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

Maria Baldini, FNAL

US LUA Annual Meeting

12-15 December 2023

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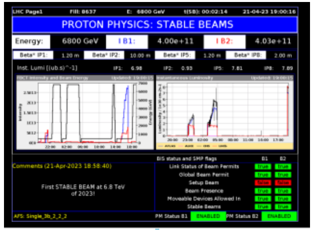
- LHC status and plans
  - 2023 summary and status
  - 2024 plan
- HL-LHC upgrade long term plan
  - HL-LHC AUP: status and milestones
- Future colliders
  - R&D work at FNAL

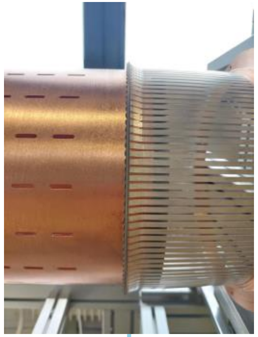
2023 LHC Machine Main Events Timeline

Courtesy of R. Steerenberg

20.03.2023
Beam 1 Crystal collimator mechanics broke after testing

21.04.2023
1st stable beam of 2023

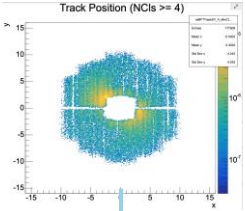




24.05.2023
RF finger module issue.
Vacuum spikes caused by beam induced arcing/heating.
Partially plasticised spring.
Intensity limit 1.6×10^{11} ppb

31.08.2023 (B)
08.09.2023 (A)
2 x injection protection device (TDIS)
Point 8 vacuum leak.
Preventing p+ operation, but Pb ion possible

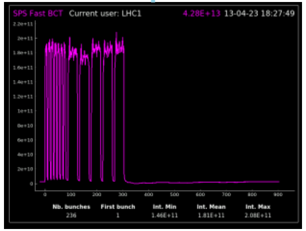
End Sep – Early Oct
ALICE background issue followed by studies and solution



2023

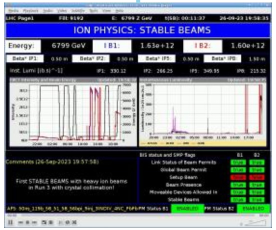
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

02.04.2023
RF Rupture discs B1 & B2 following trip of the LHC 18kV SVC point 4

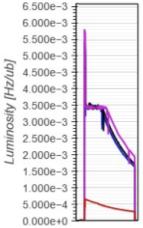


12.05.2023
1st collisions
2374 bunches
mixed scheme
1x8b4e + 3x36b
minimising heat load maximising lumi

17.07.2023
Fallen tree in VD causing power glitch, magnet quench, and leaking bellow between cold mass and insulation vacuum

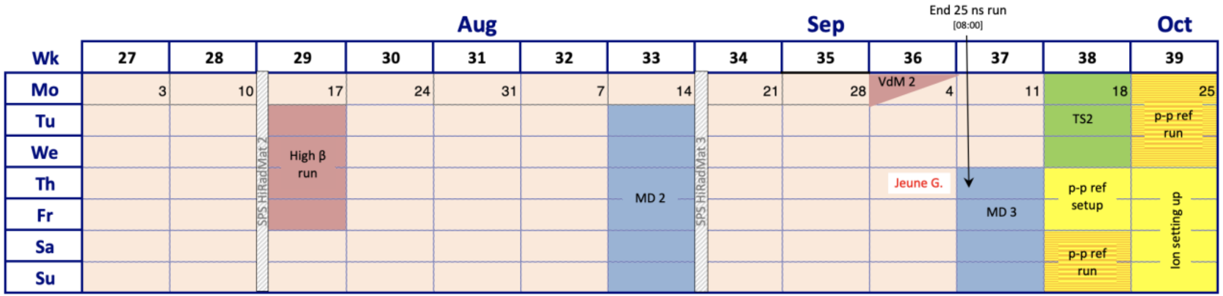


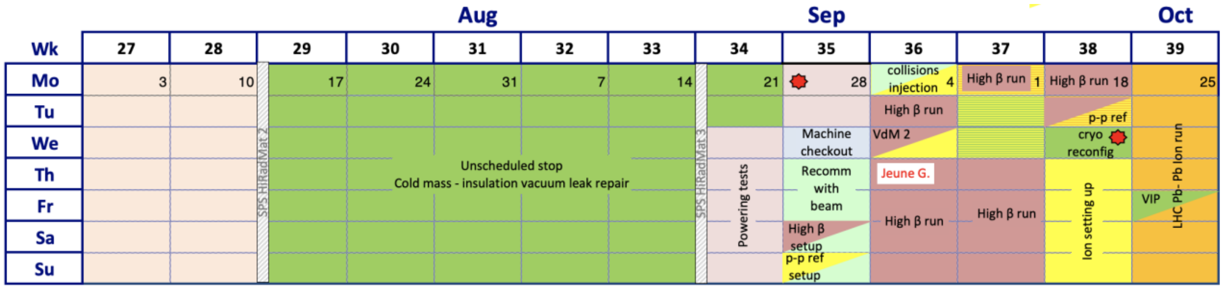
26.09.2023: 1st stable Pb ion beam of 2023



October
Beam loss induced SEU causing trips, quenches, etc.
Studies, Lumi levelling

2023 LHC Schedule Q3





- Proton run was cut short
- Machine Development sessions were cancelled
- The re-start in end of August was efficient
- All activities squeezed in September period – very challenging
- p-p reference run to be scheduled in 2024
- Pb ion period extended, but with a challenging start

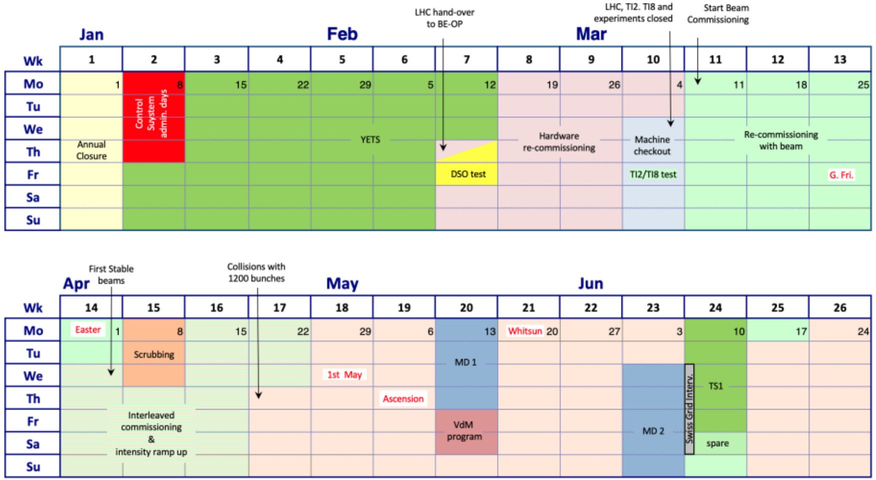
Courtesy of R. Steerenberg

Year 2023 in summary

- The Injectors complex is running well with good beam performance and availability
  - HL-LHC beam parameters demonstrated
  - Slip-stacking for Pb ion commissioned successfully
- LHC had a challenging year working in unchartered territory for Protons and Pb ions
  - Unpresented stored proton beam energy and very efficient performance ramp-up
  - Serious issues caused substantial down time – Proton run was cut short to 49% of initial time schedule
  - Pb ion run with double the number of bunches came with more challenges than anticipated – lately very good running
- First 2024 beam expected in the LHC on 11 March
  - 2024 baseline schedule available.

Courtesy of R. Steerenberg

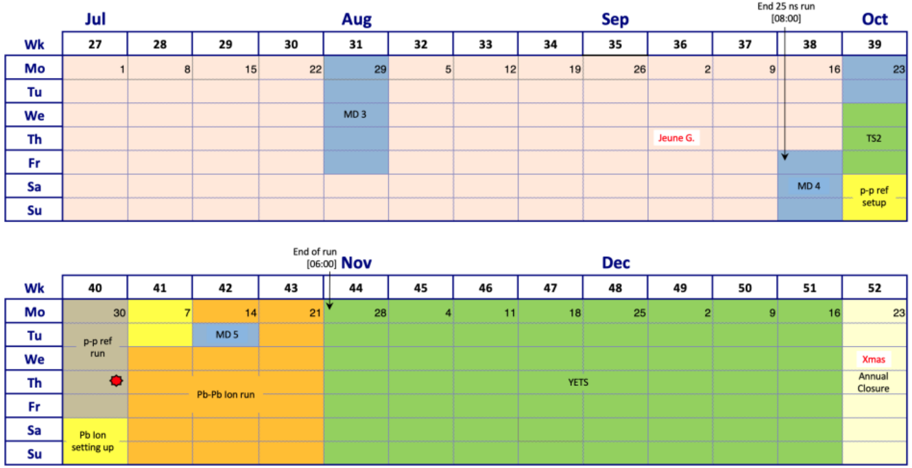
2024 version 0.8b



Same as for version 0.8a apart from the p-p reference run that has moved to the end of the 2024

The 5.5 weeks of Pb ion running until LS3 to be share over 2024 and 2025 with a Pb ion run at the end of each year.

The Oxygen ion run to be moved from 2024 to 2025



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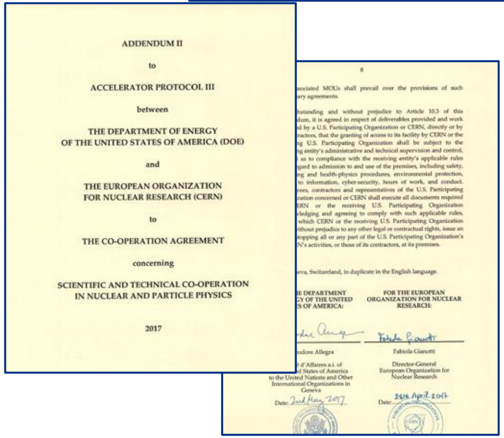
Context: DOE and HL-LHC

- The 2014 P5 High Energy Physics (HEP) strategic plan called for continued involvement in the LHC, including full participation in the high luminosity upgrade of the LHC (HL-LHC) and its detectors.
  - **Support reinforced by 2023 P5 Report**

- DOE-HEP has been actively developing an enhanced partnership with CERN since the P5 report was issued.
  - An international cooperation agreement with CERN has been signed and protocols on neutrinos, the LHC experiments, and contributing to the HL-LHC accelerator upgrade are complete.

- Following DOE-CERN Cooperation & Protocol Agreements in 2014 & 2015, in April 2017 an Addendum to the agreements further specified the HL-LHC Upgrade activities of mutual interest to the Parties ® *spawned 413.3b HL-LHC AUP*

Recommendation 10: Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.


ADDENDUM II

to

ACCELERATOR PROTOCOL III

between

THE DEPARTMENT OF ENERGY
OF THE UNITED STATES OF AMERICA (DOE)

and

THE EUROPEAN ORGANIZATION
FOR NUCLEAR RESEARCH (CERN)

to

THE CO-OPERATION AGREEMENT

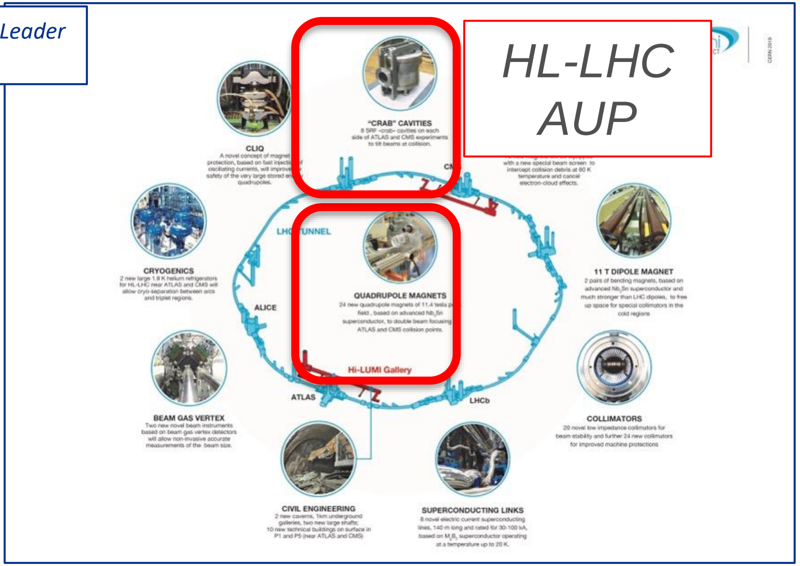
concerning

SCIENTIFIC AND TECHNICAL CO-OPERATION
IN NUCLEAR AND PARTICLE PHYSICS

2017

US Contribution to HL-LHC

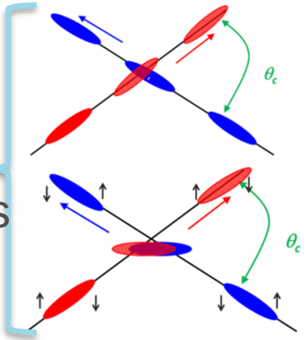
From HL-LHC Project Leader
O. Bruning - CERN



Quad Magnets $L = \gamma \frac{f_{rev}\, n_b\, N_b^{\,2}}{4\pi \varepsilon_n \beta^*} R$

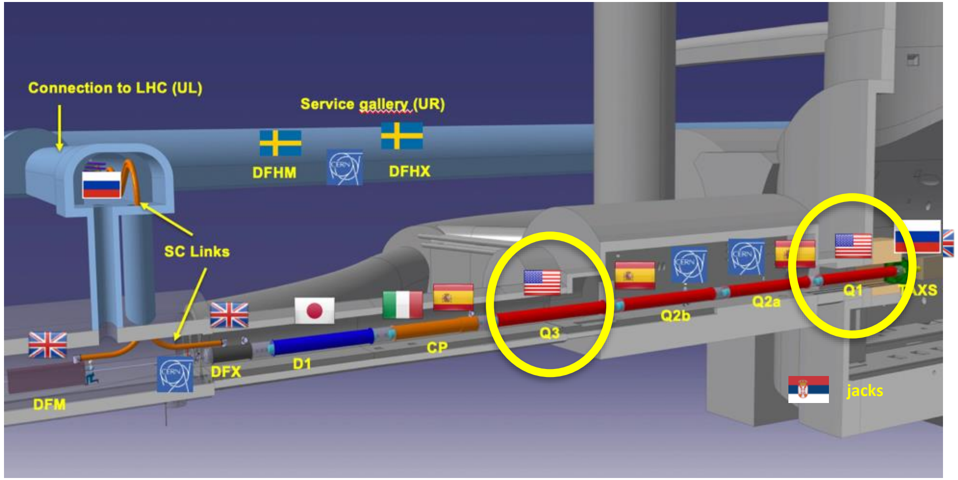
Beam size

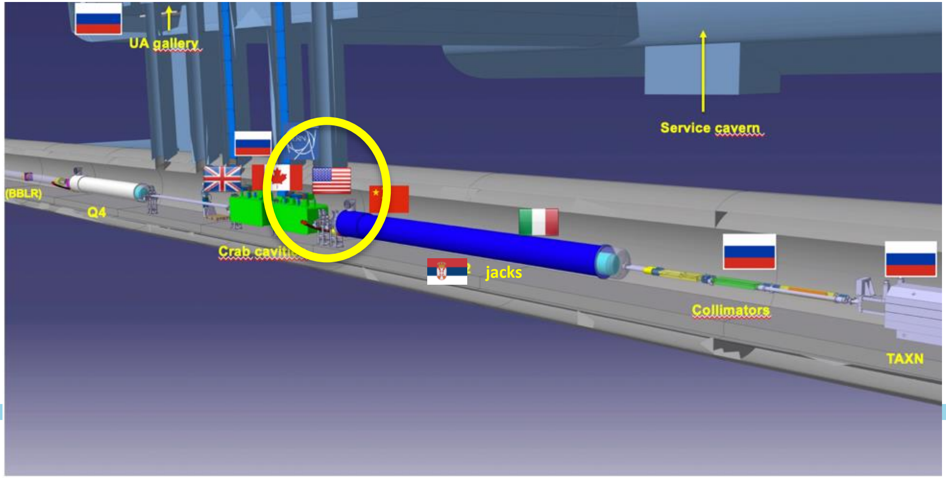
Crab Cavities



- HL-LHC: from 300 fb^{-1} to 3000/4000 fb^{-1}
- LARP (DOE supported R&D Program) established the necessary technology (Nb_3Sn) for the HL-LHC Focusing Magnets and Crab Cavities
- DOE *baselined* **HL-LHC AUP** Project in 2019 (FNAL, BNL, LBNL with contributions from ANL, SLAC, JLAB, ODU & FSU)

The Inner Triplet & Matching Section regions

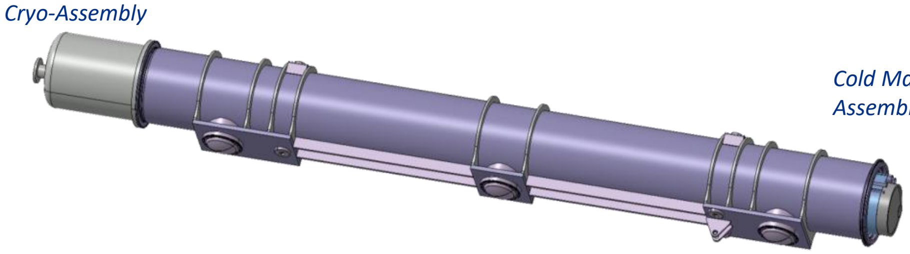


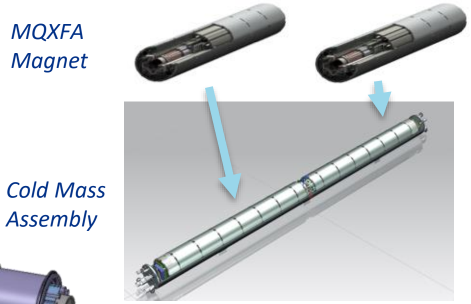


HL-LHC AUP Deliverable Scope Technical Details

- Q1/Q3 Cryoassembly

(10 CryoAssemblies with 20 Magnets)

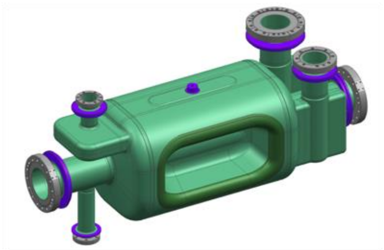




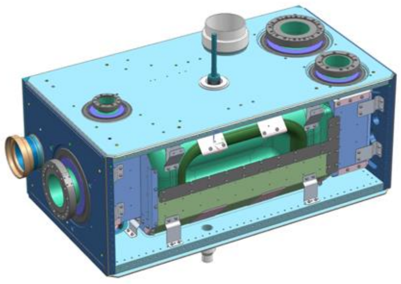
- Cable fabrication: LBNL
- Coil fabrication: BNL and FNAL
- Magnet assembly: LBNL
- Magnet vertical test: BNL
- Cold Mass + Cryo-assembly fabrication: FNAL
- Horizontal test: FNAL

- Dressed RFD Cavity

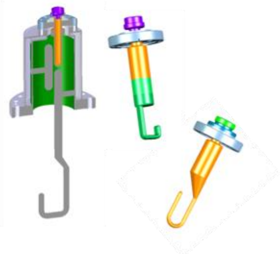
(10 Dressed Cavities & Ancillaries)



Bare RFD Cavity

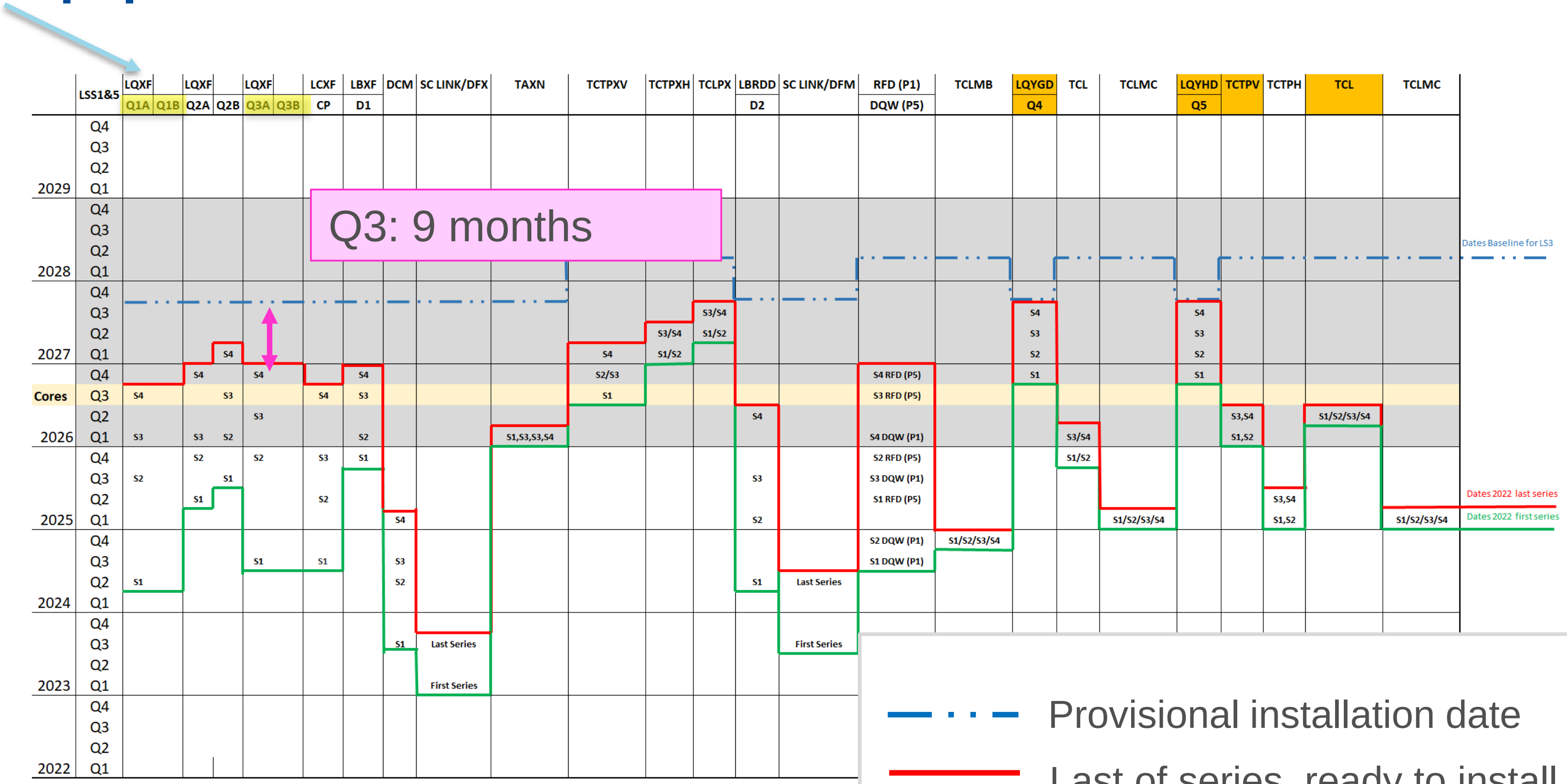


Dressed RFD Cavity
(front wall removed to show internal components)



RF Ancillaries

Equipment readiness for tunnel



Provisional installation date

Last of series, ready to install

First of series, ready to install

HL-LHC AUP Critical Decision (CD) Timeline

- ✓ CD-0: Achieved (April 2016)

  Approved Mission Need Statement

- ✓ CD-1/3a (Oct. 2017)

  Approved Cost and Schedule Range

  Approval for full procurement of Nb_3Sn strand.

- ✓ CD-2/3b (Feb. 2019)

  CD-2 approval of performance baseline

  CD-3b for construction approval of fraction of coils and magnets parts

- ✓ CD-3 (Dec. 2020)

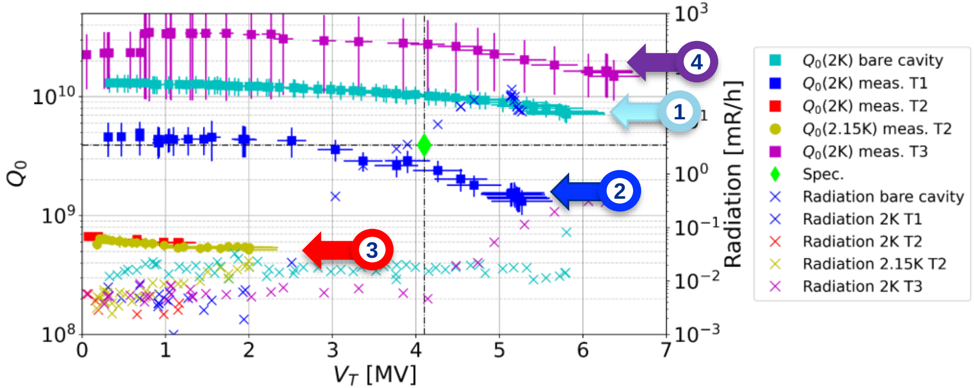
  Construction approval of remaining items (all coils and magnets, cold mass and cryo-assemblies, RFD cavities)

- ✓ CD3 Rebaseline (Dec. 2022)

  Approval for increased TPC to account for COVID/Abnormal Escalation Impacts

Technical Status – Crab cavities

#2 Bare Cavity (NRFDP002)



- This cavity exceeded acceptance requirements in the “bare” state at FNAL in 2021 (#1 above).
- Multiple tests at Jlab this year were hindered by challenges with vacuum leaks and RF losses (#2 & #3 above).
- Through a collaborative effort, we were able to progressively understand the root causes and implement corrective actions, which culminated finally in a successful test in August (#4 above).

Fermilab

Technical Status – Crab cavities

End-Caps

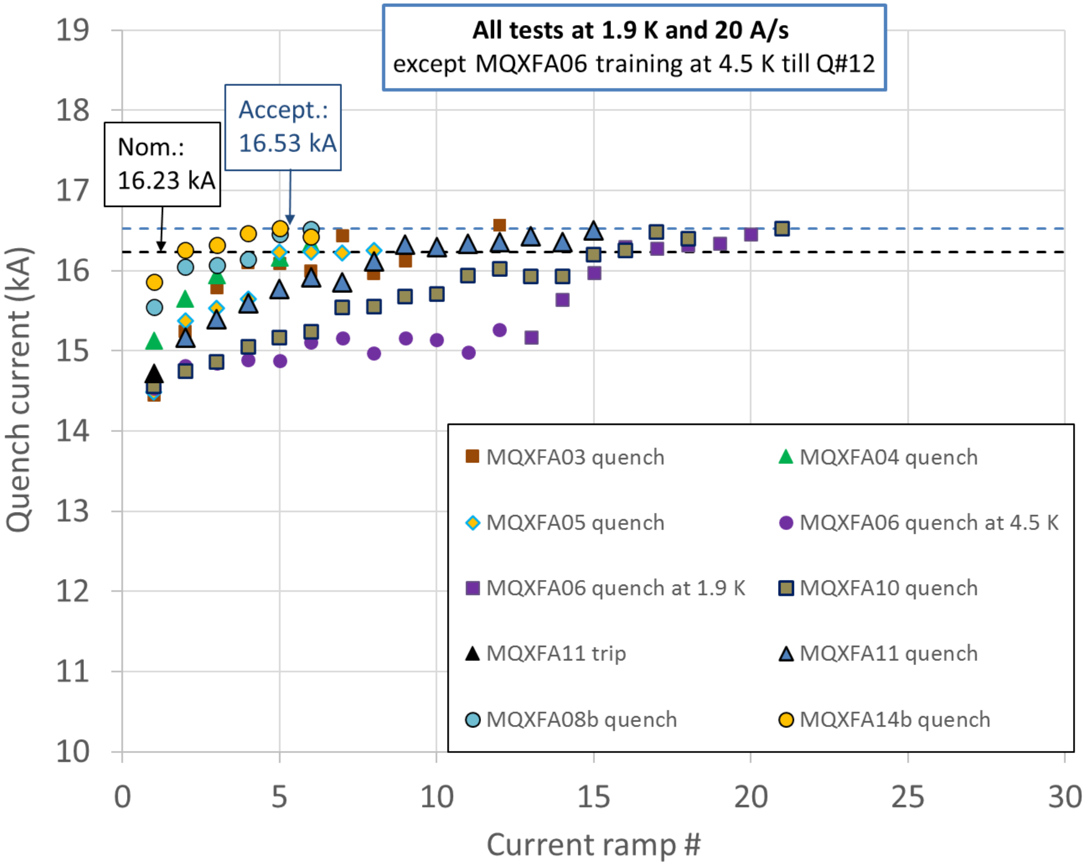
Deflecting poles

Pole Corners

RFD Series - Manufacturing at ZRI

- Series cavity fabrication in full swing, progressing not without surprises, with NCRs being managed successfully.
- Raw materials yield within estimates despite having to discard 6 poles due to residual issues with forming.

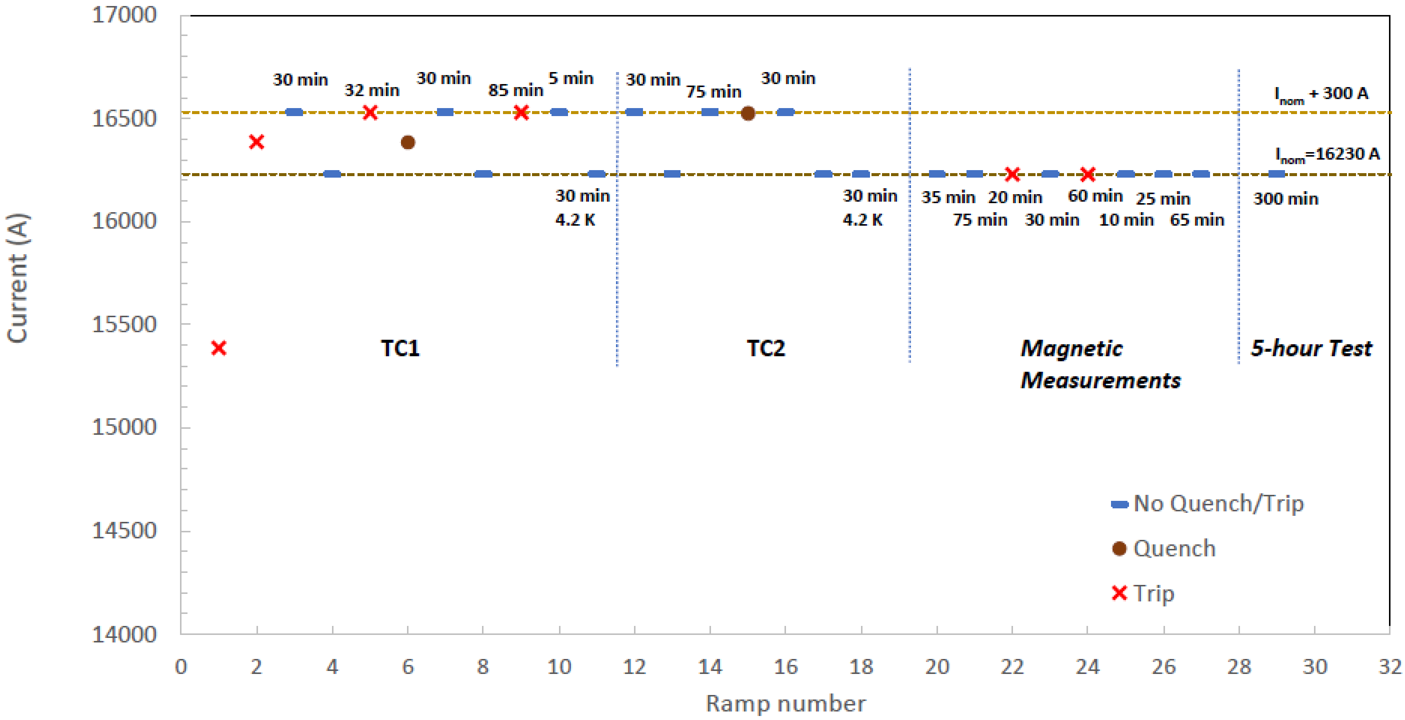
Technical Status – MQXFA Magnets



- 9 Accepted Magnets after vertical test at BNL out of 12 tested
- 16 Magnets produced (~60% of deliverables), coils at ~95%, cables at ~99%
- MQXFA05 underwent endurance test with 50+ induced quenches.
- MQXFA08b 1st reworked magnet successfully tested

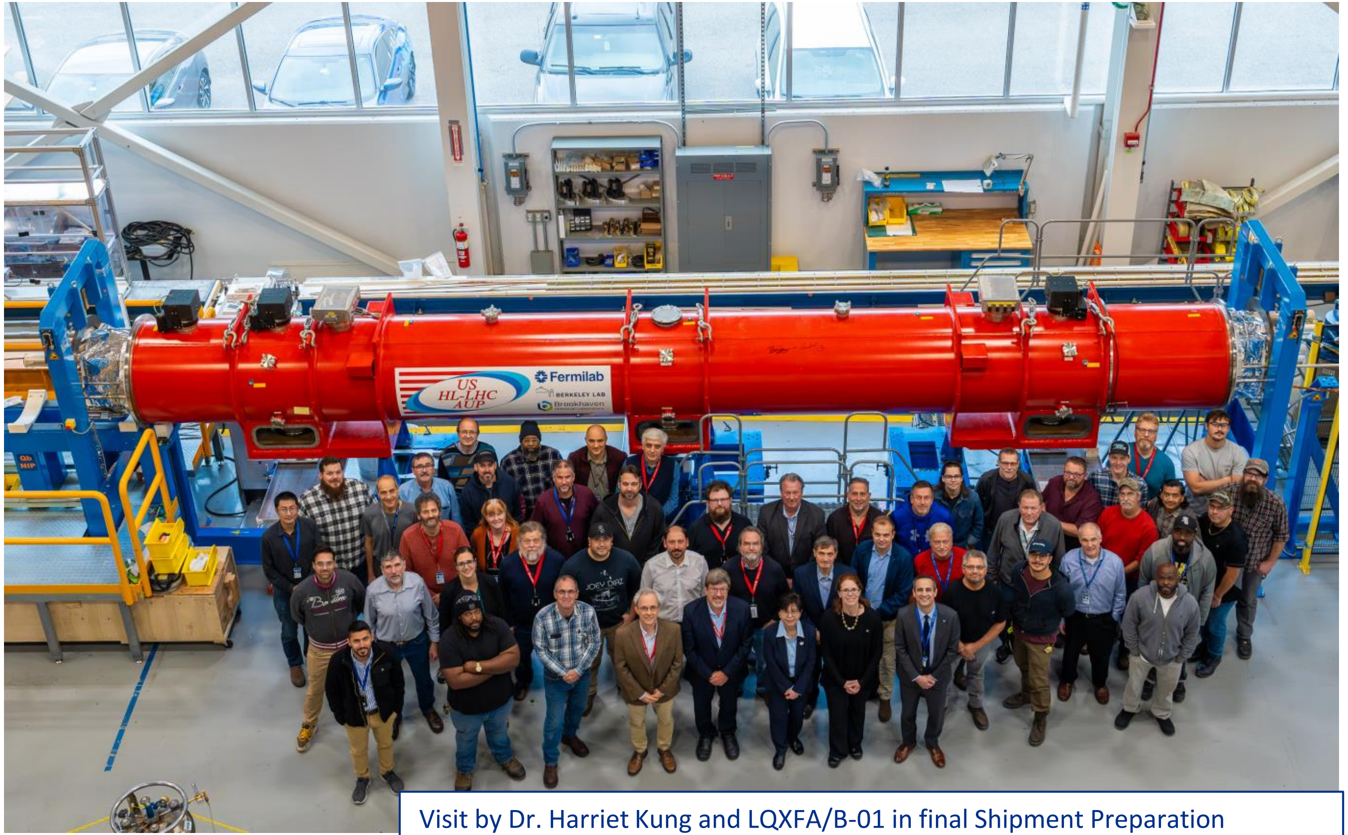
LQXFA01 quench performance

- Test performed successfully at FNAL



Fermilab

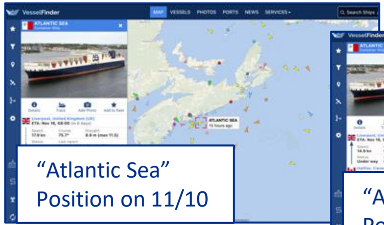
H. Kung visit to FNAL



Visit by Dr. Harriet Kung and LQXFA/B-01 in final Shipment Preparation

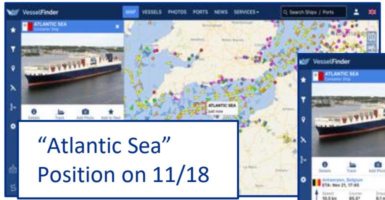
LQXFA/B-01 Delivery

Oct. 30th 2023

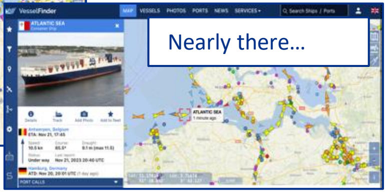


“Atlantic Sea” Position on 11/10

“Atlantic Sea” Position on 11/15



“Atlantic Sea” Position on 11/18



Nearly there…

Nov. 22th 2023

- LQXFA/B-01 at CERN, being prepared for Horizontal Test in SM18.

Delivery Dates to CERN

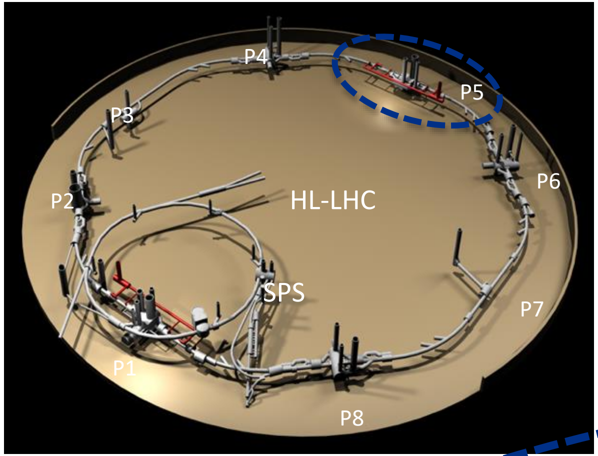
Assembly Optimistic Delivery Dates

	Agreed Early Delivery Date	July 2023 Success Oriented Schedule	Agreed Late Delivery Dates
Q1/Q3 Delivery 01	Nov-23		Oct-24
Q1/Q3 Delivery 02	Jun-24		May-25
Q1/Q3 Delivery 03	Aug-24	Oct-24	Jul-25
Q1/Q3 Delivery 04	Nov-24	Jan-25	Oct-25
Q1/Q3 Delivery 05	Mar-25	May-25	Feb-26
Q1/Q3 Delivery 06	Jun-25	Aug-25	May-26
Q1/Q3 Delivery 07	Aug-25	Oct-25	Jul-26
Q1/Q3 Delivery 08	Nov-25	Jan-26	Oct-26
Q1/Q3 Delivery 09	Apr-26		Mar-27
Q1/Q3 Delivery 10	Aug-26		Jul-27

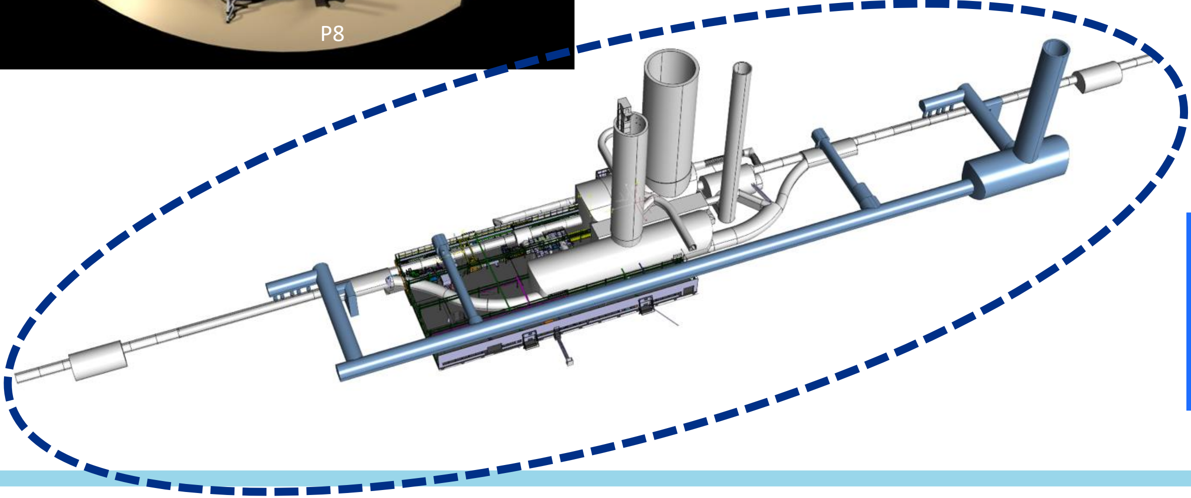
Cavity Optimistic Delivery Dates

	Agreed Early Delivery Date	July 2023 Success Oriented Schedule	Agreed Late Delivery Dates
Cavities 01 & 02	May-24		Apr-25
Cavities 03 & 04	Jul-24	Sep-24	Jun-25
Cavities 05 & 06	Aug-24	Nov-24	Jul-25
Cavities 07 & 08	Oct-24	Jan-25	Sep-25
Cavities 09 & 10	Nov-24	Mar-25	Oct-25

HL-LHC IT STRING: P5L



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 andof the superconducting link, magnet powering, vacuum, alignment, interconnections between magnets, and the superconducting link itself).



CA installation end 2024

The first important results on the collective behaviour is expected at the end of the first thermal cycle: by May 2026.

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Fermilab

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."

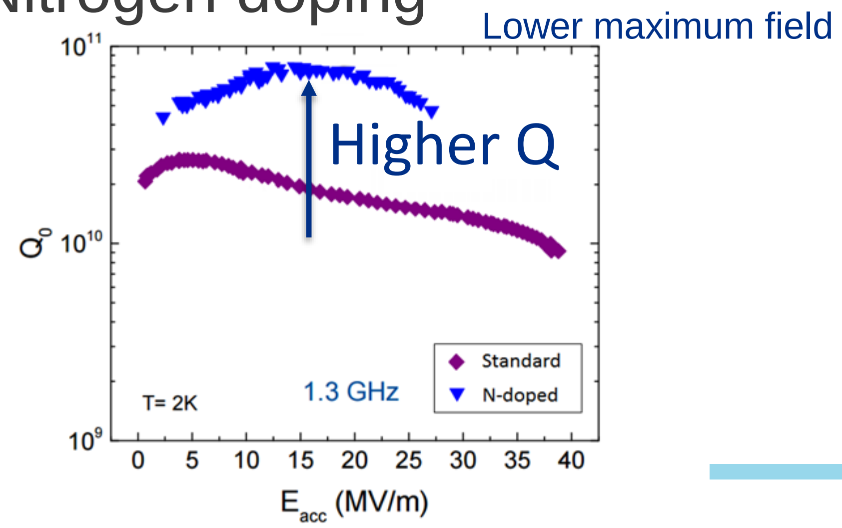
Courtesy of Pushpa Bhat

Summarizing SRF needs for potential future colliders

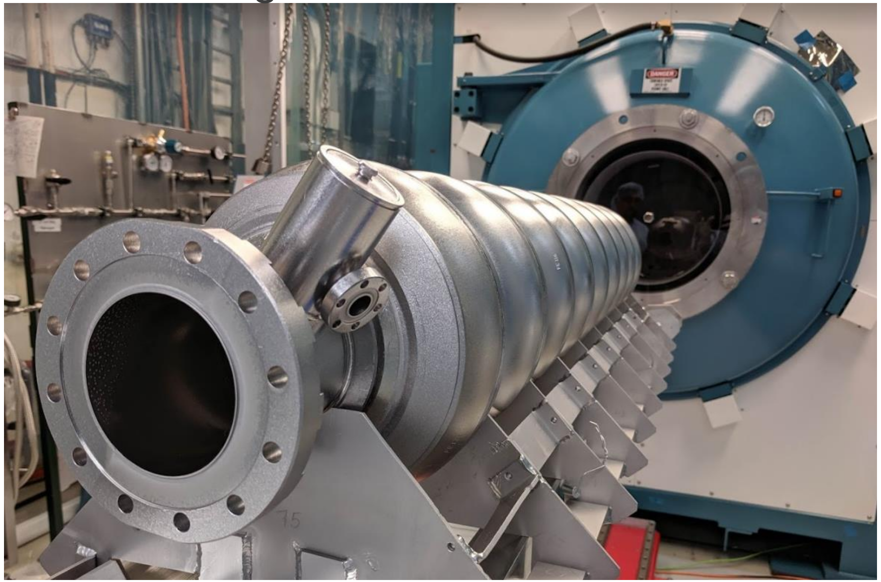
In general . . .

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

Nitrogen doping



Nb_3Sn cavities



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

Need to ramp up R&D NOW!

Challenges

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

Opportunities

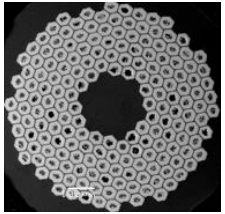
- HTS
- Fusion driving REBCO cost


U.S. MAGNET DEVELOPMENT PROGRAM
BERKELEY LAB
Brookhaven National Laboratory
Fermilab
ASC

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

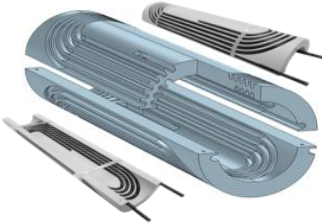
- 15 T dipole; stress management (SM) structures for coils in magnets above 16T (16-20 T)

HTS

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

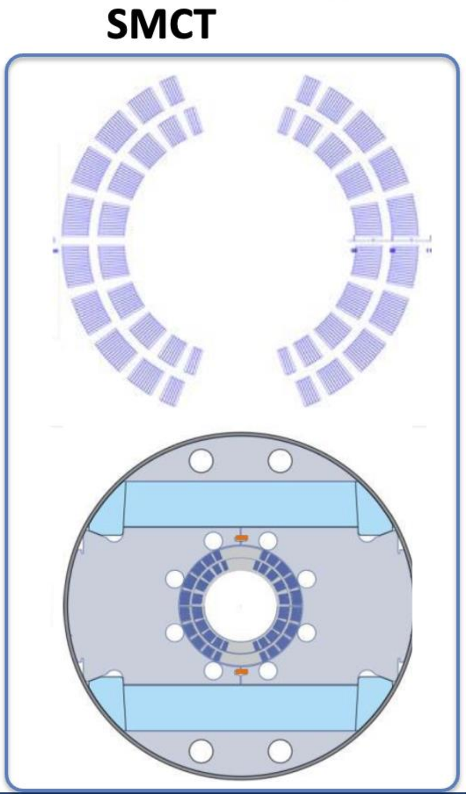
Technology R&D

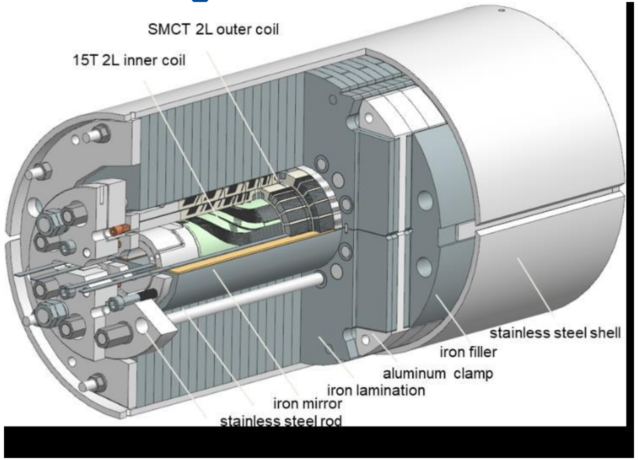
- Training and diagnostics – fibers as strain gauges, training studies and QCD device
- Instrumentation and quench protection - new accurate quench antennas, fibers for HTS QP
- Material studies - new epoxy and insulation material tests, high-Cp materials in cable and epoxy
- Modeling and simulation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



Exploring stress management configurations: Nb_3Sn

- Stress-managed Cosine Theta:
  - 2 layers
    - Bore field of 11 T
    - Bore diameter: 120mm

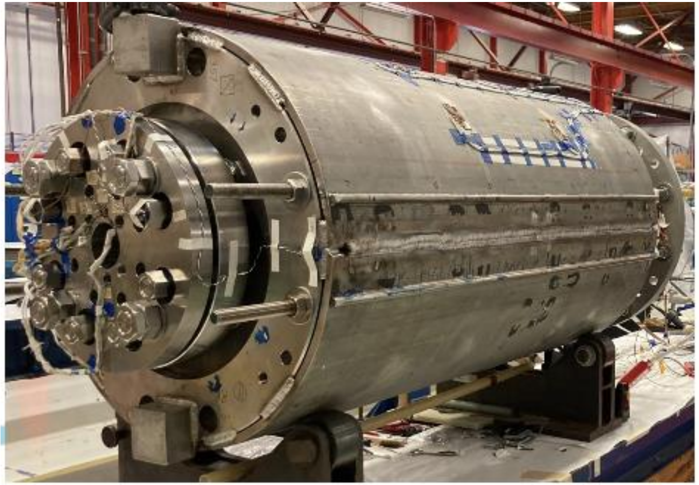




Test at 1.9 K of 4-layer mirror magnet is ongoing

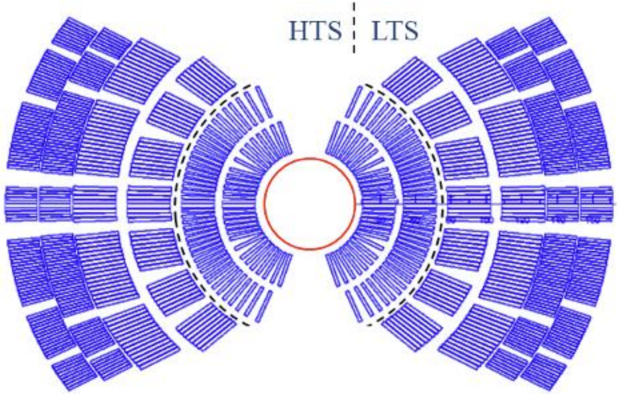
- SMCT 2L outer coil
- 15 T 2L inner coil

Nb3Sn: High field dipole



14.5 T Nb_3Sn dipole

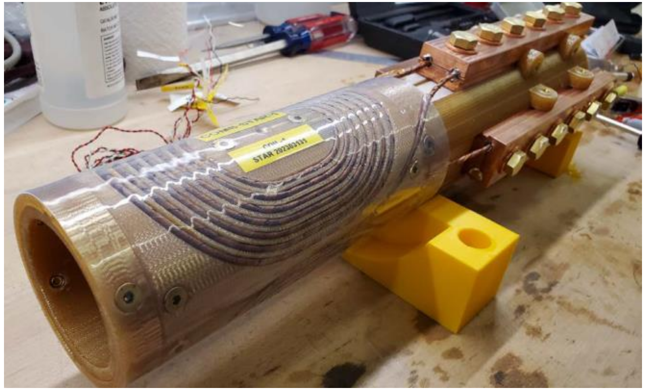
Part of US Magnet Development Program (MDP)



Goal: Hybrids magnets
To reach 20 T

Bi-2212 and REBCO accelerator magnet R&D

REBCO

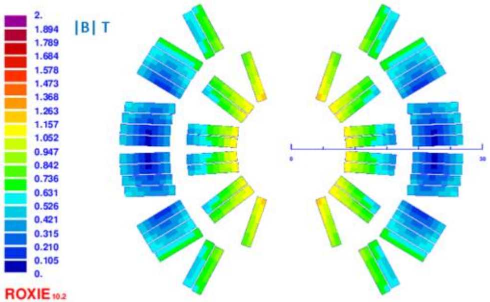


HTS dipole (60 mm clear bore) has been fabricated for Hybrid superconducting magnet and will be tested in January 2023

CORC/ STAR wire: selection of high-performance tapes/ very expensive

- Test in liquid Nitrogen was successful
- Test in liquid He is under preparation

REBCO tape stack: leverage fusion REBCO tape production



HTS-Bi-2212 insert magnetic design

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Conclusion: LHC and HL-LHC

LHC:

•First 2024 beam expected in the LHC on 11 March: 2024 baseline schedule available

- The 5.5 weeks of Pb ion running to be shared over 2024 and 2025 with a Pb ion run at the end of each year.
- The Oxygen ion run to be moved from 2024 to 2025
- At present there are discussions on the timing of the p-p ref run remaining

AUP HL-LHC

•**Crab cavities:**

- Pre-Series cavities completed at Zanon with improved quality compared to prototypes. Cold tests ~ Jan-Feb 2024.
- Series cavities reaching peak production without showstoppers.

•**Magnets and Cryo-assemblies:**

- Magnet assembly at peak production at LBNL. Coil fabrication at BNL and FNAL to be completed shortly.
- MQXFA07b is being tested at BNL. MQXFA15 at BNL as well.
- MQXFA16 (untested) at FNAL for CM05
- LQXFA/B-02 Cold Mass in final steps of assembly
- LQXFA/B-01 at CERN.

Conclusions

The 2023 P5 report aligns strongly with the U.S. HEP community's aspirations and recommends vigorous R&D towards future colliders, emphasizing to plan for a 10 TeV Muon Collider at Fermilab.

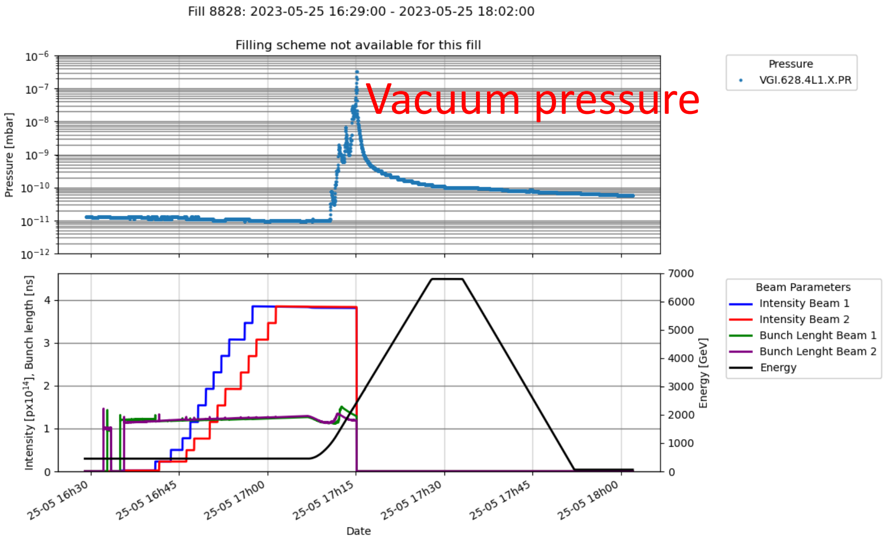
Nb_3Sn Technology is mature but not easy

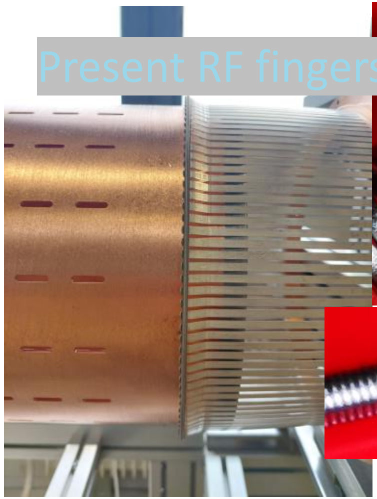
- Needs to be more robust and affordable.
- 16 - 17T operating field is a real challenge for future hadron colliders
- Demonstrate technology for large-scale accelerator deployment: **this is the time to develop cost-effective design & technolog**

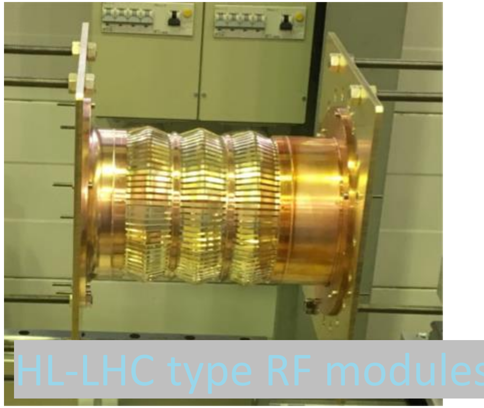
HTS is at its infancy but has a great potential and many challenge:

- Enabling technology for magnets with fields > 16 T (magnet architecture/ conductor degradation)
- Higher temperature margin and stability (quench detection and protection)
- Operation at higher temperature (dry-cooling, He gas cooling, LH2, LN2): find optimum temperature

Collaborations / Partnerships / Members [19.5pt Bold]

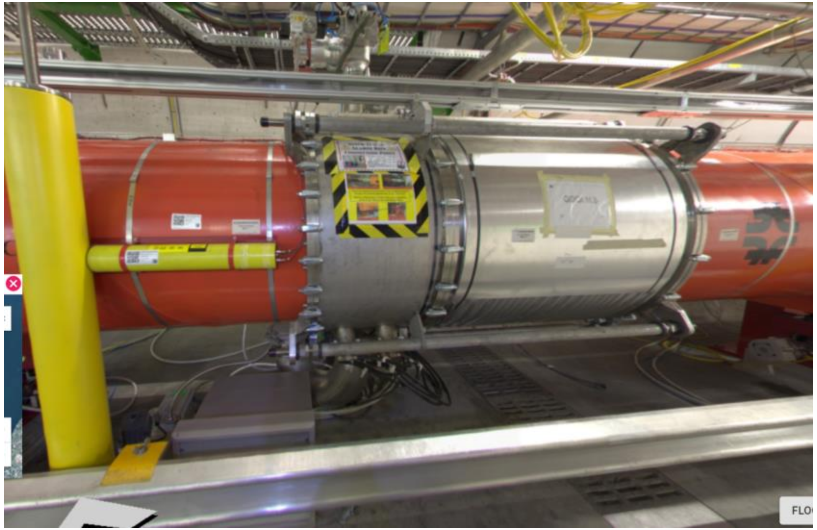


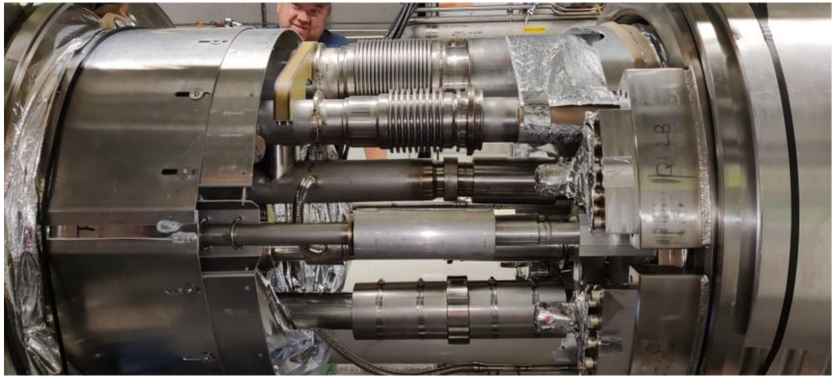


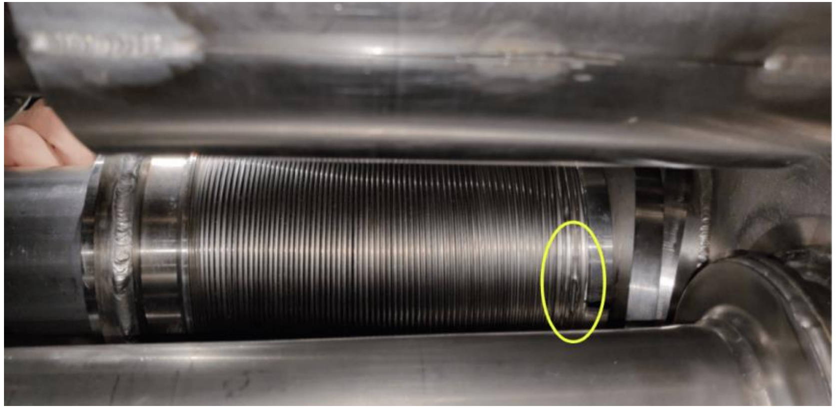


Vacuum pressure spikes during the ramp with beam dump due to losses

- Limiting bunch intensity to 1.6x10^{11} p/b
- Will partly be addressed during Year End Technical Stop 23-24







- A small hole (1 mm^2) in an edge welded bellow with major consequences
- Thinking out of the box by expert teams allowed for a restart in 2023
- Photo story in CERN Bulletin

Nb_3Sn accelerator magnet: a road map for success

LARP = US LHC Accelerator Research Program (2003-2018)
AUP = US HL-LHC Accelerator Upgrade Project (2016 – present)

20+ Yrs

- Mini-series (20) Production
- Full Length Prototypes (3+
- Short Models Basic R&D (conductor, other materials, magnetic & structural design, …)

In this field range (12-14 T) <u>now</u> we can develop cost-effective design & technology

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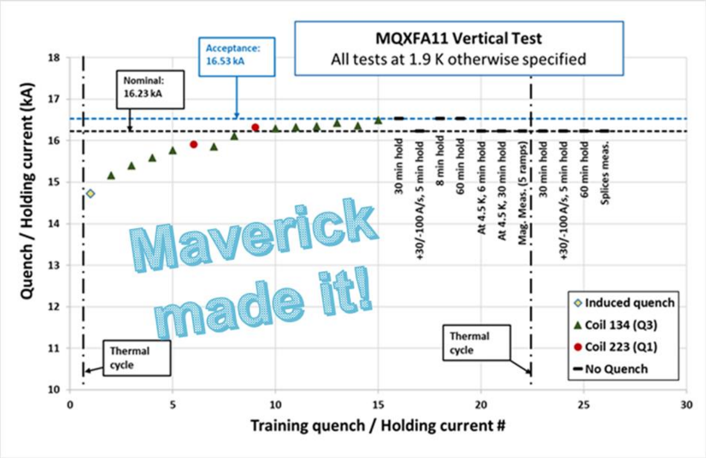
MQXFA11 truck incident

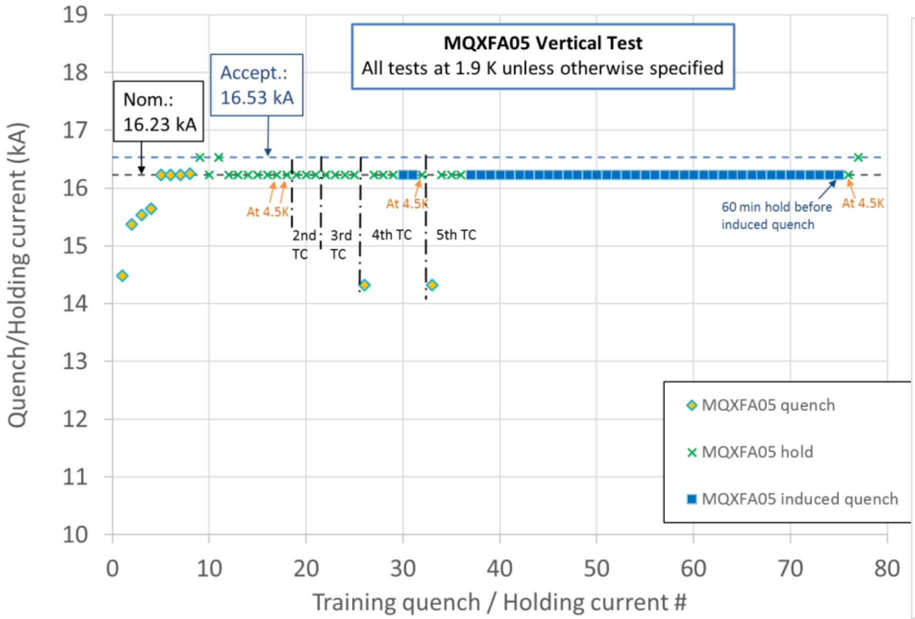
- The truck transporting the MQXFA11 magnet from LBNL to BNL was rear ended by another truck on 7/20/22.
- The main hit took place on the right back corner. During the incident the truck rear axle disengaged as displayed below.
- The magnet was moved to FNAL on 7/28/22. Upon arrival a visual inspection was performed followed by electrical checkout, metrology survey, analysis of the fiber optic sensors and accelerometer data analysis
  - Max shock: 6 or 10 g vertical (depending on the device in the same accelerometer unit)
  - Duration: 5 ms
- All tests and analyses were OK. Magnet was shipped to BNL

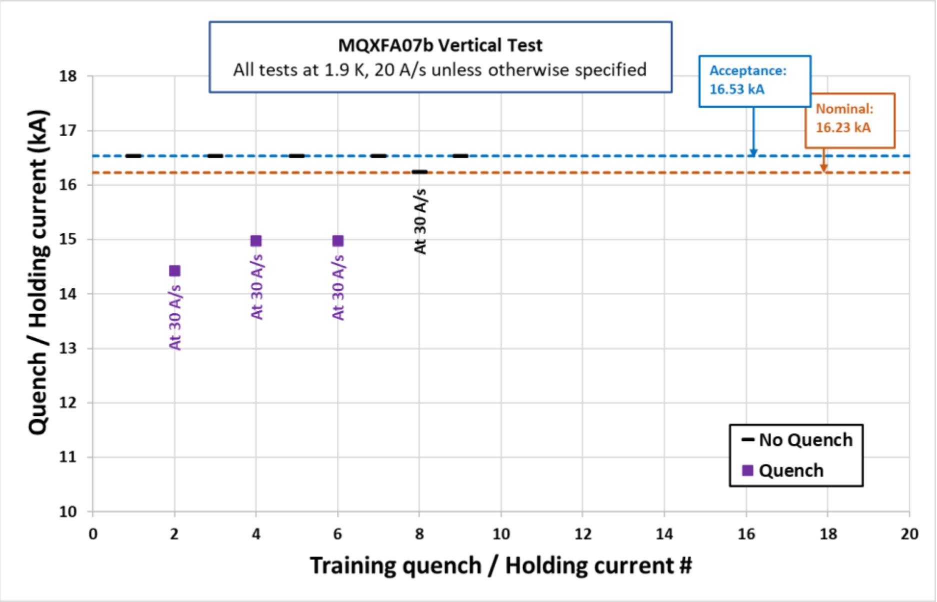


Courtesy of T. Cruise


No Personal Injury to driver

Technical Status – MQXFA Magnets





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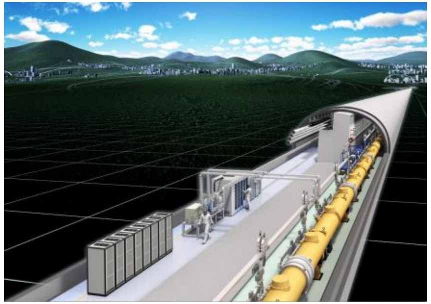
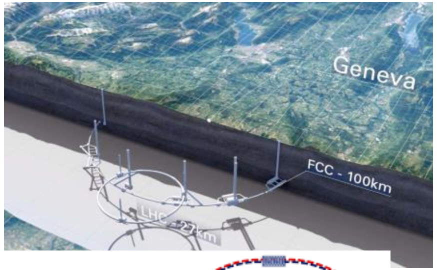
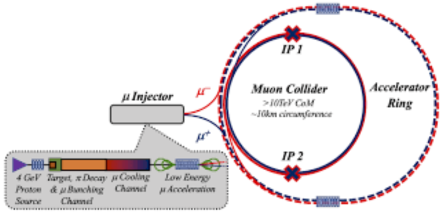
U.S. Engagement in Global Projects



- The International Linear Collider
  - U.S. scientists engaged in efforts of the ILC-IDT (ILC International Development Team)
    - SRF R&D for ILC main linacs and ILC++
    - Polarized Positron Source and Damping Ring, ..
- Future Circular Colliders (FCC-ee/hh)
  - CERN conducting Technical and financial feasibility studies; Final report by ~2025-26
  - CERN/DOE agreement signed in Dec. 2020
    - Opportunities for engineering design studies, beam physics studies, High Q_0 SRF R&D, magnet R&D,..



- Muon Collider Collaboration
  - Intense work in progress in the International Muon collider Collaboration; US community engag
    - Machine scenarios, beam induced background, neutrino radiation, demonstrator facility, detector/physics studies
    - Exploring formal U.S. engagement



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Fermilab APS TD activities and R&D

- Projects
  - Mu2e
  - Proton Improvement Project II (PIP II)
  - Accelerator Upgrade Project (AUP)

- Superconducting RF R&D –

- Superconducting Magnet R&D –
    - Nb_3Sn stress limiting structures
  - High Temperature Superconductors (Bi-2212 and REBCO)
  - Conductor developments

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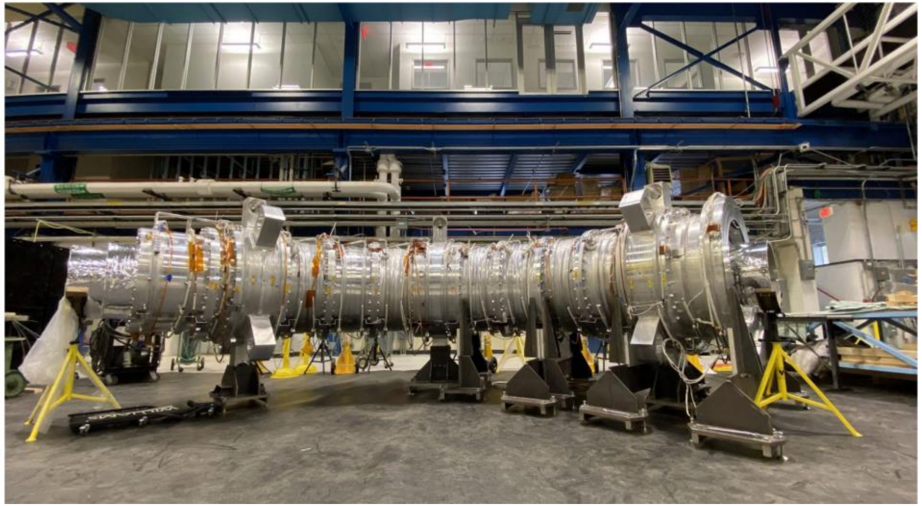
Accelerator Technology: 2023 Fermilab highlights

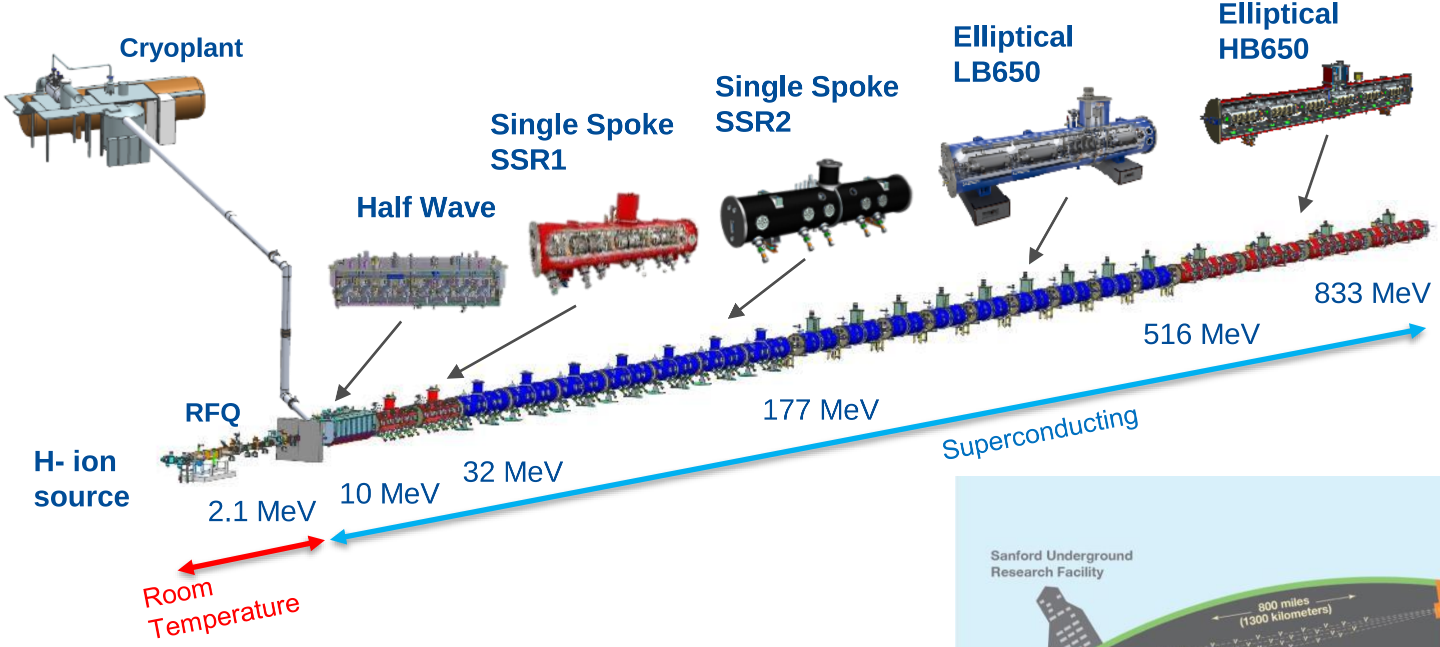
Nb_3Sn Interaction Region Quadrupoles for Hi-Lumi LHC Upgrade

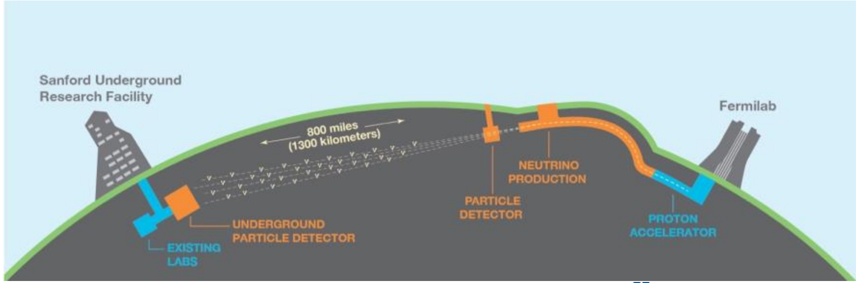
Mu2e: Transport solenoid completed and moved to experimental hall



Accelerator Technology: 2023 Fermilab highlights

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





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SSR1
PROTONS ACCELERATED UP TO 148,876,891 MPH
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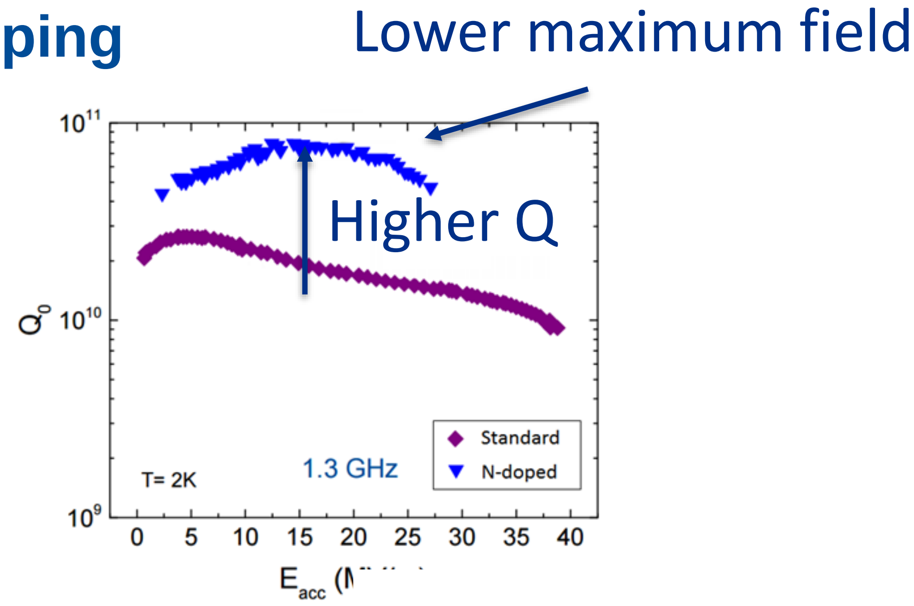
Superconducting RF: Nitrogen Doping



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

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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

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