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LARP: LHC Accelerator R&D Program

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Fermilab Institutional Review

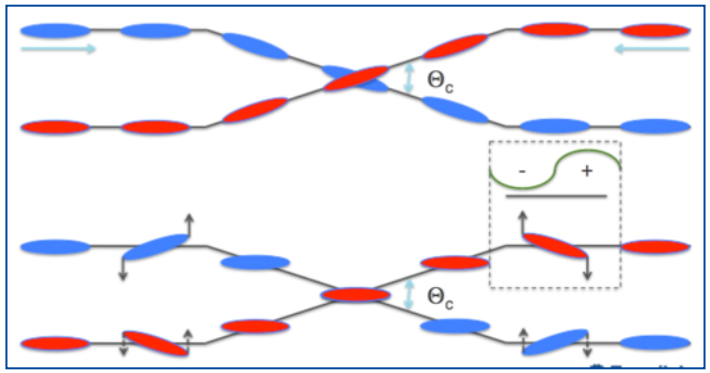
12th February 2015

HL-LHC (2010) in a Nutshell …

- After a ~decade of LHC running and 300 fb^{-1} delivered by ~2020, there will be a need to increase the delivered luminosity by a factor of 10 (to 3000 fb^{-1}) to avoid the well-known "error halving-time" problem.
- Since $\mathcal{L} \propto n_1 n_2/\beta$, HL-LHC will increased $\mathcal{L}$ by:
  - More particles in the bunches (from 1.1 x 10^{11} to 2.2 x 10^{11})
  - Lower β at Collision (from 0.55 cm to 0.15 cm)
- Lower β at collision point implies a larger beam at the location of the final focusing quadrupoles
  - Well known "blow-up before focusing" effect from *Optics 101*.
- Larger beam at Final Focusing quads location implies:
  - *Larger aperture quads(from 7 cm to 15 cm diameter), with higher field on coils and consequent need of Nb_3Sn technology*
  - More separated beams (to keep constant beam separation in σ) and therefore a larger crossing angle. To prevent a larger crossing angle from nullifying the effect of lower β, *a local geometrical correction applied by a scheme using Crab Cavities is envisioned.*
  - *Leveled Luminosity of 5(7.5!)x10^{34} $cm^{-2}s^{-1}$ and PU < 150 (CMS-ATLAS)*
- **Nb_3Sn Quads and SRF Crab Cavities are the hinges of HL-LHC**

…enter "LARP"…

- The US LHC Accelerator Research Program (LARP) was formed in **2003** as a **National Program** to coordinate US R&D related to the LHC accelerator and injector chain at FNAL, BNL, LBNL and SLAC
- FNAL assigned LARP responsibility by Office of Science – HEP
  - LARP Director and Activities Management at FNAL
- LARP has contributed to the initial operation of the LHC, but much of the program has been focused on future upgrades:
  - Increase Luminosity
  - Beam Handling/Monitoring
- The program is currently funded at a level of about $12-14M/year (with present needs of ~16 M$/y) divided among:
  - Magnet research (~half of program)
  - Crab Cavities (~1/5 program)
  - Accelerator research (WBFS, e-hollow lens,..)
  - Programmatic activities, including support for Toohig Fellowship

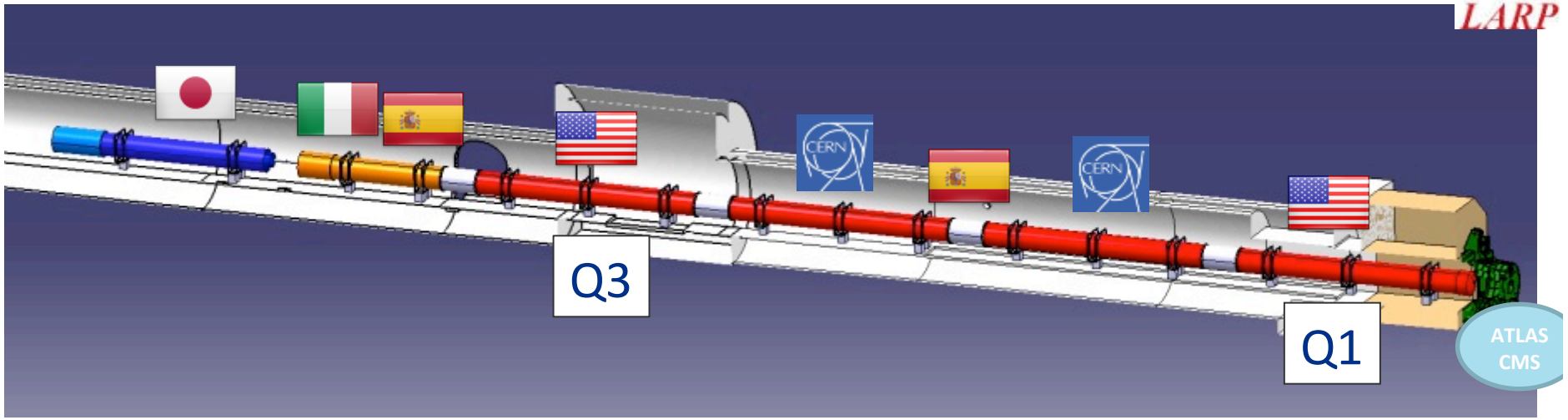


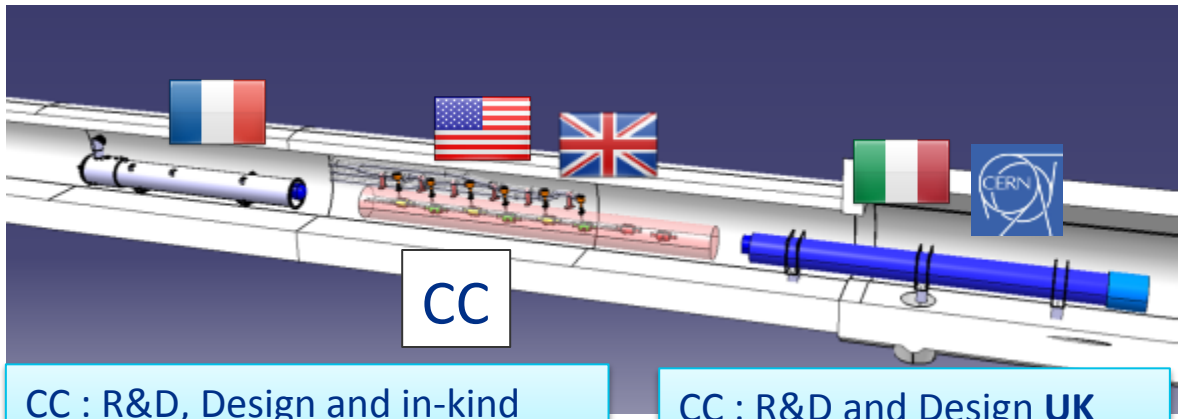
… P5 Report

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.

- LARP in FY15-FY17/18
  - Overall goal: minimize the risk of HL-LHC US in-kind contribution Project in FY18-FY23

Possible Deliverables





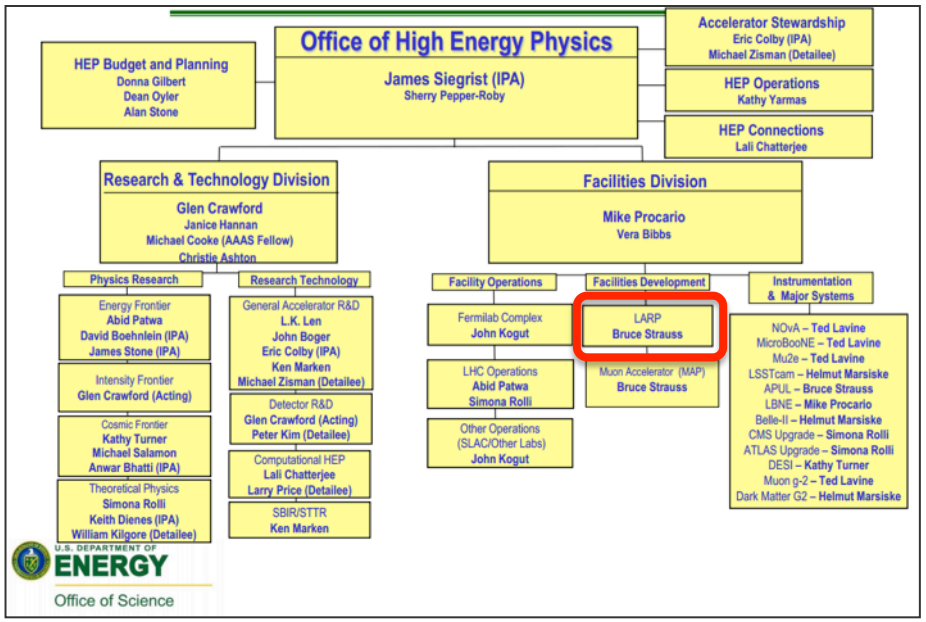
CC : R&D, Design and in-kind **USA**

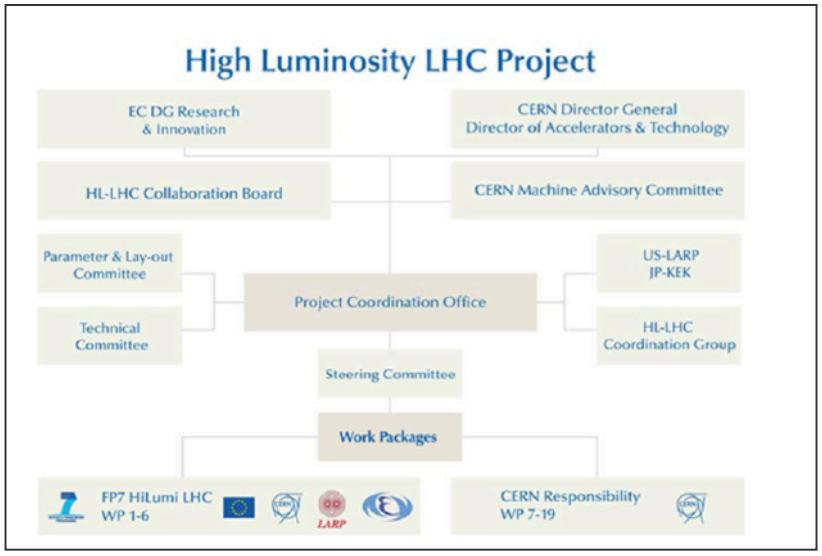
CC : R&D and Design **UK**

Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

- FNAL is **the main player** in Nb_3Sn Quad together with LBL and BNL.
- LBL+BNL+ODU(JLAB)+SLAC leading effort on development of the SRF Crab Cavities.

LARP in DOE and HL-LHC Yellow Book





LARP Goals (FY15-FY17)

- Overall goal: minimize the risk of HL-LHC US in-kind contribution Project in FY18-FY23 for "Baseline Activities" and Support R&D for "Potential Baseline Activities":
  - Build 5 QXF Magnets and 2 Mirror Magnets
    - 1 1-m long SQXFM
    - 2 1-m long SQXF
    - 1 4-m long LQXFM
    - 3 4-m long LQXF (including 2 Mechanical Structures)
    - Develop/Commission 2 production lines (FNAL/BNL)
  - Deliver Four Dressed Crab Cavities for SPS Test
    - 2 QWR
    - 2 RFD
  - Prepare for DOE 413.3B Construction Project
  - Support Toohig Fellowship
  - Support R&D on Acc. Science (if possible)
    - Deliver Fully Functional WBFS for SPS Test
    - Support studies on e-hollow lenses

LARP@FNAL

Risk Reduction

Programmatic/R&D Support

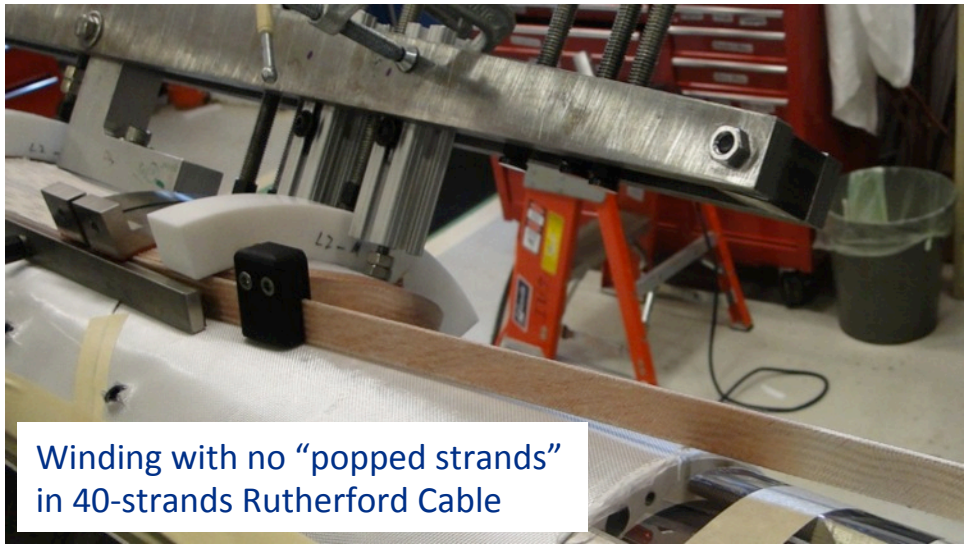
LARP@FNAL

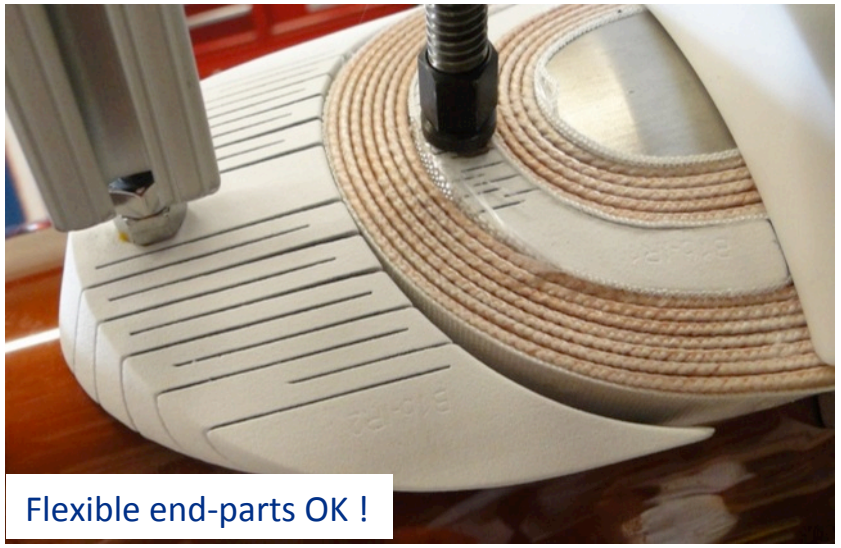
1st 150 mm QXF Coil

LARP

- The quality and significance of the laboratory's recent scientific and technical accomplishments within each of the crosscuts identified above that comprise its entire physics program; and the merit, feasibility and projected impact of its future planned physics program and its alignment with OHEP future plans as expressed in the P5 report;

FNAL Achievements



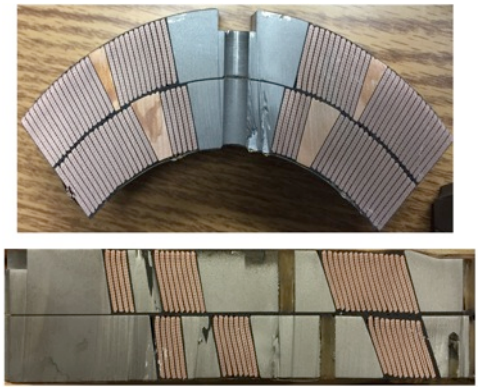


Technology Transfer

MQXFS (Short Models) Coil at FNAL

- MQXFS Coil 01: W&C at FNAL, R&I at BNL.
  Coil 01 was cut and inspected.
- MQXFS Coil 02: W&C, R&I at FNAL.
  Coil 02 ready for Mirror test.
- MQXFS Coil 03: W&C at FNAL, R&I at BNL.
- MQXFS Coil 04: W&C at FNAL, will be R&I at LBL
- MQXFS Coil 05: W&C at FNAL, will be R&I at BNL

Cured Coil
Shipping for R&I

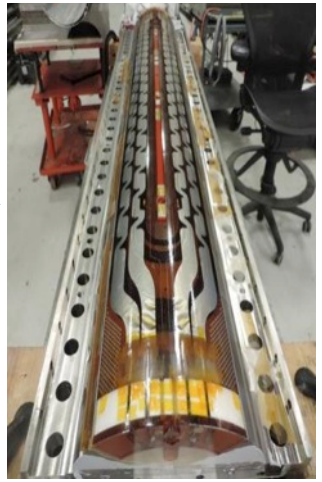


Coil 01 autopsy
inspection

Coil Winding

Coil Curing

Reacted Coil

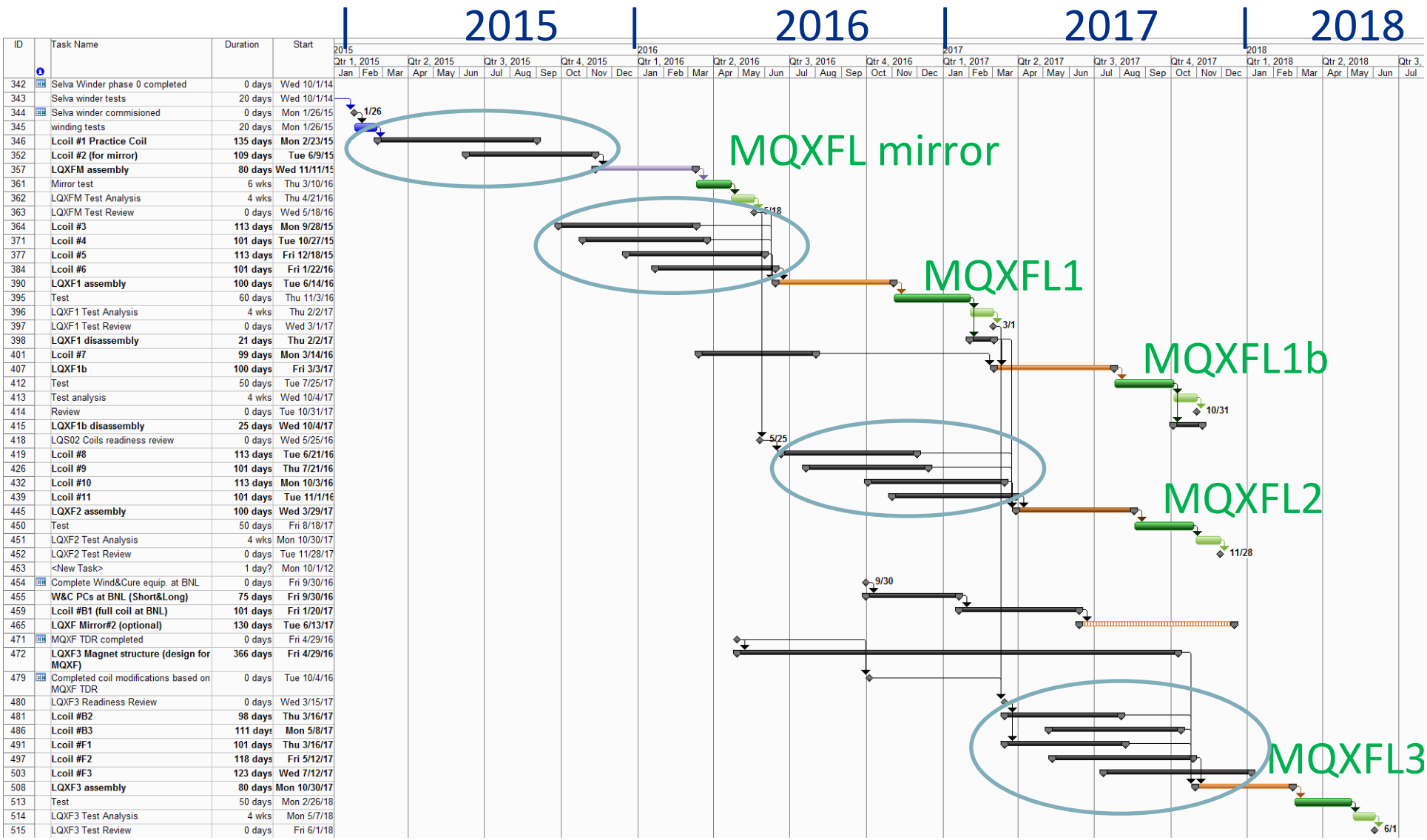


Impregnated Coil

First QXF Coil (in the World) Ready for Testing

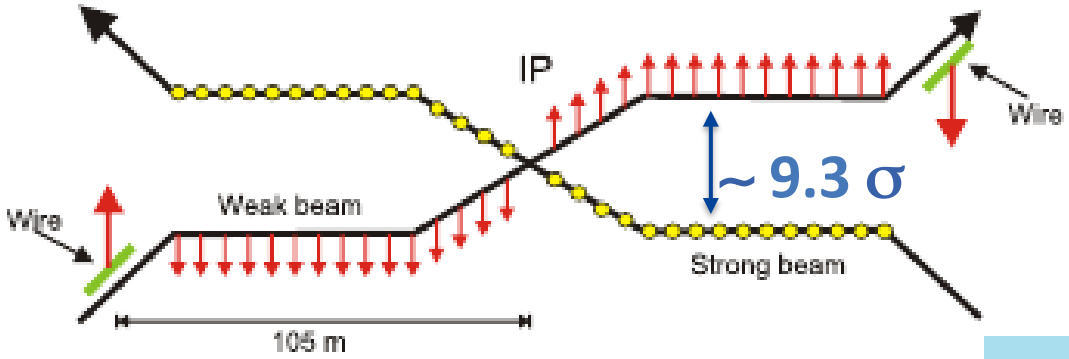
SSL:	21.5 kA
Operations (80% SSL):	17.2 kA

MQXFL (Long Models) at LARP



ID	Task Name	Duration	Start
342	Selva Winder phase 0 completed	0 days	Wed 10/1/14
343	Selva winder tests	20 days	Wed 10/1/14
344	Selva winder commisioned	0 days	Mon 1/26/15
345	winding tests	20 days	Mon 1/26/15
346	**Lcoil #1 Practice Coil**	**135 days**	**Mon 2/23/15**
352	**Lcoil #2 (for mirror)**	**109 days**	**Tue 6/9/15**
357	**LQXFM assembly**	**80 days**	**Wed 11/11/15**
361	Mirror test	6 wks	Thu 3/10/16
362	LQXFM Test Analysis	4 wks	Thu 4/21/16
363	LQXFM Test Review	0 days	Wed 5/18/16
364	**Lcoil #3**	**113 days**	**Mon 9/28/15**
371	**Lcoil #4**	**101 days**	**Tue 10/27/15**
377	**Lcoil #5**	**113 days**	**Fri 12/18/15**
384	**Lcoil #6**	**101 days**	**Fri 1/22/16**
390	**LQXF1 assembly**	**100 days**	**Tue 6/14/16**
395	Test	60 days	Thu 11/3/16
396	LQXF1 Test Analysis	4 wks	Thu 2/2/17
397	LQXF1 Test Review	0 days	Wed 3/1/17
398	**LQXF1 disassembly**	**21 days**	**Thu 2/2/17**
401	**Lcoil #7**	**99 days**	**Mon 3/14/16**
407	**LQXF1b**	**100 days**	**Fri 3/3/17**
412	Test	50 days	Tue 7/25/17
413	Test analysis	4 wks	Wed 10/4/17
414	Review	0 days	Tue 10/31/17
415	**LQXF1b disassembly**	**25 days**	**Wed 10/4/17**
418	LQS02 Coils readiness review	0 days	Wed 5/25/16
419	**Lcoil #8**	**113 days**	**Tue 6/21/16**
426	**Lcoil #9**	**101 days**	**Thu 7/21/16**
432	**Lcoil #10**	**113 days**	**Mon 10/3/16**
439	**Lcoil #11**	**101 days**	**Tue 11/1/16**
445	**LQXF2 assembly**	**100 days**	**Wed 3/29/17**
450	Test	50 days	Fri 8/18/17
451	LQXF2 Test Analysis	4 wks	Mon 10/30/17
452	LQXF2 Test Review	0 days	Tue 11/28/17
453	<New Task>	1 day?	Mon 10/1/12
454	Complete Wind&Cure equip. at BNL	0 days	Fri 9/30/16
455	**W&C PCs at BNL (Short&Long)**	**75 days**	**Fri 9/30/16**
459	**Lcoil #B1 (full coil at BNL)**	**101 days**	**Fri 1/20/17**
465	**LQXF Mirror#2 (optional)**	**130 days**	**Tue 6/13/17**
471	MQXF TDR completed	0 days	Fri 4/29/16
472	**LQXF3 Magnet structure (design for MQXF)**	**366 days**	**Fri 4/29/16**
479	Completed coil modifications based on MQXF TDR	0 days	Tue 10/4/16
480	LQXF3 Readiness Review	0 days	Wed 3/15/17
481	**Lcoil #B2**	**98 days**	**Thu 3/16/17**
486	**Lcoil #B3**	**111 days**	**Mon 5/8/17**
491	**Lcoil #F1**	**101 days**	**Thu 3/16/17**
497	**Lcoil #F2**	**118 days**	**Fri 5/12/17**
503	**Lcoil #F3**	**123 days**	**Wed 7/12/17**
508	**LQXF3 assembly**	**80 days**	**Mon 10/30/17**
513	Test	50 days	Mon 2/26/18
514	LQXF3 Test Analysis	4 wks	Mon 5/7/18
515	LQXF3 Test Review	0 days	Fri 6/1/18

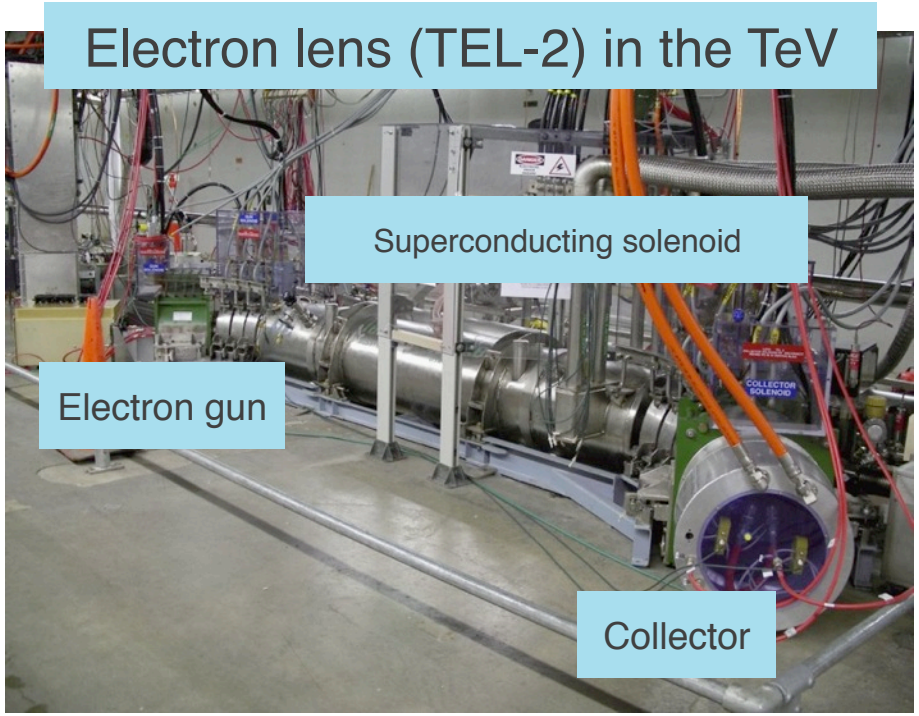
Long Range Beam-Beam Control



- One or two wires placed at ~10 mm from the beam and aligned with the beam to compensate beam-beam effects.
  - Never tested, BB studies in LHC can be unsafe with risk to collimation and machine protection, only B field effect from wire current (200 Am) on beams

….or …..

- Electron lenses for long-range beam-beam compensation are a safer, less demanding alternative, with pulsing option



Facility Operations at LARP

- The effectiveness and efficiency of facility operations, and the planning for future facility upgrades to support the research program as organized into the crosscuts, including appropriateness of the proposed performance metrics in terms of being realistic and maximizing the scientific productivity of the facility;

- At FNAL, LARP benefits immensely from the Magnet Assembly Facilities (TD, mostly IB3 and IB2) put in place by ~40 years of activities in the field of SC-HFM. Specifically related to Nb_3Sn Technology, LARP (*should*) benefit from:
  - 6 m long Reaction Oven
  - Coil Winding Machinery of different kinds (Rotating Tables, SELVA winder,..)
  - Magnet Curing and Impregnation Infrastructure
- Other facilities need to be upgraded for LARP and HL-LHC US Contribution
  - Vertical and Horizontal Magnet Test stands.

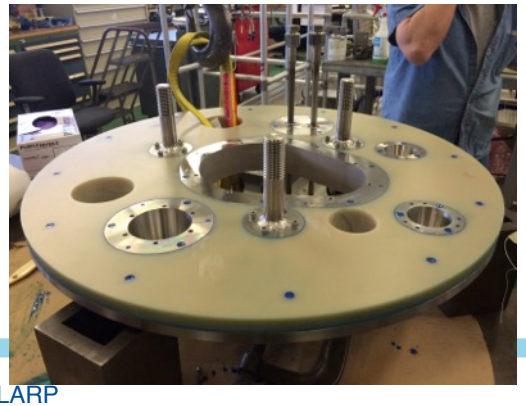
SELVA Winding Machine
Upgraded from Native Control language with LARP Support

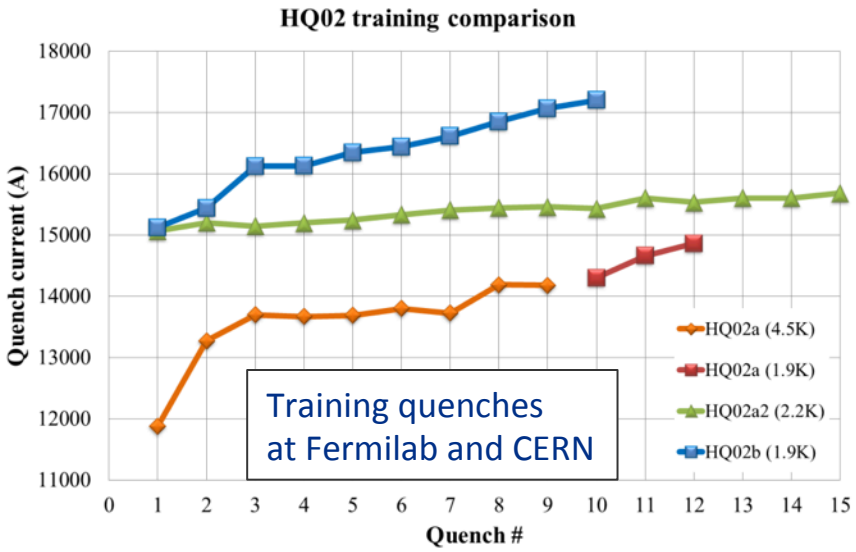
Prioritization Totem @ FNAL

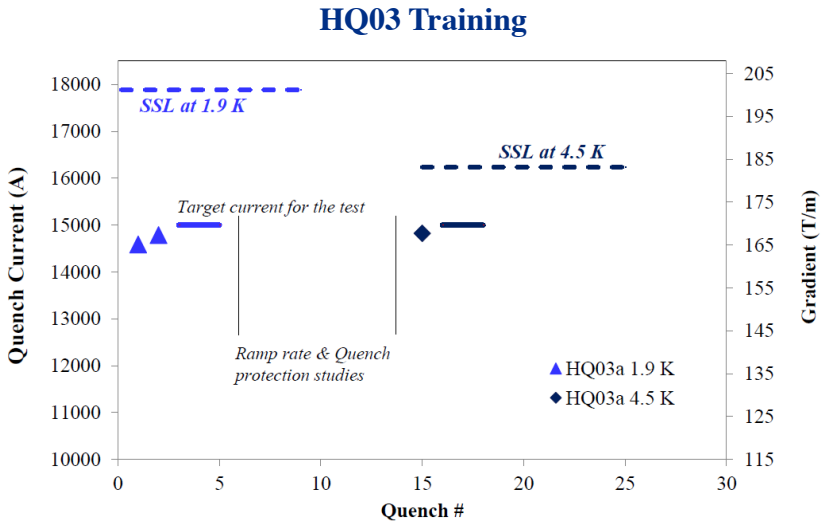
- In the present list of FNAL activities LARP does not appear at, or near, the top of the Lab priorities.
- LARP affected several times at FNAL by prioritization of resources in FY15-Q1
- Engaging TD-HQ in discussion of Prioritization vs. Criticality

Vertical Magnet Testing at FNAL

- Existing infrastructure in VMTF (Vertical Magnet Test Facility) is limited in current performance (up to 15kA)
- New Infrastructure development (30kA limit) is presently LARP bottleneck at FNAL (even though fully funded by LARP in FY15)
  - Resources from Magnet Assembly to Magnet Testing
  - Weekly interaction with Div. Management
- Test with old infrastructure focused on HQ magnet series (120 mm aperture).
  - Confirmed use of SS Core in Rutherford Cable (HQ02a) and agreement of hysteresis with calculations (HQ02a)
  - Proved CLIQ Quench Protection Mechanism (HQ02b at CERN)
  - Confirming coil alignment scheme (HQ03a)
  - Reproducibility between HQ02 and HQ03
  - All magnets extensively tested on ramp-rate dependence



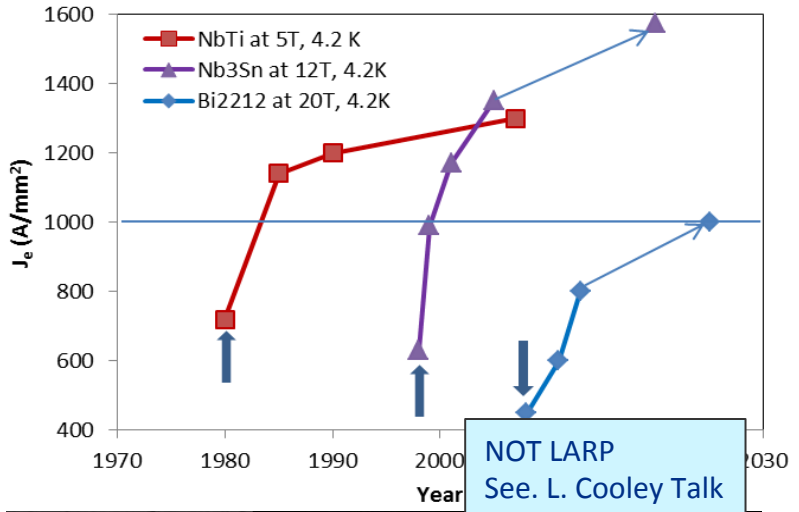


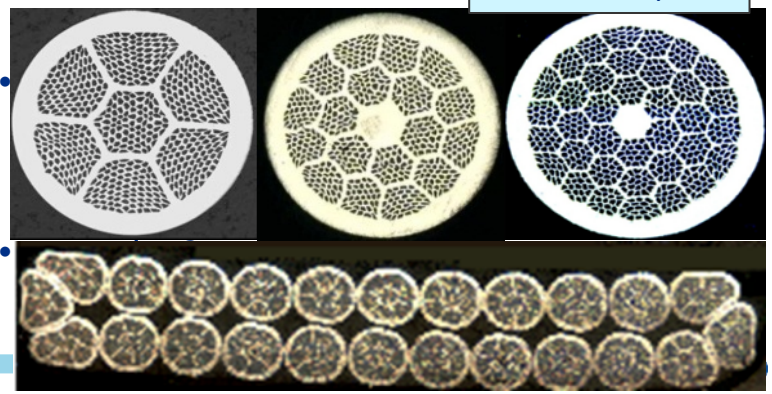


Strategic Planning

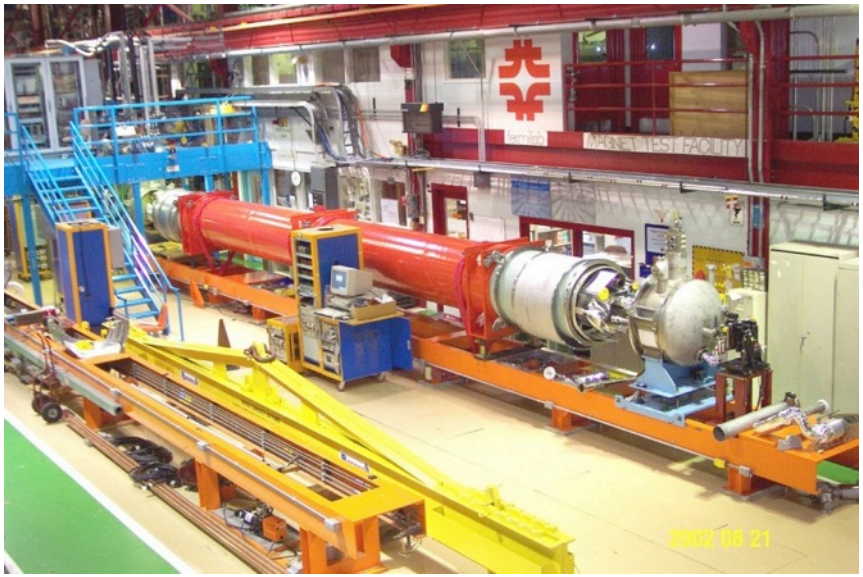
- The effectiveness of current laboratory management in strategic planning, developing appropriate core competencies, implementing a prioritized and optimized program, and promoting and implementing a safe work environment;

- LARP could have not been successful without Core Capabilities in:
  - SC Strand Development and QC Capabilities
  - SC Magnet Assembly Capabilities & Infrastructure
  - SC Magnet Testing Capabilities
- GARD and other R&D programs (Early Career) need to maintain and reinforce core capabilities





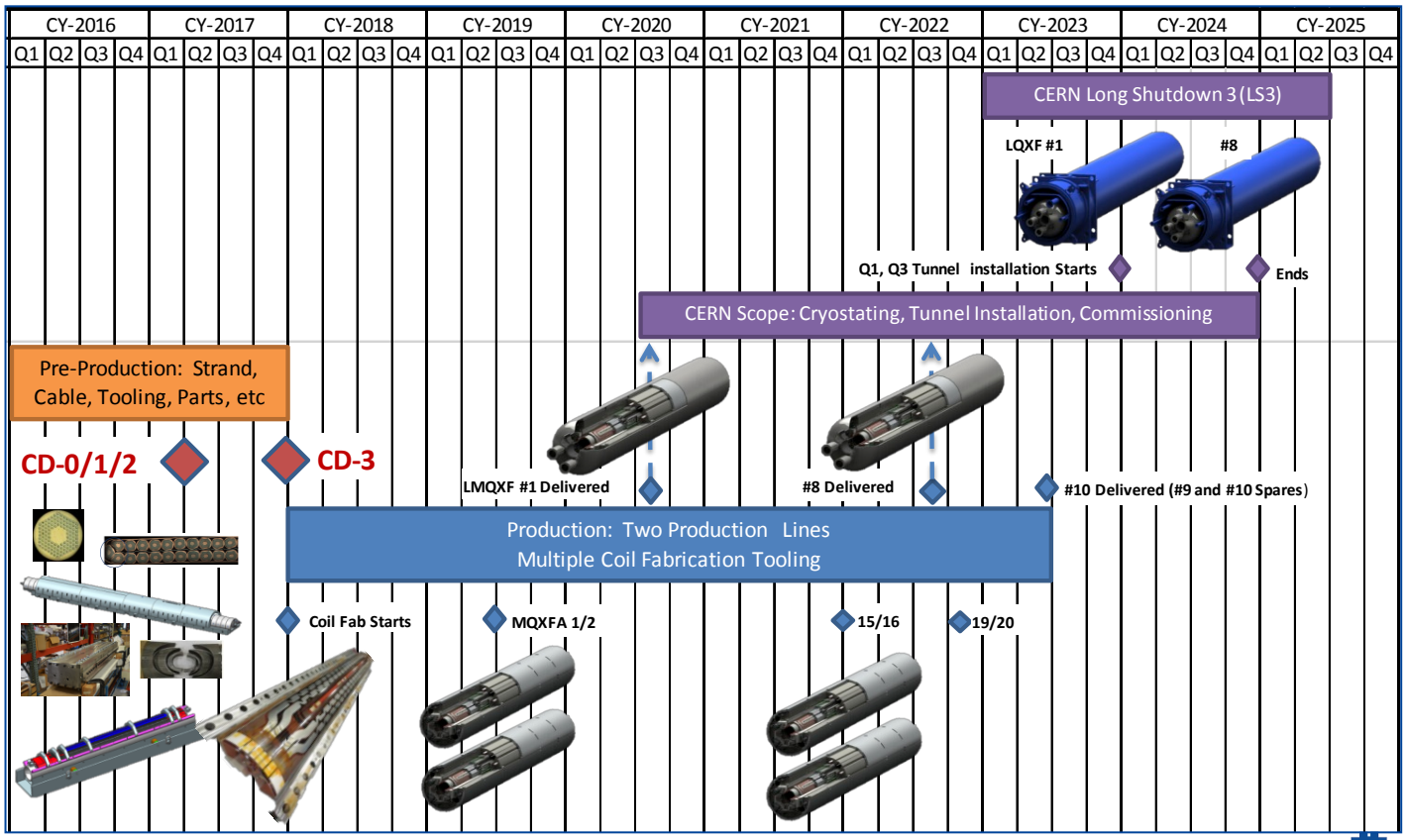
FNAL Horizontal Magnet Test Facility



- Previously used for the present US-LHC Q2 magnets
- Best option for testing ~10 m long new US-HiLumi Q1 and Q3 cold masses
- Needs to be upgraded for higher current (20 kA), larger aperture (150 mm), and new mechanical interfaces
- Requires a re-usable cryostat for testing cold masses
- Engineering effort needed in FY15 to refine cost estimate and conduct initial design activities
- A “match-made-in-heaven” with facilities and capabilities available at FNAL
  - If not funded/supported, bad for LARP, FNAL and HEP in this country.

Development & Oversight of Projects

- The effectiveness of laboratory development and oversight of projects, including the laboratory's efforts to integrate its project efforts with active university and other HEP laboratories involvement;



Scope, Cost & Schedule

- Scope
  - Draft MQXFA Functional Requirements Specification
  - Draft Work Breakdown Structure (WBS)
  - Draft WBS Dictionary
- Cost
  - Bottoms-up Cost Model based on standard activity Basis of Estimate Templates (BOEs) developed by US-HiLUmi
  - More than 135 BOEs generated by L1s, L2s, and L3s provide, for each activity: labor hours by resource type, direct M&S estimates, and duration estimates
  - Cost Model includes FNAL, BNL, LBNL, and SLAC labor rates and M&S Overhead; uncertainty contingency; and escalation
  - Activities are allocated by Fiscal Year (from high level schedule), so a time-phased budget is also generated.

U.S. HiLumi Project	MQXFA Magnets Functional Requirements Specification	US-HiLumi-doc-36 Rev. No. DRAFT v1 Date: 1/9/2015 Page 1 of 20

U.S. HiLumi Project

MQXFA Magnets

FUNCTIONAL REQUIREMENTS SPECIFICATION

Prepared by: Date: Ruben Carcagno, US-HiLumi Project Engineer	Organization FNAL	Contact ruben@fnal.gov (630) 840-3915
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Reviewed by: Date: Ezio Todesco, HL-LHC WP3 (IR Magnets) Manager	Organization CERN	Contact Ezio.Todesco@cern.ch
Reviewed by: Date: GianLuca Sabbi, HL-LHC WP3 (IR Magnets) Manager	Organization LBNL	Contact glsabbi@lbl.gov
Approved by: Date: Giorgio Apollinari, US-LARP Director	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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Toohig Fellowship

> • The quality and appropriateness of the laboratory's interactions with, and nurturing of its scientific community; and

- Commitment to maintain Toohig Fellow program in LARP and US-HiLumi to facilitate the involvement of PostDocs in the US to work at the leading Energy Frontier Machine for the next ~2 decades.
- New Toohig Fellow:
  - Trey Holick (U. Texas A&M)
- Given present uncertainty on existence of a "LARP 2" (i.e. an R&D program in parallel to **US-HiLumi** Project to support R&D efforts and a generic fellowship) it is necessary to "evolve" the Toohig fellowship toward direct support of **US-HiLumi** deliverables:
  - I. Pong: QA/QC on SC Strand/Cables
  - T. Holick: QA/QC on Coils/Magnet Construction
  - S. Verdu: CC Construction and Testing

Conclusions

- LARP manages activities across the US-DOE Lab System to position our country in the best possible way for a US in-kind contribution to HL-LHC
  - Prove Technology and Minimize Risk
- FNAL, as an Institution, masters the capabilities to contribute proficiently to what appear the two most likely candidates for US deliverables:
  - Nb_3Sn Magnets for Q1 and Q3 Focusing Quadrupoles
  - Dressed Crab Cavities
- FNAL leading preparation for DOE 413.3B Construction Project, with consolidated CD-0/1/2 DOE Review anticipated in Spring 2017.
- FNAL resources in LARP are efficiently using available infrastructure to focus on the production-readiness of Nb_3Sn quadrupoles.

Support Slides

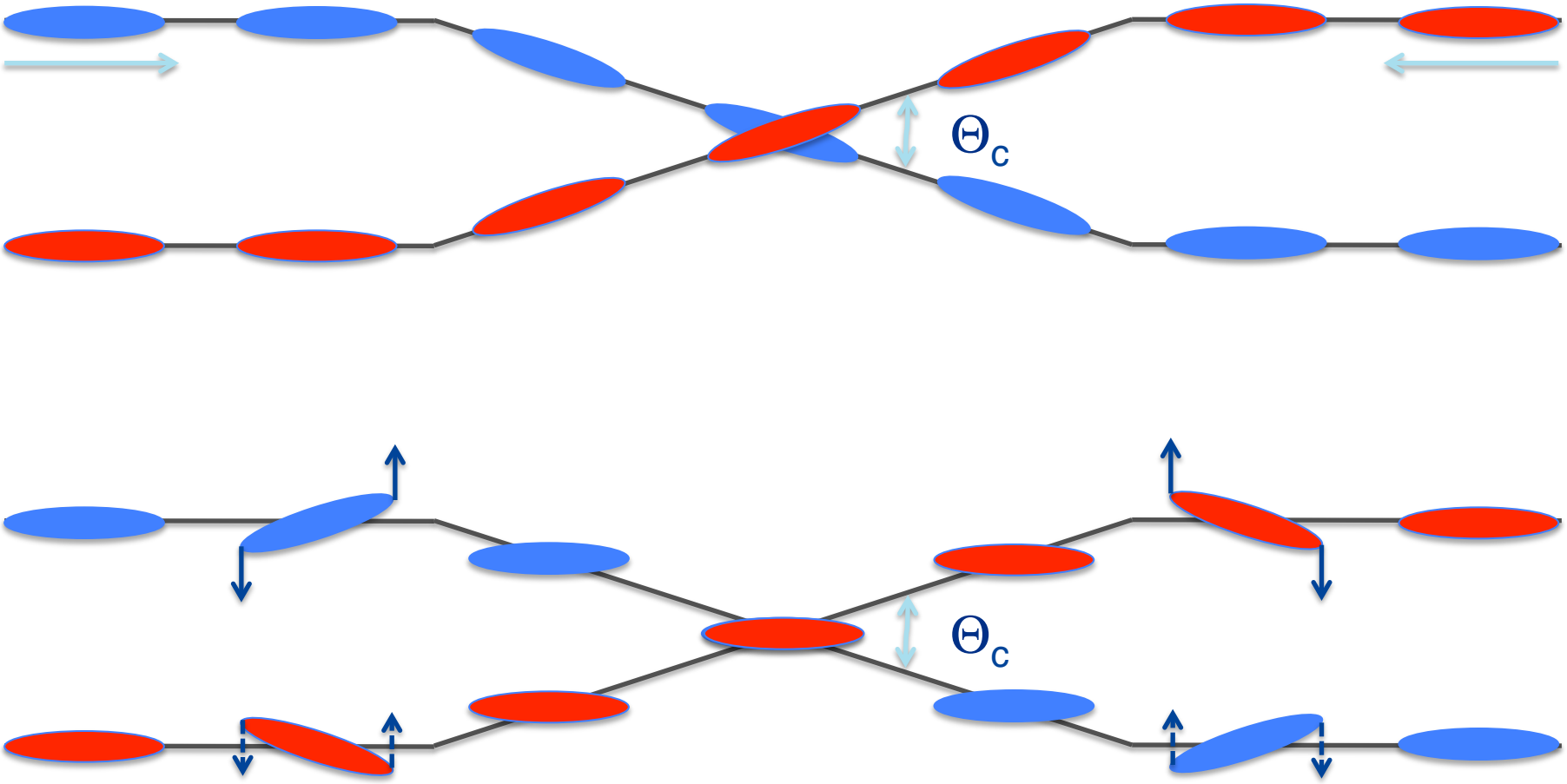
International Technical Reviews of LARP/CERN Magnet Design

"This significant milestone (i.e. MQXF for HL-LHC) will open up the route to much higher energy accelerators than the LHC using for the first time superconductors beyond Nb-Ti in its main magnets."

- Series of critical design reviews for MQXF design
  - November '14: Conductor and Cable
  - December '14: Magnet Design
  - 2015-16: Final Tech. Des. Rev & Production Review
- Int. Conductor and Cable Review (CERN Nov 5-6, '14)
  - Reduce keystone angle of PIT cable and support PIT R&D
  - Consider same change for RRP cable
  - Optimize margin & Confirm strand/Cable specs by model program
- Int. Magnet Design Review (CERN Dec 10-12, '14)
  - Increase Margin (longer length, lower gradient)
- In general, work and cooperation sharing between LARP labs and CERN defined exemplary.

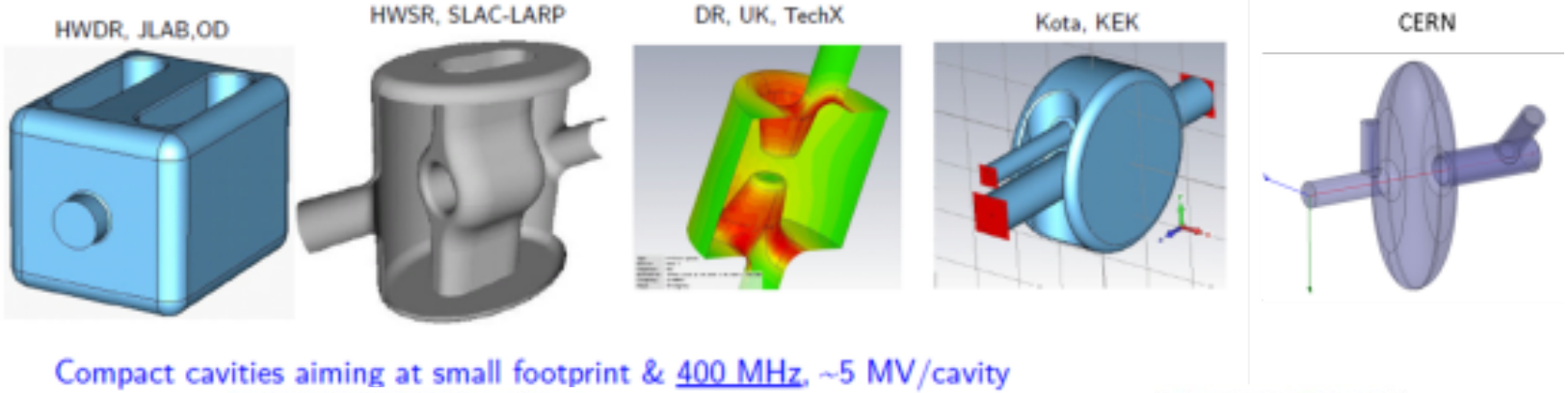
Crab Cavities

- Larger Crossing angle (~300 μrad in HL-LHC vs. ~150 μrad in LHC) calls for a correction of individual bunches orientation



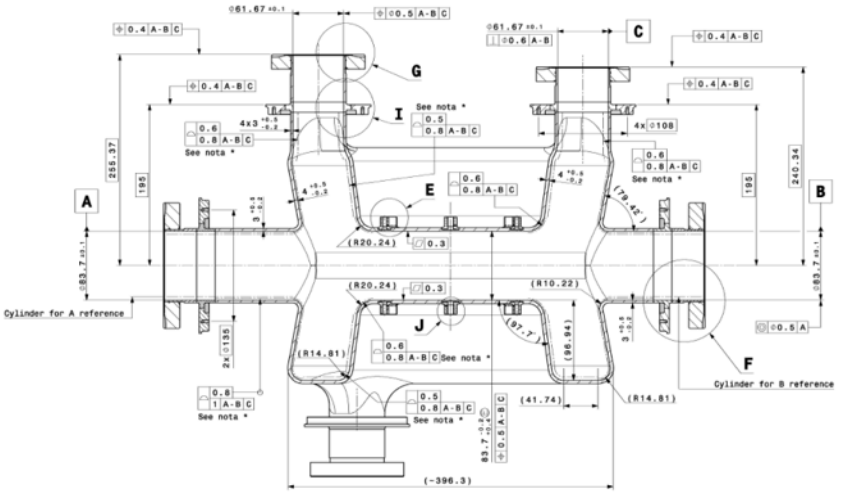
From Several Models to 2 Candidates

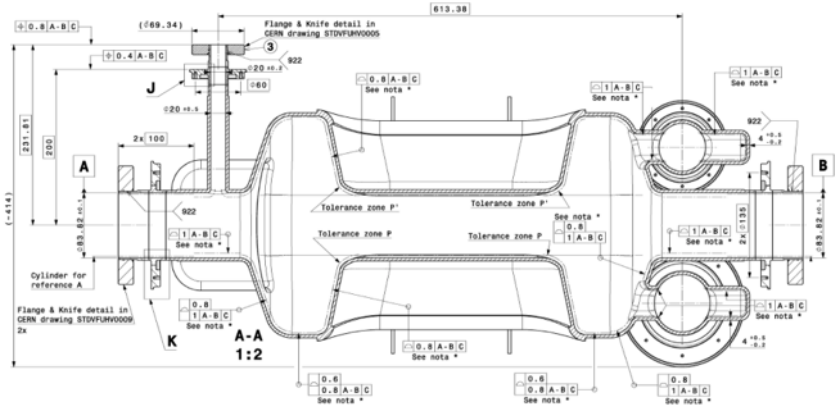
- Lot of Different ideas
- LARP "commitment" to SPS Test with delivery of He-dressed cavities
  - Cryomodule dropped from LARP contribution at time of 2013 HiLumi-LARP meeting at Daresbury

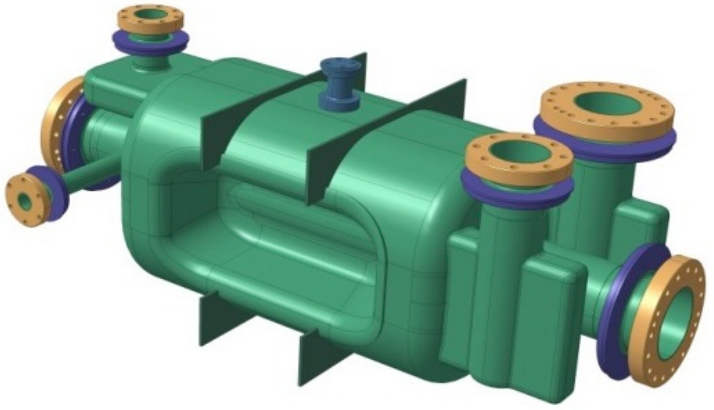


Int. Review on May 2014:
Concentrate on two designs (RFD & DQW)

Bare cavities with interfaces



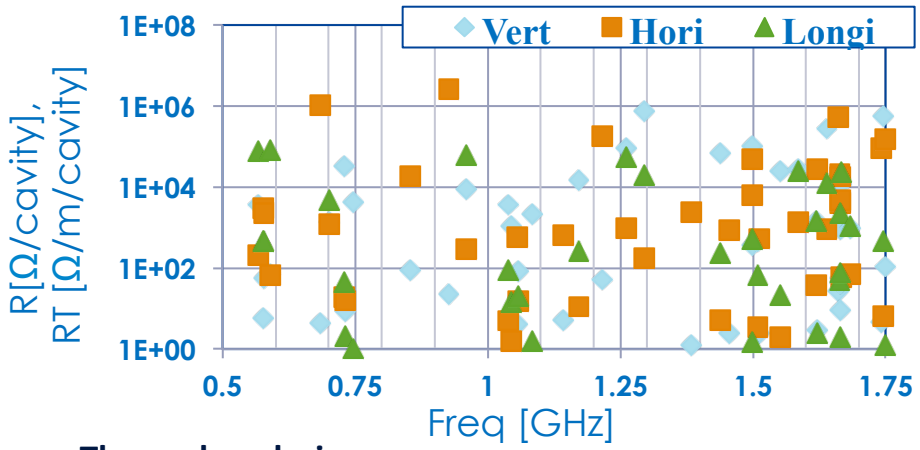




DQW HOM Filter

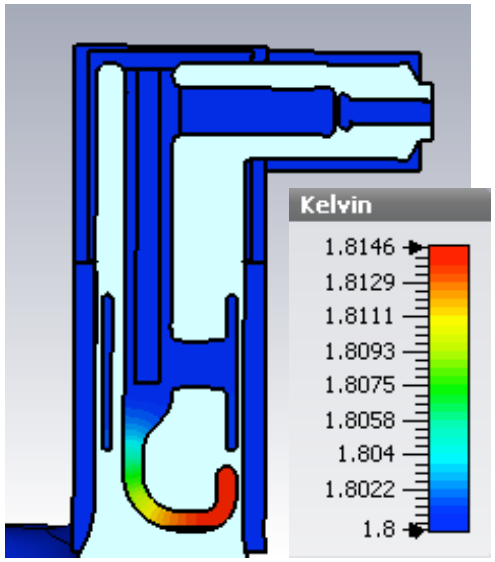
LARP

HOM Impedance

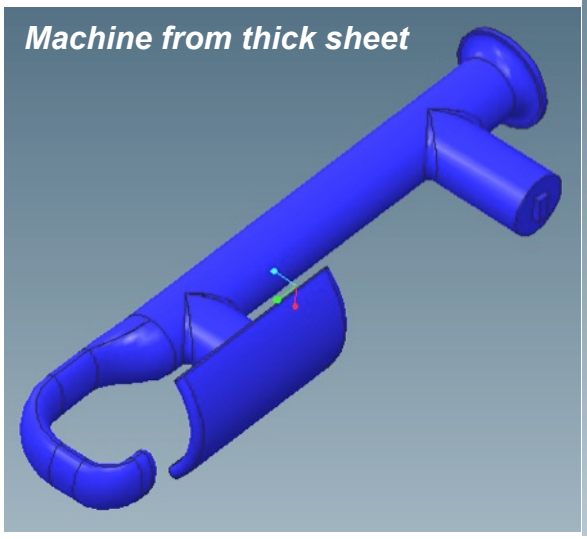


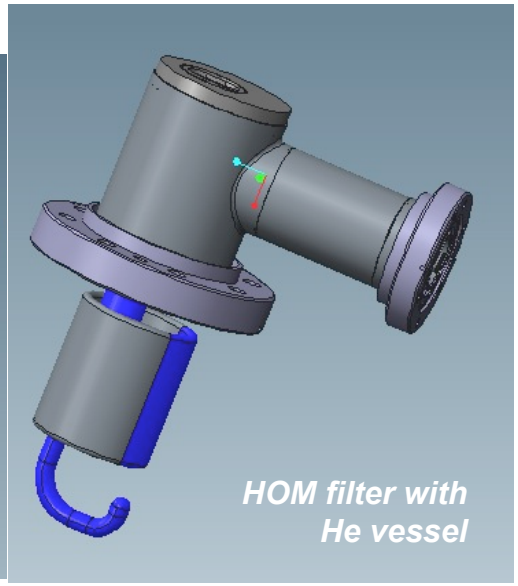
- Impedances are calculated considering the assembling errors. Tables are generated and sent to CERN for verification.
- HOM power is about 69 Watts per cavity. Power of transverse modes estimated based on 5mm offsets.
- In the worst case the power increased to 86 Watts if HOM frequencies shift in ±2.5 MHz range.
- HOM induced heat on the Cu gaskets and Cu pins are in mW range.
- Thermal analysis is on-going
- Machining study is on-going

Thermal analysis

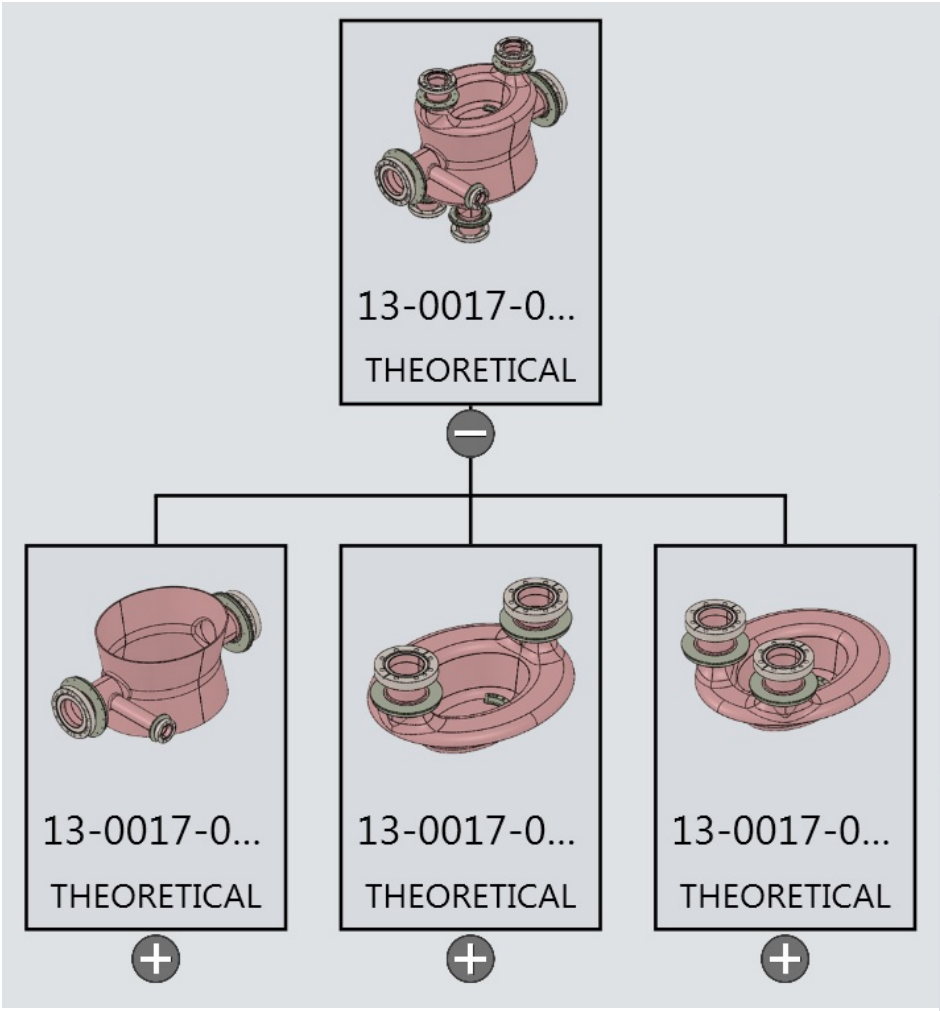


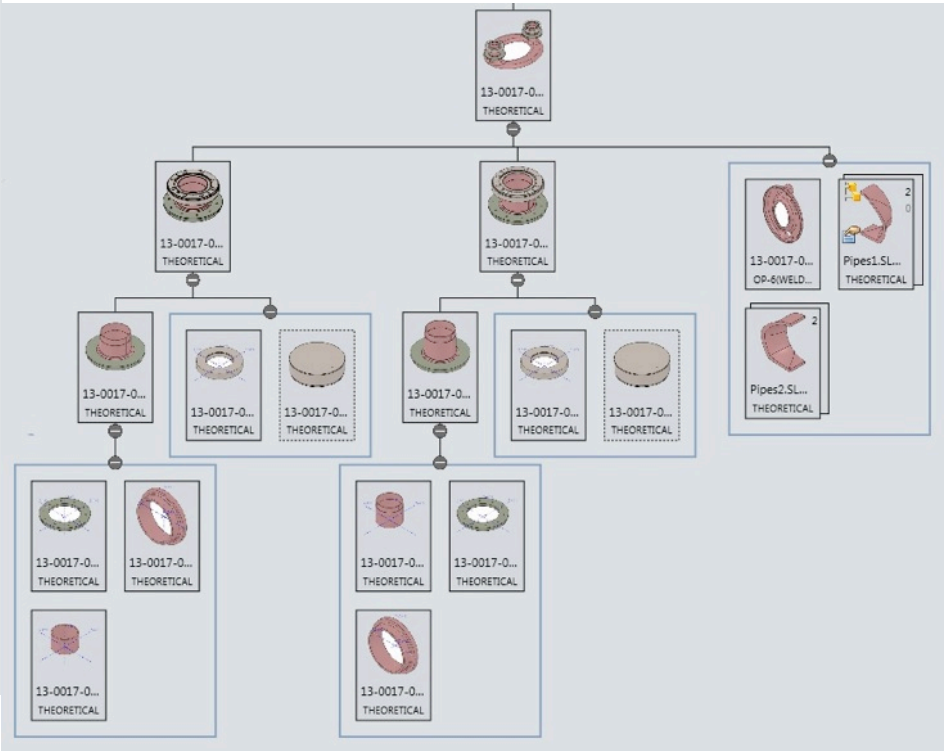
Machining study



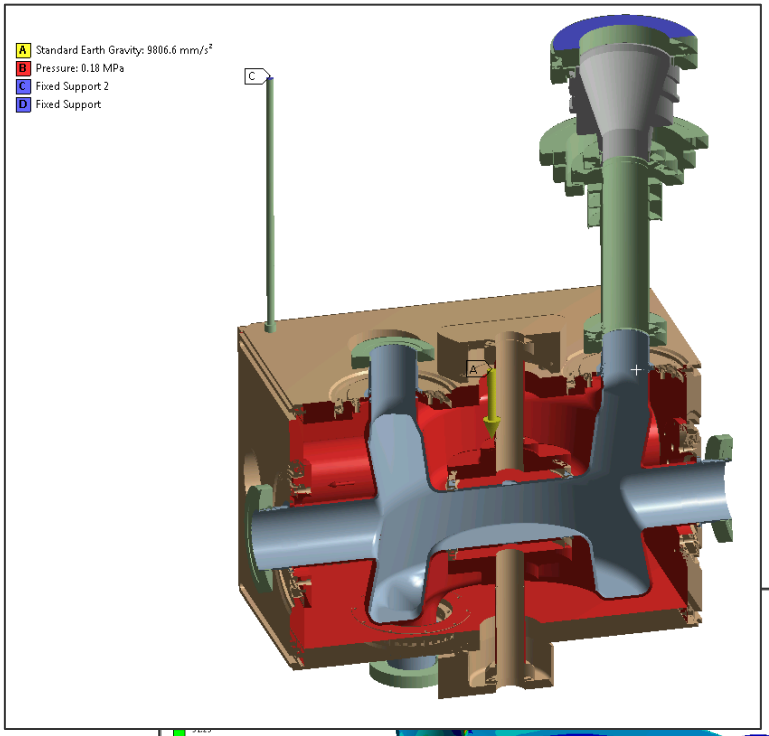


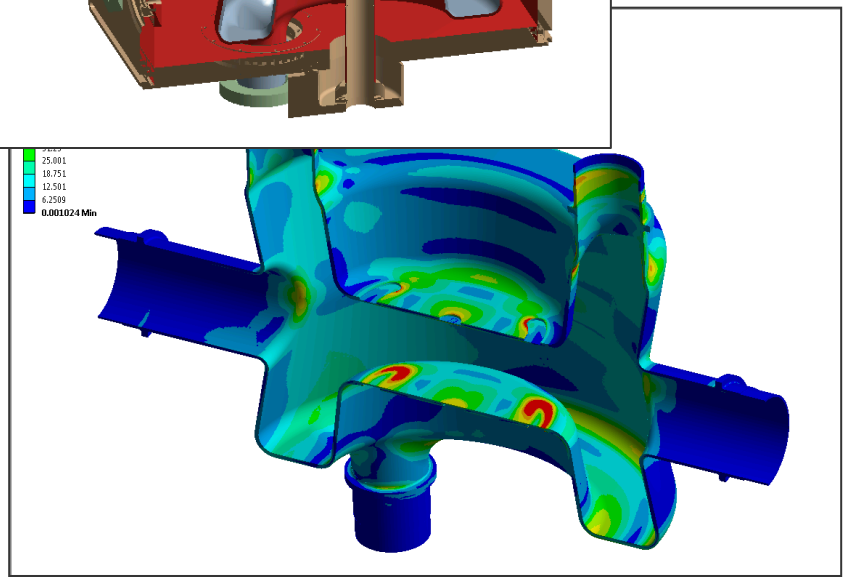
Cavity Design and Assembly at Niowave



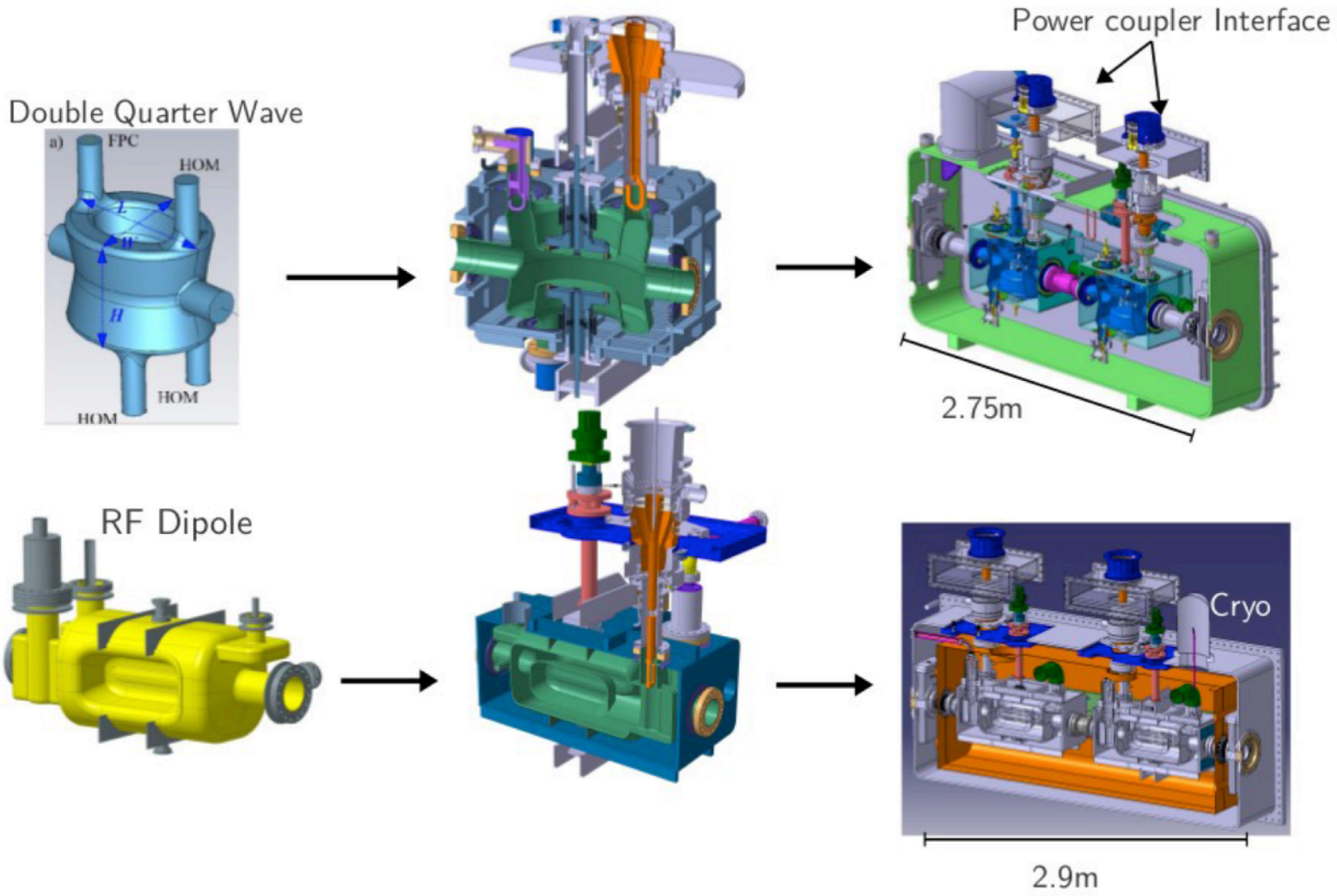


He Vessel – Cavity



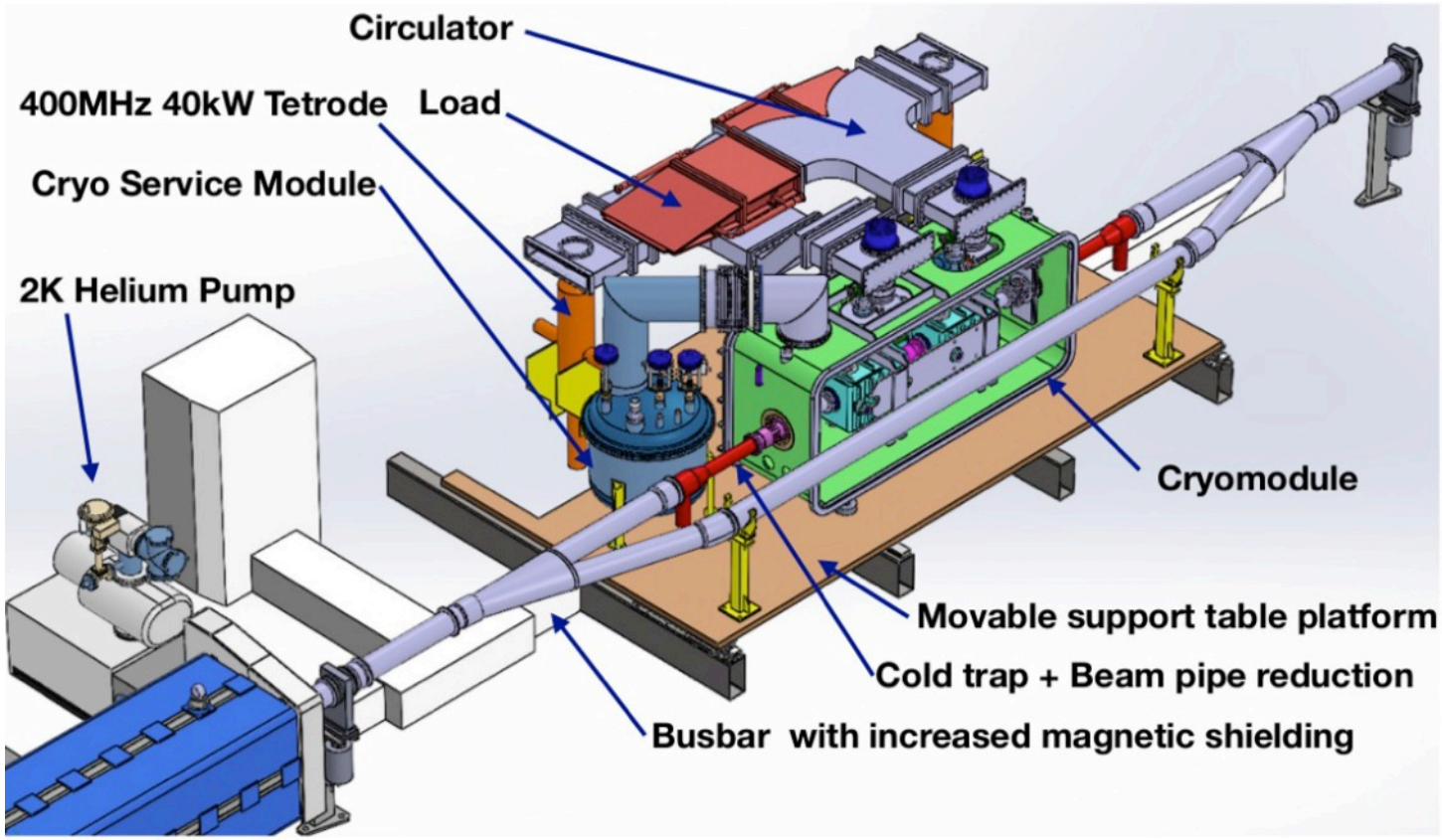


SPS Cryomodule by CERN



SPS Integration

- SPS installation of 2 Cavities and RF/Cryo infrastructure.
- Movable table for CC Machine Development studies

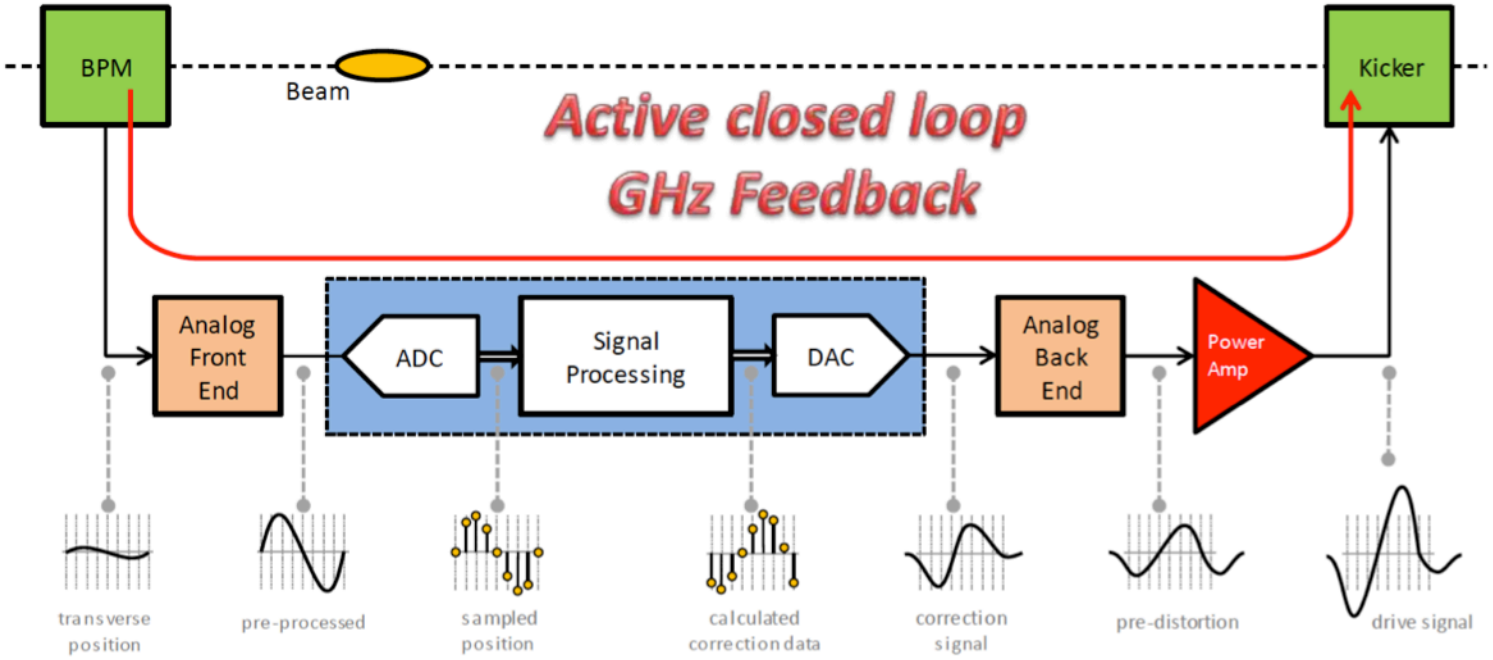


Goals for CC-LARP

- Complete SPS Cavities
  - Challenges: M&S funding for HOM and tuning mechanics in FY15.
- Complete set of International Reviews a-la-MQXF
  - HOM design review in early '15 (?)
- Planning beyond SPS Test
  - Do we need an LHC Prototype ? *YES*
  - What will LARP or US-HiLumi provide to LHC Prototype ?

    ? 3-V and 3-H Cavities ?
    - Aggressive timing (start by 2016) a challenging resources allocation problem within LARP for LHC Prototypes
  - Defensible baseline by late'15 is a must to allow inclusion of CC in US-HiLumi deliverables in a FY18-FY23 Project

WBFS for Stability Control



- Control of Ecloud and Impedance-driven transverse instabilities in the SPS as HL-LHC Injector - Demo system achieved closed loop control November 2012 before LS1
- GHz Bandwidth Digital Signal Processing via reconfigurable architecture
- Optimal Control Formalism - allows formal methods to quantify stability and dynamics, margins
- Research Phase uses numerical simulations (HeadTail), Reduced Models, technology development, 1 bunch Demonstrator, SPS Machine Measurements

Stripline kicker & Power Amplifiers

- CERN, LNF-INFN, LBL and SLAC Collaboration. Design Report SLAC-R-1037
- Stripline fabricated by E. Montesinos et al , Installed with 3 kicker support system.
- New wideband power amps evaluated. Selection of 1 GHz amps for Dec. 2014
- Slotline Kicker design in optimization (S. Verdu) - fab in 2015

MD Studies in FY15 & FY16

- The Demo system is being upgraded for MD studies, and technology development through the end of 2016
  - Explore scrubbing fill control - MD November 2014, closed-loop December 2014
  - Explore Q20 control methods (New filters? Multiple pickups?) - optimize system performance
  - Validate multi-bunch control Spring FY2015
  - Diagnostic and beam instrumentation techniques to optimize feedback parameters and understand system effectiveness
  - Evaluate Stripline and Slotline wideband kickers and RF Amplifiers with beam
  - We benefit from synergistic combination of simulation models, machine measurements, and technology development
- Technology Development and system estimation for 4 -8 GS/sec Full-function system
  - lab evaluation and firmware development
  - estimation of possible bandwidths, multiple pickup/kicker architectures, technology options
- WBFS has been estimated and budgeted within the LARP system for future production decision