High Field Magnet Development Toward the High Luminosity LHC

Giorgio Apollinari, Fermilab

for the HiLumi-LHC/LARP Collaboration

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Contributors

BNL, CERN, FNAL, LBL, SLAC

F. Borgnolutti, G. Ambrosio, S. Izquierdo-Bermudez, D. Cheng, D. R. Dietderich, H. Felice, P. Ferracin, G. L. Sabbi, A. Ballarino, E. Todesco, B. Bordini, M. Yu, M. Anerella, R. Bossert, A. Ghosh, A. Godeke, P. Fessia, S. Krave, M. Juchno, J. C. Perez, L. Oberli, H. Allain, F. Cerutti, L. Esposito, P. Wanderer, R. Van Weelderen, R. De Maria, S. Fartoukh, R. Gupta, R. Kersevan, N. Mokhov, T. Nakamoto, I. Rakno, J. M. Rifflet, L. Rossi, M. Segreti, F. Toral, Q. Xu, N. Andreev, E. Barzi, M. Buehler, G. Chlachidze, J. DiMarco, J. Escallier, R. Hafalia, G. Jochen, M.J. Kim, P. Kovach, M. Lamm, M. Marchevsky, J. Muratore, F. Nobrega, D. Orris, E. Prebys, S. Prestemon, J. Schmalzle, C. Sylvester, M. Tartaglia, D. Turrioni, G. Velev, X. Wang, G. Whitson, A.V. Zlobin, S. Caspi, R. Hafalia, R. Hannaford, V.V. Kashikhin, A. Lietzke, A. McInturff, I. Novitsky, S. Peggs, X. Wang

…and many others….

Content

- Strategy, Justification and Needs
- HL-LHC High Field Magnets Scope
  - IR Quadrupoles
  - 11 T Dipoles
- Design Considerations
- Technology Development and Achievements
- Plans
- Conclusions

HEP Strategy

European Strategy for Particle Physics - Update 2013

*Europe's top priority should be the **exploitation of the full potential of the LHC**, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030…*

US Prioritization for Particle Physics (P5) - May 2014

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 (Recommendation to HEPAP).

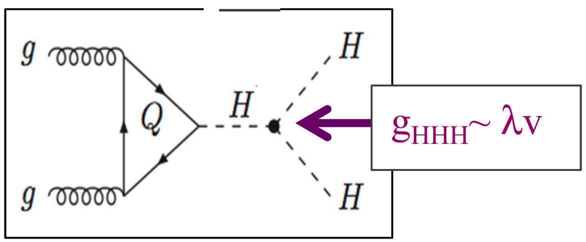
HL-LHC from a study to a PROJECT

$300\ fb^{-1} \rightarrow 3000\ fb^{-1}$

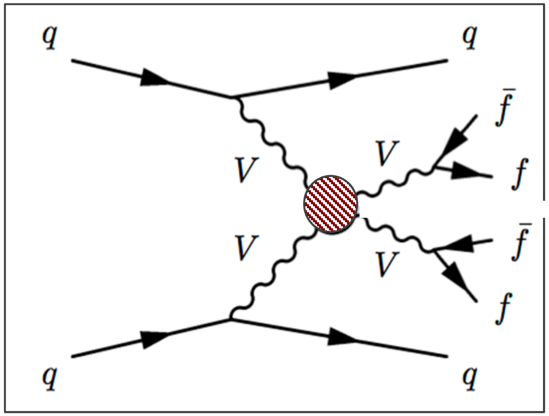
Justification & ….

- "Known" Justifications
  - Measure as many Higgs couplings to fermions as precisely as possible
  - Measure Higgs self-coupling
  - Verify that Higgs boson fixes the SM problem with W/Z scattering at high E
- "Unknown" Justifications/Questions
  - Why is Higgs so light ?
  - What is nature of Matter-Antimatter asymmetry in Universe ?
  - Why is gravity so weak ?
  - What is Dark Matter ?
- *Access to rare processes* -> Luminosity

Self-coupling

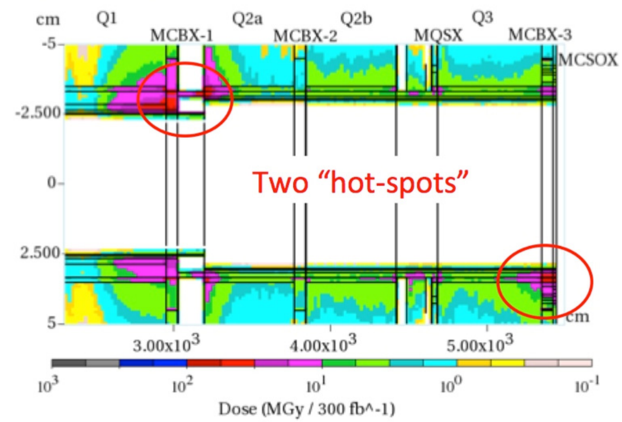


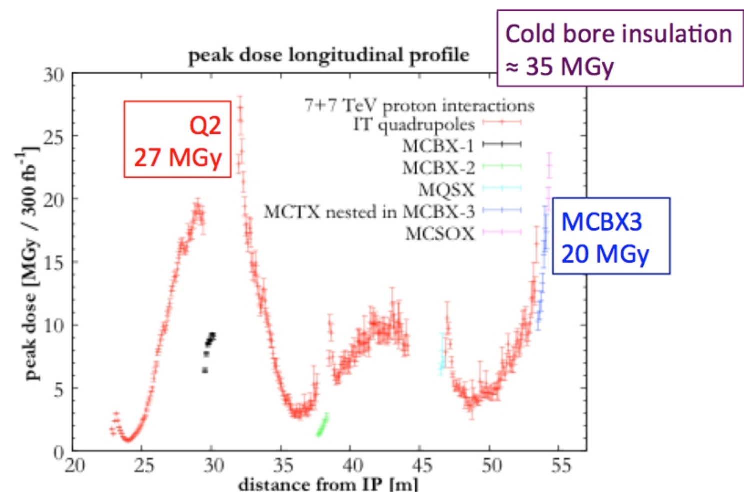
Vector boson fusion



...Needs

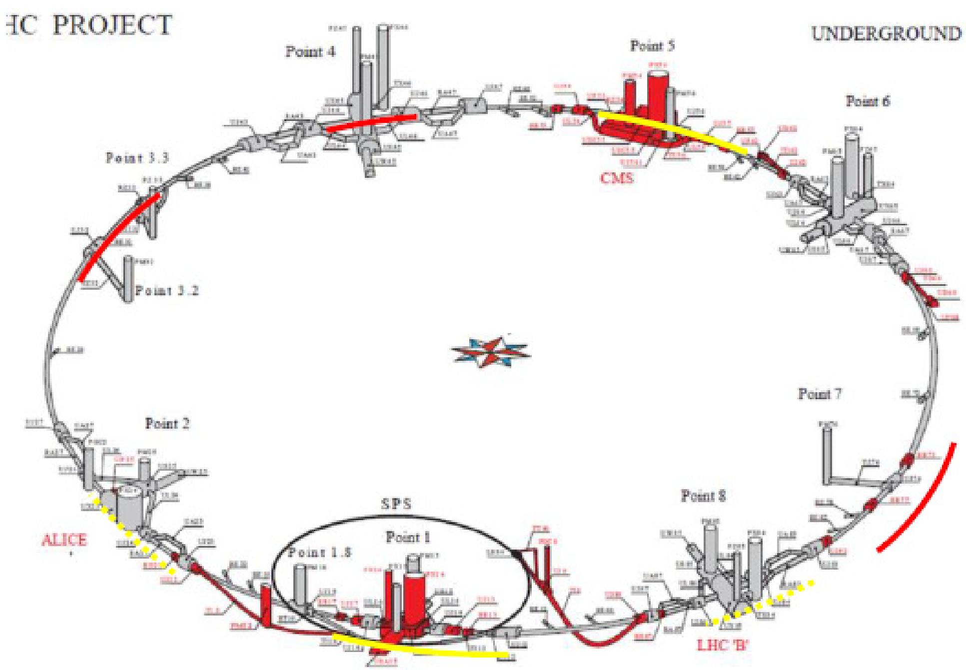
- Radiation dose in present IR Focusing Triplet after 300 fb^{-1}
  - Peak dose as high as ~30MGy (~50% uncertainty)
  - Bonding strength (shear) of epoxies is strongly degraded (80%) above 20 MGy.
  - Fracture strength of insulating materials degrades by about 50% in the 20 MGy (G11) to 50 MGy (kapton) range
- Triplets magnets may experience mechanically induced insulation failure in the range of 300 fb^{-1} (~LS3)
- Not a surprise (known since~ 2001)





The HL-LHC Project

- Physics driven requirements:
  - Increase luminosity limiting Pile-Up (PU) to ~140 events/crossing
    - $L = 5 \times 10^{34}\ cm^{-2}\ s^{-1}$
  - Limit PU linear density to ~1 event/mm



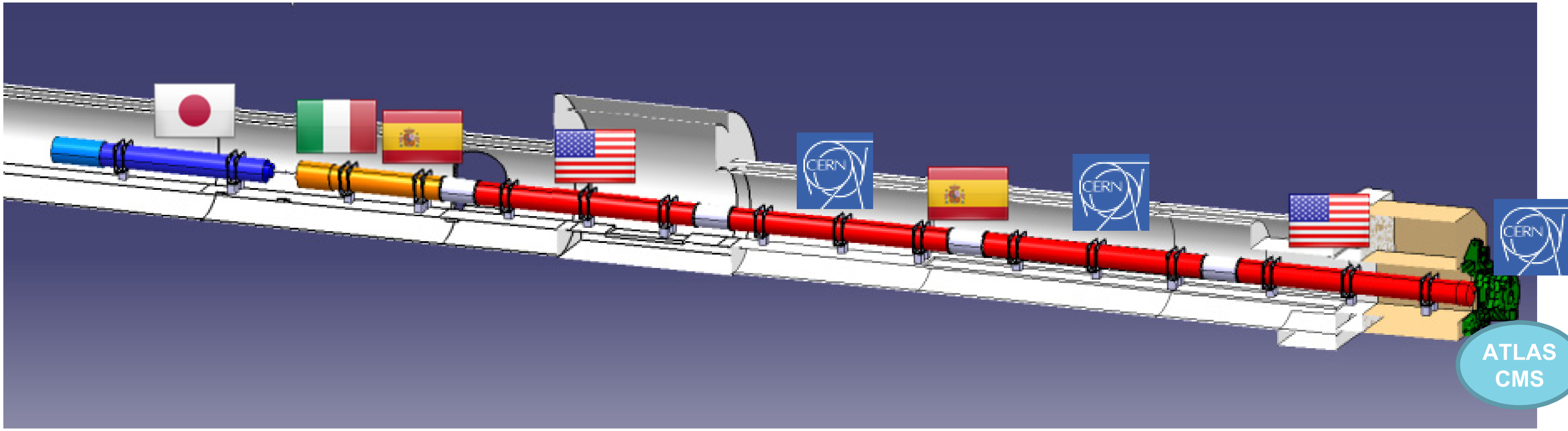
- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Crab Cavities
- Collimation upgrade
- Cryogenics upgrade
- Machine protection
- …

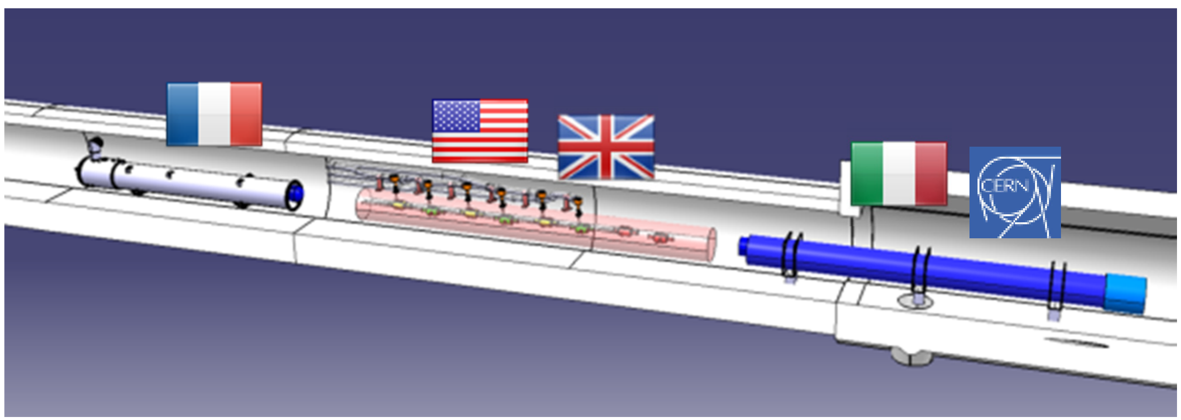
Major intervention on more than 1.2 km of the LHC

High Luminosity LHC

New IRs

LARP





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

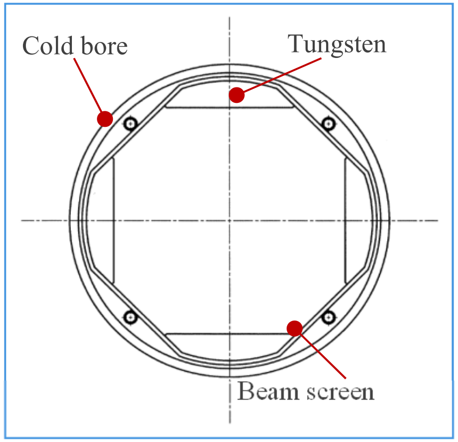
CC : R&D and Design **UK**

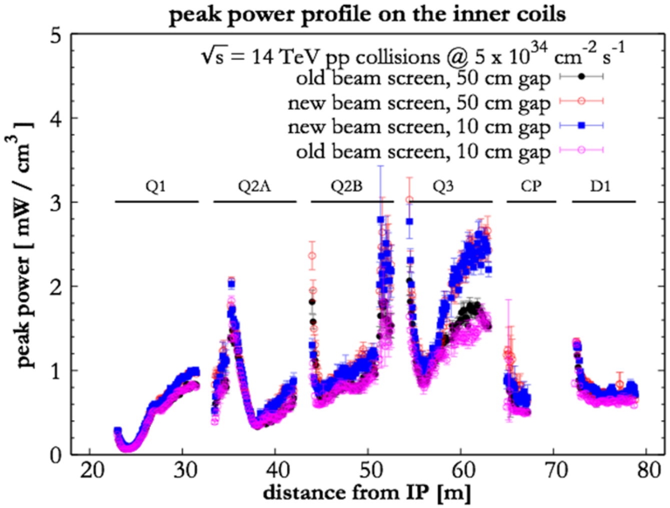
Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

IR Magnets Design Constraints

- Goal: Peak Luminosity leveled at 5×10^{34} $cm^{-2}s^{-1}$
  - Higher intensity and larger focusing in IP. Beam size reduced by a factor of 2 (i.e. doubling aperture of IR quads)
    - Critical design parameter is peak magnetic field in coil: NbTi (8T) to Nb_3Sn(15T) allows ~50% higher field
  - Radiation Damage goals: limit radiation to 25 MGy on essential components for magnet fabrication
  - Heat Deposition goals: limit heat deposition to 4 mW/cm^3
  - Field quality not critical at injection (b_6~ 25) but critical at full energy (b_6 <0.5)
    - Large set of correctors in the layout

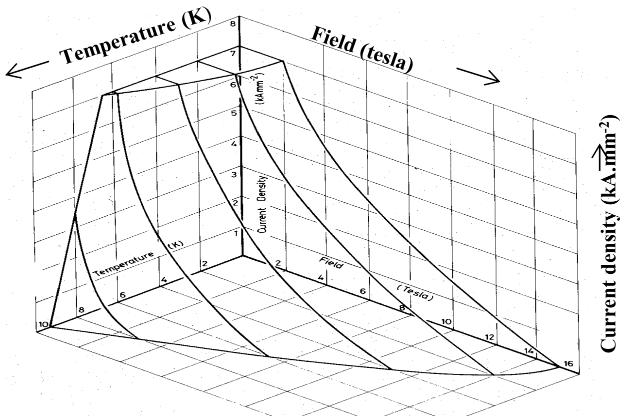
Shielding is the answer:

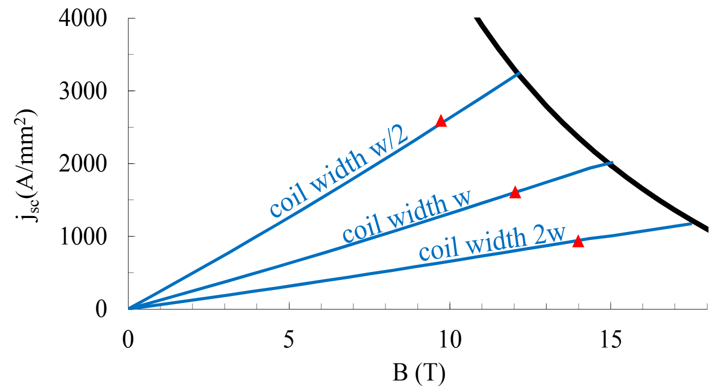




Super Conductor/Coil Design

- In SC Magnet, field is proportional to current density in coil
- SC Critical surface defines the maximum field in relation to the critical current and temperature.

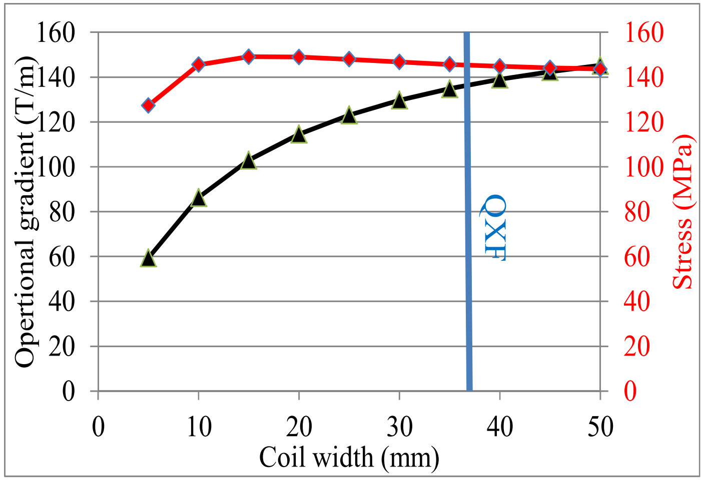


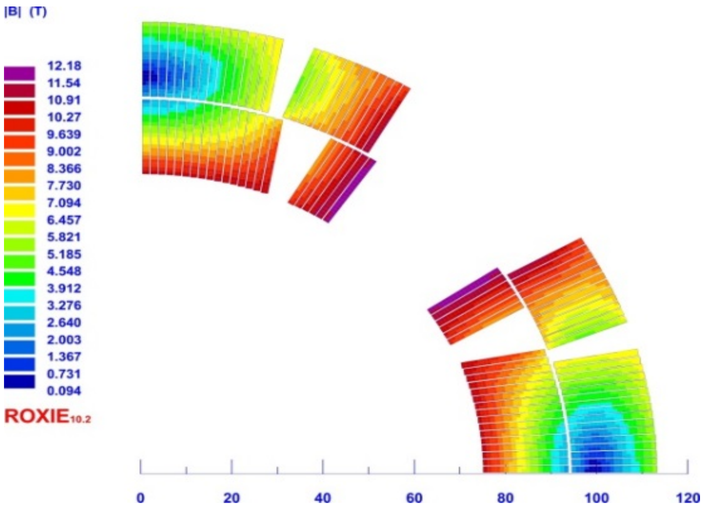


- With large coil widths, loadline has lower slope and higher fields can be reached:
  - Not only a cost/size problem: higher current densities induce larger mechanical stresses (in compact magnet forces may damage SC or insulation) and difficult protection during quenches

Coil Design

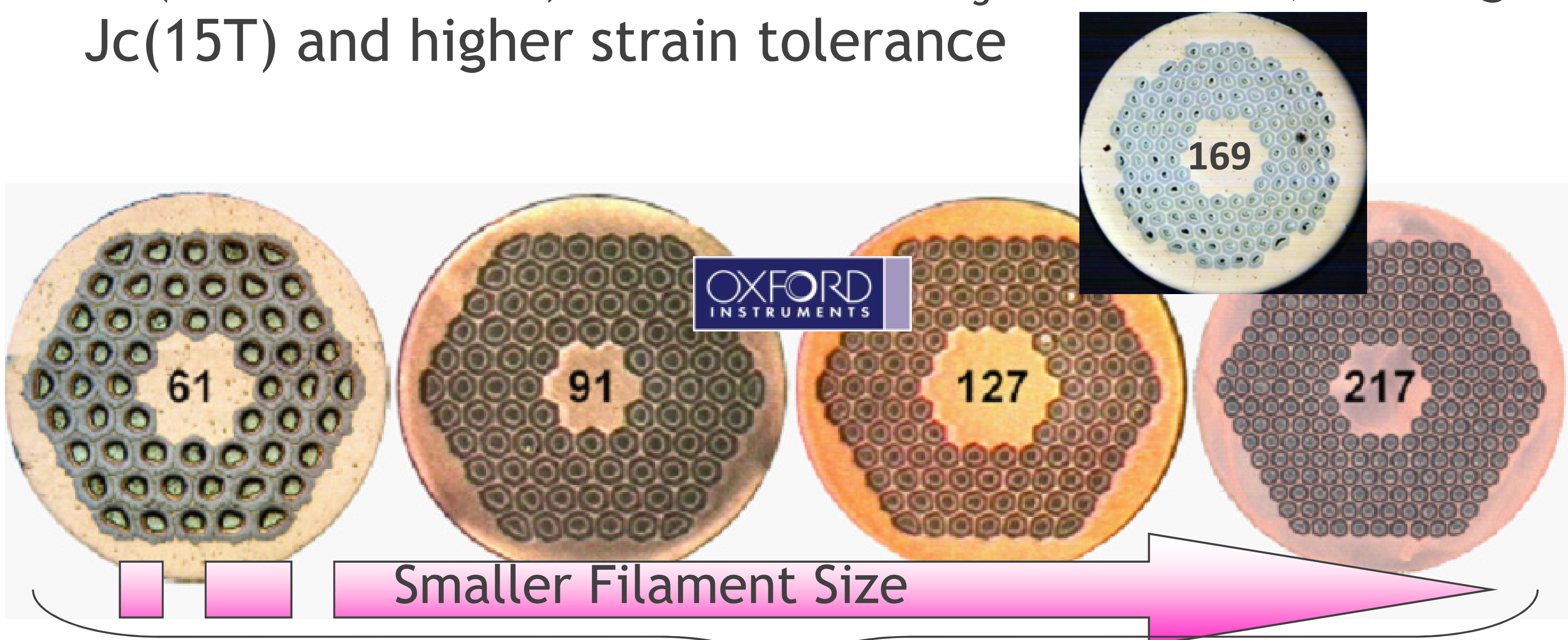
- In order to maintain stresses under ~200 MPa in 150 mm aperture quadrupoles, a coil width of ~<u>35 mm was selected</u>
  - Gradient ~ 140 T/m
  - Benefit from experience in 90 mm and 120 mm aperture quads and SC cables
- Cable Choice
  - 40 strands Rutherford Cable with 0.85 mm strands and 25 μm thick SS core
- Coil Design
  - Double Layer, four Blocks





Nb_3Sn Conductor

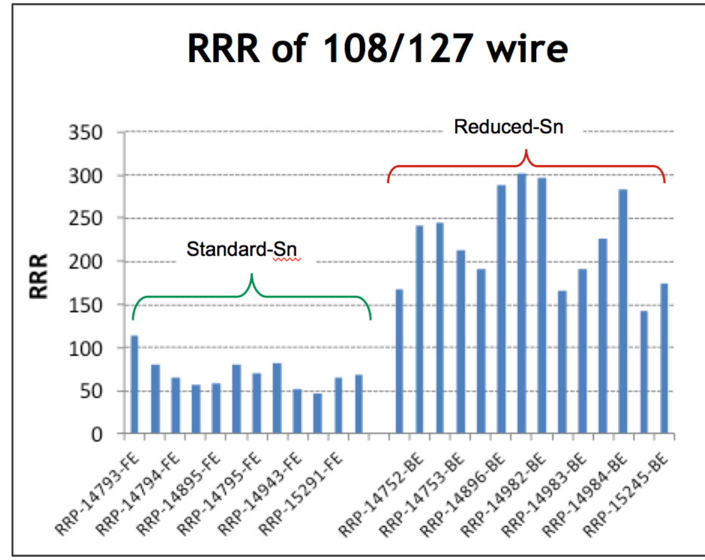
- The 150 mm aperture QXF magnets will use either 132/169 RRP® Ti-Ternary strand or 192 PIT
  - Sub-element size kept below 50 μm to minimize flux jumps (improve stability) and decrease filament magnetizations
  - Ti (rather than Ta) accelerates Nb_3Sn reaction, has higher Jc(15T) and higher strain tolerance

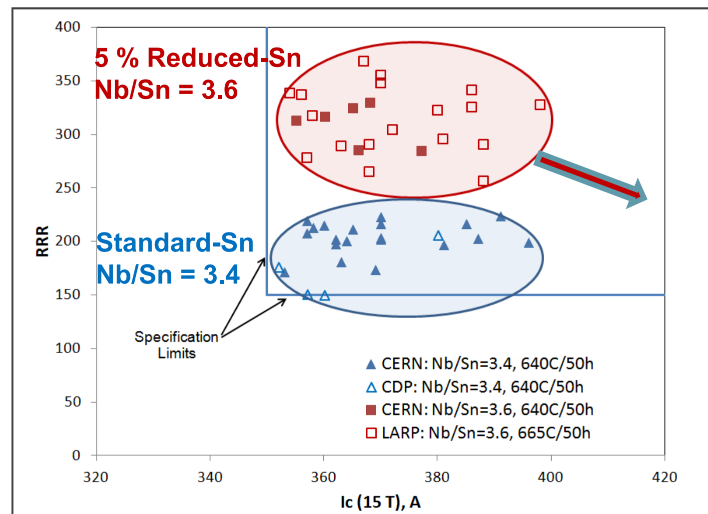


Courtesy of Jeff Parrell (OST)

Specification for SC Strand

Strand Diameter, mm	0.85 ± .003
I_c(15 T) at 4.2 K, A	> 361
I_c(12 T) at 4.2 K, A (for reference)	(≥ 684)
n-value	> 30
D_s, μm (sub-element diameter)	< 50
Cu : Non-Cu volume Ratio	1.2 ± 0.1
RRR (after full reaction)	≥ 150
Twist Pitch, mm	19 ± 3
Twist Direction	Right-hand screw
Strand Spring Back, deg.	< 720
Magnetization Width at 3 T, 4.2 K, mT	< 300
Minimum Piece length, m	TBD
High temperature HT duration, h	≥ 48





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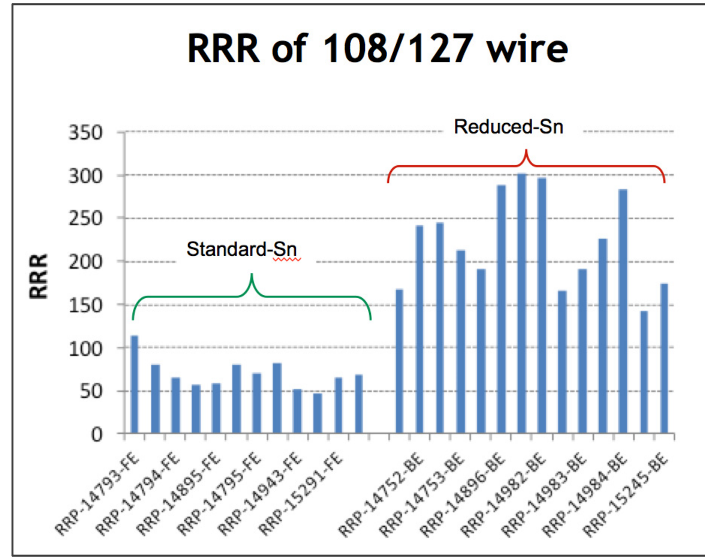
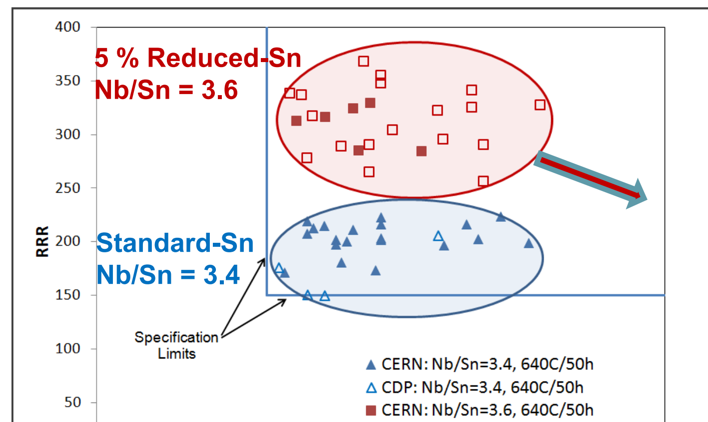
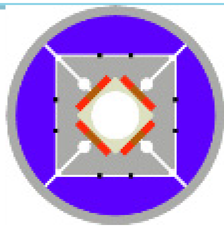


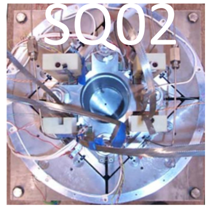


- Recent Nb_3Sn Delivery
- Headroom in RRR to increase Ic by longer treatment at 665 C
- Manufacturing margin in Ic increased by better Nb/Sn Control

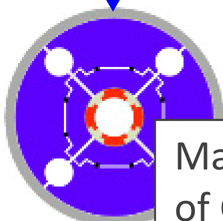
Development History (LARP)

Subscale Quad. SQ
0.3 m long
110 mm bore
2004-2006



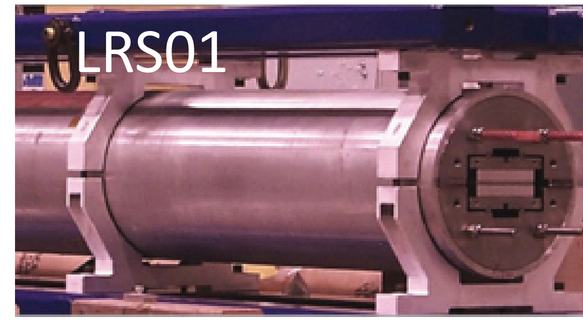


Technology Quadrupole TQS - TQC
1 m long
90 mm bore
2006-2010

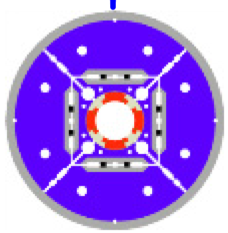


Manufacturing & Reproducibility of Cos2θ Coils, Mech. Structure

Long Racetrack LRS
3.6 m long
No bore
2006-2008

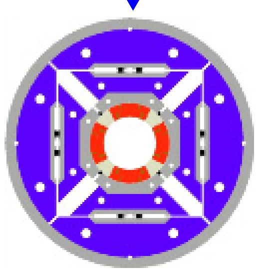


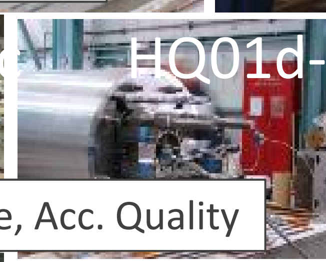
Long Quadrupole LQS
3.7 m long
90 mm bore
2007-2012



First (and only) length scale up

High Field Quadrupole HQ
1 m long
120 mm bore
2008-2014

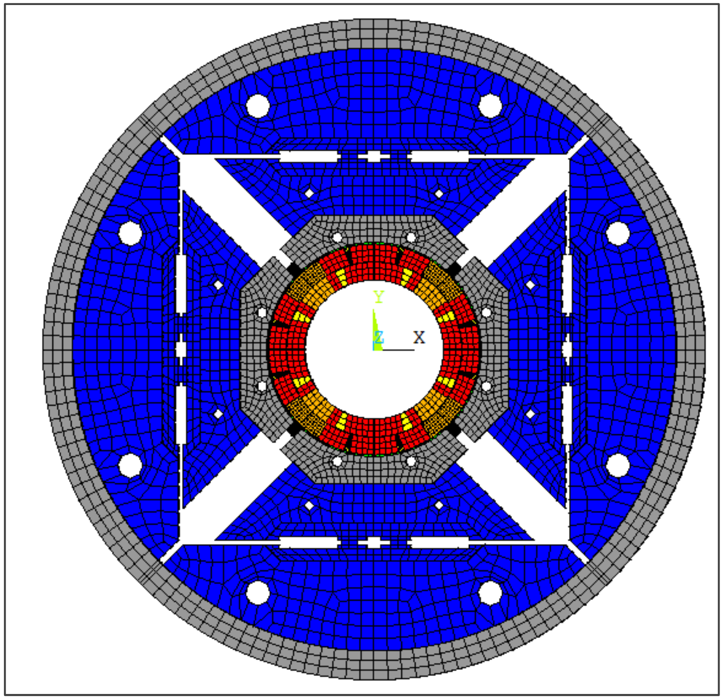




Aperture increase, Acc. Quality

Mechanical structure

- Two mechanical structure developed during the LARP phase:
  - “Traditional” SS Collars
  - Al Shell preloaded using water-pressurized bladders and interference keys during assembly
- After test of several models, the bladder and key structure demonstrated a better capability of controlling stresses and was selected as the default option.



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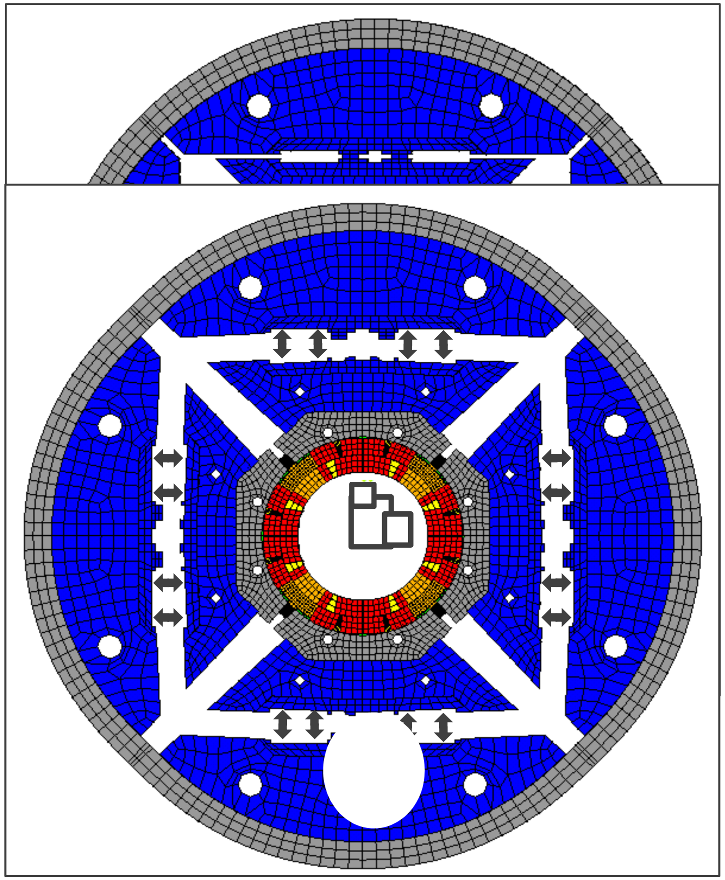

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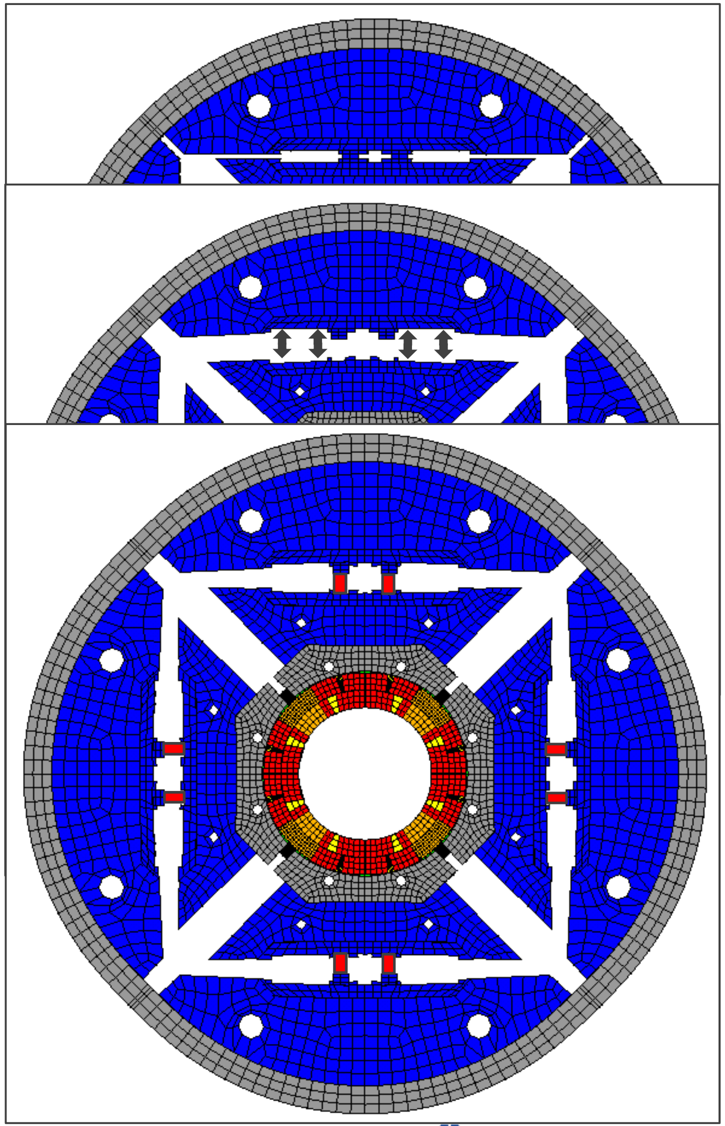
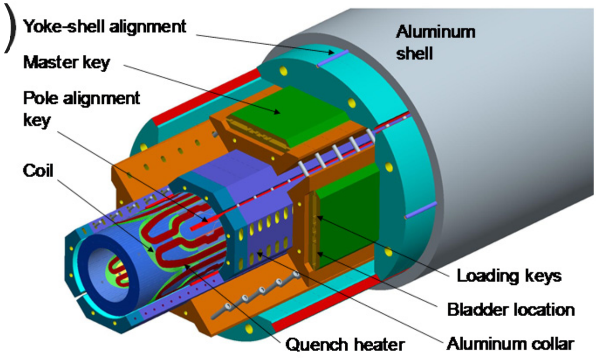
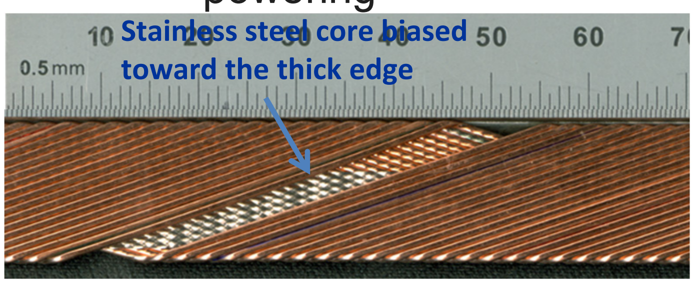


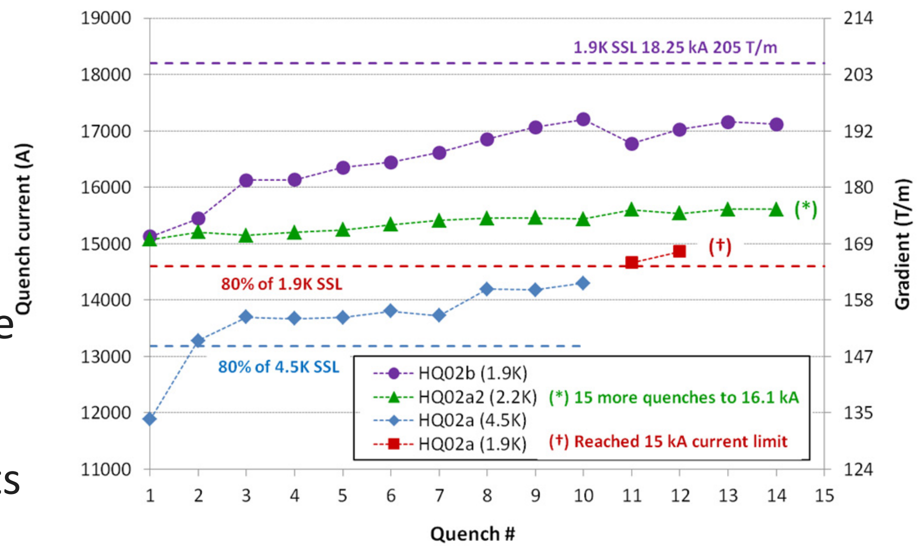
HQ (120 mm) Achievements

- Goal to demonstrate all performance requirements for Nb_3Sn IR Quads in the range of interest for HL-LHC (magnetic, mechanical, quench protection etc.)
  - 120 mm aperture, 15 T peak field at 220 T/m (1.9K)
  - First LARP design incorporating all provisions for accelerator field quality:
    - Control of geometry, saturation, magnetization, eddy currents
    - Alignment at all stages of coil fabrication, assembly & powering



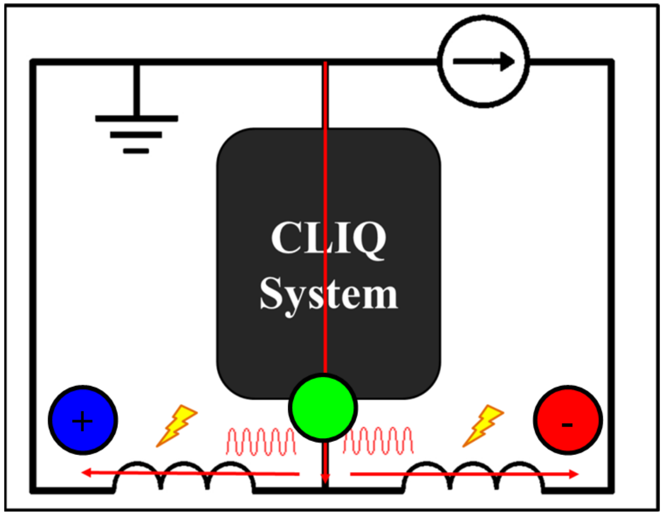


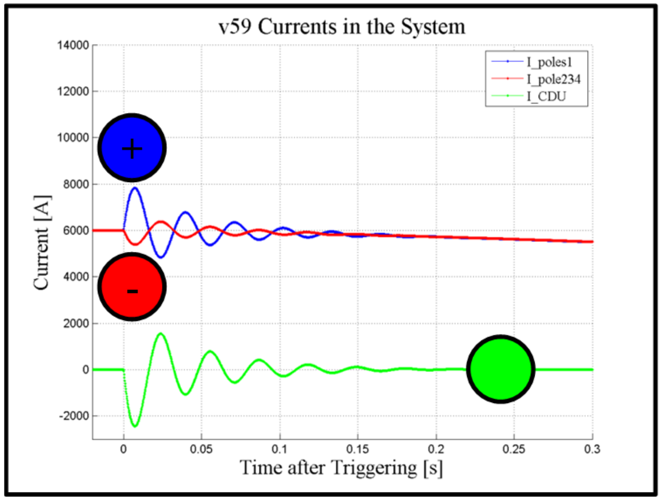
- Dramatic reduction of ramp rate dependence
  - 14.6 kA (80% SSL) up to 150 A/s (1.9K)
  - Safe discharge up to 300 A/s
- Partial core coverage to control eddy currents while maintaining current sharing



HQ Quench Protection

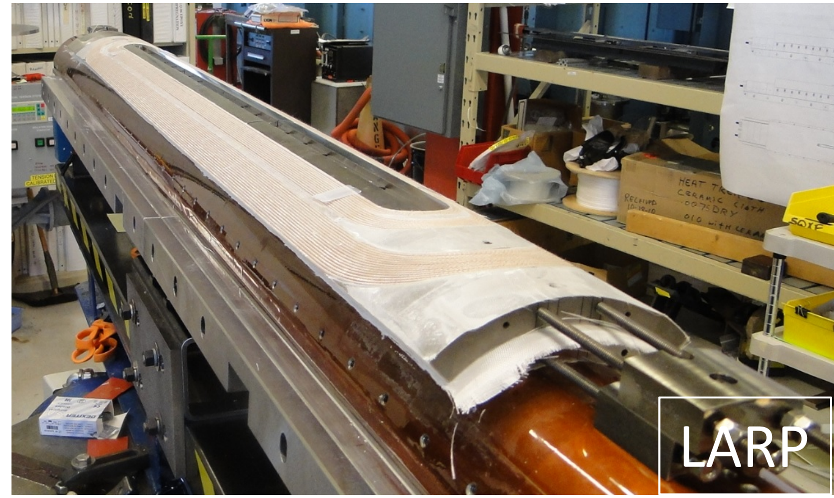
- Significant challenges in protection of high field, large aperture magnets
  - Energy density, brittle SC
- HL-LHC/LARP adopted HQ as the focus of quench protection studies.
  - Basic Plan: Energy distribution using quench heaters.
- Innovative idea under study: CLIQ = Coupling Loss Induced Quench system
- HQ tests have shown no or small permanent degradation at hot-spot temperature of ~ 400 K
  - MQXF target is hot-spot temperature less than ~ 300 K

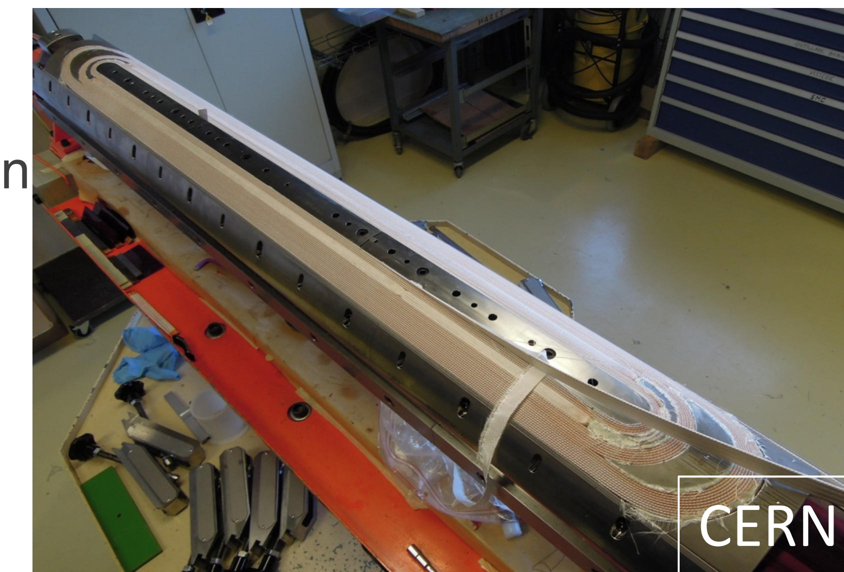




QXF (HL-LHC Quads) Plans

- Short model program: **2014-2016**
  - First SQXF coil test (Mirror struct.) in Dec. 2014
  - First magnet test (SQXF1) in May 2015
  - 2 (LARP) + 3 (CERN) short models + reassembly (~4)
- Long model program: **2015-2018**
  - Coil winding starts in 2015: Jan. (LARP)
  - First LQXF coil test (Mirror structure) in Dec. 2015
  - First model test in Oct. 2016 (LARP) and July 2017 (CERN)
  - 3 (LARP) + 2 (CERN) models in total
- Series production: **2018-2022**



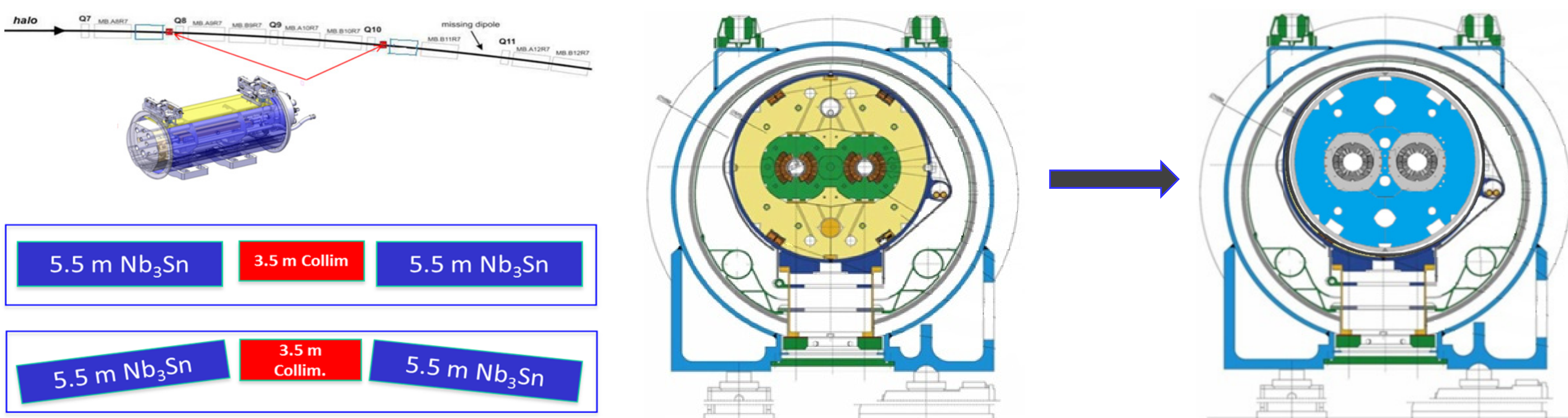


Risk Control

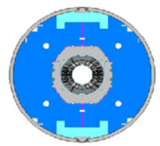
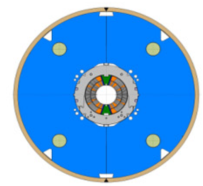
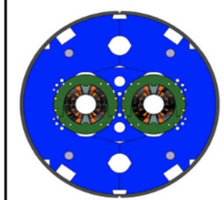
- The 120 mm LARP program is providing risk reduction before we start testing QXF models
  - HQ02 reached 95% of SSL at 1.9K:
    - Coil fabrication technology is OK
    - Magnet assembly process is OK
  - Quench protection tests:
    - With sufficient prestress hot-spot 300+ K is OK
    - CLIQ is very effective for Nb_3Sn coils
  - Field Quality OK with magnetic shims
  - LHQ (2.5 m long) coil test in a few months
- Items to address
  - Developing different heater designs and different techniques to avoid heater detachment from coil (observed in HQ)
  - Modifications to test facilities for testing/demonstrating CLIQ on S/LQXF

11 T Dipoles Motivation

- LHC particles losing momentum due to diffractive scattering or interactions at IR can only be intercepted by cold collimators in the Dispersion Suppression (DS) regions where the Main Dipoles are located.
- Due to the high filling fraction of the LHC arcs, the only viable solution is to create space by substitution an 8 T main dipole with an upgraded 11 T, shorter dipole



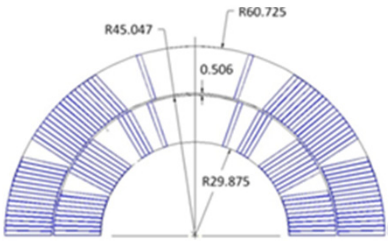
Magnet Design

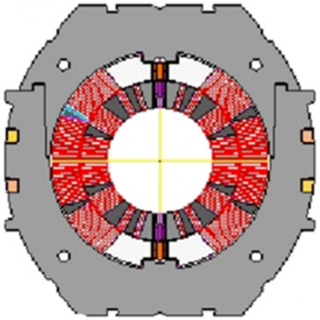
Parameter	Single-aperture FNAL 		Single-aperture CERN 	Twin-aperture 
	MBHSP01	MBHSP02		
Aperture (mm)	60			
Yoke outer diameter (mm)	400		510	550
Coil length (m)	1.80	0.88	1.8	0.88 - 1.8 - 5.4
Nominal bore field @11.85 kA (T)	10.86	11.07	11.25	11.25
Short-sample bore field at 1.9 K (T)	13.6 [1]	14.1 [2]	13.9 [1]	13.9 [1]
Margin B_{nom}/B_{max} at 1.9 K	0.80 [1]	0.78 [2]	0.81 [1]	0.81 [1]
Stored energy at 11.85 kA (kJ/m)	473	482	484	969
F_x per quadrant at 11.85 kA (MN/m)	2.89	3.11	3.16	3.16
F_y per quadrant at 11.85 kA (MN/m)	-1.57	-1.56	-1.59	-1.59

1) OST ø0.7 mm RRP-108/127
2) OST ø0.7 mm RRP-150/169


0.7 mm Nb_3Sn RRP strand


40-strand cable



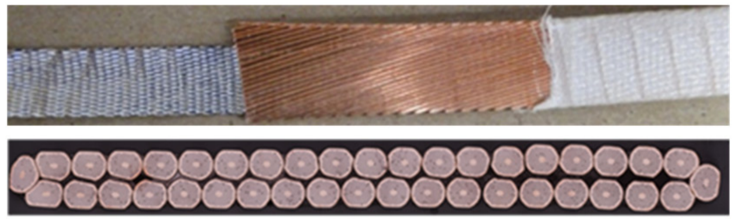

Stainless steel collar

- Chellenges: high field, forces, stored energy

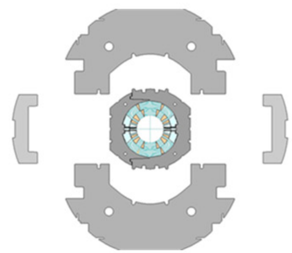
Fabrication

- Fabrication: from cable to magnet
- Test: VMTF, quench performance, magnetic measurements, quench protection



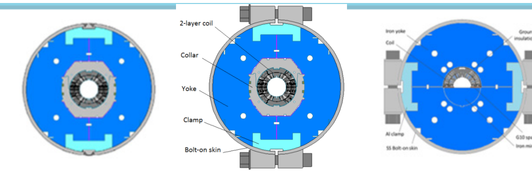


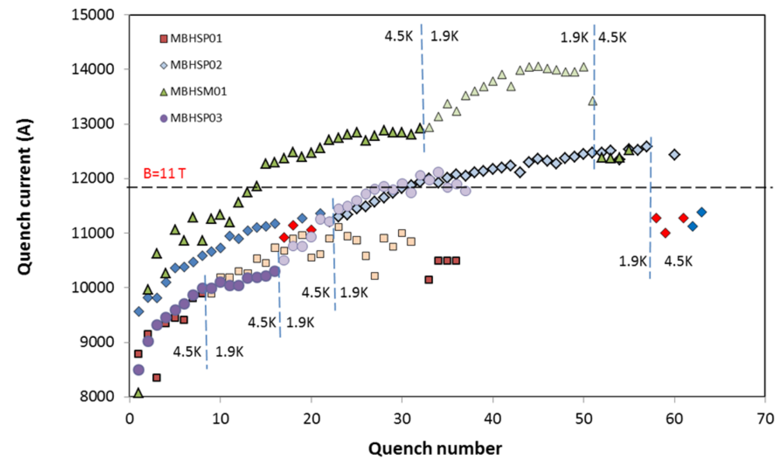


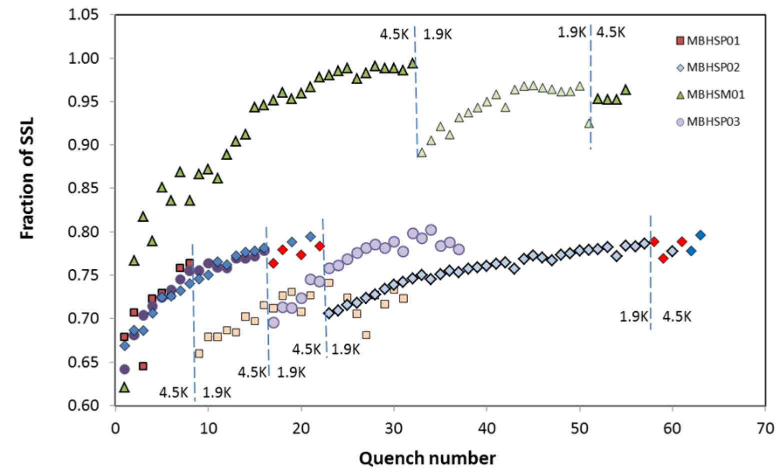




Quench Performance (FNAL)

- MBHSP01:
  - B_{max}=10.4 T at 1.9 K, 50A/s
  - strong ramp rate sensitivity
  - holding quenches
- MBHSP02:
  - B_{max}=11.7 T at 1.9 K
  - 97.5% of B_{des}=12 T
  - low ramp rate sensitivity
  - holding quenches
- MBHSM01:
  - B_{max}=12.5 T at 1.9 K
  - ~100(97)% at 4.5 (1.9) K of SSL
  - low ramp rate sensitivity
  - no holding quenches
- MBHSP03: test just concluded

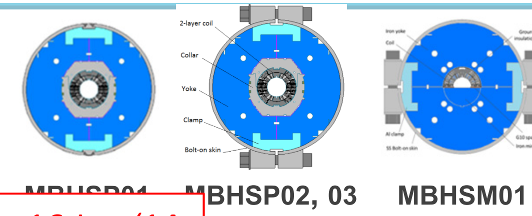


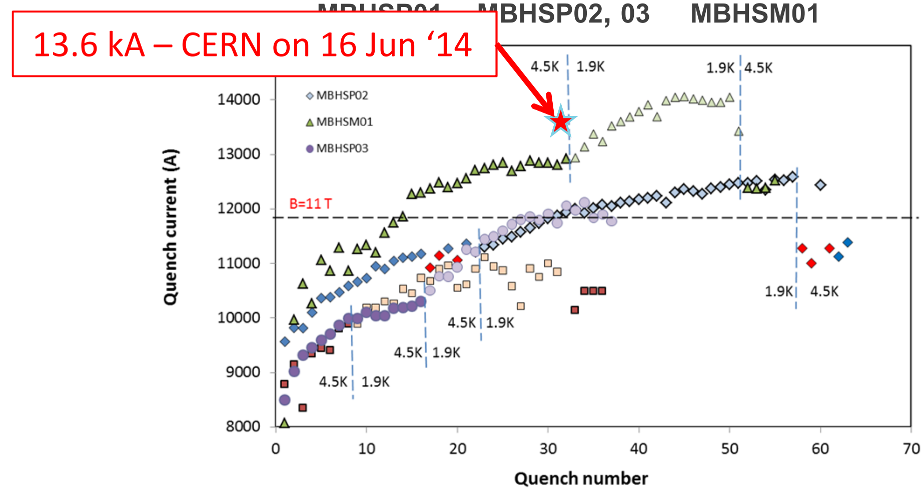


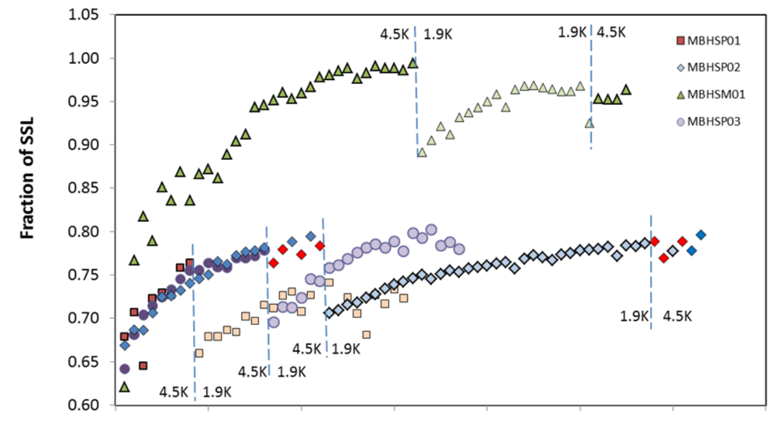


Quench Performance (FNAL)

- MBHSP01:
  - B_{max}=10.4 T at 1.9 K, 50A/s
  - strong ramp rate sensitivity
  - holding quenches
- MBHSP02:
  - B_{max}=11.7 T at 1.9 K
  - 97.5% of B_{des}=12 T
  - low ramp rate sensitivity
  - holding quenches
- MBHSM01:
  - B_{max}=12.5 T at 1.9 K
  - ~100(97)% at 4.5 (1.9) K of SSL
  - low ramp rate sensitivity
  - no holding quenches
- MBHSP03: test just concluded







G. Chlachidze – WEPRI097 WEPRI098 WEPRI099

Conclusions

- After a decade of development, Nb_3Sn magnets have reached maturity for application in accelerators.
- Nb_3Sn IR Focusing Quadrupoles (G ~140 T/m, 150 mm aperture) and Dipoles (11 T) are foreseen for upgrades to the LHC in order to deliver ~3000 fb^{-1} to the CMS and ATLAS experiments in the next decades
- The CERN/LARP Collaboration has finalized the design of the Quadrupoles and Dipoles needed for the HL-LHC and is now embarking in a ~3 years program to transfer technology and to deliver working prototypes of each magnet.
- Construction of the magnets is planned in the '18-'22 period with installation during LS3.