE-MSC)

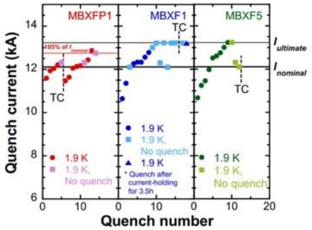


**High-order corrector magnets** production completed; all magnets tested and accepted; cryostating of first corrector package underway at SMI2.

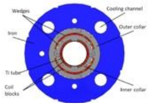
**Courtesy of M. Statera** (INFN-Milano)
**and E. Gautheron** (CERN TE-MSC)



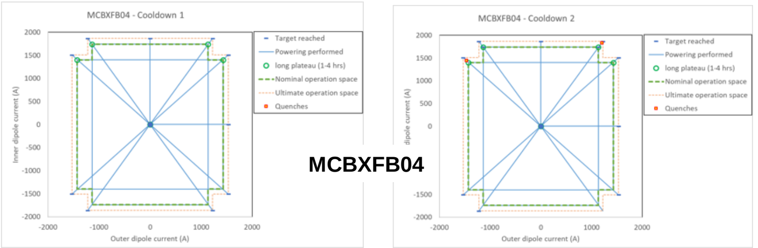



6.7-m-long, 150-single-aperture **D1 dipole magnet** (5.6/6.58 T bore/peak field @12.11 kA)

**Courtesy of T. Natsumoto** (KEK)
**and J.-C. Perez** (CERN TE-MSC)



Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas




**MCBXFB04**

1.2/2.2-m-long, 150-single-aperture **nested dipole magnet corrector** (2.1/4.13 T bore/peak field @1.58 kA)

**Courtesy of F. Toral** (CIEMAT)
**and J.-C. Perez** (CERN TE-MSC)

A. Devred, *et al.*

STATUS

# Status MQXFA – Q1 & Q3- Assemblies at AUP

- 8 out of 20 magnets build, tested a

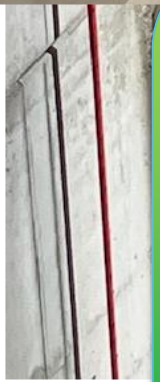
CA01 Arriving @ CERN November 28th 2023

CA01 Leaving FNAL October 30th 2023

# in Pt1 and Pt5

ny CERN teams (EN-ACE, SCE, HSE WP17,...)

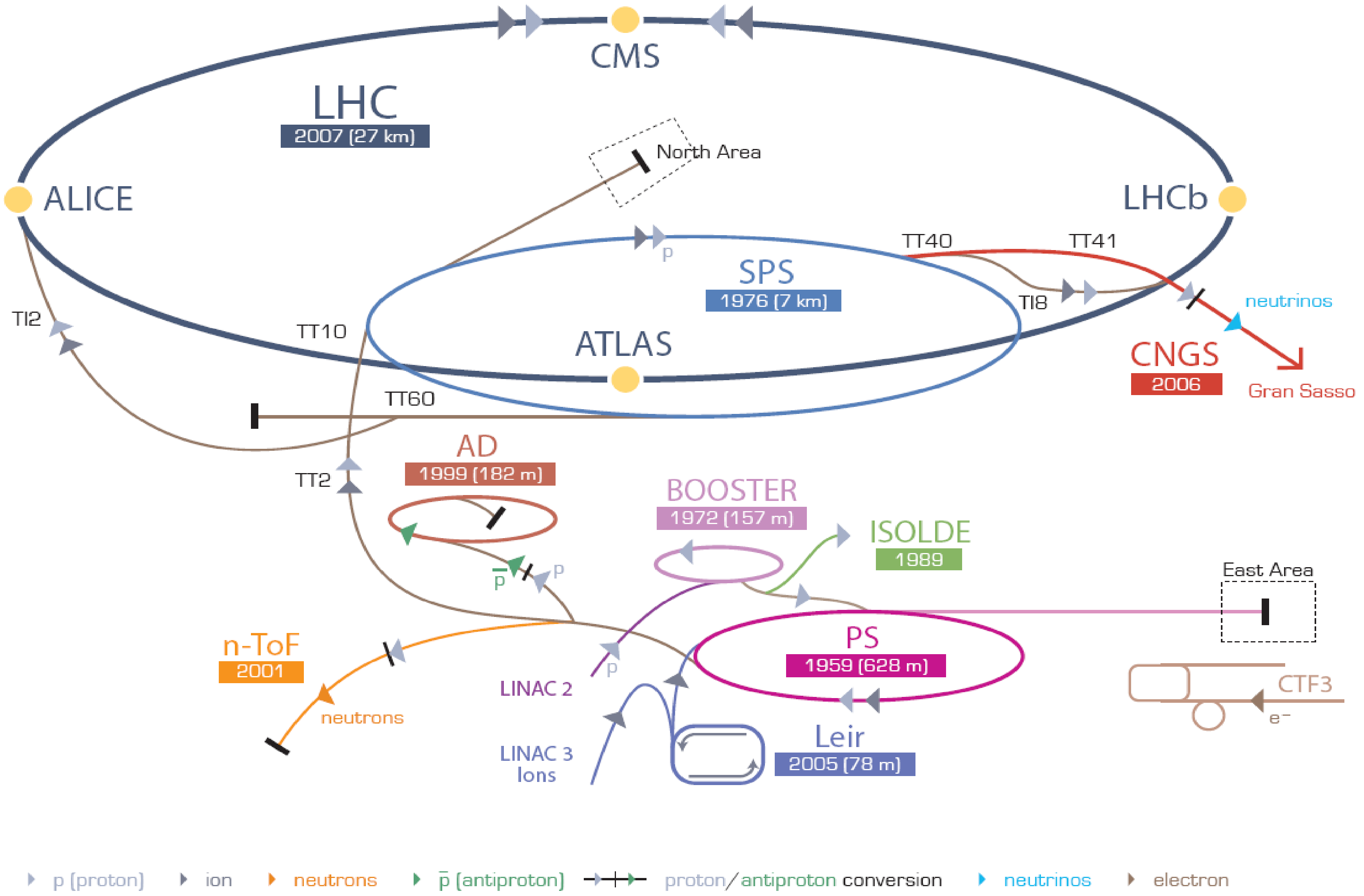
| /02/2023 | 30/06/2023 |
| --- | --- |

Impact on Schedule minimized by swapping start of Lift Installation from Pt1 to Pt5, but overall ca. 6 month lost for installation of technical infrastructure

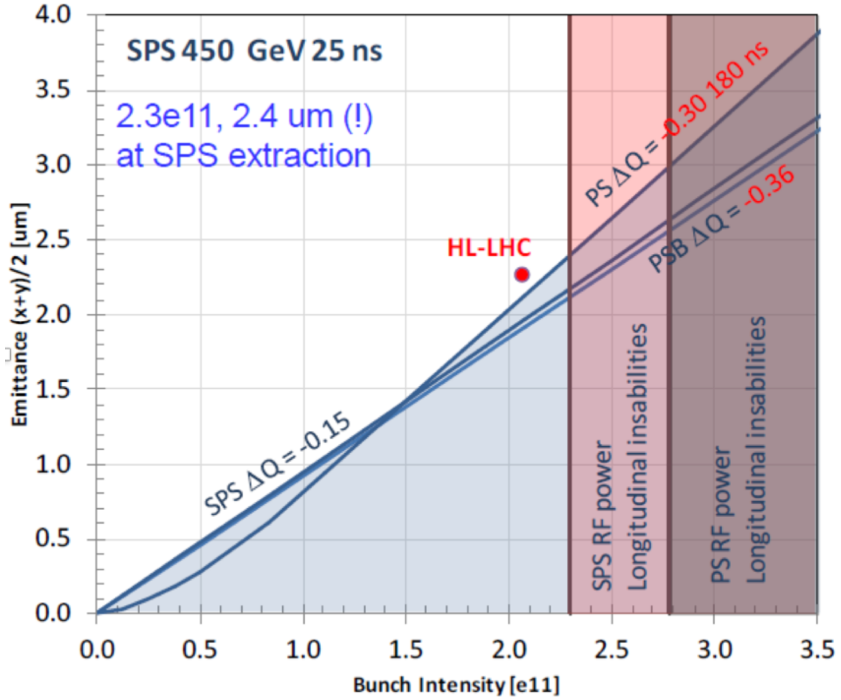
➔ Not critical, completion of Technical Infrastructure installation still before start of LS3

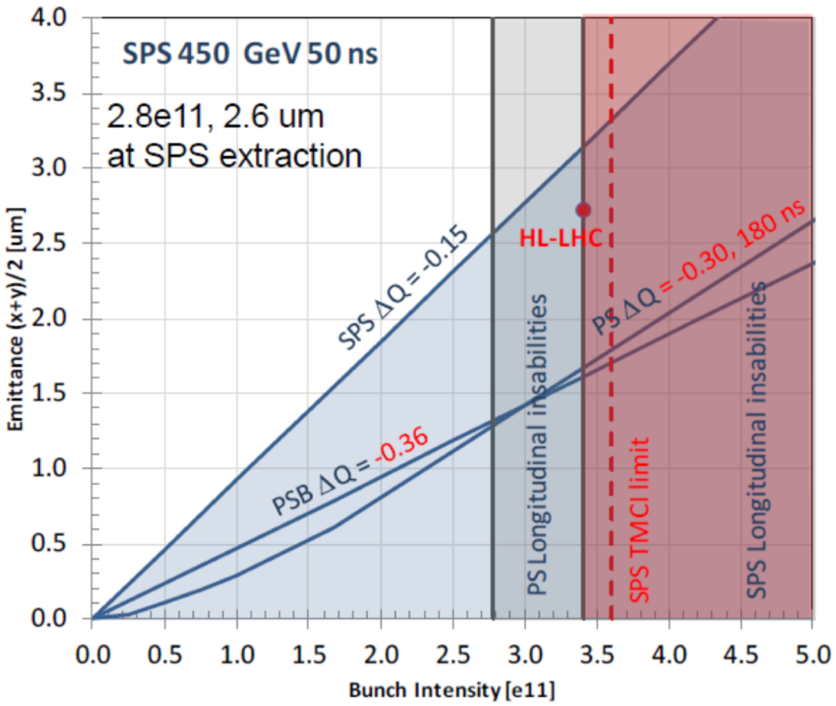
# CERN accelerator complex



# LHC Injector Upgrade Project (LIU)

- 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



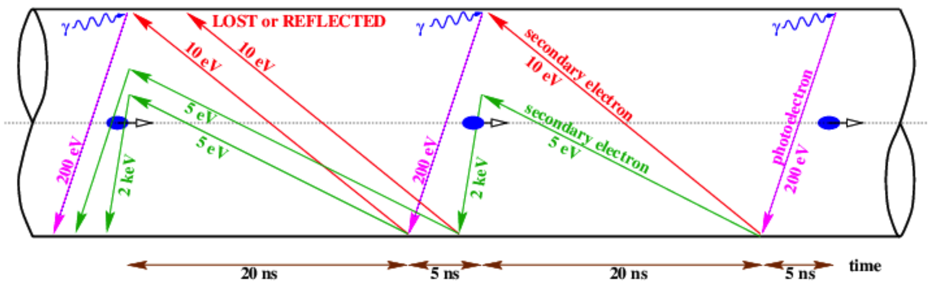
# LHC Injector Upgrade Project (LIU)

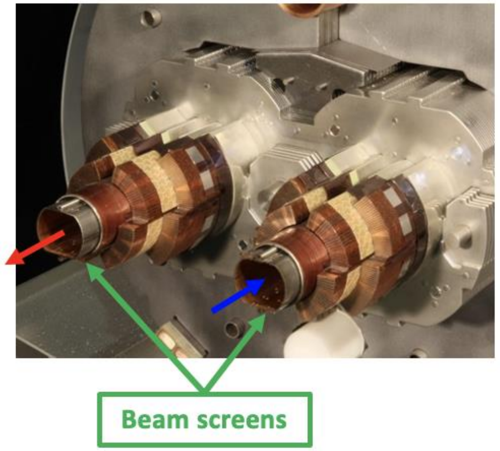
| | |
|---|---|
| Linac4 in for Linac2 | • $H^-$ injection into PSB at 160 MeV<br>• Expected double brightness for LHC beams … e PSB |
| Booster | • Increase energy to 2 GeV<br>• New RF system<br>• New main power supply |
| PS | • Injection at 2 GeV<br>• Beam production …<br>• Feedback syste… wide-band longitudinal feedback; transverse feedback a… ad-tail and e-cloud instabilities |
| SPS | • Po… ade of the main 200 MHz RF system<br>• … cloud mitigation through a-C coating (baseline) or beam induced …bing |

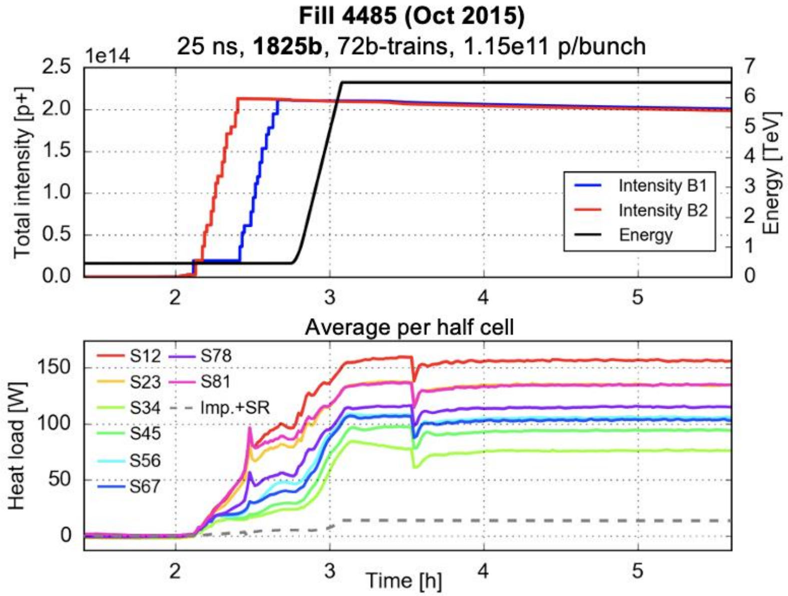
Successfully deployed during LS2 in 2019/2020

# Electron cloud and cryogenic heat load

- Electrons are inevitably produced inside the LHC beam chamber. Seed electrons (e.g. from synchrotron radiation) hitting chamber's walls and ejecting secondary electrons
- These electrons can subsequently be accelerated by the proton bunches. When they hit the vacuum chamber wall, they have a probability of ejecting more electrons, the cycle continues, and the electron cloud (e-cloud) is created.
- Parameter of interest is the Secondary Emission Yield (SEY), which is the average number of electrons produced per impact
- E-cloud both affects beam quality and considerable increases heat load on cryogenic system -> Potential limitation + electricity cost!



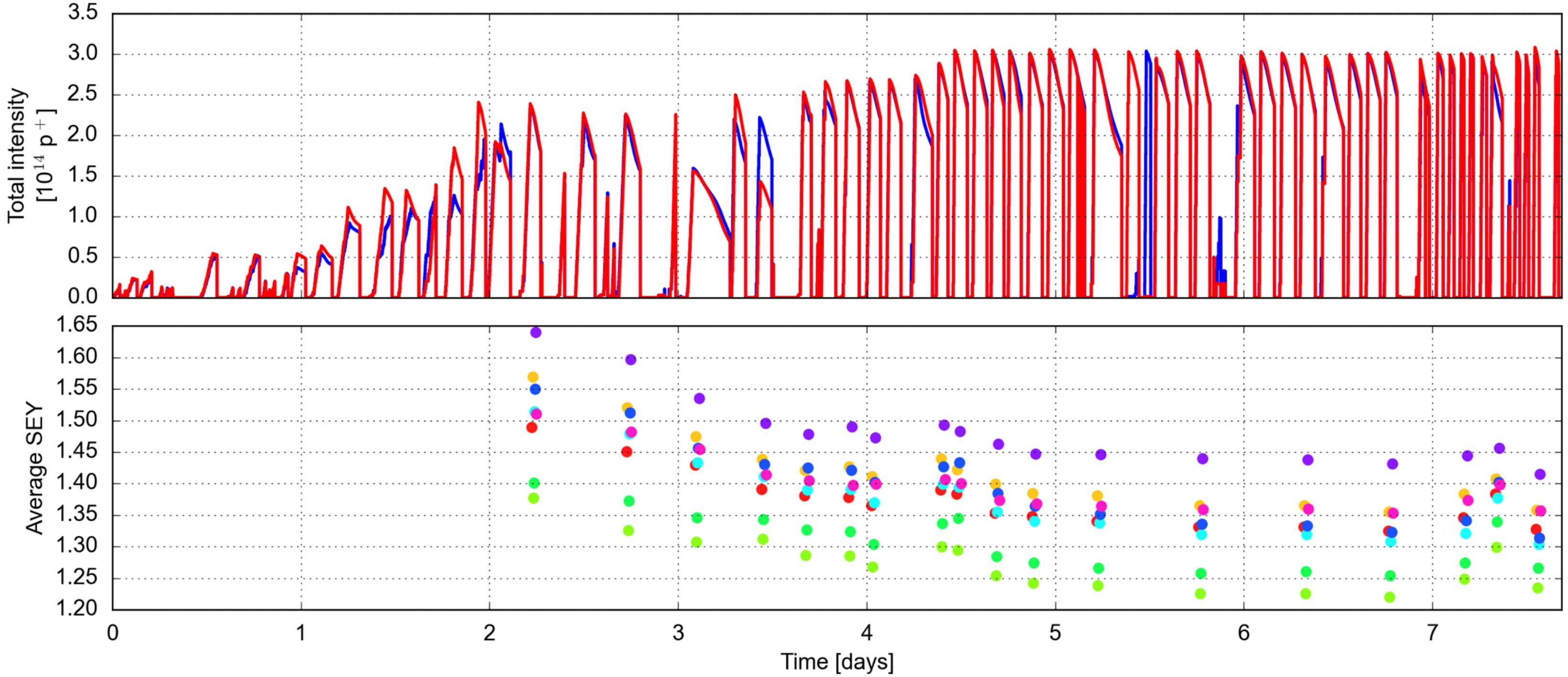



# Electron cloud and cryogenic heat load

Mitigation: ‘Scrubbing’ runs where increased bunch intensity and train lengths are injected to condition the beam screens

Evolution of the secondary emission yield (SEY) over the 2022 scrubbing run has shown a

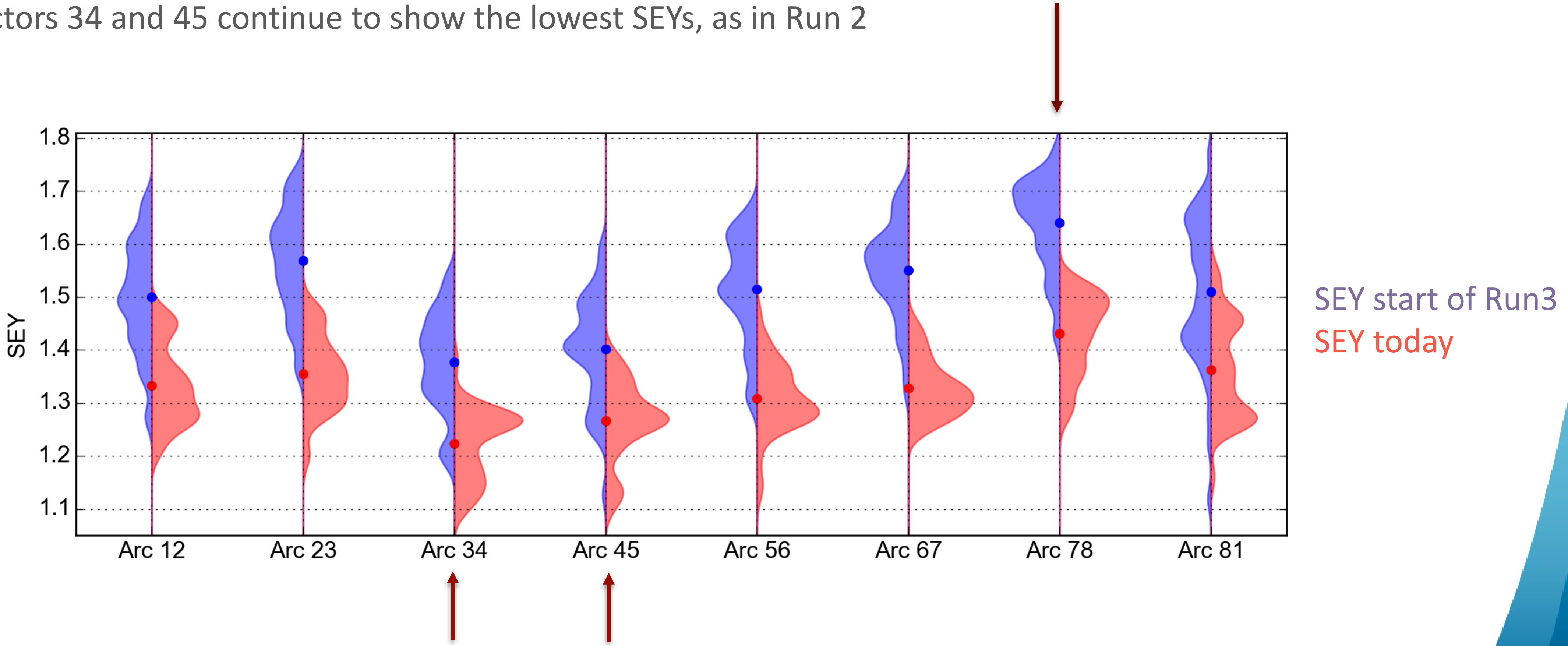
- A clear reduction of the average SEY is observed in every sector
- Conditioning is initially fast and gets slower as the SEY decreases




L. Mether

# SEY evolution over scrubbing run

- Significant conditioning has taken place in every sector
  - Sector 78 showed significantly higher SEY than the other sectors from the beginning, and stays higher even after conditioning
  - Sectors 34 and 45 continue to show the lowest SEYs, as in Run 2

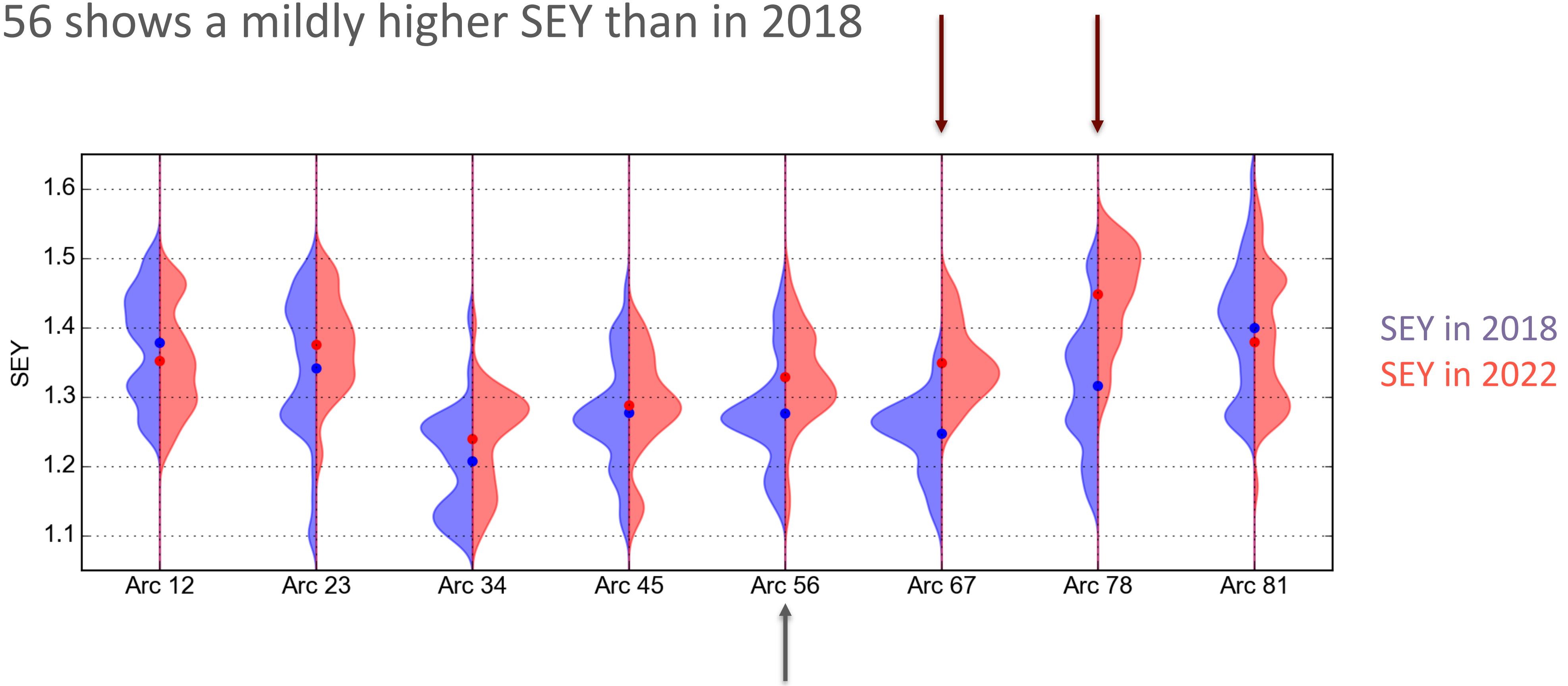



L. Mether

# SEY comparison to 2018

A first analysis has been performed to compare the present cell-by-cell SEY to 2018

- In most sectors, the SEYs are currently very close to their 2018 values (at 450 GeV)
  - The differences are within the error bars of the analysis
- Sectors 67 and 78 still show much higher SEY than in 2018
- Sector 56 shows a mildly higher SEY than in 2018




L. Mether

# Outline

- HL-LHC design parameters and upgrade goals
- Start of LHC Run 3 and lessons learnt for HL-LHC era
  - Completion of LHC Injector Upgrade
  - E-cloud and heat load
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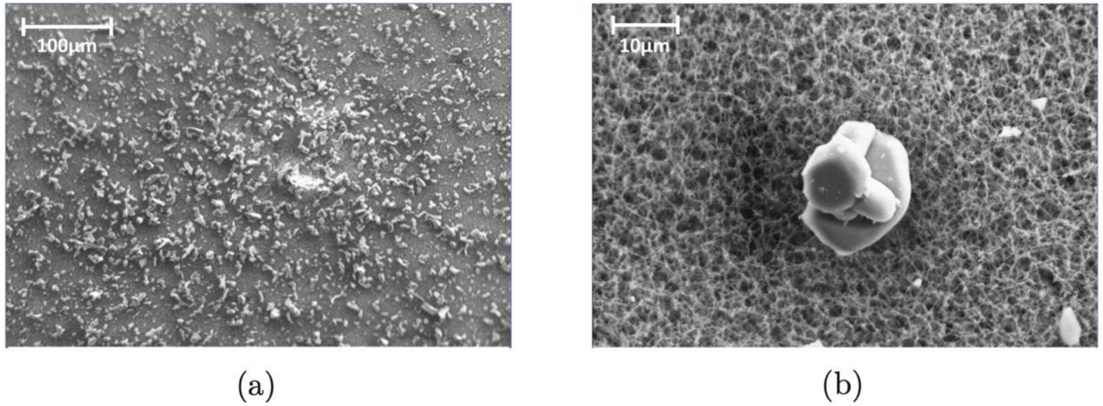
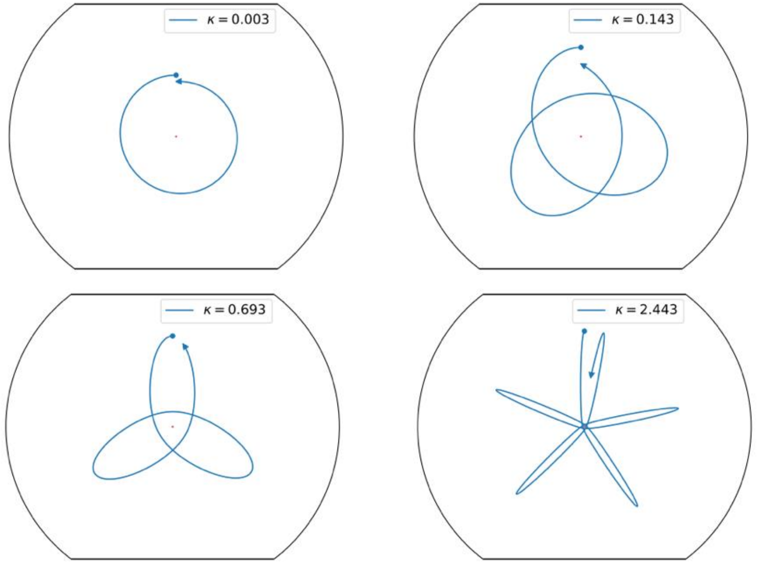
# UFOs and their interactions with the LHC beams

- Dust particles are inevitably present in the LHC vacuum chamber
- They get charged and can travel along the electric and magnetic fields of the beam and the surrounding magnets
- Interactions with the high intensity proton beams generate fast, localised beam losses that affect operation (and can generate magnet quenches)

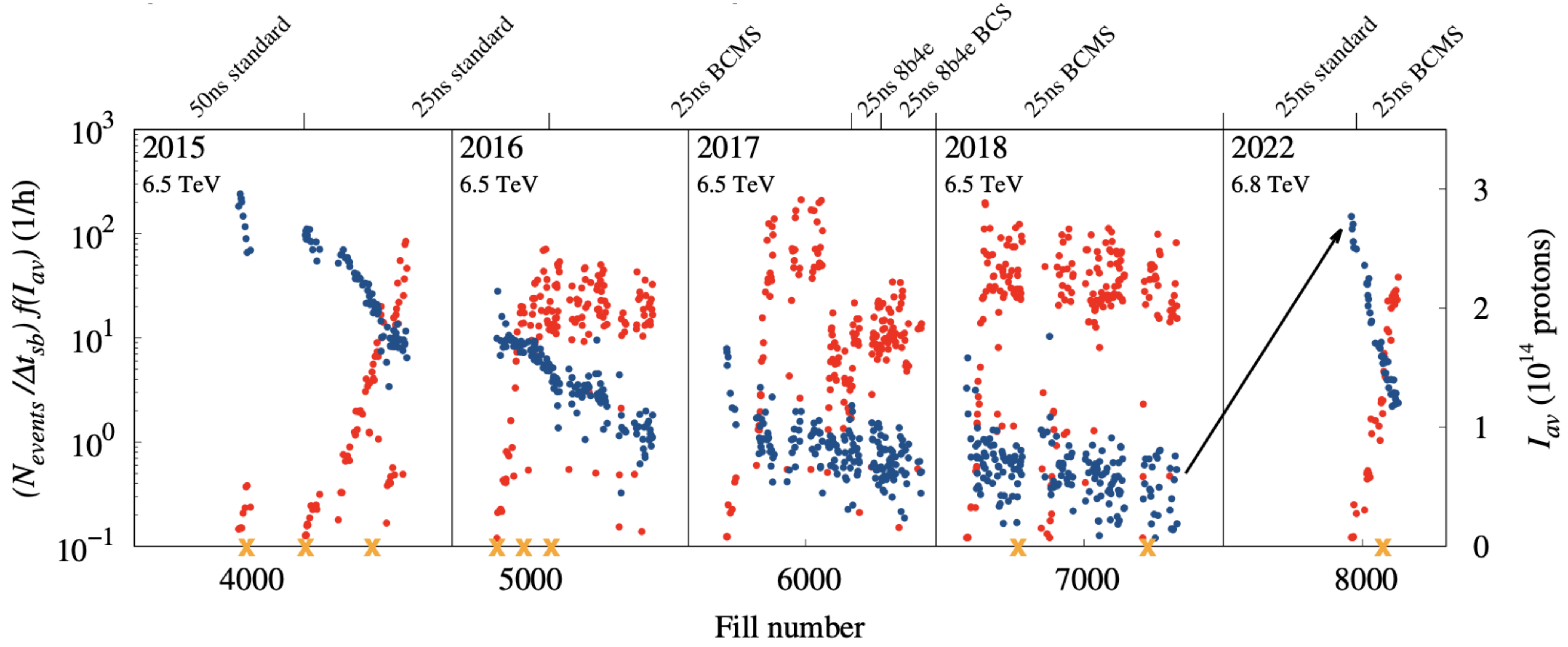



Dust samples from the ceramic tube of an injection kicker magnet. (b) shows an enlarged view of an $Al_2O_3$ particle with a radius of about 5 um




Examples of orbits of charged dust particulates around the LHC beam. Beam screen height is ~37 mm

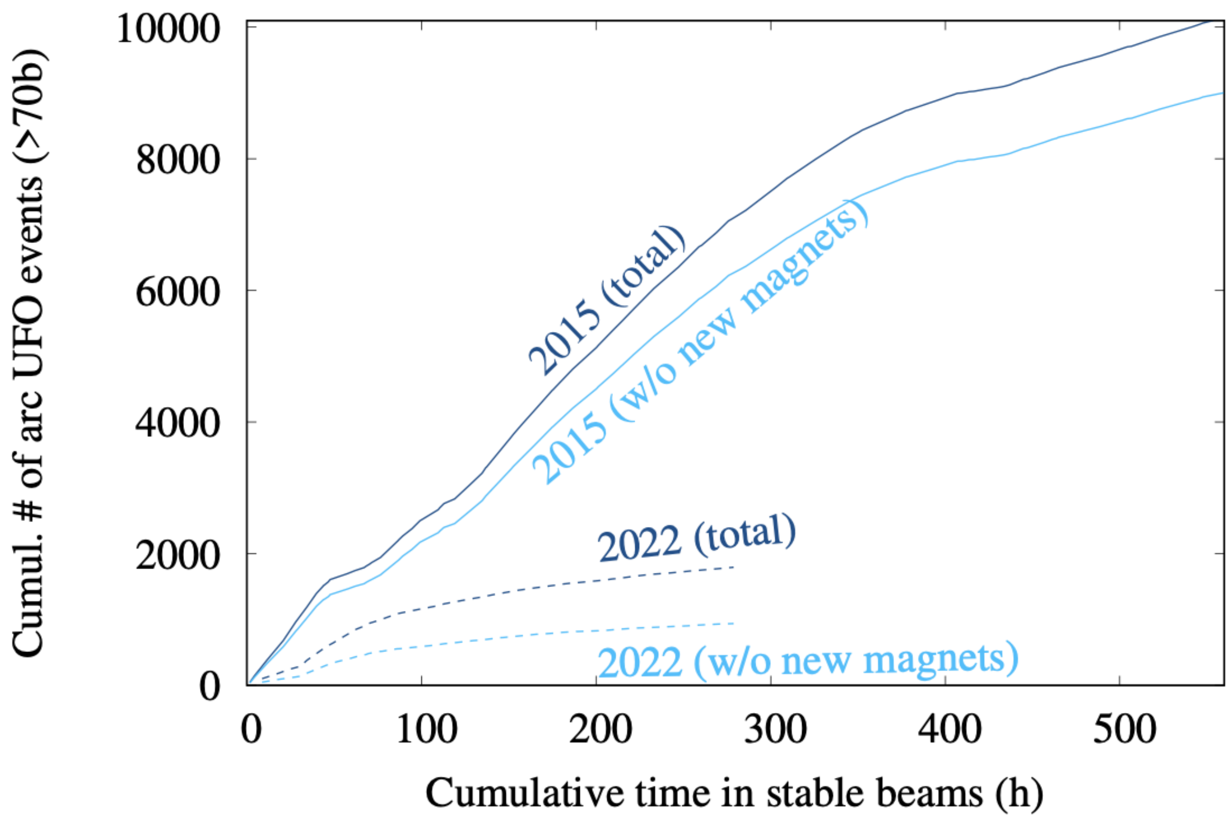
# UFO conditioning in Run2 compared to 2022




Blue dots = **UFO rate**, red dots = **fill-averaged intensity**, orange crosses = **quench**

L. Mether

# UFO rate 2015 vs 2022




- In general, situation much better than in Run 2 due to the very fast conditioning of the UFO rate
- But the impact of UFOs evidently depends on the BLM threshold strategy

**Conclusion:**

- Expected re-conditioning of UFOs at the start of Run3.
- Much lower quench margins at 7 TeV and with HL-LHC beam parameters
  - Could have a considerable impact on machine availability (especially early in the run)!
- (Part) of physics behind UFO mechanism still not fully understood

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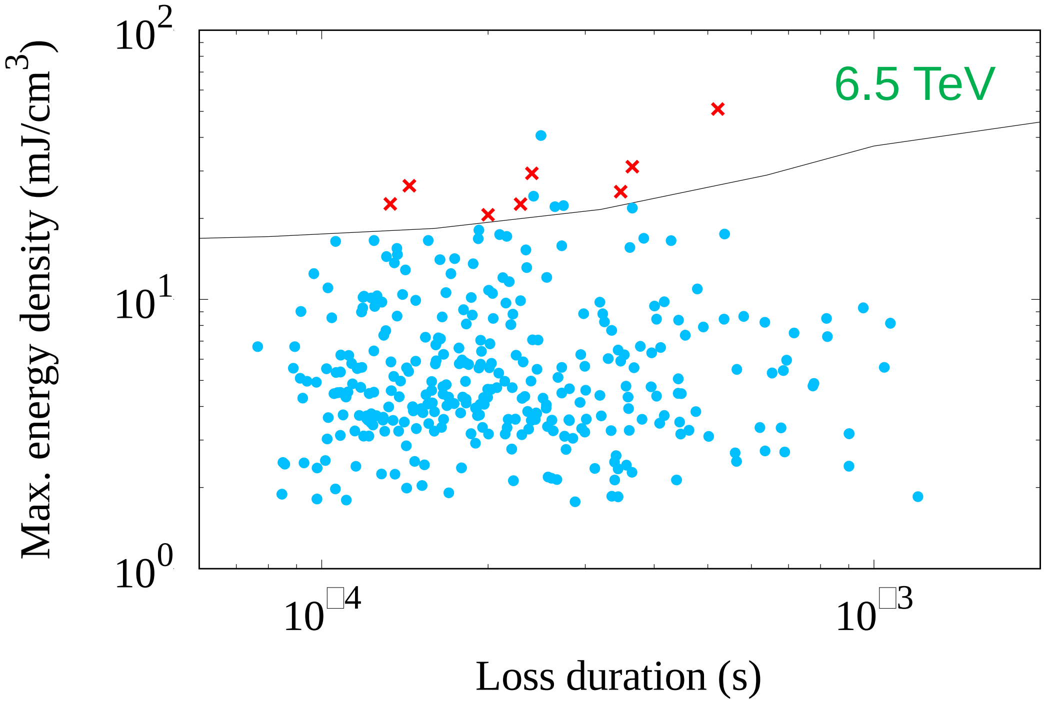
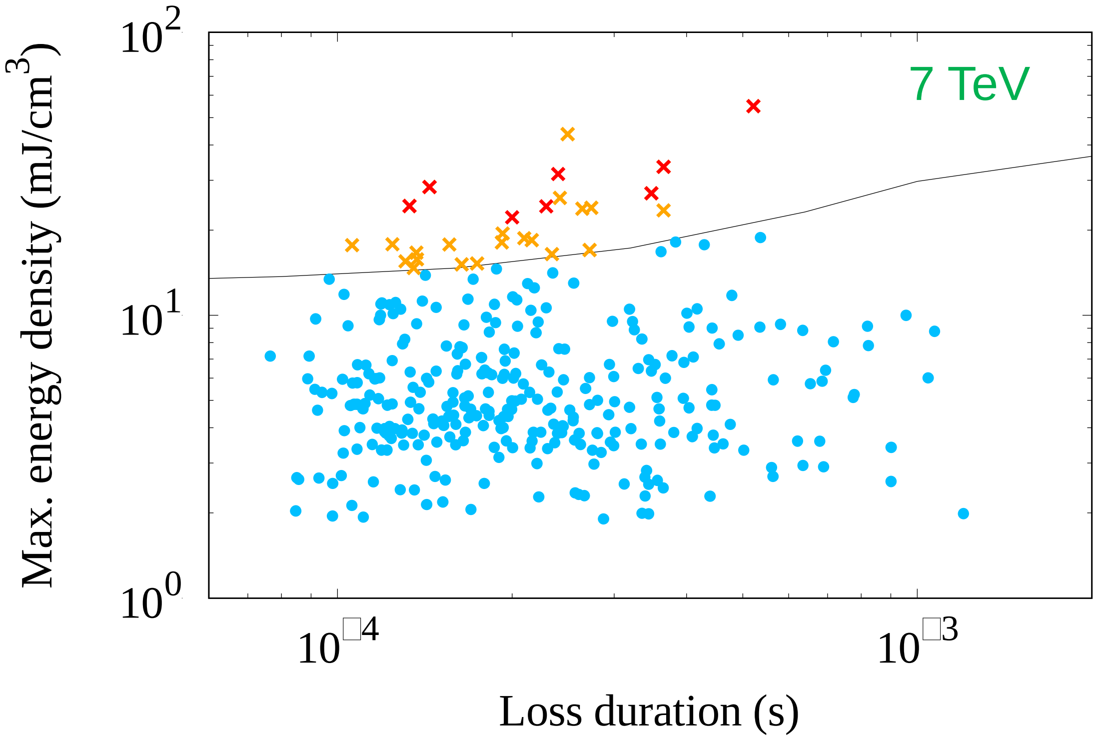
# Quench limits vs UFOs




**Conclusion:**

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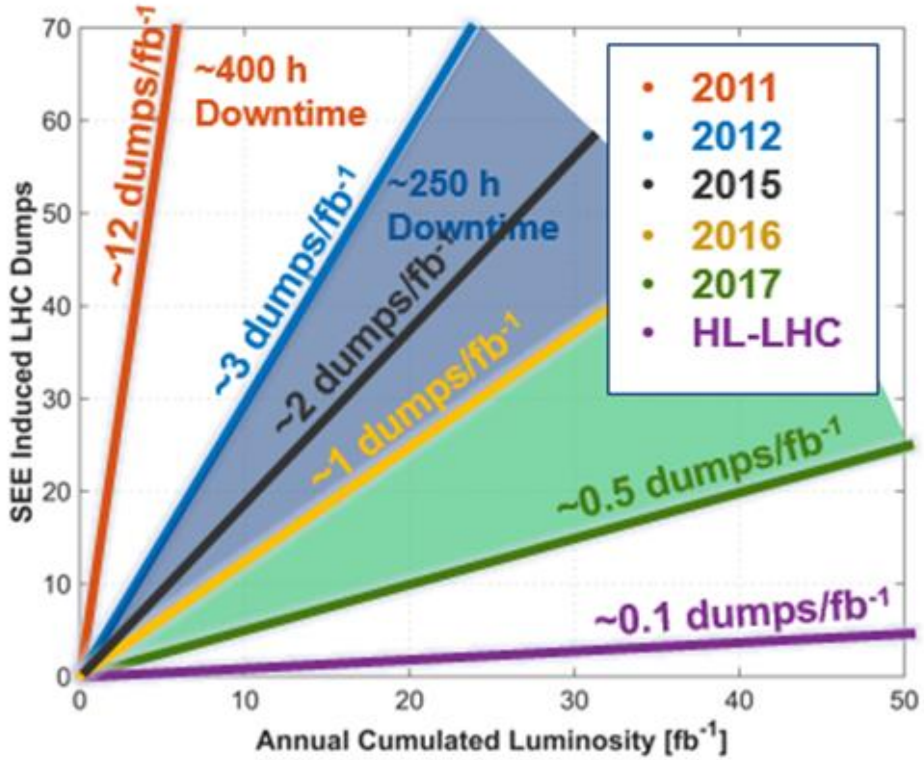
# Radiation to Electronics




2015:
- Start of the year: nQPS SEEs (introduced in LS1)
- Rest of the year: mainly FGC2 in the arc

2016:
- SEE rate reduction mainly due to lower arc radiation levels (vacuum conditioning)

2017:
- Further improvement thanks to FGClite deployment in ARC; most R2E events in power converters in RR (upgraded in LS2 with radiation tolerant versions)

2018:
- Increased radiation levels in DS of IP1 and IP5 due to TCL6 opening → impact on QPS equipment (possibly lifetime related, i.e. no longer linear versus integrated luminosity)

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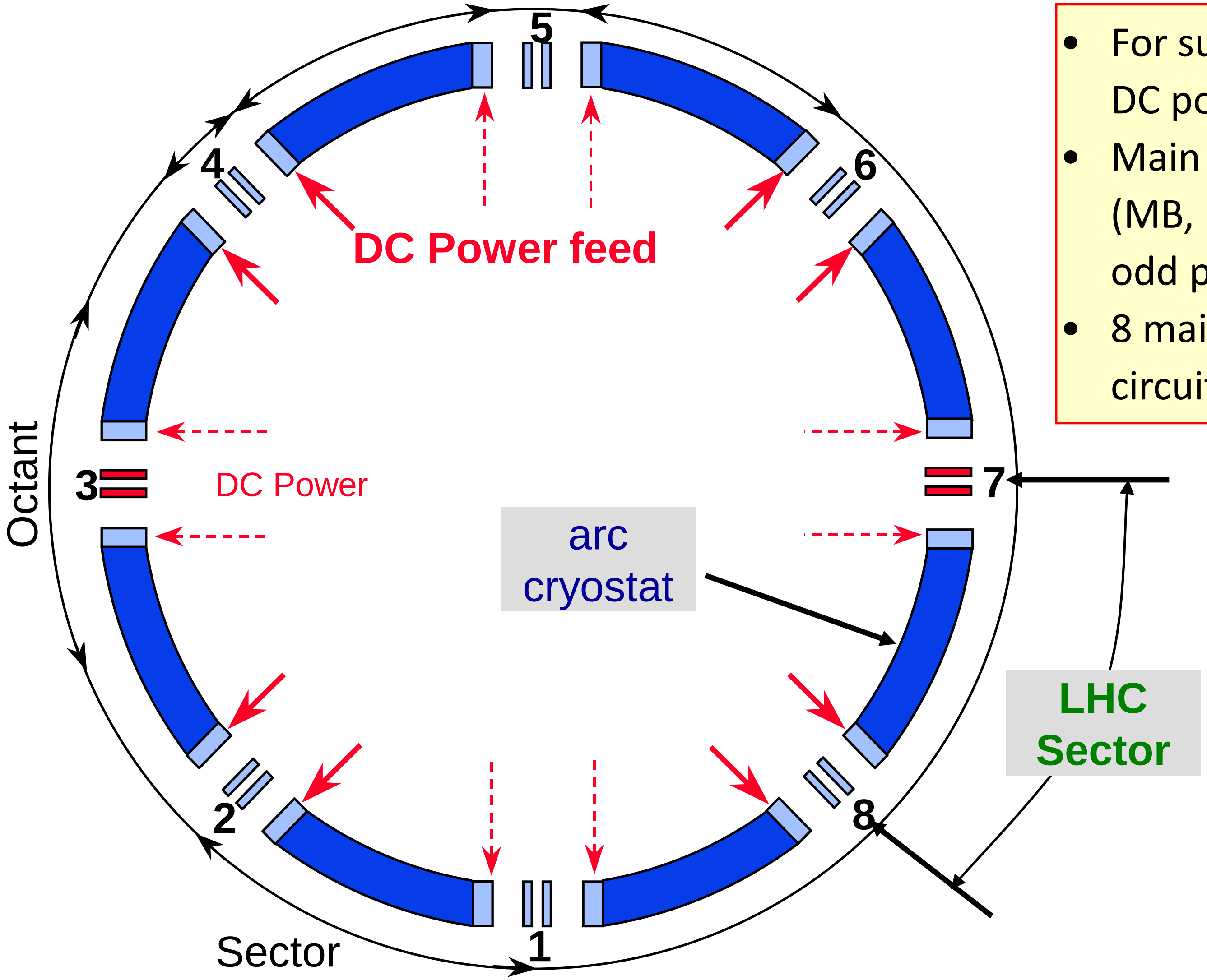
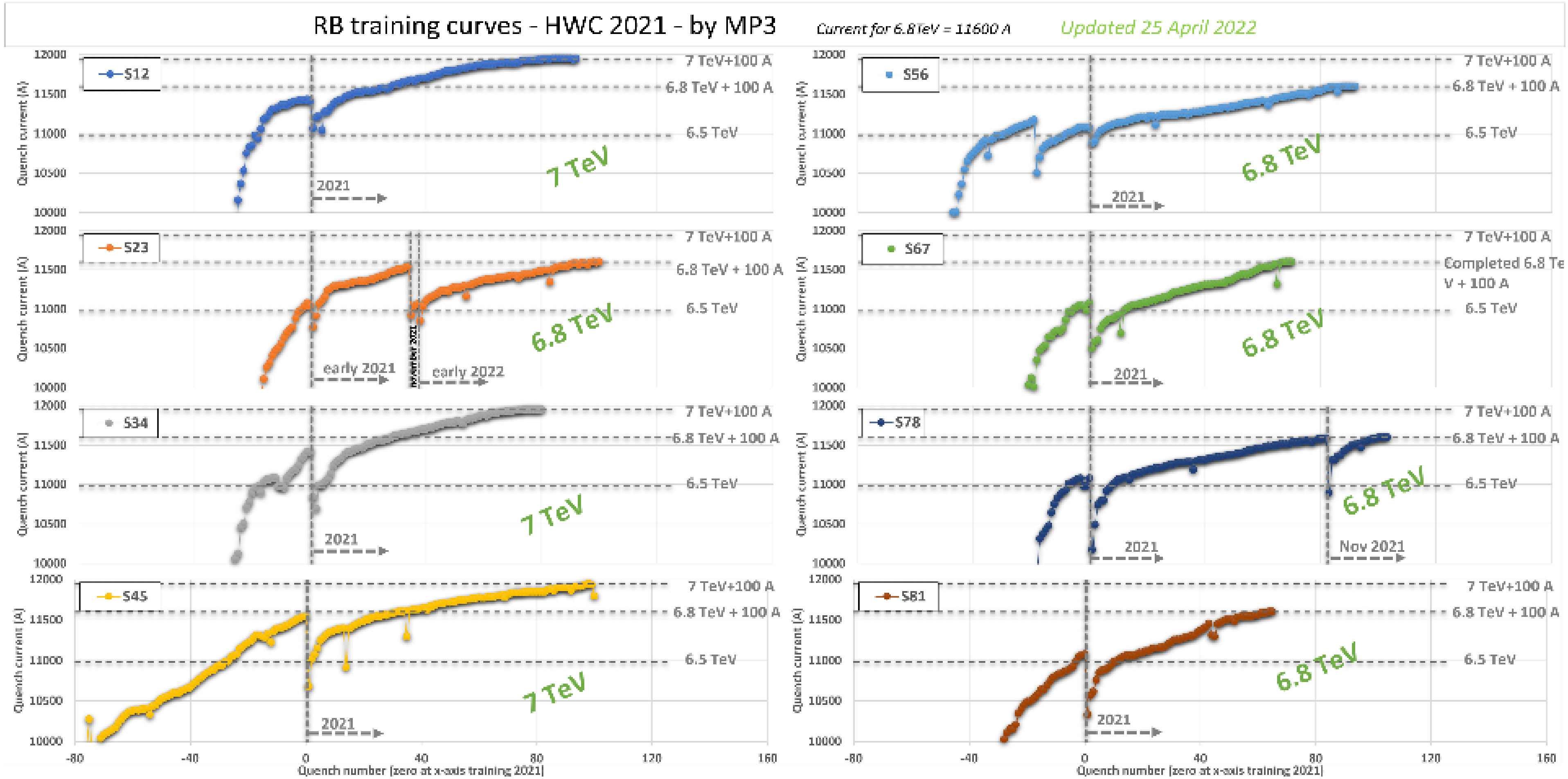
# LHC machine sectorisation




- For superconducting magnets, no DC powering across IPs
- Main DC power feed at even points (MB, MQ), some DC power feed at odd points
- 8 main dipole + 16 quadrupole circuits in LHC

- Commissioning possible for each sector independent of other sectors
- More complex powering system and tracking between sectors

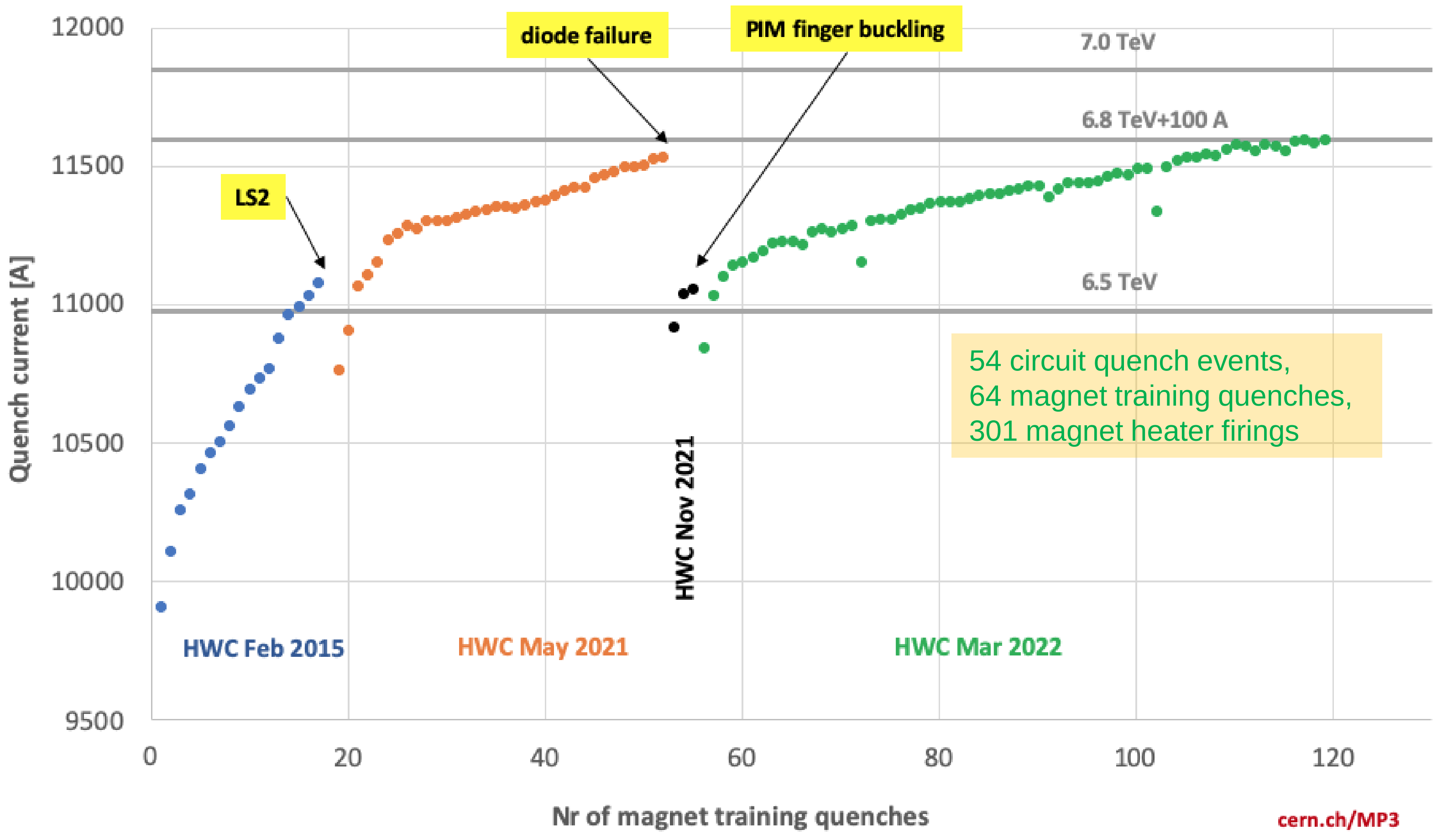
# Training quenches RB Circuits




**Collision energy of (HL-)LHC is strictly linked to achievable current of the 1232 (= 8 x 154) LHC main dipole magnets**

- 5 sectors reached 6.8 TeV equivalent, 3 sectors reached 7 TeV
- No sign of permanent degradation.

# Training history RB.A23




- The 64 quenches in S23 after the 2nd additional TC came as a surprise, as usually training goes faster after a TC
- Detailed analysis of the dipole training campaigns is ongoing, including results from reception tests in SM18.

# Total nr of quenches in LHC main dipoles

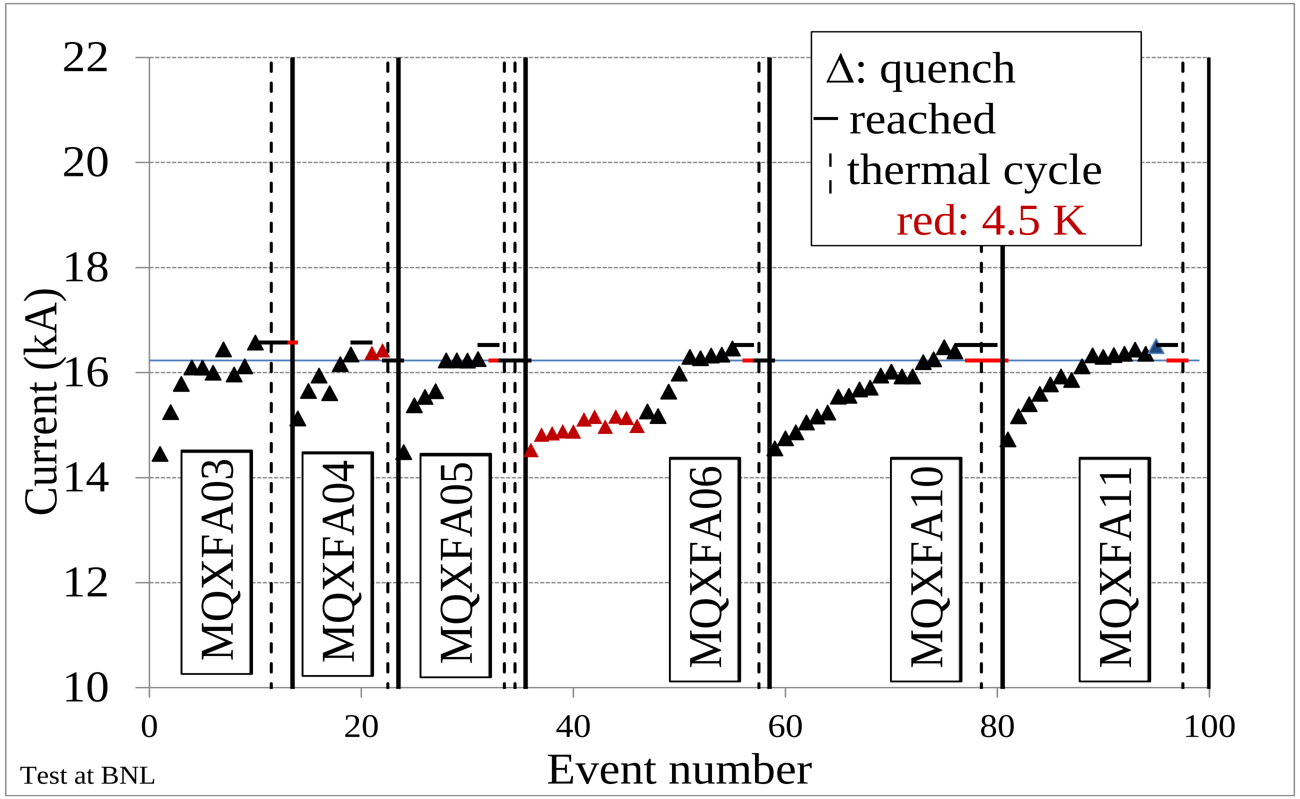
| Nr of quenches in the same dipole magnet | Nr of dipole magnets |
|---|---|
| 5 | 3 |
| 4 | 11 |
| 3 | 56 |
| 2 | 154 |
| 1 | 446 |
| 0 | 562 |

**Conclusion:**

- Still 562 dipole magnets (45%) never experienced a training quench in the LHC since 2008.
- Some circuits (including corrector circuits) showed much longer training than in previous campaigns, and their behavior will be closely monitored in the coming years.
- Desired operating currents can still be reached (with only a few exceptions) 14 years after the start of the LHC, with several thermal cycles, numerous current cycles, radiation, and large number of quenches.
- a quench is a very violent process (especially in the high-current circuits), and that each quench implies a certain unavoidable risk (short-to-gnd, internal short, quench heater failure, etc).
- Decision of collision energy post LS3 will inevitably involve a cost/benefit analysis of required re-training effort (which implies technical risks and considerable time!)

# Progress and (initial) training of HL-LHC triplet magnets

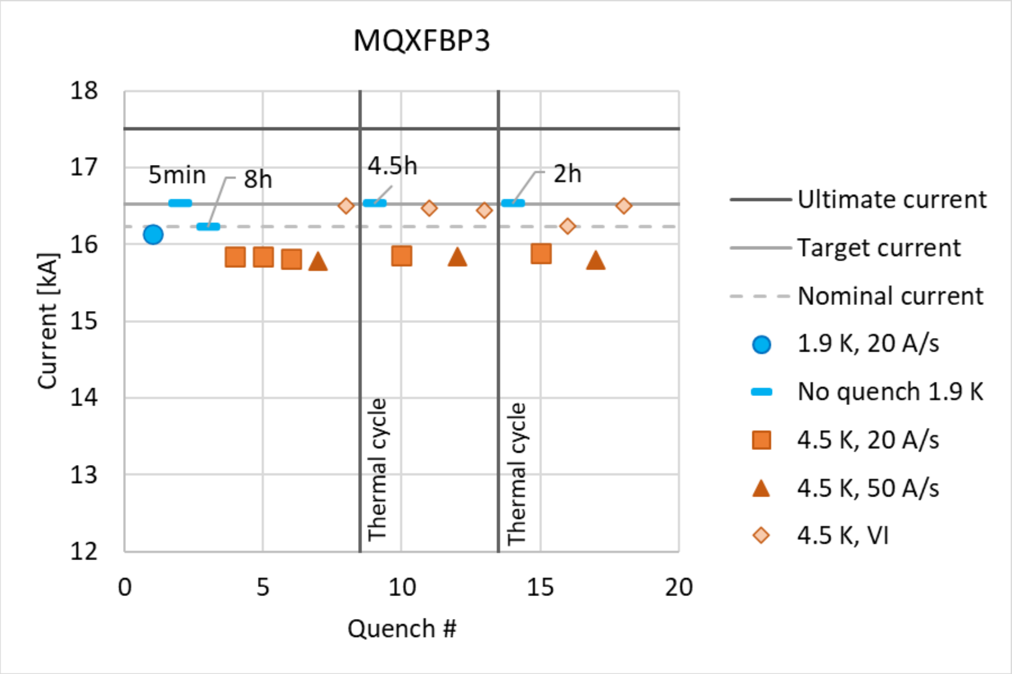
- Six magnets of type MQXFA from AUP reached performance
  - Operation at nominal current plus 300 A, both at 1.9 K and 4.5 K
  - Perfect memory, i.e. no retraining, and some robustness




Powering test of conform MQXFA magnets (J. Muratore, B. Ahia, S. Feher et al.)

# Progress and (initial) training of HL-LHC triplet magnets

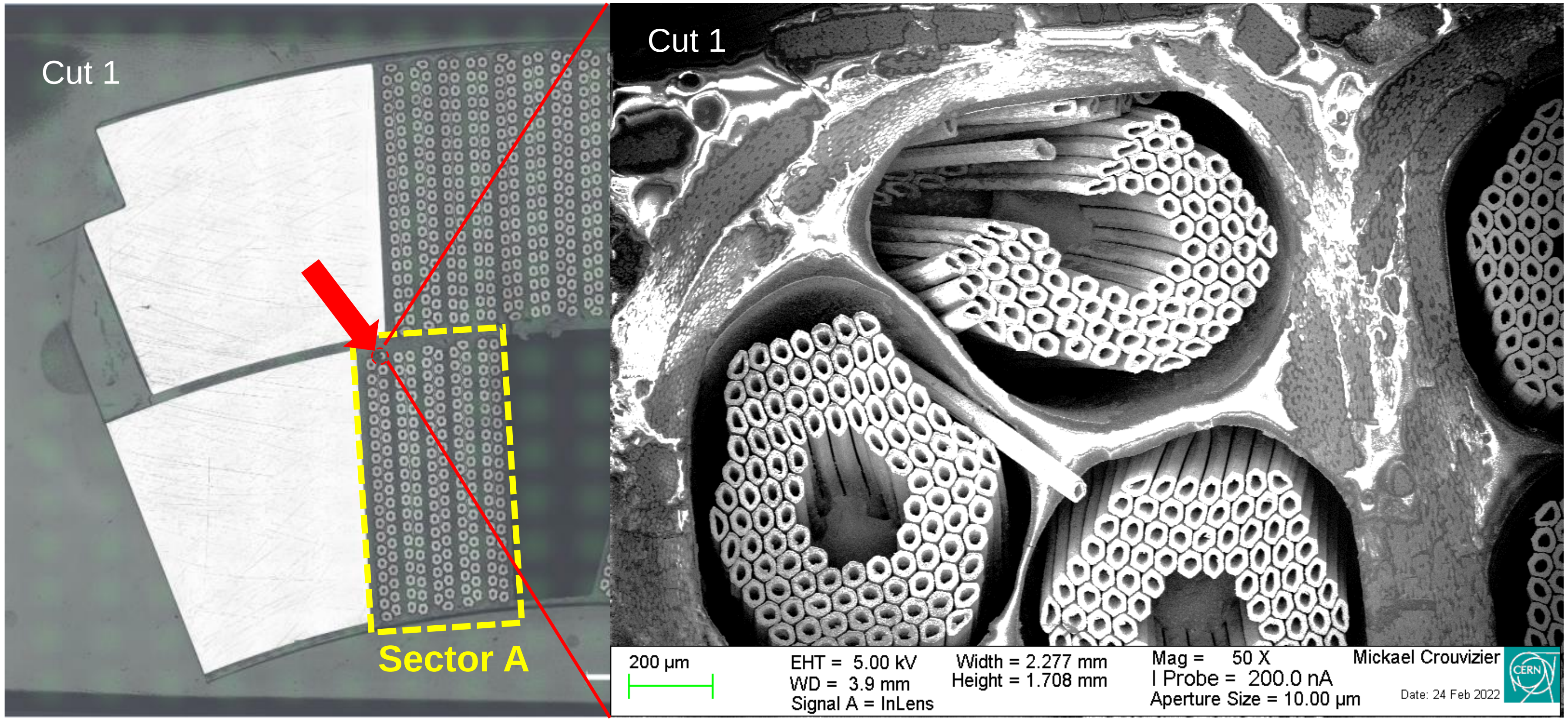
- MQXFBP3 includes the new procedures used for LHe vessel integration
  - Nominal plus 300 A reached during first powering with one training quench
  - No degradation, three thermal cycles




MQXFBP3 on SM18 test bench (left) and test results (right)
(S. Izquierdo Bermudez, F. Mangiarotti, et al.)

# Advancements on MQXFBP1 diagnosis

- MQXFBP1 performance limitation (6.5 TeV) analysis had a significant breakthrough in January 2022: analysis of limiting coil 108
  - Broken filaments in a strand always in the same position of the cross-section, in several sections close to the transition in the poles –in agreement with voltage tap and quench antenna localization




Broken filaments in coil 108, limiting MQXFBP1 (M. Crouvizier, A. Moros, S. Sgobba, et al.)

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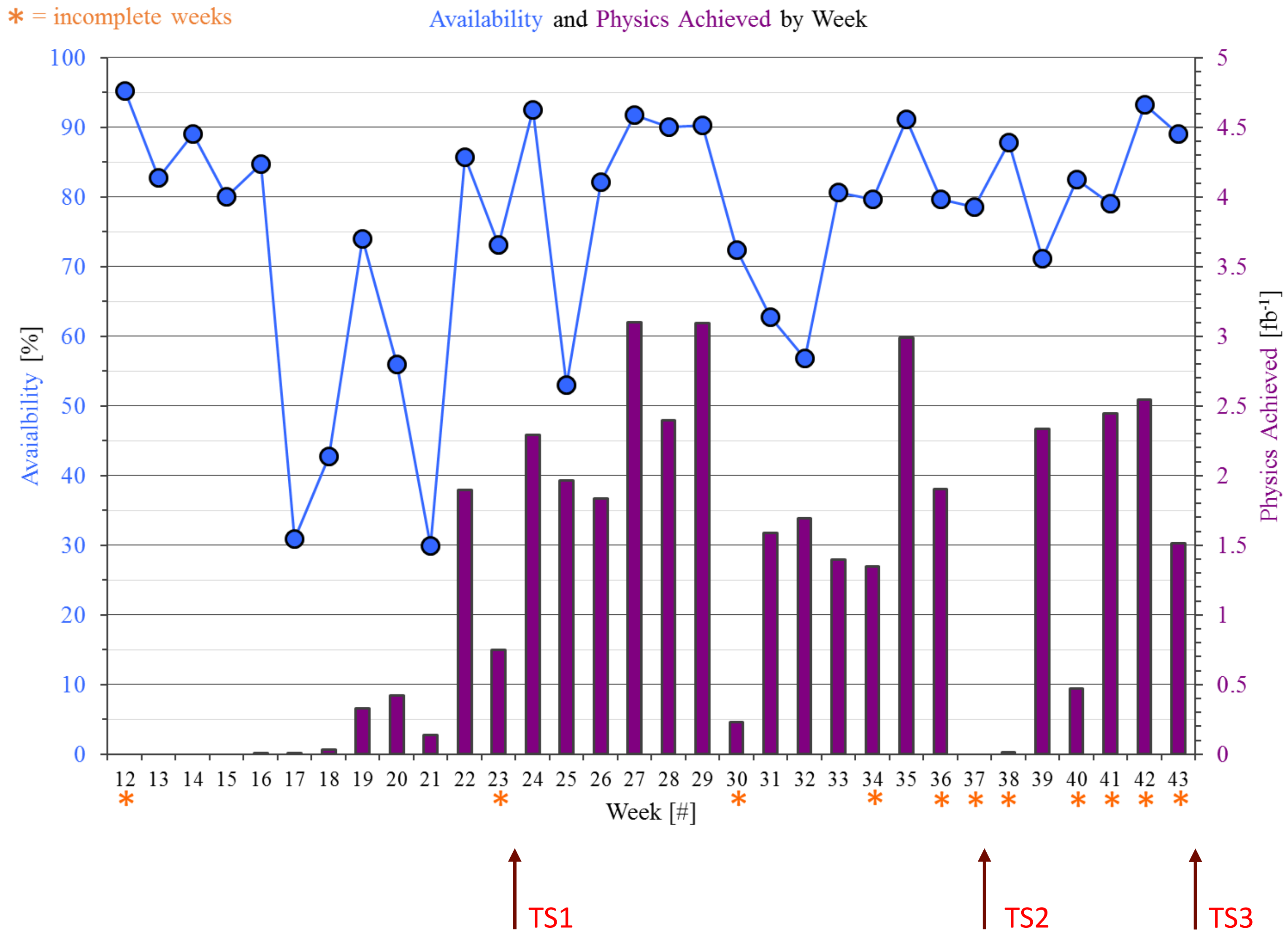
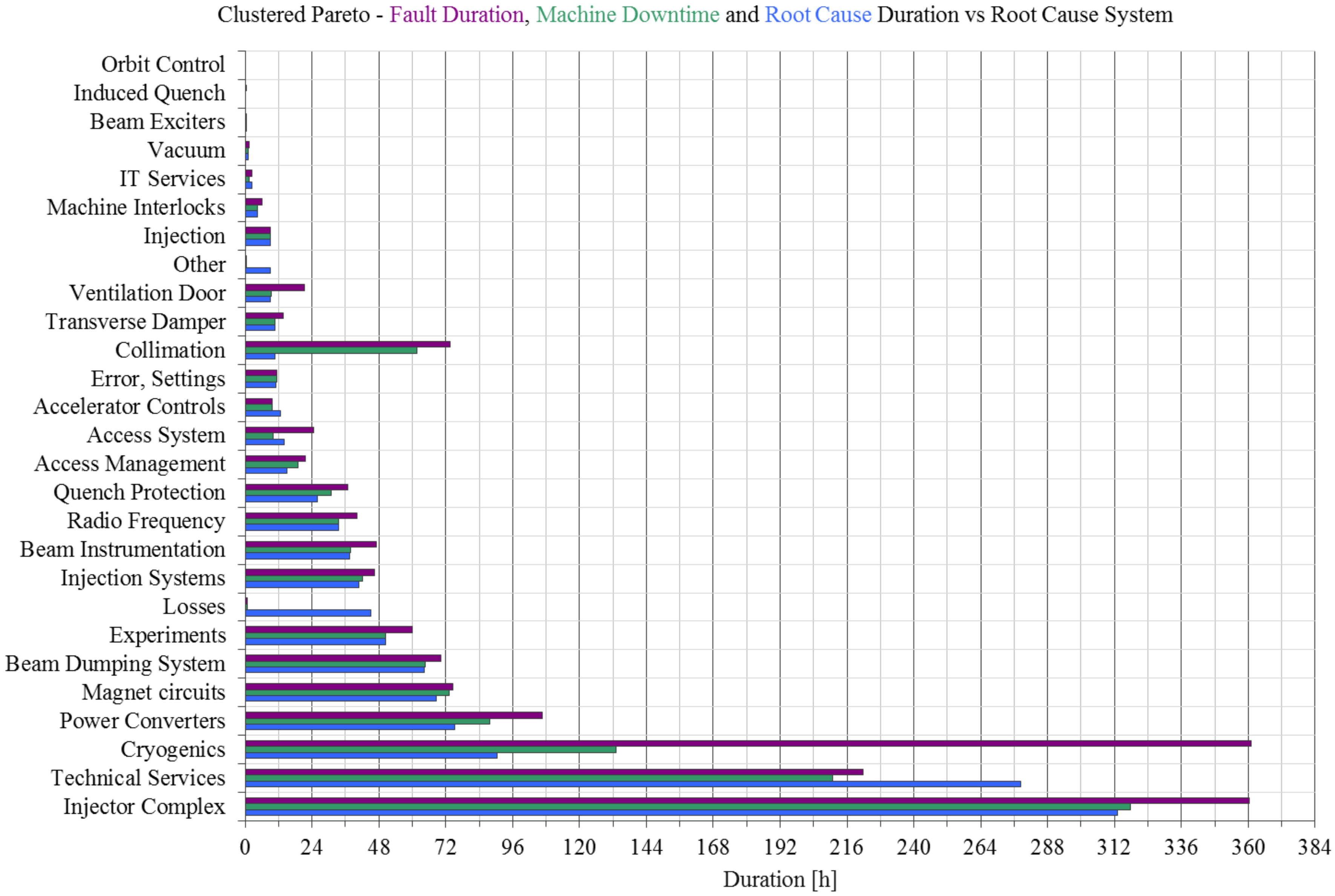
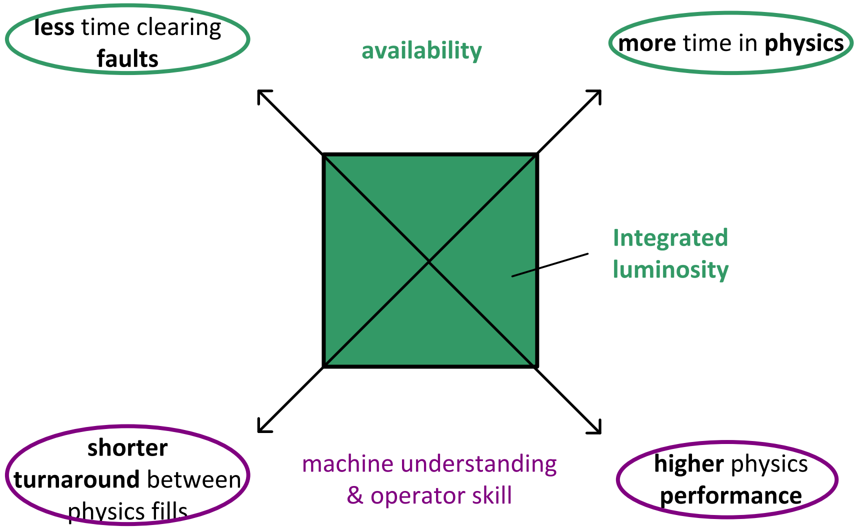
# Machine Availability vs Physics output – an example



# Machine Availability vs Physics output – an example



# What defines the productivity / physics output?



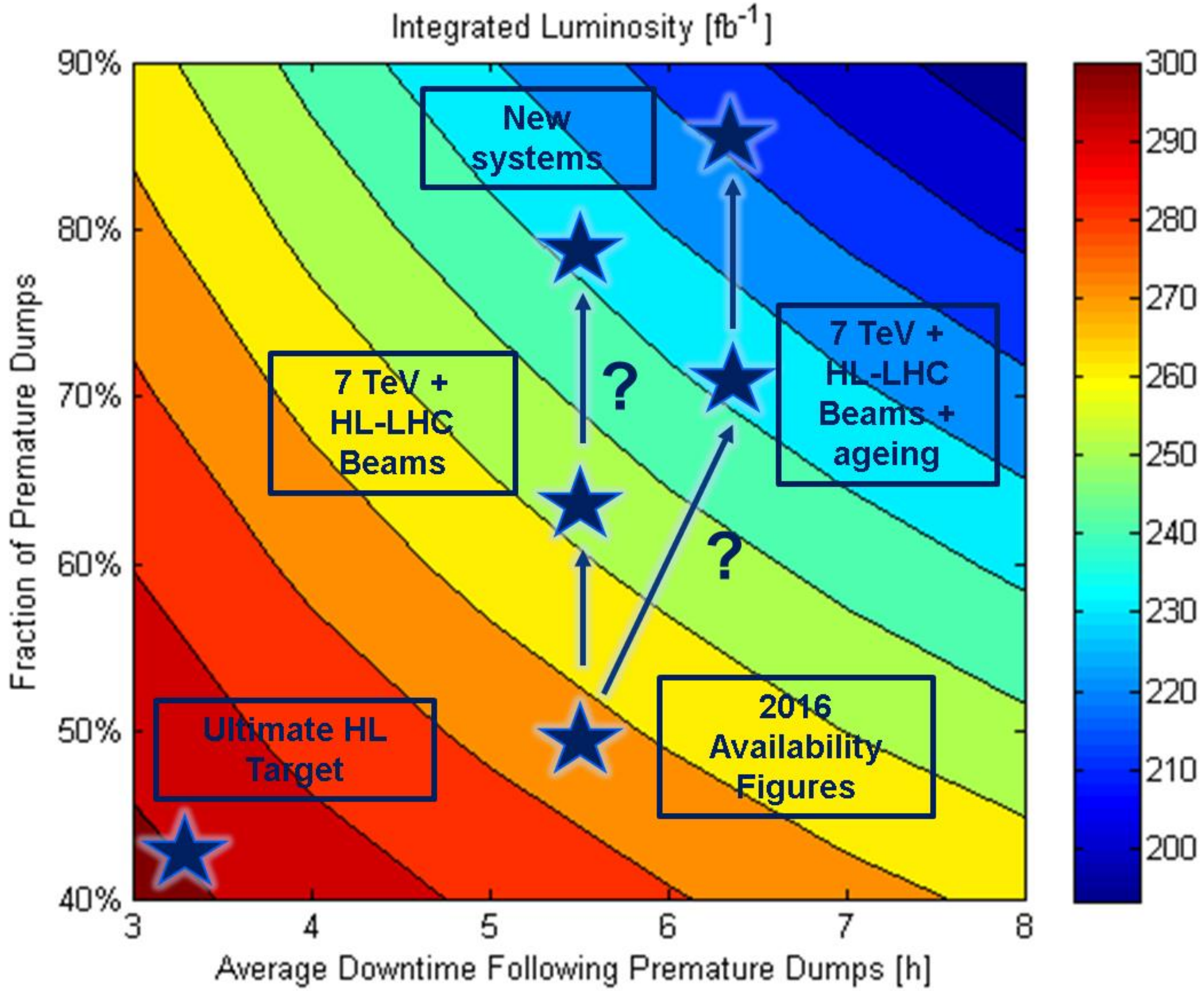

Physics output is a function of…

machine understanding & operator skill

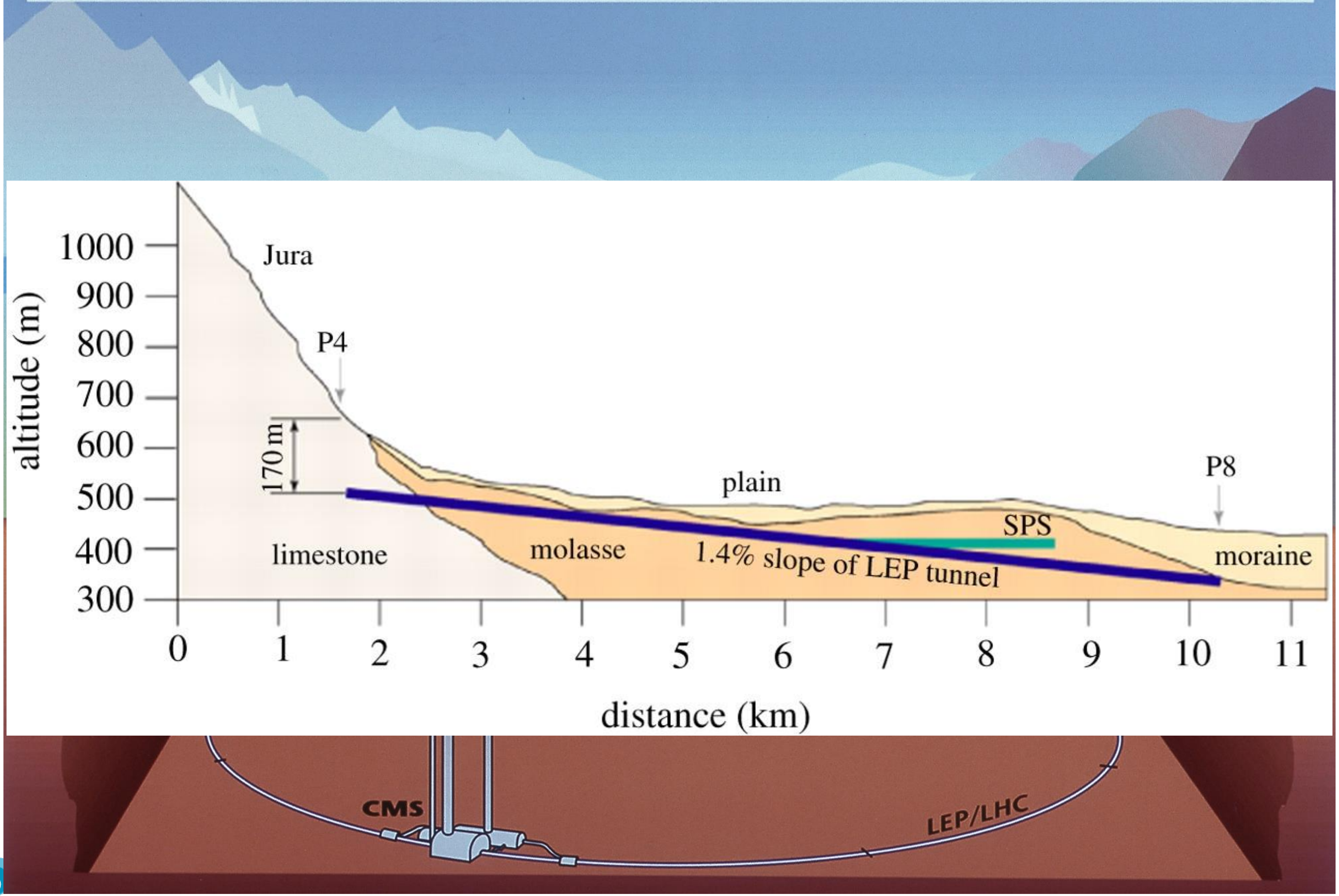
1. time producing physics beams
2. turnaround between successive experiments
3. time to clear faults
4. physics performance during experiments

Availability
Maintainability
Scheduling

# Availability vs HL-LHC luminosities



# Overall view of the LHC experiments.



# 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!!!

HiLumi HL-LHC PROJECT

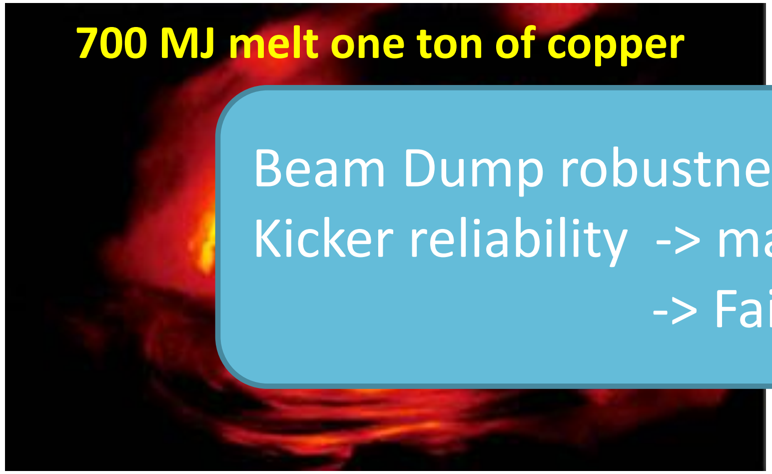
# Energy management Challenges in the LHC

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


Sectorization!!

-> Tracking
-> [ppm]!!!


**Energy stored in the two beams: 720 MJ** *[ 6 $10^{14}$ protons (1 ng of H+) at 7 TeV ]*

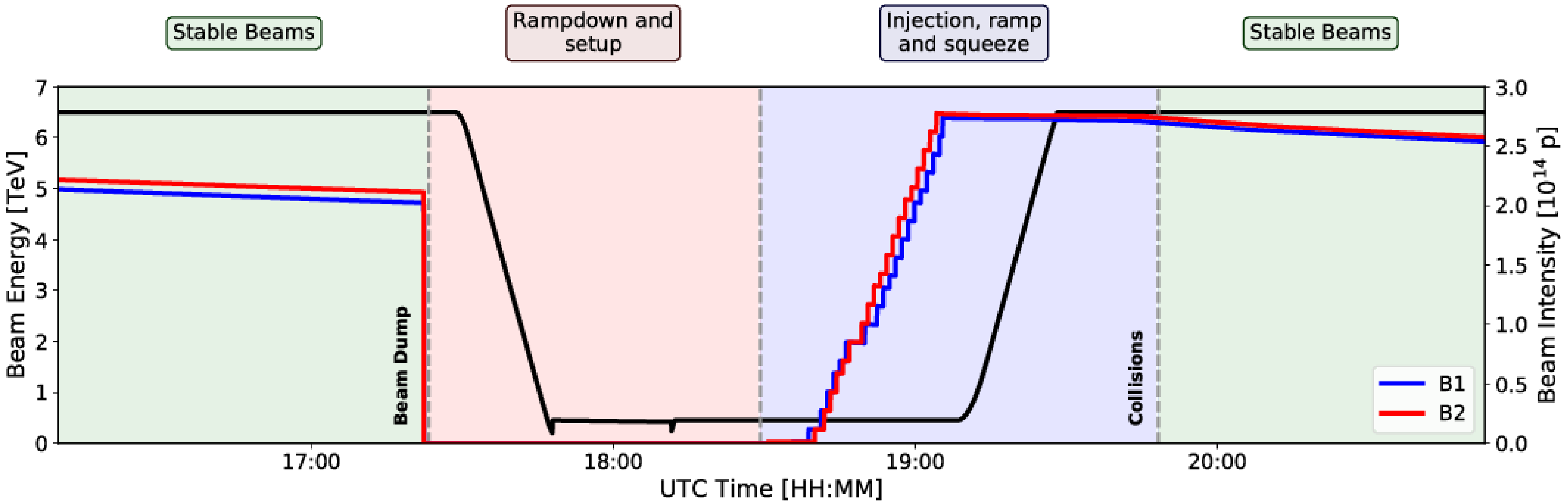



700 MJoule dissipated in 88 us (1 turn)

Beam Dump robustness [core and windows]
Kicker reliability -> many kicker elements
-> Failure likelihood & reliability

**1 electron volt = 1,602× $10^{-19}$ joule**

# (Ideal) LHC cycle and machine efficiency

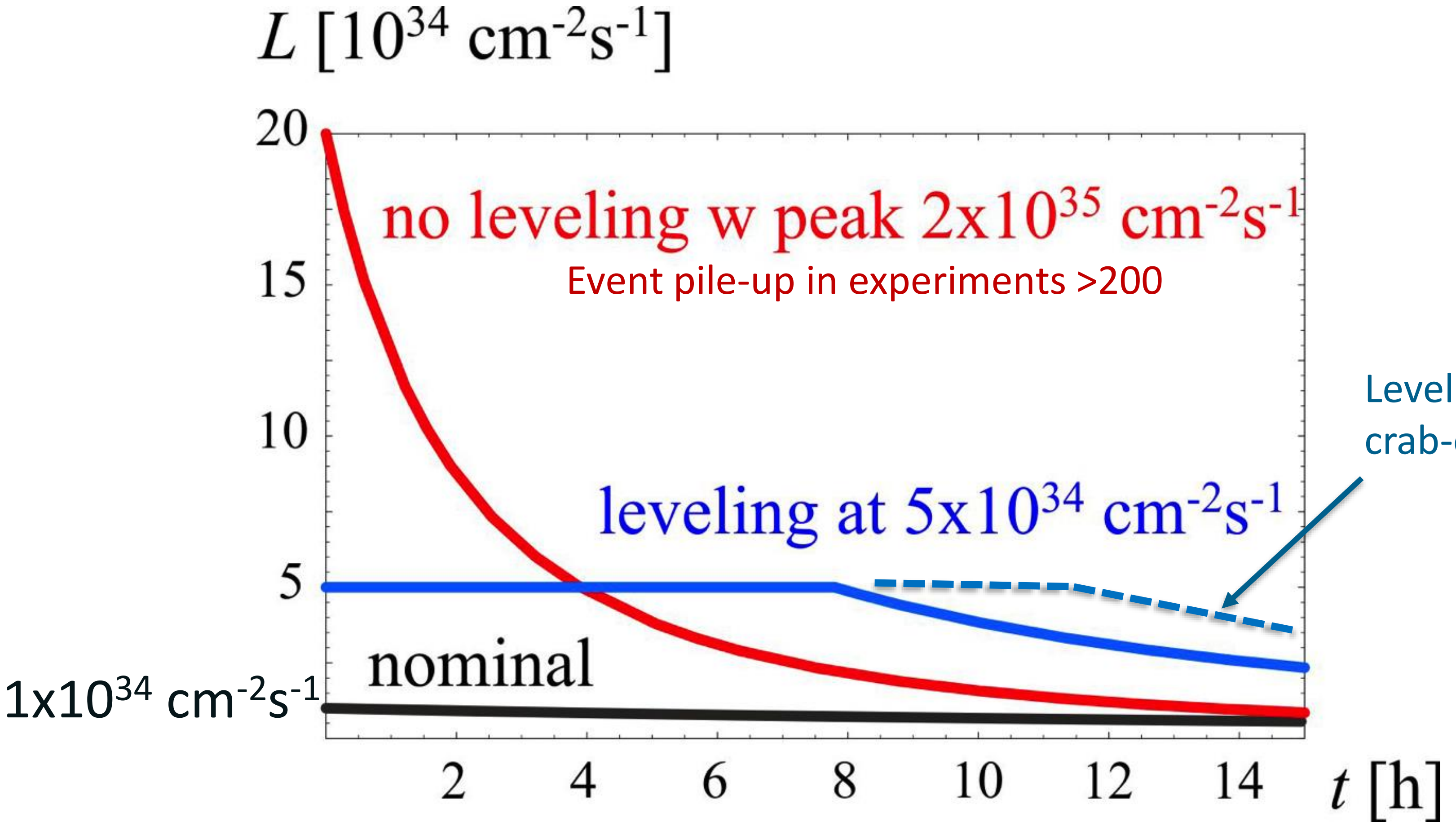



This becomes more challenging with increased Collider size and Requires even more powerful injector complex!!!!

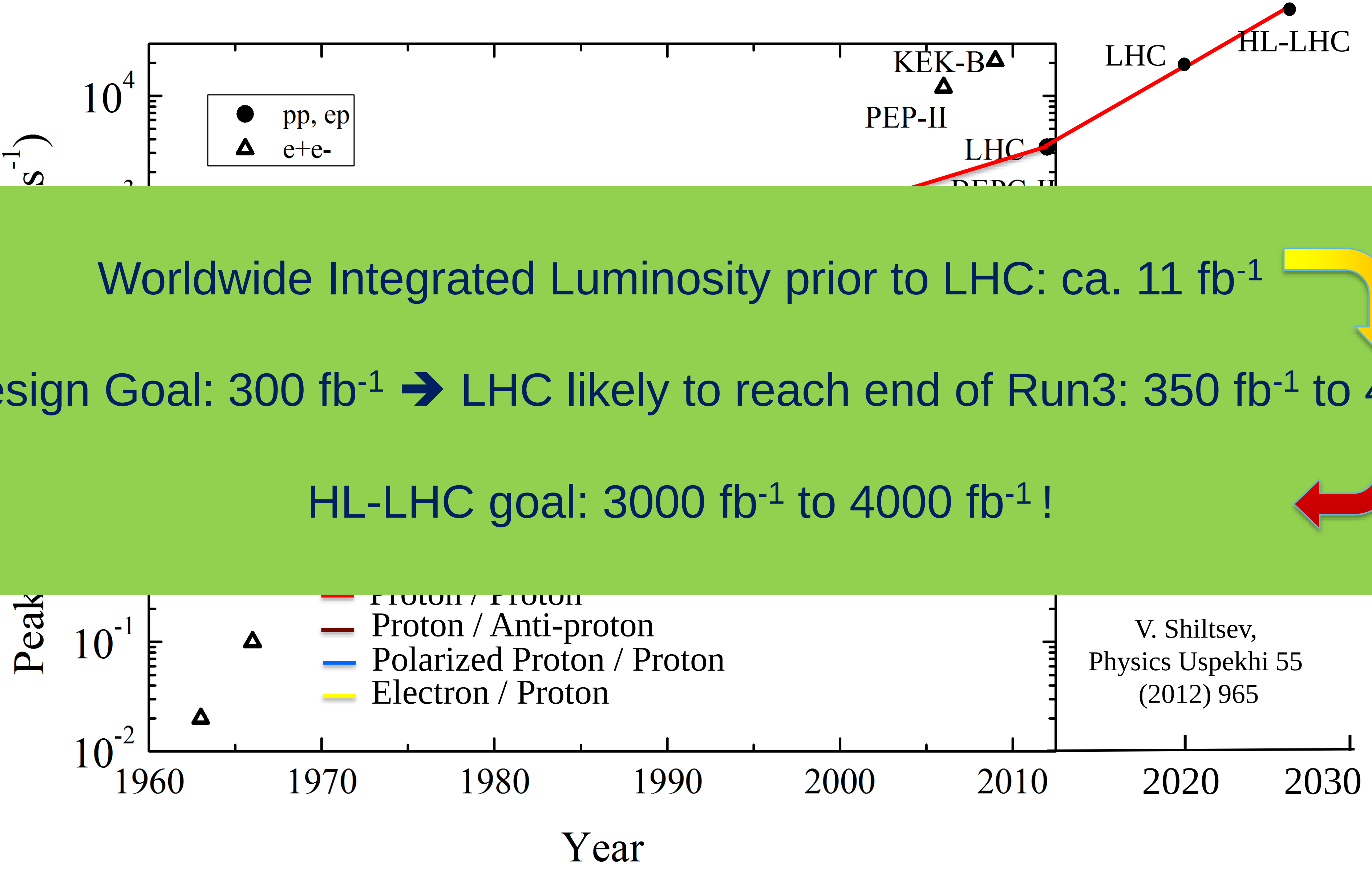
➔ ca. 50% in LHC operation including faults at best conditions!

# Reality…. 3 typical weeks of LHC Machine operation….

# Ideal HL-LHC operation with luminosity levelling



# Peak luminosities of Hadron Colliders




Worldwide Integrated Luminosity prior to LHC: ca. 11 $fb^{-1}$

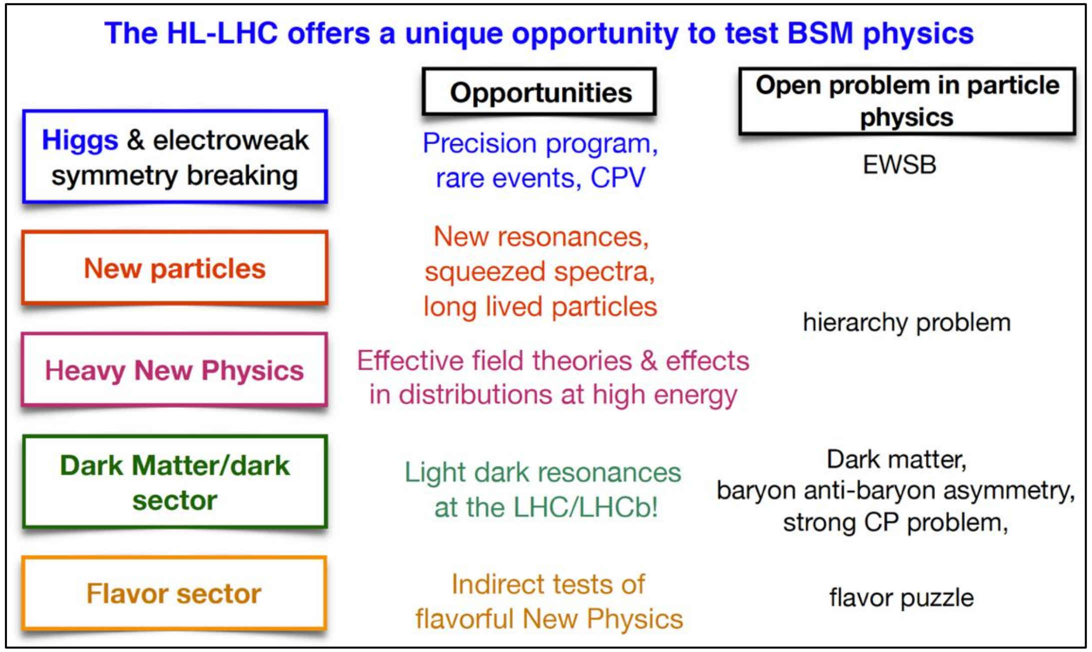
x 35

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 $fb^{-1}$ !

# HL-LHC targets a rich and diverse physics programme

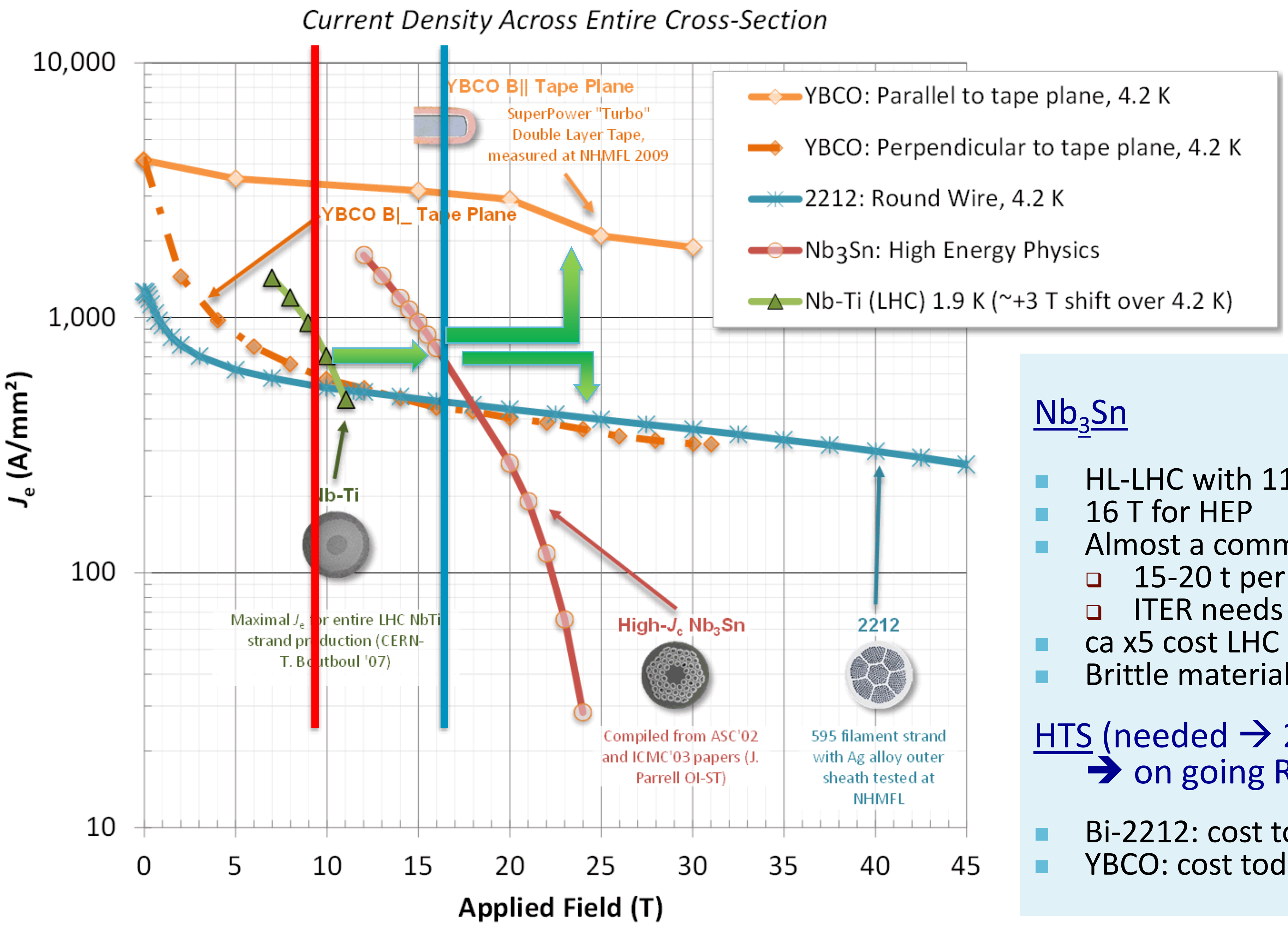



**Headline deliverable is 3 ab$^{-1}$ p-p but the physics programme promises to be impressively diverse…**

Ions (ALICE 3 proposed for LS4)
b-physics (LHCb upgrade proposed for LS4)
Forward physics (PPS2)
Neutrinos (SND, FASERnu, **FPF**)
Long Lived Particles (GPDs, FASER, MoEDAL, *CODEX-b, milliQan, MATHUSLA, ANIBUS,* **FPF***)*
Fixed target (SMOG-2, Crystal-FT)

https://www.ichep2022.it

# 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

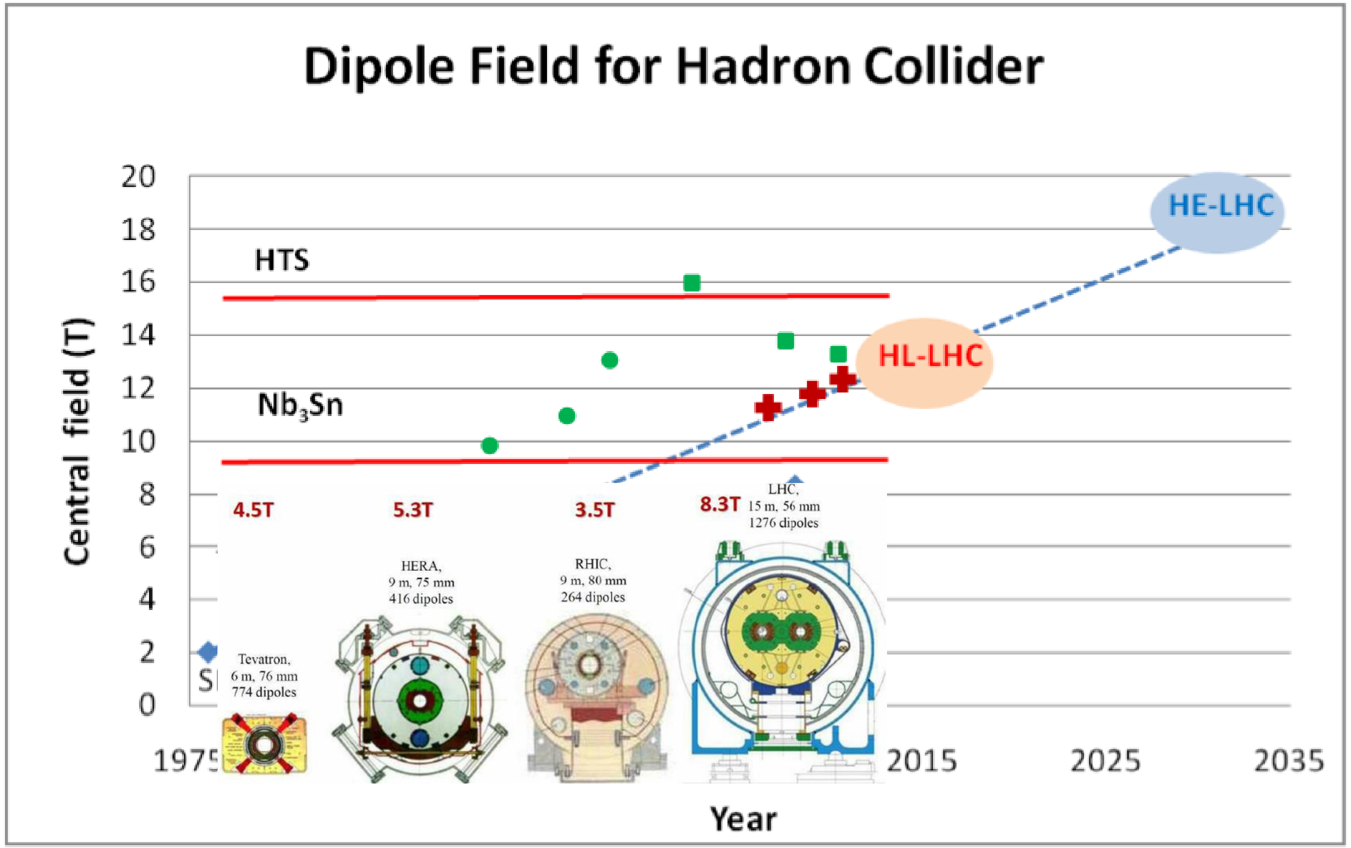
## HTS (needed → 20 T)

→ on going R&D!

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

# High Field superconducting Magnets

Magnet development requires substantial R&D effort!!!




◆ Nb-Ti operating dipoles; ● Nb3Sn cosϑ test dipoles ■ Nb3Sn block test dipoles ✚ Nb3Sn cosϑ LARP QUADs

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)