QXF Progress & Recent Results

G. Ambrosio
on behalf of the MQXF team

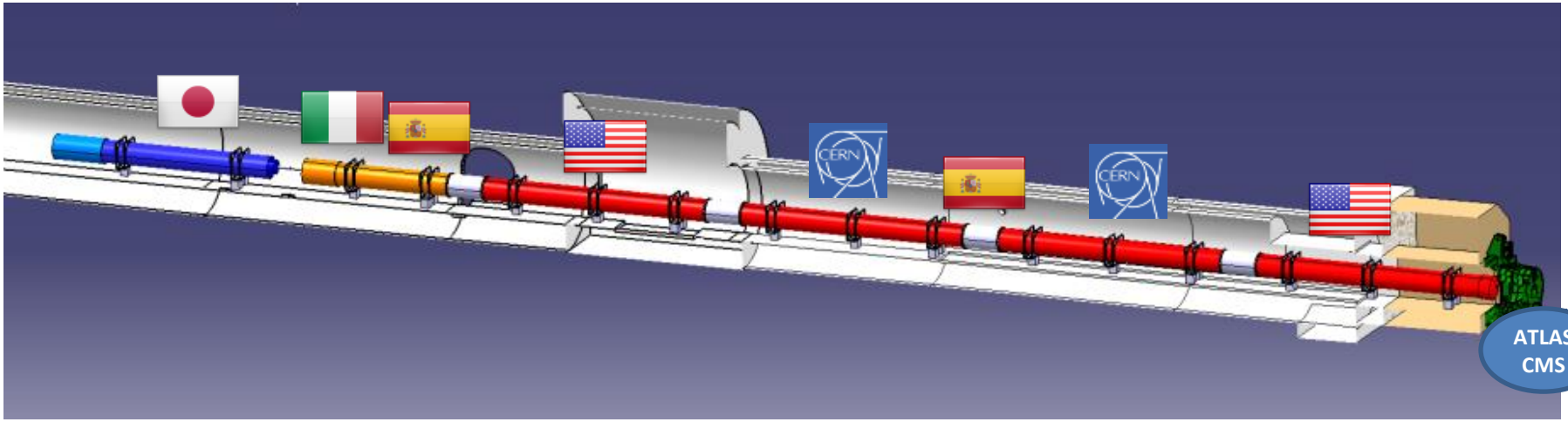
4th Joint HiLumi LHC-LARP Annual Meeting
November 17-21, 2014
KEK

Outline

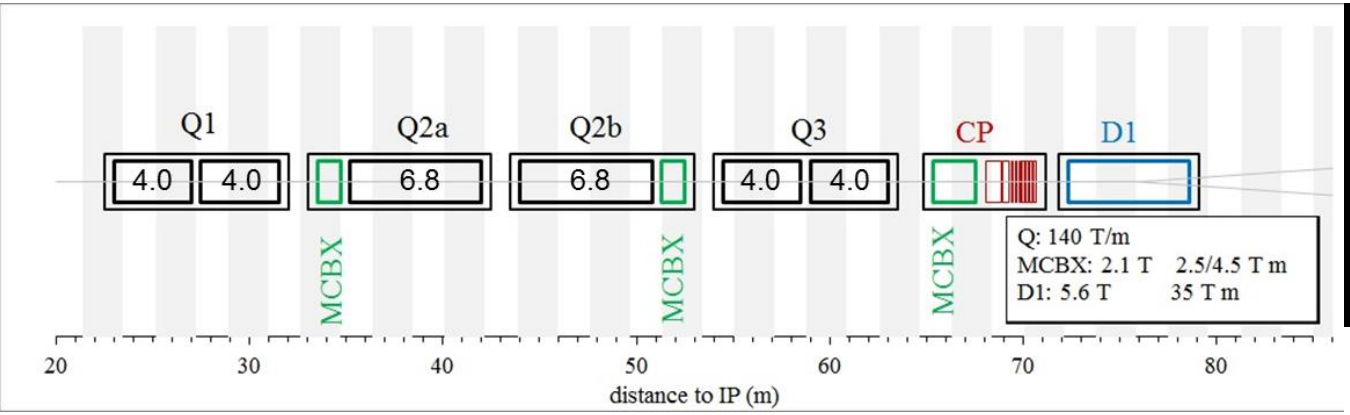
- Main features
- Design Progress
- Short Models status
- Long Prototypes status
  - LHQ coil test results
- Conclusions

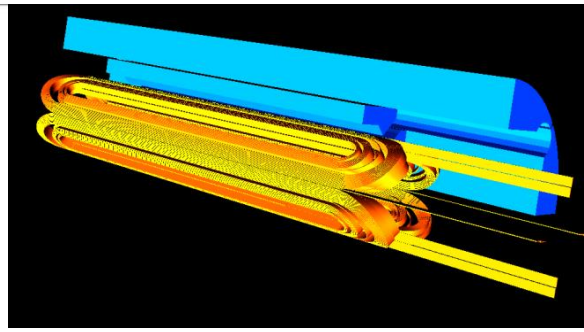
MQXF Main Parameters

- 140 T/m in 150 mm coil aperture
- Q1/Q3 length: 8 m
- Q2 length: 6.8 m
- Max outer diameter: 630 mm
- 1.9 K operating temperature
- Radiation strength: > 33 MGy
- Field quality: see WP3 page at *https://espace.cern.ch/HiLumi/WP3/SitePages/Home.aspx*



MQXF Lengths





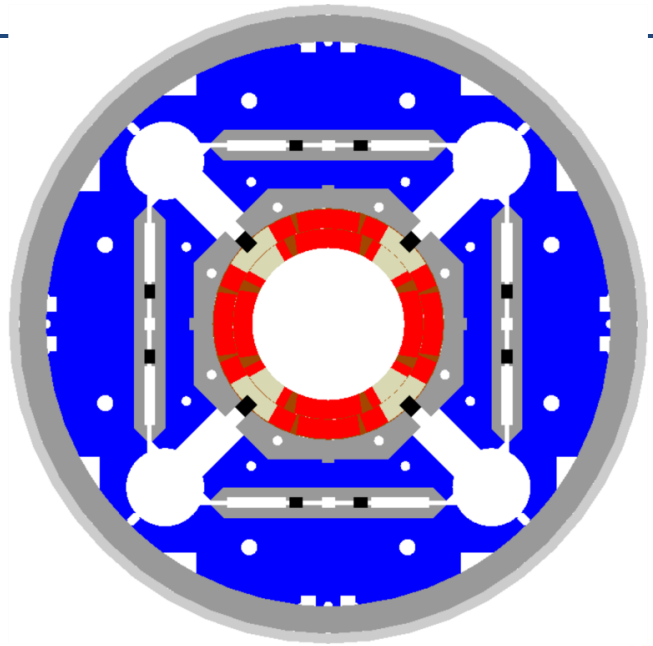
	Short model	Q1/Q3 (half unit)	Q2
Magnetic length [m]	1.2	4.0	6.8
"Good" field quality [m]	0.5	3.3	6.1
Cable unit length per coil [m]	150	450	710
Strand per coil [km]	6.5	18.9	30

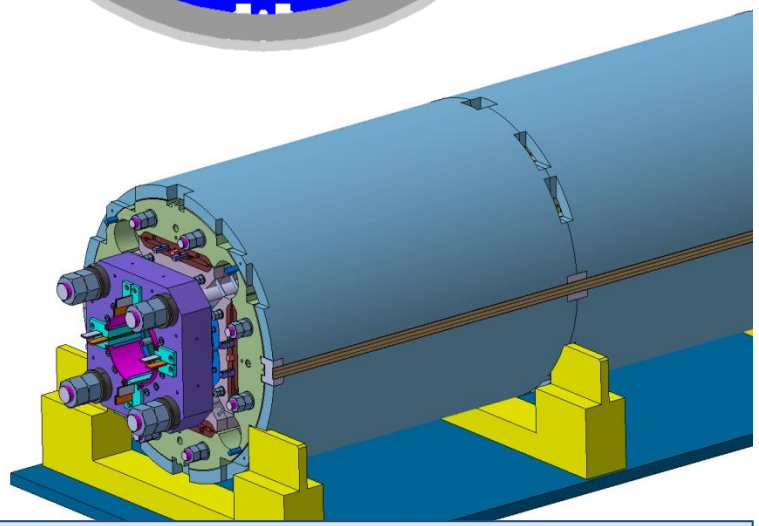
E. Todesco, et al., "A First Baseline for the Magnets in the High Luminosity LHC Insertion Regions", *IEEE Trans. Appl. Supercond.*, Vol. 24, No. 3, pp. 4003305, June 2014

MQXF Main Design Features

Same design for Q1/Q3 and Q2s:

- Two-layer coils
  - Without internal splice
  - With one wedge per layer
- Al shell structure preloaded by bladders and keys
  - Segmented Al shell
- Axial preload by tie-rods
- Quench protection by active heaters
  - and possibly CLIQ





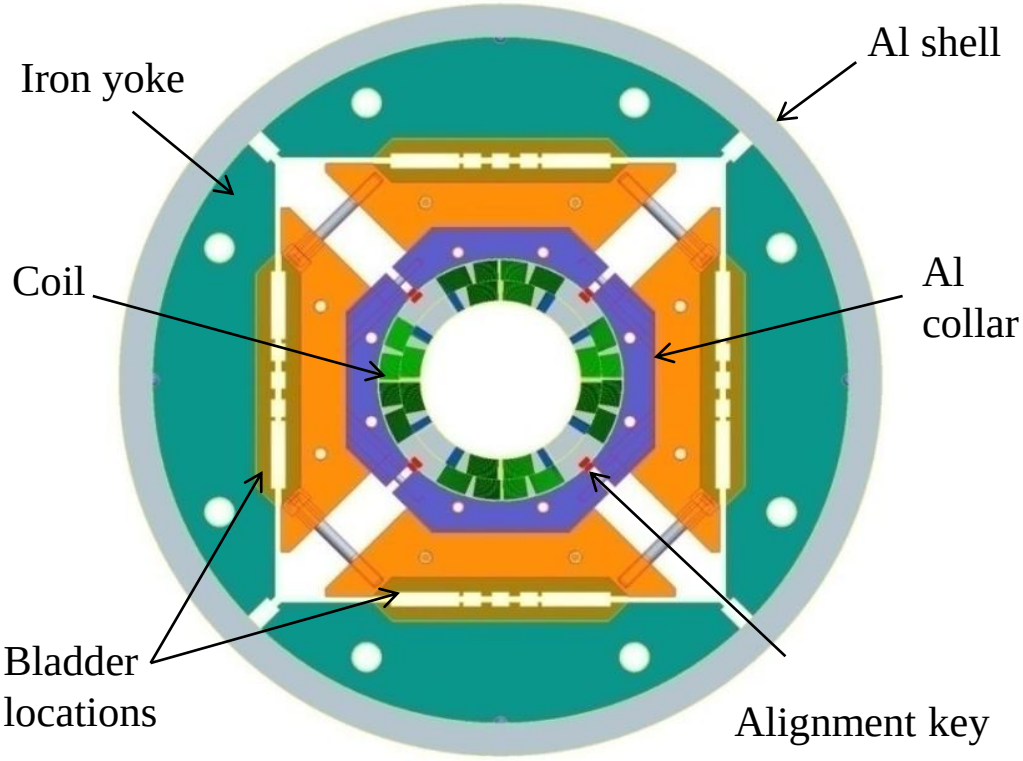
P. Ferracin, *et al.,* "Magnet design of the 150 mm aperture low-β quadrupoles for the high luminosity LHC," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, p. 4002306, Jun. 2014

High Field Quadrupole (HQ)

- Goal: **demonstrate all performance requirements for Nb_3Sn IR Quads** *in the range of interest for HL-LHC* (magnetic, mechanical, quench protection etc.)
- Main design parameters and features in the latest models tested (HQ02a/b):

Conductor and cable	
Strand diam. (mm)	0.778
Cu/Sc	1.2
No. strands	35
Cable width (mm)	14.8
Cable thickness (mm)	1.375
Keystone angle (deg.)	0.75

Short Sample Performance		
Param.	4.5K	1.9K
I_{ss} [kA]	16.4	18.2
B_{pk} [T]	12.9	14.2
G_{ss} [T/m]	186	205



HQ02 Results

Quench performance

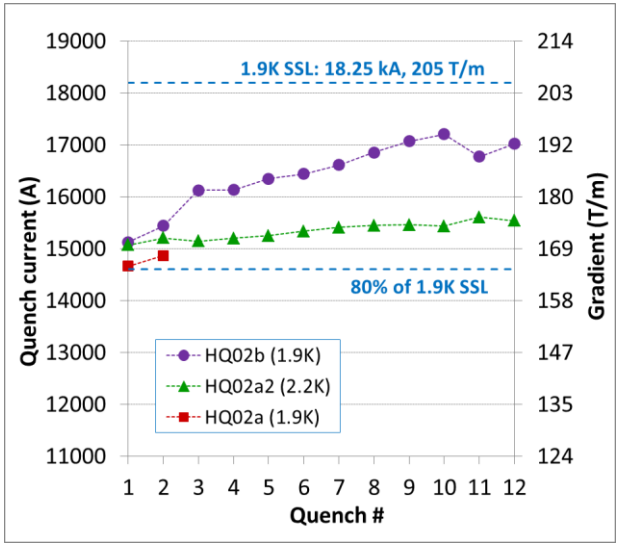
- HQ02: 98% at 4.5K
- HQ02b: 95% at 1.9K with 200 MPa pre-load

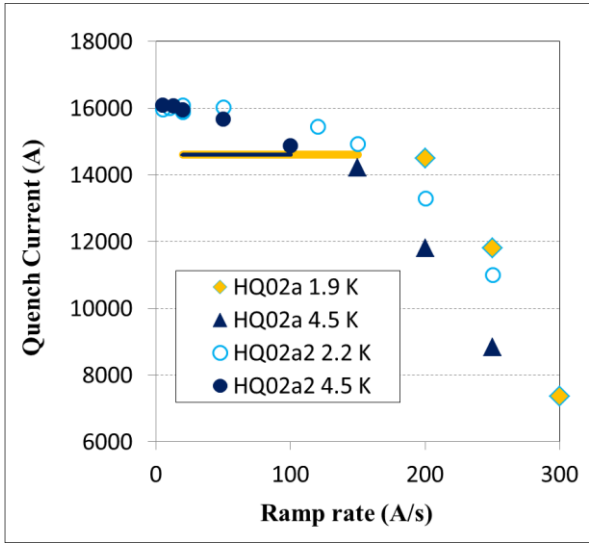
Accelerator Quality

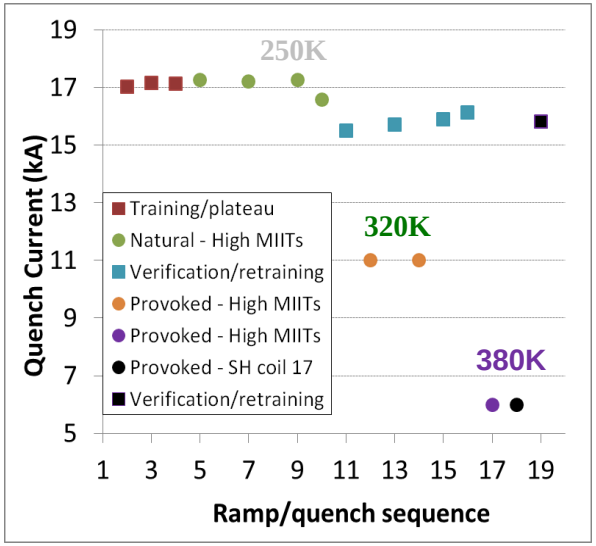
- Order of magnitude reduction of dynamic effects (ramp rate, field quality) with cable core

Quench protection

- 380K quench temperature without degradation
- Successful first test of the CLIQ system in Nb_3Sn

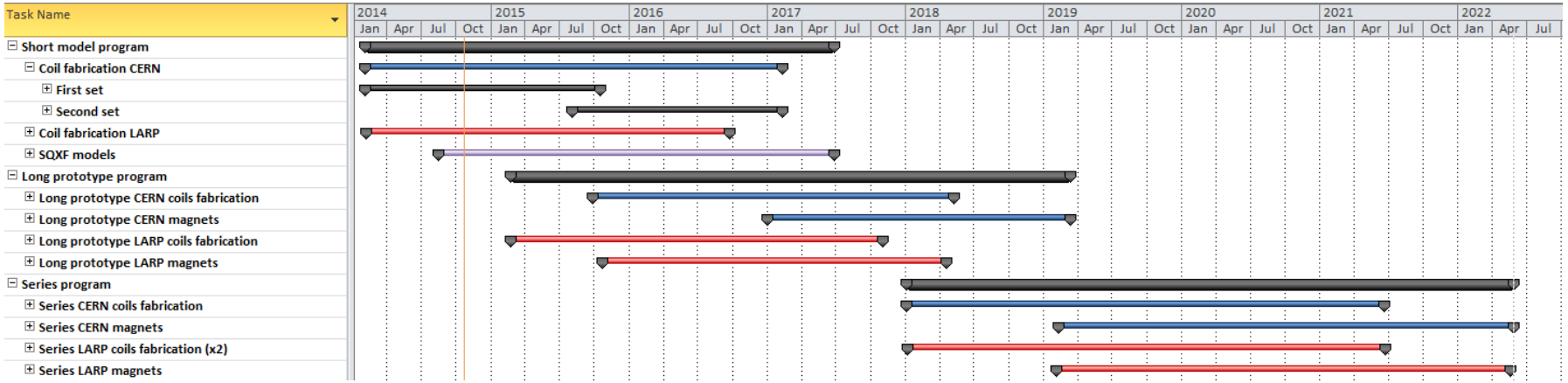






H. Bajas, et al., "Cold Test Results of the LARP HQ02-b magnet at 1.9 K", to be published in *IEEE Trans. Appl. Supercond.*, 2015.

MQXF Schedule

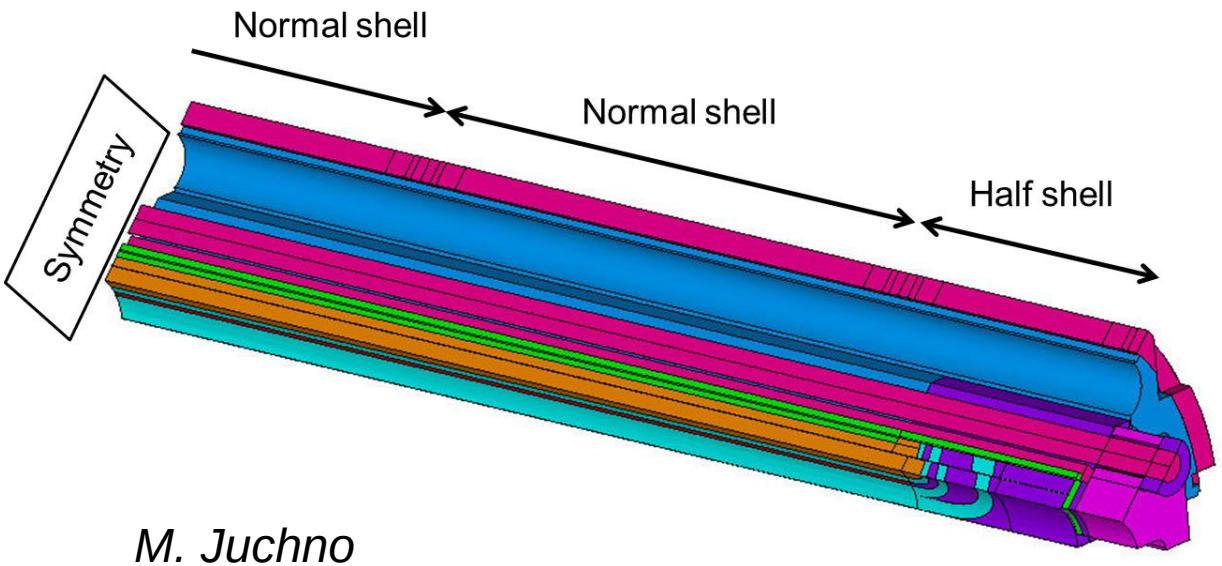


- Short model program: *5 CERN-LARP models*, **2014-2017**
  - Coil fabrication started in 03/2014
  - First magnet test (MQXFS1) in 07/2015 (3 LARP coils, 1 CERN coil)
- Long prototype program: *2 (CERN) + 3 (LARP) models*, **2015-2018**
  - Coil fabrication starts in 2015: 02 (LARP), 10 (CERN)
  - First magnet test in 11/2016 (LARP) and 07/2017 (CERN)
- Series production: *10 (CERN) + 10 (LARP) cold masses*, **2018-2022**
  - Coil fabrication starts in 01/2018
  - First magnet test in 10/2019

RECENT DESIGN PROGRESS

Structural Design

- 3D model used for optimization of structure
  - Design adjustments in order to reduce stress variations due to segmented shell and assembly features
  - Stress variation from +/-20 MPa to +/-10 MPa



M. Juchno

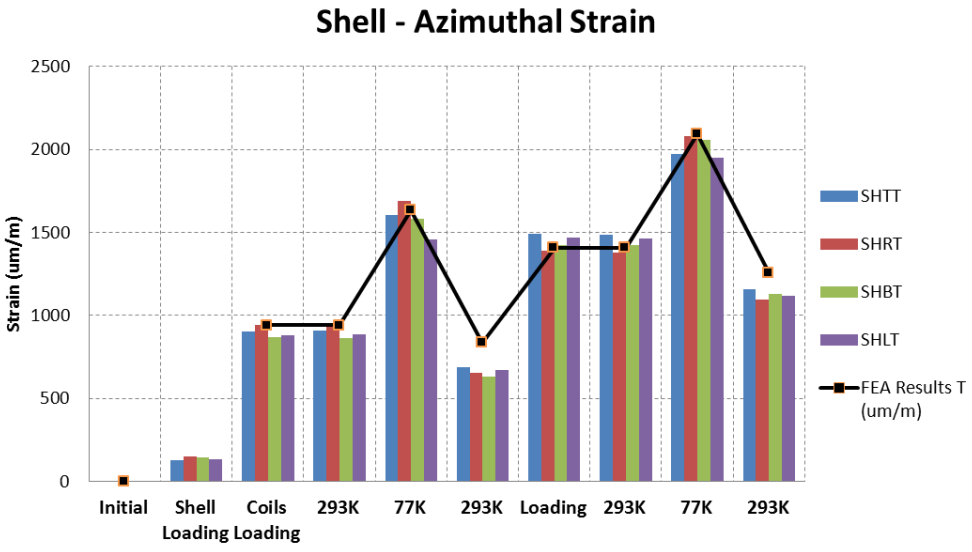
M. Juchno, et al., “Support Structure Design of the Nb3Sn Quadrupole for the High Luminosity LHC”, to be published in *IEEE Trans. Appl. Supercond*., 2015.

Design Verification: Mock-up

Short mock up, 150 mm long

- Full assembly done
- Preload with the bladders at different pressures
- Cool down at LN

➔ Good agrement between FEM and shell gauges

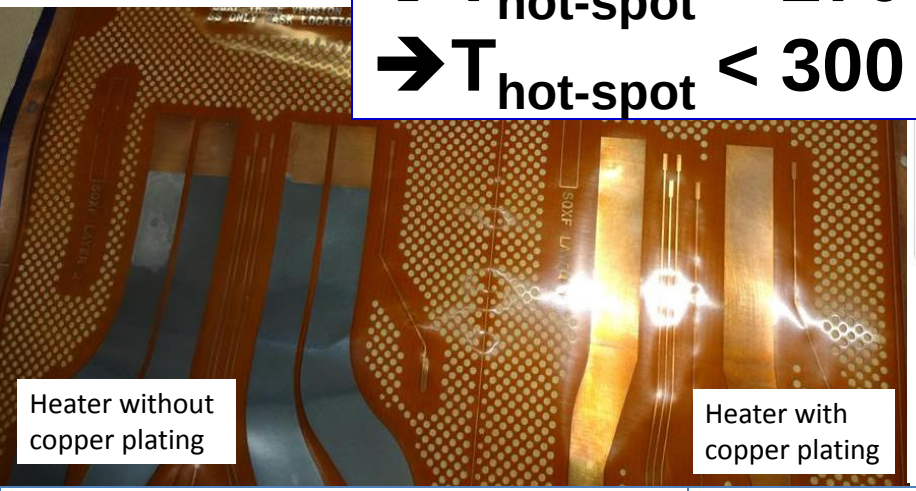


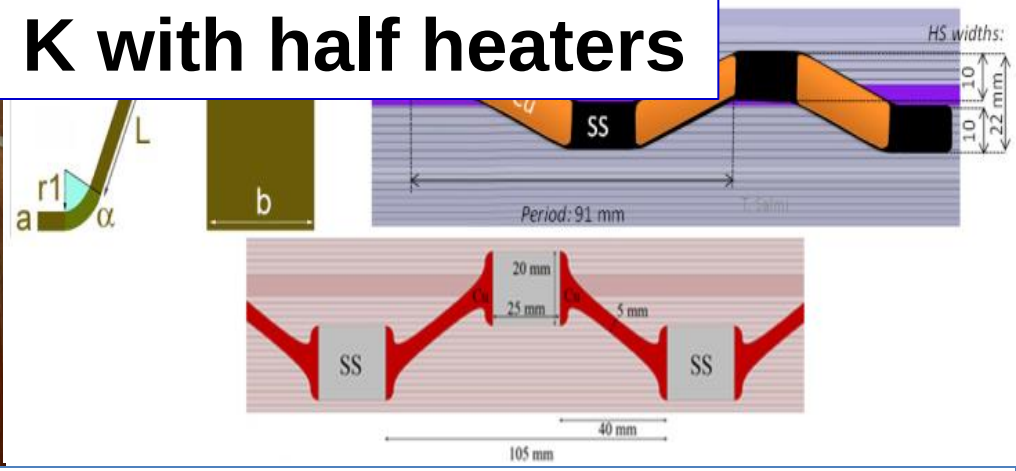
E. Cavanna, N. Bourcey, P. Ferracin, S. Izquierdo Bermudez, J. Mazet, J. C. Perez, F-O. Pincot X. Sarasola

Quench Protection Improvements

- Understanding "dynamic effects" = energy extraction and quench propagation caused by inter-filament losses
- Development of heaters with copper-cladding
- Development of heaters for inner layer (to be demo.)

➔$T_{hot\text{-}spot}$ ~ 270 K with all heaters
➔$T_{hot\text{-}spot}$ < 300 K with half heaters





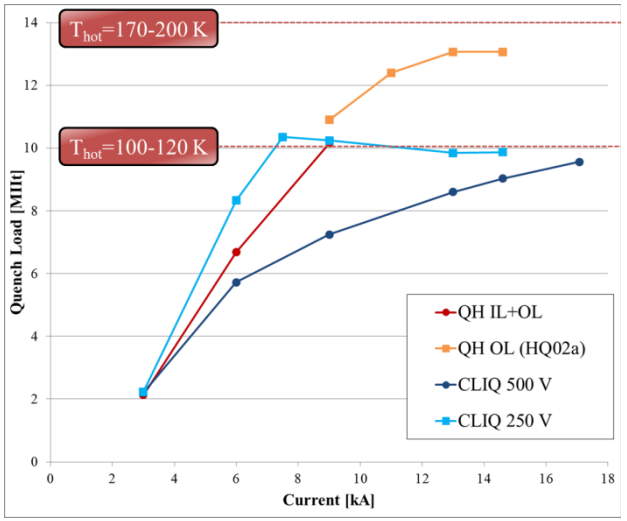
Courtesy J. C. Perez

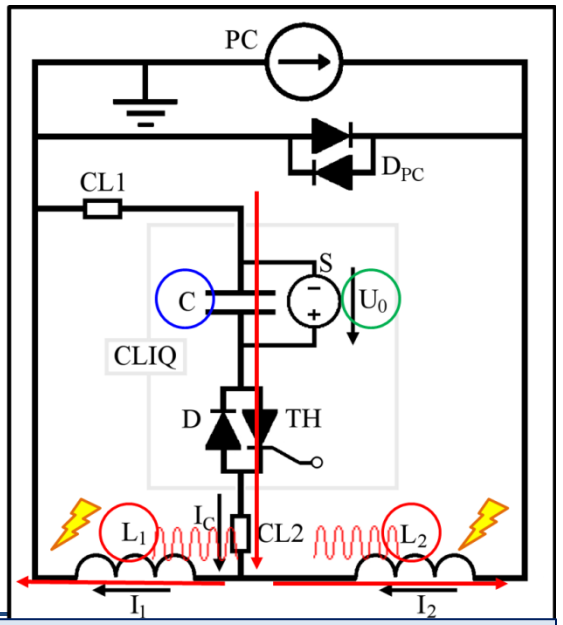
Courtesy M.Marchevsky, E.Todesco, D.Cheng, T.Salmi

V. Marinozzi, et al., "Study of quench protection for the Nb3Sn low-beta quadrupole for the LHC luminosity upgrade (HiLumi-LHC)", to be published in *IEEE Trans. Appl. Supercond*., 2015.

CLIQ

- Coupling-Loss Induced Quench System
- Very effective on HQ02 test
- To be demonstrated for long magnets
- Could provide perfect redundancy with heaters on outer layer





Courtesy of E. Ravaioli

E. Ravaioli, et al., "First Test of CLIQ, the New Coupling Loss Induced Quench Protection System, on a Nb3Sn Magnet", to be published in *IEEE Trans. Appl. Supercond*. 2015.

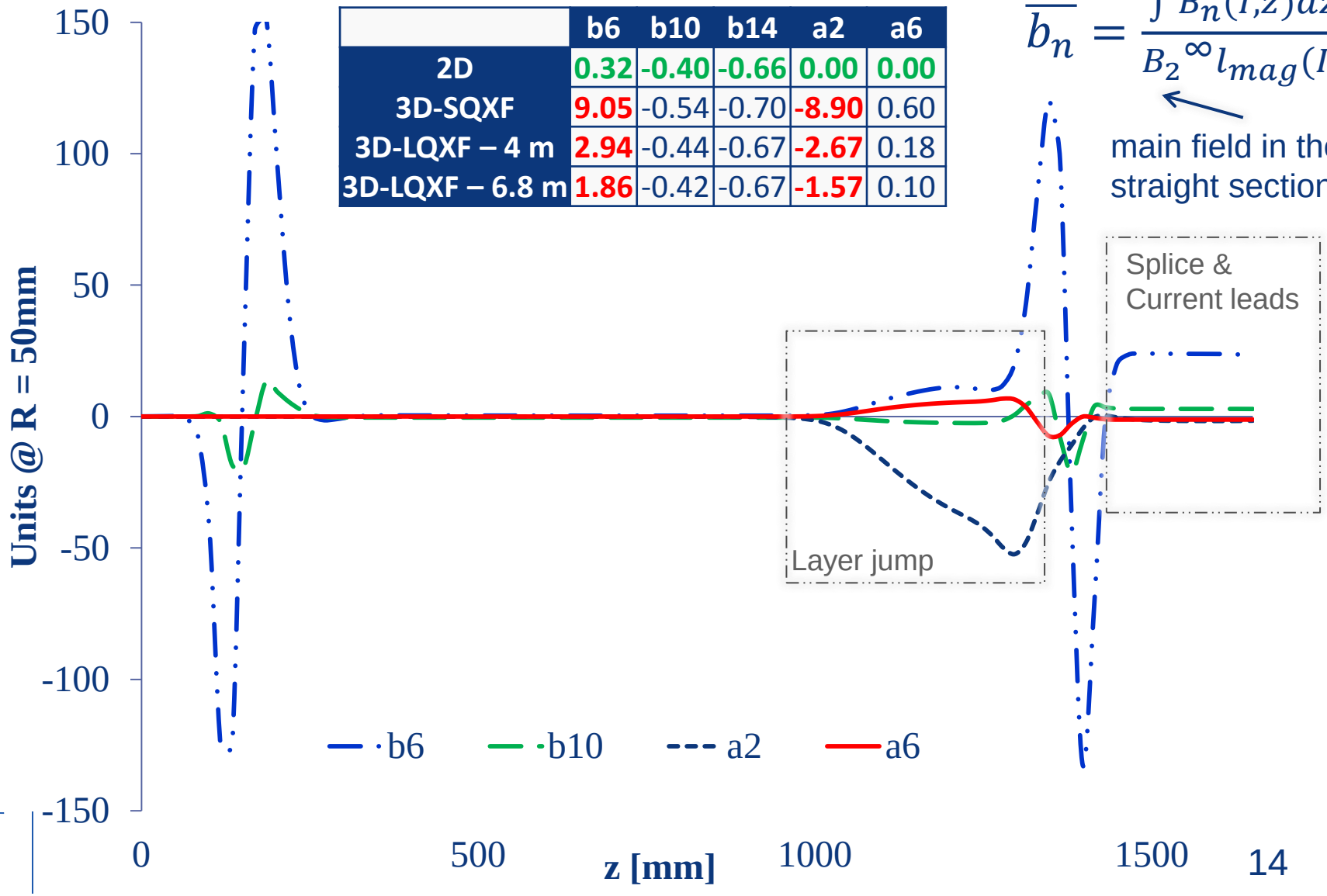
Integrated Field Harmonics

By S. Izquierdo Bermudez

	b6	b10	b14	a2	a6
2D	0.32	-0.40	-0.66	0.00	0.00
3D-SQXF	9.05	-0.54	-0.70	-8.90	0.60
3D-LQXF – 4 m	2.94	-0.44	-0.67	-2.67	0.18
3D-LQXF – 6.8 m	1.86	-0.42	-0.67	-1.57	0.10

$$\overline{b_n} = \frac{\int B_n(I,z)dz}{B_2{}^{\infty} l_{mag}(I)}$$

main field in the straight section

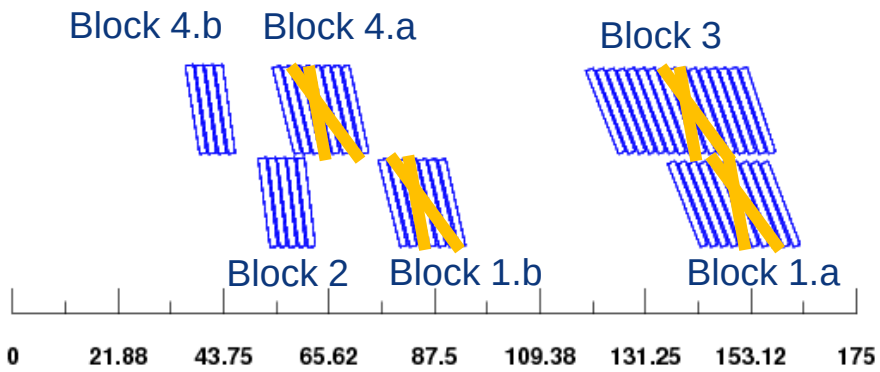


Sensitivity analysis

By S. Izquierdo Bermudez

Δβ = 0.5˚/turn

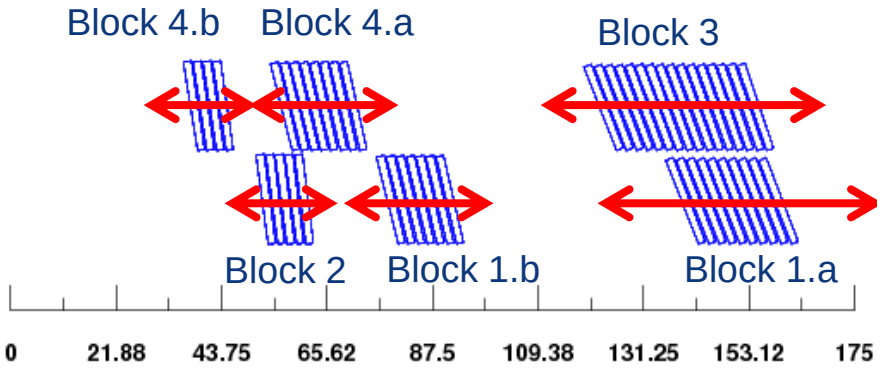
Integral only in the return end (over 400 mm length)

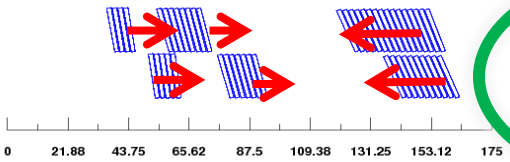


$$\overline{\Delta b_{6\ return}} < 0.5\ units$$

$$\overline{\Delta b_{10\ return}} < 0.1\ units$$

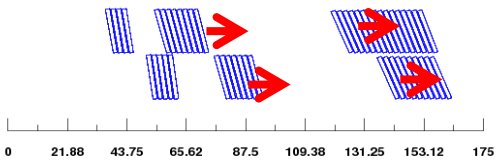
Δz = 2 mm/block





$$\overline{\Delta b_{6\ return}} = -3.6\ units$$

$$\overline{\Delta b_{10\ return}} = -0.1\ units$$



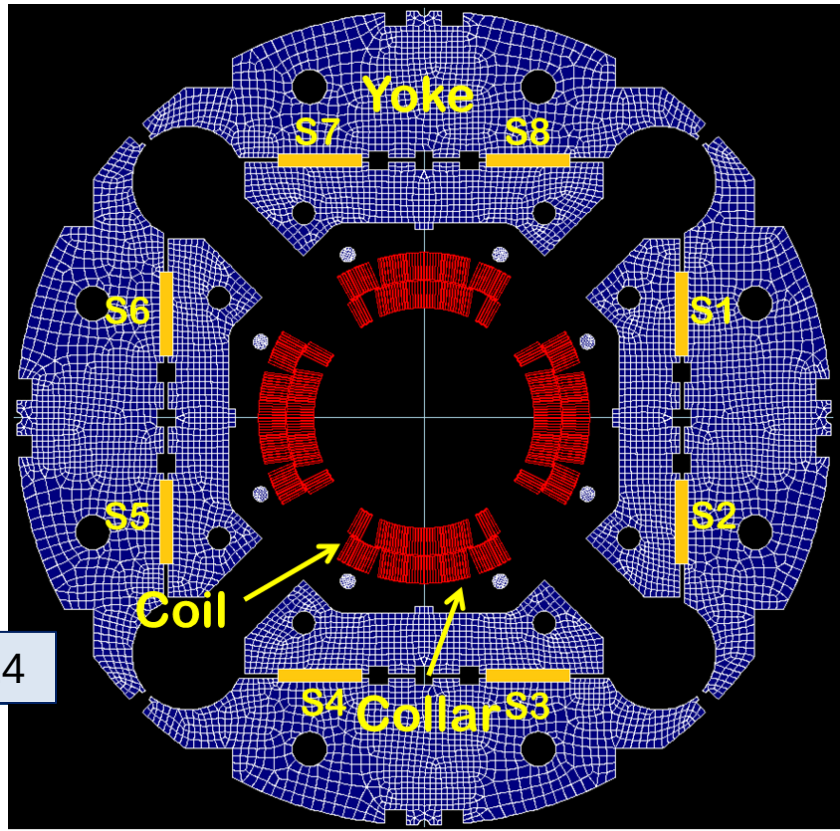
$$\overline{\Delta b_{6\ return}} = 1.1\ units$$

$$\overline{\Delta b_{10\ return}} = -0.1\ units$$

Magnetic Design – Field Quality Adjustment

- Magnetic shims in bladder slots can be used to correct low order harmonics
  - To be demonstrated by HQ03 (120 mm quad.)

Shim combination	Multipoles	Value (units) @ 17.5 kA
S 1,2,3,8	+b3 (+b5)	+3.0 (+0.2)
S 4,5,6,7	-b3 (-b5)	-3.0 (-0.2)
S 1,2,4,7	+b3 +b5	+4.6 (+0.6)
S 3,5,6,8	-b3 -b5	-4.6 (-0.6)
S 1,2,5,6	+b4	+2.8
S 3,4,7,8	-b4	-2.8
S 1,3,4,6	+a3 -a5	+4.6 (-0.6)
S 2,5,7,8	-a3 +a5	-4.6 (+0.6)
S 1,4,5,8	-a4	-0.8
S 2,3,6,7	+a4	+0.8
S 1,6,7,8	-a3 (+a5)	-3.0 (+0.2)
S 2,3,4,5	+a3 (-a5)	+3.0 (-0.2)



P. Hagen and P. Ferracin, LARP-HiLumi Collab Mtg, 2014

CONDUCTOR

Baseline Conductor

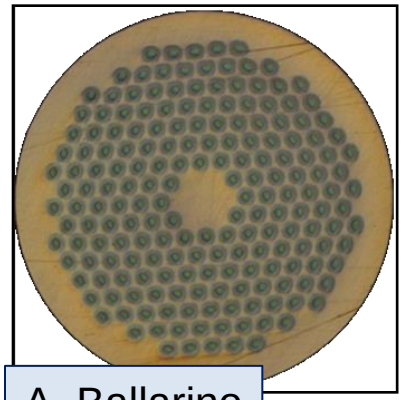
STRAND

- **0.85 mm** strand
- Filament size **<50 µm**
- Cu/Sc: **1.2 ± 0.1** → 55% Cu
- Critical current at 4.2 K and 15 T
  - **361 A** at 15 T (632 A at 12 T)

CABLE

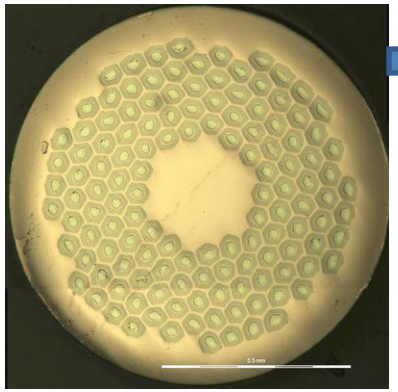
- **40**-strand cable
- Mid thickness: **1.525 mm**
- Width: **18.150 mm**
- Keystone angle: **0.55 deg.**
- SS core **12 mm** wide and **25 µm** thick

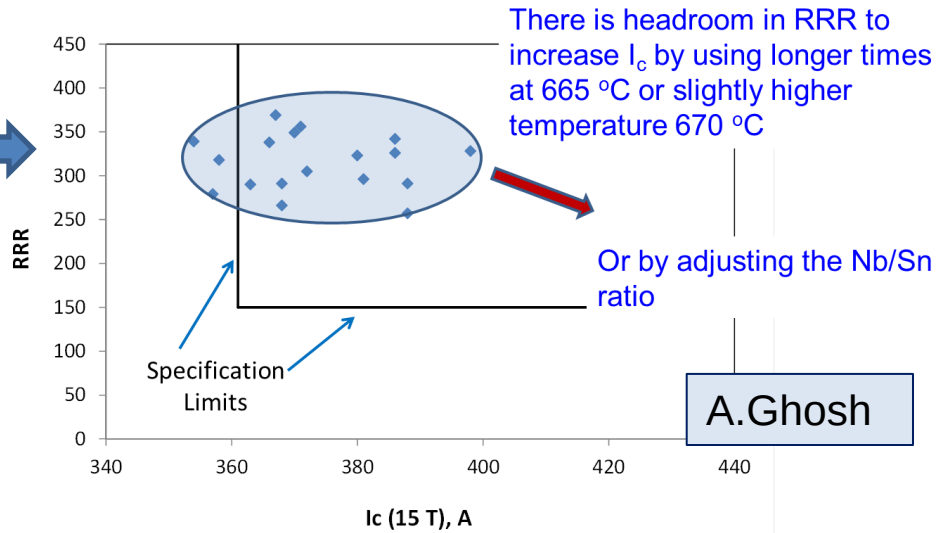
Bruker PIT strand, 192



A. Ballarino

OST RRP strand, 132/169





A.Ghosh

RRP cable

D. Dietderich

Recent & Upcoming Reviews

- HL-LHC-LARP International Review of MQXF Cable:

(CERN November 5-6, 2014)

- I_c target not completely reached, try increasing margin (longer magnets)
- Relate conductor requirements to magnet performance
- Reduce keystone angle of PIT cable, consider it for RRP cable
- Keep two vendors and increase support if one is late

- HL-LHC-LARP International Review of the Inner Triplets Quadrupole (MQXF) Design

(CERN, December 10-12, 2014)

We plan to discuss recommendation about margin at this review, and then address the comments and recommendations of both reviews

SHORT MODEL STATUS

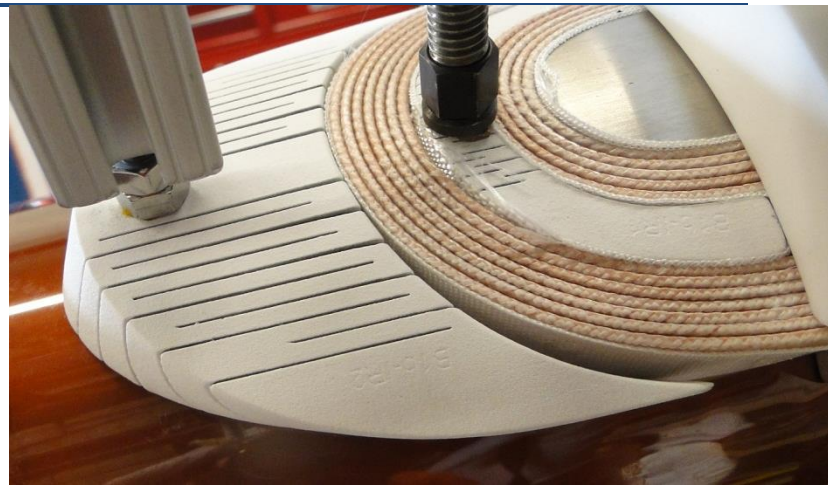
- COILS
- STRUCTURE

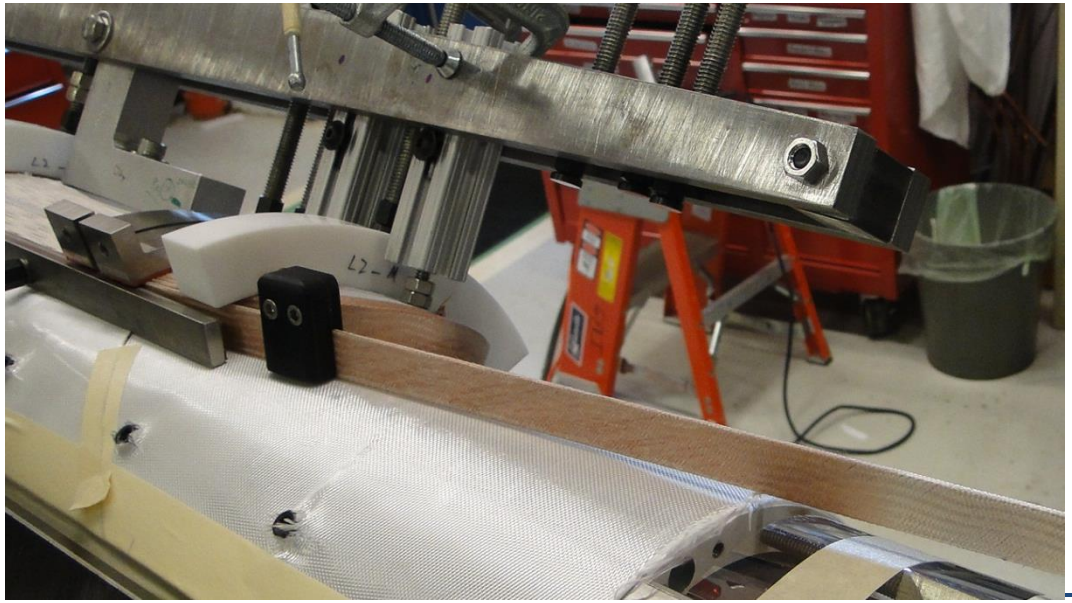
Coil Fabrication Status

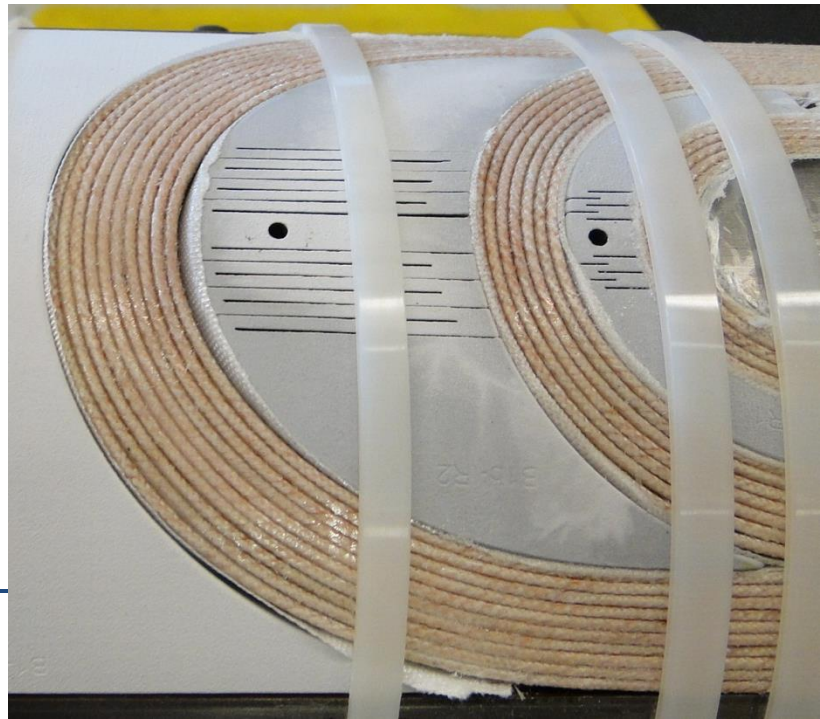
- LARP:
  - #1 (practice coil): completed
  - #2 (for mirror test): instrumentation in progress
    - Test start by end of February
  - #3 (for MQXFS1): prep for potting in progress
  - #4 (for MQXFS1): winding in progress
- CERN:
  - 001 (Cu practice coil): post potting
  - 101 (low Nb3Sn practice): prep for potting in progress
  - 102 (for MQXFS1): prep for reaction in progress
  - 103 (for MQXFS1): prep for winding in progress

Feedback from Winding & Curing

- No popped strands during winding
- Flexible features of end parts are working well

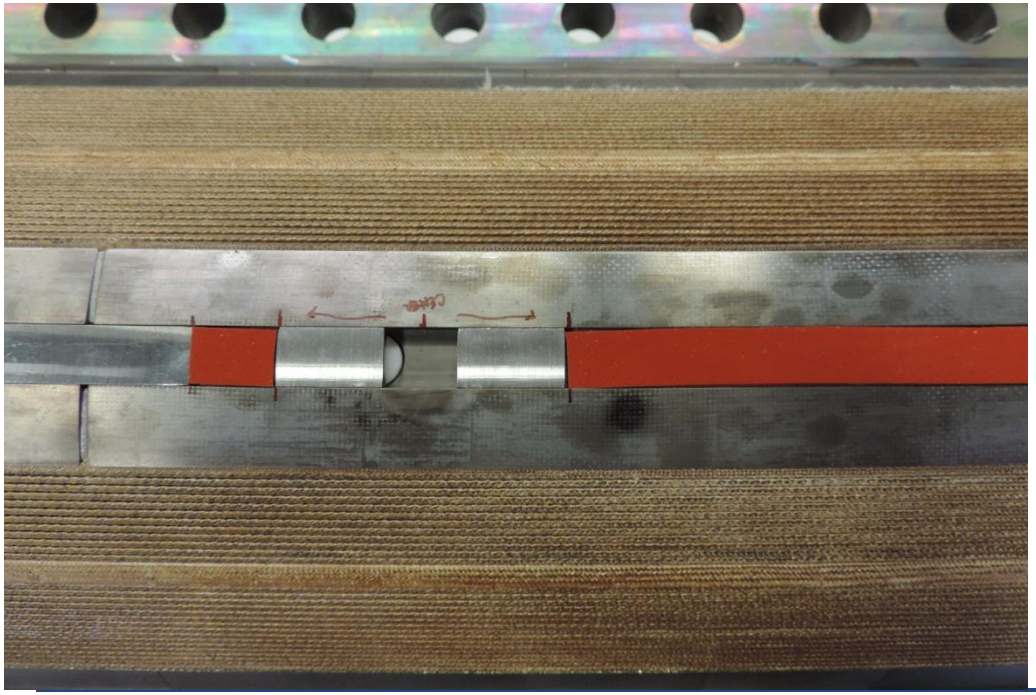


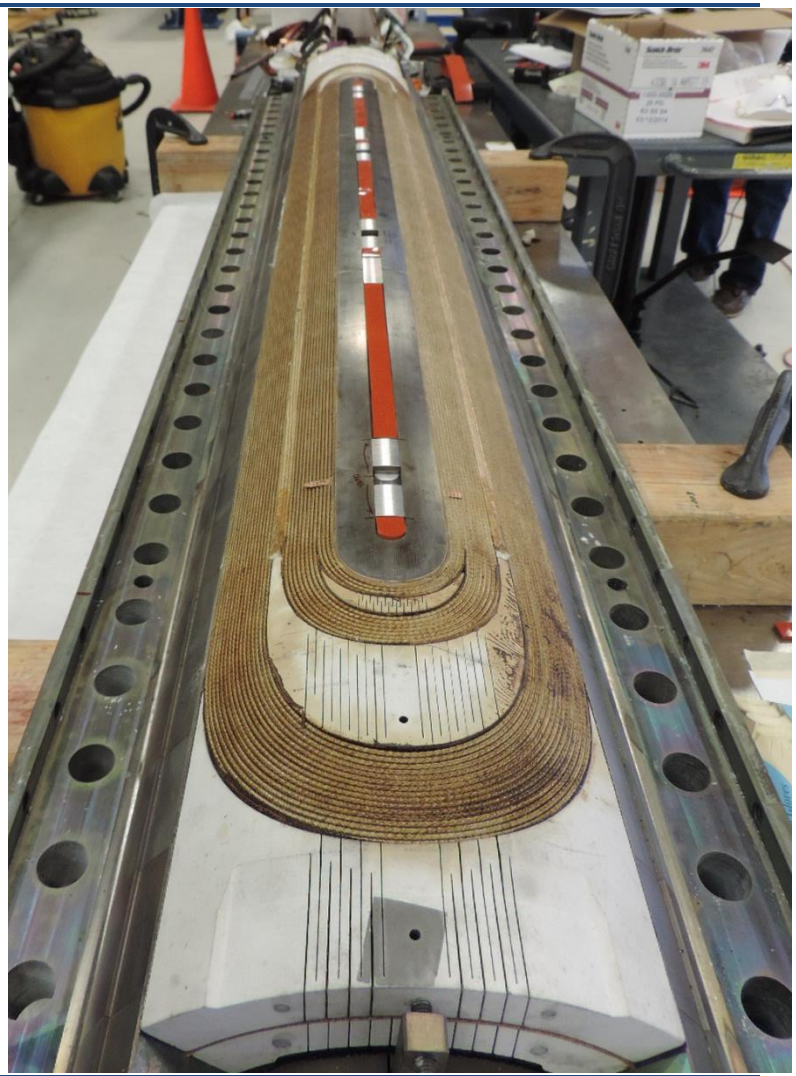




Feedback from Reaction

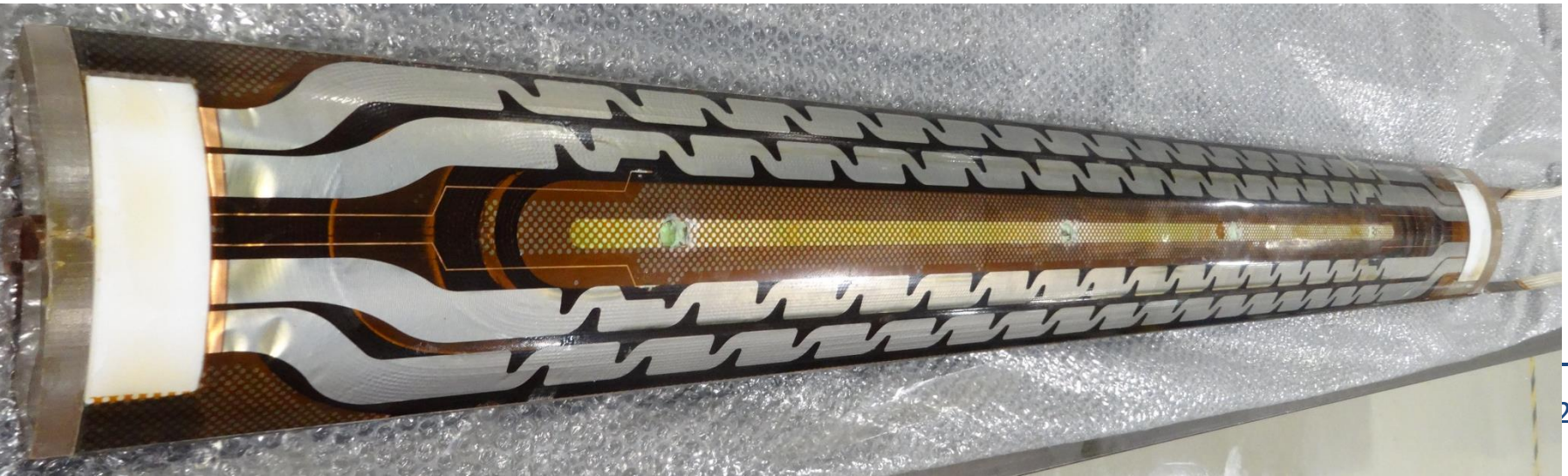
- Coils look very nice
- Pole gaps are almost closed





Feedback from Potting

- A few small issues found:
  - Adjustments implemented to equipment and procedures
- Overall coils look nice
  - Coil #1 inside was very good
  - CMM in progress



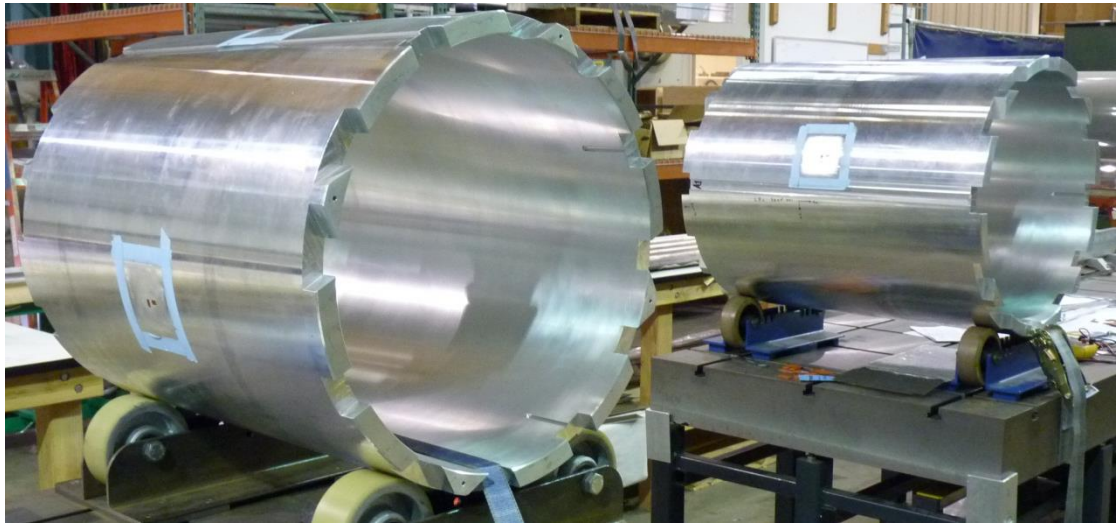
Electrical QC Tests

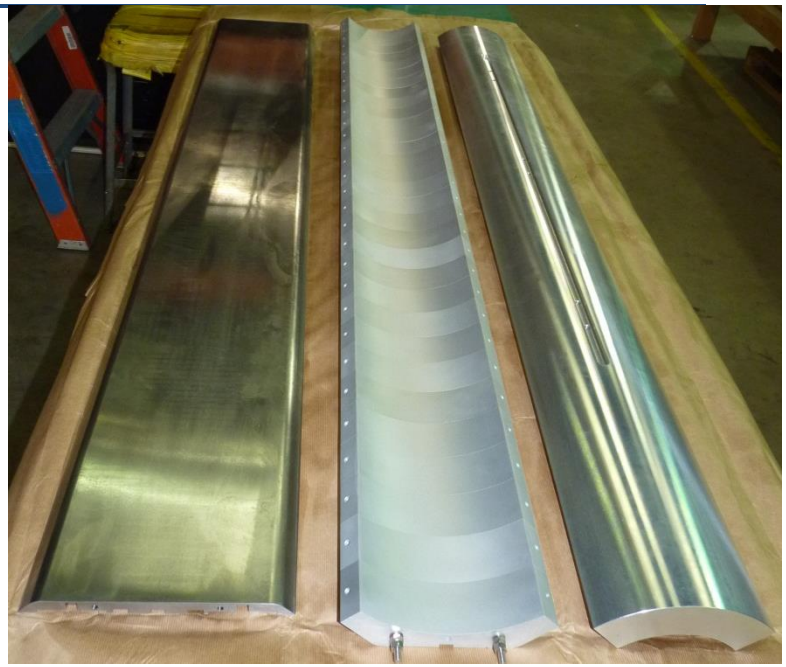
- All standard test (up to 2 kV) – passed
- Heaters-to-coil up to 5 kV – passed
- Impulse test up to 5 kV – passed up to 4.6 kV

SQXF01	Coil	Hipot Checks							
PHA01	2000 / 2000								
PHA02	2000 / 2000	PHA01	PHA02	Actual / Target					
PHB01	2000 / 2000			(< 1 uA leakage)					
PHB02	2000 / 2000			PHB01	PHB02	PHB03	PHB04		
PHB03	2000 / 2000								
PHB04	2000 / 2000							LE IL Endshoe	RE IL Endshoe
LE IL Endshoe	1200 / 1200	1000 / 1000	1000 / 1000						
LE OL Endshoe	1200 / 1200			1000 / 1000	1000 / 1000	1000 / 1000	1000 / 1000	600 / 600	
RE IL Endshoe	1200 / 1200	1000 / 1000	1000 / 1000						
RE OL Endshoe	1200 / 1200			1000 / 1000	1000 / 1000	1000 / 1000	1000 / 1000		600 / 600
Pole	500 / 500								

Structure Procurement

Procurement in progress:



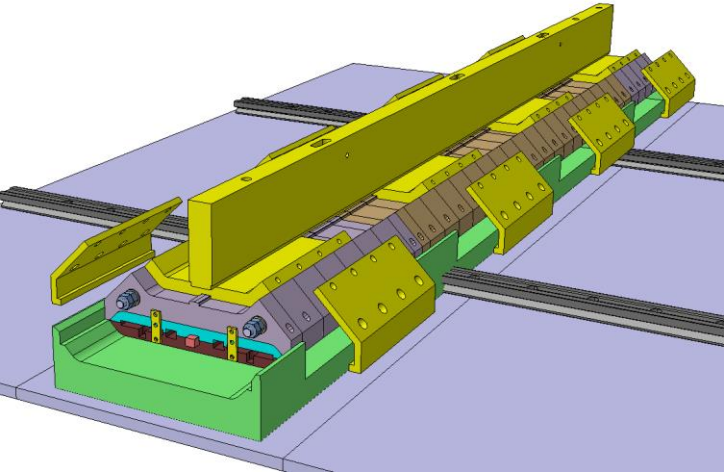


QC:

- Two sets of support structures fabricated, including dummy aluminium coils
- Shell out of tolerance
  - Inner perimeter ok, but shape and pins not within spec.
  - Decision to proceed with current shells, but fabrication of 2 additional sets launched
- No major issue in other components
- Consistent CMM measurements at CERN and LBNL

Assembly Procedures

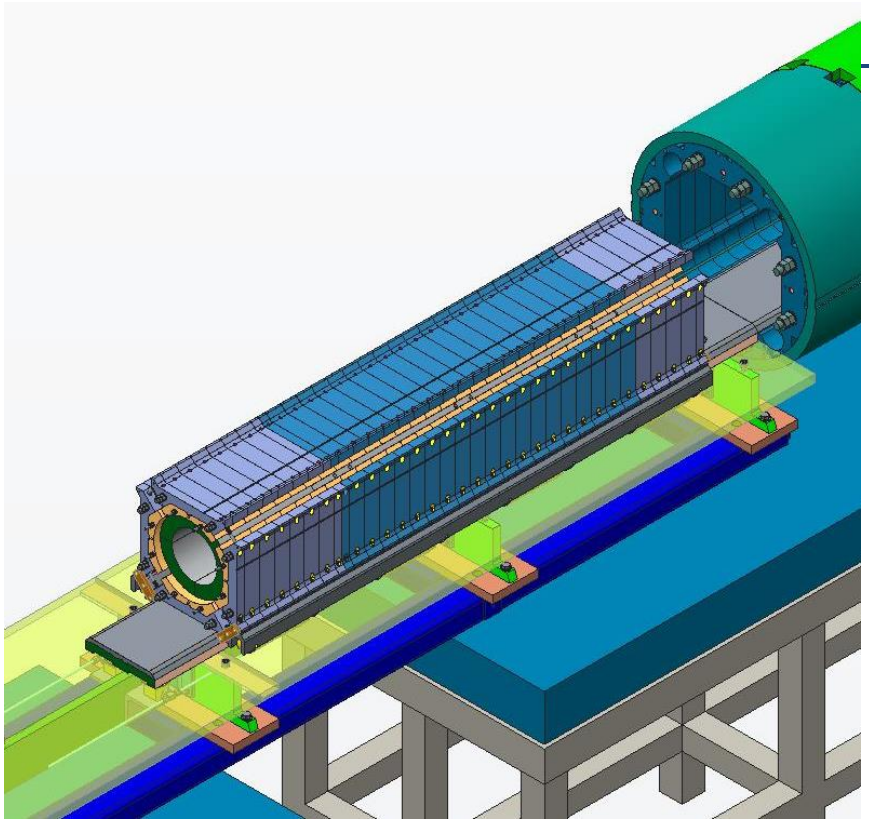
- Assembly procedures are being finalized
- Small differences btw CERN and LARP
  - Short models and prototypes will be used to fine tune assembly procedures

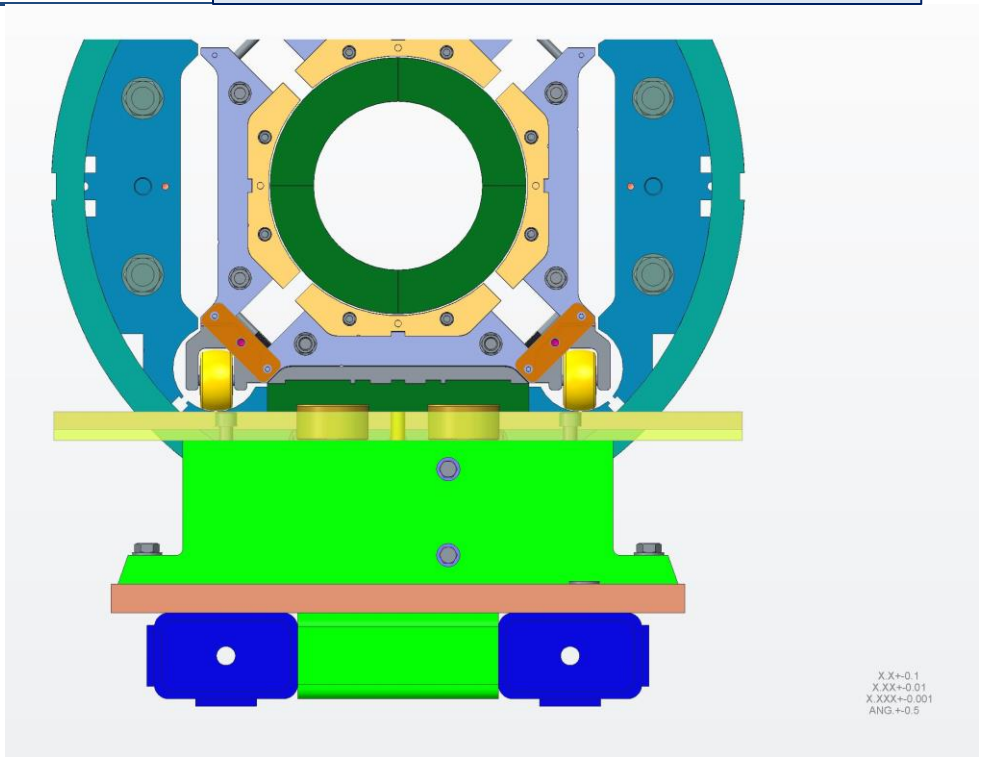


J. C. Perez, 07/22/14 LARP Mtg

Assembly Procedures

D. Cheng, 11/07/14 LARP Mtg





- Assembly with Al-dummy coils: March 2015
- Cold test with Al-dummy coil: April 2015
- Assembly of MQXFS1 start: May 2015
- Cold test of MQXFS1: August 2015

PROTOTYPES

Tooling & Equipment

- LARP is taking the lead with 4m coil fabrication starting in February 2015.
- Equipment upgrades in progress:
  - Automatic (Selva) winder (FNAL)
  - Curing mold (FNAL)
  - Vertical test facility (BNL)
- Coil tooling is under procurement
- Structure assembly tooling under design

Winding Tests

- Short QXF coil successfully wound in manual mode

No popped strands

Plans and Risk Mitigation

- Start practice coil fabrication: February 2015
- First coil test in mirror: March 2016
- MQXFL1 test: November 2016

➔Risk mitigation:

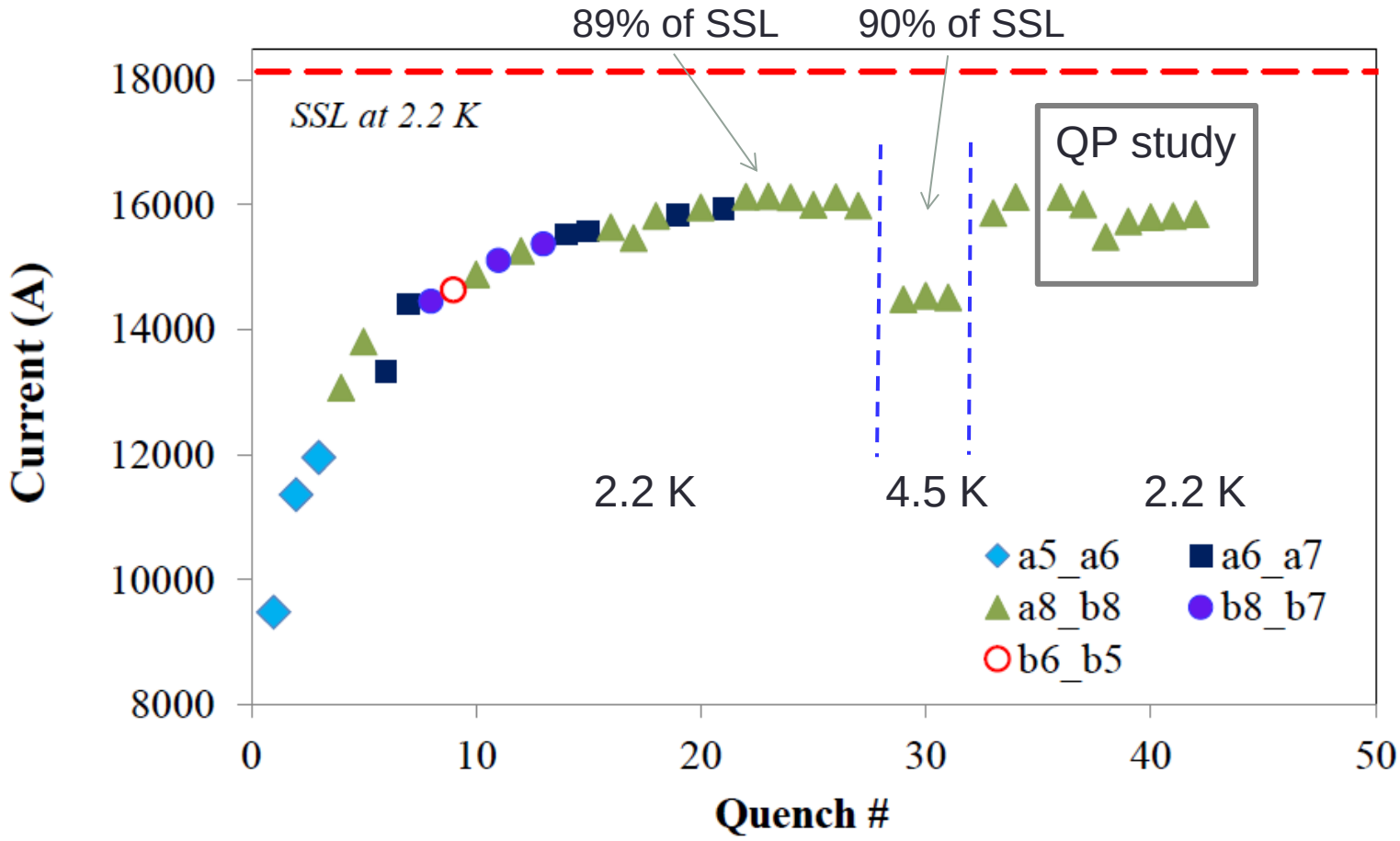
- LHQ coil (120 mm ap., 3 m magnetic length) has been tested in mirror structure

LHQ Coil

- LHQ coil #3 has all the features of MQXF coils not tested in previous long coils (90 mm, 3 m)
  - Ti ternary RRP strands
  - Stainless steel core (25 um thick)
  - Braided insulation
  - Stainless steel end parts
  - Use of tool and binder during winding
  - Flexible features in saddles
- Different protection heaters for MQXF optimization

LHQM01 Quench Training

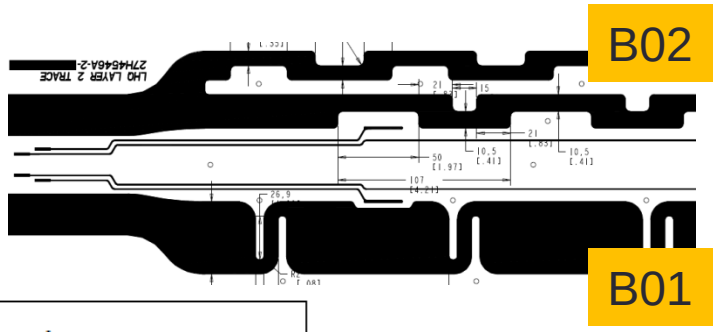
Quench training at 20 A/s

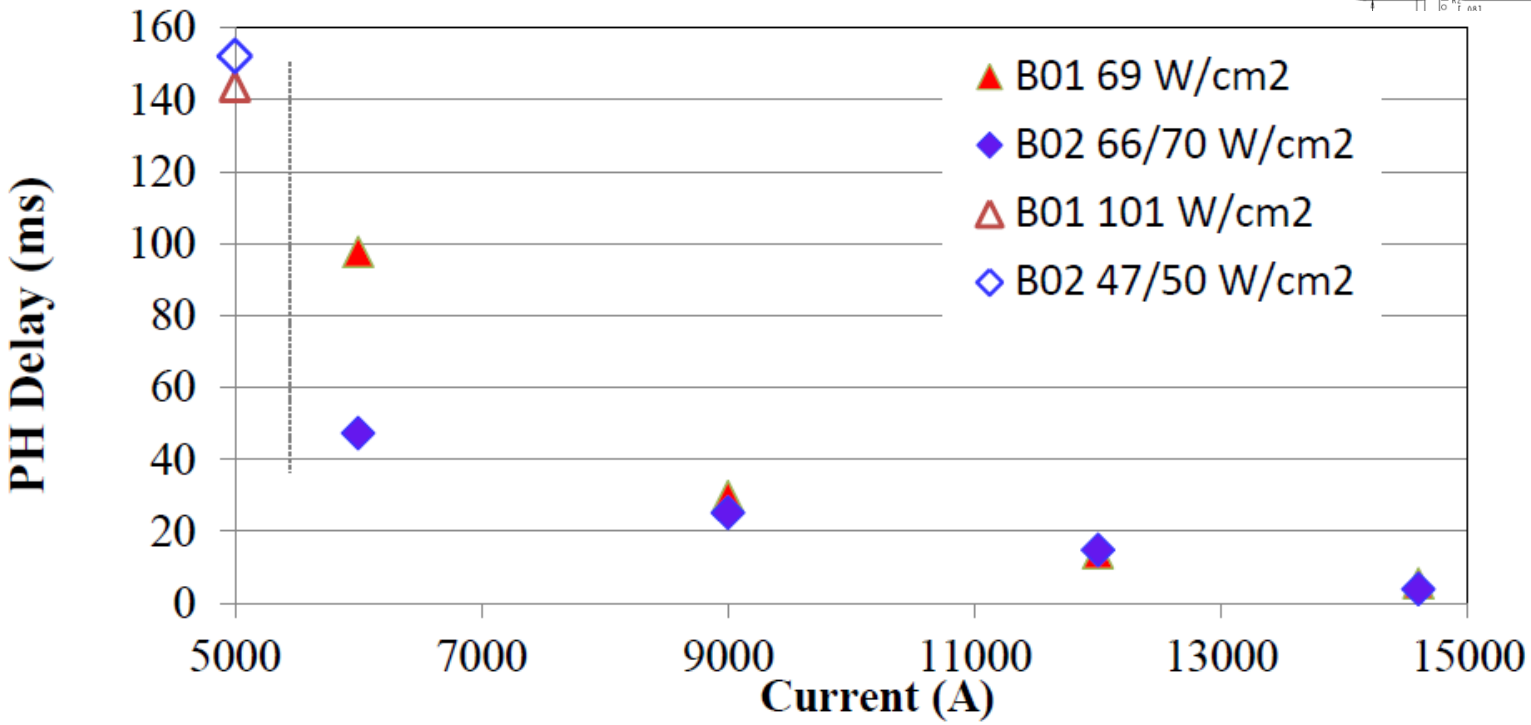


Protection Heater Studies

- Both heaters are very efficient (delay < 10 ms) at operating current
- Similar performance under similar conditions

Analysis in progress





Conclusions

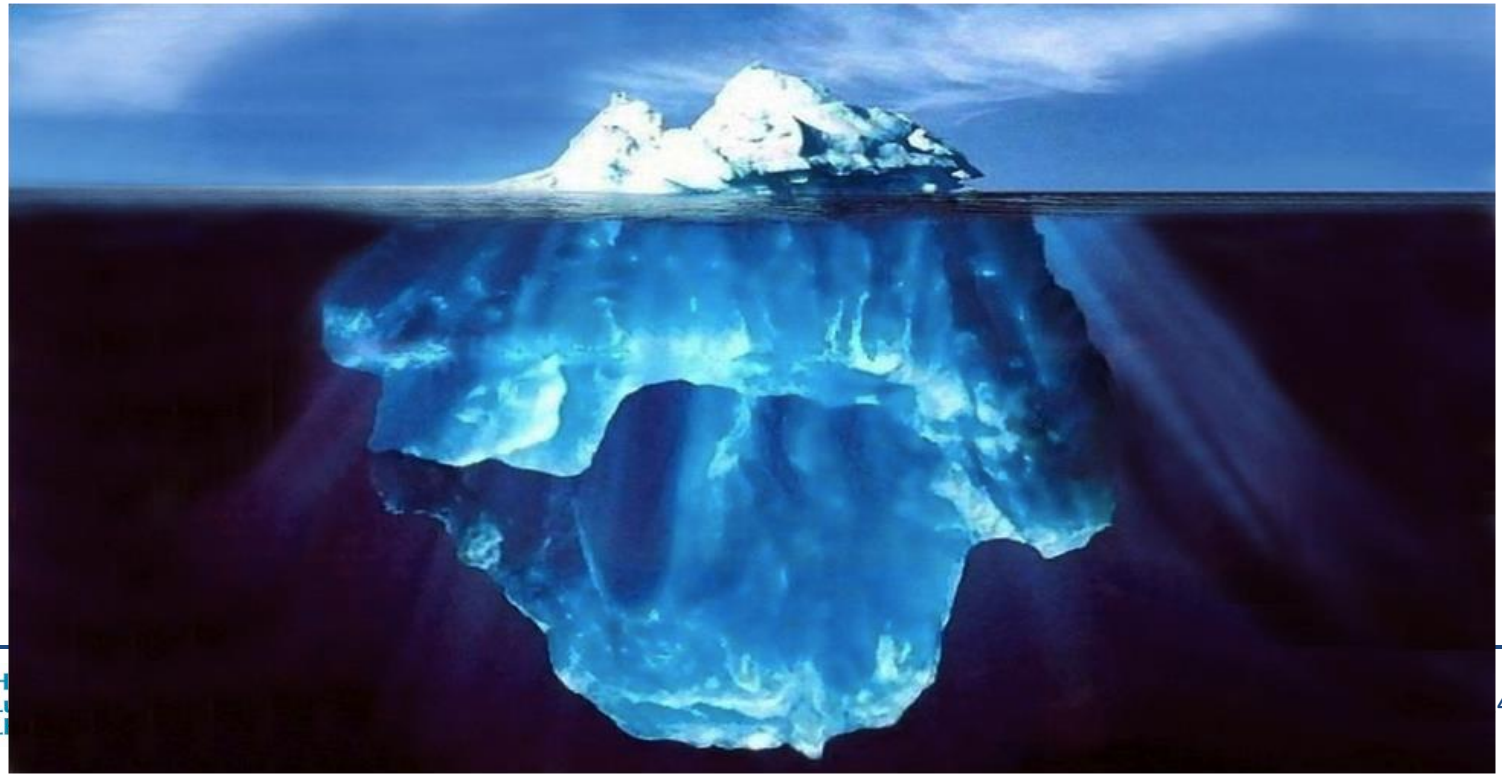
- The MQXF
  previous c
  - Quench
- The short
  - Coils fabri
  - At next Hi-Lumi Collab Mtg we will discuss test results
- The long prototype program is starting soon
  - The 120mm magnets/coils have provided risk reduction
- Test of QXF coils is starting in a few months

The demonstration of MQXF magnets for HL-LHC upgrade is getting closer and closer!

Back up splides

Past Experience - Risk Reduction

- Conductor and magnet parameters have been selected taking into account many years of conductor development and magnet R&D in the US and at CERN



Overview of LARP Magnets