Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

LARP–LHC Upgrades

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Fermilab Users Meeting

June 16th, 2016

In partnership with: LARP, HiLumi HL-LHC PROJECT

Berkeley Lab, Brookhaven National Laboratory, SLAC National Accelerator Laboratory, Jefferson Lab, Old Dominion University 1930, CERN

Content

- What is LARP? Its history? Its goals?
- Nb_3Sn Interaction Region Quadrupoles
  - Magnetic and Mechanical Design
  - Coil and Magnet Fabrication
  - First Model Magnet Results
  - Status Update
- RF Crab Cavities
  - Design, Status
- e^- Lens
  - Purpose, Design

What is US-LARP?

- The US – LHC Accelerator Research Program brings ~12 years of Intellectual and Development effort for HL-LHC

> Members of the CERN staff, as well as U.S. scientists, have already proposed upgrades to the LHC at international conferences. These upgrades cover improved interaction region final focusing as well as an energy doubler. The U.S. team is in an excellent position to play a leading role to both of these activities because of the expertise developed in the U.S. LHC Accelerator Construction Project as well as the base program in high fiel

LARP Mandate - 2004

- Many successful efforts have been supported by LARP:
  - Magnets, Crab Cavities, e-lens, Wide Band Feedback System, Rotating Collimators, Luminosity Monitors, Accelerator Physics, Beam Instrumentation, Irradiation assessment, etc.
- HiLumi-LHC became an official CERN project late 2015

High Luminosity LHC → HiLumi HL-LHC PROJECT

- CD-0 for the HL-LHC Accelerator Upgrade Project (AUP) was approved in March

Some Context

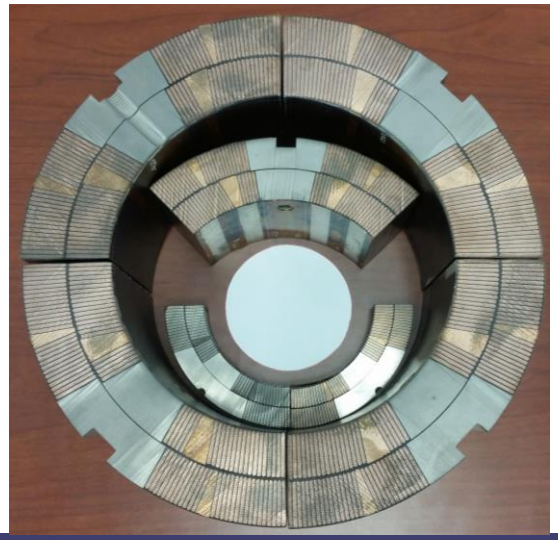
- P5 report places Hi-Lumi LHC as its highest-priority near-term large project.

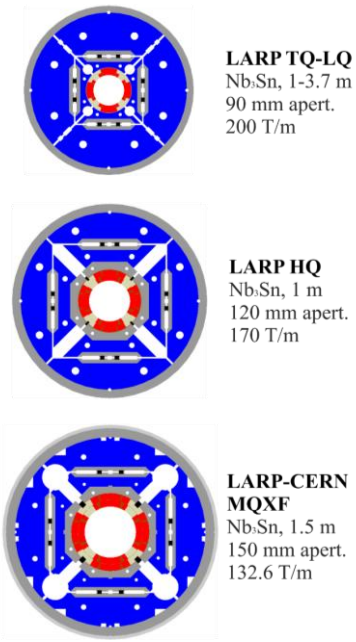
US LHC Accelerator Research Program (LARP)

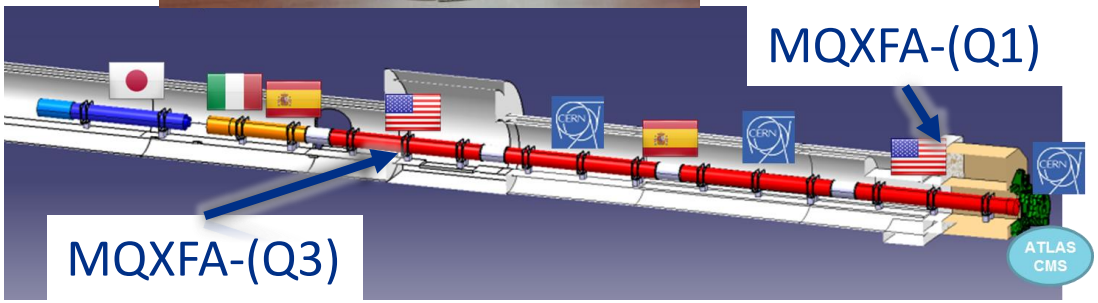
- LARP is a collaboration between BNL, FNAL, LBNL, and SLAC along with CERN in the context of HL-LHC

- Since 2004, LARP has developed Nb_3Sn as a viable material for the Low-β IR quads enabling HL-LHC

- US will provide 10 cold masses
  - 8 coils per cold mass
  - Coils fab. at BNL and FNAL
  - Magnet Assembly at LBNL







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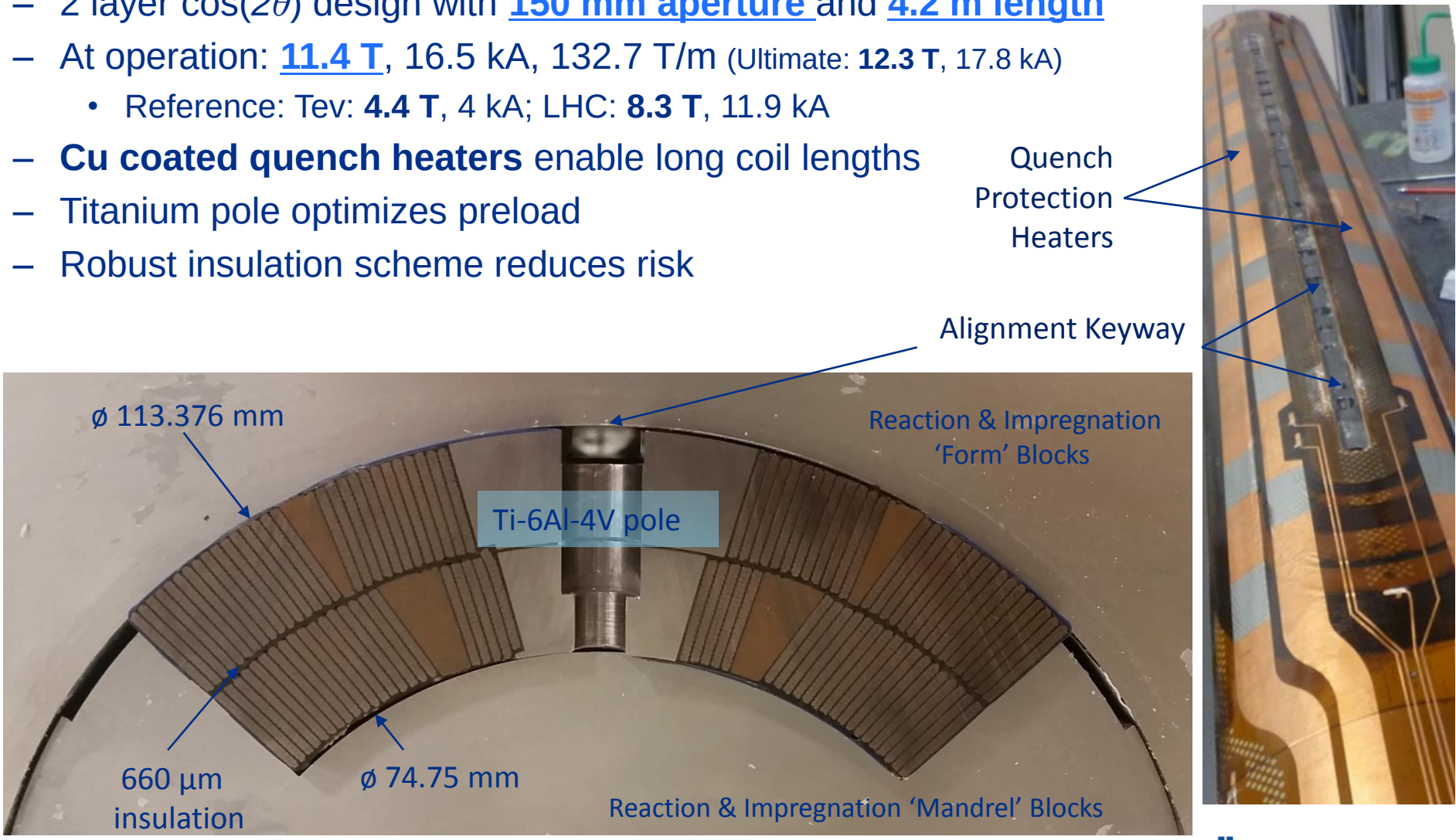
MQXF Design

- 2 layer cos(2θ) design with **150 mm aperture** and **4.2 m length**
- At operation: **11.4 T**, 16.5 kA, 132.7 T/m (Ultimate: **12.3 T**, 17.8 kA)
  - Reference: Tev: **4.4 T**, 4 kA; LHC: **8.3 T**, 11.9 kA
- **Cu coated quench heaters** enable long coil lengths
- Titanium pole optimizes preload
- Robust insulation scheme reduces risk



Nb_3Sn Cable Technology

- Convergence on Oxford ST RRP® 108/127 wire.
- 40 wire Cable with SS core and Braided-On Insulation for long cable unit lengths
- Nb_3Sn Cable **expands laterally** when heat treated.
- Nb_3Sn Cable **contracts axially** when heat treated.
- Room is left in coil cavity for cable to expand during heat treatment.
- Gaps are left in the pole to allow cable to contract

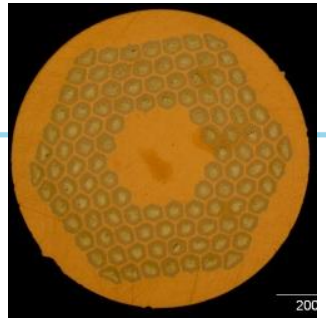
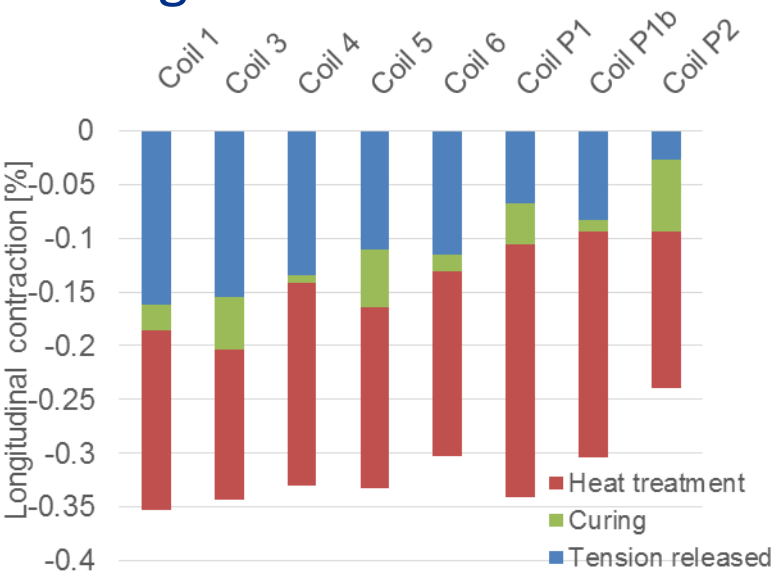
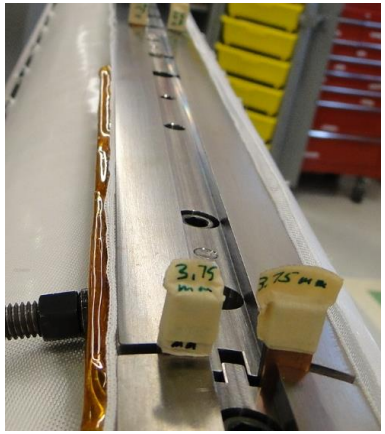


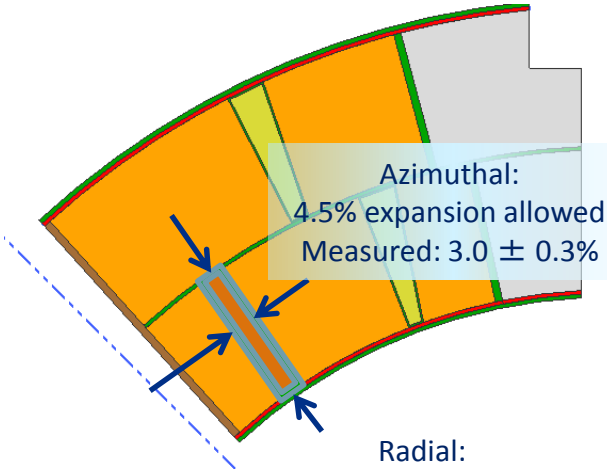
Photo courtesy of P. Ferracin

Longitudinal Contraction

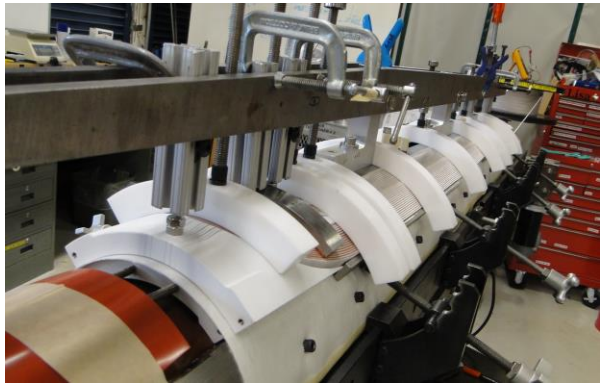




Pole Gaps allow Contraction

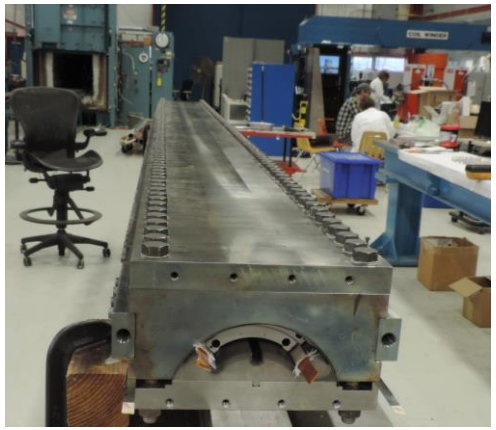


QXF Nb_3Sn Quad Coil Technology

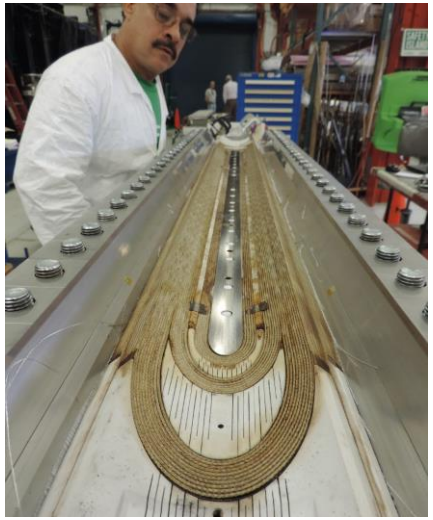


Winding & Curing

Coils have 25 kg of winding tension and cured with a ceramic binder

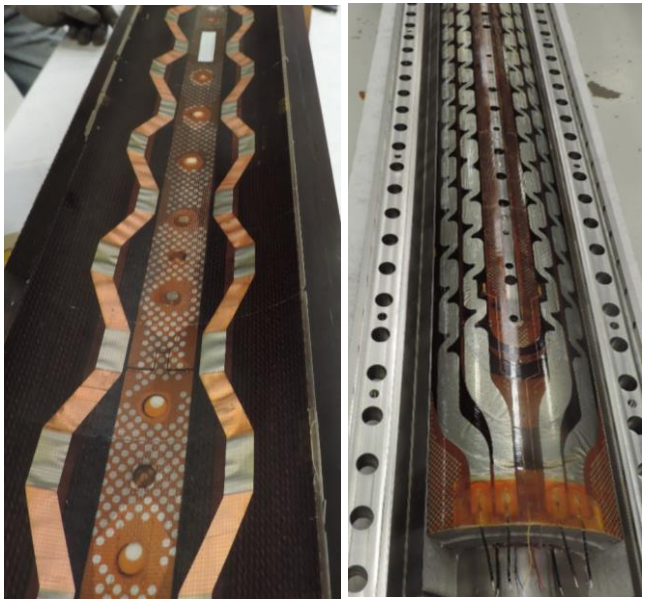


Reaction



Nb_3Sn Formation ~9 days with peak plateau at 650°C

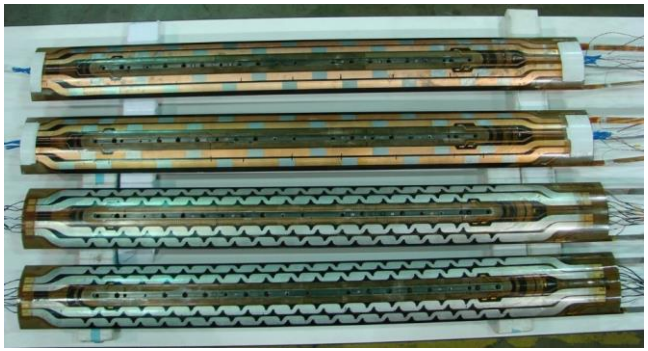
Impregnation

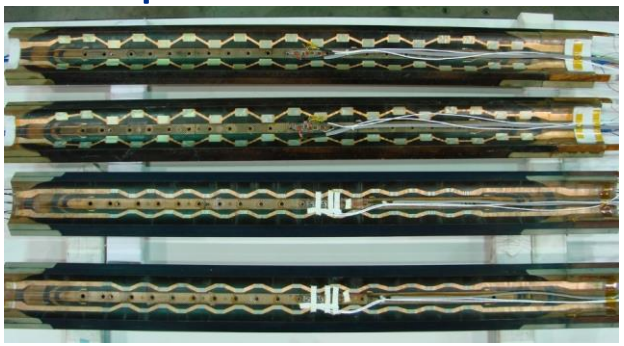


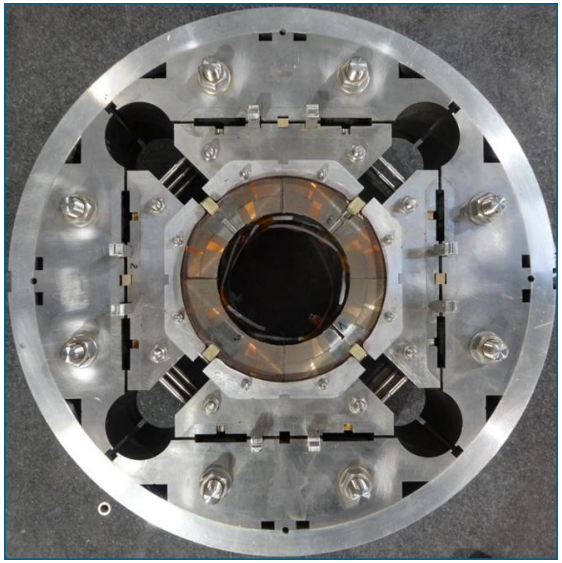
Impregnation protects conductor from Lorentz force

Mechanical Structure / Magnet Assembly

MQXFS1a Quadrupole Coils



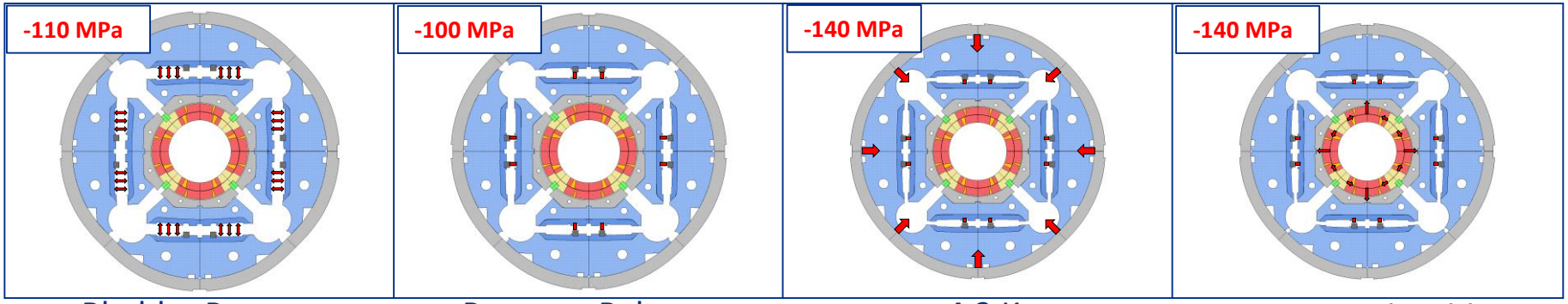




- **6x** the e.m. forces than current MQXA/B Quads
- '**Bladder & Key**' Technology from HQ series
- Peak stress **-140 MPa or less**

Deformed shape and coil peak azimuthal stress from ANSYS

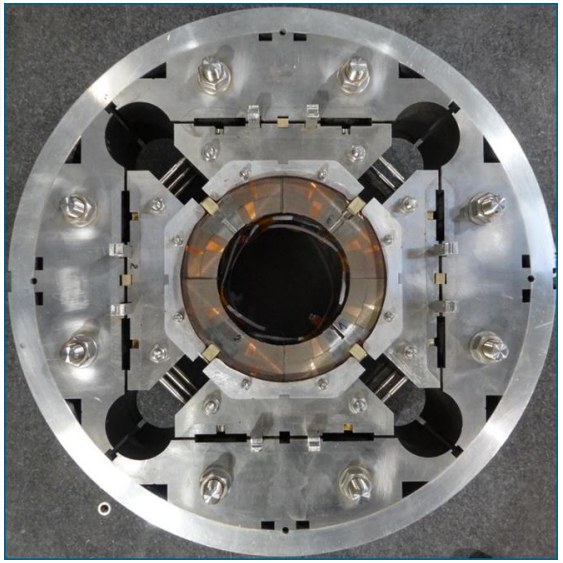
Courtesy Paolo Ferracin



Bladder Pressure | Pressure Release | 4.2 K | Nominal Field

Mechanical Structure / Magnet Assembly

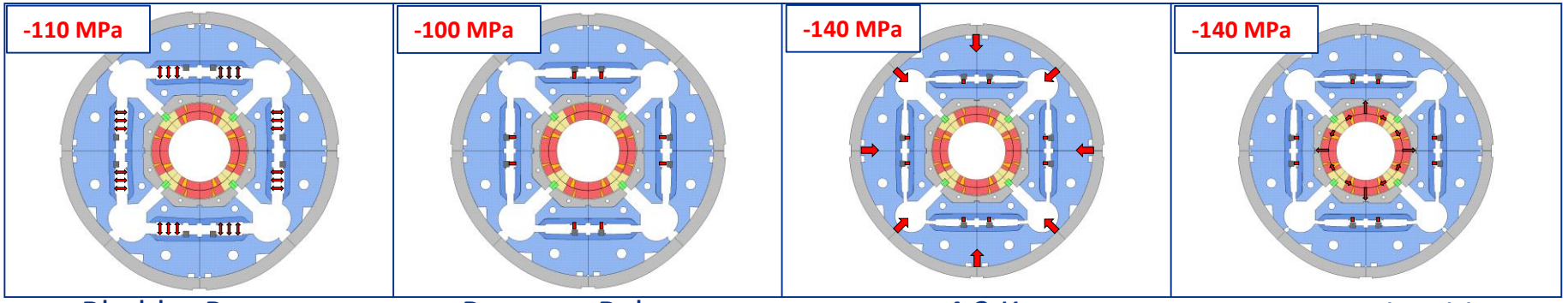
MQXFS1a Quadrupole Coils



- **Very Strong** collaboration between LARP and CERN
- **Very integrated** design and development plan
- Exchanging parts, procedures, **and coils!!**

Deformed shape and coil peak azimuthal stress from ANSYS

Courtesy Paolo Ferracin



Bladder Pressure | Pressure Release | 4.2 K | Nominal Field

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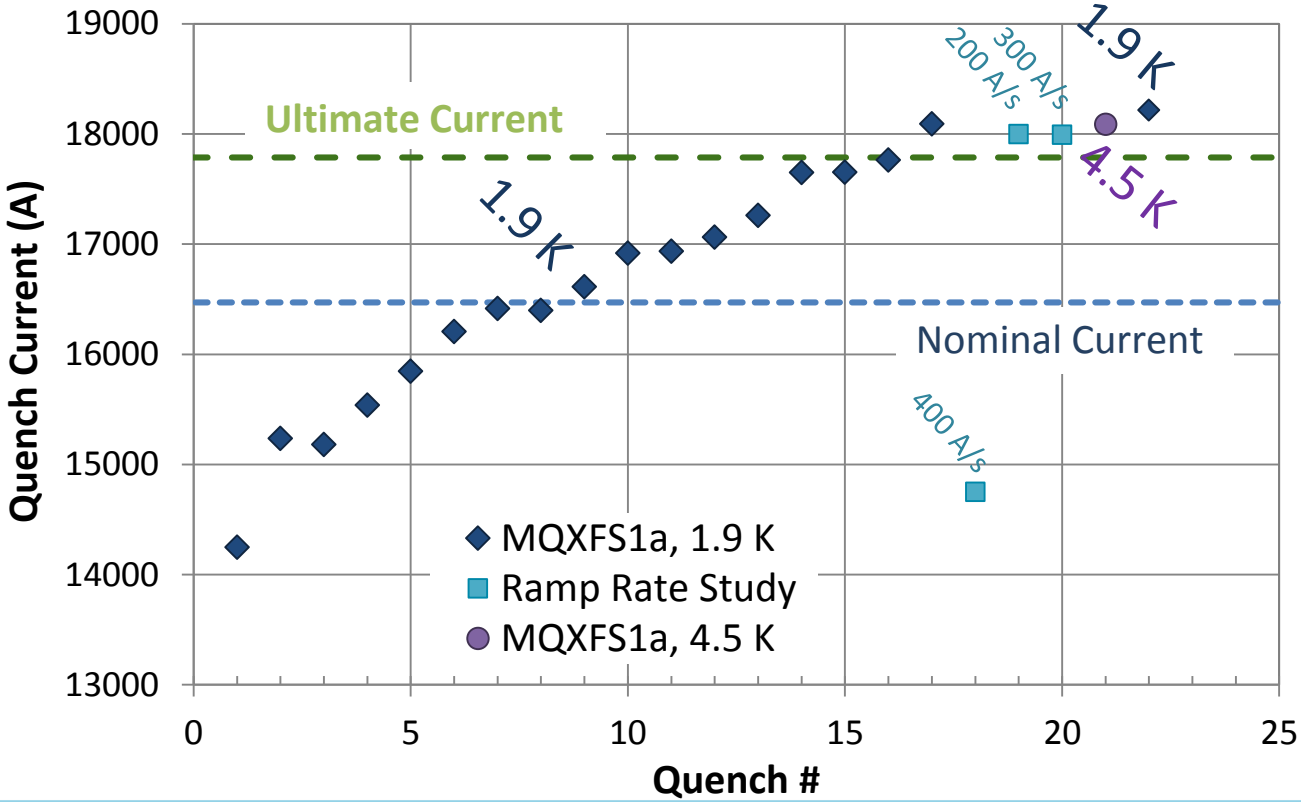
Testing the first model MQXF magnet: Training Curve

Ramp rate of 20 A/s used for training

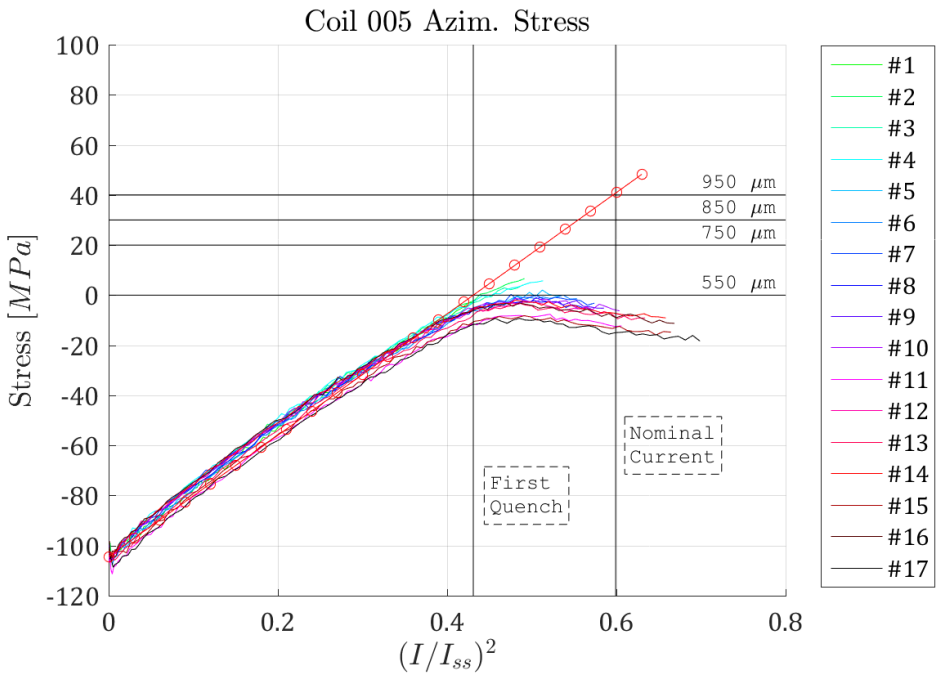
- 50 A/s at the beginning, then 20 A/s to quench

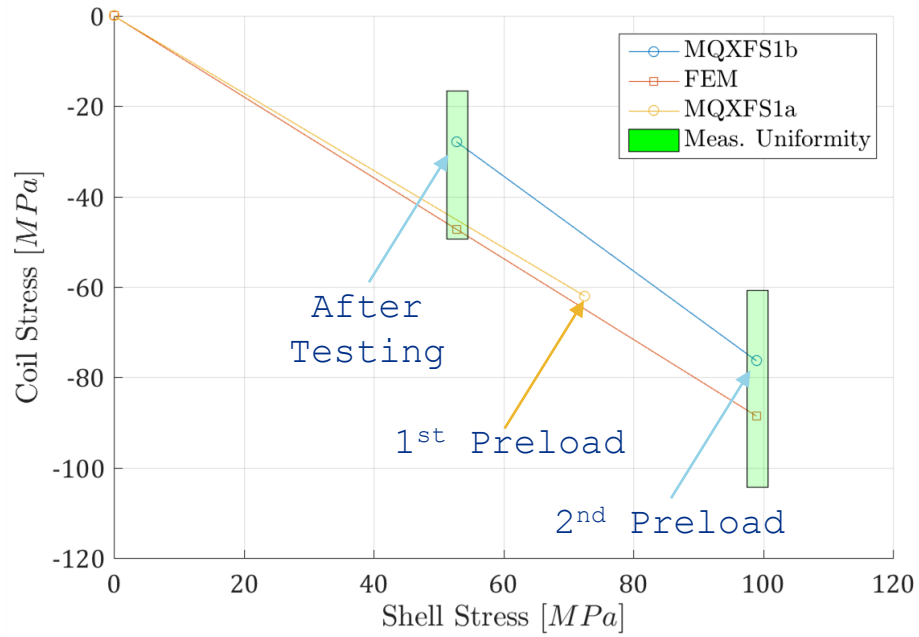


A quench at 4.5 K reached 18.1 kA – same current as at 1.9 K! >93% SSL

-> Large Temperature Margin

MQXFS1 Strain Gauge Data and Pre-load





- MQXFS1a, 550 μm simulated interference: unloading at $I \sim 14.2\ kA$
- MQXFS1b, 850 μm simulated interference: unloading expected at $I \sim 16.0 - 17.0\ kA$
- Pole stress increase:
  - $\sim 15\ MPa$ more than MQXFS1a after loading
  - $\sim 50\ MPa$ more than MQXFS1a after testing
  - $\sim 30 - 35\ MPa$ more than MQXFS1a after cooldown (to be confirmed)
- **MQXFS1b to be tested at VMTF starting in July!**

MQXFS1a Field Quality – Final focusing…

Standard Fourier analysis of accelerator magnets

$$\int_{-z_0}^{z_0} B_\varphi(r,\varphi,z)dz = \sum_{n=1}^{\infty}\left[\frac{r}{r_0}\right]^{n-1}(A_n \sin n\varphi + B_n \cos n\varphi)$$

$$\int_{-z_0}^{z_0} B_r(r,\varphi,z)dz = \sum_{n=1}^{\infty}\left[\frac{r}{r_0}\right]^{n-1}(-A_n \cos n\varphi + B_n \sin n\varphi)$$

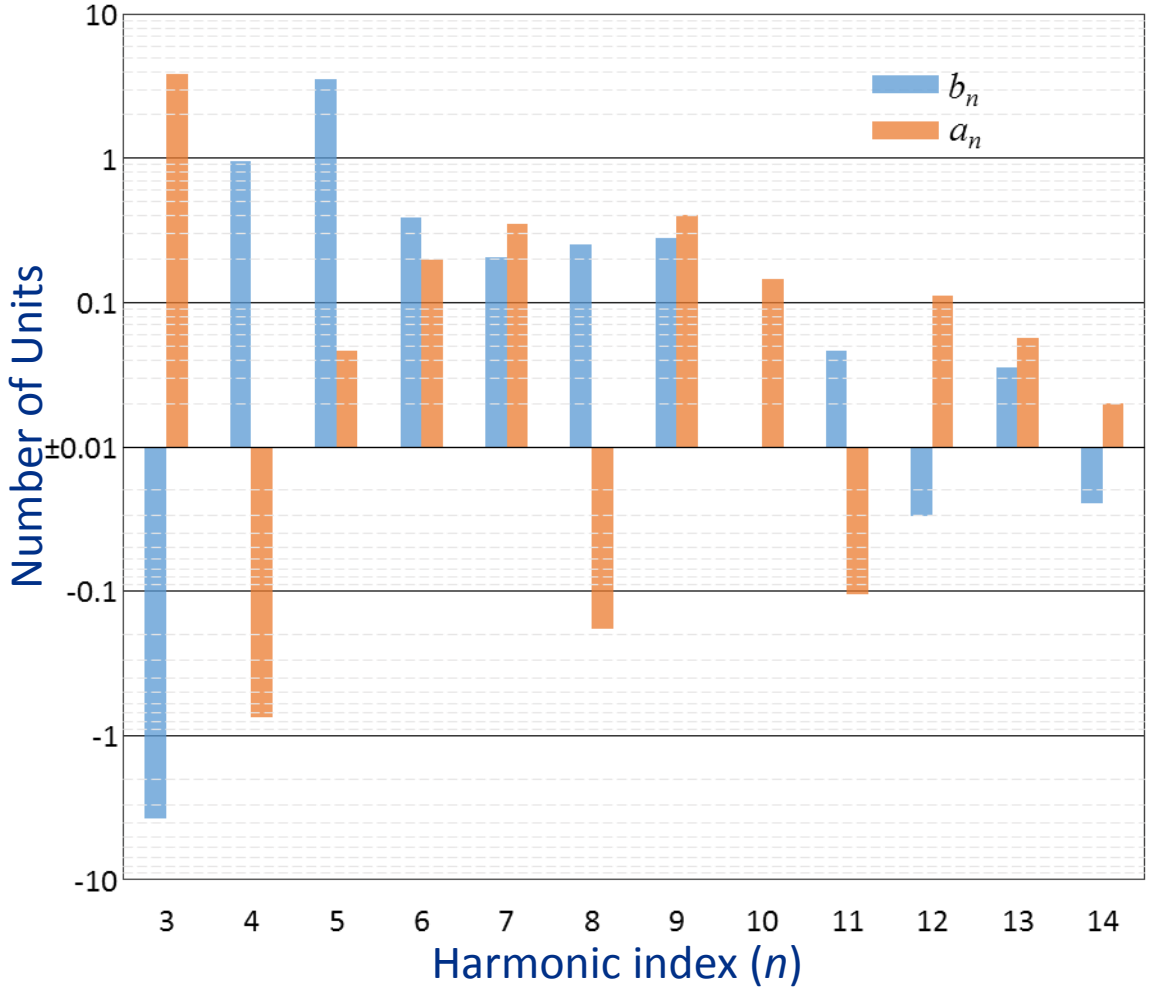
$b_n = \frac{B_n}{B_2}10^4$ = Normal harmonics

$a_n = \frac{A_n}{B_2}10^4$ = Skew harmonics

- Harmonics take into account asymmetric assembly shimming.
- Only **a_3, b_3, and b_5** are larger than anticipated
- Everything else is within expectation or **< 1 unit**

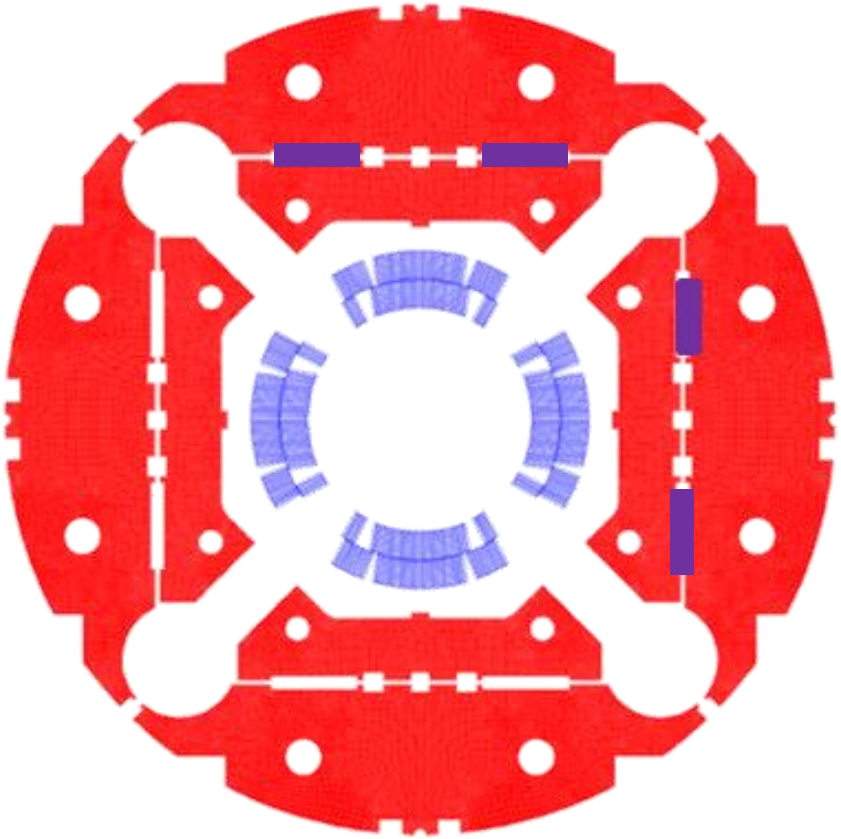
MQXFS1a Field Quality

Error Bars are from Random Conductor Displacements



Magnetic Shims, Correcting b_3 and a_3

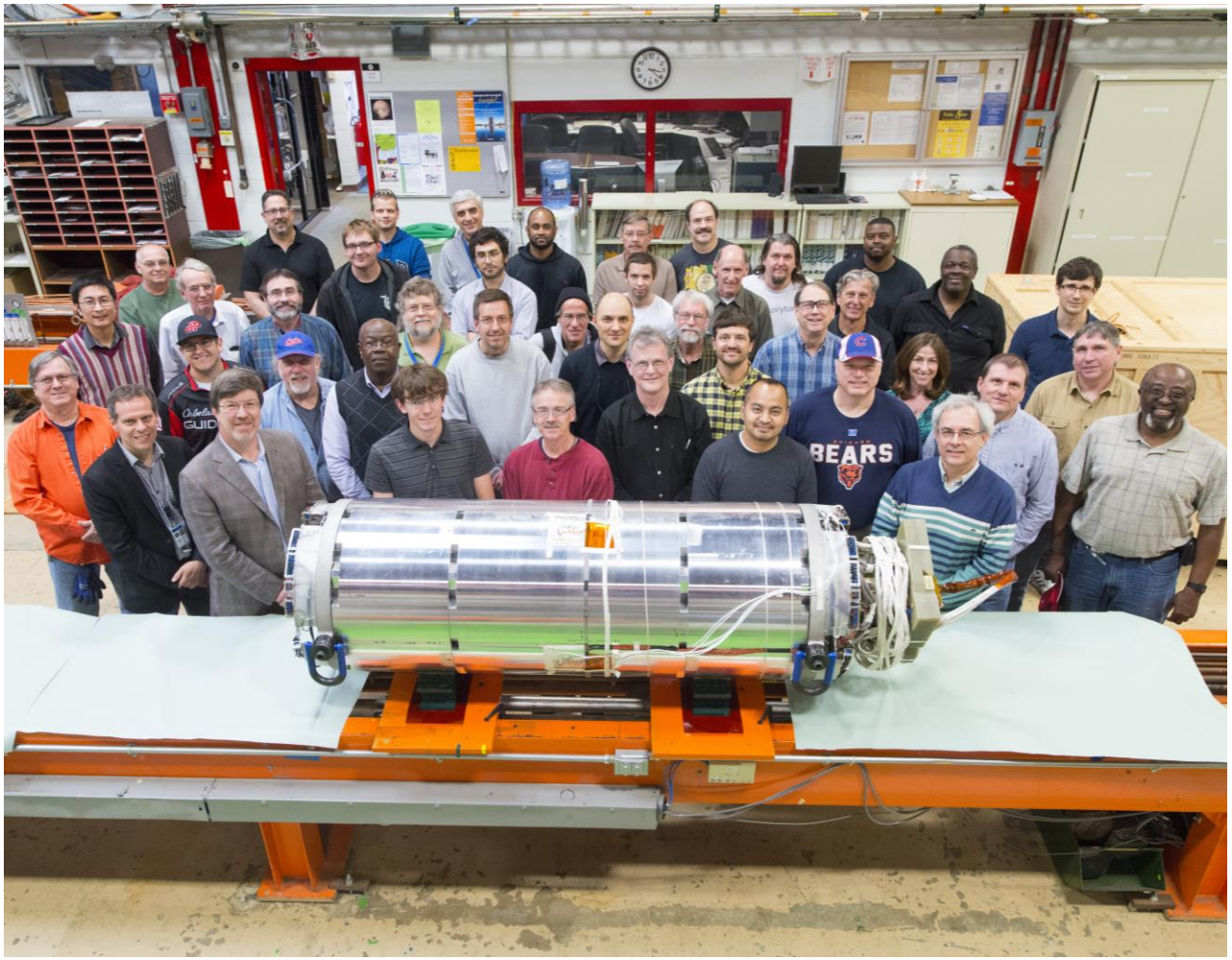
- Measured normal and skew sextupole can be corrected inserting **magnetic shims** in the bladders slot
  - Magnetic shims installed in MQXFS1b to prove the correction capabilities



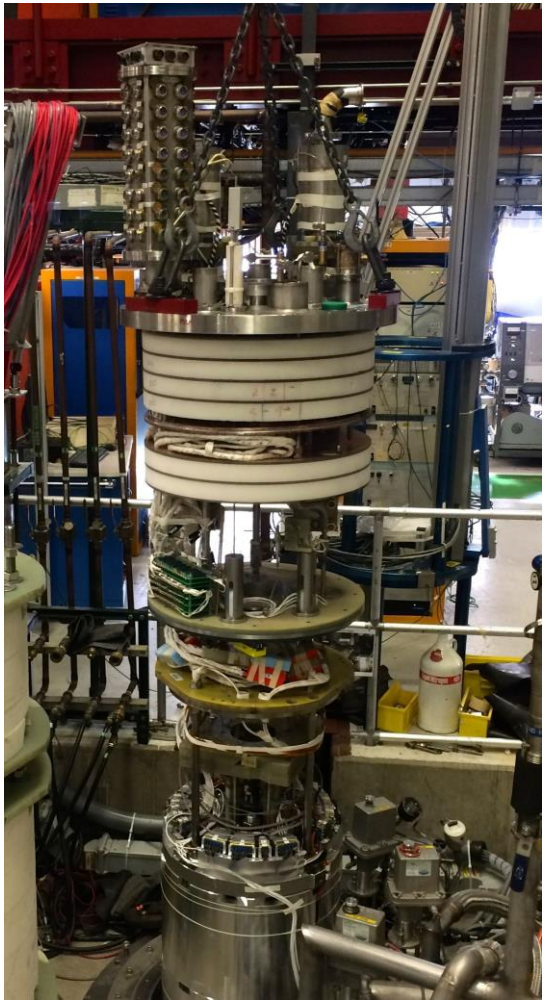
Correction capabilities using 9x58 mm shim in the bladder slots		
Order	b_n	a_n
3	4.24	-4.24
4	0.00	0.00
5	0.40	0.40
6	0.00	0.00

MQXFS1 Meas.	b_3	a_3
	-4.44	**3.37**

Testing the first model MQXF magnet:



MQXFS1a after first test in bldg 1 of the Industrial Building Complex of FNAL Technical Division



Installing MQXFS1a in the Vertical Magnet Test Facility

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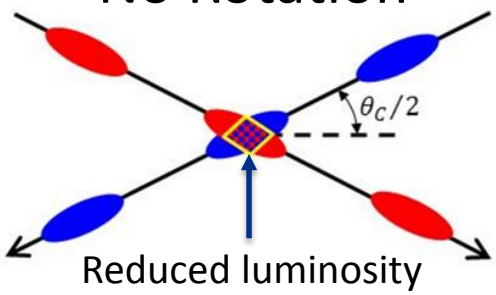
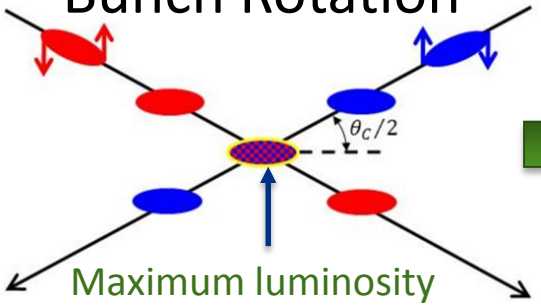
Crab Cavities – another key to High Lumi.

- Crab cavities rotate each bunch to increase luminosity

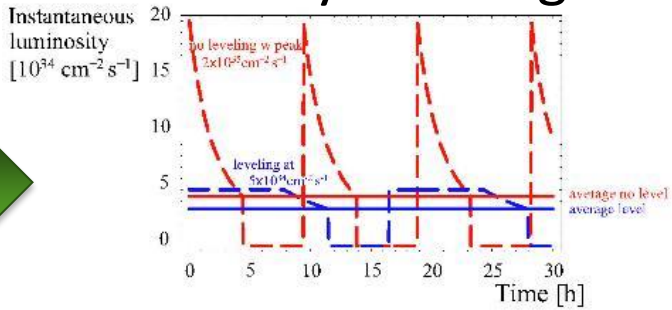
No Rotation



Bunch Rotation

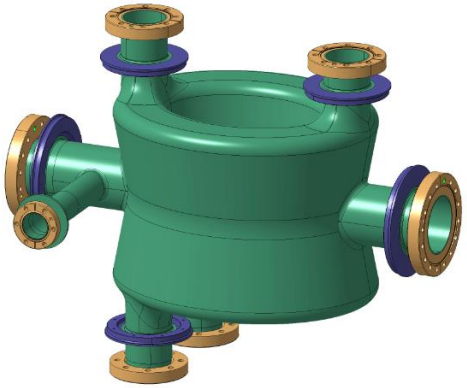


Luminosity Leveling

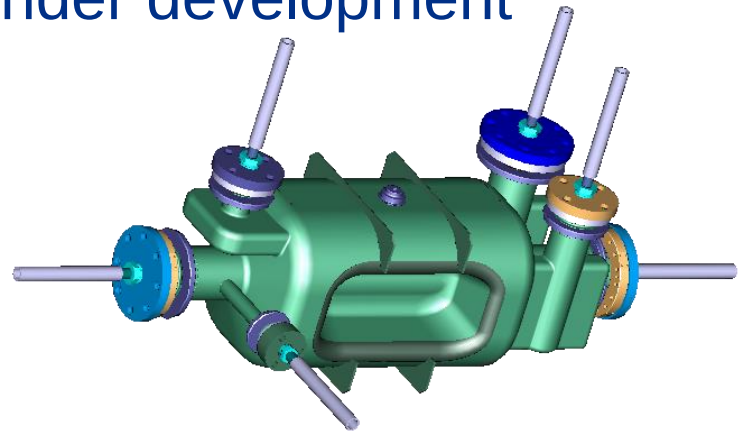


Maximum Integrated luminosity

- DQW and RFD designs under development



Double Quarter Wave CC

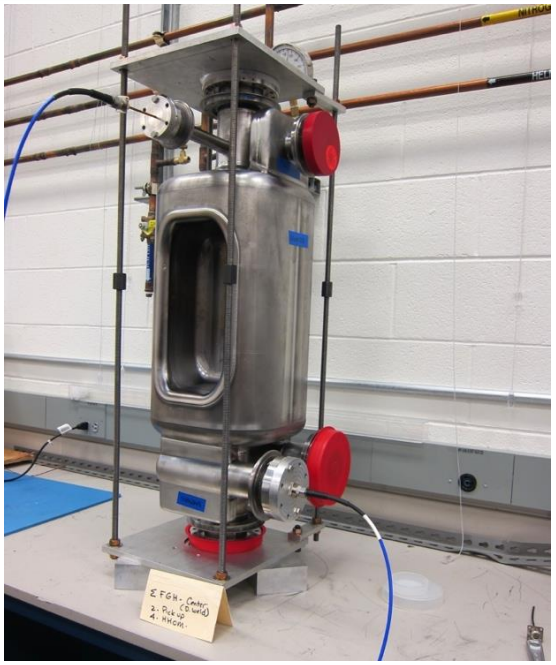


RF Dipole CC

Leonardo Ristori

Status of Crab Cavities

- Have received two RFD cavities from vendor
  - LARP is supporting JLAB, BNL, and ODU efforts to characterize and learn from NW cavities
  - Mechanical Measurements, X-rays, processing, final weld “tuning”,… up to test in vertical configuration
- 2 DQWs are expected from vendor in June.



- FNAL Engineering leadership will work for the qualification and acceptance - by CERN - of SRF vendors under US contract
  - LARP to fund qualification of Cavities Suppliers (1 or more). CERN to review and grant qualification.
  - Full reliance on FNAL SRF Facilities

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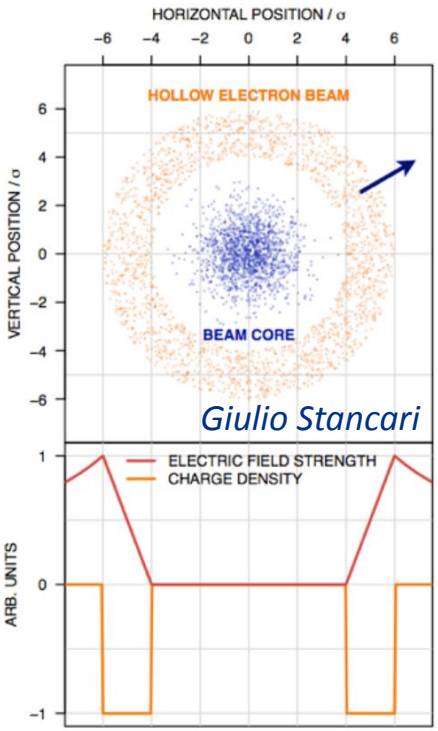
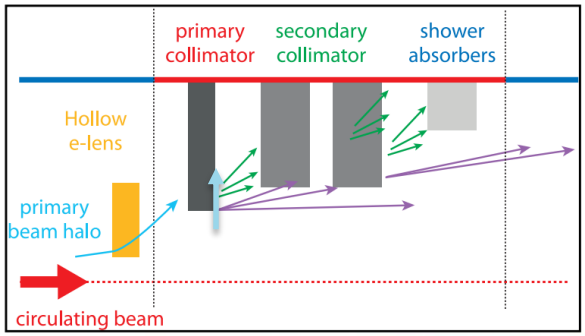
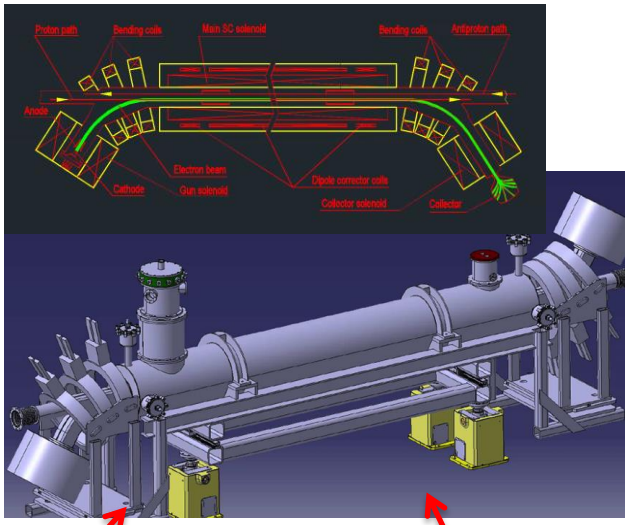
e^- Lens – High intensity beam collimation

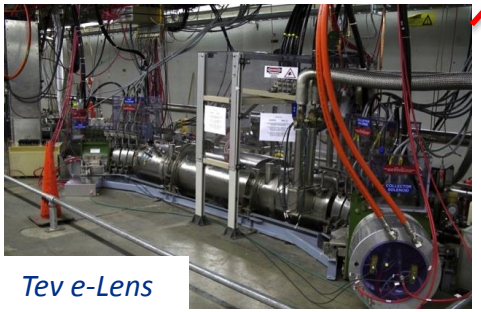
- Power deposited on collimators is doubled for HL-LHC
- Hollow e-lens beams selectively divert particles above a certain amplitude
- Novel technology developed at Fermilab and based on existing FNAL/BNL designs
- -> Robust, low-risk HL-LHC contribution
  - BNL on SC Solenoid
  - FNAL on Gun/Collector & other magnets



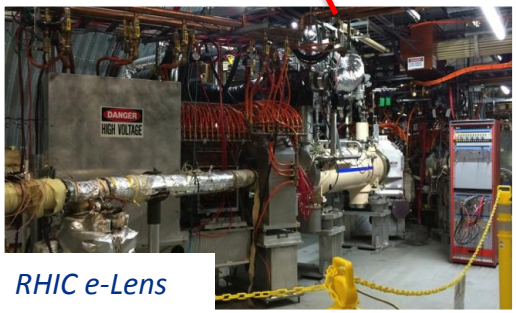
Giulio Stancari







Tev e-Lens



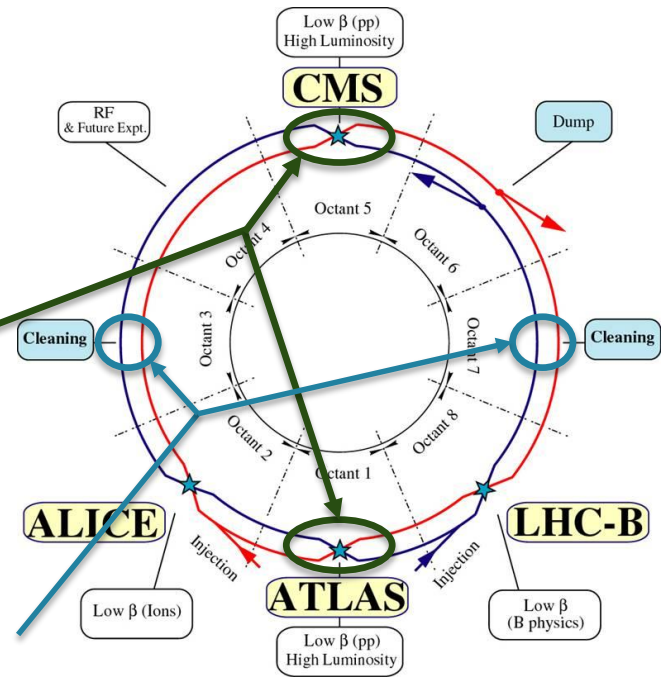
RHIC e-Lens

Summary

- LARP has **substantially** developed U.S. expertise in several areas especially Nb_3Sn.
- The first MQXF model magnet reached **ultimate LHC operational current** with sufficient margin.

- **Nb_3Sn magnets** will be installed in a ring for the **first time** and are the **backbone** of HL-LHC.
- LARP developed **crab cavities** maximize the integrated luminosity and are part of the baseline

- Tevatron and RHIC hollow **e-lens expertise** should significantly contribute to HL-LHC collimation



- LARP and LAUP have strong collaboration with CERN and strong P5 support
- LAUP passed CD-0 in March with CD-1 scheduled in early FY17
- Combined CD-2/3 is scheduled in FY18 and is largely dependent on long MQXF prototypes and baselined crab cavity and e-lens efforts

THANK YOU!!!

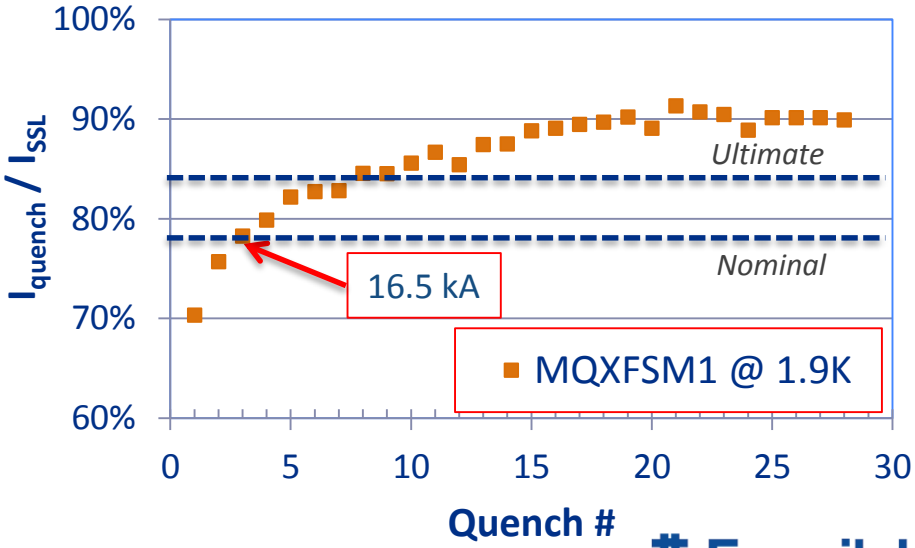
Extra Slides

Moving forward in HL-LHC AUP…

- Retest MQXFS1b with increased preload and magnetic shims
  - Already reached the ultimate current!
  - The magnet demonstrated stable operation at the nominal current (16480 A) for more than 8 hours ("Holding Current" test)
  - A single test at 4.5 K reached 93.6% SSL

- Coil Fabrication for Long QXF Prototypes
  - All coils for first long prototype (MQXFP1) are Wound and Cured with assembly and test in FY 17
  - Parts procured for QXFA coils (Full Q1/Q3 prototype)
    - Winding to begin in July!

- CD-1 approval by early FY17 and Consolidated CD-2/3 approval by Q3 FY18.
  - Will requires 2 successful Prototype magnets
  - Will require 'baselined' crab cavity and e-lens efforts

Mirror Test of First HL-LHC 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!
- Next Goal: Test of first 4-coil complete QXF quadrupole!!!