U.S. Activities for HL-LHC

G. Apollinari
LARP Director

HEPAP Meeting
December 9th – 11th, 2015

Content

- Status and Progress of *LARP*
  - 2015 Achievements
  - 2016 Goals
  - New Toohig Fellows
  - “LARP+” Program

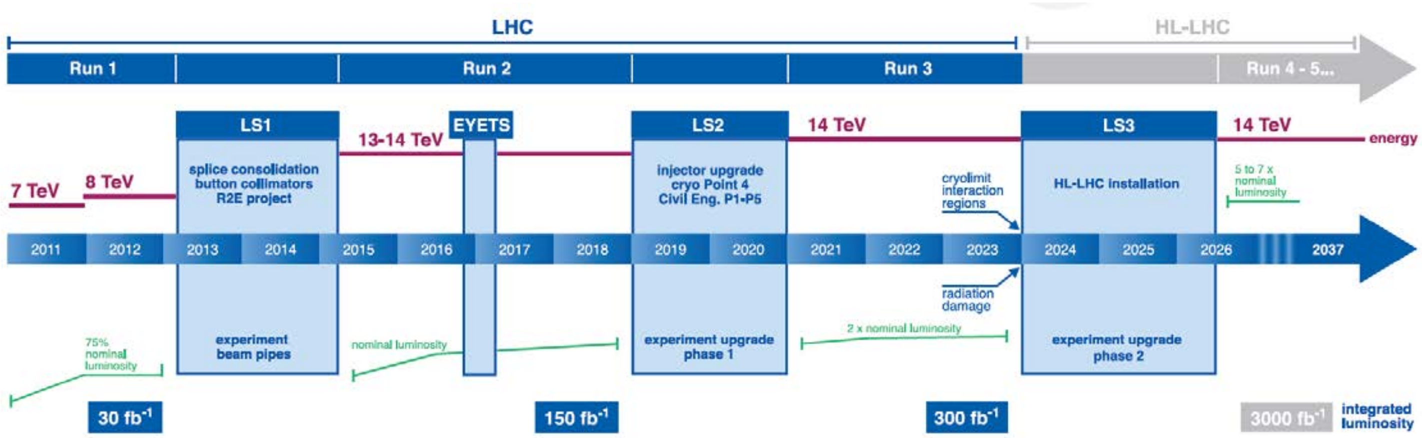
- Transition to *US-HiLumi*
  - Definition of Deliverables
  - Functional and Technical Specs
  - Preliminary Funding Profile
  - Conceptual US-HiLumi Schedule

LARP History and Evolution

- The US LHC Accelerator Research Program (LARP) was formed in 2003 to coordinate US R&D related to the LHC accelerator and injector chain at Fermilab, Brookhaven, Berkeley and SLAC.
  - Has involvement from Jefferson Lab, Old Dominion University and UT Austin
- LARP has contributed to the initial operation of the LHC, but much of the program is focused on future upgrades
  - Increase Luminosity (HL-LHC)
  - Beam Handling/Monitoring
- The program funding increased from $12-13M/year (FY13) to ~15.5 M$ (FY16 Guidance)
  - Magnet research (~half of program in FY13, ~75% in FY15)
  - Accelerator research (Crab cavities, WBFS, Collimators, e-hollow lens,..)
  - Programmatic activities, including support for Toohig Fellowship
- FY14-FY18 Evolution
  - Initial convergences on deliverables for HL-LHC
  - <u>Program to be handled like a “project” to *Reduce Risk* of US Contributions to HL-LHC Project</u>

From LHC to HL-LHC

- LHC operating at 6.5 TeV
- In the period 2015-2023
  - Peak luminosity of $2 \cdot 10^{34}$ cm^{-2}s^{-1}
  - Integrated luminosity of 300 fb^{-1}
- HL - LHC
  - Upgrade the Interaction Region in 2024-2026
  - Peak luminosity of $5 \cdot 10^{34}$ cm^{-2}s^{-1}
  - 3000 fb^{-1} integrated luminosity in following ~12 years



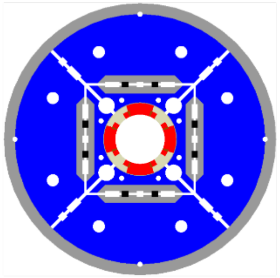
HL-LHC in a Nutshell

$$L = \gamma \frac{n_b N^2 f_{rev}}{4\pi \beta^* \varepsilon_n} R; \quad R = 1 / \sqrt{1 + \frac{\theta_c \sigma_z}{2\sigma}}$$

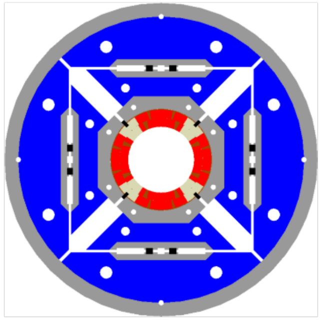
1. More Luminosity: increase squeeze at interaction region
   - Increase magnet aperture, therefore increase field.
   - Use Nb_3Sn Technology as *Baseline*
2. More beam: larger beam-beam interactions in region where they are brought close together.
   - Solution 1: keep beam as separated as possible increasing crossing angle from 300 μrad to 600 μrad. Use Crab Cavities as *Baseline*
   - Solution 2 (Plan B): If solution 1 does not work, reduce crossing to 300 mrad and mitigate beam-beam interaction with Long Range Beam Beam Wire or hollow e-lens (*R&D effort, soon to Baseline*).
   - Control possible transverse instabilities or e-cloud effects with Wide Band Feedback System (*R&D effort*).

LARP History on Focusing Quads

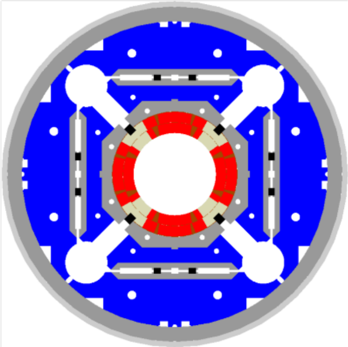
- LHC Accelerator Research Program (since 2003)
  - R&D on Nb_3Sn quadrupoles for LHC luminosity upgrade
- From TQ/LQ series to MQXF
  - From 90 to 150 mm
- MQXF scale-up of HQ
  - Similar coil lay-out
  - Same structure concept
  - Successfully tested



LARP TQ-LQ
Nb_3Sn, 1-3.7 m
90 mm apert.
200 T/m



LARP HQ
Nb_3Sn, 1 m
120 mm apert.
170 T/m

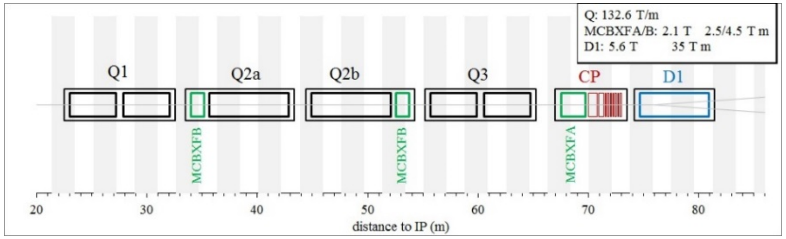


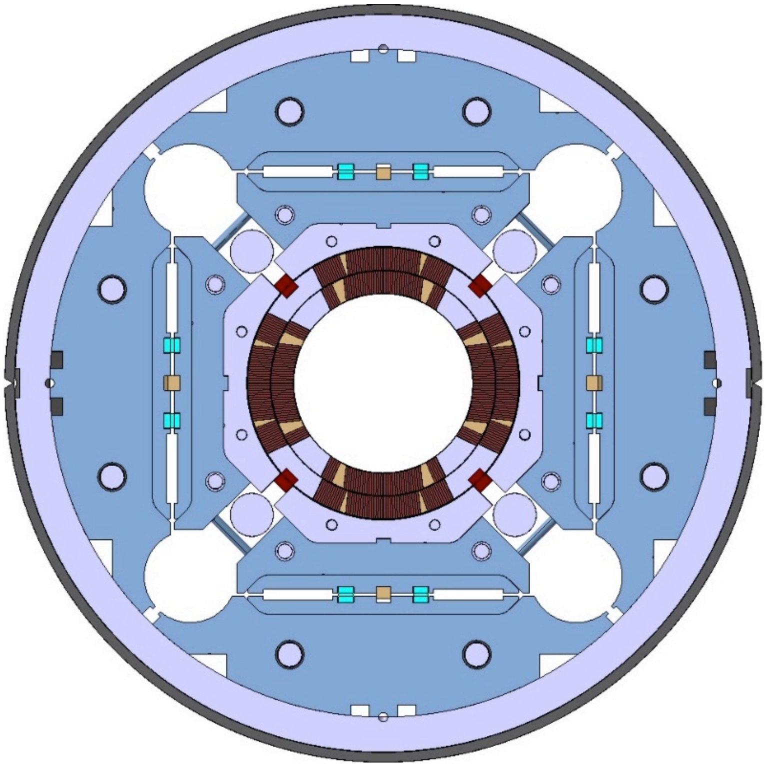
LARP-CERN MQXF
Nb_3Sn, 1.5 m
150 mm apert.
132.6 T/m

HL-LHC low-β quadrupole

- Target: 132.6 T/m
  - 150 mm coil aperture, 11.4 T B_{peak}
- Q1/Q3 (by *US-HiLumi* Project)
  - 2 magnets MQXFA with 4.2 m
- Q2a/Q2b (by CERN)
  - 1 magnet MQXFB with 7.15 m
- Different lengths, same design

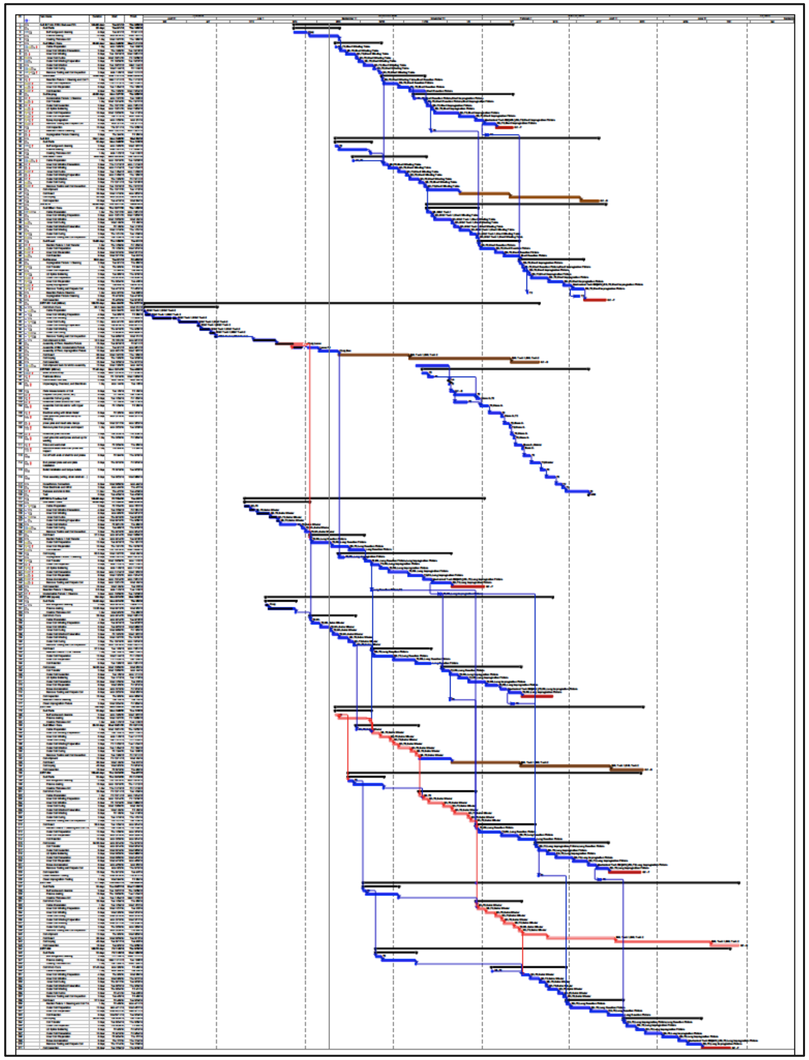
- Short model phase in progress
- Long prototype fabrication started
  - Handled as *"Project"* by LARP



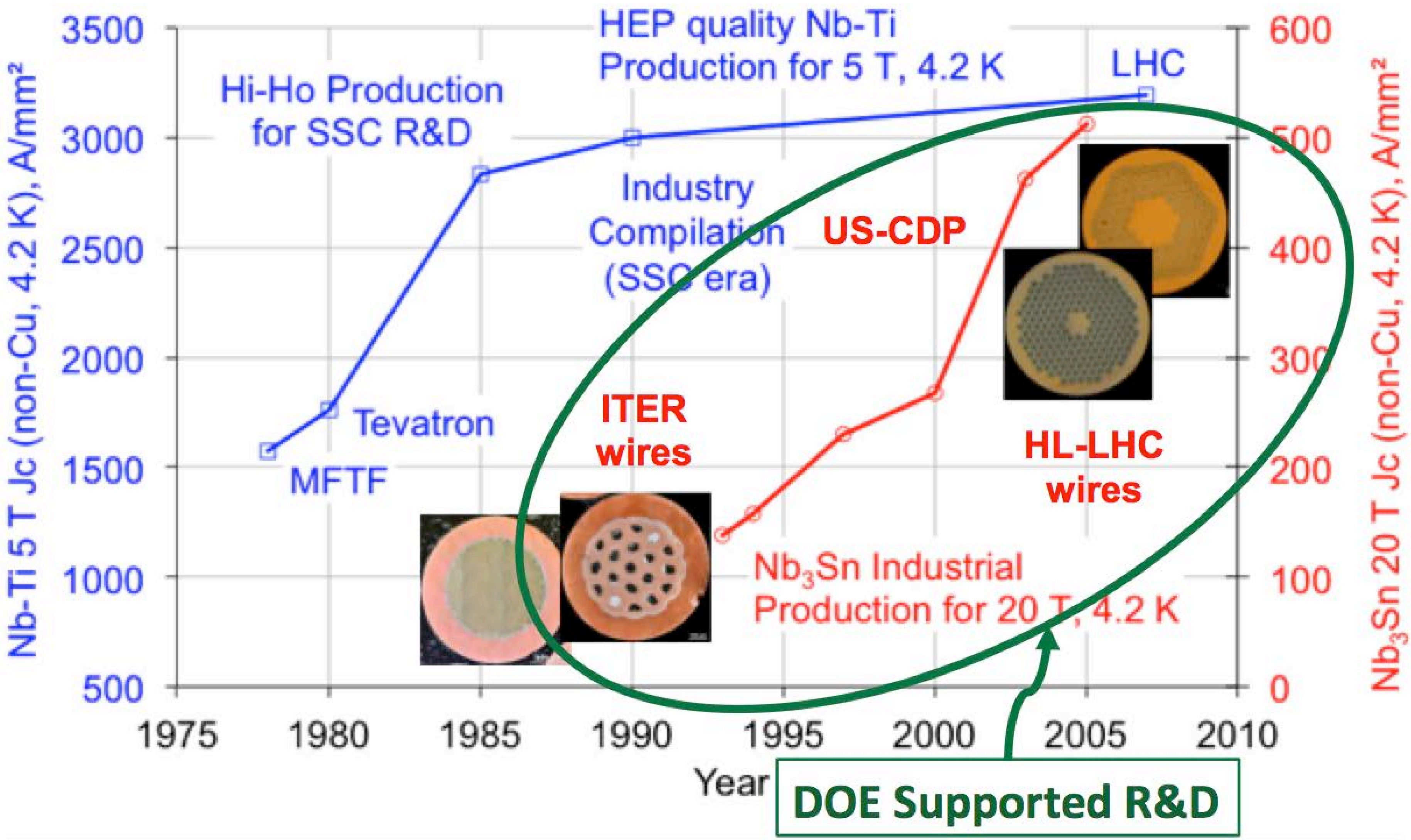


FY16 Goals: Complete First Long (4 m) MQXF Quad

- Complete first long (4m) quadrupole in US
  - Coil winding at FNAL
  - Reaction/impregrantion shared with BNL
  - Structure Procurement and Assembly at LBL
    - Summer 2015 Internal LARP Review with full participation from CERN
  - Test by early FY17
- Magnet assembly treated as Project with "poor-man" EVMS to confirm effort estimates for US-HiLumi Project
- <u>Overall Goal: complete 2 long prototype by early FY18 (CD-3)</u>



At 54, LTS's Have Reached ~~Maturity~~ Splendor!



Conductor Procurement

U.S. HiLumi Project	Specification for Quadrupole Magnet Conductor	US-HiLumi-doc.40 Rev. No. Original Release Date: 04-May-2015 Page 15 of 15

ANNEX – SUMMARY OF PERFORMANCE REQUIREMENTS

Parameter or characteristic	Value	Unit
Superconductor composition	Ti-alloyed Nb_3Sn	
Strand Diameter	0.850 ± 0.003	mm
Critical current at 4.2 K and 12 T	> 632	A
Critical current at 4.2 K and 15 T	> 331	A
n-value at 15 T	> 30	
Count of sub-elements (Equivalent sub-element diameter)	≥ 108 (< 55)	(µm)
Cu : Non-Cu volume Ratio Variation around mean	≥ 1.2 ± 0.1	
Residual Resistance Ratio *RRR* for reacted final-size strand	≥ 150	
Magnetization* at 3 T, 4.2 K	< 240 (< 300)	kA m^{-1} (mT)
Twist Pitch	19.0 ± 3.0	mm
Twist Direction	Right-hand screw	
Strand Spring Back	< 720	arc degrees
Minimum piece length	550	m
High temperature HT duration	≥ 40	Hours
Total heat treatment duration from start of ramp to power off and furnace cool	≤ 240	Hours
Heat treatment heating ramp rate	≤ 50	°C per hour
Rolled strand (0.72 mm thk.) critical current at 4.2 K and 12 T	> 600	A
Rolled strand *RRR* after reaction	> 100	

*Magnetic moment (A m^2) divided by the volume (m^3) of a strand piece in transverse magnetic field, without removing copper

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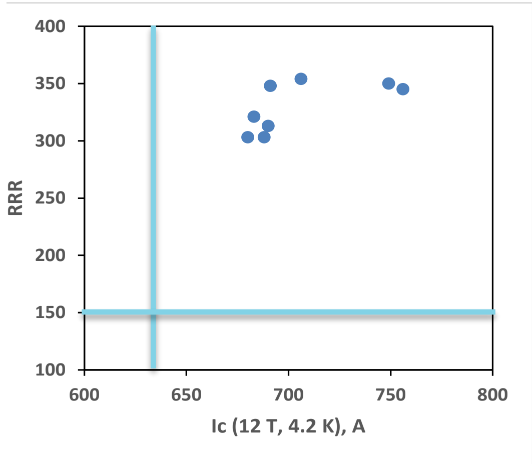
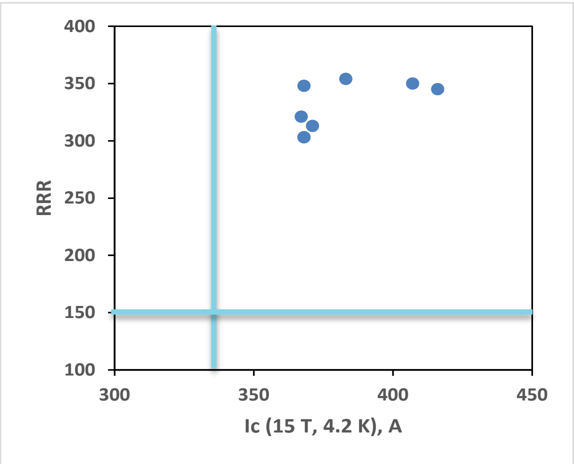
- Convergence on 108/127 based on performance and cost analysis (May'15)
- Common specs US-LARP/CERN
- Order placed by FNAL for ~200 km in Sep '15
  - ~10% of US needs for full Project
- First data from OST very promising.
  - Lab verification in progress

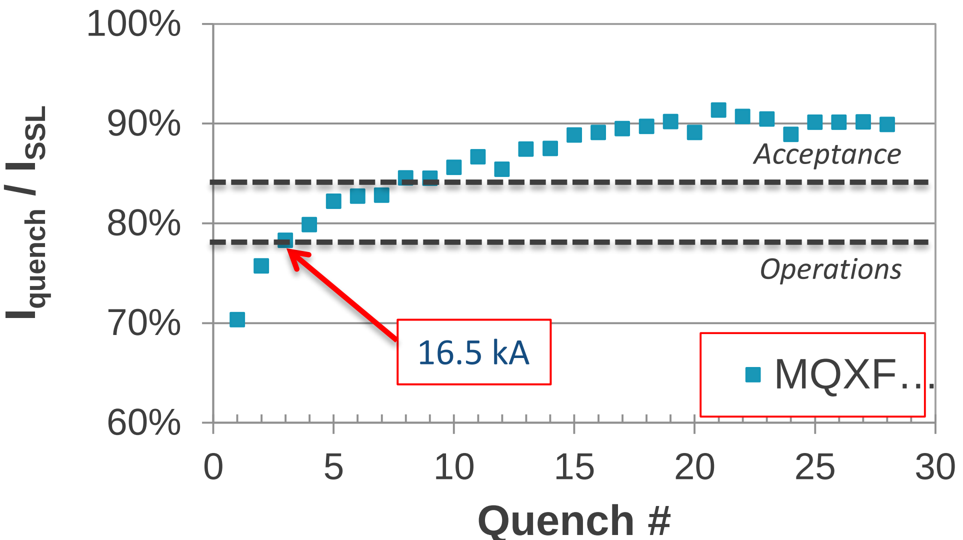




Successful Test of First MQXF Coil

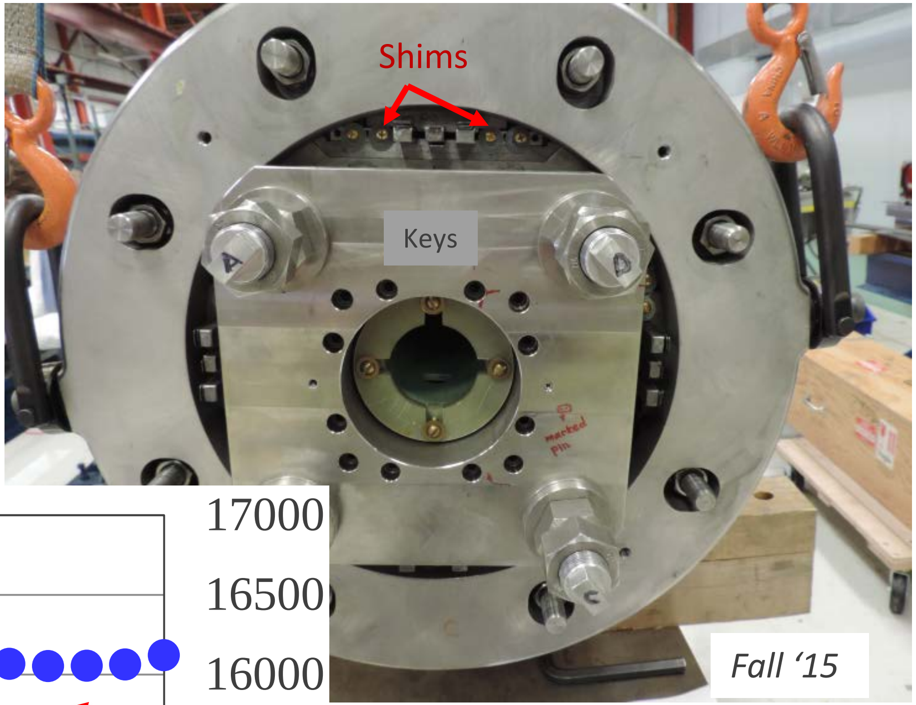
- First model coil for HL-LHC magnets assembled and tested in mirror configuration at FNAL. The Mirror Magnet was tested in the IB1 Vertical Magnet Test Facility using for the first time an upgraded 30kA setup.
  - Higher current needed for higher-performing Nb_3Sn magnets

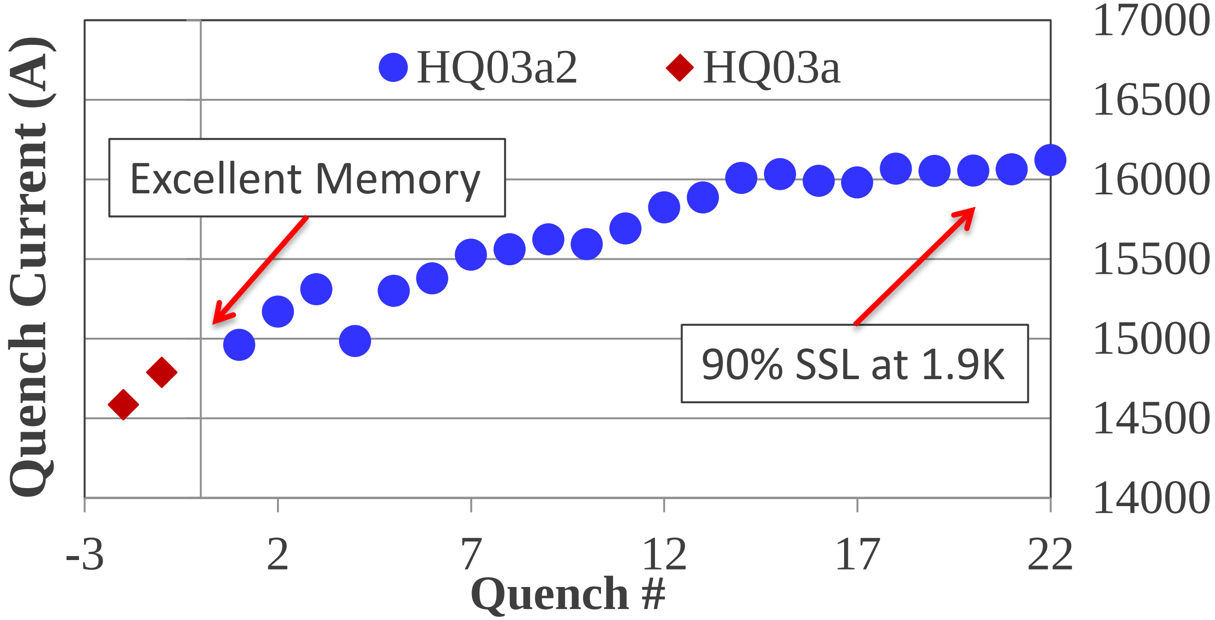
- Coil achieved HL-LHC "operating current" (16.5kA) in 3 quenches during the first day of testing !



Successful Test of HQ03a

- 120 mm Aperture
  - Excellent Memory
  - Achieved 90% SSL at 1.9K, 98% at 4.5K.
  - The shims achieved expected change the b3 and b5 harmonics with little effect on other harmonics.

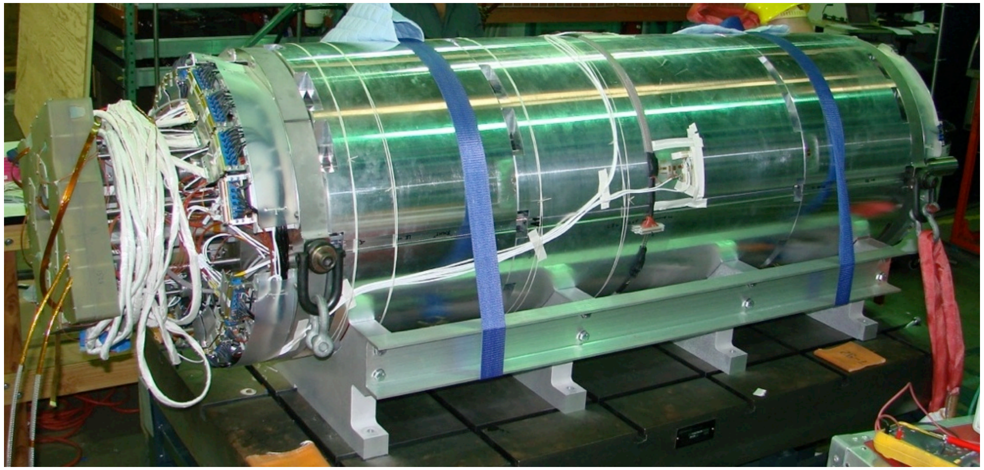


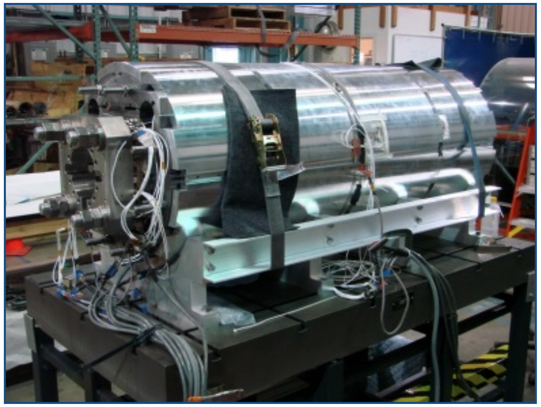


Successful Assembly of First MQXFS

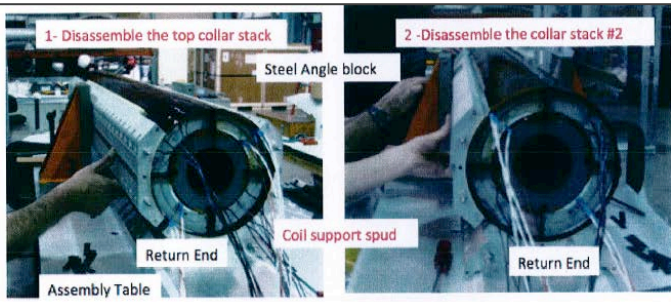
- Two identical structure assembled and pre-loaded with aluminium coils at LBNL and CERN, and then with real coils at LBNL

- Component instrumented with strain gauges
  - Very good agreement with calculations

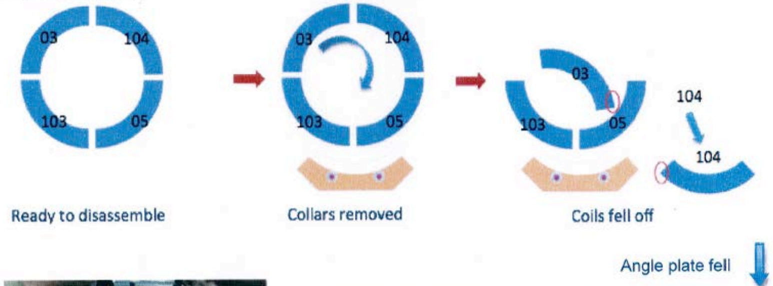


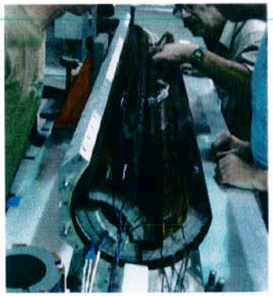


Assembly Mishap during MQXFS1



Sequence of events





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LARP Magnet Coil Investigation and Apparent Cause Analysis

Prepared By:

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Marshall Granados, Engineering Division Causal Analyst	(signature)	10-9-15 (date)
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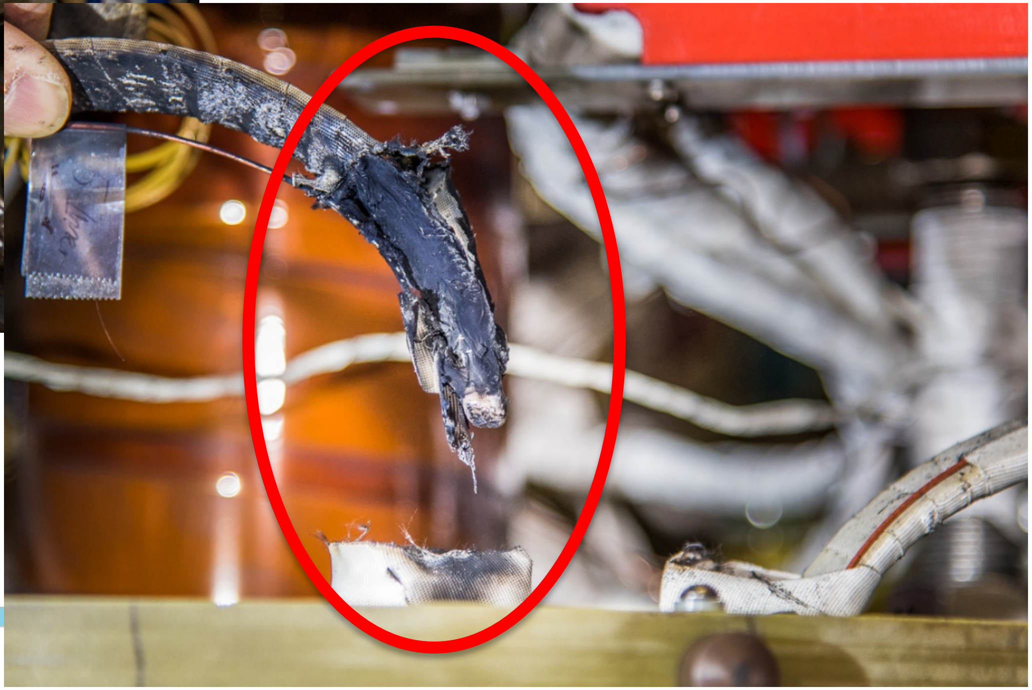
LARP

High Luminosity LHC

Fermilab

…and then the lightning stroke !

- MQXFS1 went SC on Nov 12th '15.
- "Quench and open circuit event" on late Nov 12th !



Findings

- The failure of the quench detection system to protect the superconducting lead was traced to human error: a quench detection cable connected to the wrong receptacle, followed by missing identification of quench detection signal anomalies in the standard checkout data. It was found that one of the two quench detection cables was connected to the wrong receptacle, and as a result the quench detection system was monitoring the wrong voltages not only for the superconducting bus sections, but also for the copper section of the current leads. The other quench detection cable bringing the coil voltages was connected correctly.
- This incorrect connection was not identified during standard checkouts performed prior to ramping the magnet, although there were clear indications in the checkout data that there was something wrong with the leads quench detection signals.

From Committee Chair Presentation to LARP/CERN on Dec 9th 2015

Conclusions

- The investigation team provided a list of recommendations to the TD Division Head in the three critical directions: technical, procedural, and organizational.
- Main recommendations:
  - **The Test and Instrumentation (T&I) Department must ensure that a test stand and quench protection systems subject matter expert is available to perform critical initial tests of the quench protection system and to review and approve all checkout data before allowing the magnet test with current to proceed.**
  - **Add a second formal safety signoff addressing verification of the quench protection system and clearance to ramp the magnet to quench. This should be a joint signoff by the test facility Magnet Test Area Leader, representing the T&I department, and the test Principal Investigator, representing the Magnet Systems department.**
  - **Every time critical quench protection connectors are plugged, include a formal checkout procedure to verify that they were installed in the correct receptacles.**

From Committee Chair Presentation to LARP/CERN on Dec 9th 2015

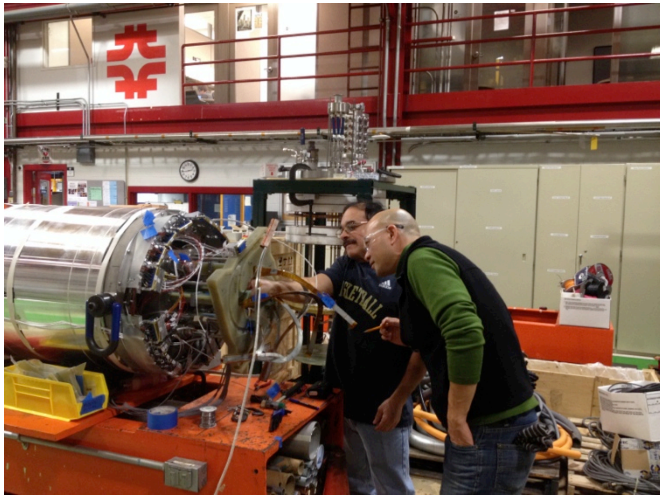
Conclusions –cont.

- This is the first incident damaging a magnet for ~ 18 years of operation of the VMTF stand. The investigation team did not find any problems with the stand itself or the stand Quench Protection system. After the repair of the stand and magnet leads, and satisfying the short term committee recommendations, we believe that the magnet test can resume.

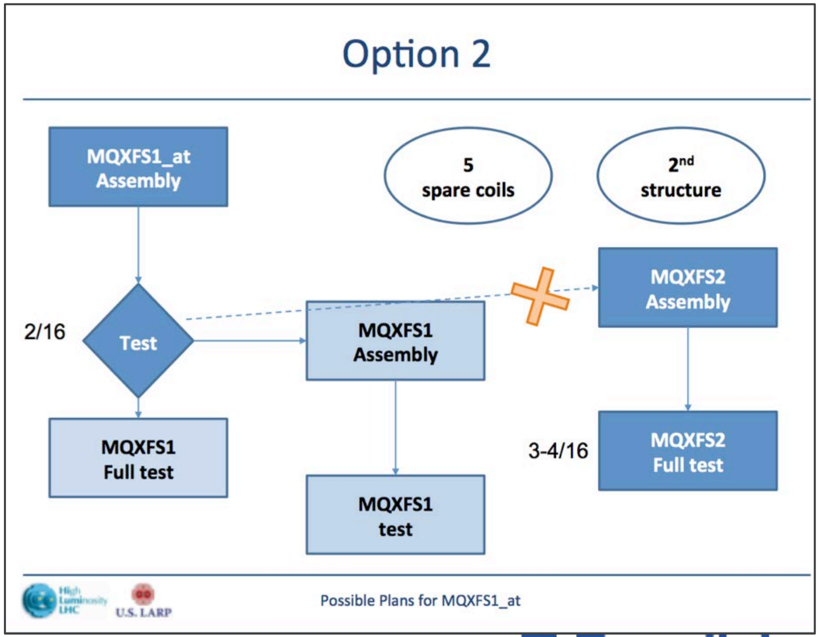
From Committee Chair Presentation to LARP/CERN on Dec 9th 2015

Plans for MQXFS1 and MQXFS2

- "Consolidation" in full swing
  - Repair VMTF Top Plate and 30 kA leads. Certification by Jan '16.
  - Repair damaged portion of Magnet SC lead. Completion by mid-Jan '16.
  - Aim at MQXFS1 test by Feb '16



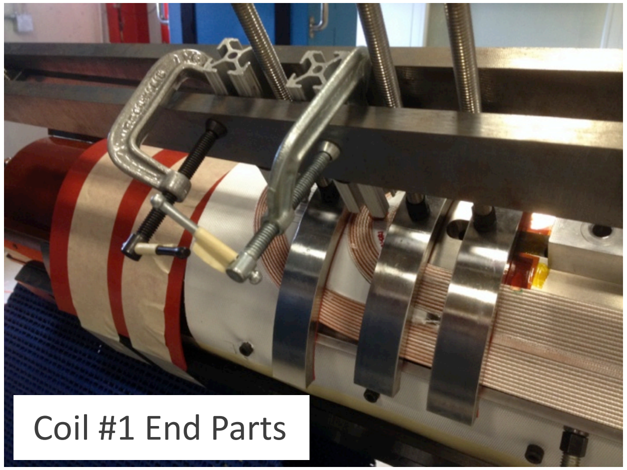
- Initiate assembly of MQXFS2 (at CERN with US and CERN coils) without waiting for MQXFS1 results
  - Increased risk in determining proper pre-load levels, mitigated by decision to apply conservative pre-load.



FY16 Goals: Test of Long MQXF Mirror Coil & First Long (4 m) MQXF Quad

- 3 US-LARP long (4 m) coils produced
  - Wound and cured at FNAL
  - Reacted and under impregnation at BNL
- Plan for mirror configuration test in April '16
  - BNL Vertical Stand
- 1st Long Prototype later in CY16 or earlier CY17.
- 2nd Long Prototype by early CY18.

Coil #1 on Selva

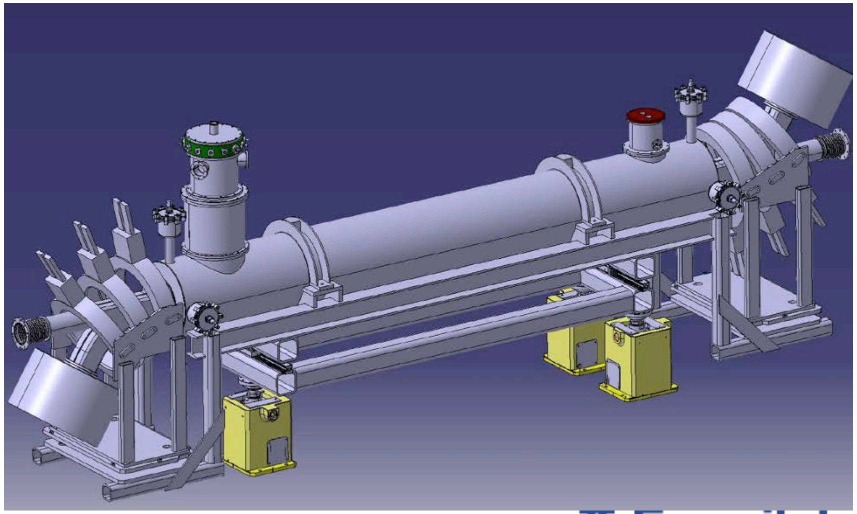

Coil #1 End Parts

Crab Cavities Situation

- What worked:
  - Parts stamped OK at Niowave (SBIR)
- What didn't:
  - Plan to weld cavities at JLAB not accepted by NW
  - NW continued, and plans to complete, the welding of 2 RFD and 2 DQW, failing to deliver welding qualifications & certifications requested by CERN
- What's next:
  - Decision on acceptance of NW cavities
  - If accepted, plans for chemical processing and assembly of the He Vessel at JLAB
  - Alternatives explored, including production of cavities at CERN.

R&D Activities: e-lens

- **Collimation with hollow electron beams**
  - Beam studies on halo population and active control in LHC
  - Tests and characterization of CERN hollow gun at Fermilab
  - Numerical tracking and calculation of loss maps
- **Long-range beam-beam compensation with electron wire**
  - Definition of conceptual design
  - Beam dynamics simulations of compensation scenarios
- **Common to collimation and beam-beam compensation**
  - Study magnetized electron beams with self fields
  - Maintain and improve Fermilab electron-lens test stand

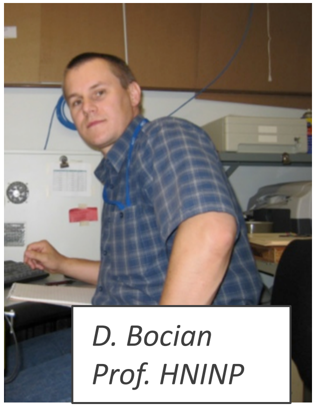


Toohig Fellowship

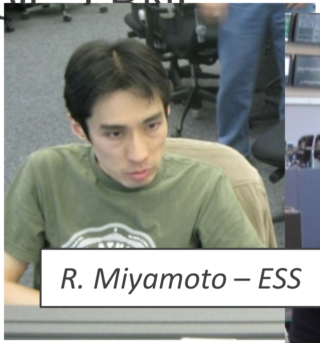
- Following May'15 HiLumi/LARP Meeting, 2 candidates were offered a Toohig Fellow position at US National Labs:
  - M Fitterer – FNAL
  - oli – LBNL


R. Calaga – CERN


H. Felice – CEA


D. Bocian
Prof. HNINP


R. DeMaria –CERN


R. Miyamoto – ESS


T. Mastoridis
Prof. CPU


V. Previtali
Teacher, Geneve


S. White – ESRF


J.Cesaratto
Phillips


I.Pong
LBNL


S. Verdu
BNL

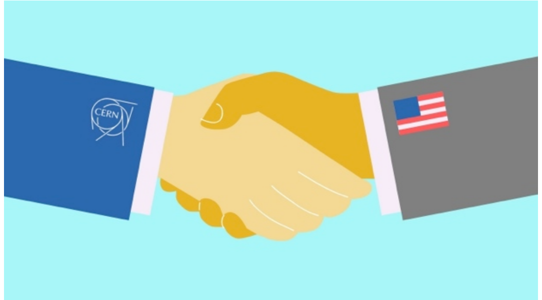

T. Holik
FNAL


E. Ravaioli
LBL


M. Fitterer FNAL

Some Definitions !

- **LARP** (FY15-FY18):
  - Continue LHC R&D with emphasis on minimizing risk of US in-kind deliverables for HL-LHC Project.
    - Deliver 5 QXF Models/Prototypes & dressed CC (SPS Test)
    - Support Toohig Fellowship and - if possible - Acc. Phys. activities
- *US-HiLumi Project* (FY18-FY24):
  - US in-kind deliverable to HL-LHC, controlled as a 413.3b Project
    - Follows
      - DOE-CERN agreement on ICA (done)
      - DOE-CERN Protocol (~end CY15)
      - Coll. Agreement with in-kind deliverables (early CY16?)



- LARP+ (FY19-FY30):
  - Program to support US involvement in aspect of HL-LHC improvements not covered by *US-HiLumi Project*

…onward to US-HiLumi

(413.3b DOE Project)

International Partnerships

Successful partnerships key to implementing U.S. long-term strategy

New Bilateral U.S.-CERN Agreement

Signed May 7, 2015

U.S.-CERN Agreement

- **Considering:**
  - That research in nuclear and particle physics is important for the further development of fundamental science and technological progress;
  - [U.S.] interest in participating in the scientific programme of CERN;
  - CERN's interest in participating in the scientific programmes of [the U.S.];
  - The established contacts between CERN and [the U.S.], including the activities conducted under the . . . "1997 Agreement";
- **The Parties desire to create a framework to ensure, on a long-term basis, opportunities for participation by scientists, engineers and technicians from one Party in research projects of the other Party, and for the provision of such other contributions as the Parties may agree;**
- **Scope**
  - This Co-operation Agreement ("Agreement") constitutes the framework within which the Parties may, on the basis of reciprocity, further develop their scientific and technical co-operation.
- **Implementation**
  - This Agreement shall be implemented through the conclusion of Protocols between CERN on the one hand, and [the U.S.] on the other hand

CO-OPERATION AGREEMENT

between

THE DEPARTMENT OF ENERGY
OF THE UNITED STATES OF AMERICA

and

THE NATIONAL SCIENCE FOUNDATION
OF THE UNITED STATES OF AMERICA

and

THE EUROPEAN ORGANIZATION FOR
NUCLEAR RESEARCH

concerning

Scientific and Technical Co-operation in Nuclear and
Particle Physics

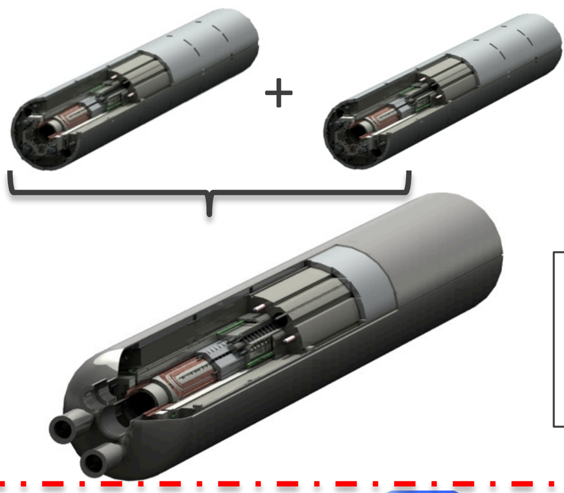
2015

U.S.-CERN Agreement Annexes

- U.S. Department of State granted OMB Circular-175 authorization in August 2015 and Annexes (≡Protocols) to the Cooperation Agreement are now under negotiation with CERN
  - Accelerator Protocol (III)
    - LHC Accelerator Research Program (LARP)
    - U.S. Contributions to the HL-LHC Accelerator Upgrades
    - Future Circular Collider Initiatives with CERN (as an Addendum)
  - Experiments Protocol (II)
    - U.S. and CERN responsibilities for HL-LHC ATLAS and CMS detector upgrades
    - U.S. contributions towards the HL-LHC ATLAS and CMS detector upgrades
    - Framework of LHC Resources Review Boards (RRBs) and U.S. contributions to Common Funds
  - Neutrino Protocol (I)
    - CERN contributions to U.S.-hosted international neutrino program, including the Fermilab Short-Baseline Neutrino Program and LBNF/DUNE
    - Framework of Fermilab LBNF/DUNE RRBs and CERN contributions to Common Funds
- Protocols do not include detailed cost and scope, which will be specified through MOUs (non-binding) and Addenda (binding)

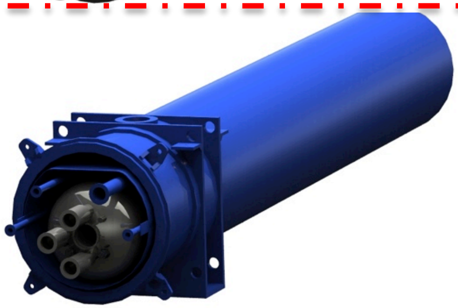
US-HiLumi Deliverables: Magnets

- US-HiLumi Focusing Magnets
  - Deliver 10 Cold Masses to CERN by end CY24. Each CM contains two 4.2m long, 150 mm aperture magnets



US-HiLumi Scope "Contingency"

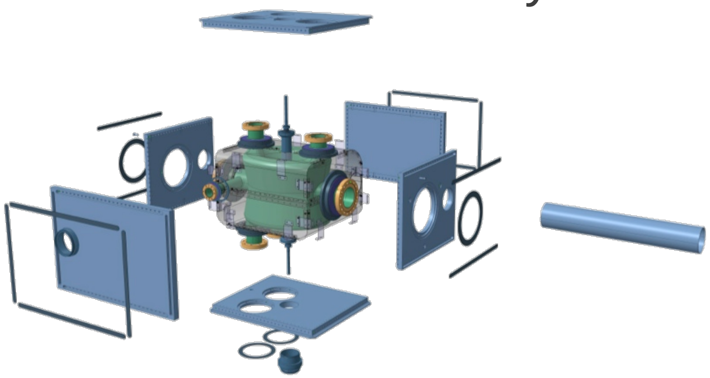
US-HiLumi Baseline Scope



CERN Scope

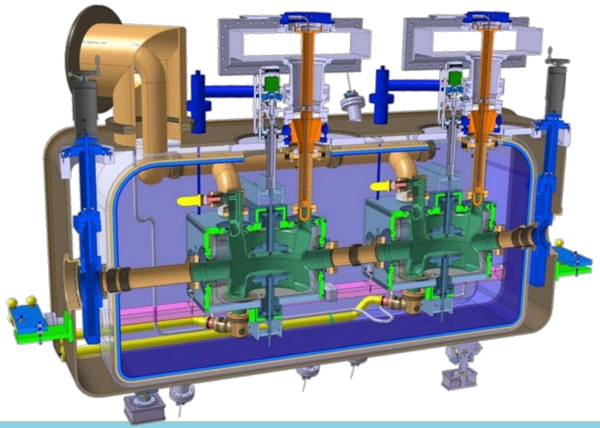
US-HiLumi Deliverables: Crab Cavities

- US-HiLumi Crab Cavities
  - Deliver 40 Individual He-Vessel Dressed Crab Cavities with HOM and tuners to CERN by end CY24.



US-HiLumi
Baseline Scope

US-HiLumi
Scope Contingency



CERN Scope

Functional Requirements for MQXF Magnets

U.S. High Luminosity LHC | MQXFA Magnets Functional Requirements Specification | US-HiLumi-doc-36 Date: Oct 13, 2015 Page 1 of 20

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MQXF

FUNCTIONAL REQUI

Prepared by:

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Reviewed by: Date:

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Approved by:

Giorgio Apollinari, US-HiLumi Project Mar

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Lucio Rossi, CERN HL-LHC Project Coor

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U.S. High Luminosity LHC | MQXFA Magnets Functional Requirements Specification | US-HiLumi-doc-36 Date: Oct 13, 2015 Page 18 of 20

14. Functional Requirements Summary Tables

Table 4: MQXFA Threshold Functional Requirements Specification Summary Table

ID	Description
R-T-01	The MQXFA coil aperture requirement **is 150 mm**. This aperture is the coil inner diameter at room temperature, excluding ground insulation, cold bore and beam screens.
R-T-02	The MQXFA physical outer diameter must not exceed **614 mm**.
R-T-03	The MQXFA magnet must be capable of reaching a nominal operating gradient of **132.6 T/m** and an ultimate gradient of **143 T/m**. These values are in superfluid helium at 1.9 K and for the magnetic length specified in R-T-04.
R-T-04	The MQXFA magnetic length requirement **is 4.2 meters** at 1.9 K.
R-T-05	MQXFA magnets must be capable of operation in pressurized static superfluid helium (HeII) bath at **1.3 bar** and at a temperature of **1.9 K**
R-T-06	The MQXFA cooling channels must be capable of accommodating **two (2)** heat exchanger tubes running along the length of the magnet in the yoke cooling channels. The minimum diameter of the MQXFA yoke cooling channels that will provide an adequate gap around the heat exchanger tubes is **77 mm**
R-T-07	At least **40%** of the coil inner surface must be free of polyamide
R-T-08	The MQXFA structure must have provisions for the following cooling passages: (1) Free passage through the coil pole and subsequent G-10 alignment key equivalent of **8 mm** diameter holes repeated every **50 mm**; and (2) free helium paths interconnecting the yoke cooling channels holes
R-T-09	The MQXFA magnet structure must be capable of sustaining a sudden rise of pressure from atmospheric up to **20 bar** without damage and without degradation of subsequent performance.
R-T-10	The MQXFA magnet structure must be capable of surviving a maximum temperature gradient of **TBD K** during testing without degradation in its performance.
R-T-11	The MQXFA magnets must be capable of operating at **14 A/s**
R-T-12	The MQXFA magnet must withstand a maximum operating voltage of **800 V to ground** during quench.
R-T-13	MQXFA magnets must be delivered with a (+) Nb-Ti superconducting lead and a (-) Nb-Ti superconducting lead rated for **18 kA** and adequately stabilized for connection to the Cold Mass LMQXFA or LMQXFAB electrical bus
R-T-14	Voltage Taps: the MQXFA magnet shall be delivered with **three (3)** quench detection voltage taps located on each magnet lead and at the electrical midpoint of the magnet circuit; **two (2)** voltage taps for each quench strip heater; and **two (2)** voltage taps for each internal MQXFA Nb_3Sn-NbTi splice.
R-T-15	The MQXFA magnet coils and quench protection heaters must pass a hi-pot test in liquid helium at 1 atm pressure as specified in **Table 3** (to be defined)
R-T-18	MQXFA magnets must be delivered trained to ultimate current of **108% (17.8 kA)** of the nominal operating current.
R-T-19	MQXFA magnets must not quench while ramping down at **300 A/s** from the nominal operating current
R-T-20	The MQXFA quench protection components must be compatible with the CERN-supplied quench protection system and comply with the corresponding interface document specified by CERN [3] (to be defined)
R-T-21	The MQXFA magnets must meet the detailed interface specifications with the following systems: (1) other LMQXFA(B) Cold Mass components; (2) the CERN supplied Cryogenic System; (3) the CERN supplied power system; (4) the CERN supplied quench protection system, and (5) the CERN supplied instrumentation system. These interfaces are specified in [3] (all to be defined)
R-T-22	The MQXFA magnets must meet the corresponding Work Package Launch Safety Agreement (LSA) specification [4] (to be defined)

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- MQXF Functional Requirements already exchanged with CERN.
- Handled in terms of ~22 "Threshold Requirements", i.e. minimum goals for magnet performance before shipment to CERN:
  - Ex: MQXF trained to 108% (17.8 kA) of operating current, withstand 800V to ground during quenching, etc..
- Few of these requirements will become "Target KPPs (Key Performance Parameters)" used by US Congress to monitor US-HiLumi Project during its execution.
  - Plan to investigate with DOE whether Achievement of Threshold KPP and Acceptance by CERN can be used as synonymous.

US-HiLumi Project

- A DOE construction project is governed by DOE Order 413.3B
  - https://www.directives.doe.gov/directives-documents/0413.3-BOrder-b
  - Applies to capital assets projects having a Total Project Cost greater than or equal to $50M
- DOE projects typically progress through five Critical Decision (CD) gateways, which serve as major milestones
  - Each CD marks an authorization to increase the commitment of resources by DOE and requires successful completion of the preceding phase or CD

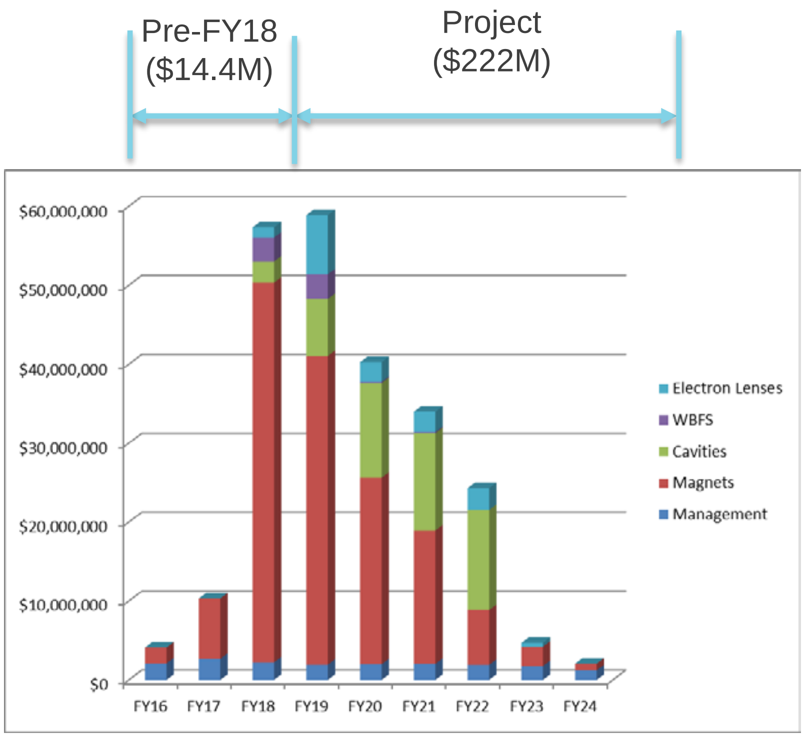
Critical Decisions

- Critical Decision (CD) Gateways
  - CD-0: Approve Mission Need
  - CD-1: Approve Alternative Selection and Cost Range
  - CD-2: Approve Performance Baseline *(when KPP are frozen !)*
  - CD-3: Approve Start of Construction/Execution *(Production Start !)*
  - CD-4: Approve Start of Operations or Project Completion
- A project shall be completed at CD-4 within the original approved performance baseline (CD-2)

- CD-0 approval is now expected by early FY16
  - Mission Need based on DOE/CERN agreements
  - US-LARP acting as if we already received CD-0 for US-HiLumi and preparing actively for CD-1
- CD-1 approval by ~Jan 17?
  - Requires preparation in 2016 for CD-1 Director's review and CD-1 DOE review
- Consolidated CD-2/3 approval
  - Approval by Q3 FY18, based on 2 successful long magnet prototypes

Funding Profile: History

- Feb ’15 presentation to DOE-Germantown:



Feb 2015 FY18-22 Estimate	
Management	$13M
Magnets	$138M
Cavities	$47M
E-lenses	$17M
WBFS	$7M
TOTAL	**$222M**

- DOE Feedback in May ‘15 at HiLumi/LARP Collaboration meeting:
  - Plan for funding profile
    - starting in FY18 at ~20 M$
    - integrating to ~181 M$ by FY24

Other Relevant "High Level" Inputs

- CERN C&S Review – Feb 2015
  - Recommendation to consider installation of ~50% of the Crab Cavity System in LS3, with the remaining 50% installed in LS4
- CERN Council – Jun 2015
  - Plan for a contribution from US to HL-LHC at the level of ~200M$ (previously 181 M$) in the FY18-FY24 timeframe
  - Consider possible contribution from US to HL-LHC at the level of ~50 M$ in the FY24-FY29 timeframe
    - Homework to CERN to define possible scope for additional contribution
      - Very preliminary un-official feedback on "50M$" scope definition (July 2015)

1a)	Hollow e-lens	(LS3)
1b)	Complete CC - HOM, Main PC	(50% in LS3, 50% in LS4)
3)	e-beam Compensator	(LS4)
4)	SPS/HL-LHC WBFS	(LS3)
5)	Contribution to 11 T	(LS4)

Possibilities

	Up to LS3 (~ 200 M$)				Up to LS4 (~50 M$)	
	Manag. + Magnets	Crab Cavities			Hollow e-lens	Compensator
Scenario #1	~ 160 M$	~ 40 M$			~20 M$	~30 M$

To be shown today

	Up to LS3 (~ 200 M$)				Up to LS4 (~50 M$)	
	Manag. + Magnets	50% Crab Cavities	Hollow e-lens		50% Crab Cavities	Compensator
Scenario #2	~ 160 M$	~ 20 M$	~20 M$		~20 M$	~30 M$

- What will make "Scenario #2" feasible:
  - Inclusion of e-lens in Baseline by CERN (~this year ?)
  - Endorsement by FNAL Directorate and CAO/AD:
    - Engineering Support being identified at FNAL.
    - *Timing Corollary*: a possible US contribution to Hollow e-lens in US-HiLumi (FY18-FY24) cannot rely on much R&D effort. It must be an almost "ready-to-go" contribution based on existing and proven designs (TeV, RHIC,..)

Approach to fit DOE funding profile

- Reduce TPC estimate $222M -> ($181M + $19M = $200M):
  - Reduce scope (-$24M)
    - Removed Electron Lens (-$17M)
    - Removed Wideband Feedback System (-$7M)
- Reduce cost in early FYs:
  - CERN LS3 delayed by one year
    - Tunnel installation in 2025 instead of 2024
  - Enables starting production slowly in FY18/FY19
    - Use *LARP* tooling and *LARP* technician crew
  - As more funding becomes available in FY19/20, ramp-up production rate by adding tooling and technicians
  - "Just-in-time" procurements
    - Use phased procurements
      - Increases schedule risk and escalation cost

LARP

Magnets Manufacturing Plan

High Luminosity LHC

U.S. High Luminosity LHC	Magnets Manufacturing Plan	US-HiLumi-doc-52 Date: TBD Page 1 of 12

U.S. DEPARTMENT OF ENERGY | Office of Science

U.S. HiLumi Project

MAGNETS MANUFACTURING PLAN

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- Launched a magnets manufacturing plan effort in April 2015
- Initial focus on production rates as a function of tooling and crew size

Requirements and Specifications References
- ☐ Design Report
- ☐ Specifications
- ☐ Drawings
- ☐ Bill of Materials

Production Line Infrastructure
- ☐ Tooling and equipment
- ☐ Tooling and equipment occupancy
- ☐ Space
- ☐ Production floor layout
- ☐ Temporary Storage for Work in Progress
- ☐ Utilities

Inventory
- ☐ Parts
- ☐ Raw Materials
- ☐ Consumables
- ☐ Spares

Manufacturing Activities
- ☐ Procedures
- ☐ Travelers
- ☐ Steps
- ☐ Sequencing
- ☐ Dependencies
- ☐ Concurrency
- ☐ Routing
- ☐ Shipment

Inspection Activities
- ☐ Inspection points
- ☐ Acceptance criteria
- ☐ Measurements
- ☐ Testing
- ☐ Disposition
- ☐ Records

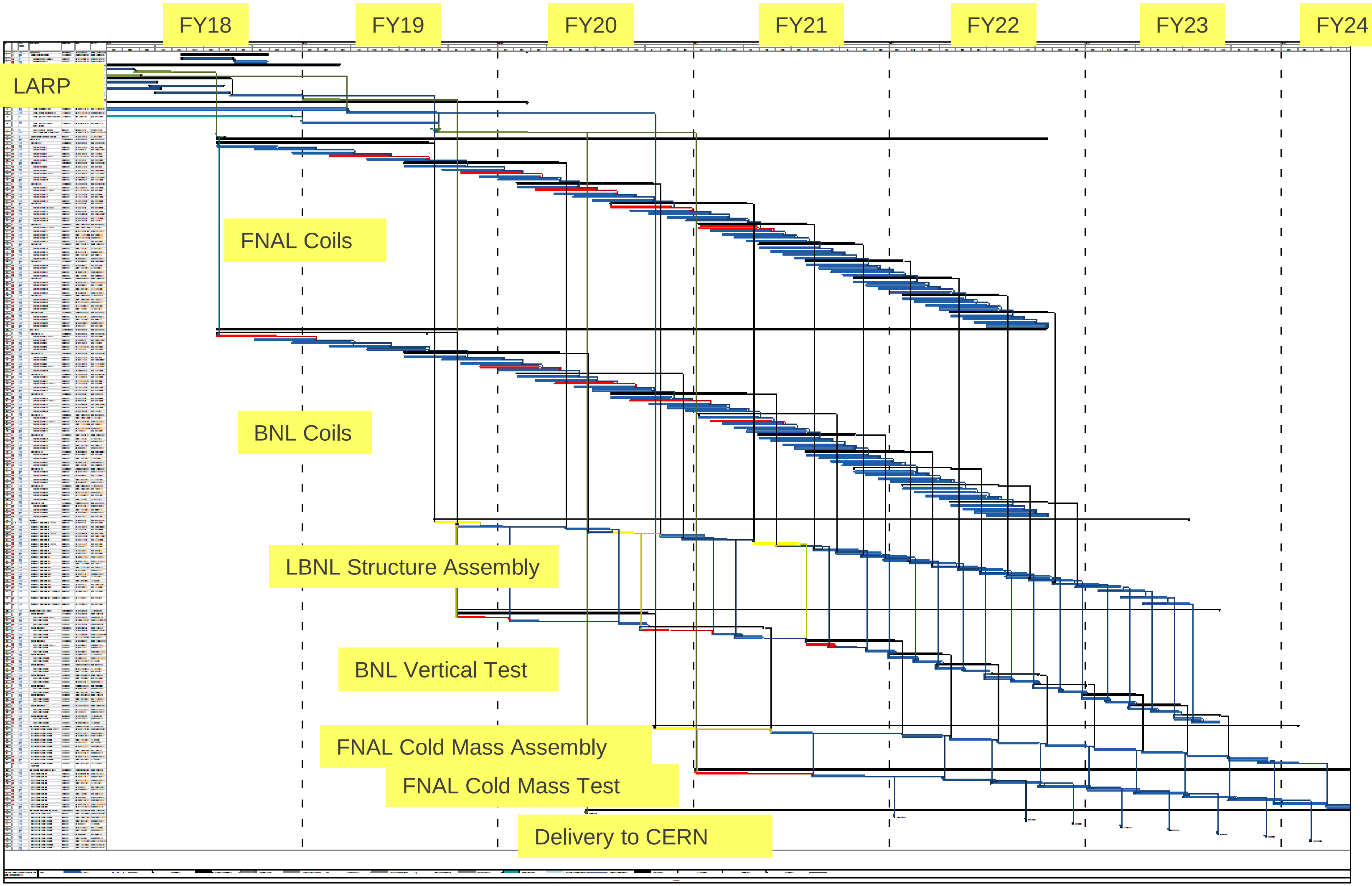
Quantities and Throughput
- ☐ Production quantities
- ☐ Throughput
- ☐ Learning Curve
- ☐ Yield

Workforce
- ☐ Crew Size
- ☐ Qualifications
- ☐ Staff Acquisition
- ☐ Training
- ☐ Other commitments
- ☐ Shift Work
- ☐ Resource leveling
- ☐ Idle time
- ☐ Coverage

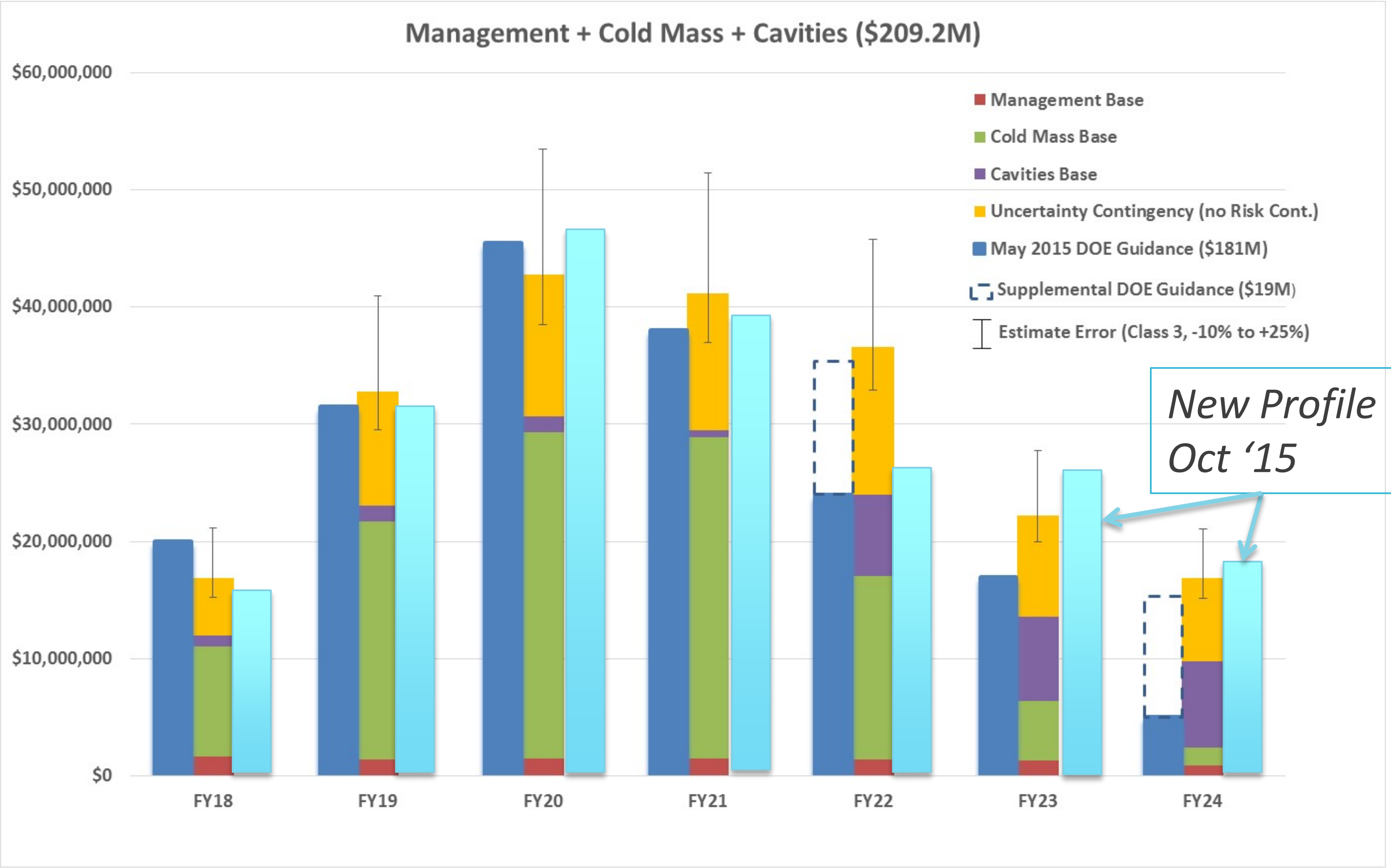
Fermilab

Preliminary Integrated Schedule

- MS Project with logic dependencies



US-HiLumi Cost Model Output



(Possible) LARP-to-HiLumi-to-LARP+

LARP as we know it today (FY16–FY18 pre-CD3)

Asymptotic LARP+ (FY20–FY21)

	FY16	FY17	FY18-pre-CD3	FY18 post-CD3	FY19	FY20	FY21
Total LARP	15.5 M$	18.5 M$	13.7 M$		5.5 M$	3.0M$	3.0 M$
US-HiLumi				15M$	31.0 M$	46.5 M$	39 M$

US-HiLumi Project (FY18 post-CD3–FY21)

- A major investment from US-HEP in LHC infrastructure !

Conclusion

- Steady progress under LARP on magnets, crab cavities and other R&D activities
  - Hick-up on magnet test facility
- Transition from LARP to US-HiLumi getting to the nitty-gritty details of deliverables, functional specifications, etc.
- Preliminary funding profile for US-HiLumi appears to allow deliveries according to CERN schedule needs, albeit at a slightly increased schedule and execution risk (JIT Production)
- Preparation of a plan for an Accelerator Physics *LARP+* phase is encouraged.