Report on the LHC, HL-LHC and the US Accelerator R&D Program

Maria Baldini, FNAL

US LUA Annual Meeting

16-18 December 2024

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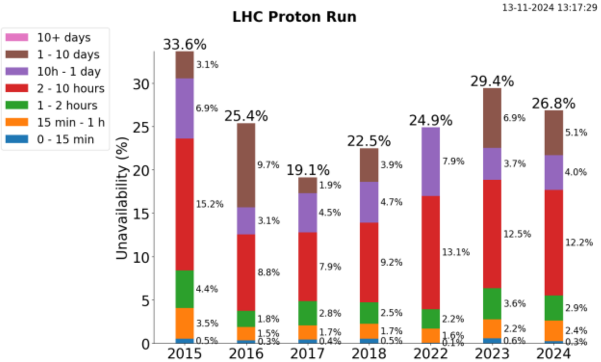
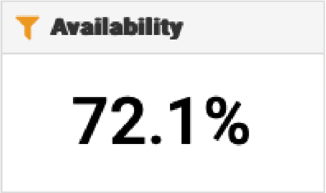
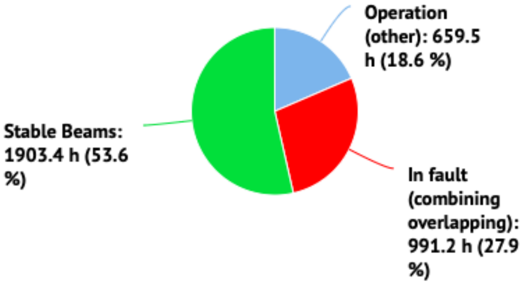
LHC Availability

- Availability is THE key factor for accelerator performance
- Availability factor was ~constant through Run2 and Run3 for small (<24h) faults
  - Availability: 72.1%
  - Stable beam ratio: 53.6%



NOTE: the availability of the proton run is calculated on the effective time from the retrospetctively calculated schedule (long faults are not included)





Minor differences in numbers are due to slightly different choices in term of dates (including or not scrubbing run, TS recovery etc)

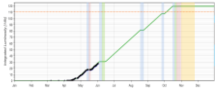
The SPS protons for LHC and HL-LHC

- A very good availability of the beam for the LHC 94.3% with main fault categories:
  - Injector Complex
  - Radio Frequency systems
  - Vacuum
  - Power Converters and Magnets
- The HL-LHC beam parameters at SPS extraction were achieved:
  - 2.3e11 p/b with a bunch length of 1.65ns

Courtesy of R. Steerenberg

2024 LHC overview

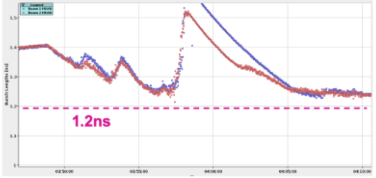
Stable Lumi Production Summer period



(YETS started on 25th November)

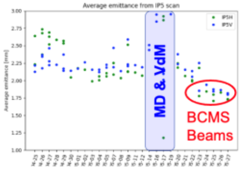
First injection: 8th March (3 days early)

Bunch length control/target Limit RF module heating risk



1200 bunches on 14th April (10 days early)

BCMS beams May



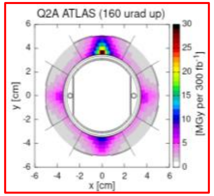
Beyond 110 fb^{-1}

ION PHYSICS: STABLE BEAMS

pp run — ref run — IONS run

March	April	May	June	July	August	September	October	November

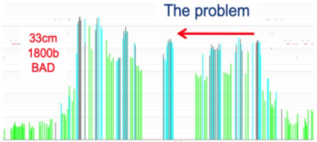
Reverse Polarity optics commissioned (~ +1 week)



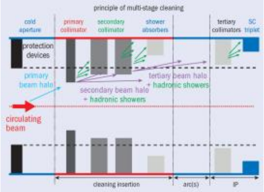
First Stable Beams @6.8 TeV 5th April (3 days early)

LHCb VELO closed for the 1st time

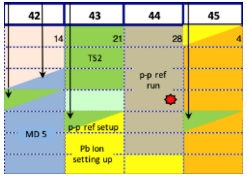
β* limited to 36 cm 17th April



β* back to 30 cm **17th** June

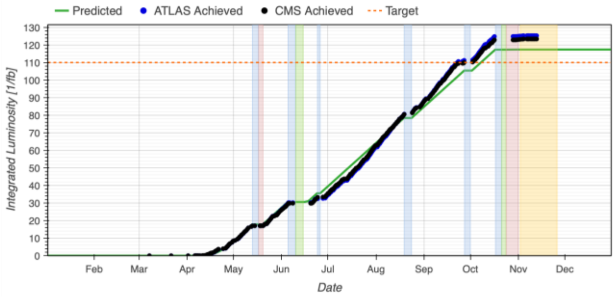


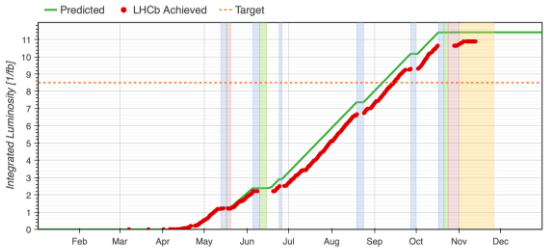
pp reference run **28th** Oct – 2nd Nov



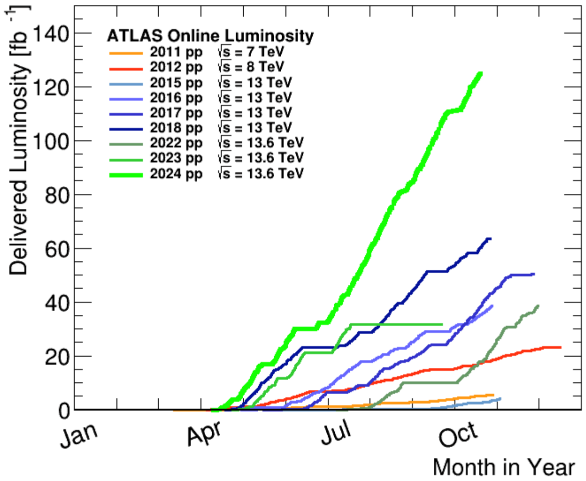
Courtesy of R. Steerenberg

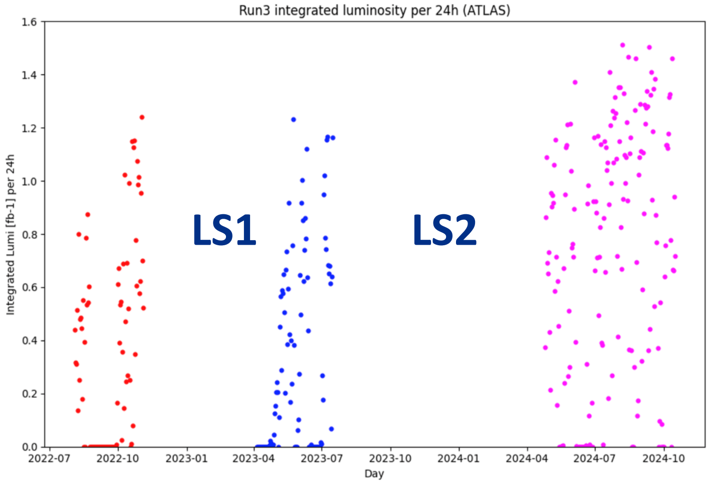
Proton operation





- 124 fb-1 in ATLAS/CMS
- 11 fb-1 in LHCb
- 67.5 pb-1 in ALICE
- **Highest production rate ever**
- Peak luminosity at **~2.1e34 cm-1 s-1** (limited by cryogenic)



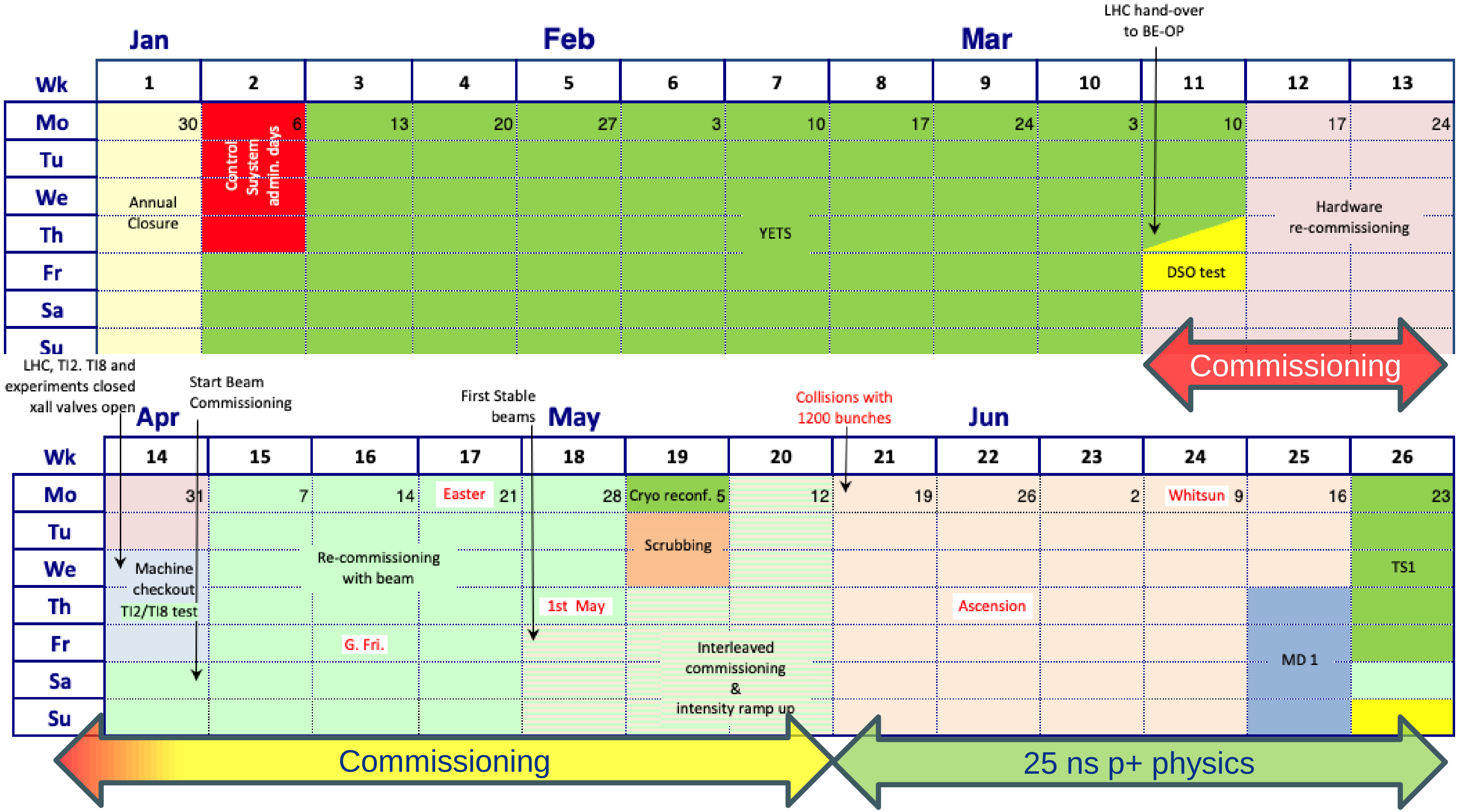


- Bunch intensities at **1.6×10^{11}** ppb at start of stable beams
- **Stored energy ~410 MJ /** beam @6.8 TeV
- Equivalent to ~100 kg TNT

Courtesy of R. Steerenberg

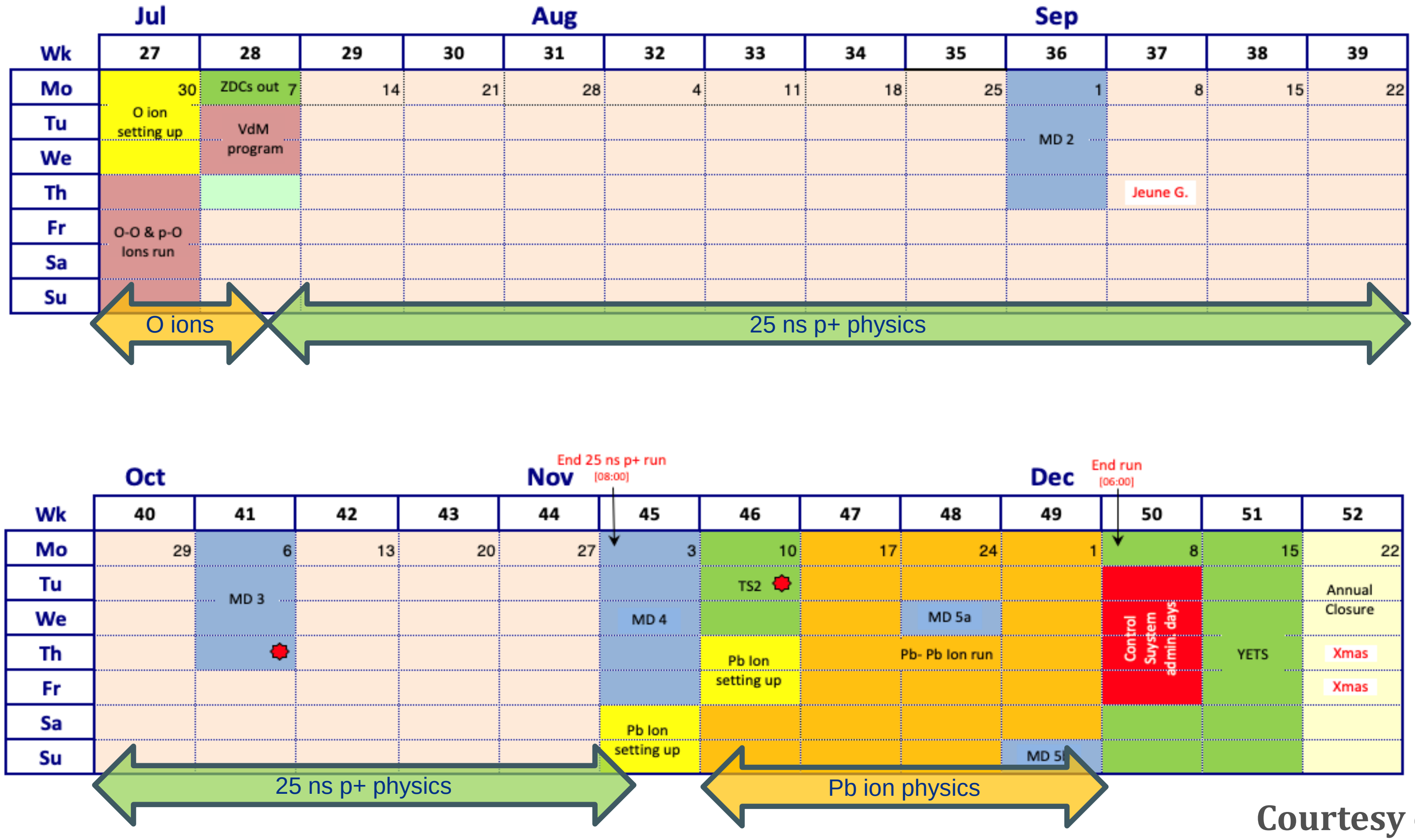
Approved LHC Schedules 2025 – Q1 + Q2

Courtesy of R. Steerenberg



Fermilab

Approved LHC Schedules 2025 – Q3 & Q4



Courtesy of R. Steerenberg

Fermilab

Approved 2025 schedule in number

Activity	Version 0.9	
	Duration [days]	Ratio [%]
Beam Commissioning & Intensity ramp-up	41	16.6
Scrubbing	2	0.8
25 ns physics (>1200 bunches)	**138**	**55.9**
Special physics runs (incl. setting-up)	**2**	**0.8**
Oxygen ion setting-up	4	1.6
Oxygen ion physics	**4**	**1.6**
Pb-Pb ions setting-up	4	1.6
Pb-Pb ions physics	**21**	**8.5**
Technical stop	8	3.2
Technical stop recovery	2	0.8
Other scheduled stops	2	0.8
Machine Development blocks (incl. floating MDs)	19	7.7
Total:	**247**	**100**

Activity	Duration [days]	Ratio
Physics time	165	67% of total beam time
MD time	19	12% w.r.t. physics time

- Possible 2025 integrated luminosity target: **~110 fb^{-1}**
    - *Assuming similar running conditions as in 2024*

Courtesy of R. Steerenberg

Fermilab

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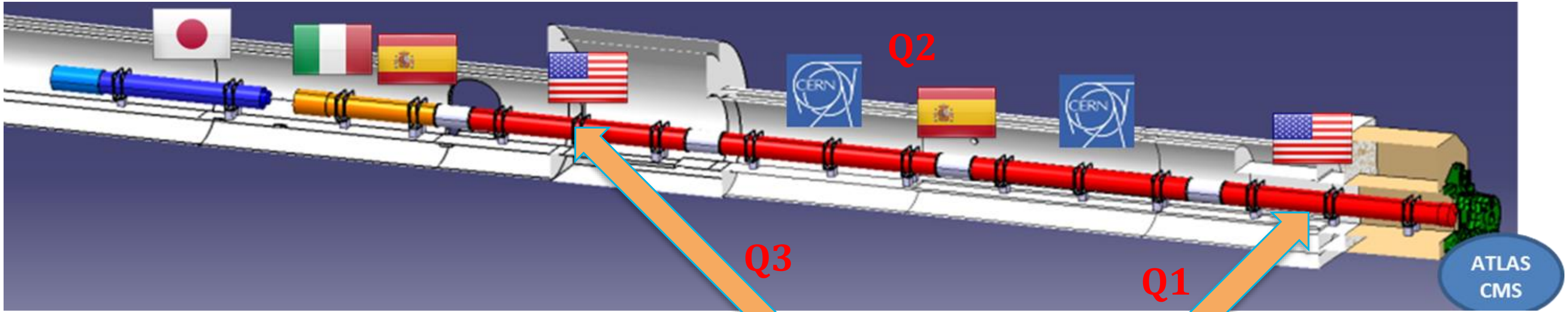
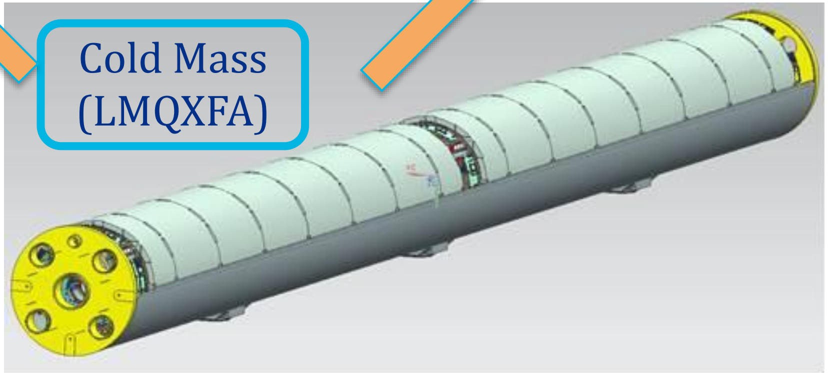
MQXFA = US Quadrupoles for HL-LHC



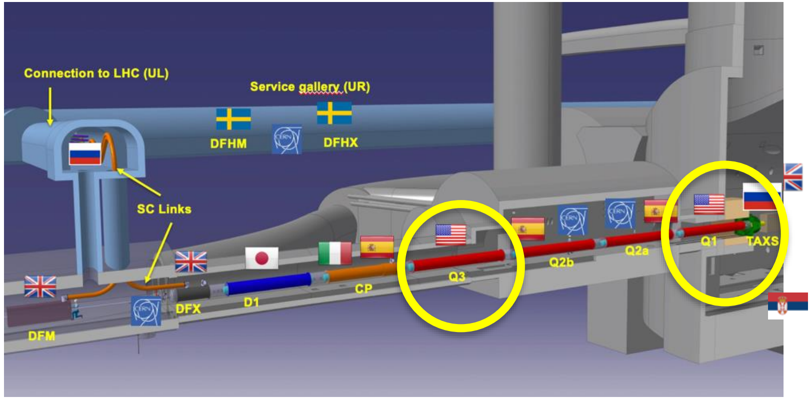
Magnet (MQXFA)

Cold Mass (LMQXFA)



- **20 Magnets/ 10 Cryo-assemblies:**
- 16 magnets for 8 Q1/Q3 to be installed in LHC tunnel and 4 magnets for 2 Q1/Q3 commissioning spares

HL-LHC AUP Project: The Inner Triplet and Matching Section regions



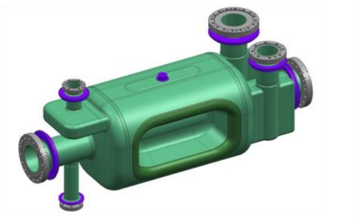
US HL-LHC AUP

Brookhaven National Laboratory

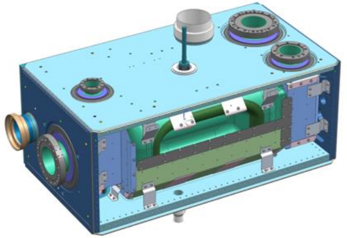
10 Dressed Cavities & Ancillaries

BERKELEY LAB

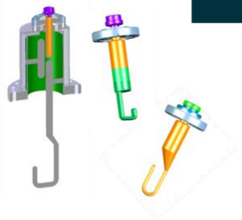
Fermilab



Bare RFD Cavity



Dressed RFD Cavity
(front wall removed to show internal components)



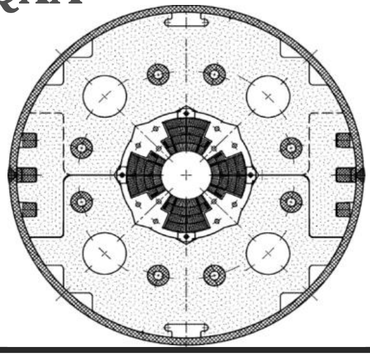
RF Ancillaries

Low-β quadrupole magnets from LHC to HL-LHC

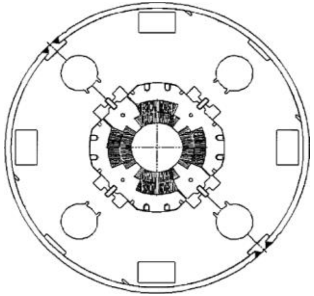
- Cold mass OD from 490/420 to **630 mm**
- More than double the aperture: from 70 to **150 mm**
- **~4 times** the e.m. forces in straight section
- **~6 times** the e.m. forces in the ends

State of the art quadrupoles at the time of ***LHC*** *construction*

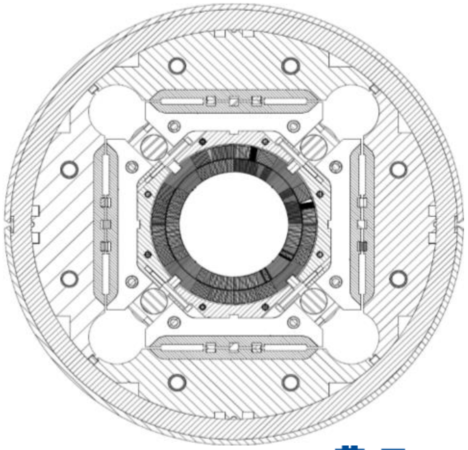
MQXA



MQXB



MQXF (HL-LHC)



Same scale for all 3 plots

MQXFA Status Summary

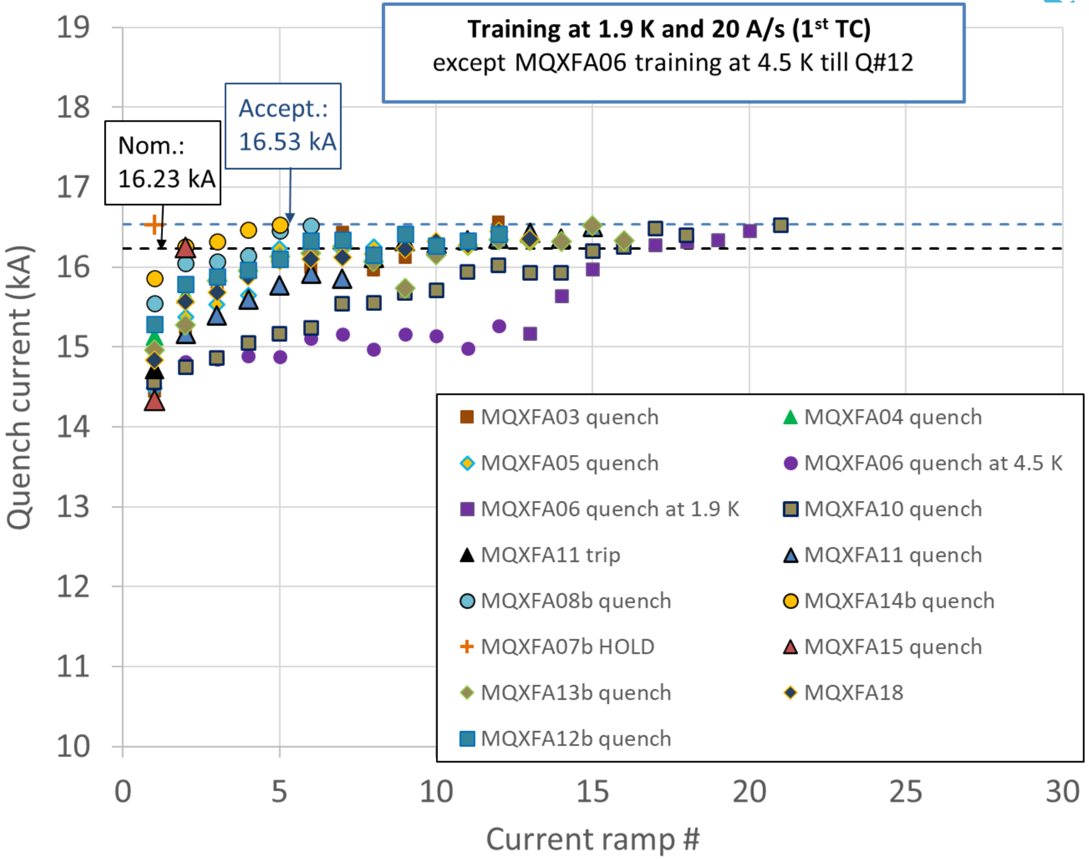
- Magnets tested in vertical cryostat: 17
- **Met requirements: 12**
- Did not meet requirements: 4
  - Affected by Covid restrictions: 2
  - **Met requirements** after replacing the limiting coil: 3
  - Magnet under test: 1

Component	Status
Strand procurement & QC (FNAL, FSU)	~100% complete
Cable fabrication & insulation (LBNL)	100%* complete
Coil fabrication (BNL & FNAL)	99%* complete
Magnet assembly (LBNL)	~75% complete

- Cable fabrication: LBNL
- Coil fabrication: BNL and FNAL
- Magnet assembly: LBNL
- Magnet vertical test: BNL
- Cold Mass + Cryo-assembly fabrication: FNAL
- Horizontal test: FNAL

We are going to fabricate 5 additional spare coils.

Technical Status – MQXFA Magnets



- 12 Accepted Magnets after vertical test at BNL out of 17 tested
- Magnets production is 75%, coils at ~99%, cables at ~100%
- MQXFA05 underwent endurance test with 50+ induced quenches.
- MQXFA08b, MQXFA07B, MQXFA13B, reworked magnets successfully tested

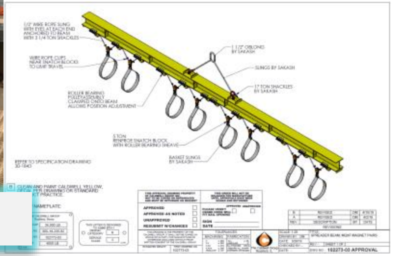
Fermilab

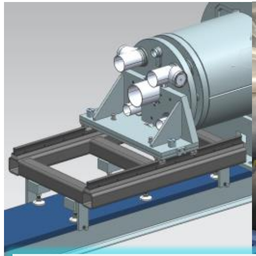
Cold Mass and Cryo-assembly fabrication

Soldering fixture

Alignment station; clamps and rollers.
Both stations have been aligned

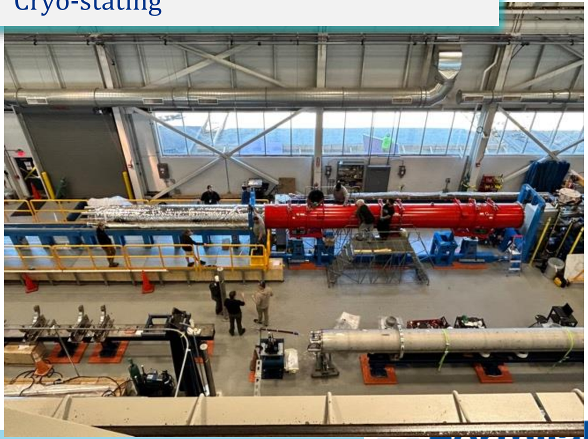
Cold Mass Welding station





End cover tooling used for End cover welding tests

Alignment station
Instrumentation station

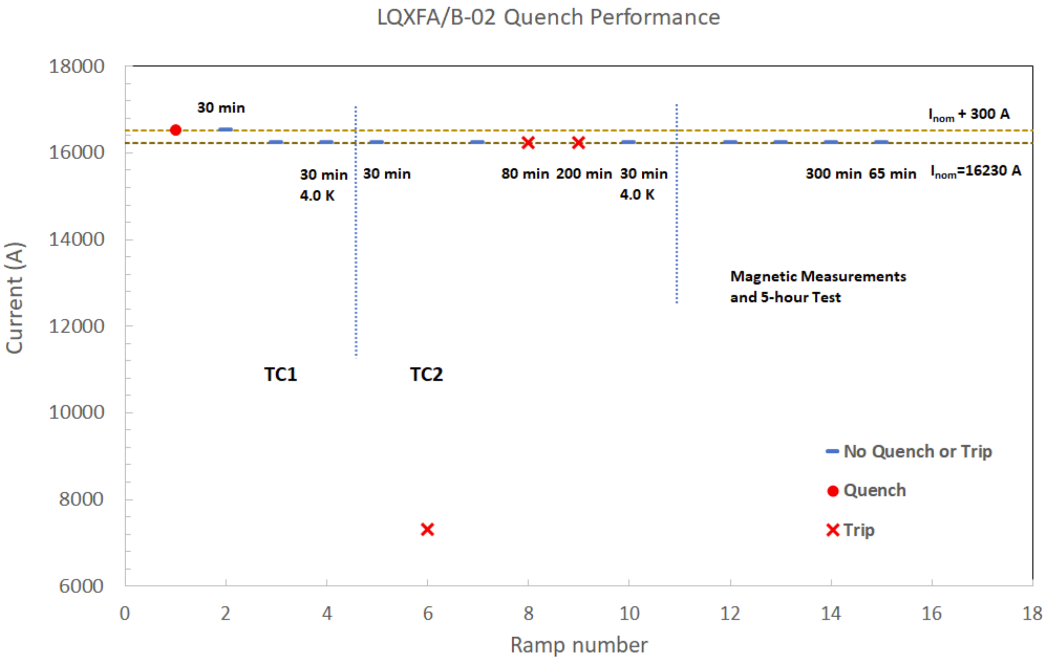


Cryo-stating

S. Feher *et al.*, "AUP First Pre-Series Cryo-Assembly Design Production and Test Overview," in *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, pp. 1-5, Aug. 2024, Art no. 4005605

LQXFA02 quench performance

- Test performed successfully at FNAL



Status of Cold Mass (CM) and Cryo-Assembly (CA)

- CA01 was tested, delivered and accepted by CERN
- Assembly of CA02 has been shipped to CERN
- Assembly of CM03 ready to be tested
- Assembly of CM04 completed
- Assembly of CM05: in progress

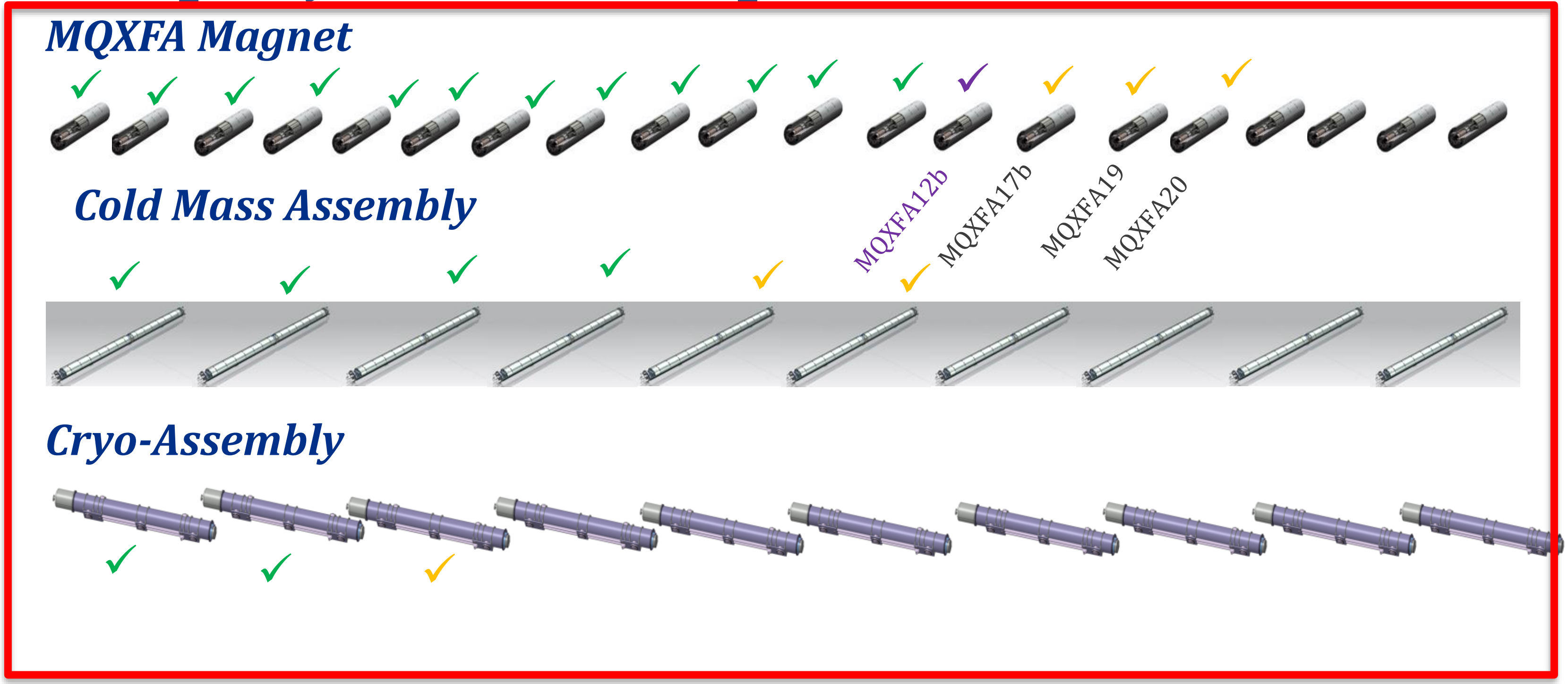
R. Rabehl, S. Feher, D. Ramos, T. Strauss and M. Struik, "AUP First Pre-series Cold Mass Installation Into the Cryostat," in *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, pp. 1-5, Aug. 2024, Art no. 4003705

Completed CM04

Assembly of CA01

A. Vouris *et al.*, "Fabrication of the Fermilab Pre-Series Cold Mass for the HL-LHC Accelerator Upgrade Project," in *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, pp. 1-5, Aug. 2023, Art no. 4002605

AUP project in a Snapshot

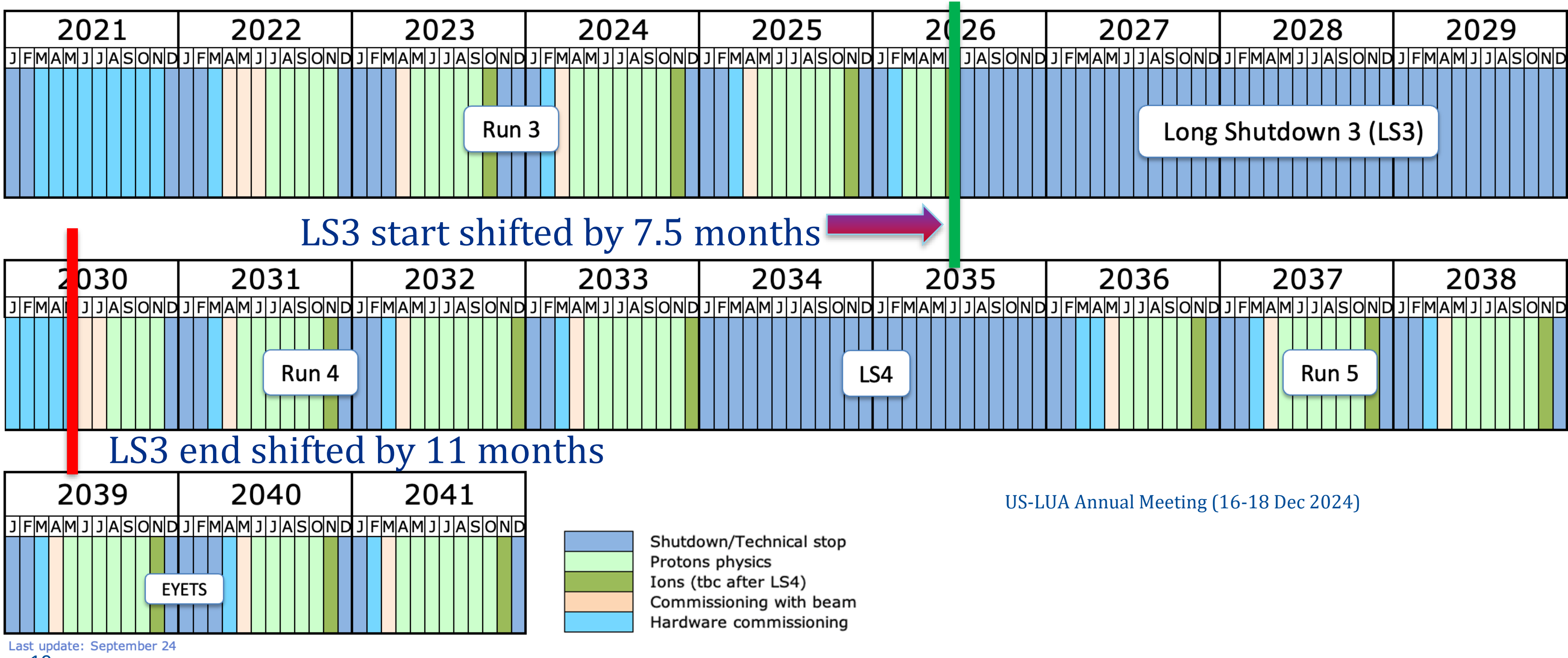


- ✓ Completed, shipped or delivered to CERN
- ✓ Under Fabrication
- ✓ Under Test

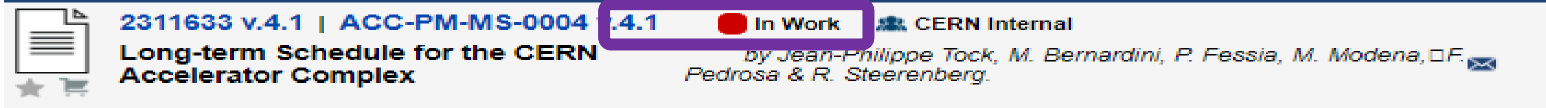
Slide by G. Apollinari

Schedule Update

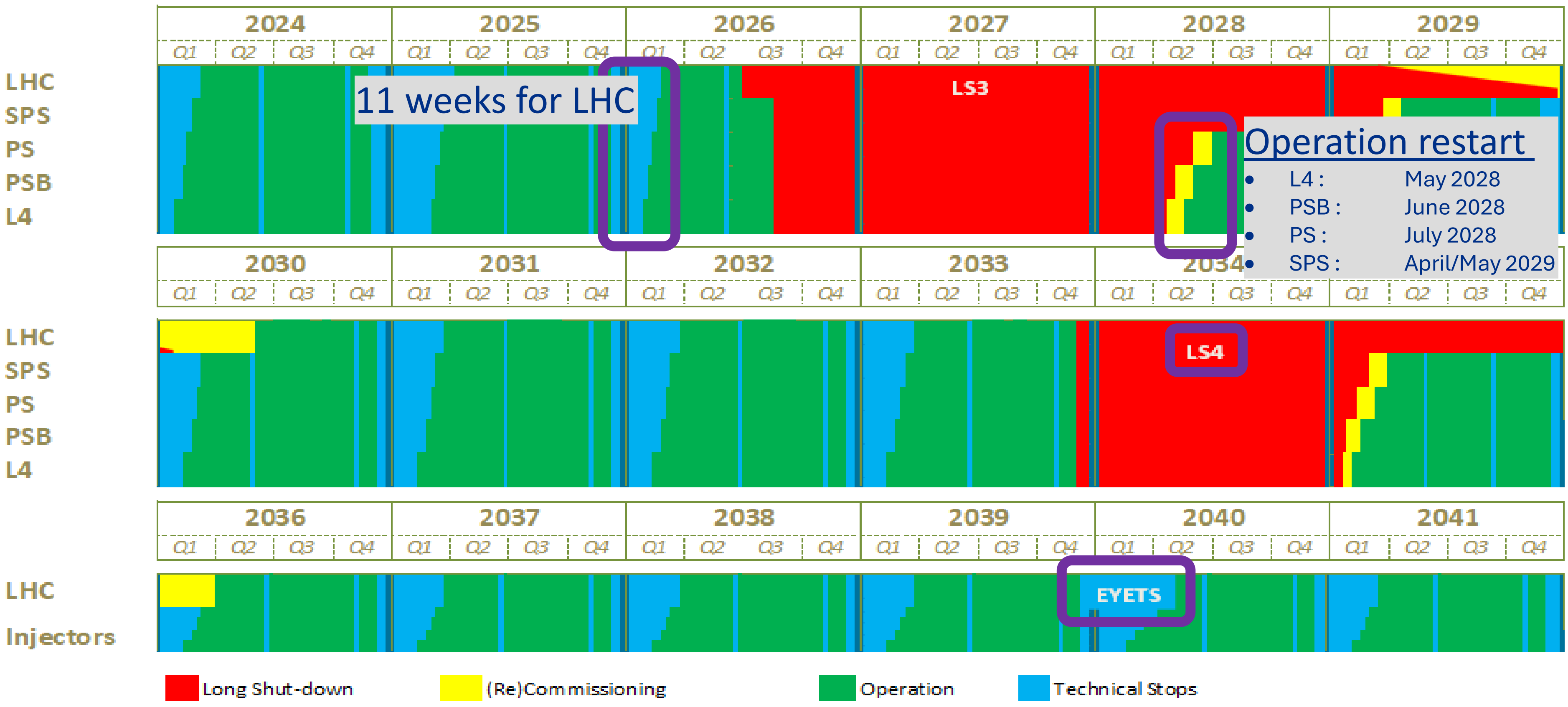
- **Schedule update following the September 2024 Research Board:**



Schedule



2311633 v.4.1 | ACC-PM-MS-0004 v.4.1
In Work
CERN Internal
Long-term Schedule for the CERN Accelerator Complex
by Jean-Philippe Tock, M. Bernardini, P. Fessia, M. Modena, F. Pedrosa & R. Steerenberg



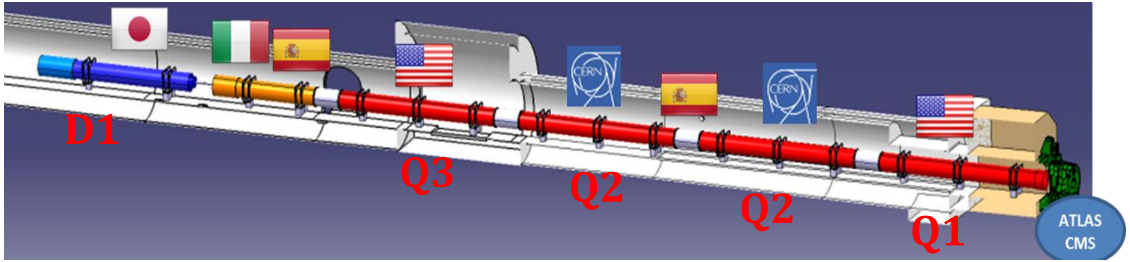
2024
2025
2026
2027
2028
2029
Q1 Q2 Q3 Q4
LHC
SPS
PS
PSB
L4
11 weeks for LHC
LS3
Operation restart
• L4 : May 2028
• PSB : June 2028
• PS : July 2028
• SPS : April/May 2029
2030
2031
2032
2033
2034
LS4
2036
2037
2038
2039
2040
2041
Injectors
EYETS
Long Shut-down
(Re)Commissioning
Operation
Technical Stops

HL-LHC IT STRING

Marta Bajko

The **HL-LHC IT STRING** will serve as a test bed [….]. The HL-LHC IT STRING should therefore validate operational modes […] in view of the hardware commissioning and operation periods in the HL-LHC era. […]

The present reporting is essentially done in this part



The IT STRING test will ensure a successful and efficient HWC of the HL-LHC!

2022 2023 2024 2025 2026 2027 2028 2029

IT STRING Installation

IT STRING Validation Program

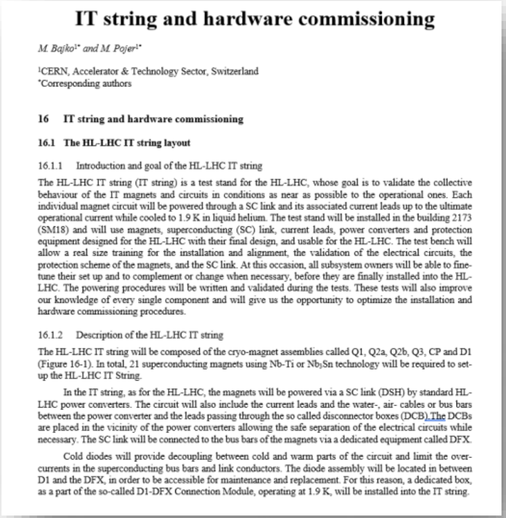
…

Hardware commissioning

IT STRING

HWC

HL-LHC IT STRING



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.

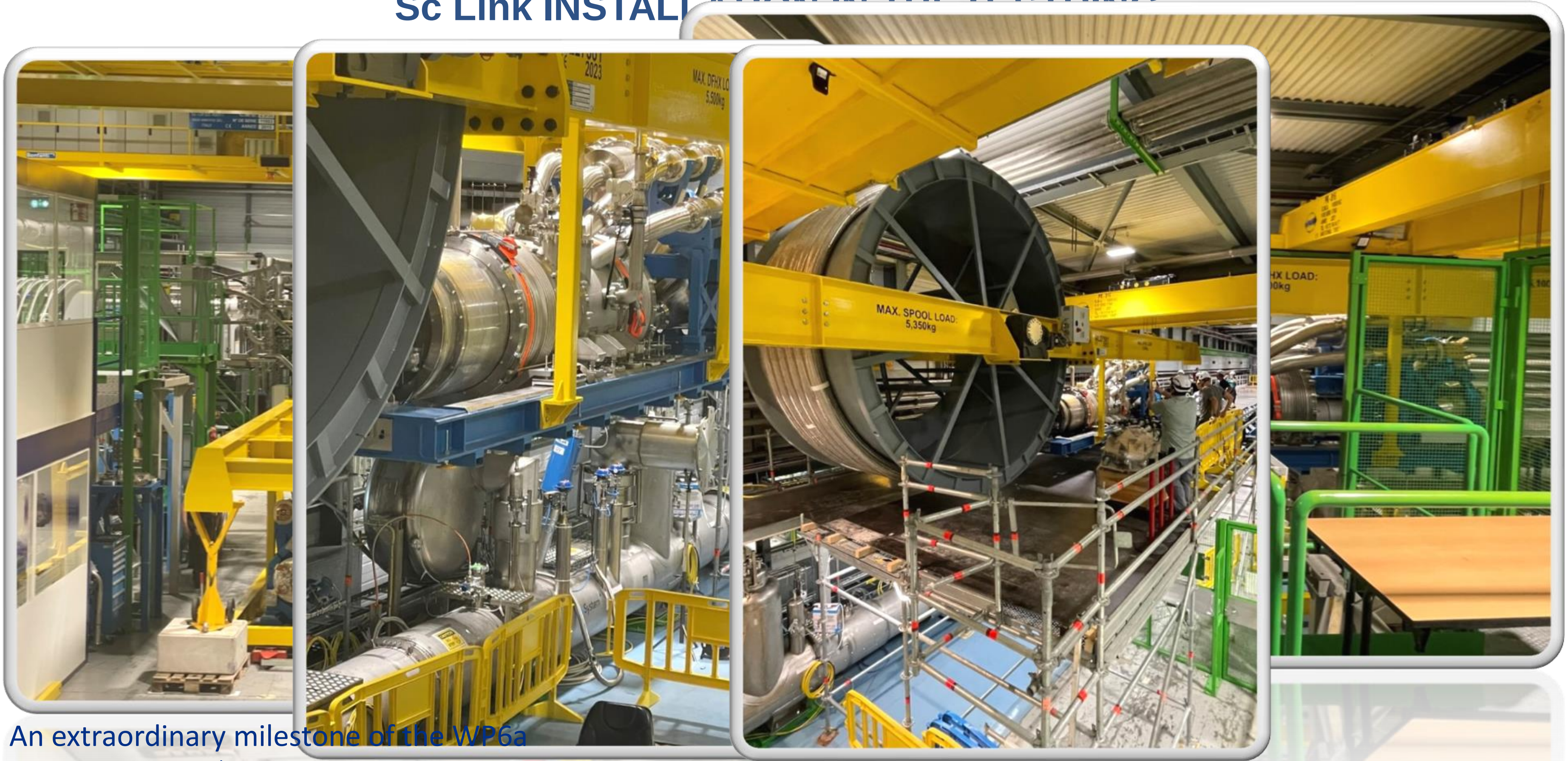
The ***scope*** of the IT STRING is to represent, as best as reasonably achievable in a surface building, the various operation modes to **STUDY and VALIDATE the COLLECTIVE BEHAVIOUR** of the different systems of the HL-LHC's IT zone (magnets, magnet protection, cryogenics of the magnets and of the superconducting link, magnet powering, vacuum, *alignment, interconnections between magnets, and the superconducting link itself). Another* key motivation is to test and optimize the **QC plans, IST, SCT and Powering Test procedures** to prepare to a smooth LS3

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

Integration by. A. Kosmicki

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

Sc Link INSTALLATION IN THE IT STRING



An extraordinary milestone of the WP6a team 21th of August 2024

Q2a cold mass installation by EN-HE teams

An extraordinary milestone of the
WP3 team 25th of September 2024

D1 cold mass installation by EN-HE teams

An extraordinary milestone of the WP3 and KEK team on the 4th of November 2024

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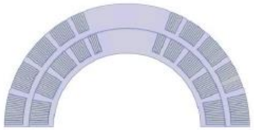
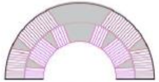
U.S. MAGNET
DEVELOPMENT
PROGRAM
BERKELEY LAB
Brookhaven
National Laboratory
Fermilab
FLORIDA STATE UNIVERSITY
1851
ASC

Exploring stress management configurations: Nb_3Sn

- Prove the concept of SMCT dipole coil design in 2-layer and 4-layer mirror configurations

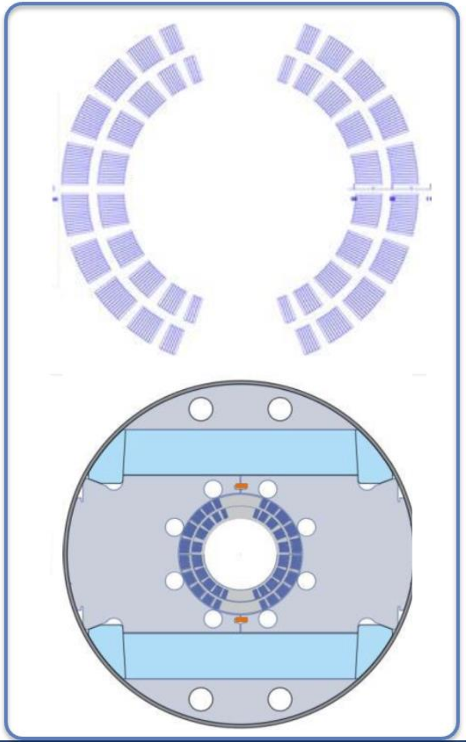


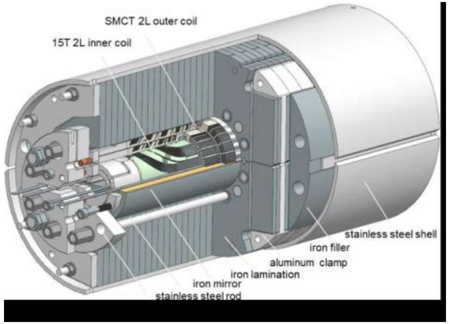
New SMCT coil ID=120 mm

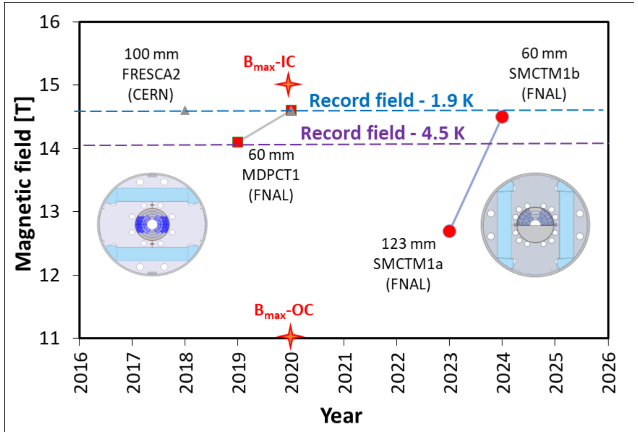


Inner coil for 15T dipole ID=60 mm

SMCT







Courtesy of A. Zoblin

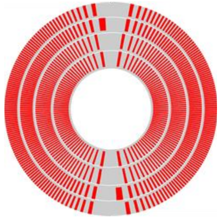
Stress-managed CCT magnets towards progressively higher field at LBNL

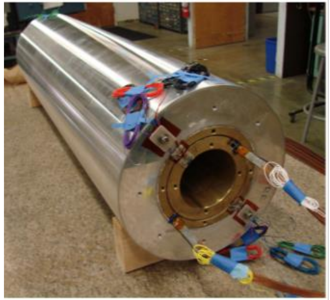
Courtesy of Diego Arbelaez

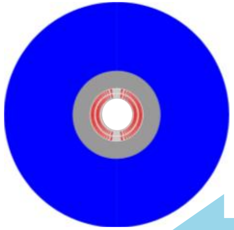
US MDP is pursuing stress management approaches: for canted cos-theta design (CCT)

- Each turn contained within a grove

D. Arbelaez, *IEEE Trans. Appl. Supercond.*, Vol. 32, No. 6, Sep. 2022, 4003207.



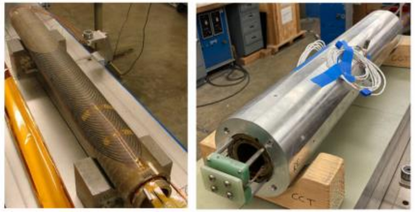


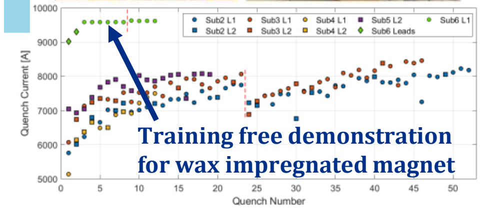


CCT5 / CCT5-W model magnets
~10 T in **90 mm aperture**

- Epoxy impregnated CCT5 Tested in 2019 (reached 88% of SSL)
- Alumina filled wax impregnated CCT5-W to be tested in 2025

Subscale Magnet Program

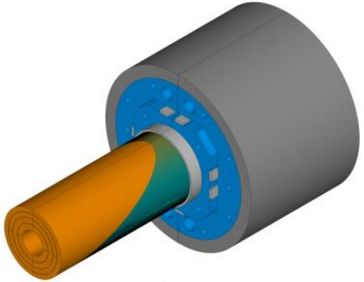


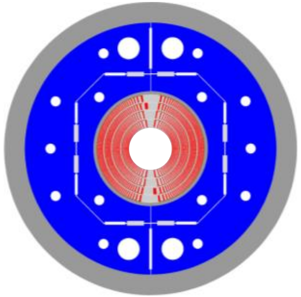


CCT6

- Design and prototyping in progress
- Fabrication to start in 2025
- Target: **12-14 T** in **120 mm aperture**

L. Brouwer, *IEEE Trans. Appl. Supercond.*, Vol. 32, No. 6, Sep. 2022, 4001805.





Inform decisions on design and impregnation choices

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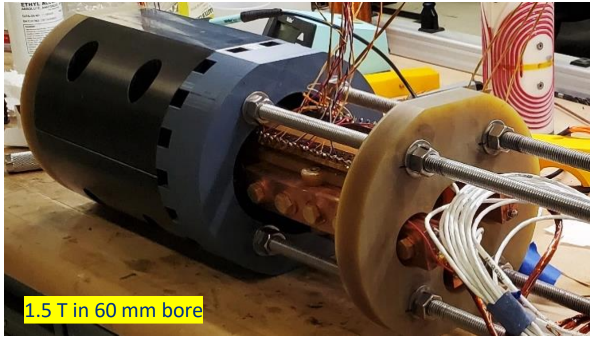
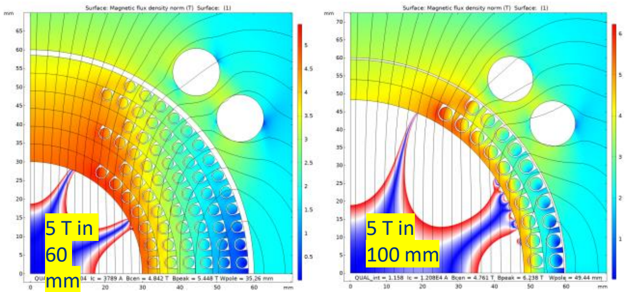
HTS (REBCO) magnet and cable development



REBCO magnets with round cables



Flat REBCO cable concept

REBCO accelerator magnet development at FNAL: Use state-of-the-art STAR and CORC round wires

First REBCO magnet tested in LHe this year

- Innovative coil structure 3D-printed from ULTEM
- Reached 1.5 T in a 60-mm bore

Two REBCO magnets to be fabricated and tested in 2025-26

Target 5 T field in 60-100 mm bore: standalone and inserts into Nb_3Sn coils

- Alternative REBCO cable designs for accelerators
- Fusion cable studies

Several proposals for collaboration with PPPL

Courtesy of Vadim Kashikhin

Fermilab

Six CCT layers using REBCO CORC® wires are ready for assembly

Aluminum shell

Layer 6

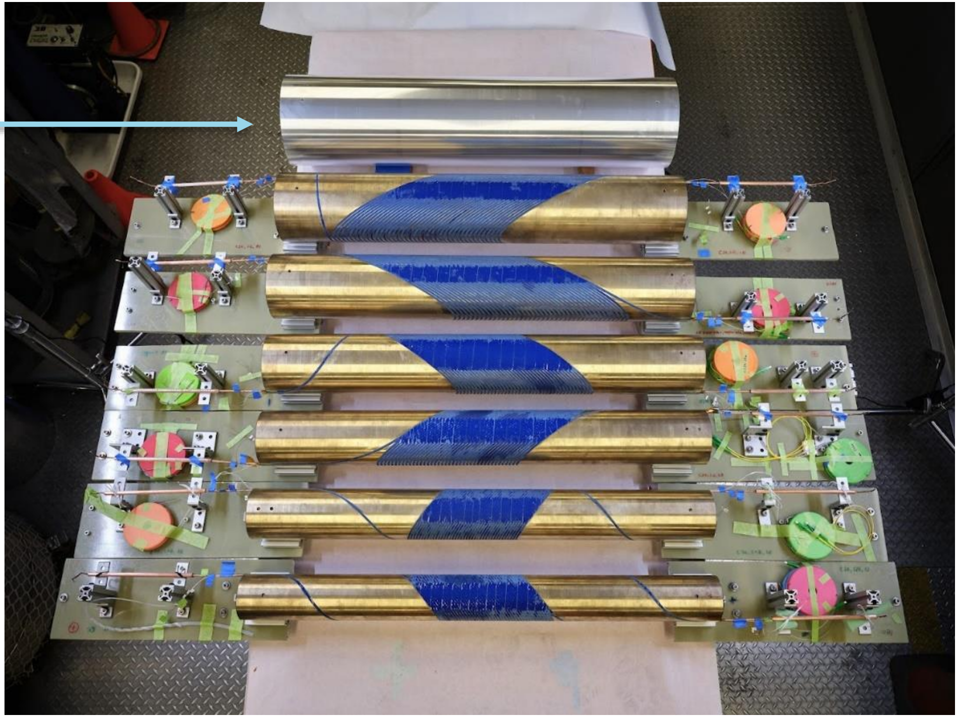
5

4

3

2

1



Six-layer CCT dipole aiming at the 5 T milestone

- Built on what we learned from C1 and C2

77 K Self-field I_c reached 60% - 90% of the expected performance

Courtesy of Xiaorong Wang

Fermilab

Conclusion: LHC and HL-LHC

LHC:

- Availability factor was ~constant through Run2 and Run3 for small**: 72%**
- In 2024 integrated luminosity was beyond 110 fb-1
- First 2025 beam expected in the LHC on early June: 2025 baseline schedule available

AUP HL-LHC

•**Magnets and Cryo-assemblies:**

- Magnet assembly at peak production at LBNL. Coil fabrication at BNL and FNAL are completed.
- 17 MQXFA magnets have been tested and 12 have been accepted.
- MQXFA12b is currently under test and MQXFA17b, 19 and 20 are at different stage of fabrication
- LQXFA/B-01 is at CERN, LQXFA/B-02 has been shipped and LQXFA/B-03 is about to be tested

Conclusions

High field magnets for future machines: R&D work in within US MDP

Nb_3Sn magnets:
Extending the capability of Nb3Sn magnets using stress management structures.
Goal: reduce large coil deformations under Lorentz forces and, thus, excessively large strains and stresses in the coil.

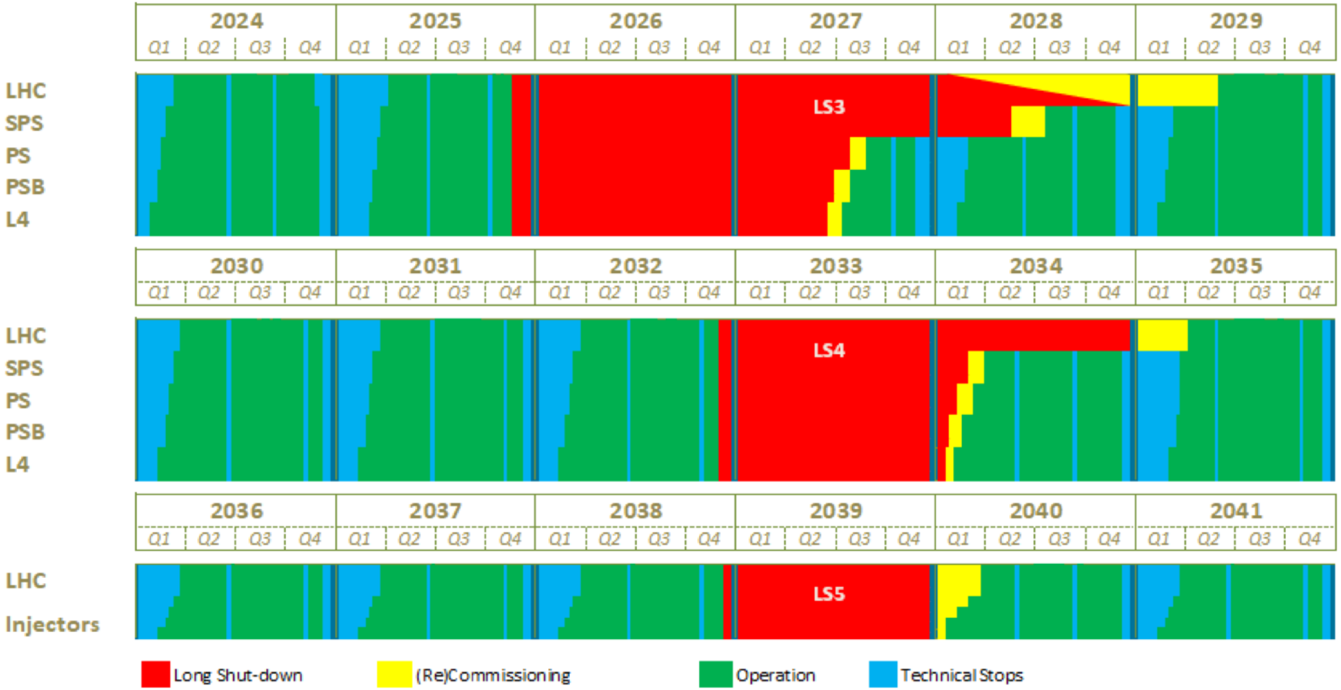
- CCT magnets at LBNL: CCT5 impregnated with Wax, Design of CCT6 is ongoing
- SMCT magnets at FNAL: Fabrication of SMCTD1 dipole magnet will take place in 2025

HTS conductors: Enabling technology for magnets with fields > 16 T; Higher temperature margin; Operation at higher temperature

- CCT REBCO magnet at LBNL: under fabrication, test in February 2025
- COMB STAR magnet at FNAL: under fabrication, test by the end of FY25

Backup slides

OBSOLETE LONG TERM SCHEDULE

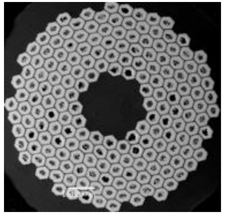


- LS3 start for LHC shifts to 29 June 2026
  - Length extended
- LS3 start for Injectors shifts to 31 August 2026
  - North Area consolidation will go beyond SPS stop
  - TCC2 may still need to be added to the scope of the NA-CONS project
- LS4 shifts by 1 year
- LS5 to be converted into an EYETS 2039-2040

Current Magnet R&D activities at Fermilab

- The R&D topics include:

Nb_3Sn conductor



- Artificial Pinning Centers (APC) and High-Cp optimization and industrialization

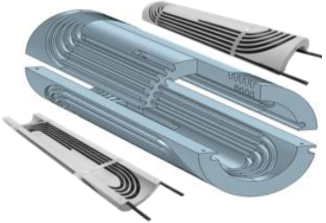
Nb_3Sn magnets

- 15 T dipole; stress management (SM) structures for coils in magnets above 16T (16-20 T)

HTS

- Specially designed structures for REBCO coils
- Bi- 2212 SM R&D

Technology R&D



- Training and diagnostics – fibers as strain gauges, training studies and QCD device
- Instrumentation and quench protection - new accurate quench antennas, fibers for HTS QP
- Material studies - new epoxy and insulation material tests, high-Cp materials in cable and epoxy
- Modeling and simulation - new tools (AI for Nb_3Sn training prediction)

Summarizing magnet needs for potential future colliders

- **In general . . .**
  - High field dipoles– up to 17T (and perhaps 20 – 24T)
  - Large aperture interaction region quadrupoles
  - Sustainability → higher operating temperatures
- **Muon Collider (in addition to above)**
  - Large apertures (~ 160mm)
  - (Very) fast ramping magnets
  - Large aperture, high field solenoids (> 30T)
  - Operation in high radiation, high heat load environment

Challenges

- He cost/availability
- High stresses
- High radiation environment
- Sustainability – power consumption

Opportunities

- HTS
- Fusion driving REBCO cost

→ **Need to ramp up R&D NOW!**

Future Colliders and R&D

- A major effort was made during “Snowmass 2021” to highlight the U.S. HEP community interest in Future Colliders

  Various e+e- Higgs Factory options and multi-TeV parton Center-of-Momentum (pCM) hadron colliders and muon colliders were studied and documented.

  See e.g., https://arxiv.org/abs/2203.08088 and references therein.

  Strong resurgence of interest in ~10 TeV muon collider!

  A targeted national collider R&D program was proposed to enable studies/R&D: See https://arxiv.org/abs/2207.06213v1

  The Snowmass report strongly endorsed the community’s interest in early U.S. engagement in future collider projects planned abroad (FCC-ee, ILC) and the community’s ambition to host a high energy collider in the U.S. (e.g., a Muon Collider)

Courtesy of Pushpa Bhat

Future Colliders in the P5 2023 Report

- The just released P5 report (https://science.osti.gov/-/media/hep/hepap/pdf/Reports/P5Report2023_120123-DRAFT-to-HEPAP.pdf) strongly supports the U.S. Community's aspirations on Future Colliders, particularly emphasizing vigorous R&D for a 10 TeV pCM Muon Collider!

Recommendation 2c endorses an off-shore Higgs factory and urges the US to actively engage.

Recommendation 4a supports vigorous R&D toward a cost-effective 10 TeV pCM collider R&D, with a goal of being ready to build major test and demonstrator facilities within the next 10 years.

Recommendation 4g asks to develop plans for improving the Fermilab accelerator complex that are consistent with the long-term vision of the report, including neutrinos, flavor, and a 10 TeV pCM collider.

Area Recommendation 10 bolsters support for Collider R&D:

"To enable targeted R&D before specific collider projects are established in the US, an investment in collider detector R&D funding at the level of $20M per year and collider accelerator R&D at the level of $35M per year in 2023 dollars is warranted."

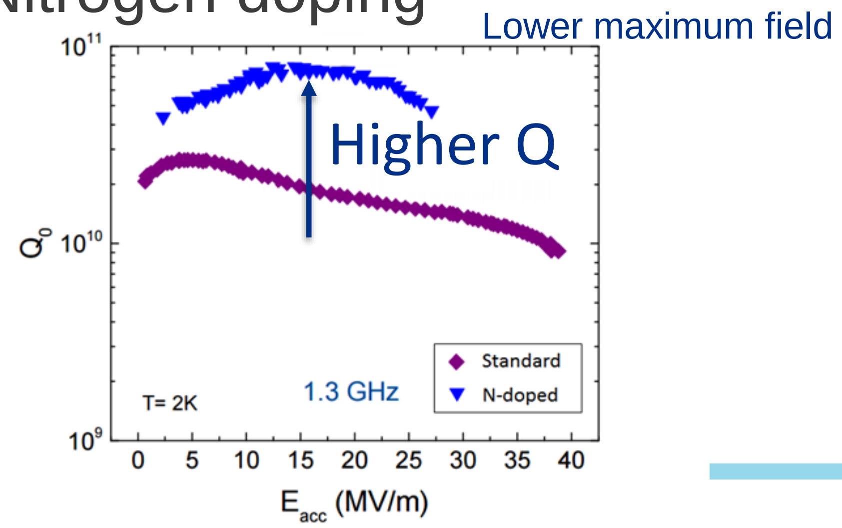
Courtesy of Pushpa Bhat

Summarizing SRF needs for potential future colliders

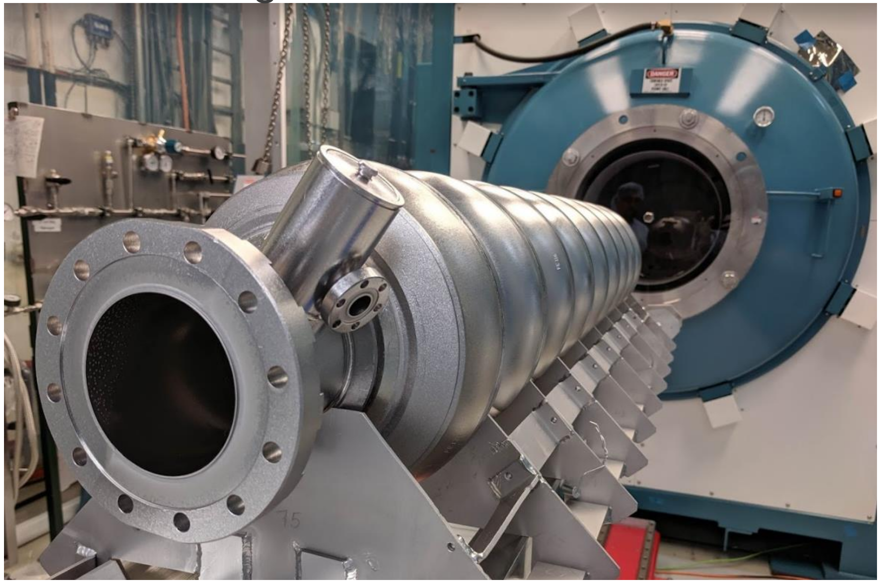
In general . . .

- High gradient, high efficiency SRF cavities
- High gradient NCRF
- High efficiency power sources

Nitrogen doping

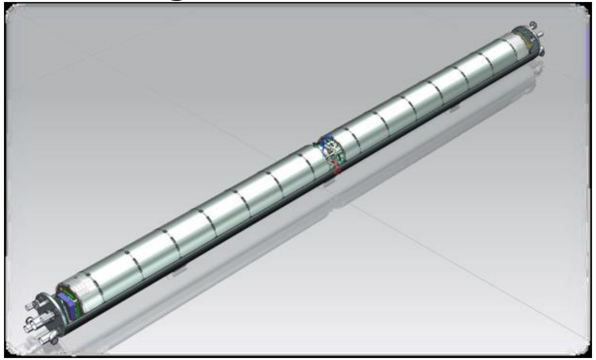


Nb_3Sn cavities

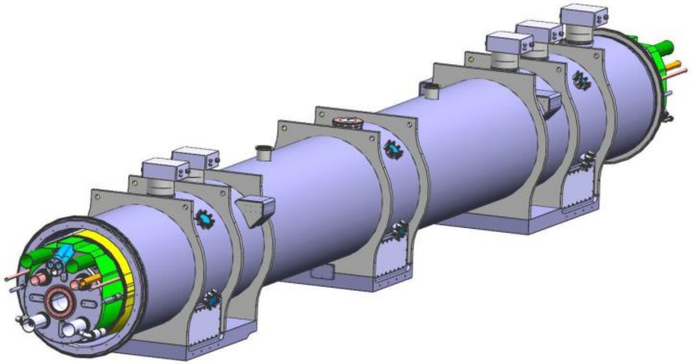


Cryo-assembly

The **Cold Mass** is the He pressure vessel assembly containing two 4.2 m Nb3Sn magnets

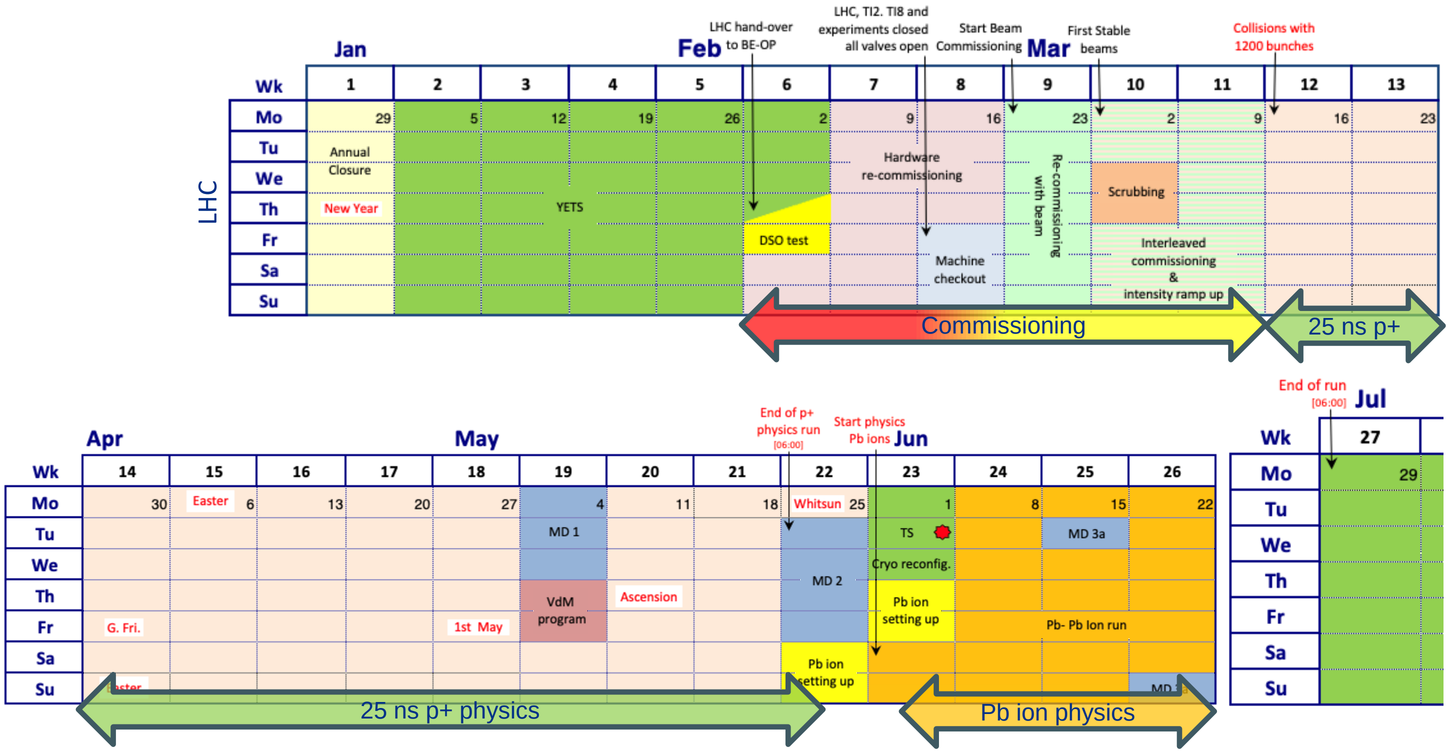


HL-LHC cryo-assembly



- Cold mass + Cryo-assembly fabrication+ Horizontal test is done at FNAL

Cryostat is a CERN design and the procurement of the cryostat and tooling was done by CERN


LHC
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5
12
19
26
2
9
16
23
2
9
16
23
LHC hand-over to BE-OP
LHC, TI2. TI8 and experiments closed all valves open
Start Beam Commissioning
First Stable beams
Collisions with 1200 bunches
Annual Closure
New Year
YETS
DSO test
Hardware re-commissioning
Machine checkout
Re-commissioning with beam
Scrubbing
Interleaved commissioning & intensity ramp up
Commissioning
25 ns p+
Apr
May
Jun
Jul
End of p+ physics run [06:00]
Start physics Pb ions
End of run [06:00]
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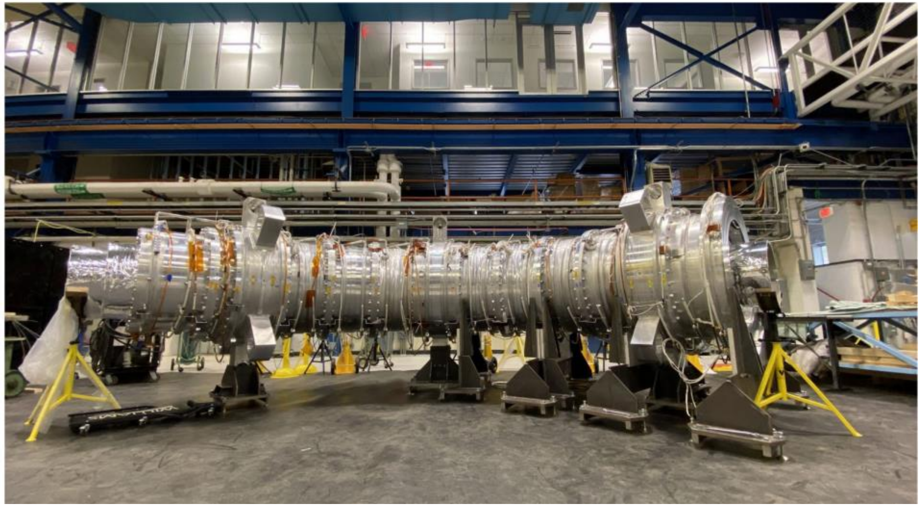
29
MD 1
VdM program
Ascension
G. Fri.
1st May
MD 2
Pb ion setting up
TS
Cryo reconfig.
MD 3a
Pb- Pb Ion run
25 ns p+ physics
Pb ion physics

Accelerator Technology: 2023 Fermilab highlights

Nb_3Sn Interaction Region Quadrupoles for Hi-Lumi LHC Upgrade

Mu2e: Transport solenoid completed and moved to experimental hall



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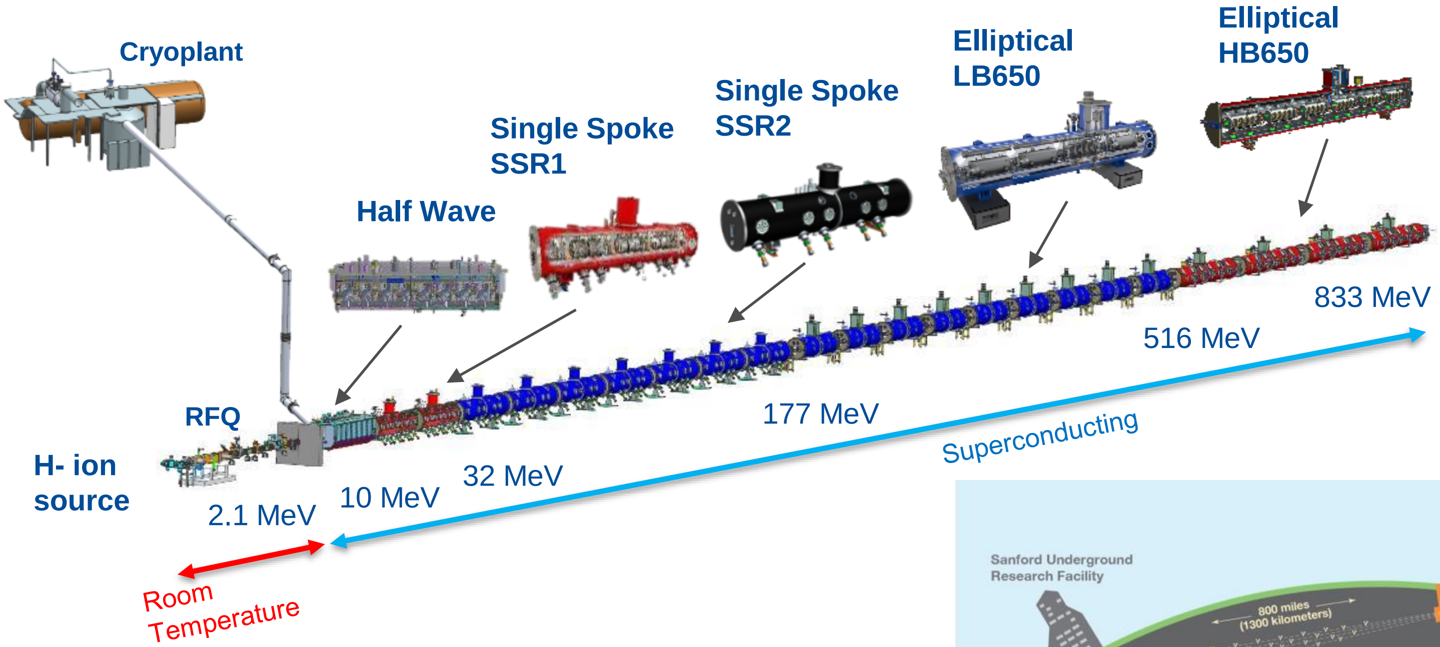
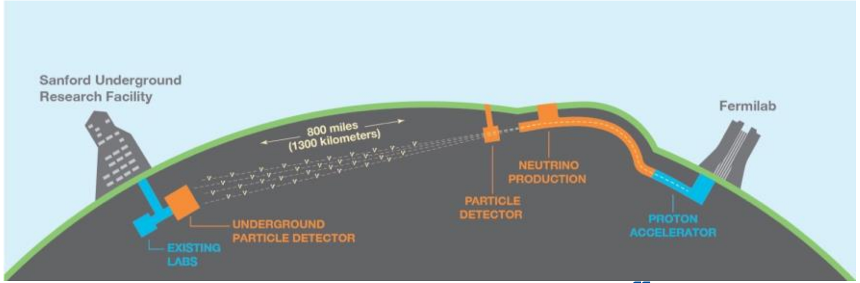
Accelerator Technology: 2023 Fermilab highlights

- PIP-II linac is technically complex, state of the art superconducting RF accelerator





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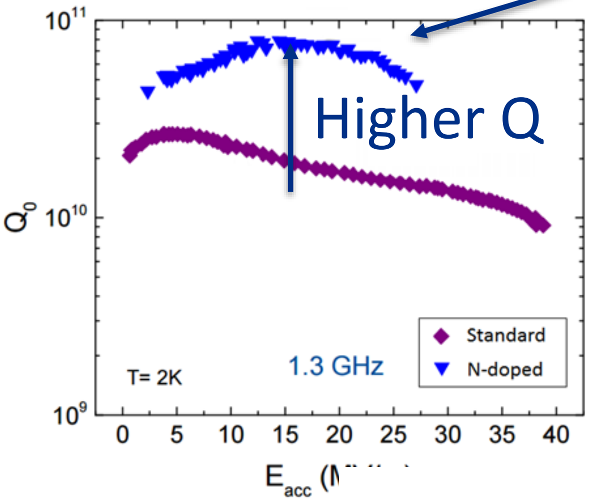
Fermilab
SSR1
PROTONS ACCELERATED UP TO 148,876,891 MPH
Fermilab

Superconducting RF: Nitrogen Doping



$$Q = \frac{\omega_0 U}{P_d}$$

Nb_3Sn Cavities for Particle Accelerators

- Nb has long been the material of choice for SRF accelerators
- Nb_3Sn is under development, and we have shown that it can achieve high Q even at ~4 K (Nb is typically 2 K)
- Immediate promise for 'compact accelerators'
- With continued R&D, Nb_3Sn is predicted to exceed Nb maximum field
- Fermilab R&D: first Nb_3Sn 9-cell cavity, new record Nb_3Sn CW accelerating gradient