HiLumi
HL-LHC PROJECT

HL-LHC Project
Status and prospects

Hector Garcia Gavela
on behalf of the HL-LHC Project

42nd ICHEP – Prague July'24

Outline

1. HL-LHC upgrade goals
2. (Main) Technical challenges of the HL-LHC upgrade
3. Inner Triplet String
4. Conclusions

Outline

1. **HL-LHC upgrade goals**
2. **(Main) Technical challenges of the HL-LHC upgrade**
3. **Inner Triplet String**
4. **Conclusions**

Goal of HL-LHC

From EC-FP7 HiLumi LHC Design Study application of 2010

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of L_{peak} = **5×10^{34} cm^{-2}s^{-1} with levelling**, allowing:

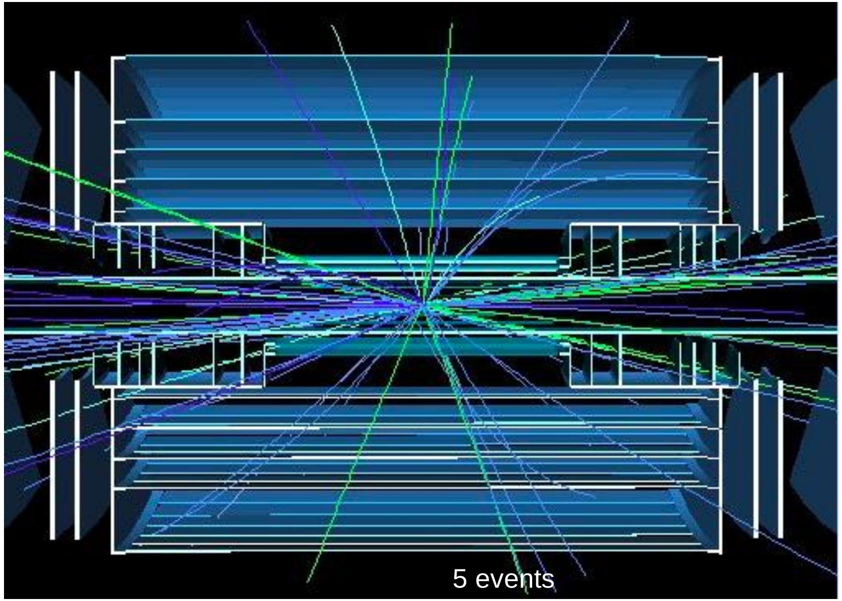
An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.

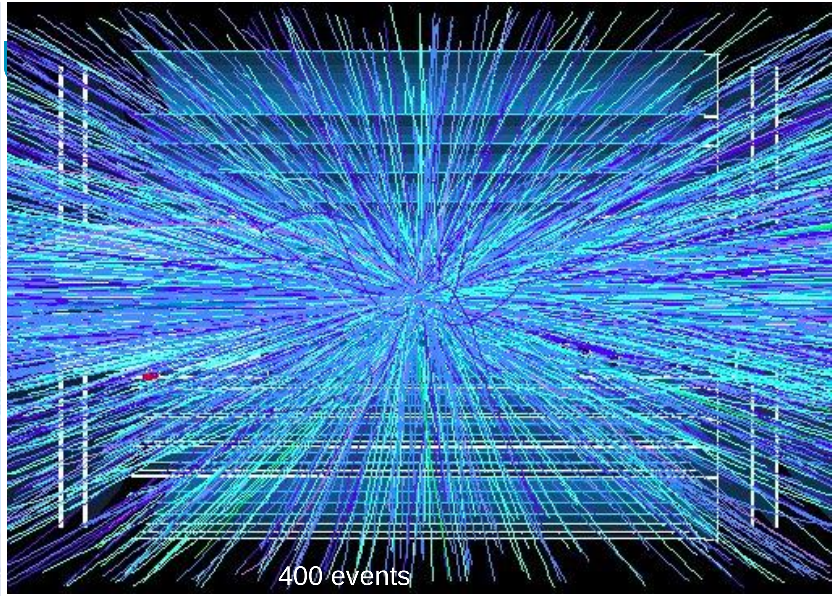
This luminosity is **more than ten times** the luminosity reach of the first 10 years of the LHC lifetime.

Ultimate performance established 2015-2016: with same hardware and same beam parameters: use of **engineering margins:**

$L_{peak\ ult} \cong 7.5\ 10^{34}$ cm^{-2}s^{-1} and **Ultimate Integrated $L_{int\ ult}$ ~ 4000 fb^{-1}**

LHC should not be the limit, would Physics require more…



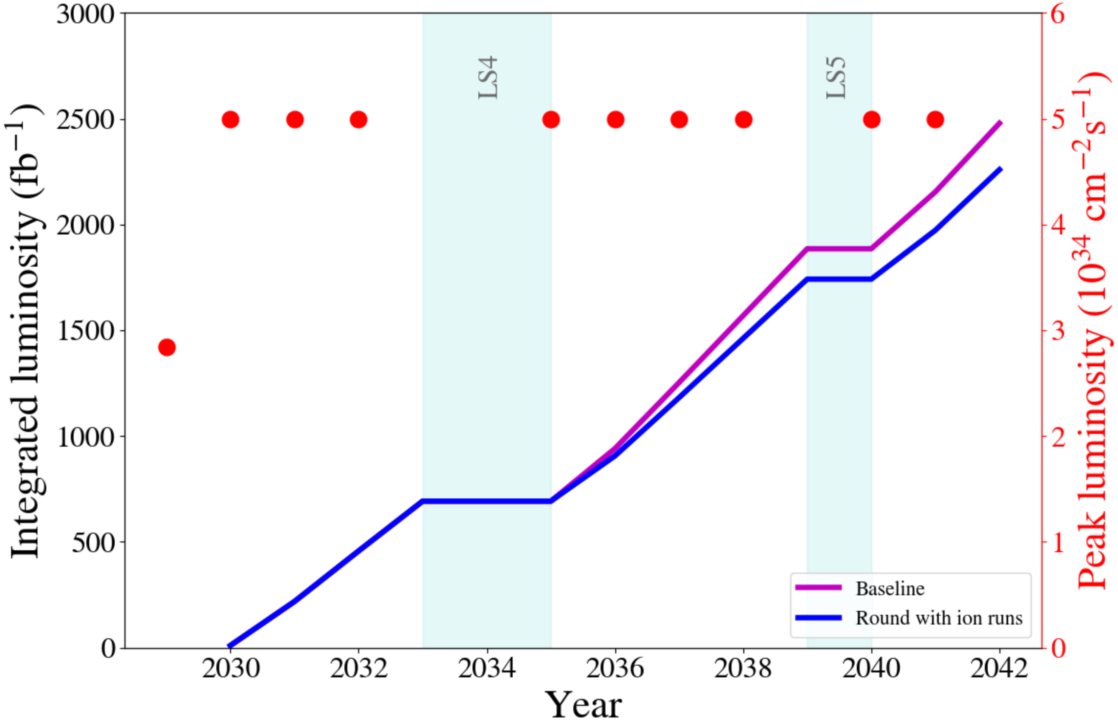


Implies overcoming several limitations in the existing LHC!!!
Cryo cooling of triplet magnets & radiation damage in triplet magnets & machine efficiency!

But also for the experiments!!

➔ Need for an Upgrade!

Luminosity performance

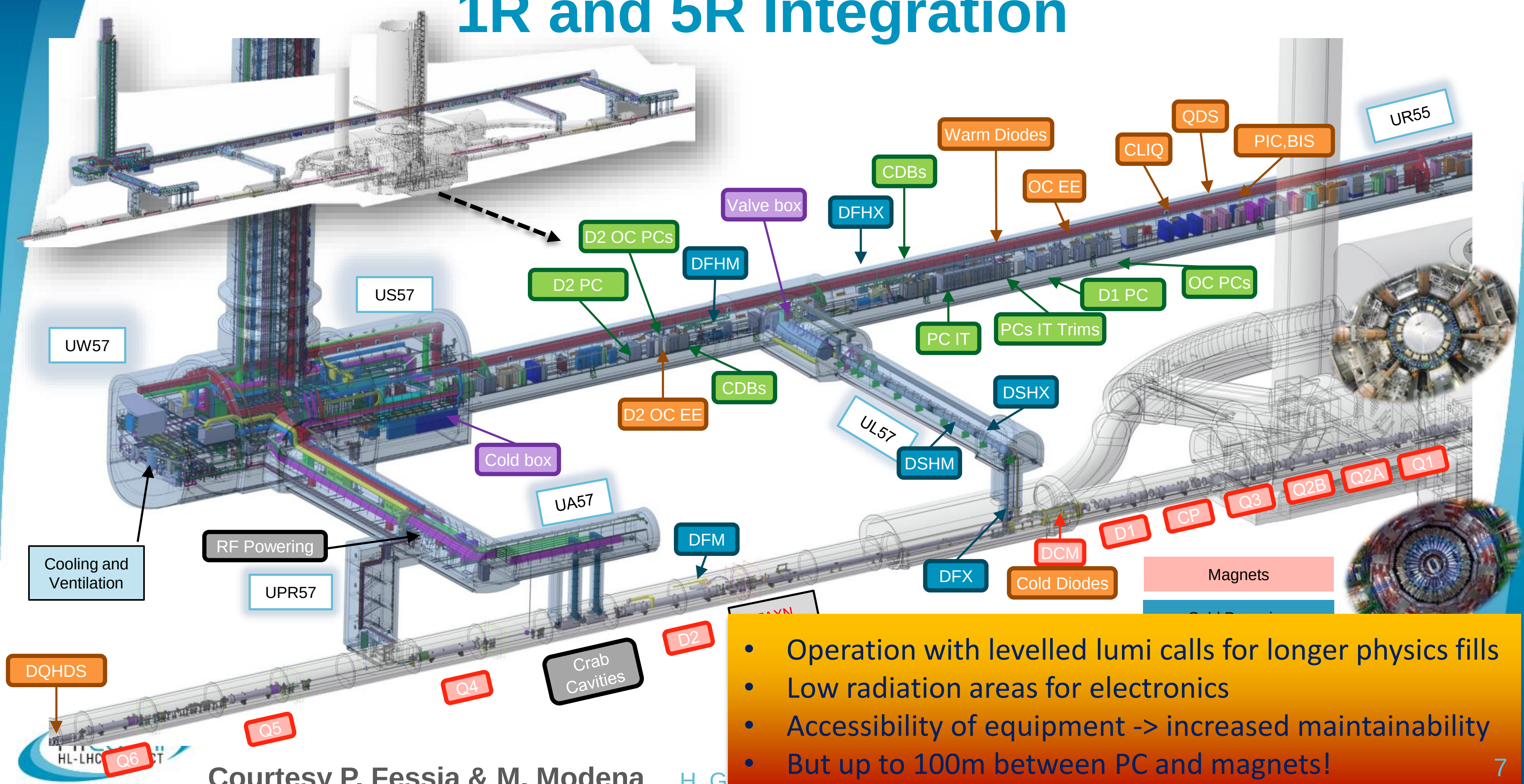


Courtesy N. Mounet

(Note that **~460 fb^{-1}** should be added for the **LHC runs)**

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

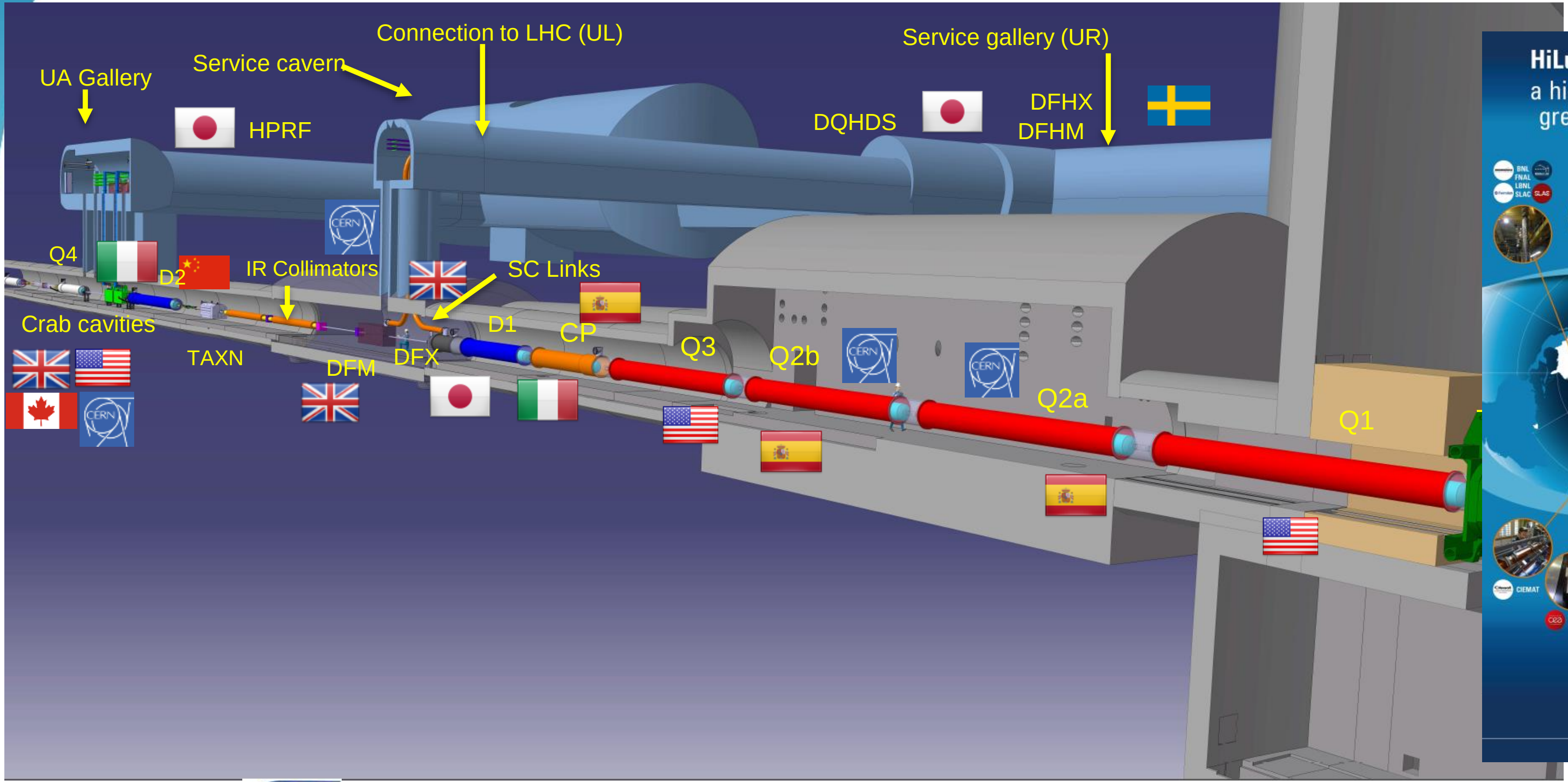
1R and 5R Integration



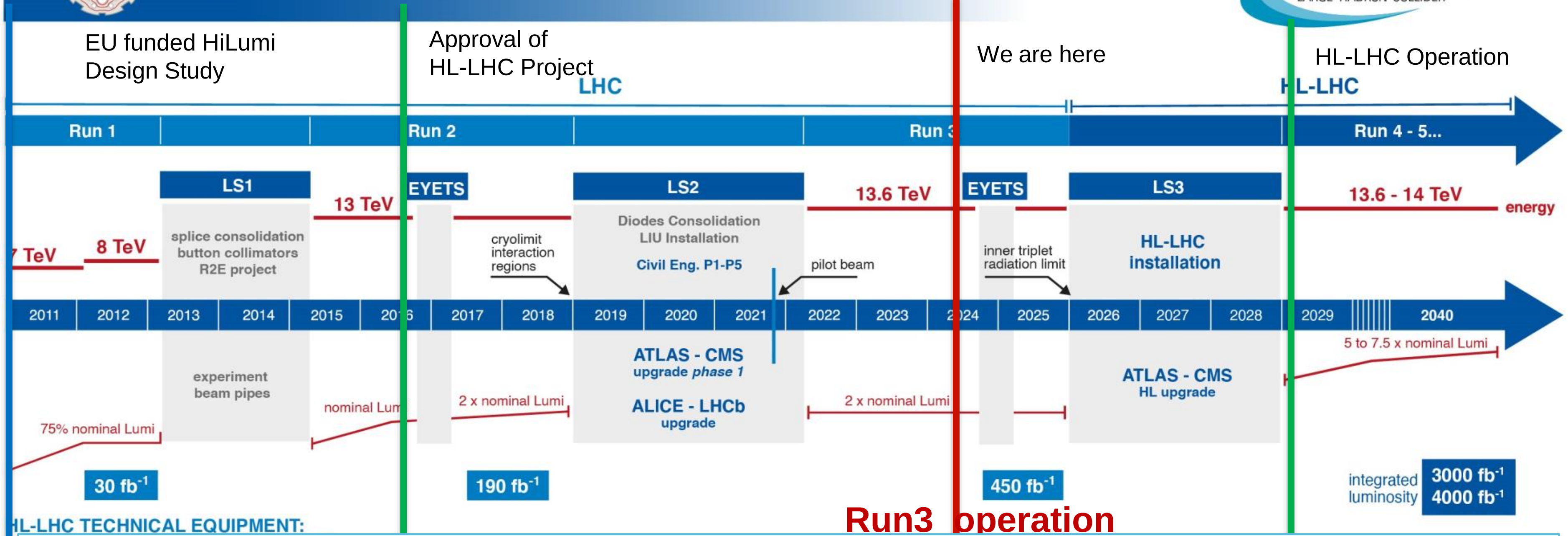
- Operation with levelled lumi calls for longer physics fills
- Low radiation areas for electronics
- Accessibility of equipment -> increased maintainability
- But up to 100m between PC and magnets!

Courtesy P. Fessia & M. Modena

HL-LHC - A truly international collaboration



LHC / HL-LHC Plan



➔ <1.5 years until start of Long Shutdown 3 (Nov-25)

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

➔ The project is ready for LS3 installation start in 2026! ➔ endorsed by 2023 C&SR

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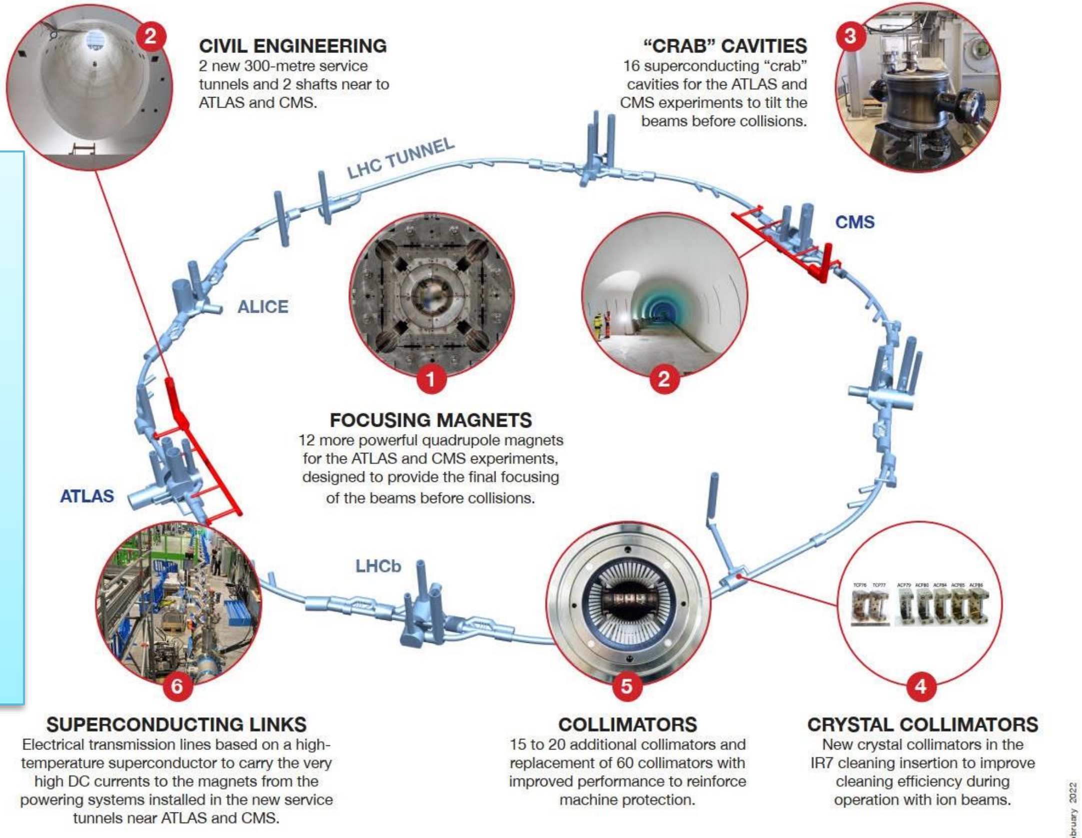
HL-LHC technology landmarks

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

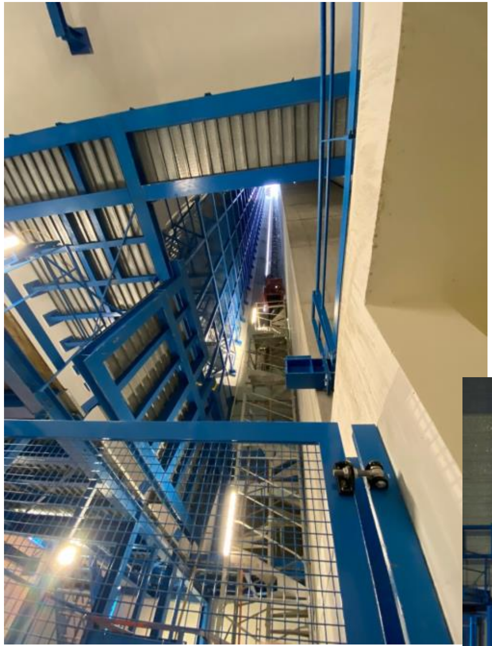


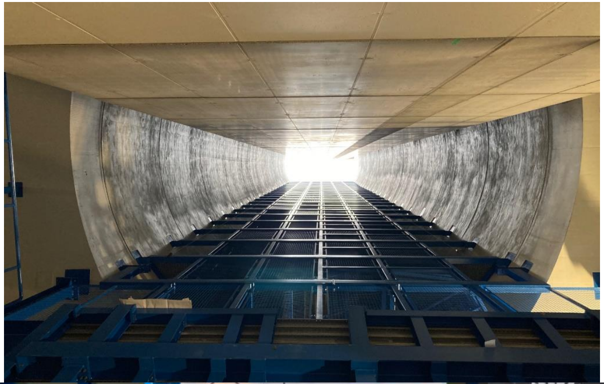
IR1/5 underground civil engineering completed in 2022

Construction Finished End 2022

work was conducted during LS2 ➔ vibration impact

Ceremony for completion of CE on January 20th 2023





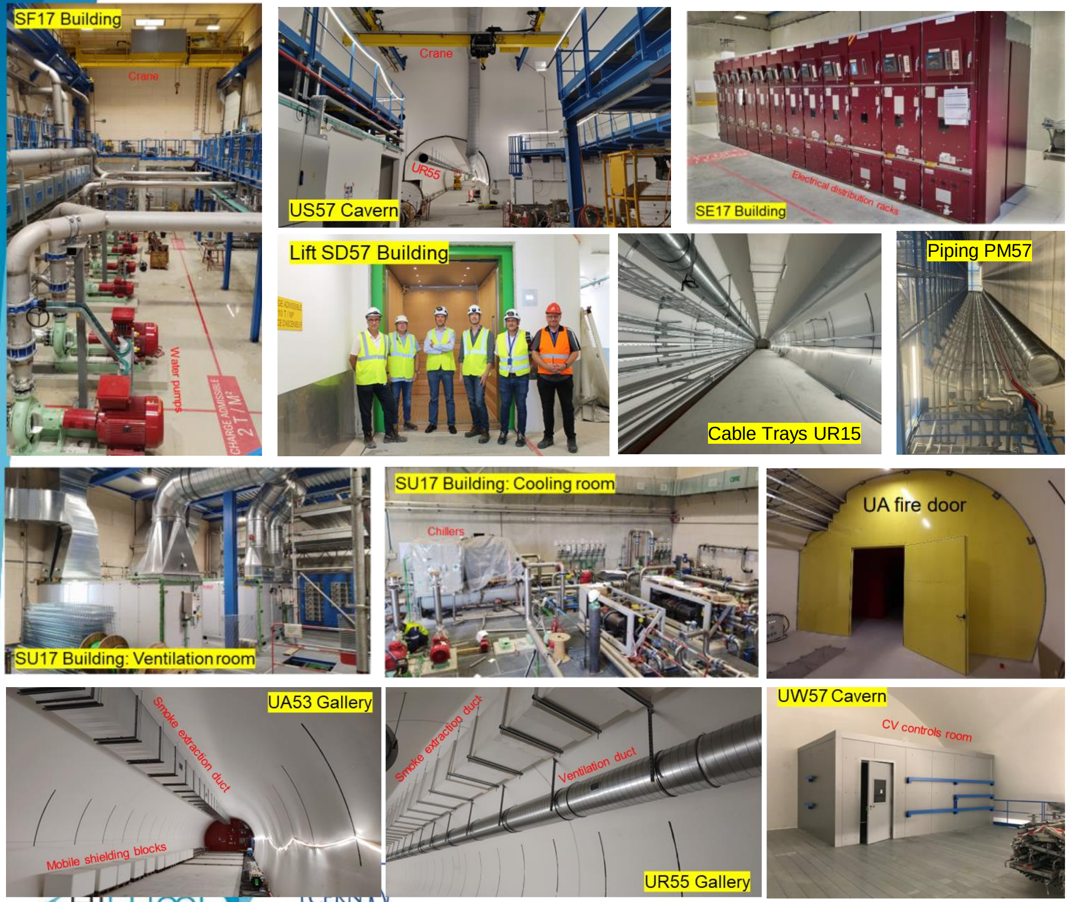
Completion of Surface buildings in 2023

Work Ended Spring 2023

Point 1

Point 5

Technical Infrastructure – Installation Services



Technical Services in full swing for installation:

- ✓ **Sectional doors**
- ✓ **Lifts**
- ✓ **Overhead Cranes**
- ✓ **Fire safety**
- ✓ **Cable trays & cabling**
- ✓ **Lighting**
- ✓ **Switchboards**
- ✓ **Racks**
- ✓ **Power Transformers**
- ✓ **Ventilation system**
- ✓ **Cooling system**

HL-LHC Technical Challenges: Triplet Magnets

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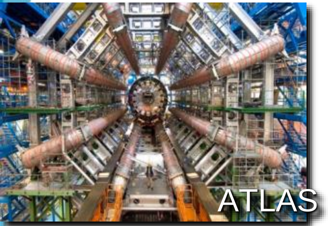
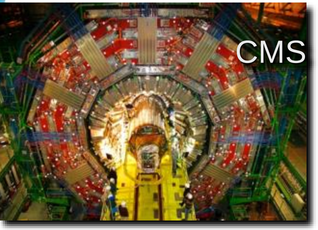
!!





Operation beyond 2025:

Requires replacement of LHC Triplet magnets

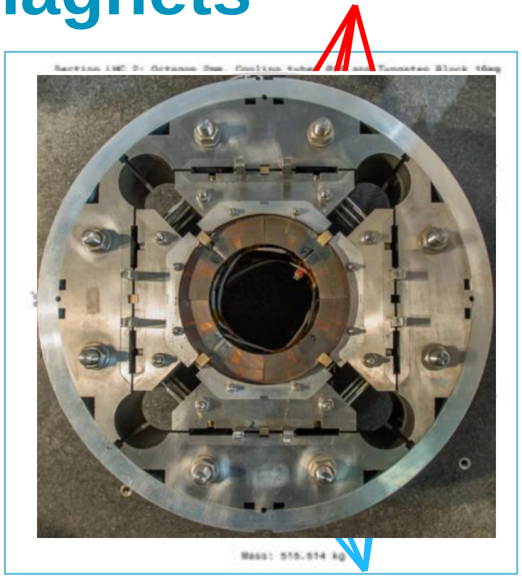
10 x the luminosity ➔ Requires new, more radiation resistant triplet magnets

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!

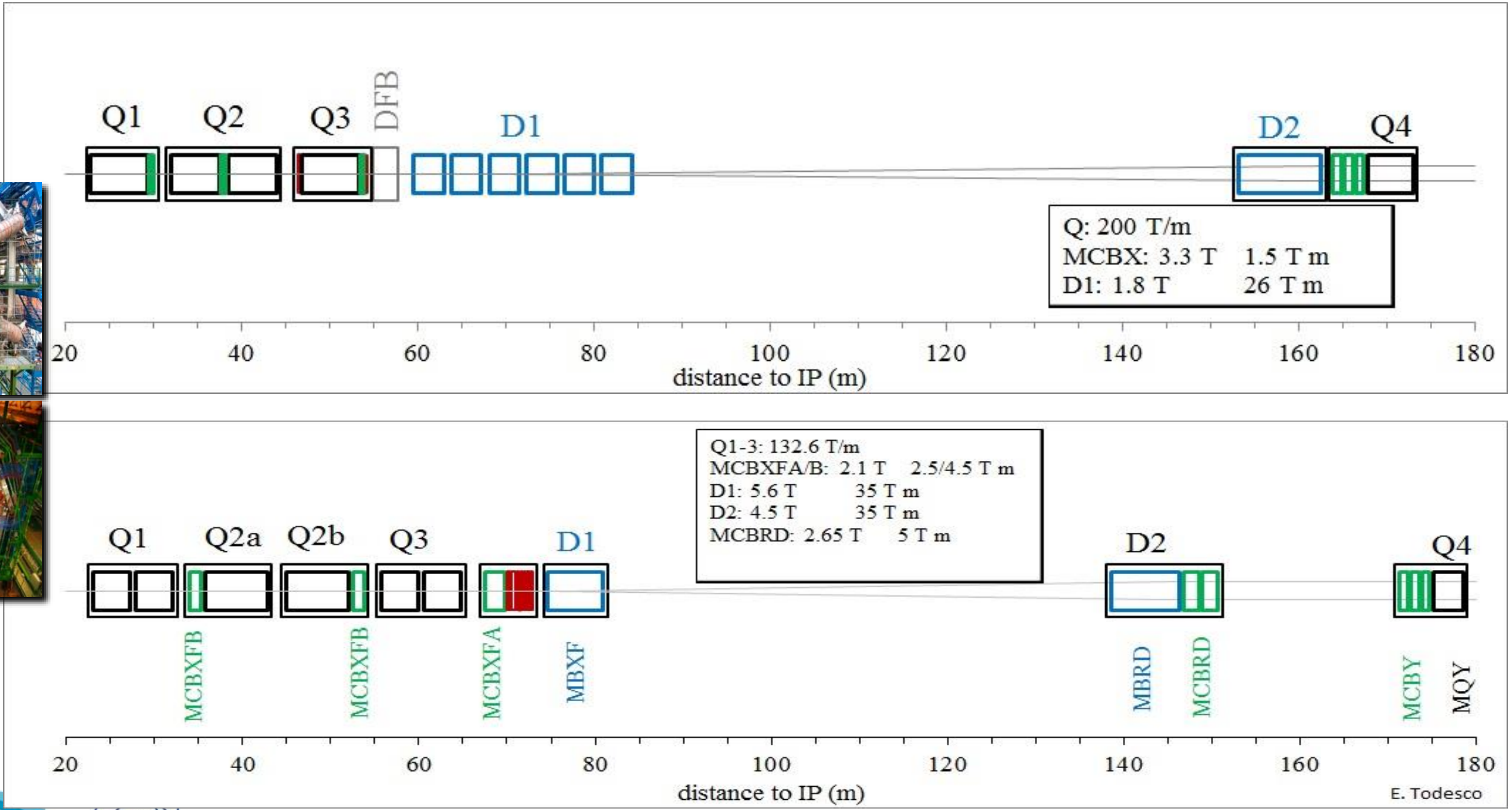
- ➔ Requires larger aperture!
- ➔ New magnet technology!
- ➔ 70 mm at 210 T/m ➔ 150 mm diameter 140 T/m

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

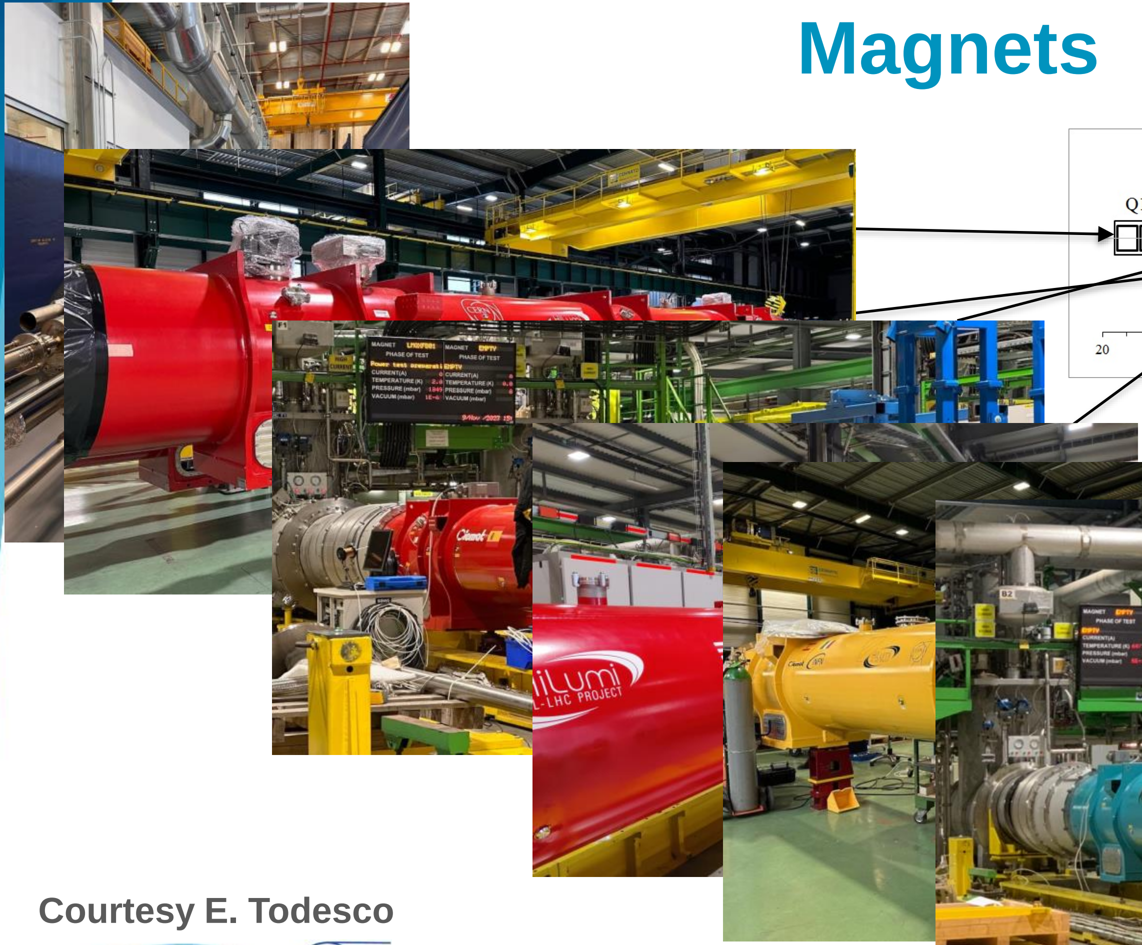


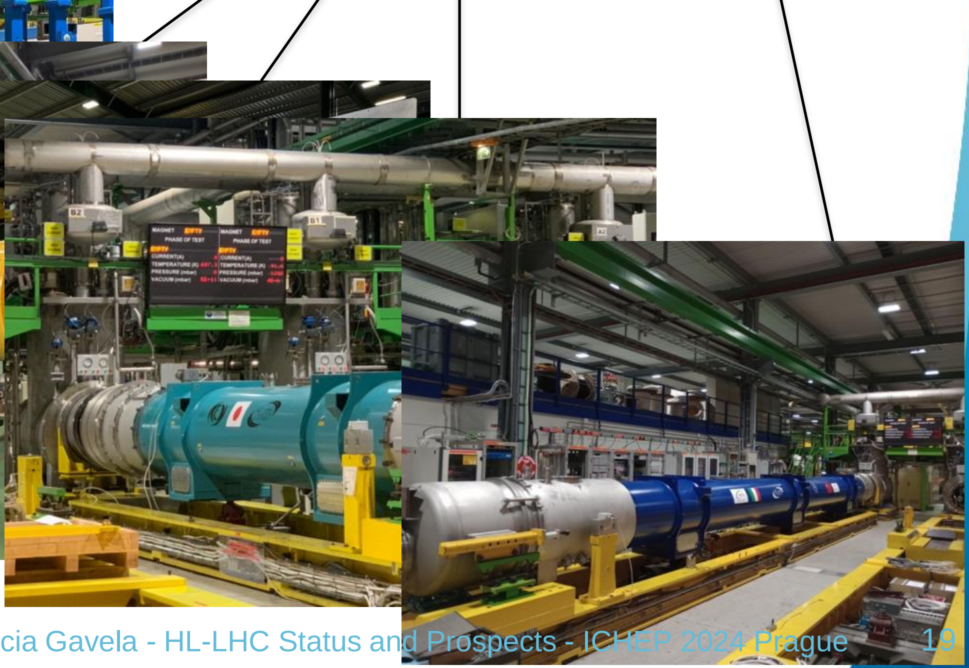
US-LARP MQXF magnet design Based on Nb_3Sn technology

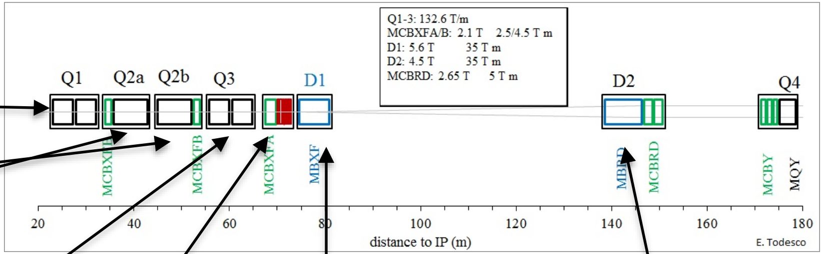
New HL-LHC Triplet Layout



Magnets



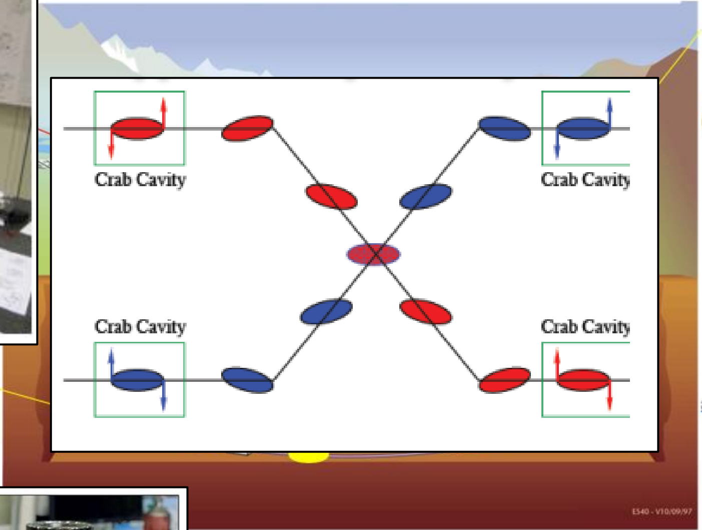




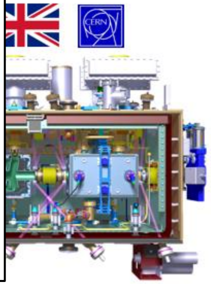
Courtesy E. Todesco

Crab Cavities *See R. Calaga's presentation*

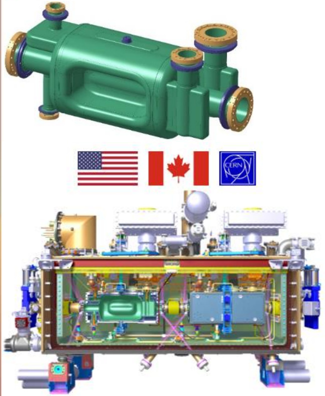
cavities emerged **in ~2006**. Since then, many years of **R&D, Proof of Principle Cavities, design.**



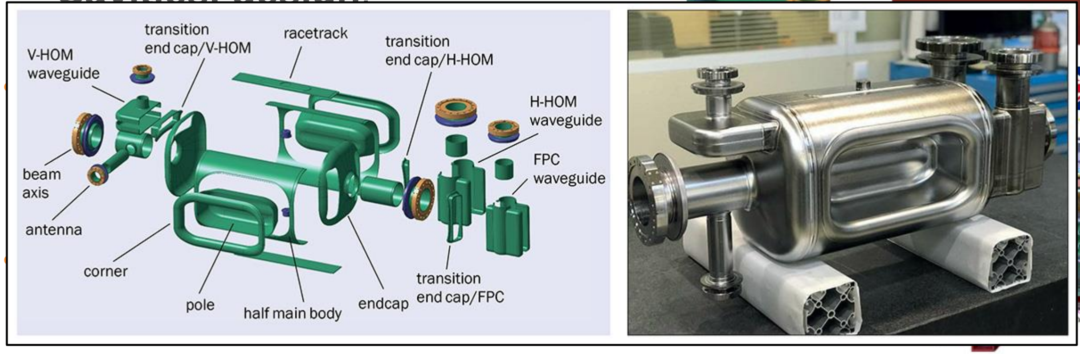
4+1 DQW Cryomodules
UK, CERN



4+1 RF Dipole cryomodules
US-AUP, Canada, CERN



RF powering & control

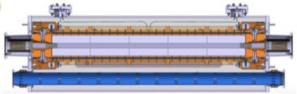


Collimation

See S. Redaelli's presentation

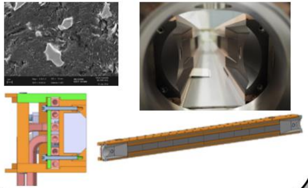

LS3

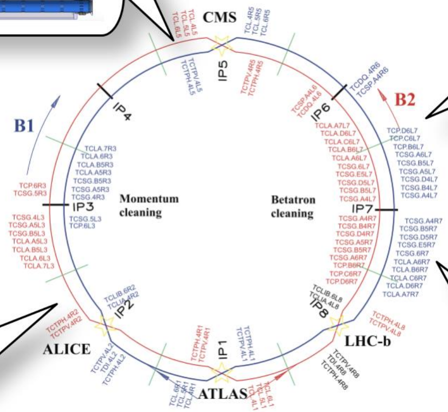
IR collimation: Completely new layouts and collimator designs: IR1+IR5: incoming and outgoing. Full remote alignment system (FRAS)



LS2+LS3

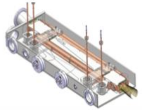
Impedance reduction: low-impedance, high robustness secondary collimators: coated MoGr
Un-coated MoGr primary collimators.





LS2

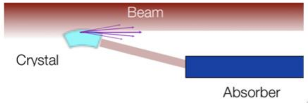
Dispersion suppressor collimation: Secondary beams from ion physics



Consolidation (not HL): low-impedance primaries (material from WP5), renew controls, maintain / replace rest of system

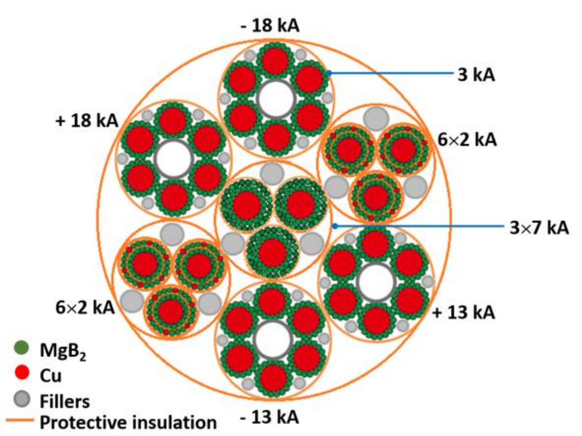
LS2+YETS

Crystal-assisted collimation (Pb ions)
4-8 bent crystals, 50 μrad bending
IP7 (betatron cleaning)

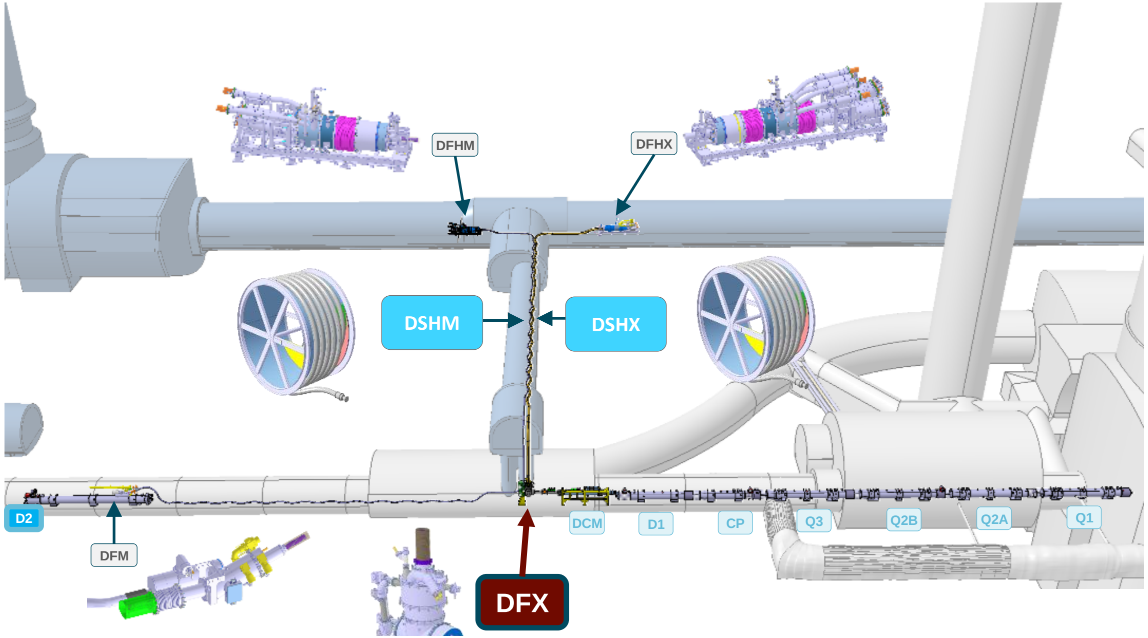


Crucial upgrades took place in LS2: the LHC is already profiting from! Moving now towards LS3 production

Cold powering systems - SC link using MgB_2 superconductor



Diam ca. 90mm
> 100kA @ 25K



- **Successful PoP validation** via **system demonstrators (DEMO)**
- **MgB2 wire production complete**
- **MgB2 cable** production at **80%**
- **DFX cryostats** delivered by **UK Collaboration**; **DFM** in production
- **DFHX cryostats** delivered by **Swedish Collaboration**; **DFHM** in production
- All **flexible cryostats at CERN**
- **Rebco Tape** in production
- **Assembly of the first complete system and successful validation test**

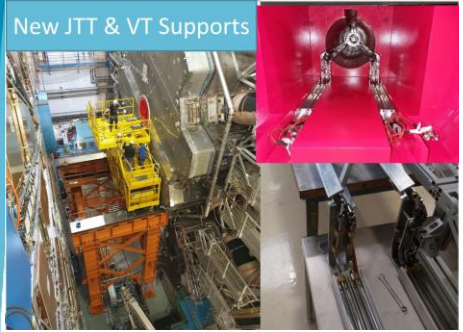
Successful test of the 1st SC Link System

- Cryogenic performance and operation
- Powering and EMC among circuits
- HV Tests including ELQA validation
- Instrumentation
- Thermal cycling and contraction of the system
- Mechanical integrity

Other major achievements


TANB absorber installed in LS2

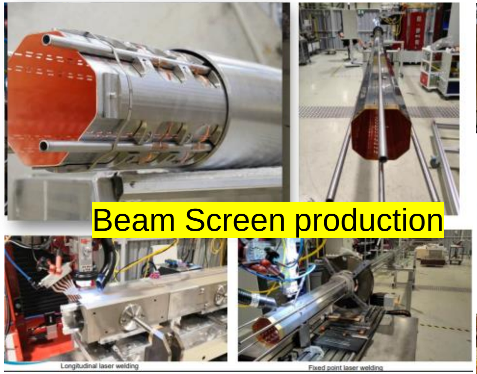

TDIS installed in LS2




BGC installed in EYETS'23


MKI installed in *EYETS'23

Warm Helium Storage Tanks at P1 & P5



Beam Screen production


BPM production


CLIQ pre-series


EE Systems pre-series

Power Converters production


TDE material HiRadMat

EYETS - Extended Year-End Technical Stop
MKI – Magnet Kicker at Injection
BGC – Beam Gas Curtain
TDIS - Target Dump Injection Segmented

CLIQ - Coupling-Loss-Induced-Quench
BPM – Beam Position Monitors
TDE – External Beam Du

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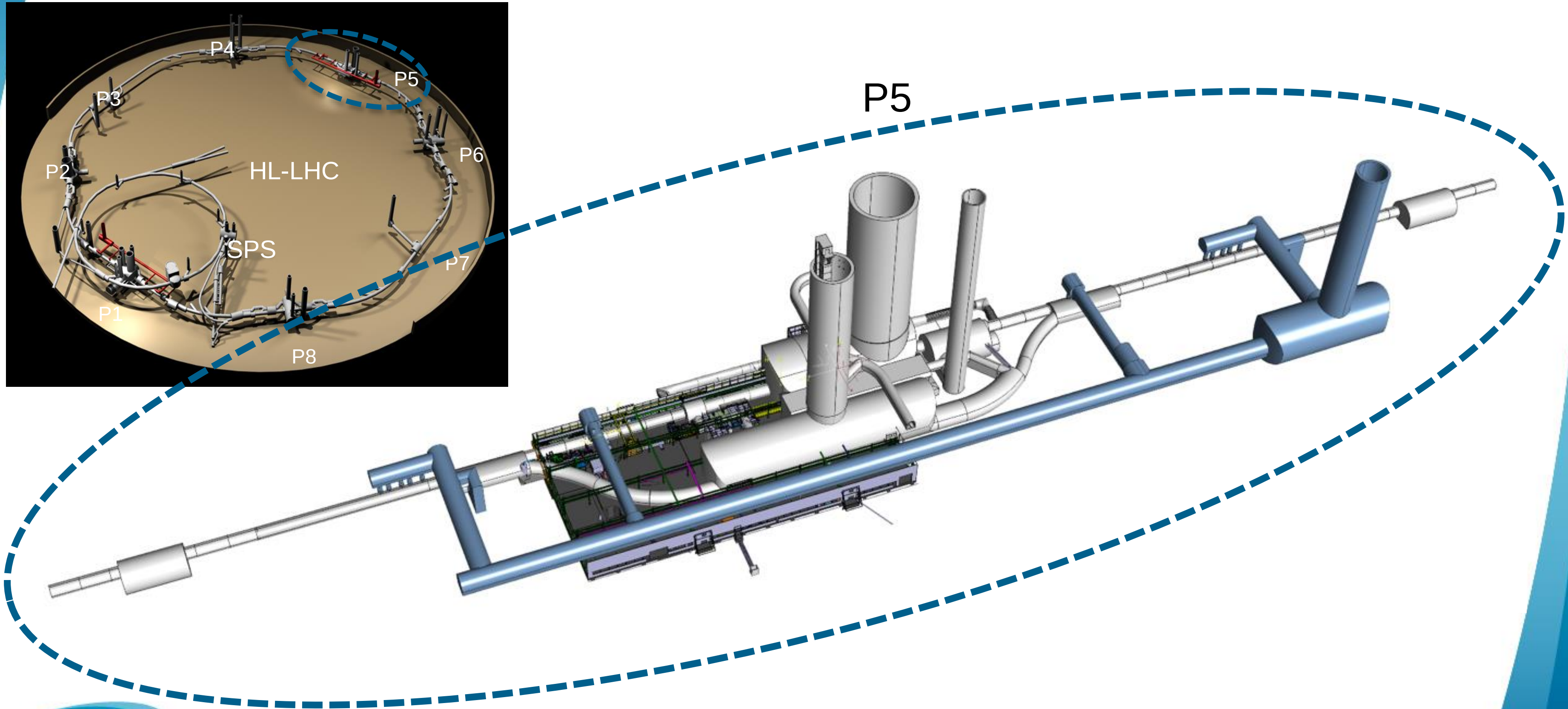
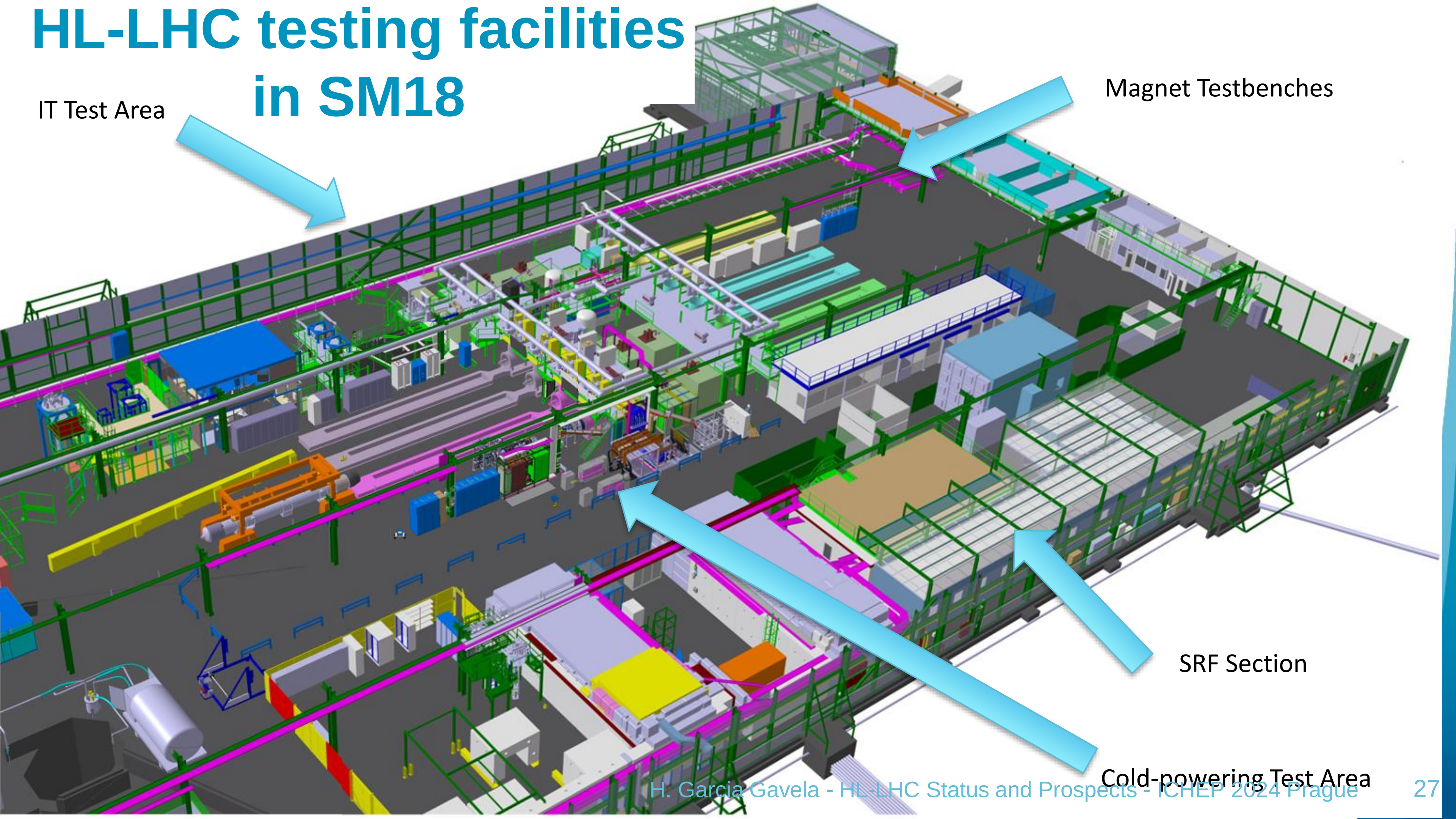
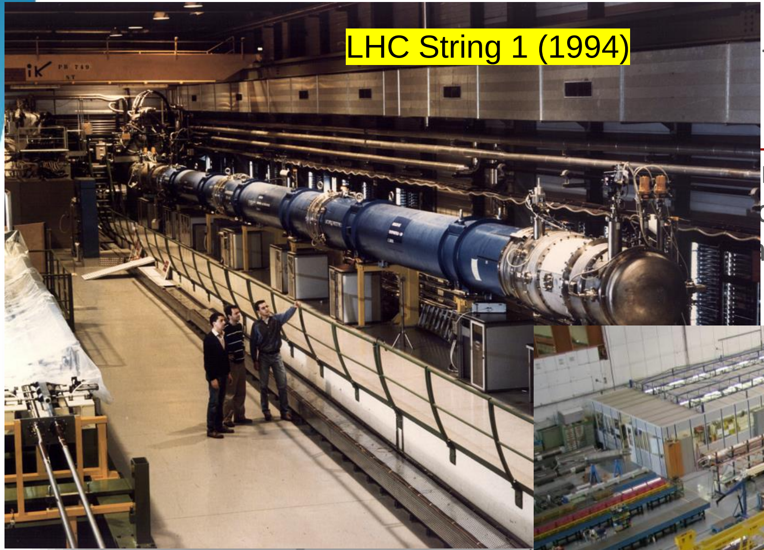
Next Milestone: HL-LHC IT STRING: P5L



HL-LHC testing facilities in SM18



The IT STRING Scope



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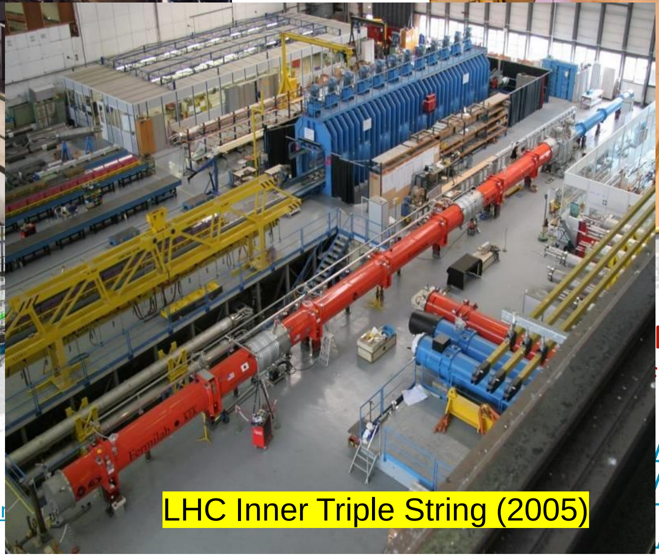

NG will deliver **the first complete experience**
installing and operating the IT zone

/indico.cern.ch/event/741801/ - Oct'18
//indico.cern.ch/event/1183794/ - Sep'22
//indico.cern.ch/event/1298459/ - Sep'23
IT String Day IV - https://indico.cern.ch/event/1408524/ - Sep'24

Ref. HL-LHC IT STRING Scope https://edms.cern.ch/documen

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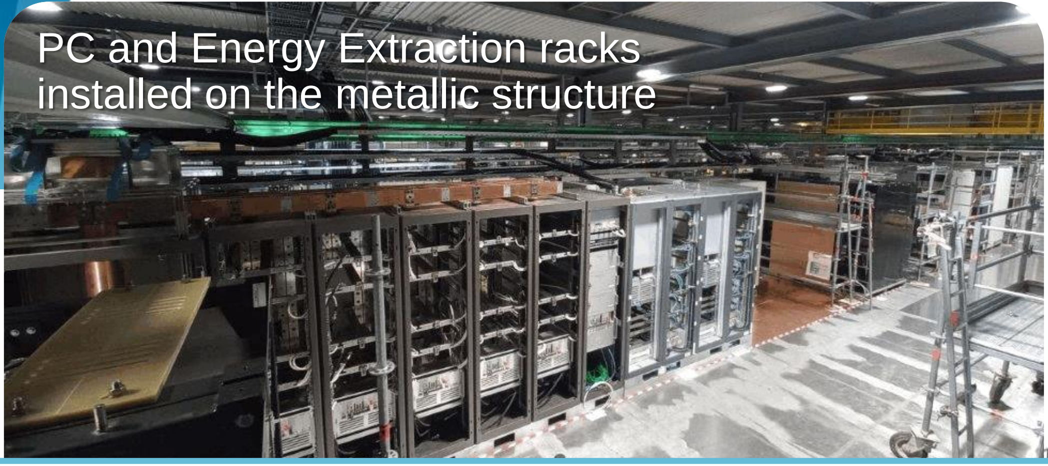
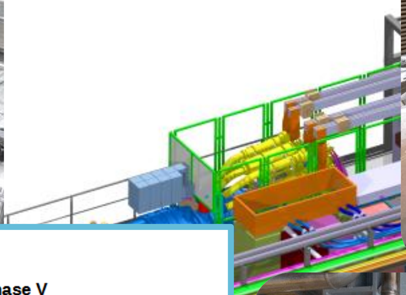
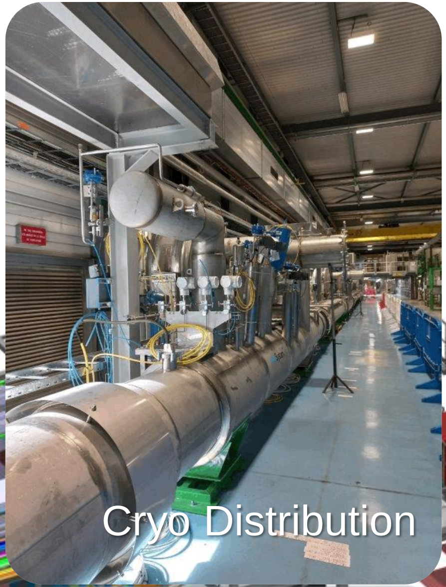
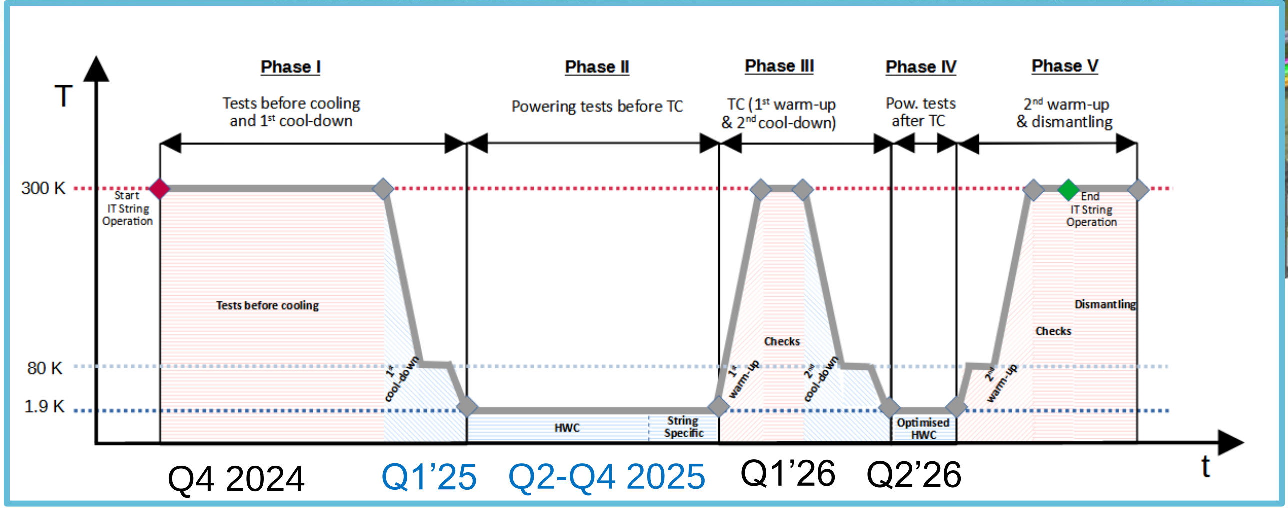
IT String Status in pictures



IST (Individual System Tests) and SCT (Short Circuit Tests) already carried out this year.







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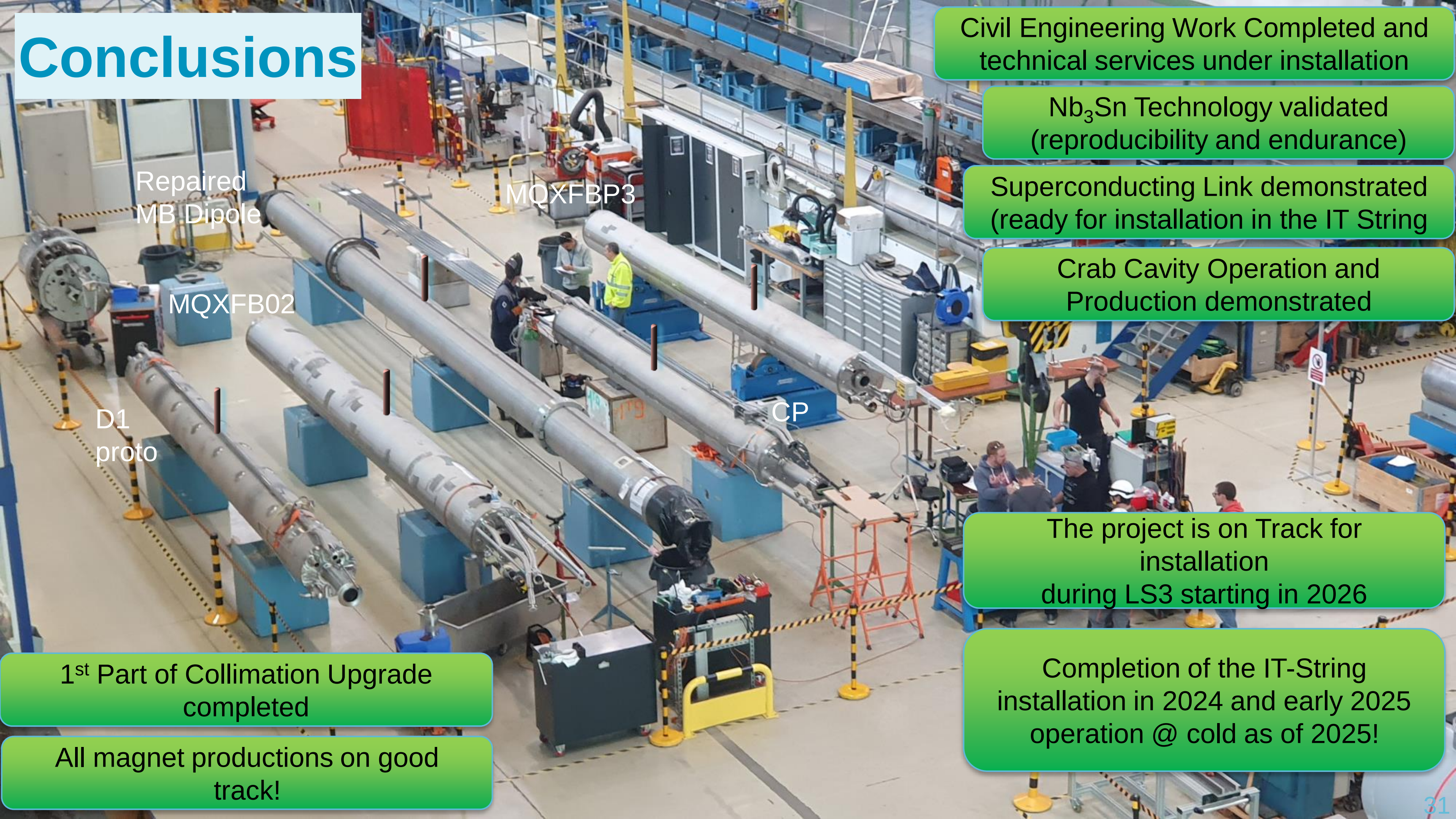
HiLumi HL-LHC PROJECT

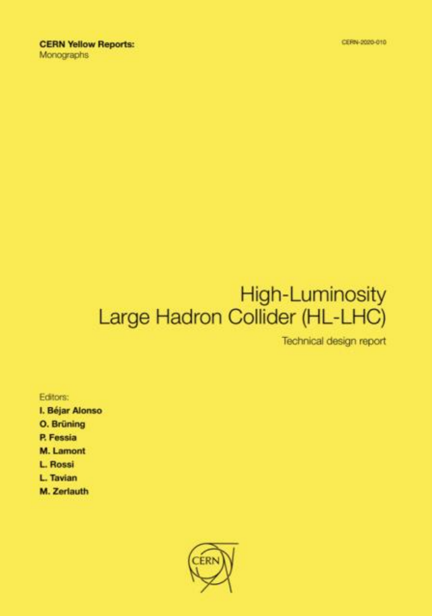
Conclusions

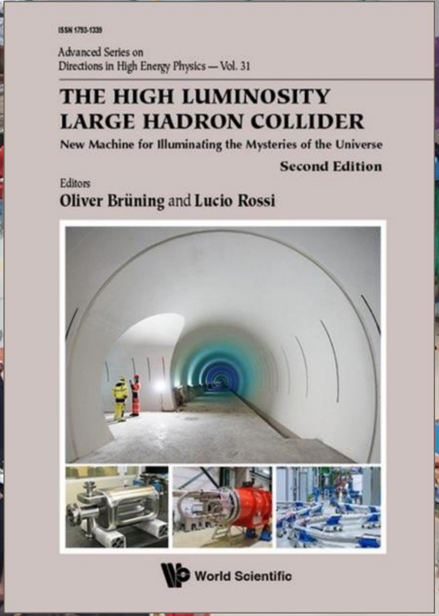


- Civil Engineering Work Completed and technical services under installation
- Nb_3Sn Technology validated (reproducibility and endurance)
- Superconducting Link demonstrated (ready for installation in the IT String
- Crab Cavity Operation and Production demonstrated
- The project is on Track for installation during LS3 starting in 2026
- Completion of the IT-String installation in 2024 and early 2025 operation @ cold as of 2025!
- 1st Part of Collimation Upgrade completed
- All magnet productions on good track!

Many Thanks!
Questions!

MQXFBP3





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

Hi-lumi Book 2nd edition
https://www.worldscientific.com/worldscibooks/10.1142/13487#t=aboutBook

Spare Slides

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 β^* [m]	0,55	0,15
ε_n [μm]	3,75	2,50
ε_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
ε_n at SPS extraction [μm] [3]	3,5	2,1

LHC Magnet system

LHC injector complex

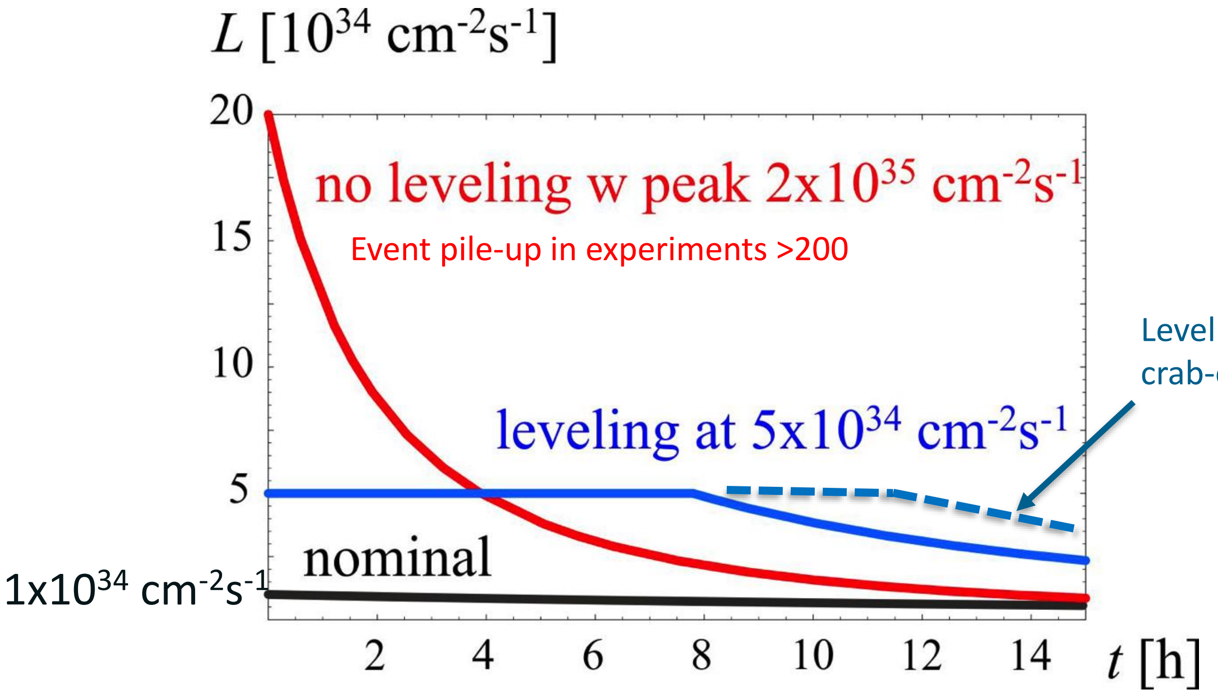
HL-LHC triplet magnets

HL-LHC crab cavities

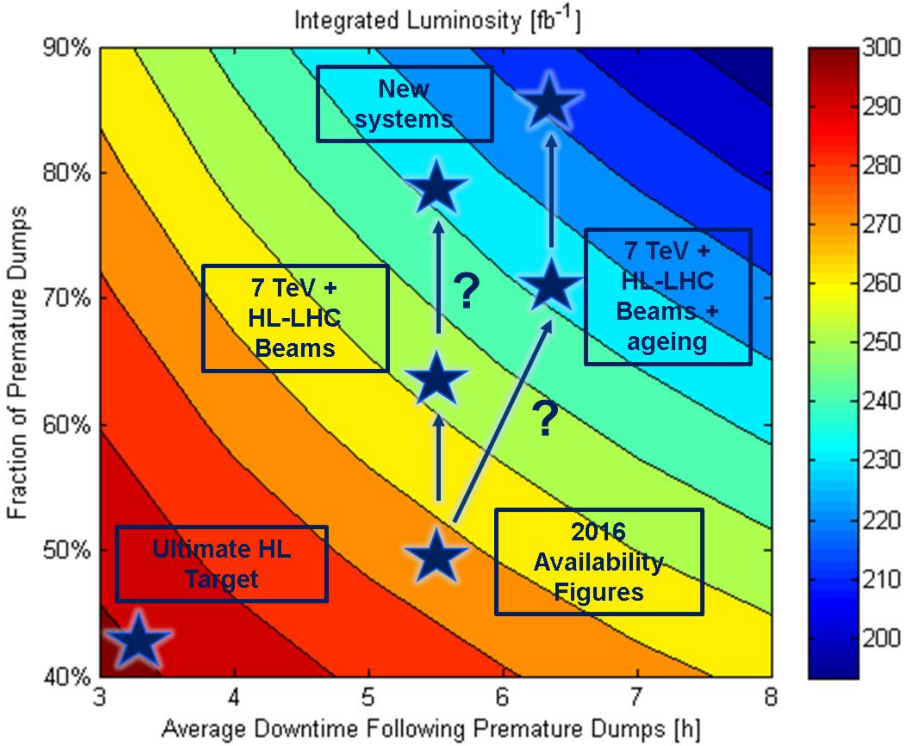
Machine operation & availability

LHC injector complex

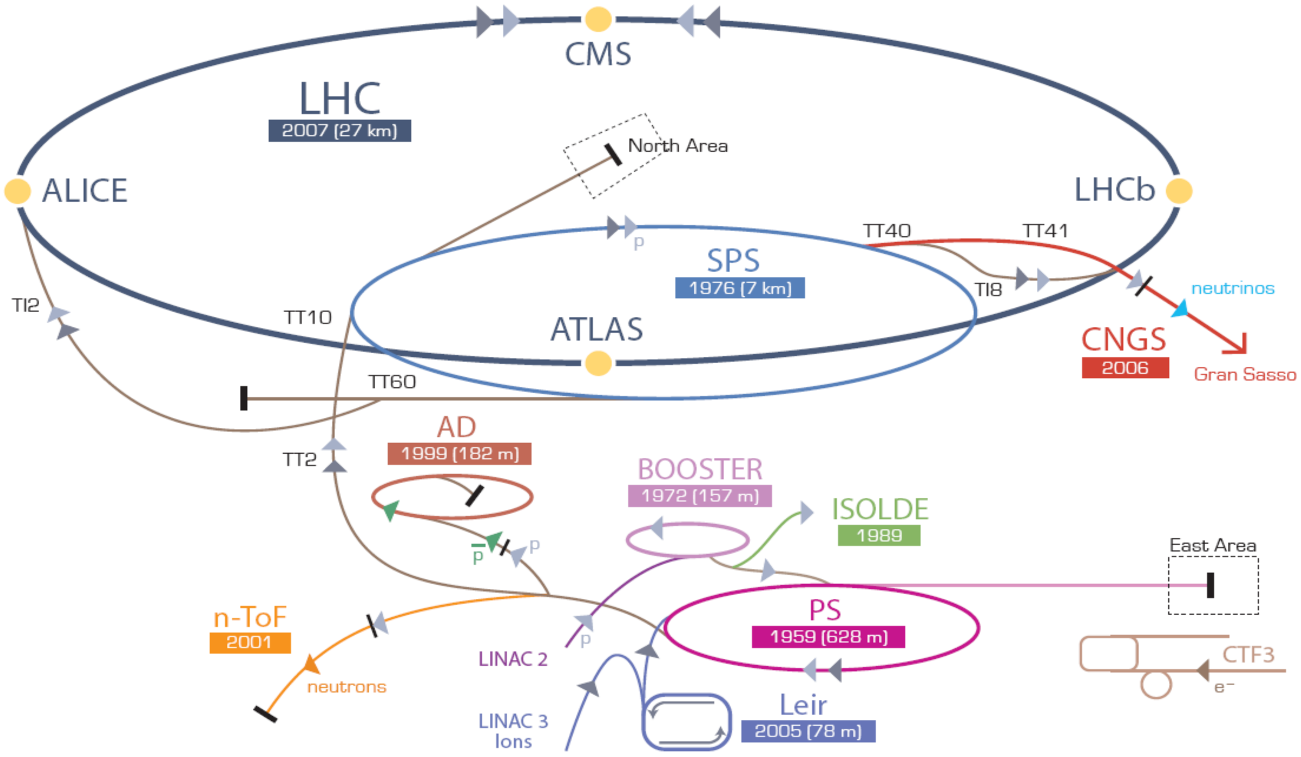
Ideal (HL-)LHC operation



Availability vs HL-LHC luminosities

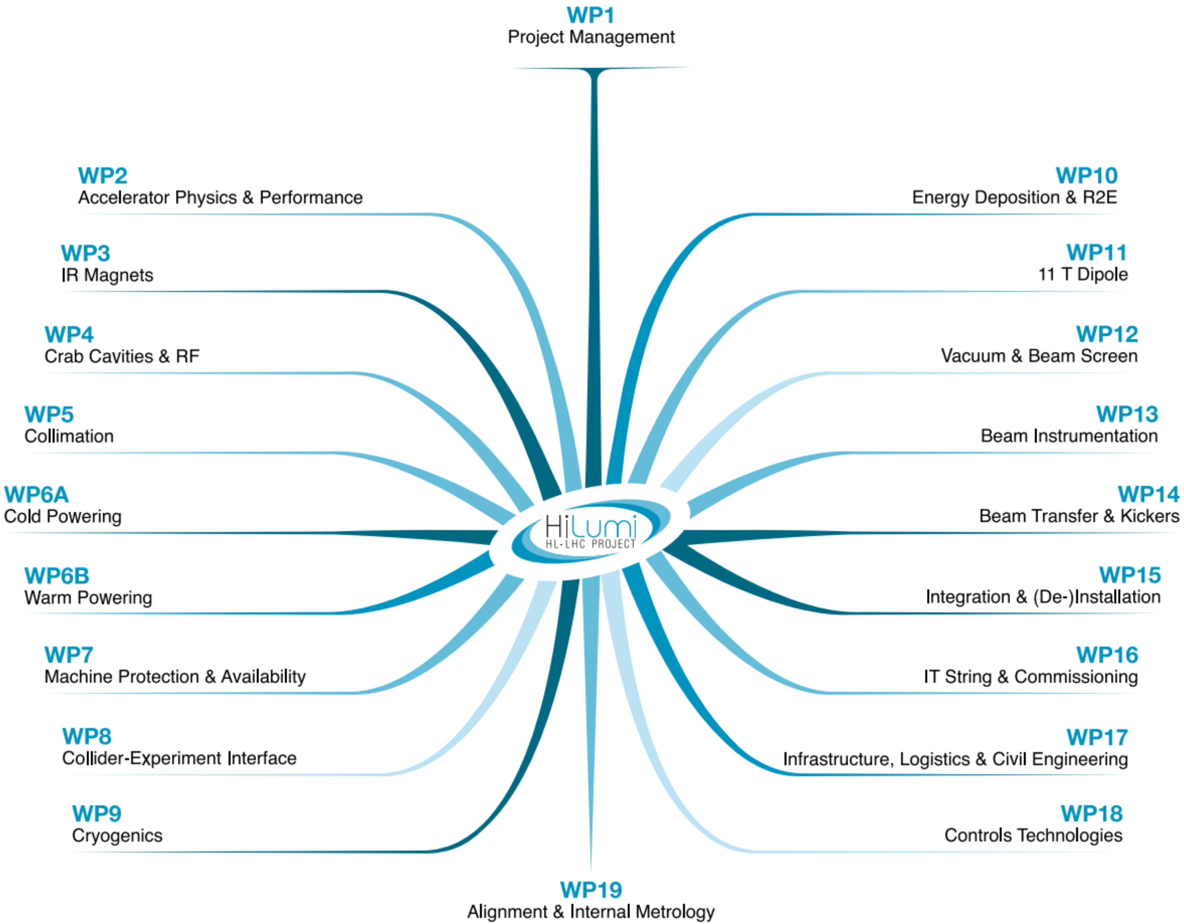


CERN accelerator complex



p (proton) ion neutrons p̄ (antiproton) proton/antiproton conversion neutrinos electron

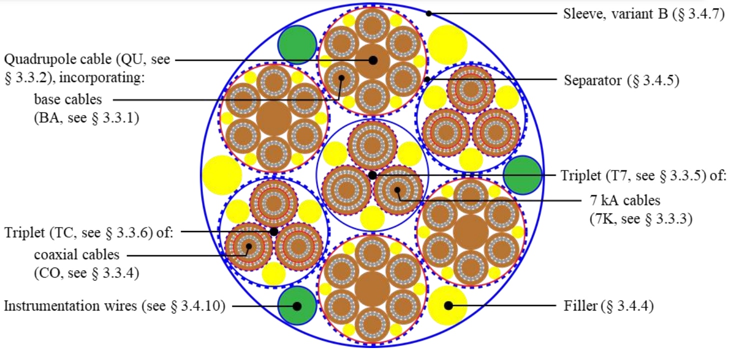
HL Project Management and Organsiation



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



$\Phi\sim$ 90 mm

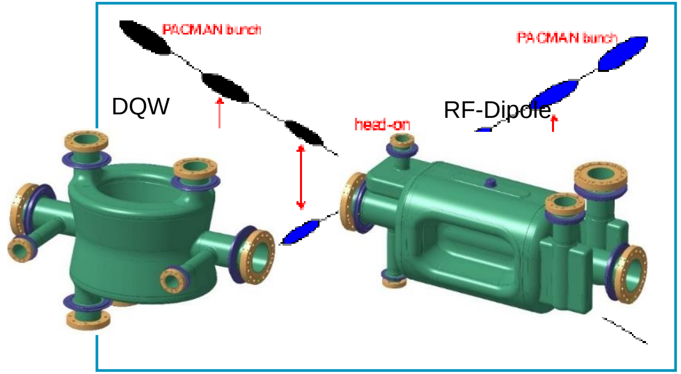
- Wire grading and cable map approval procedures established
- Continuous tests at CERN of extracted strands from each constituent cable before approving further operations – 694 test pieces in 2021
- Production planned to be completed by end 2022

To be produced: 5+5 Units

HL-LHC Technical Challenges: Crab Cavities

Geometric Luminosity Reduction Factor:

Crab Cavities:

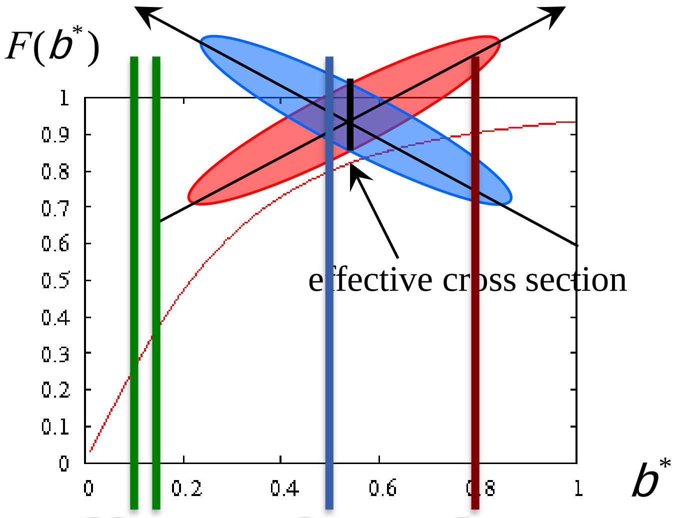


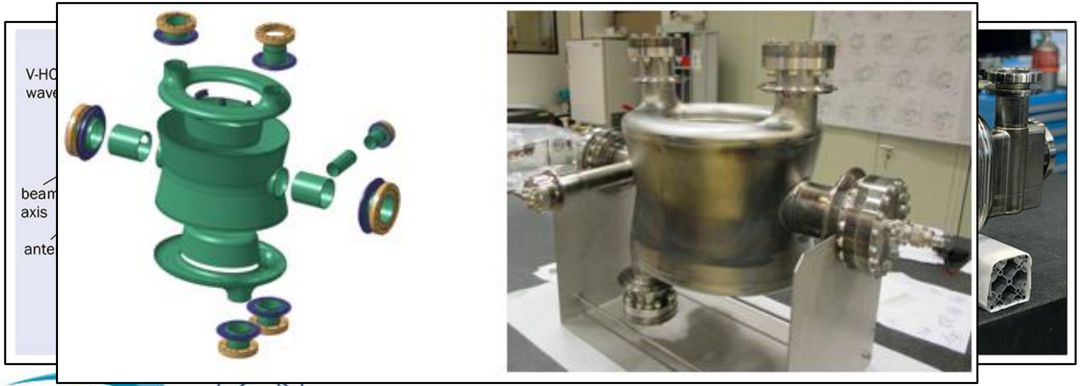
Full Crossing angle:

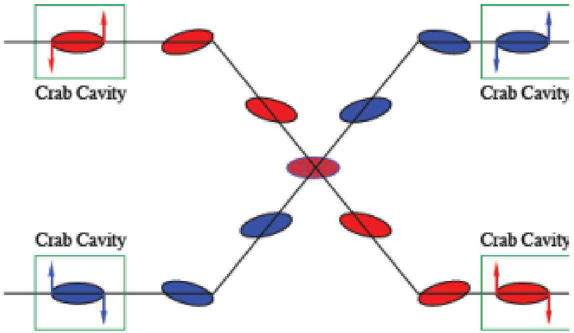
285 mrad LHC TDR

-> 329 mrad in LHC op

-> 500 mrad HL TDR



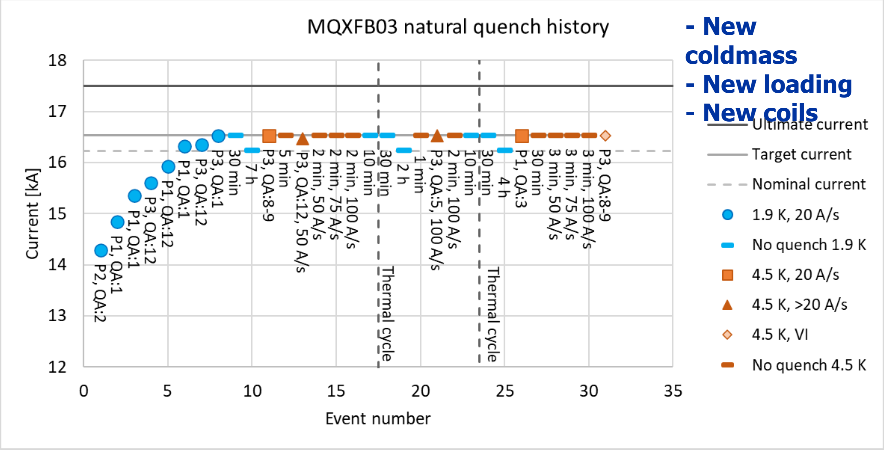




Crab cavities

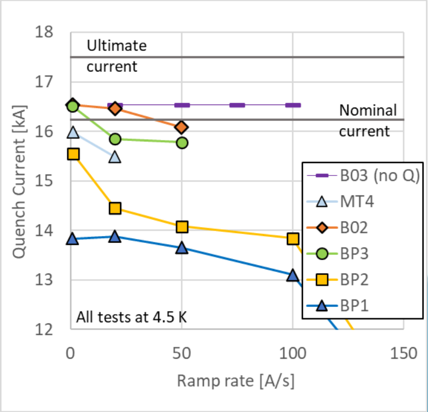
Recovery Plan for MQXFB

- 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

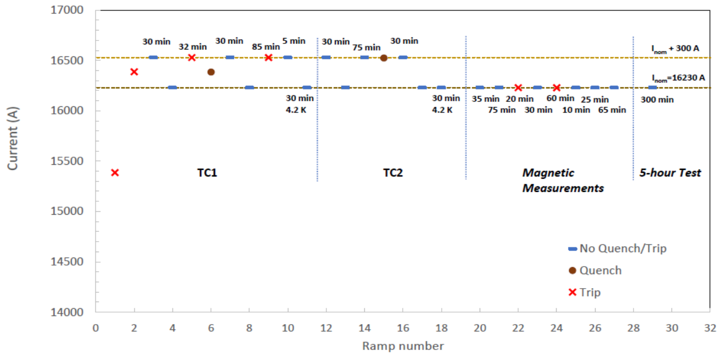


HiLumi HL-LHC PROJECT

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)

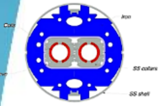
First AUP LQXFA01 cryomagnet mounted on Cryostat Tooling in SMI2 at CERN

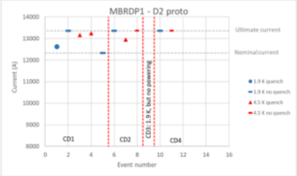
Courtesy of D. Duarte Ramos (CERN TE-MSC)

Nb–Ti Magnets for HL-LHC

After E. Todesco (CERN TE-MSC)

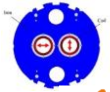
- Good progress on industrial productions of Nb–Ti magnets for HL-LHC, thanks to efficient collaborations with partner institutes; production of remaining MCBXF correctors to be internalized by CIEMAT and CERN.



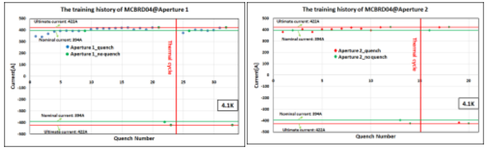


8-m-long, 105-mm-double aperture **D2 dipole magnet** prototype (4.5/5.3 T bore/peak field @12.23 kA)

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

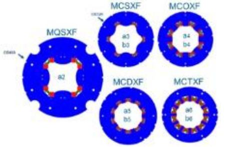


MCBRD04



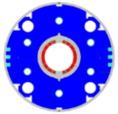
2-m-long, 105-mm-double aperture, **CCT orbit corrector magnet** (2.6/2.94 T bore/peak field @394 A)

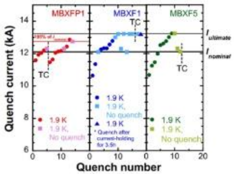
Courtesy of Q. Xu (IHEP)
and A. Foussat (CERN TE-MSC)




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

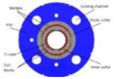
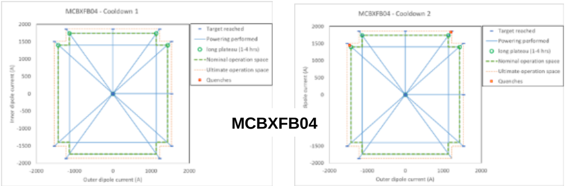
Courtesy of M. Statera
(INFN-Milano)
and E. Gautheron
(CERN TE-MSC)





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)

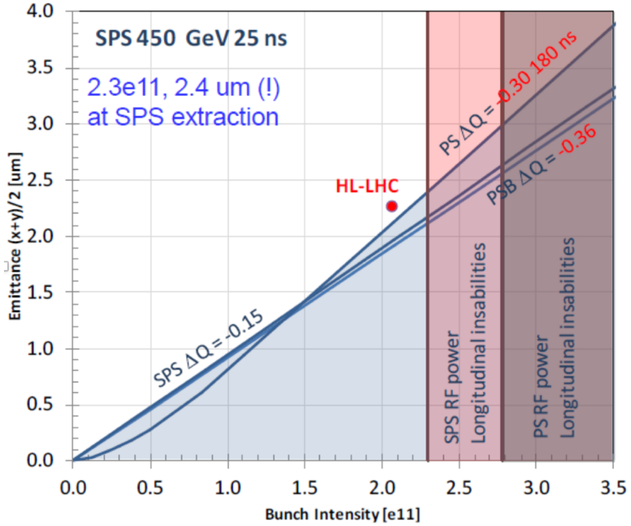
MCBXFB04

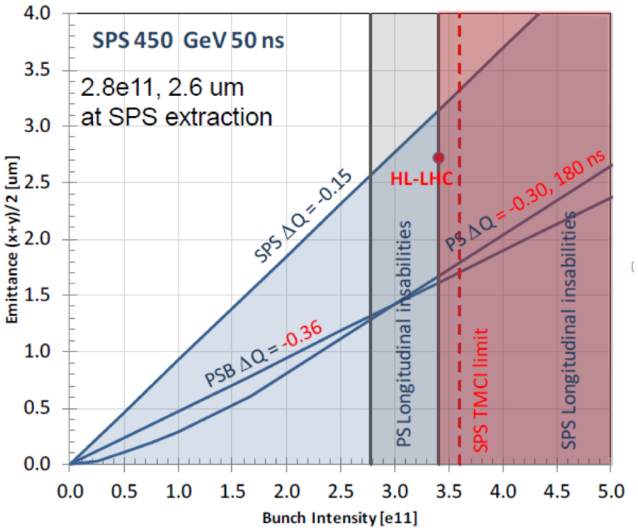
1.2/2.2-m-long, 150-single-aperture **nested dipole magnet corrector** (2.1/4.13 T bore/peak field @1.58 kA)

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

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





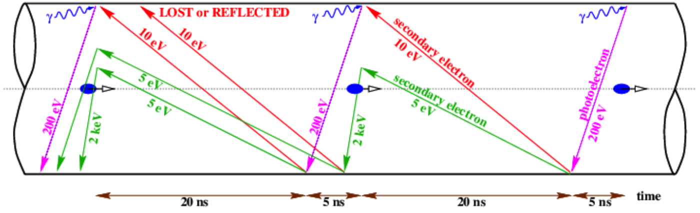
LHC Injector Upgrade Project (I…

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

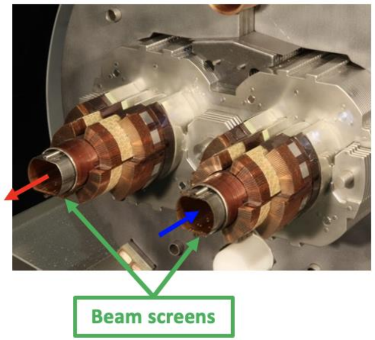
Successfully deployed during LS2 in 2019/2020

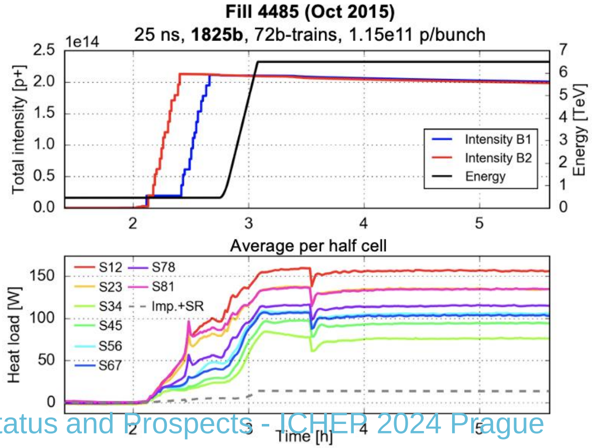
Electron cloud and cryogenic heat load

- 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!



E. Mether



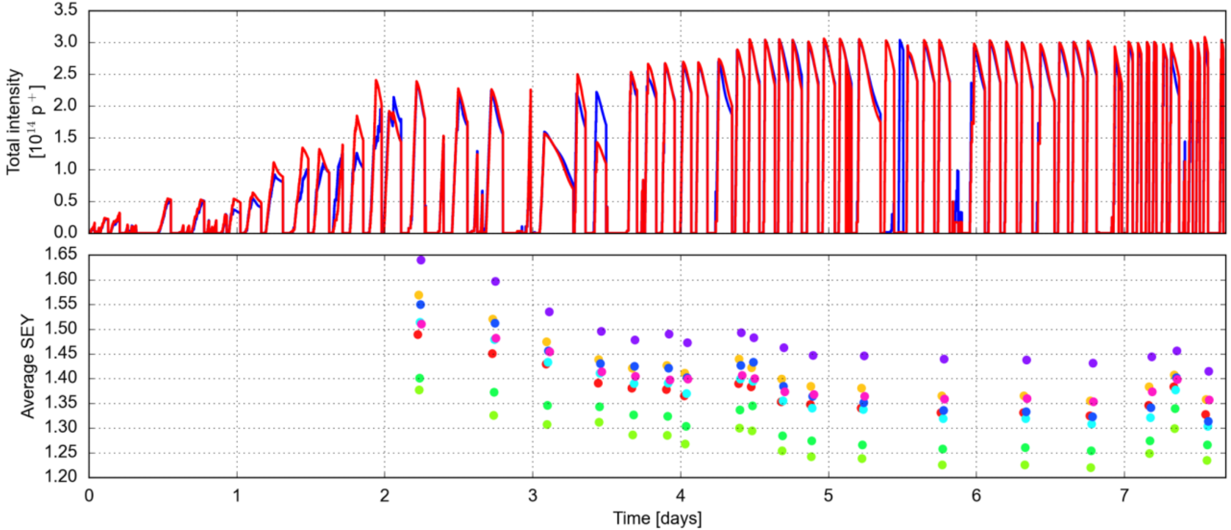


Electron cloud and cryogenic heat load

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

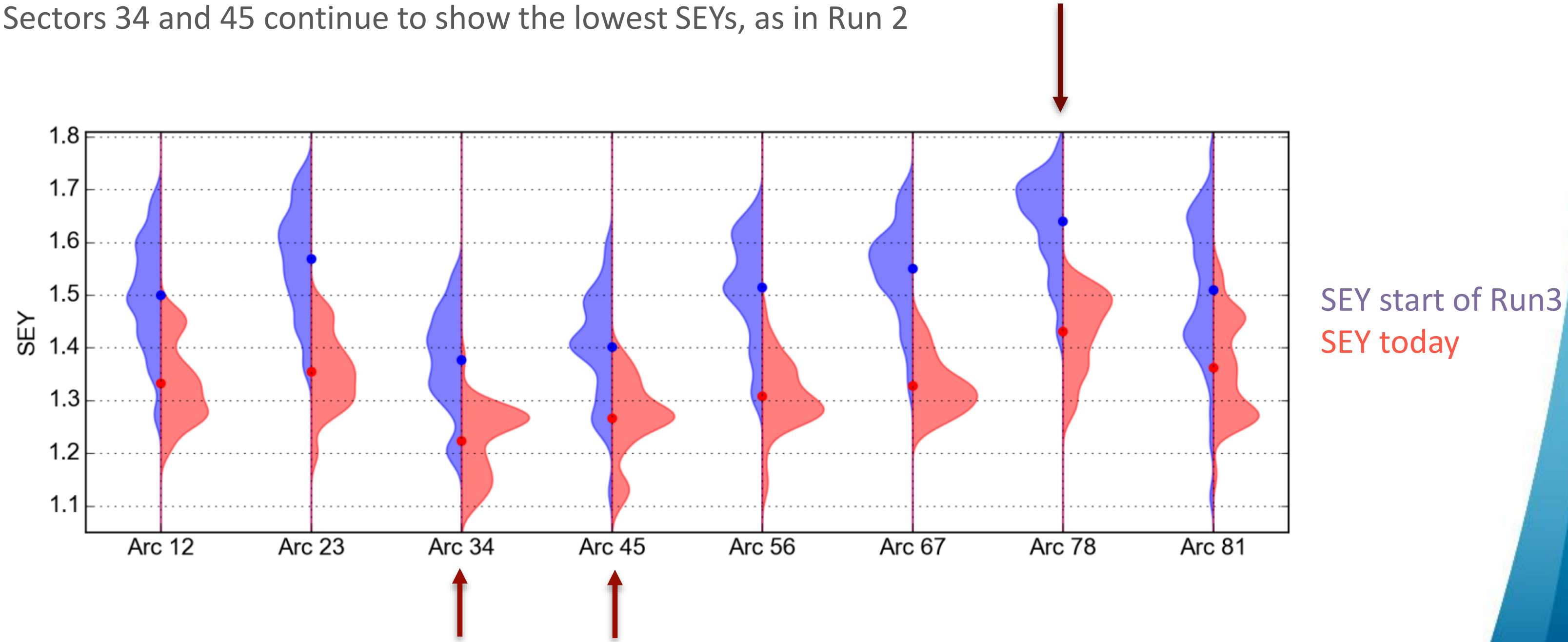
- A clear reduction of the average SEY is observed in every sector
- Conditioning is initially fast and gets slower as the SEY decreases



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

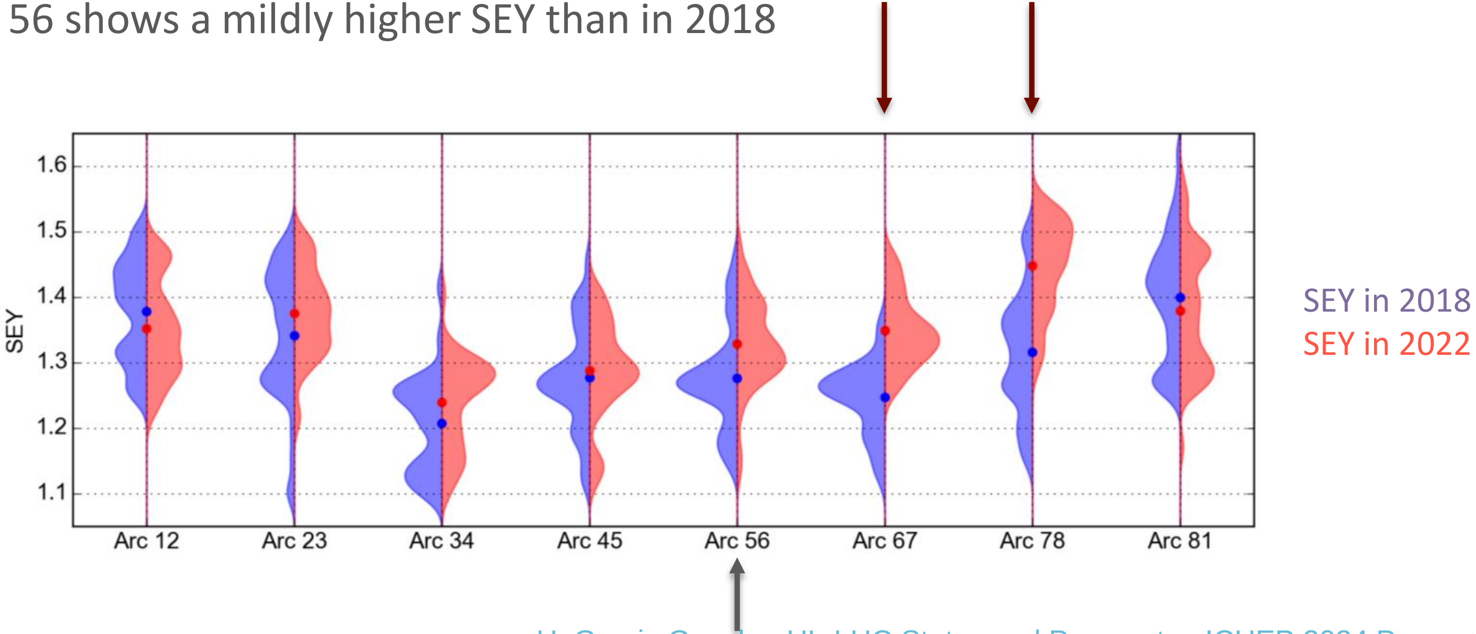


L. Mether

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



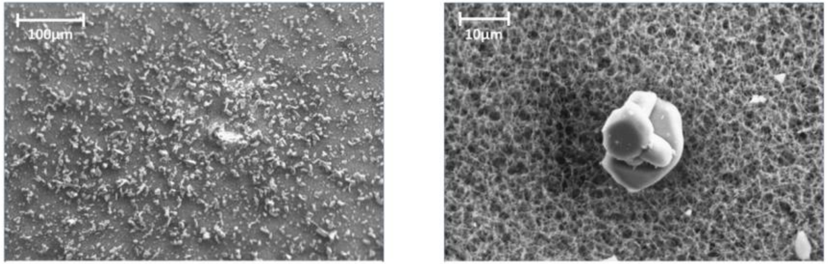
L. Mether

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
  - **UFOs and Radiation to Electronics**
  - Magnet training
  - Machine Availability and physics output
- Preparing HL-LHC operation
  - IT String
- Current Project planning and performance ramp-up

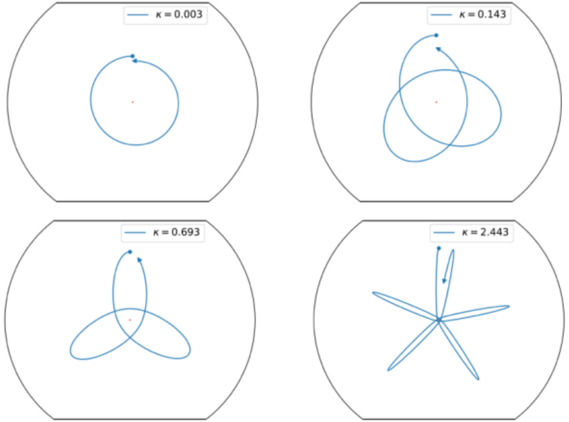
UFOs and their interactions with the LHC beams

- 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)



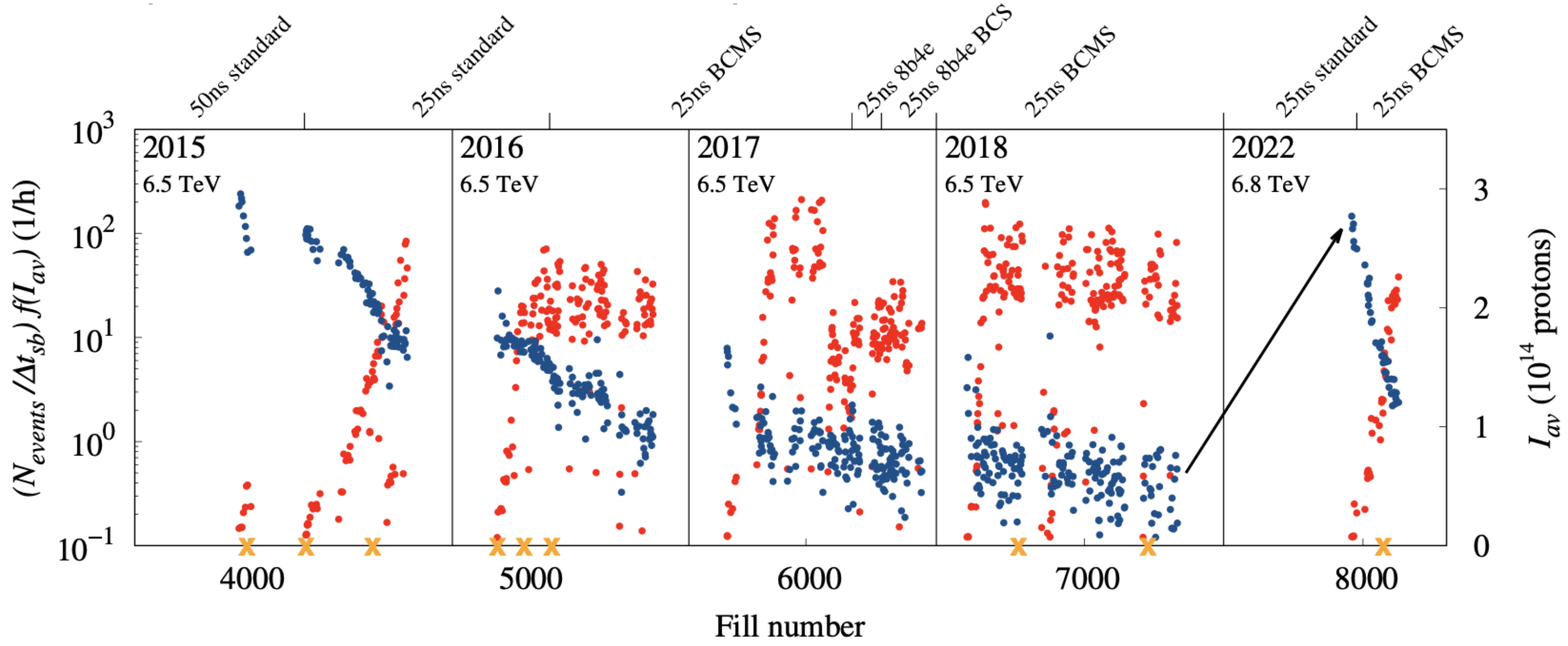
(a) (b)

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**

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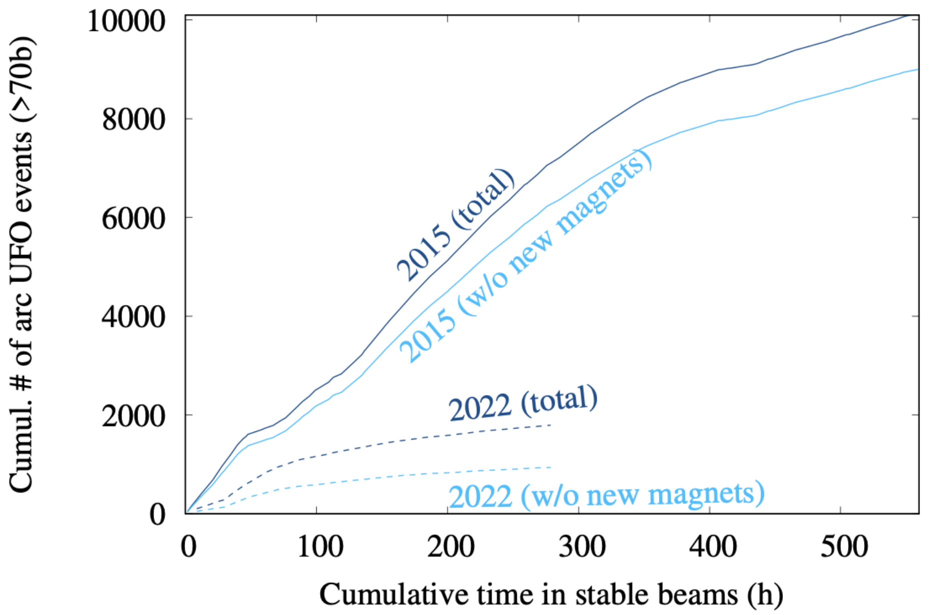
UFO rate 2015 vs 2022



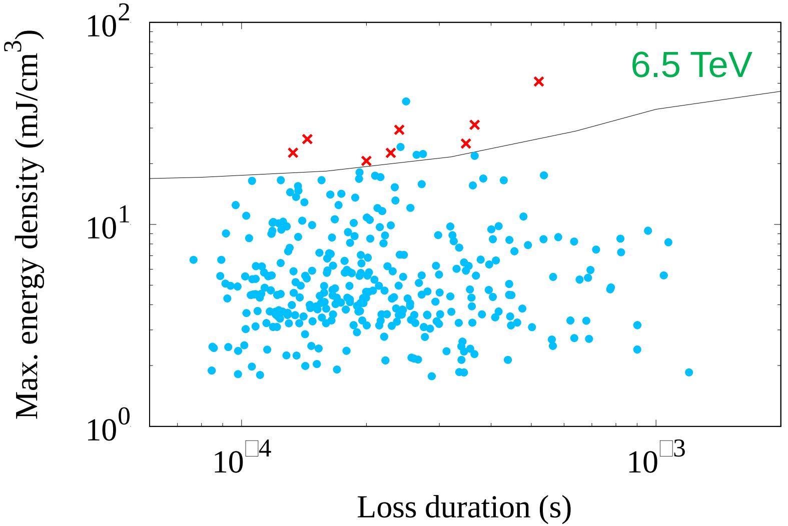
- In general, situation much better than in Run 2 due to the very fast conditioning of the UFO rate
- But the impact of UFOs evidently depends on the BLM threshold strategy

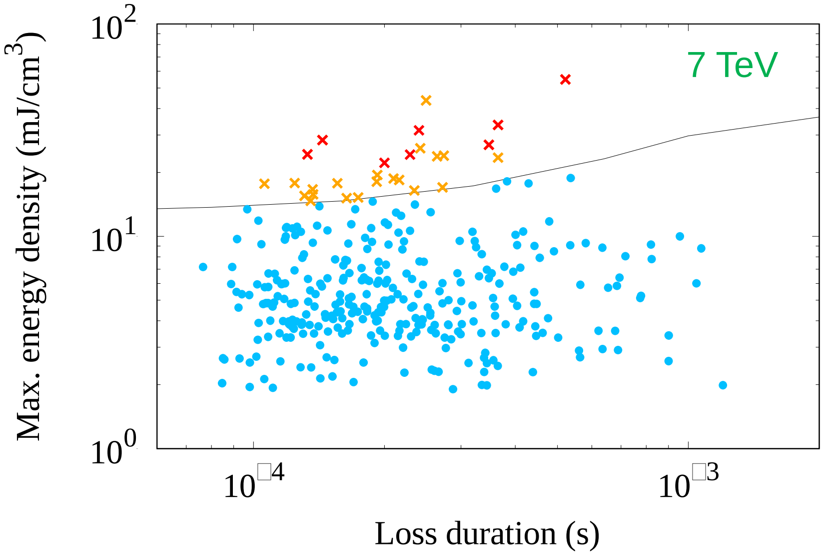
Conclusion:

- 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

L. Mether

Quench limits vs UFOs





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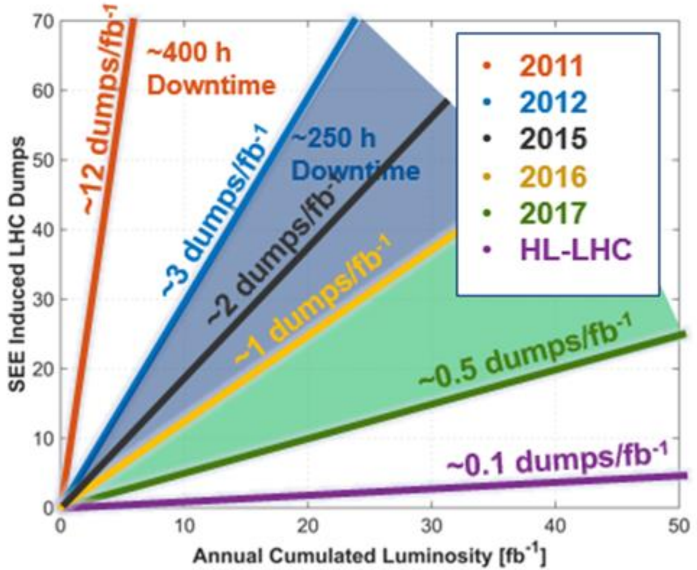
Radiation to Electronics



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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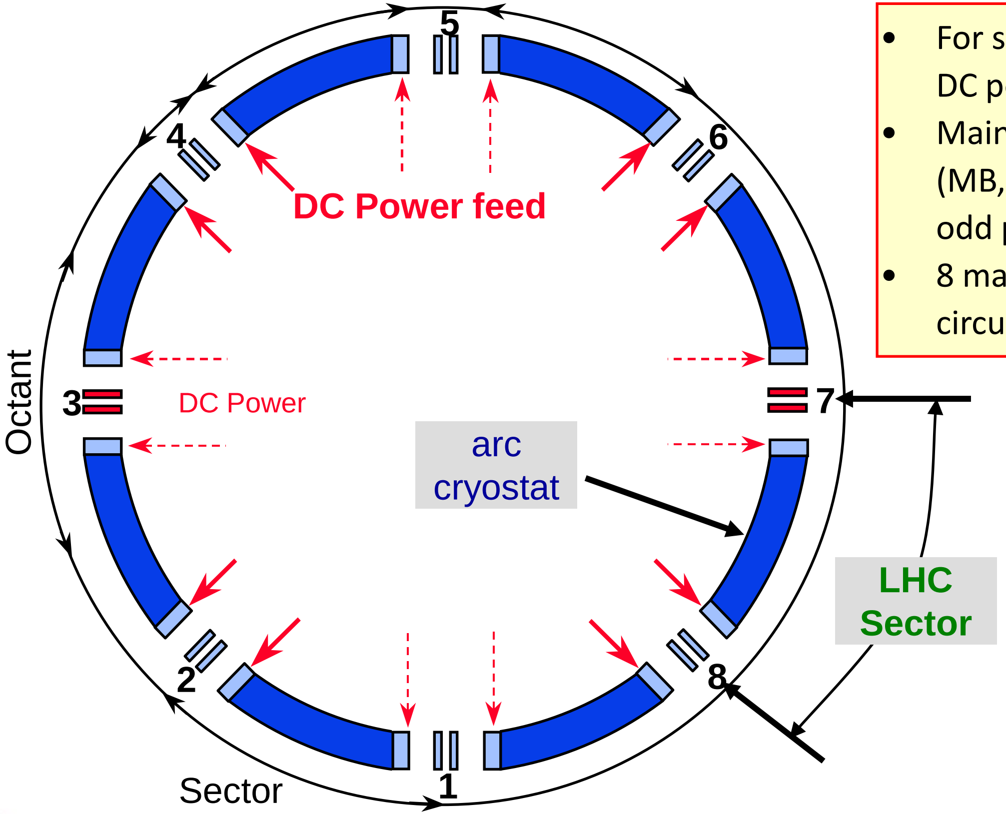
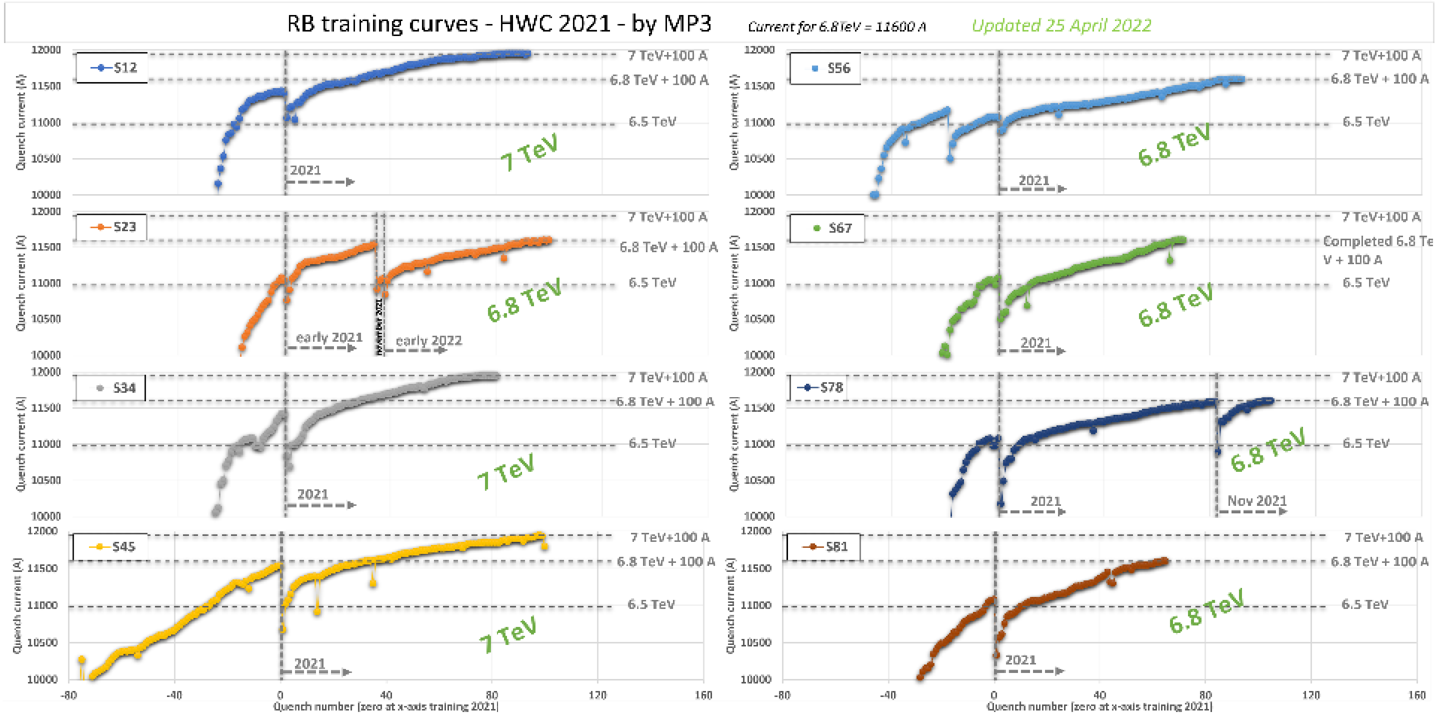
LHC machine sectorisation



- 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

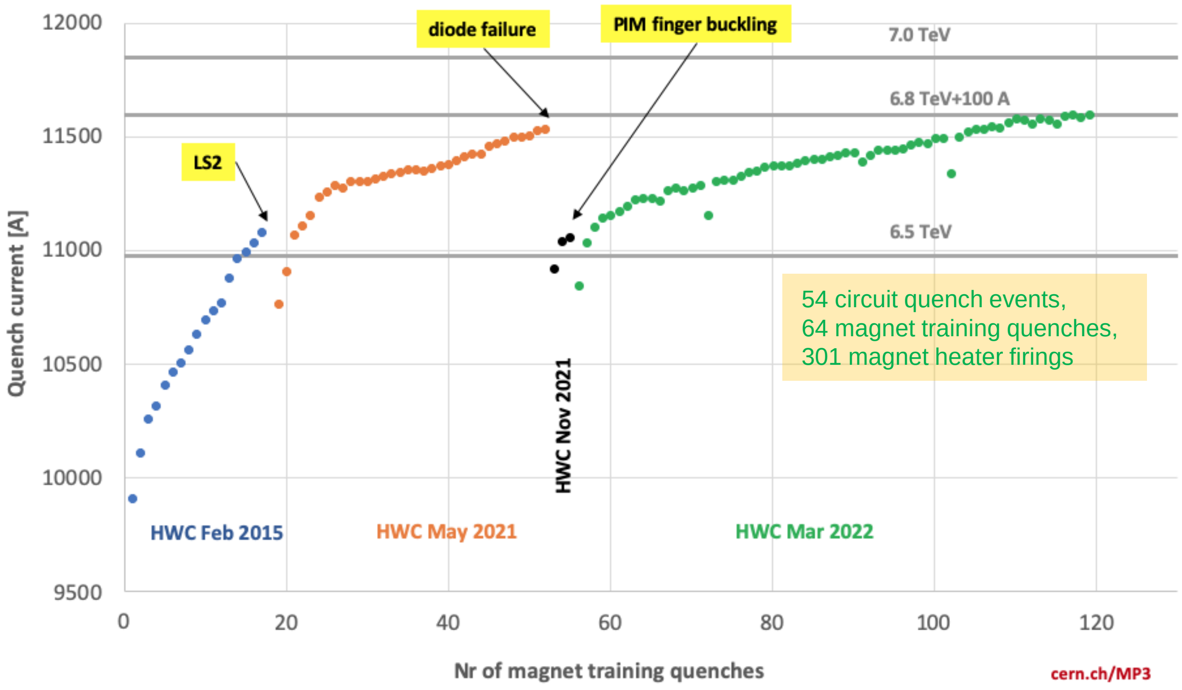
Training quenches RB Circuits



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

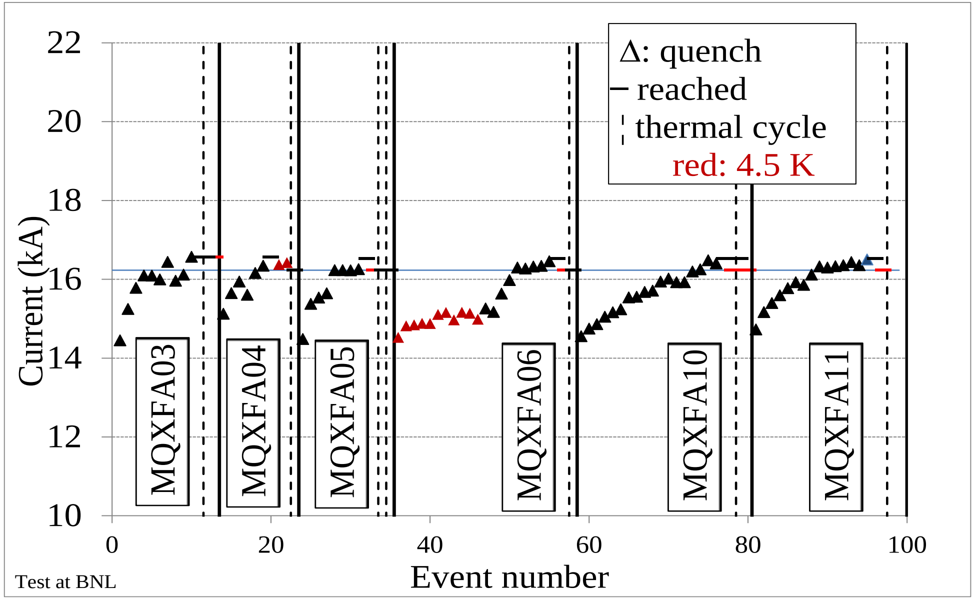
Nr of quenches in the same dipole magnet	Nr of dipole magnets
5	3
4	11
3	56
2	154
1	446
0	562

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

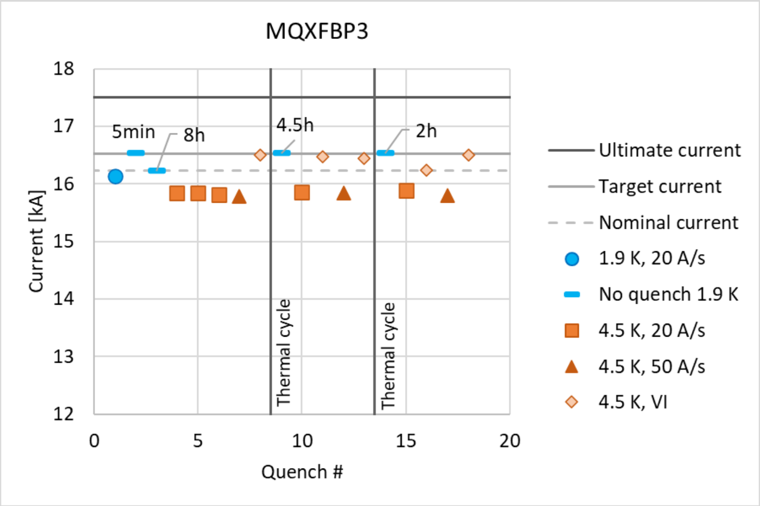
- Six magnets of type MQXFA from AUP reached performance
  - Operation at nominal current plus 300 A, both at 1.9 K and 4.5 K
  - Perfect memory, i.e. no retraining, and some robustness



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

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

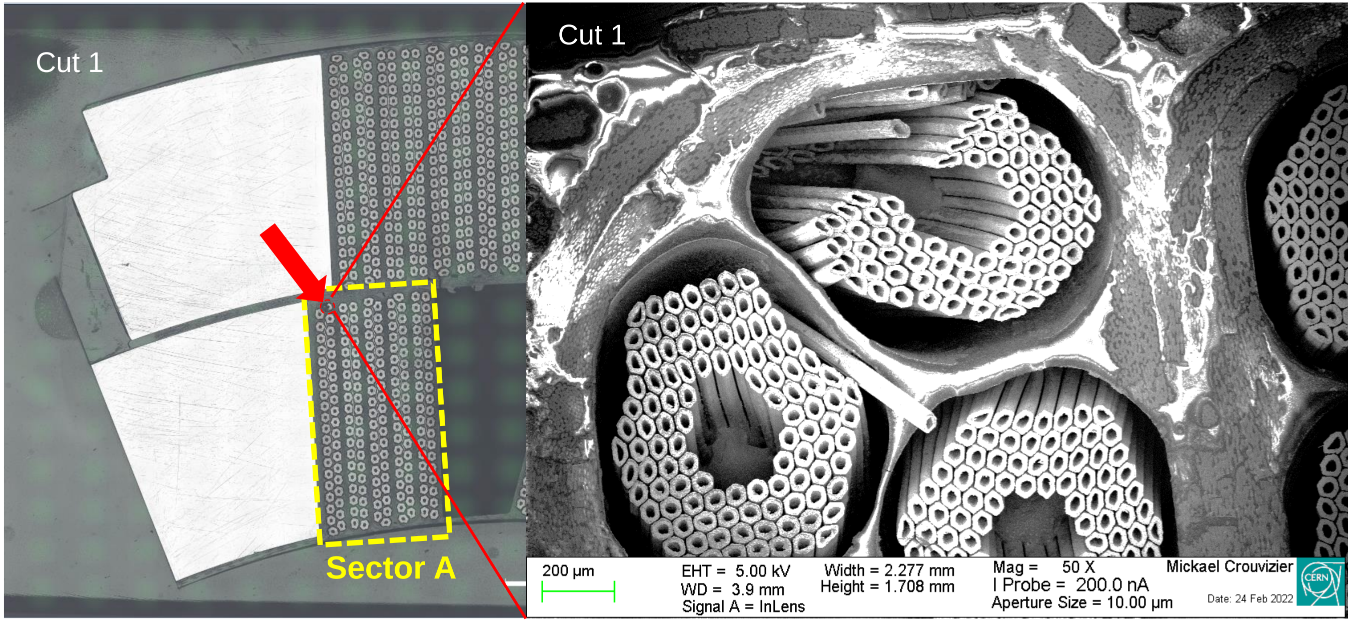
- MQXFBP3 includes the new procedures used for LHe vessel integration
  - Nominal plus 300 A reached during first powering with one training quench
  - No degradation, three thermal cycles



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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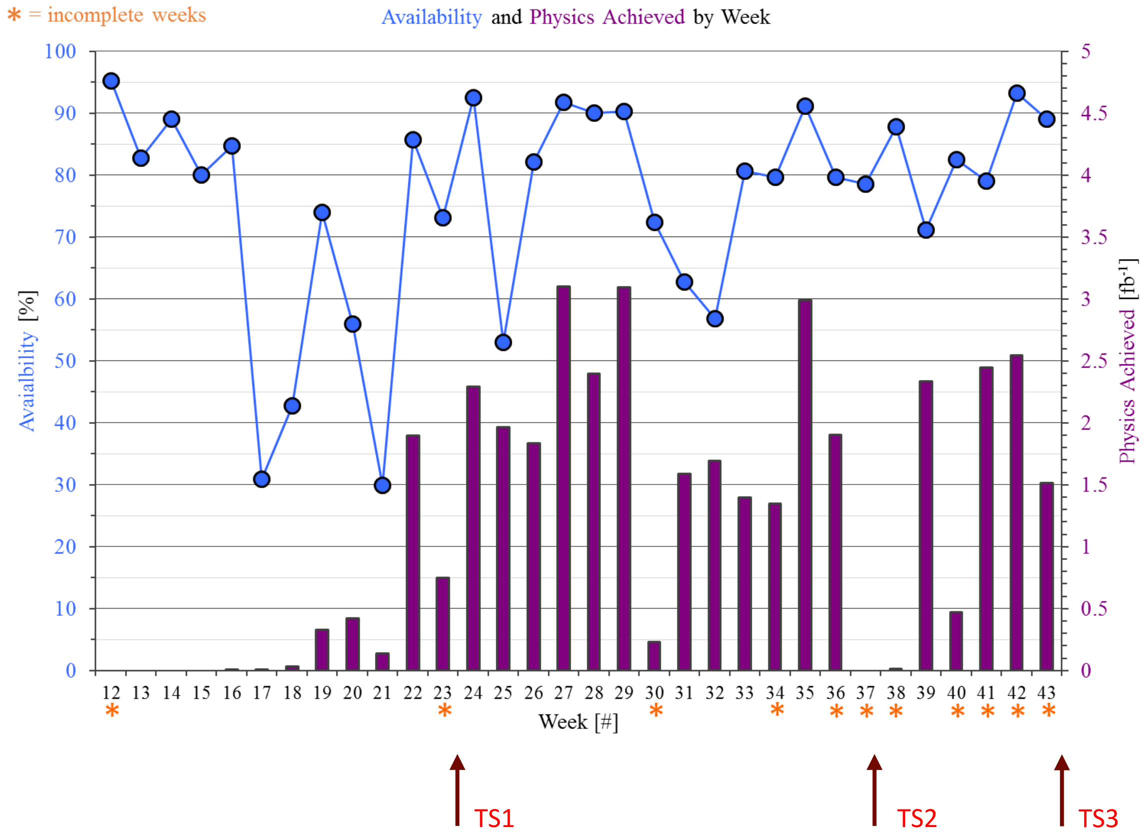
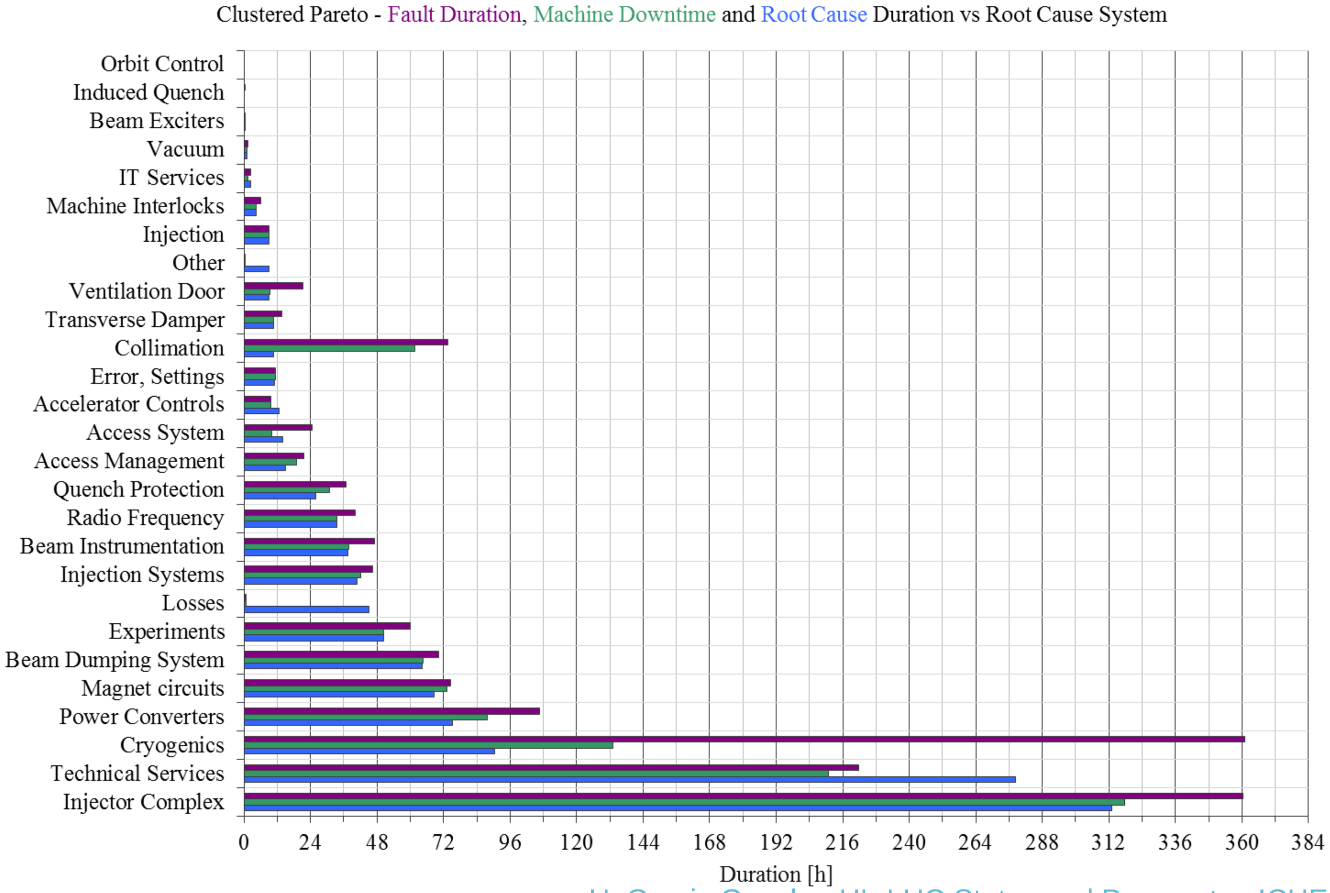
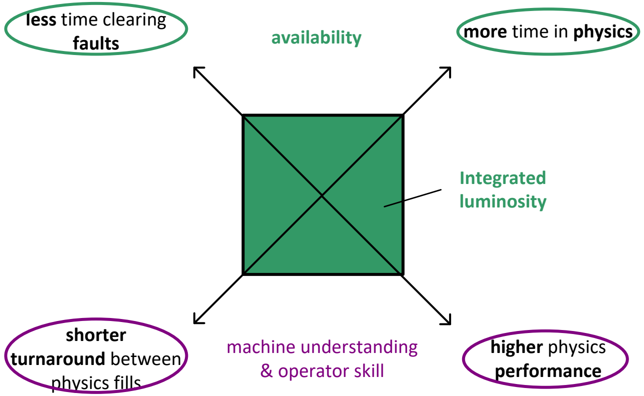
Machine Availability vs Physics output – an example



Machine Availability vs Physics output – an example



What defines the productivity / physics output?

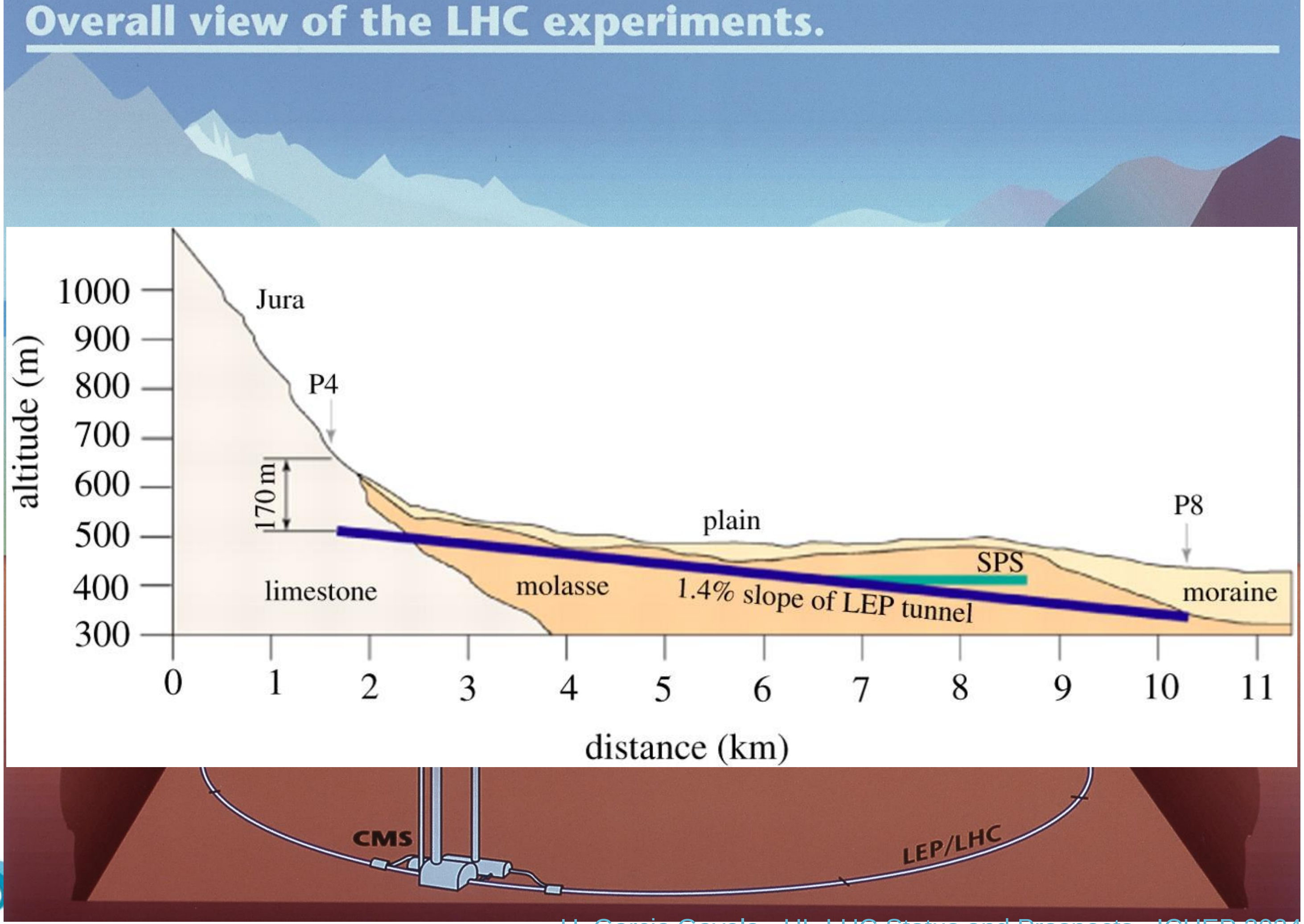


Physics output is a function of…

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


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)
CMS
LEP/LHC

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!!!

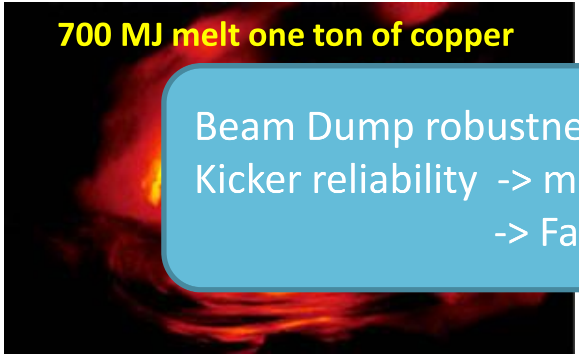
Energy management Challenges in the LHC

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]***

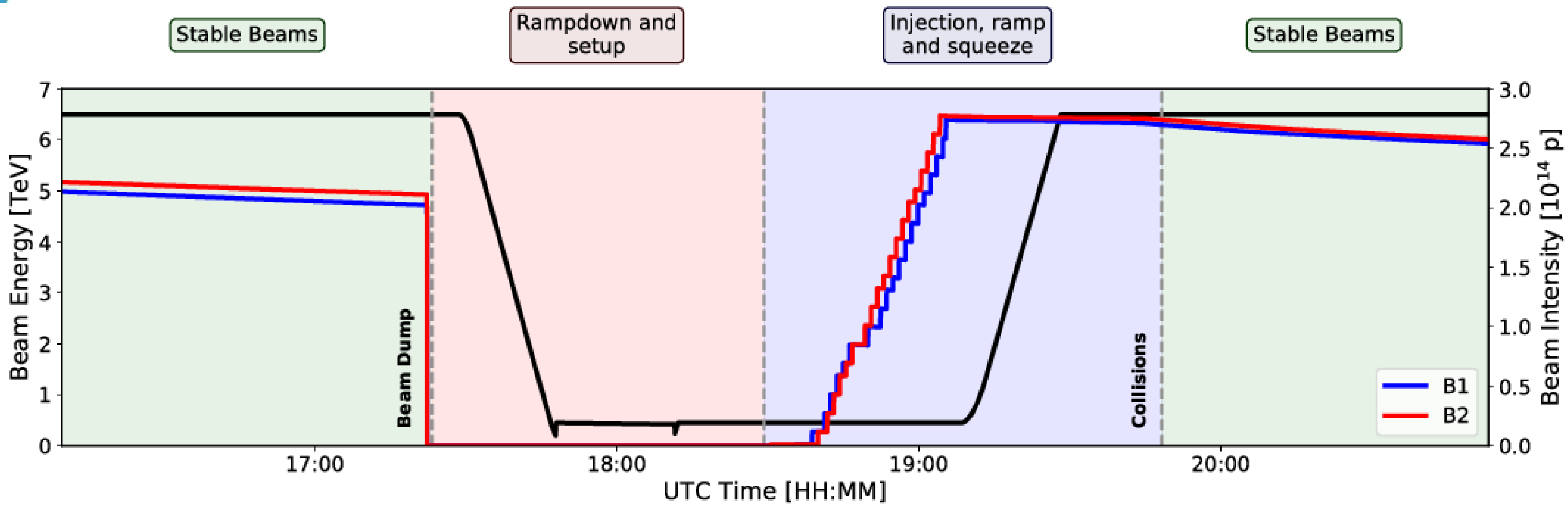


700 MJoule dissipated in 88 us (1 turn)

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

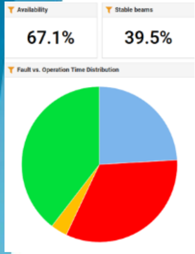


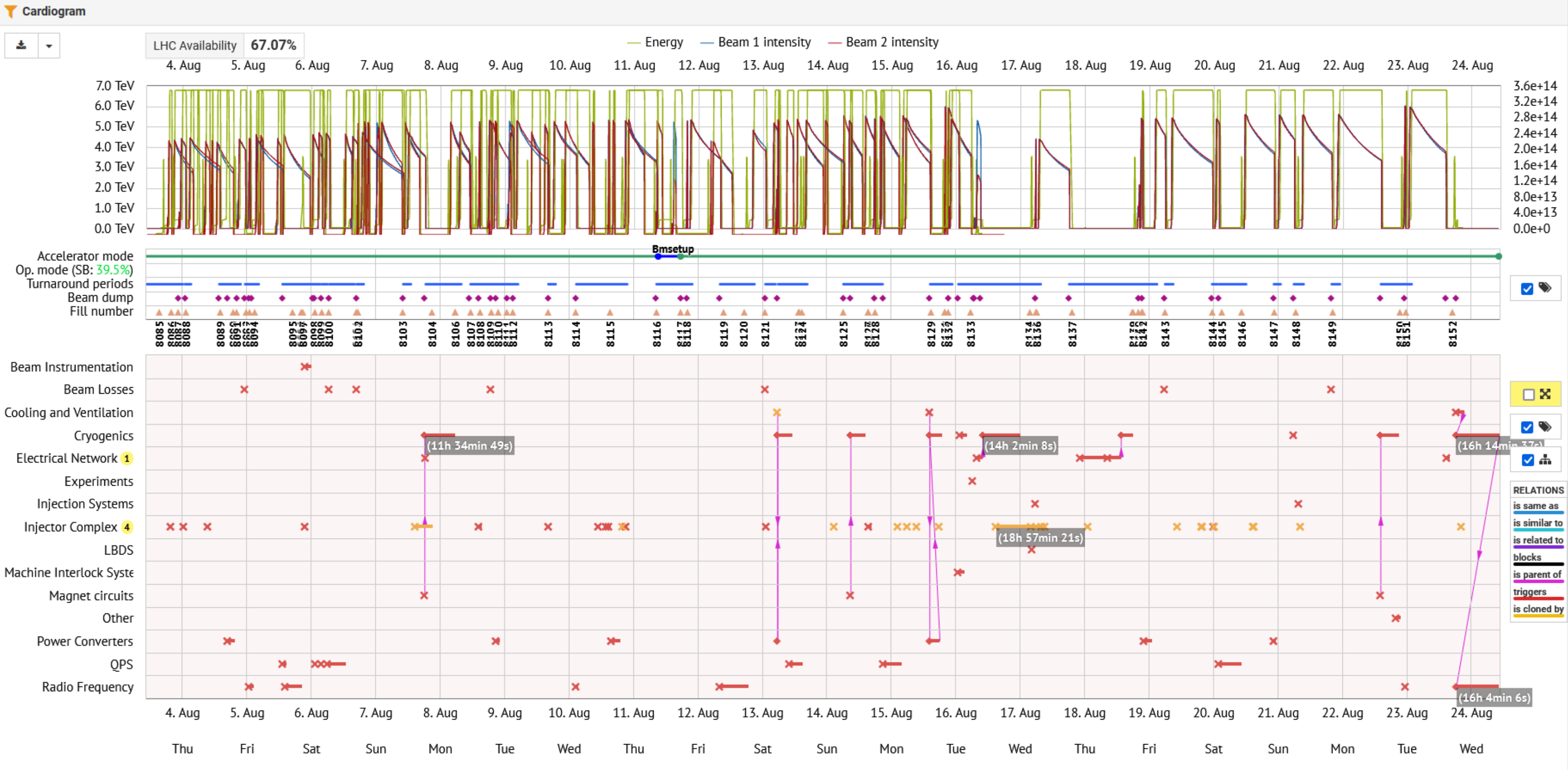
This becomes more challenging with increased Collider size and Requires even more powerful injector complex!!!!

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

HiLumi HL-LHC PROJECT

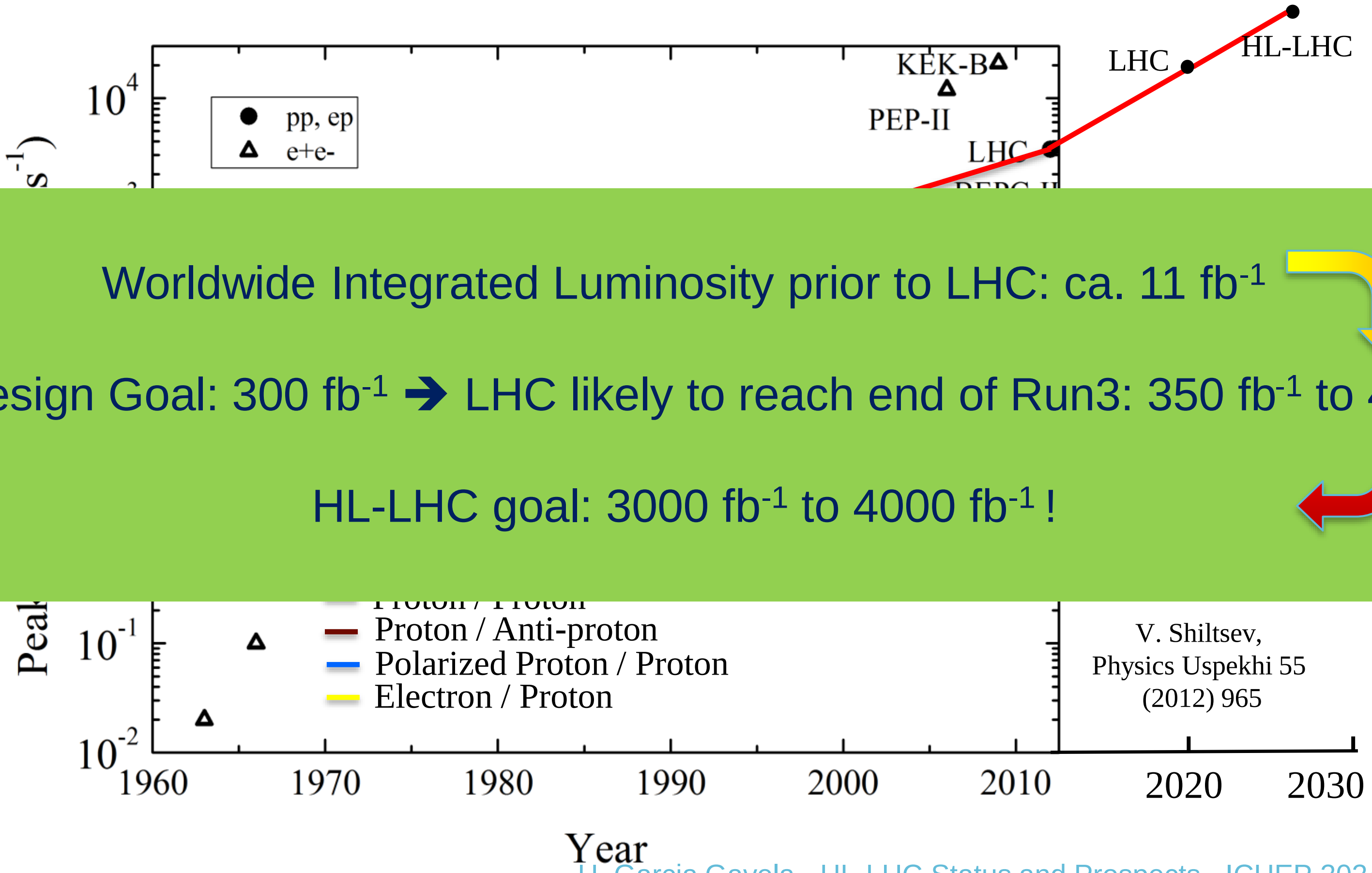
Reality…. 3 typical weeks of LHC Machine operation….





L. Mether

Peak luminosities of Hadron Colliders



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

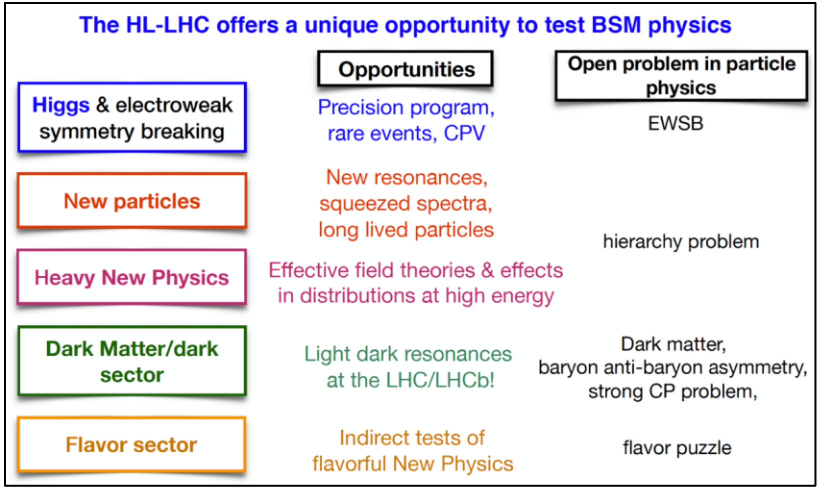
x 35

LHC Design Goal: 300 fb^{-1} ➔ LHC likely to reach end of Run3: 350 fb^{-1} to 400 fb^{-1}

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

x 10

HL-LHC targets a rich and diverse physics programme

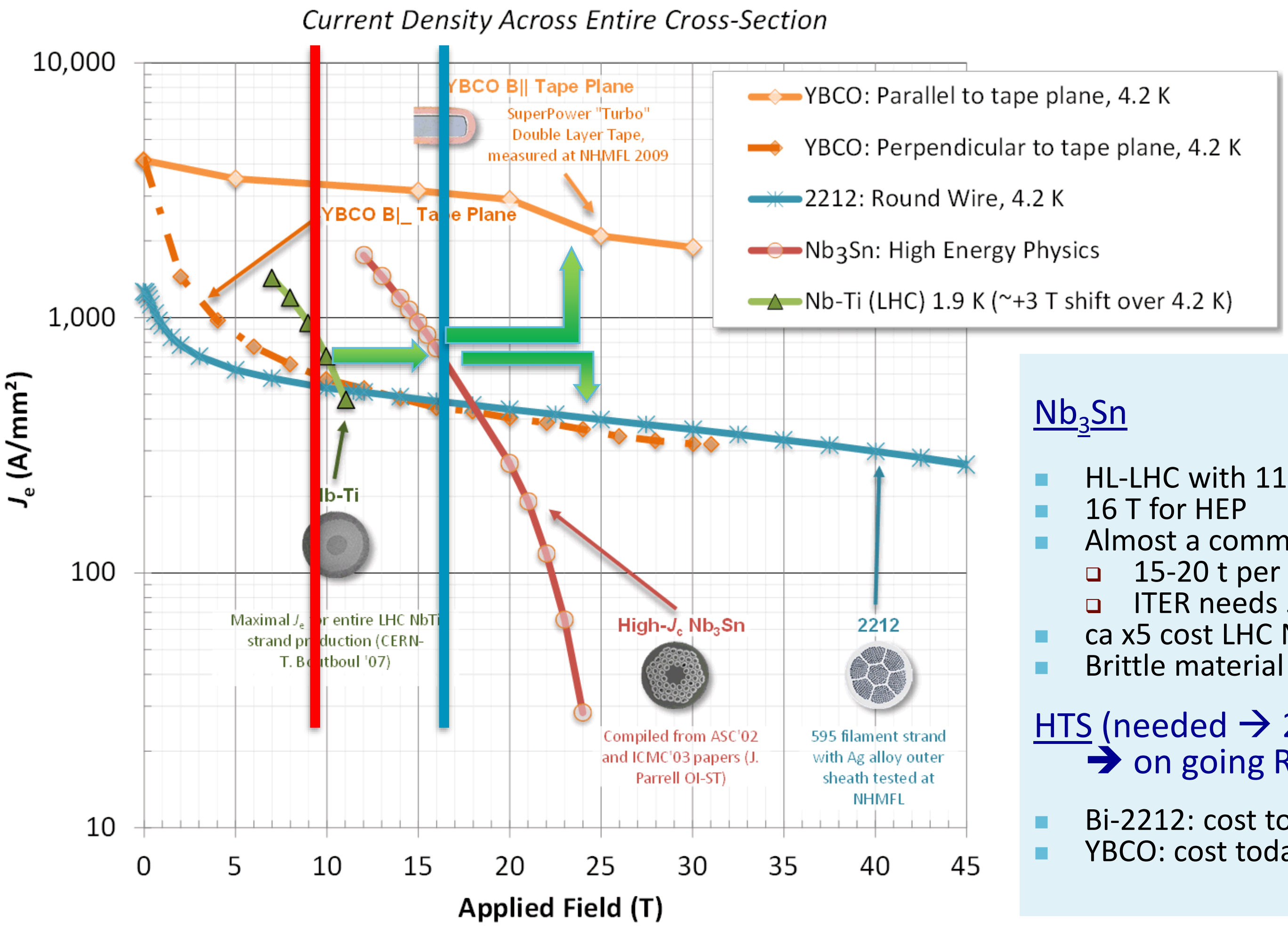


Headline deliverable is 3 ab^{-1} p-p but the physics programme promises to be impressively diverse…

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)

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

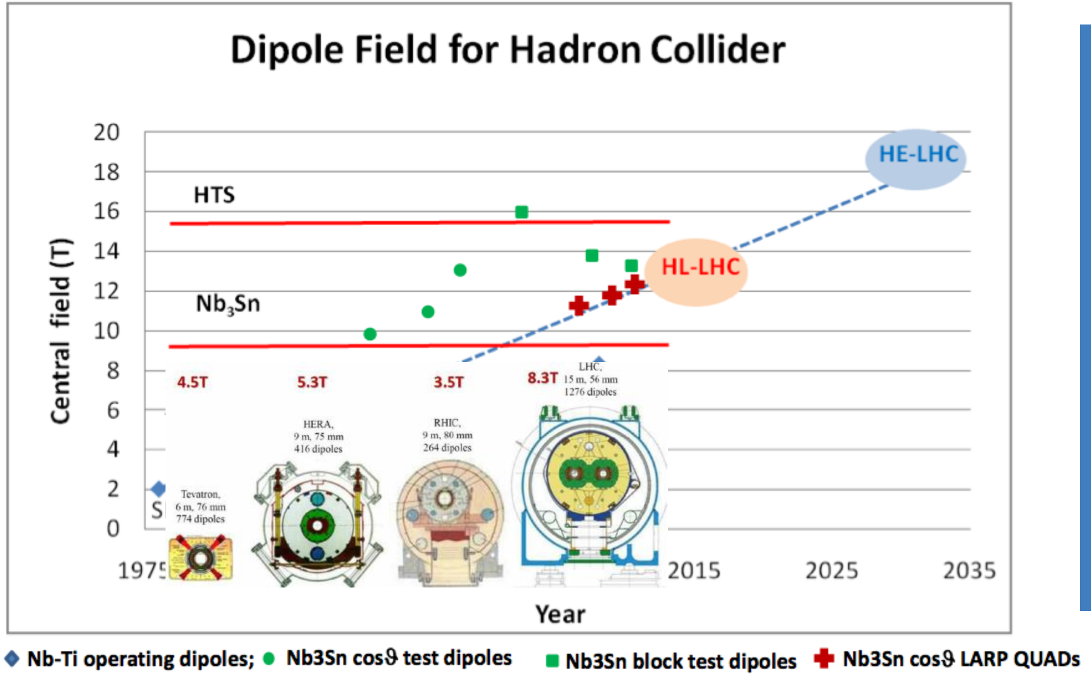
HTS (needed → 20 T)

➔ 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!!!



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

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

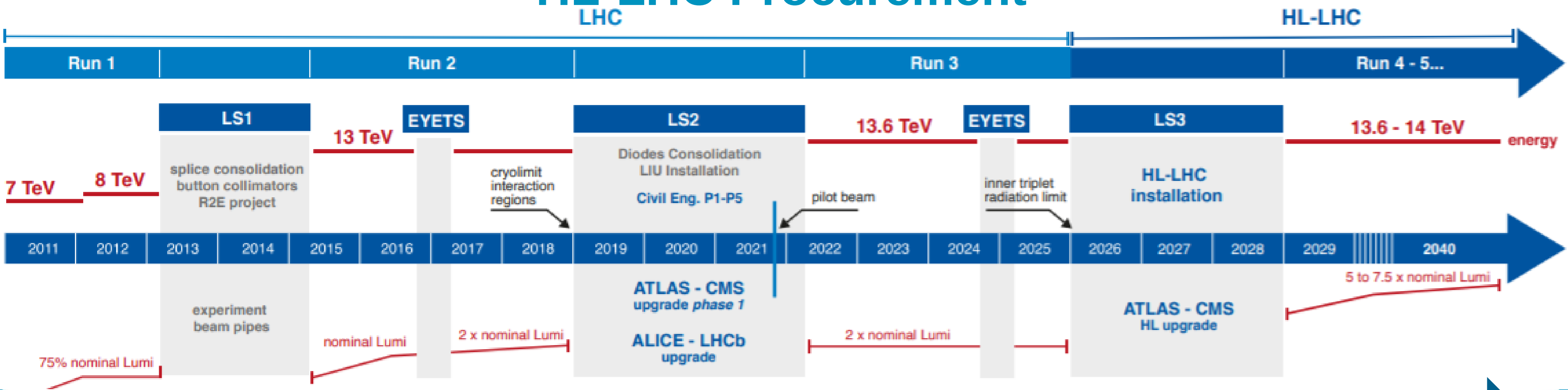
→ Started in early 2000

→ 15-20 years R&D program

→ Ready by 2025

courtesy: L. Rossi (CERN)

HL-LHC Procurement



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