From US-LARP to US-HiLumi

G. Apollinari
LARP Director

5th Joint HiLumi-LHC/LARP Annual Meeting
October 27th, 2015

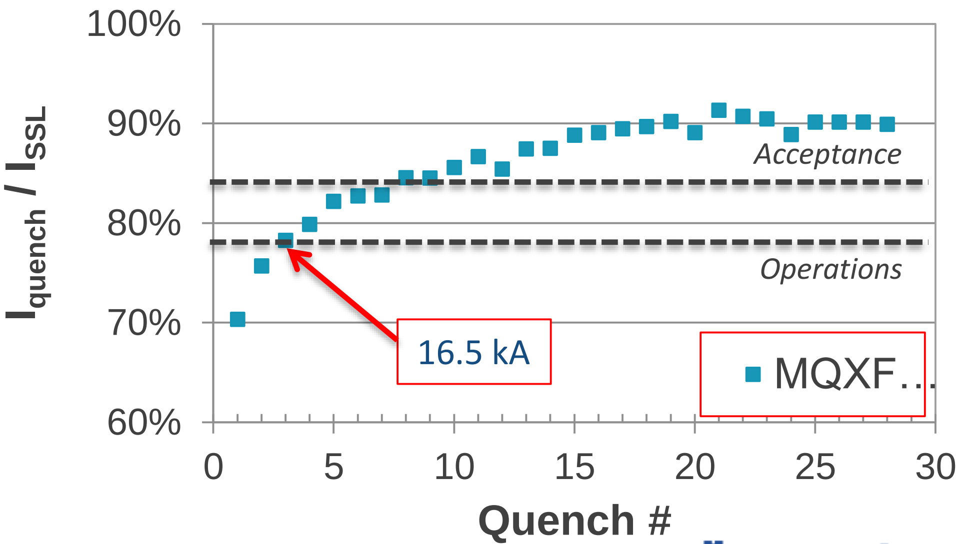
Content

- Status and Progress of LARP
  - 2015 Achievements
  - 2016 Goals
  - New Toohig Fellows
  - “LARP2” Program
- Transition to US-HiLumi
  - Definition of Deliverables
  - Functional and Technical Specs
  - Preliminary Funding Profile
  - Conceptual US-HiLumi Schedule

Successful Test of First MQXF Coil

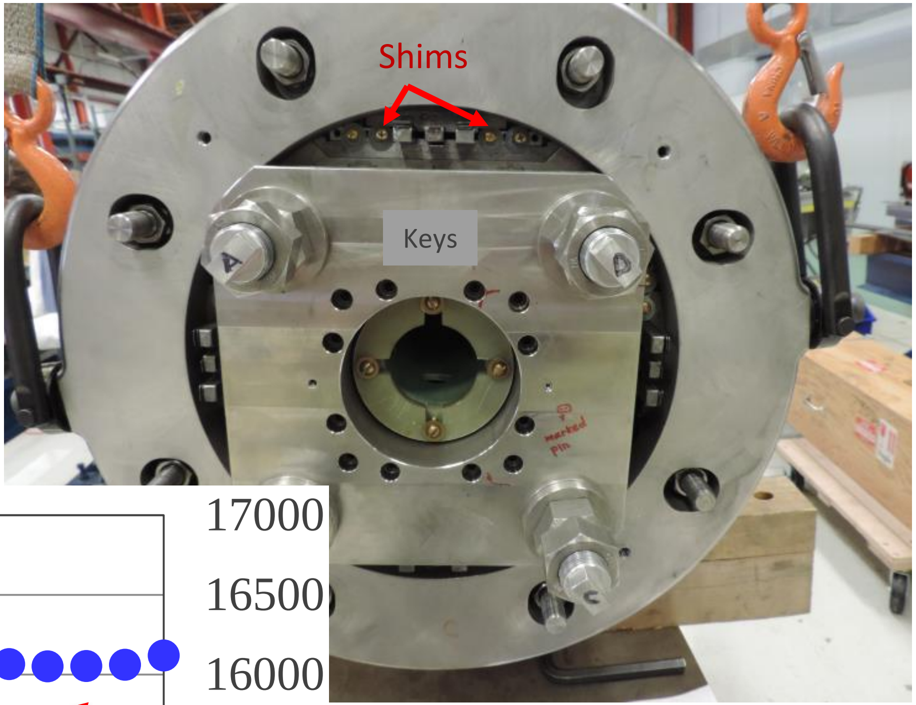
- First model coil for HL-LHC magnets assembled and tested in mirror configuration at FNAL. The Mirror Magnet was tested in the IB1 Vertical Magnet Test Facility using for the first time an upgraded 30kA setup.
  - Higher current needed for higher-performing Nb_3Sn magnets

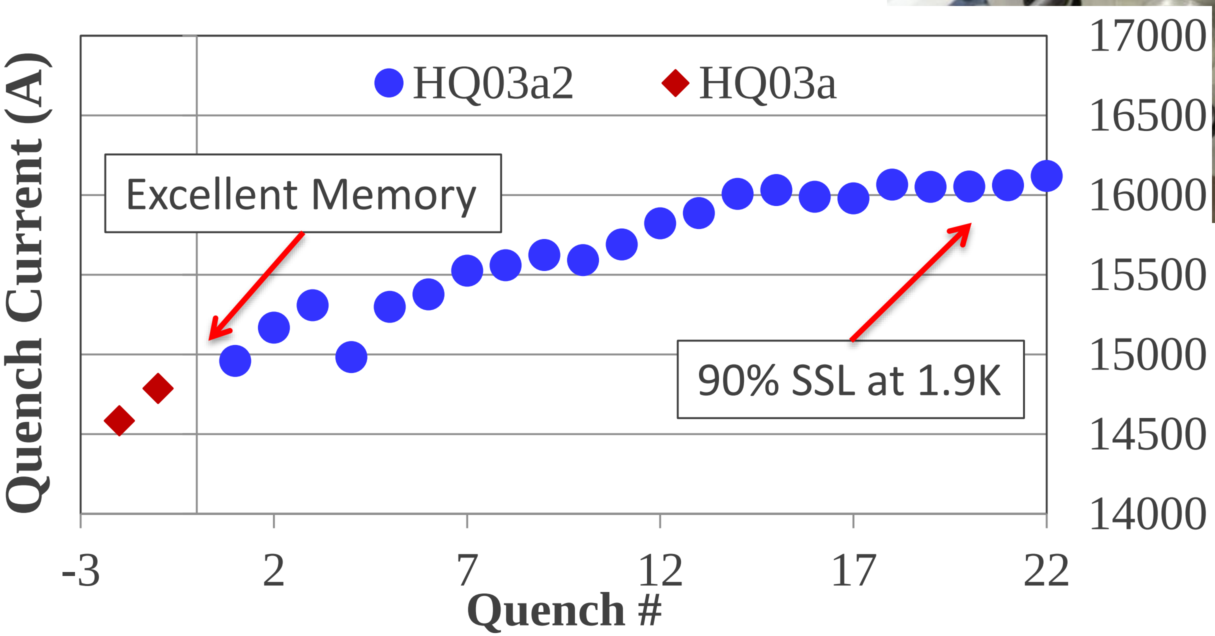
- Coil achieved HL-LHC "operating current" (16.5kA) in 3 quenches during the first day of testing !



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.

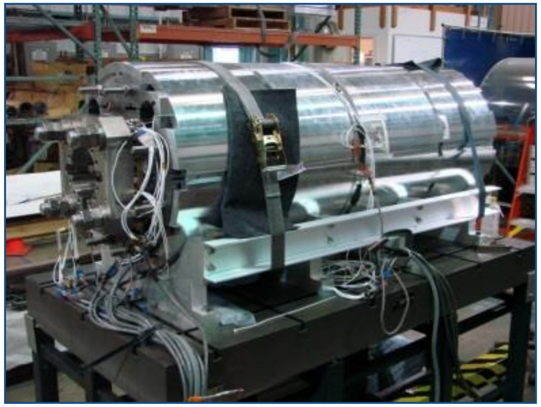




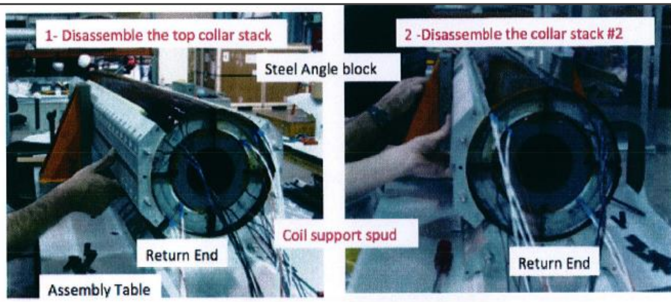
Successful Assembly of First MQXFS. Test Coming

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

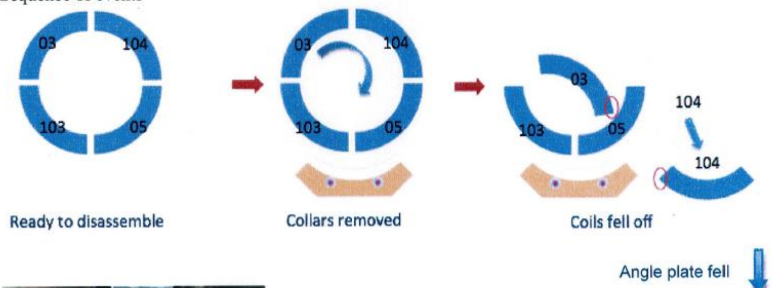
- Component instrumented with strain gauges
  - Very good agreement with calcuations

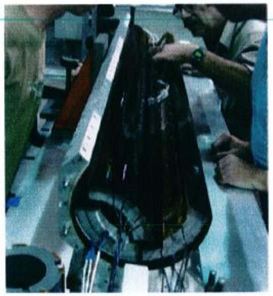


Assembly Mishap during MQXFS



Sequence of events





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LARP Magnet Coil Investigation and Apparent Cause Analysis

Prepared By:

Patricia Thomas, Team Lead, Accelerator Technology and Applied Physics Division	(signature)	10/09/15 (date)
Marshall Granados, Engineering Division Causal Analyst	(signature)	10-9-15 (date)
Herbert (Ted) Keffeler, Engineering Division Mechanical Engineering Technician Supervisor	(signature)	10-9-15 (date)
James Dougherty, Engineering Division Mechanical Engineering Technician	(signature)	10-9-15 (date)

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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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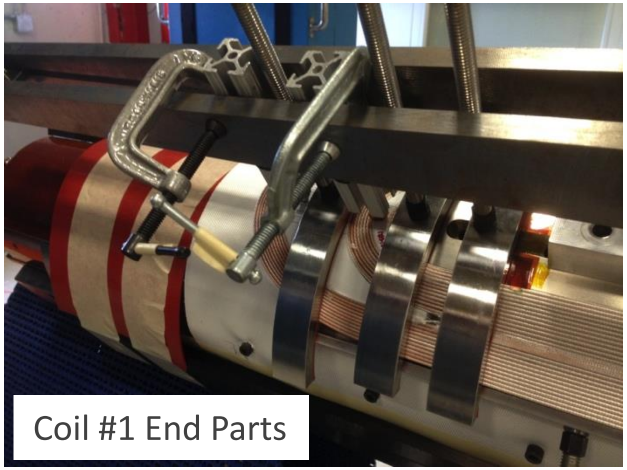
- Convergence on 108/127 based on performance and cost analysis.
- Order placed by FNAL for ~200 km in Sep '15.
- First interactions on material certifications with manufacturing company happening as we speak.

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

- First US-LARP long (4 m) coil
  - Wound and cured at FNAL
  - Reacted and under impregnation at BNL
- Plan for mirror configuration test in April '16
  - BNL Vertical Stand

Coil #1 on Selva

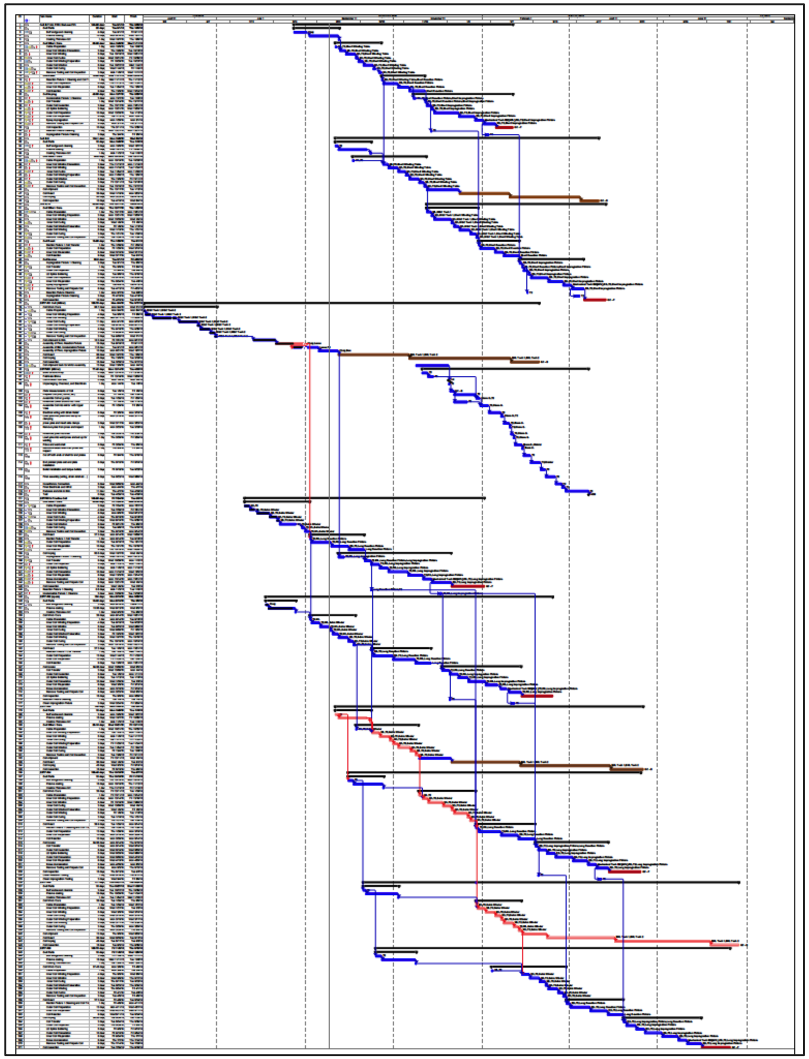


Coil #1 End Parts

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



Crab Cavities Situation

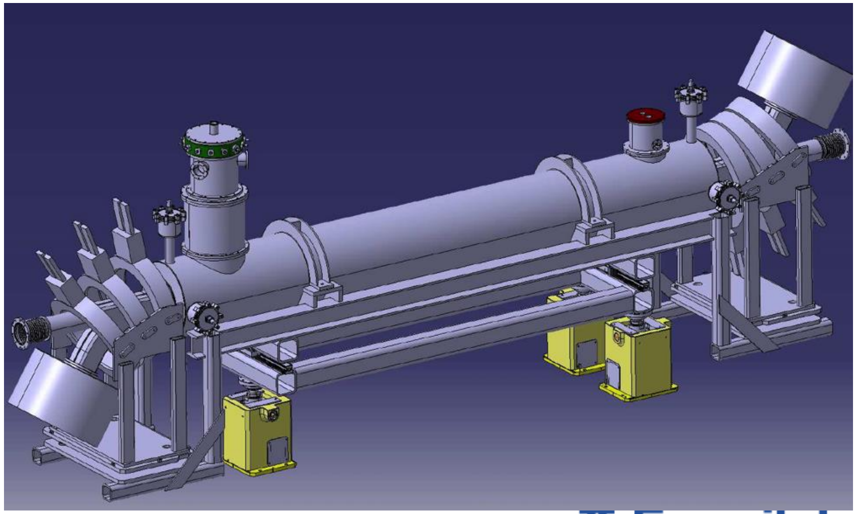
- What worked:
  - Parts stamped OK at Niowave
  - EBW limits to imperfections being renegotiated with CERN
- What didn't:
  - Plan to weld cavities at JLAB not accepted by NW
  - NW continued, and plans to complete, the welding of 2 RFD and 2 DQW
- What's next:
  - Decision on acceptance of NW cavities
  - If accepted, plans for chemical processing and assembly of the He Vessel at JLAB
  - Alternatives need to be investigated

LARP

R&D Activities: e-lens

High Luminosity LHC

- **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

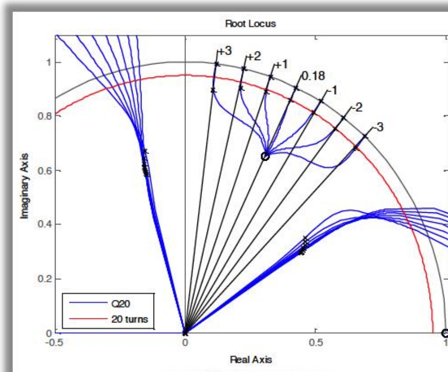


Fermilab

R&D Activities: Wide Band Feedback System

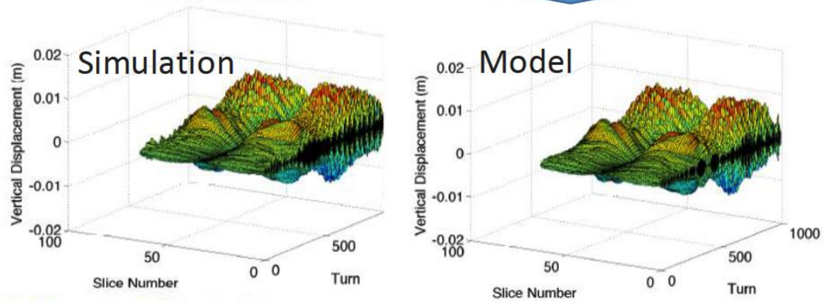
Wideband feedback system for the SPS

- The project is essential to acquire expertise on:
  - How to numerically model and study wideband feedback systems for mitigation of intra-bunch coherent motion (with noise mechanisms, numeric processing effects and saturation mechanisms to understand system design trade-offs)
    → available for LHC/HL-LHC
  - Prototyping of high speed electronics (4Gs/s digital signal processing system) & exploration of control algorithms
    → Architecture developed is reconfigurable for LHC/HL-LHC



Root locus of 5-tap FIR for Q20

Reduced model



Identification of possible control algorithms to maximize tune bandwidth. Development of reduced models of the machine-beam system.

J. Fox et al, IBIC 2015 Melbourne

Talk from K. Li at LIU/HL-LHC Oct 15th, 2015

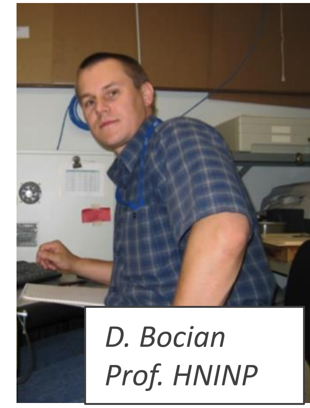
15.10.2015 Joint LIU / HL-LHC Meeting

Toohig Fellowship

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

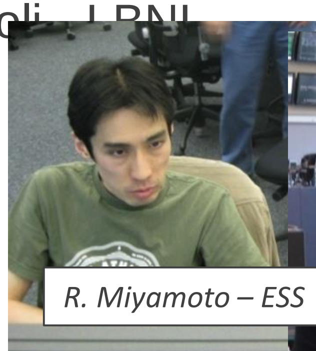
R. Calaga – CERN

H. Felice – CEA



D. Bocian
Prof. HNINP

R. DeMaria –CERN



R. Miyamoto – ESS

T. Mastoridis
Prof. CPU

V. Previtali
Teacher, Geneve

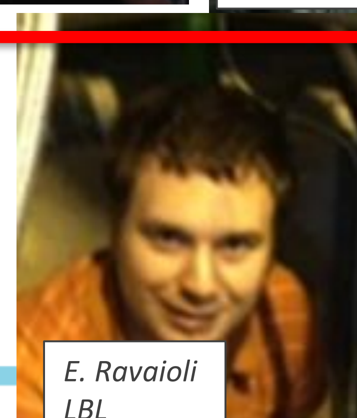
S. White – ESRF

J.Cesaratto
Phillips

I.Pong
LBNL

S. Verdu
BNL

T. Holik
FNAL



E. Ravaioli
LBL

M. Fitterer FNAL

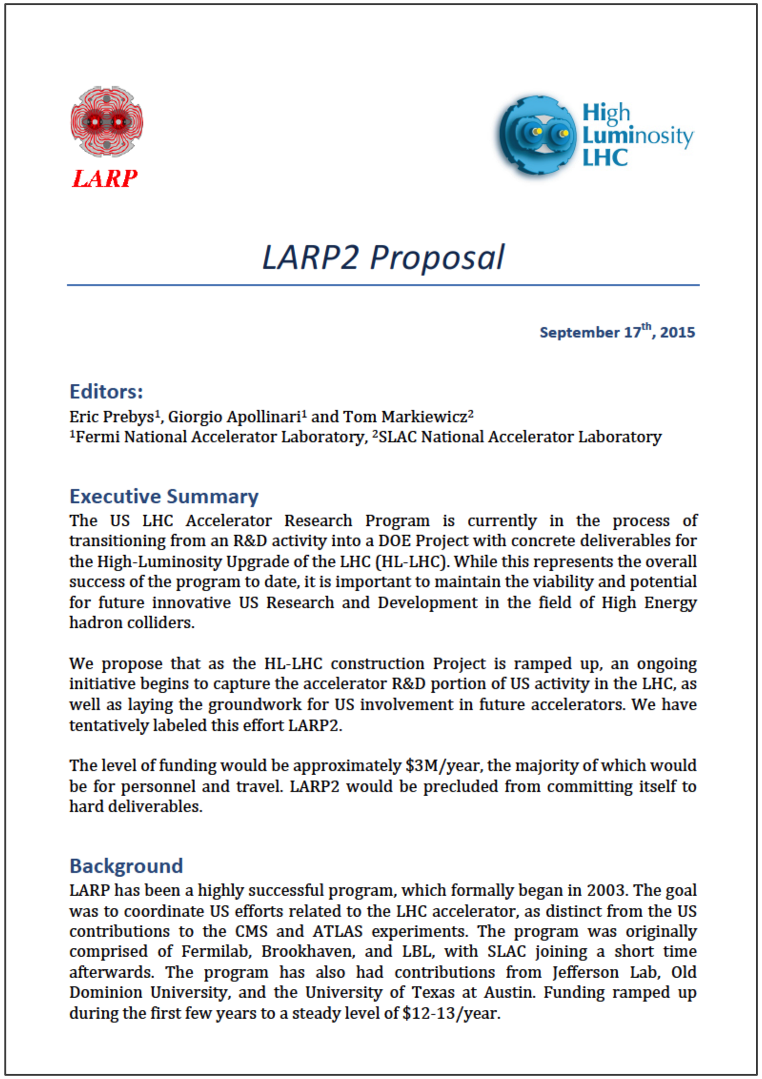
Some Definitions !

- **LARP** (FY15-FY17/18):
  - Continue LHC R&D with emphasis on minimizing risk of US in-kind deliverables for HL-LHC Project.
    - Deliver 5 QXF Models/Prototypes & 4 dressed CC (SPS Test)
    - Support Toohig Fellowship and - if possible - Acc. Phys. activities
- *US-HiLumi* (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?)

- "LARP2" (FY19-FY30):
  - Program to support US intellectual involvement in HL-LHC while *US-HiLumi* is being executed or HL-LHC operates

LARP2 (2019 and beyond)

- Basic Idea
  - Initiative to capture US Acc. R&D at the LHC during HL-LHC Construction
  - Focus on intellectual contributions and beam test
    - No deliverable to HL-LHC
    - Vision for future like LARP 10y ago
    - Directed-Program Nature
  - Support of Fellows Research fraction, LTV, studies at HL-LHC informing development of Future Colliders
- Plan
  - Organize a satellite ½-1 day workshop around next HiLumi/LARP meeting in US to converge on proposal to DOE.
  - Program driven by US interests, but will solicit feedback and support from CERN



LARP

High Luminosity LHC

LARP2 Proposal

September 17th, 2015

Editors:

Eric Prebys[1], Giorgio Apollinari[1] and Tom Markiewicz[2]
[1]Fermi National Accelerator Laboratory, [2]SLAC National Accelerator Laboratory

Executive Summary

The US LHC Accelerator Research Program is currently in the process of transitioning from an R&D activity into a DOE Project with concrete deliverables for the High-Luminosity Upgrade of the LHC (HL-LHC). While this represents the overall success of the program to date, it is important to maintain the viability and potential for future innovative US Research and Development in the field of High Energy hadron colliders.

We propose that as the HL-LHC construction Project is ramped up, an ongoing initiative begins to capture the accelerator R&D portion of US activity in the LHC, as well as laying the groundwork for US involvement in future accelerators. We have tentatively labeled this effort LARP2.

The level of funding would be approximately $3M/year, the majority of which would be for personnel and travel. LARP2 would be precluded from committing itself to hard deliverables.

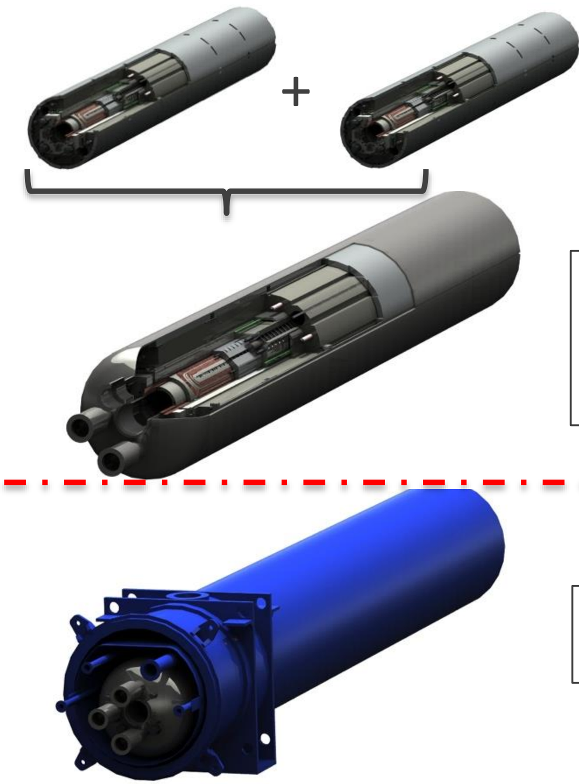
Background

LARP has been a highly successful program, which formally began in 2003. The goal was to coordinate US efforts related to the LHC accelerator, as distinct from the US contributions to the CMS and ATLAS experiments. The program was originally comprised of Fermilab, Brookhaven, and LBL, with SLAC joining a short time afterwards. The program has also had contributions from Jefferson Lab, Old Dominion University, and the University of Texas at Austin. Funding ramped up during the first few years to a steady level of $12-13/year.

…onward to US-HiLumi

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



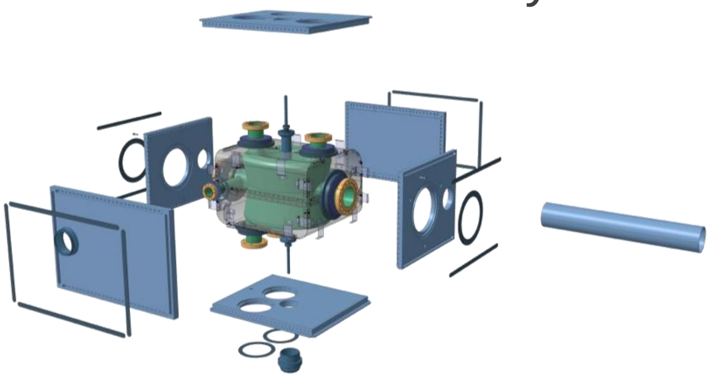
US-HiLumi Scope “Contingency”

US-HiLumi Baseline Scope

CERN Scope

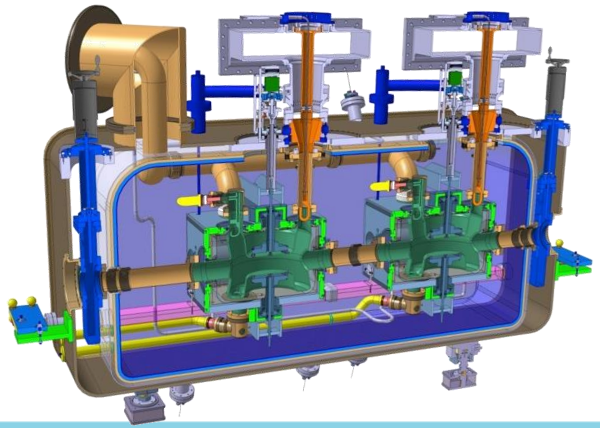
US-HiLumi Deliverables: Crab Cavities

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



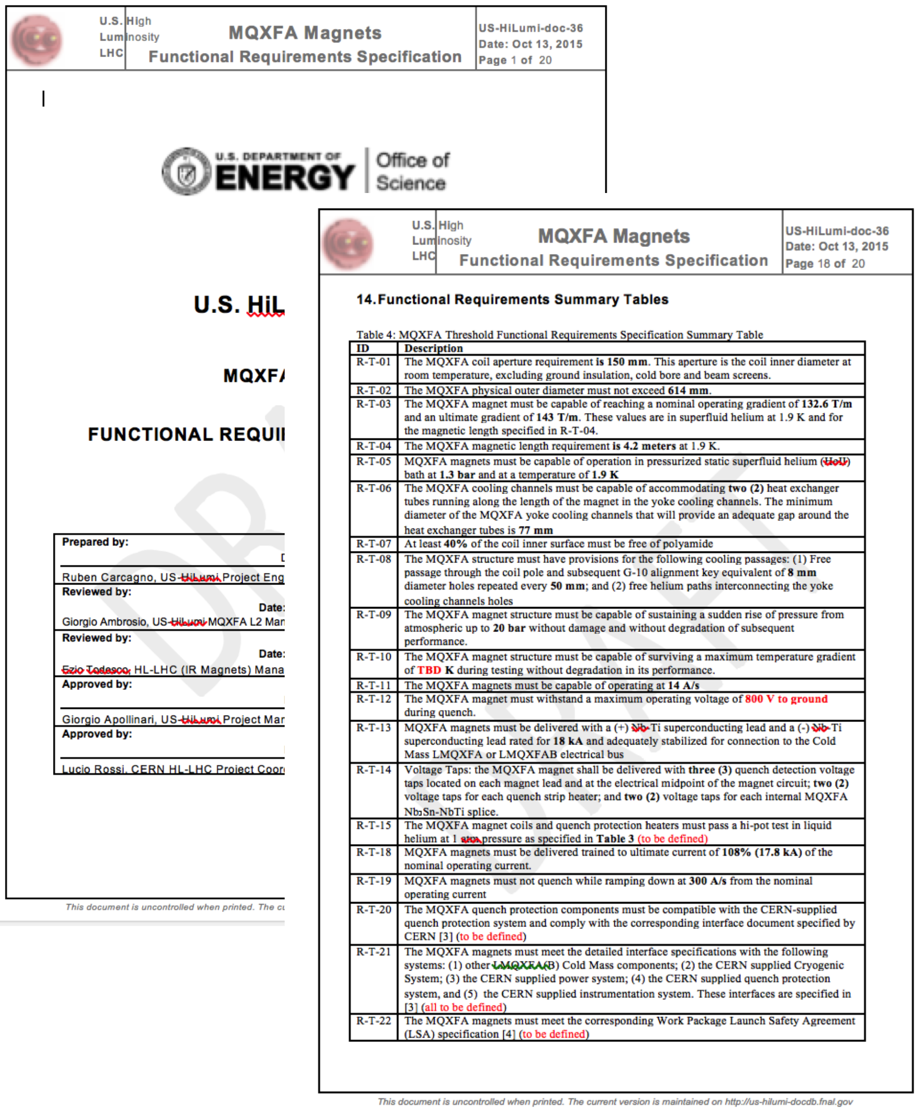
US-HiLumi
Baseline Scope

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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U.S. HiL

MQXF

FUNCTIONAL REQUI

Prepared by:

Ruben Carcagno, US-HiLumi Project Eng

Reviewed by: Date:

Giorgio Ambrosio, US-HiLumi MQXFA L2 Mar

Reviewed by: Date:

Ezio Todesco, HL-LHC (IR Magnets) Mana

Approved by:

Giorgio Apollinari, US-HiLumi Project Mar

Approved by:

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 WP2. V1 with ~6 drafts/inputs preceding it.
- 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.

Functional Requirements for Cold Mass

U.S. High Luminosity LHC	LMQXFA/B COLD MASS Functional Requirements Specification	US-HiLumi-doc-64 Date: Oct 13, 2015 Page 1 of 20

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U.S. HiLumi Project

LMQXFA/B COLD MASS

FUNCTIONAL REQUIREMENTS SPECIFICATION

DRAFT

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Reviewed by: Date: Ezio Todesco, HL-LHC (IR Magnets) Manager	Organization CERN	Contact Ezio.Todesco@cern.ch
Approved by: Date: Giorgio Apollinari, US-HiLumi Project Manager	Organization FNAL	Contact apollina@fnal.gov (630) 840-4641
Approved by: Date: Lucio Rossi, CERN HL-LHC Project Coordinator	Organization CERN	Contact Lucio.Rossi@cern.ch

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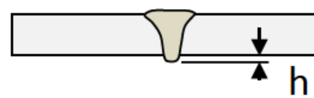
- Exchanged with WP2 by ~mid October.
- Mostly dealing with integration requirements for 2 magnets in one He Vessel.
- (Where applicable) Threshold Requirements based on what is considered feasible to achieve “form and function” and/or what has been achieved for present Q2 LHC Triplets.
- A convergence on the Functional Requirements for the Magnets and Cold Mass are necessary elements for a proper justification of Project estimates in the US (Project Cost, Contingency Levels, Schedule, etc.)

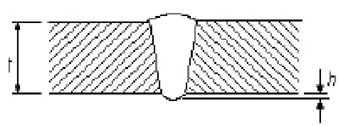
Importance of "Technical Feasibility"

- Success story of technical communication across the Atlantic !
- During the development of Technical Specification for CC, very stringent requirements on allowed imperfections of Electron Beam Welds found their way into the specification.

EN ISO 6520-1 reference	Imperfection designation	Remarks	Limits for imperfections
504	Excessive penetration		h max 0.1 mm

EDMS 1389669

- After interactions with experts at JLAB and other Labs in the US, a spec based on *Stringent Requirement* of EN-ISO 13919-2 (Al. EBW) is being considered:

No	Imperfection, designation	EN ISO 6520-1 reference	Remarks	Limits for imperfections for quality levels:		
				moderate D	intermediate C	stringent B
13	Excessive penetration	504		$h \leq 0{,}2$ mm + $0{,}3\ t$ max. 5 mm	$h \leq 0{,}2$ mm + $0{,}2\ t$ max. 5 mm	$h \leq 0{,}2$ mm + $0{,}15\ t$ max. 5 mm

h < 0.2 mm + 0.14 x 4 mm = 0.8 mm

- Converging on "technically feasible" specs prevents non-conformities, *"explosion"* of contingency in US Project estimate, schedule delays, …

Launch Safety Agreement for MQXF

- US-HiLumi PO started inquiring on the stipulation of the LSA that US-HiLumi will need to abide to in order for the US deliverables to be accepted at CERN
- Directed to WP3-HSE interactions for Crab Cavities and LSA for 11 T.
  - CE-marking

ANSWER TO THE REQUEST
As stated in the SRF EDMS 1375354, for the Crab cavities prototype Cryomodules to be tested at SPS, due to their prototype nature and considering their status as equipment liable to have major Safety implications, it was established that the prototype Cryomodules will be exempt from CE-marking but, in any case, the equipment shall meet the Essential Safety Requirements (ESRs) stated in Annex 1 of the European pressure equipment Directive 97/23/EC (PED).

EDMS 1541969

  - (Possible) US-HiLumi Project external dependence

The HSE Unit will verify the design report during the various phases of the equipment life-cycle and grant clearance based on the agreed acceptance criteria.

EDMS 1375354

  - 11T LSA

5.2 Products and materials

5.2.1 General requirements on products and materials

Products purchased on the market must comply with CERN Safety rules (or, when these are not available, with Host States Regulations or European Directives) and as such are legally required to bear the CE marking, whenever applicable.

EDMS 1472317

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

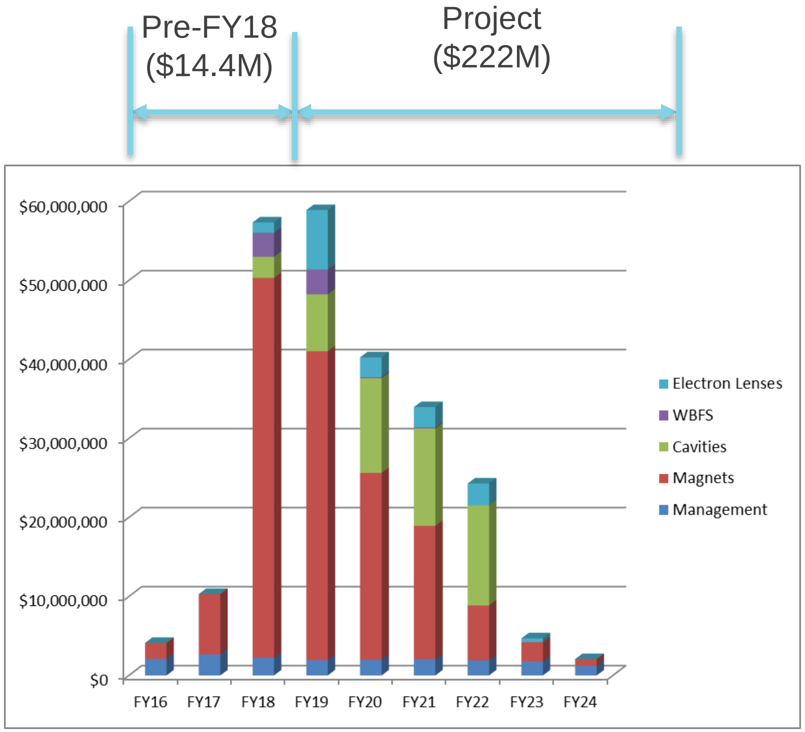
Critical Decisions

- 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 presented today

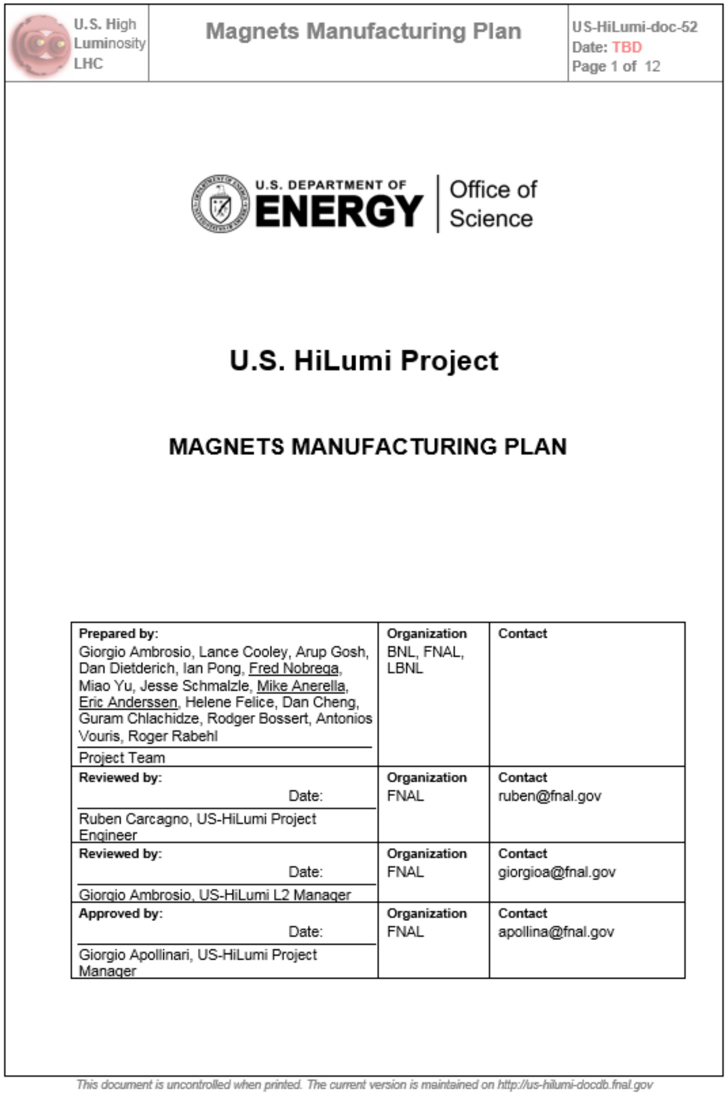
	Up to LS3 (~ 200 M$)				Up to LS4 (~50 M$)	
	Manag. + Magnets	50% Crab Cavities	Hollow e-lens		50% Crab Cavities	Compensator
Scenario #2	~ 160 M$	~ 20 M$	~20 M$		~20 M$	~30 M$

- What would need to happen for "Scenario #2":
  - Inclusion of e-lens in Baseline by CERN (~this year ?)
  - Analysis of possible US contribution (by cost and effort) with discussion and Agreement on scope of US Contribution
    - *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

Magnets Manufacturing Plan



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

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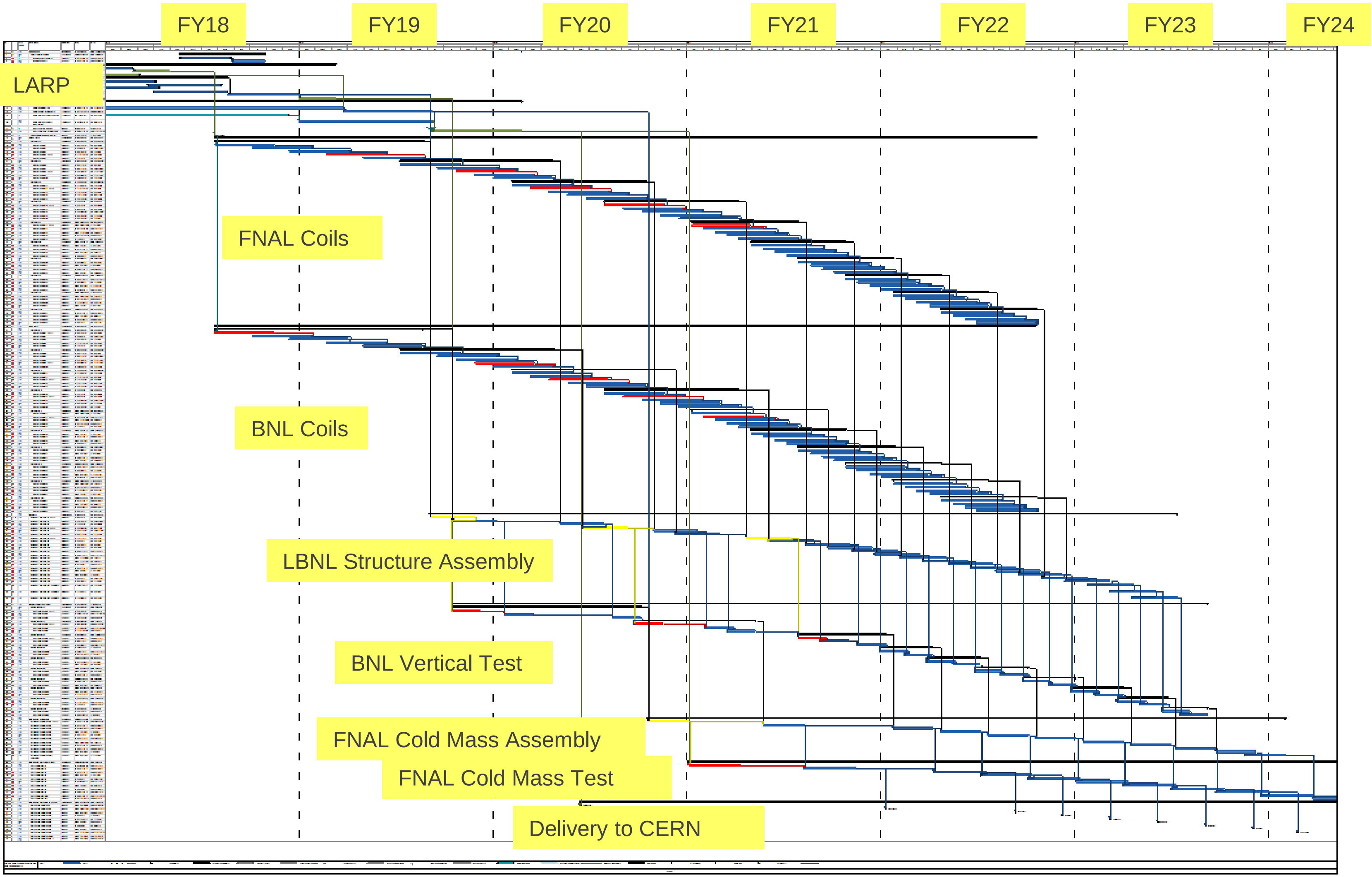
- Launched a magnets manufacturing plan effort in April 2015
- Initial focus on production rates as a function of tooling and crew size

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

Preliminary Integrated Schedule

- MS Project with logic dependencies



Preliminary LQXF CERN Delivery Dates

Cold Mass	Delivery Date
LMQXFA-1	10/11/21
LMQXFA-2	6/13/22
LMQXFA-3	9/9/22
LMQXFA-4	12/8/22
LMQXFA-5	3/8/23
LMQXFA-6	6/6/23
LMQXFA-7	9/4/23
LMQXFA-8	11/27/23
LMQXFA-9	2/19/24
LMQXFA-10	5/27/24

- US-HiLumi
  Coil Fabrication Starts 4/27/18
- Base project duration 76.2 months (6.3 years)
- New expected LHC tunnel installation in 2025 during LS3
- Last cold mass for tunnel installation (LMQXFA-8) delivered before the end of 2023
- Two spares (LMQXFA-9 and 10) delivered in 2024

Comments on Crab Cavities

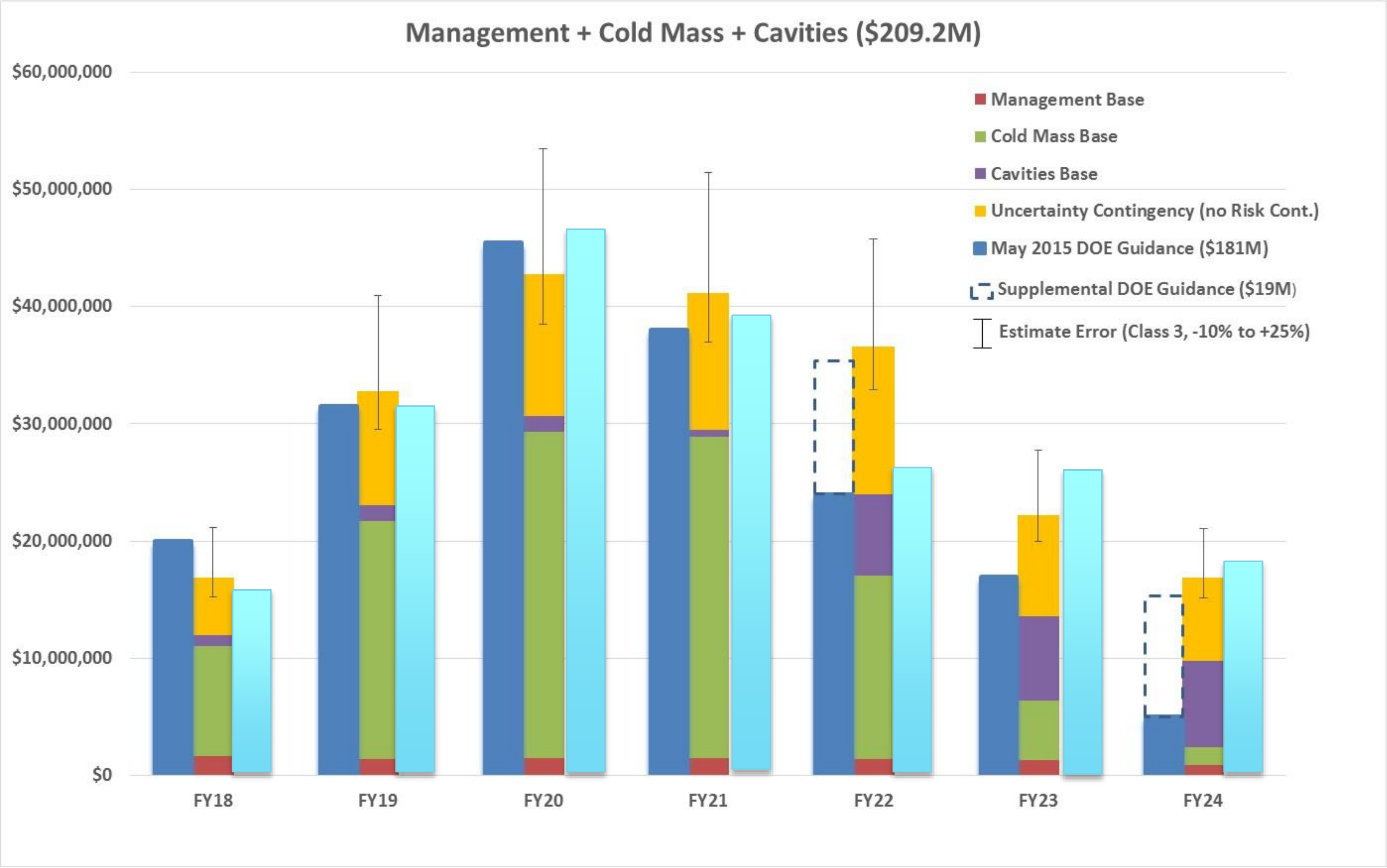
- Design for Crab Cavities is at more preliminary stage than Magnets:
  - POP LARP Crab Cav. (‘11-’14)
  - SPS LARP Cav. (Now)
  - Pre-Series Cavities (‘19-’20)
  - Series Cavities (‘21-’24)

  TQ LARP Magnets (’07-’11)
  HQ LARP Magnets (’11-’14)
  QXF LARP Prototypes (Now)
  QXF Series Magnets(’18-’24)

- Present plan: work on Pre-Series Cavities (4) under US-HiLumi in FY19-20, with Series Cavities (36) produced by US-HiLumi in FY21-FY24
  - Potential benefits from HL-LHC C&S Review (Feb ‘15) recommendation to split CC installation between LS3 and LS4

FY18	FY19	FY20	FY21	FY22	FY23	FY24
SPS Test	Pre-series (4)		Final Design	Series Cavities (36)		
LARP	*US-HiLumi*					

US-HiLumi Cost Model Output



Possible LARP-to-HiLumi-to-LARP2

LARP as we know it today

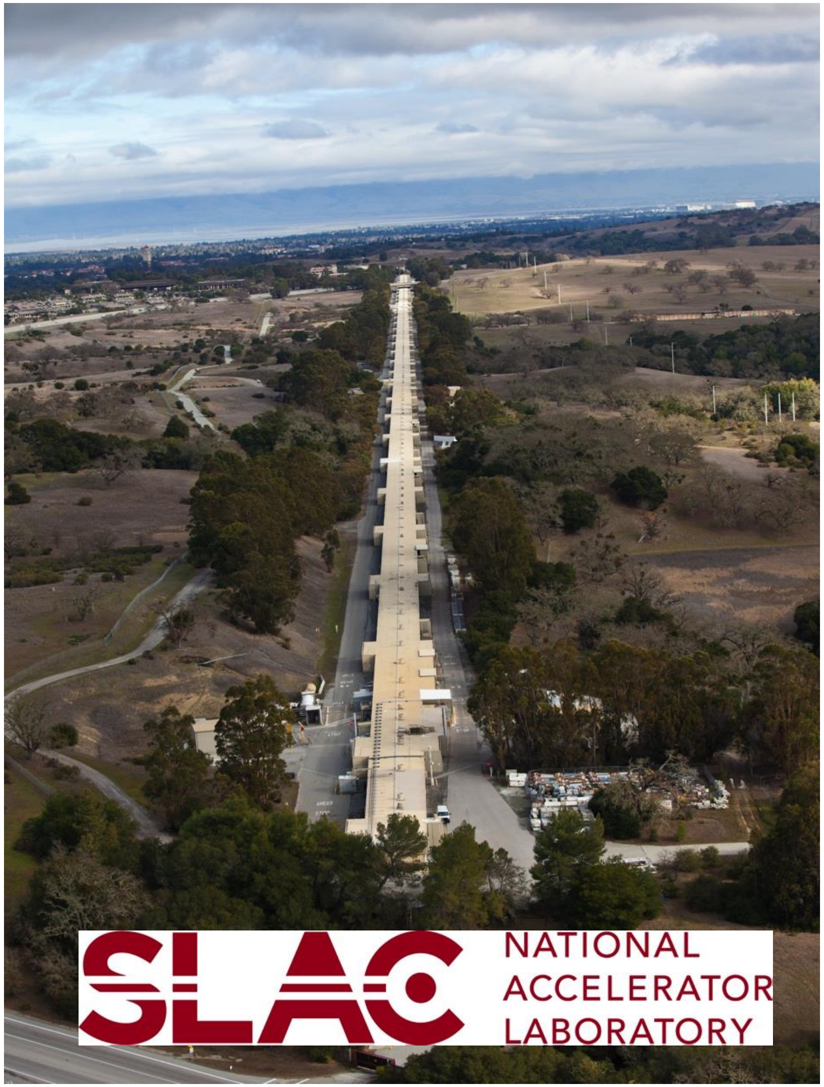
Asymptotic LARP2

	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				20M$	31.5 M$	45.5 M$	38 M$

US-HiLumi Project

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

Joint Spring LARP/HiLumi CM



- Also LARP-CM26
- Where
  - SLAC, CA – USA
- When (tentatively):
  - Week of May 2nd – 6th, 2016
    - EuCard2: April 26-28, Malta
    - IPAC16: May 9-13, Korea
- What
  - 2 ½ - 3 days format to avoid excessive compression
  - LARP2 satellite meeting. Others as needed.

Conclusion

- Steady progress under LARP on magnets, crab cavities and other R&D activities
- 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 LARP2 phase is encouraged.