IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2016.
Invited presentation 3OrCC_01 given at MT-24, Seoul, Korea, October 18-23, 2015.

Development of MQXF, the Nb_3Sn Low-β Quadrupole for the HiLumi LHC

P. Ferracin

on behalf of the MQXF collaboration

24th International conference on magnet Technology
Seoul, South Korea
19-23 October, 2015

Acknowledgments

- CERN
  - A. Ballarino, H. Bajas, M. Bajko, B. Bordini, J.C. Perez, S. Izquierdo Bermudez, P. Fessia, P. Grosclaude, M. Guinchard, M. Juchno, F. Lackner, L. Oberli, H. Prin, J. Rysti, E. Rochepault, S. Sequeira Tavares, E. Todesco
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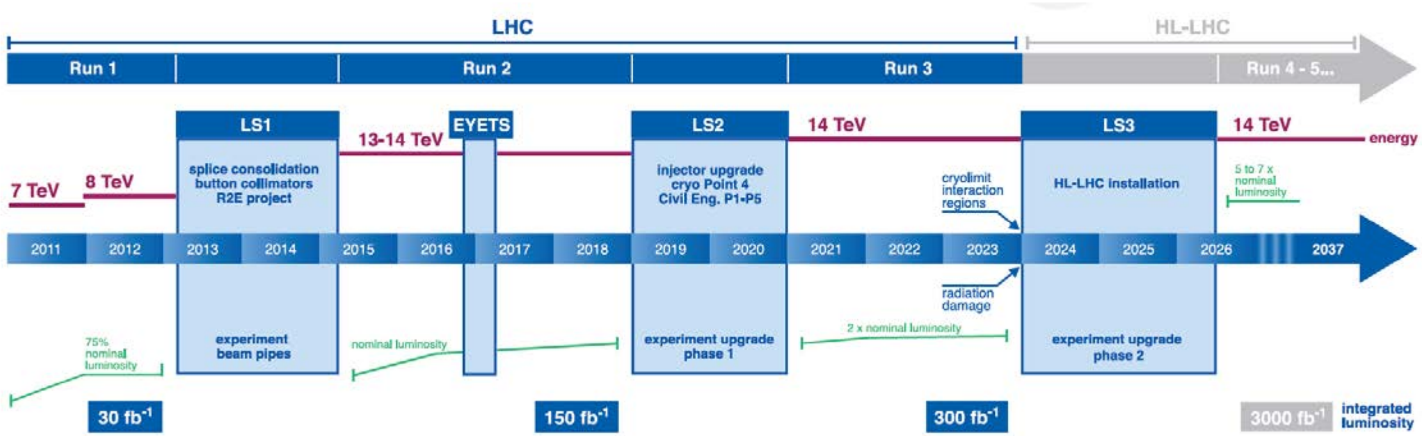
Introduction
From LHC to HiLumi LHC

- LHC operating at 6.5 TeV
- In the period 2015-2023
  - Peak luminosity of $2 \cdot 10^{34}$ cm^{-2}s^{-1}
  - Integrated luminosity of 300 fb^{-1}
- HiLumi LHC
  - Upgrade the Interaction Region in 2024-2026
  - Peak luminosity of $5 \cdot 10^{34}$ cm^{-2}s^{-1}
  - 3000 fb^{-1} integrated luminosity in following ~12 years



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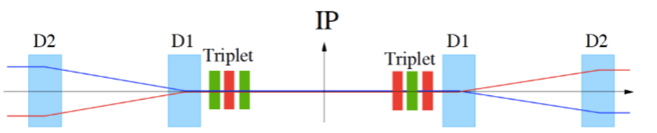
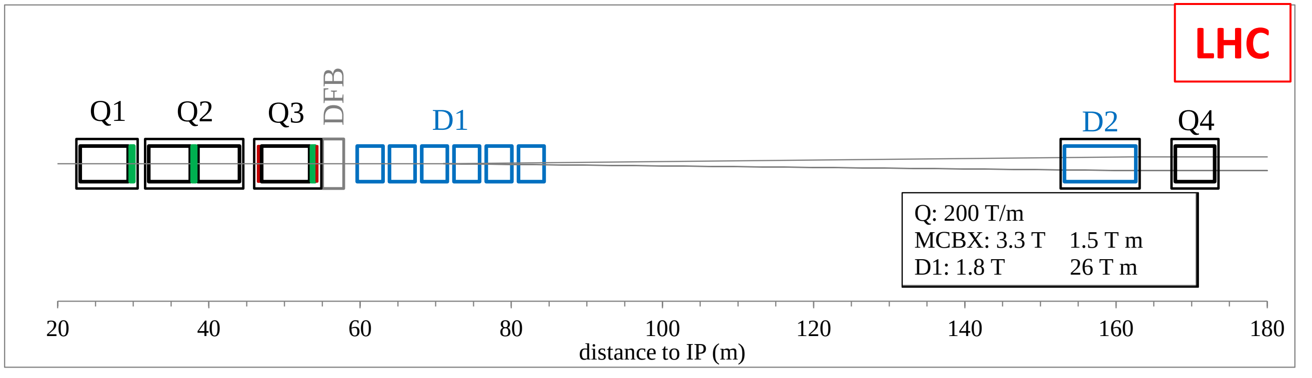
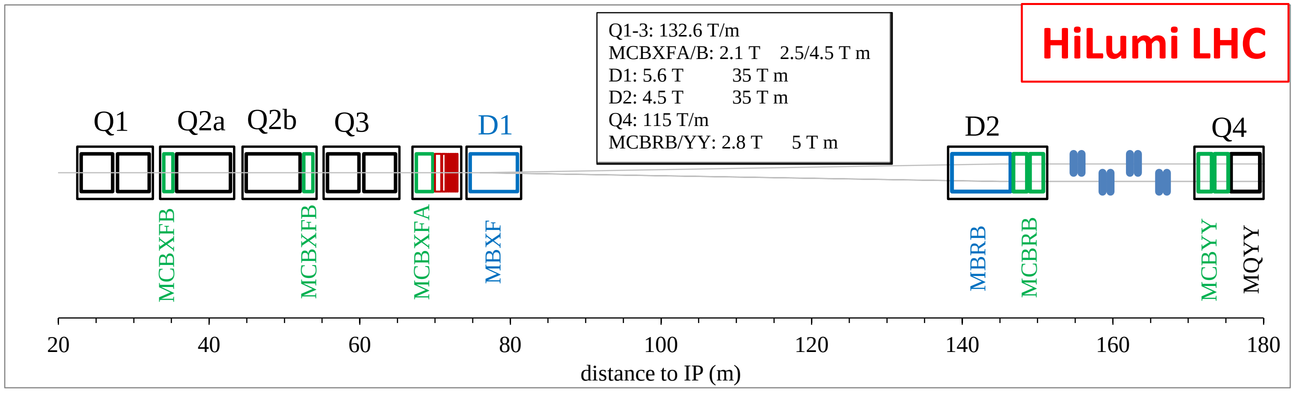
Introduction
HiLumi Interaction Region

- New inner triplet quadrupole
  - Larger aperture to reduce the beam size
    - 70 to 150 mm aperture
    - Nb_3Sn allows keeping a compact triplet notwithstanding the larger aperture

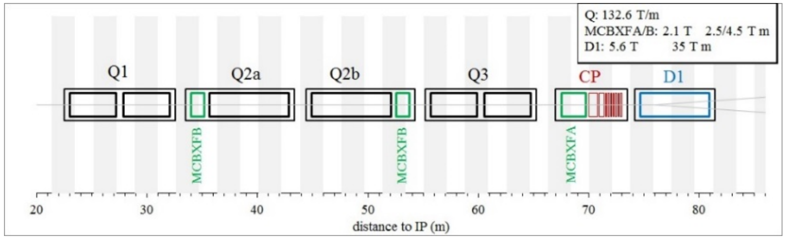




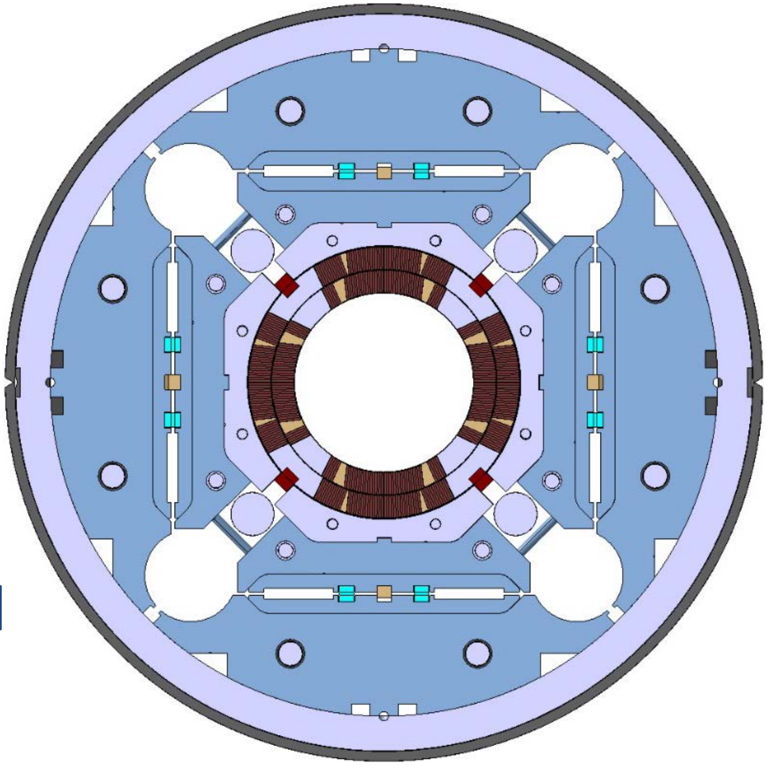


Introduction
HiLumi low-β quadrupole

- Target: 132.6 T/m
  - 150 mm coil aperture, 11.4 T B_{peak}



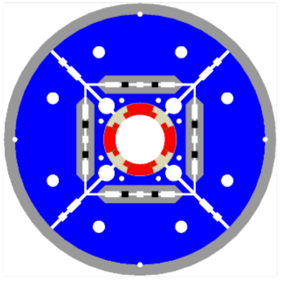
- Q1/Q3 (by US-HiLumi Project)
  - 2 magnets MQXFA with 4.2 m
- Q2a/Q2b (by CERN)
  - 1 magnet MQXFB with 7.15 m
- Different lengths, same design



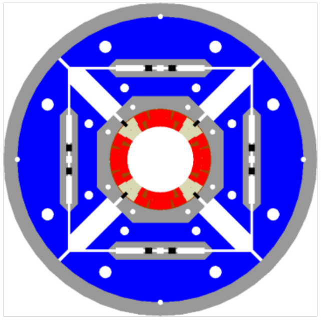
- Short model phase in progress
  - From 1st to 2nd generation design
- Long prototype fabrication started

Introduction
LARP

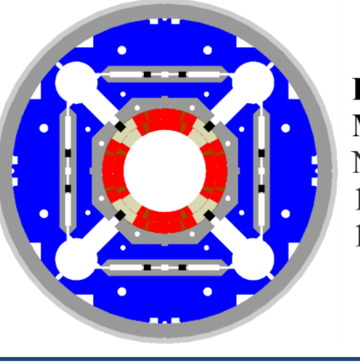
- LHC Accelerator Research Program (since 2003)
  - R&D on Nb_3Sn quadrupoles for LHC luminosity upgrade
- From TQ/LQ series to MQXF
  - From 90 to 150 mm
- MQXF scale-up of HQ
  - Similar coil lay-out
  - Same structure concept
  - Successfully tested



LARP TQ-LQ
Nb_3Sn, 1-3.7 m
90 mm apert.
200 T/m



LARP HQ
Nb_3Sn, 1 m
120 mm apert.
170 T/m



LARP-CERN MQXF
Nb_3Sn, 1.5 m
150 mm apert.
132.6 T/m

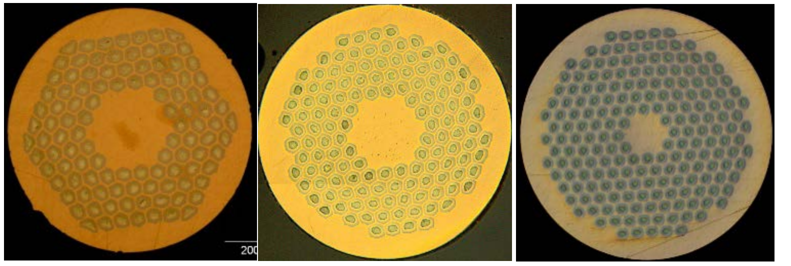
Outline

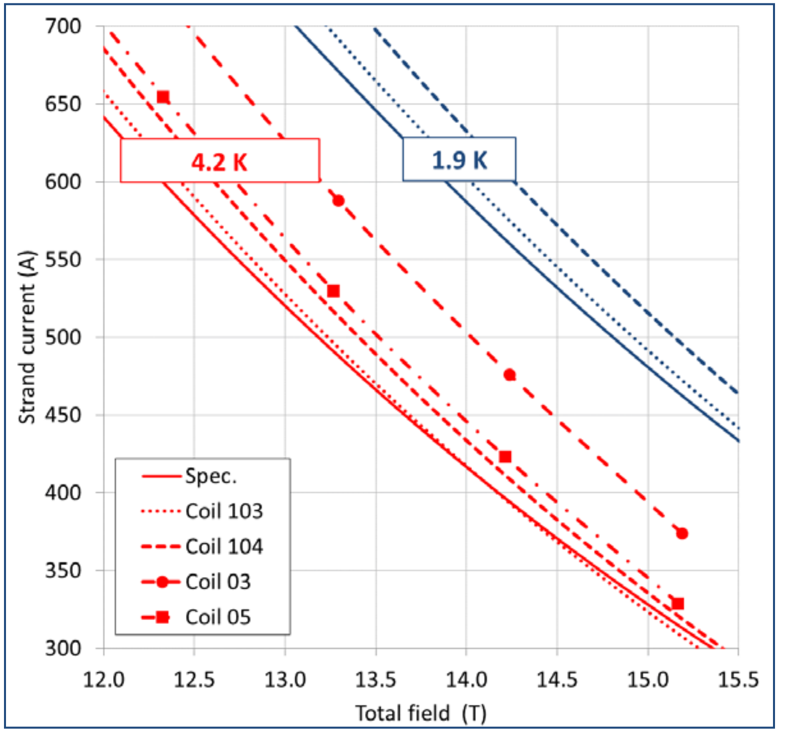
- Superconducting strand and cable
- Coil design and fabrication, and magnetic analysis
- Magnet design and mechanical analysis
- Quench protection
- Conclusions

Superconducting strand

B. Bordini, 1OrAA_03

- 0.85 mm strand, 1.2 Cu/SC
- Non-Cu J_c at 4.2 K
  - 2450 A/mm^2 at 12 T
  - 1280 A/mm^2 at 15 T
- Filament $\varnothing \leq$ 55 μm
- 3 strands used for short model
  - OST RRP 108/127, 132/169
  - EAS Bruker PIT 192
- RRP meets spec.
  - PIT still 5% less J_c, but only at 12 T
- 108/127 and PIT selected for the long prototypes



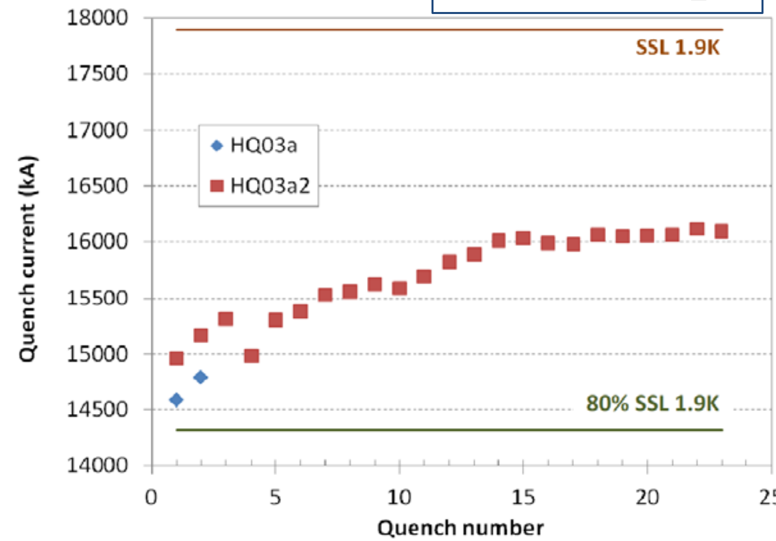


Superconducting strand
Operational margin

- From 1st to 2nd generation design
  - Length: 4.0 to 4.2 m for Q1/Q3, 6.8 to 7.15 m for Q2a/Q2b
  - Reduction of gradient from 140 to 132.6 T/m
  - Strand spec. J_c reduced from 1400 to 1280 A/mm^2 at 15 T
  - Magnet I_{op} from 82% to 77% of I_{ss}

- HQ03
  - Excellent memory
  - 90/98% I_{ss} at 1.9K/4.5K
- ....still, we need 7.5 m long coils

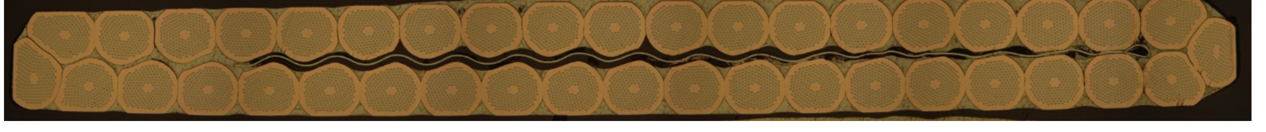
J. DiMarco, 2PoCK_14



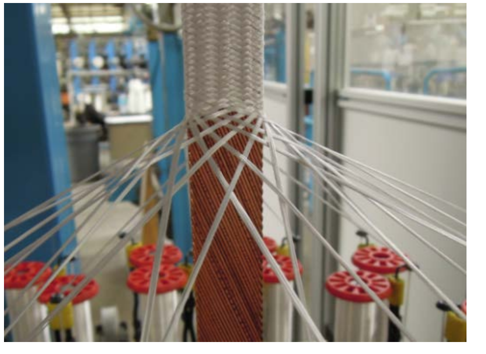
Superconducting cable

- 40-strand cable
  - Bare width X thickness: 18.150 X 1.525 mm
  - SS core 12 mm wide and 25 μm thick
- Keystone angle reduced from 0.55 to 0.4 degree
  - Cabling degradation
    - <5% for PIT; <3% for RRP
- Braided insulation: 0.145 mm (S2-Glass)

PIT



RRP

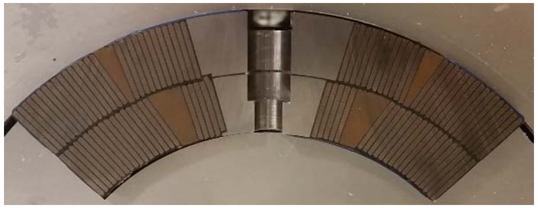


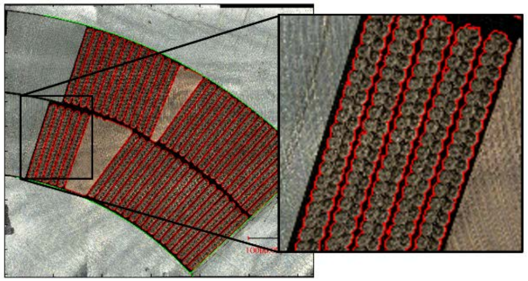
Superconducting strand and cable
Dimensional variation during reaction

E. Rochepault, 3PoBA_20

E. Holik, 3OrCC_02

- Cable/coil size after reaction is critical
  - Issue in HQ01
- Single cable, stacks, coil cross-section
  - Image analysis of cable contours
- Consistent data from different set-ups, labs, and coils
- Results
  - Volumetric expansion of +3.0 to +3.5%
    - Mainly in thickness: +2.8 to +3.2%
  - The rest is distributed between
    - Width expansion: 0.0 to +1.0 %
    - Length contraction: -0.4 to 0.0 %
  - Depending on tooling and braiding





Outline

- Superconducting strand and cable
- Coil design and fabrication, and magnetic analysis
- Magnet design and mechanical analysis
- Quench protection
- Conclusions and plans

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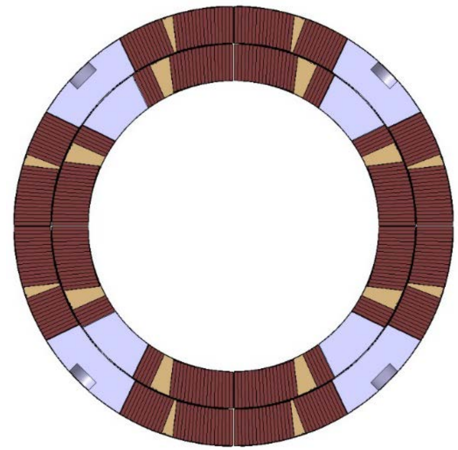
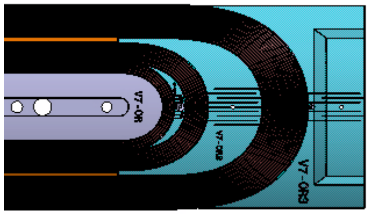
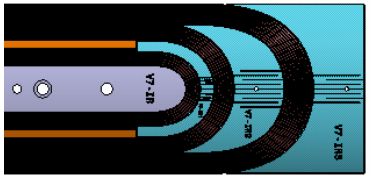
Coil design and fabrication

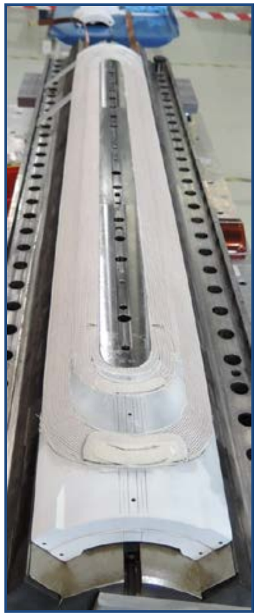
S. Izquierdo Bermudez, 2PoBA_03

- 2-layer, 4-block design
- Ti alloy pole with cooling holes, alignment key slot
- 2 end spacers for peak field reduction and field quality optim.





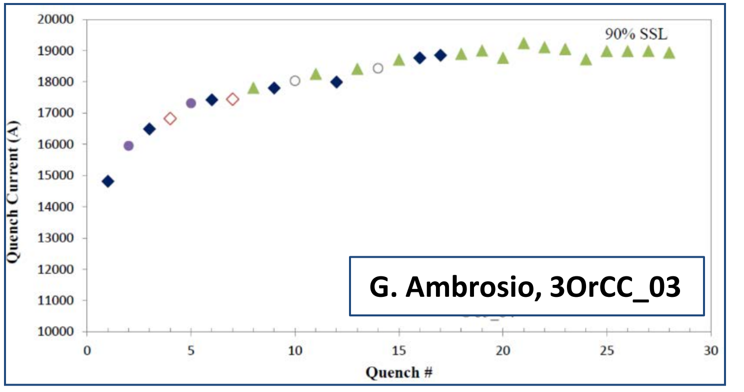


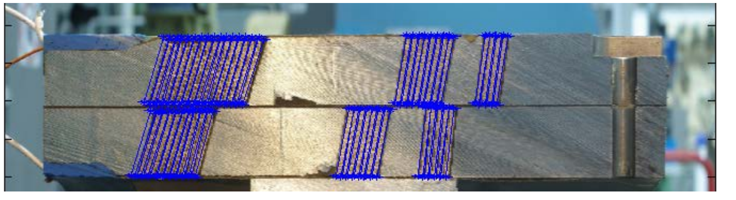


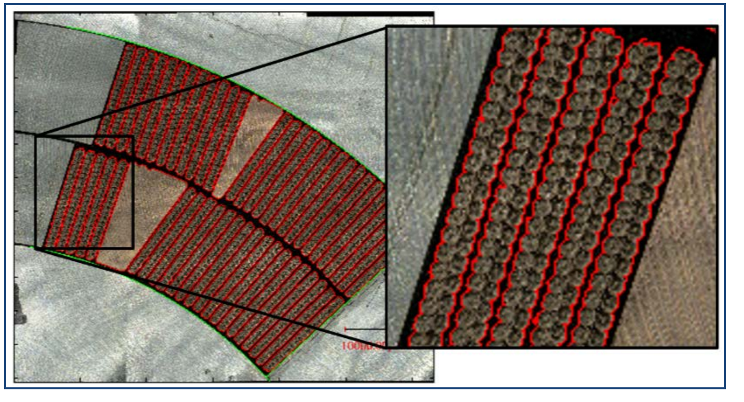
- 13 short model coils fabricated
- First 2 prototype coils reacted by LARP
- Tooling under procurement at CERN

Coil design and fabrication

- First short coil tested in mirror
  - 91% of current limits
- Image analysis of cable contours
  - Good fit of end-spacers
  - But, up to 0.5 mm azimuthal and radial shift in straight section
- Space for expansion reduced for 2^{nd} generation coils
  - From 2 to 1% on width
    - …Always "trade-off between compacting the coil and minimize risk of insulation/conductor degradation"



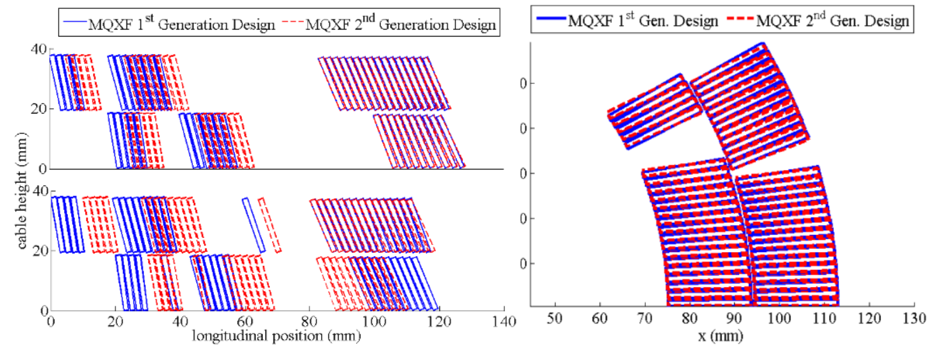




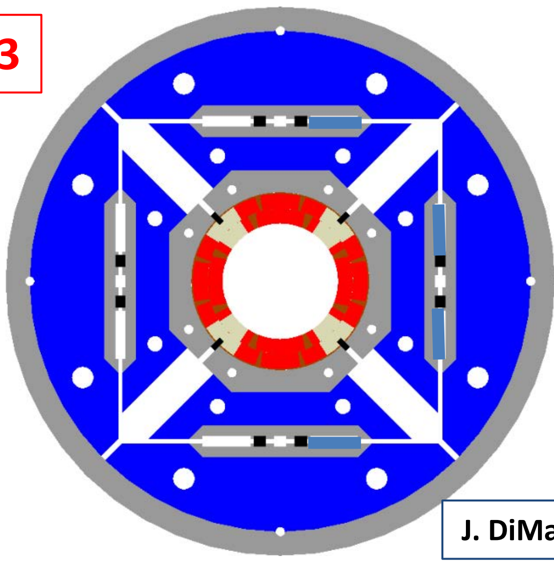
Magnetic analysis

S. Izquierdo Bermudez, 2PoBA_03

- Fine tuning of coil design from I to II gen.
  - New cable geometry compensation end-effect
- All integrated harmonics below 1 units



HQ03



J. DiMarco, 2PoCK_14

- Corrective strategies
  - Coil shim for allowed harm.
  - Magnetic shims for un-allow.
    - Successfully tested on HQ03

	Calc.	Meas.
Δb_3	2.49	2.74
Δb_5	0.28	0.31

Outline

- Superconducting strand and cable
- Coil design and fabrication, and magnetic analysis
- Magnet design and mechanical analysis
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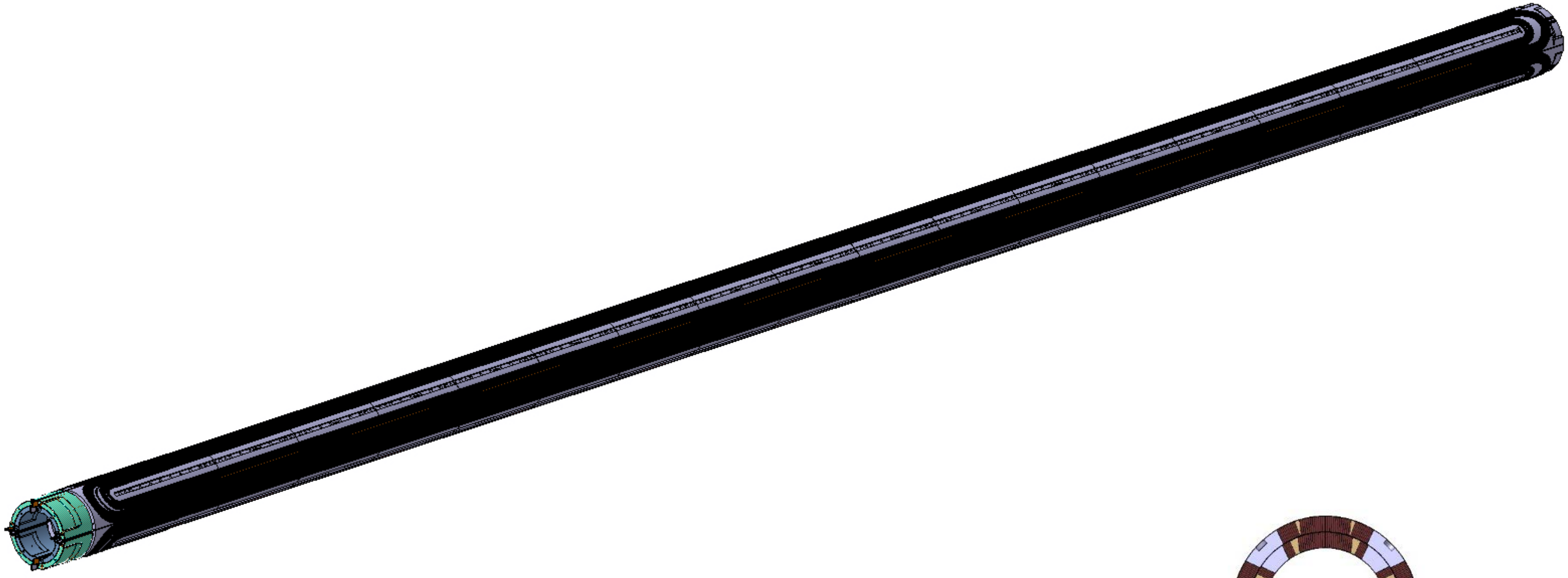
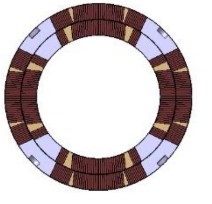
Magnet design
MQXFB





- Superconducting coil

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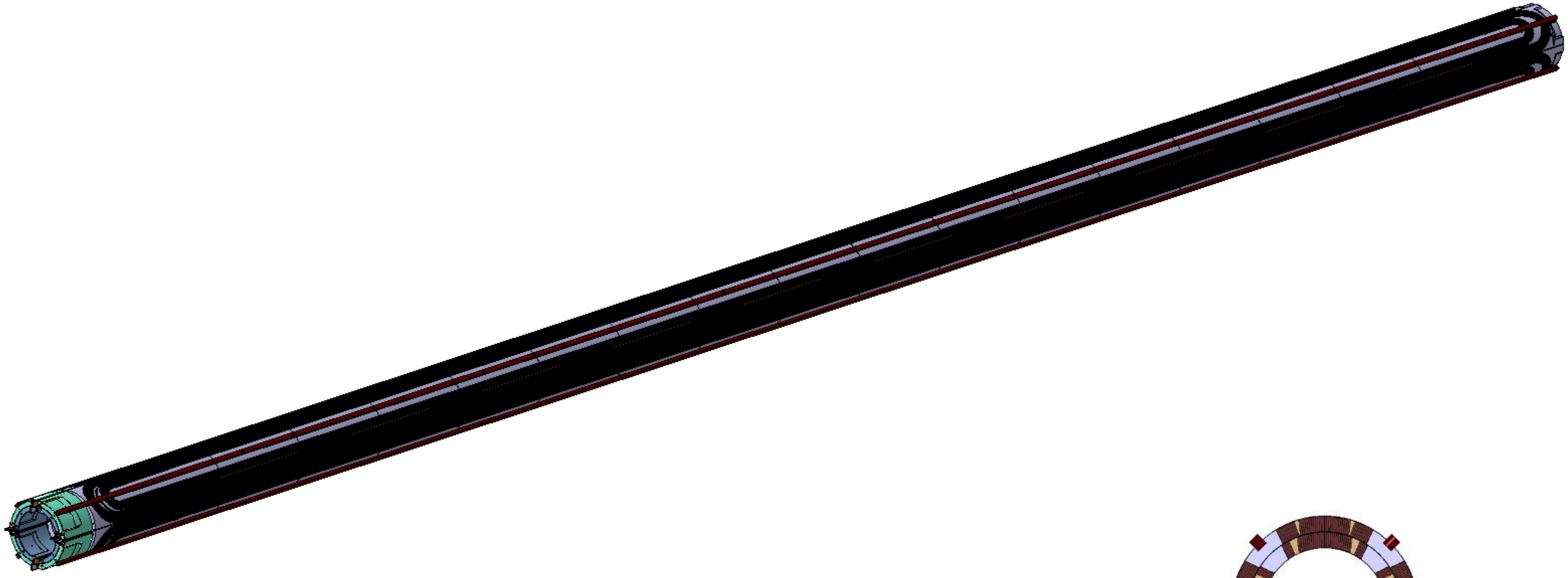
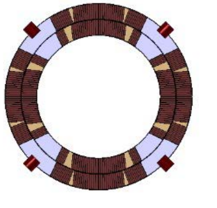
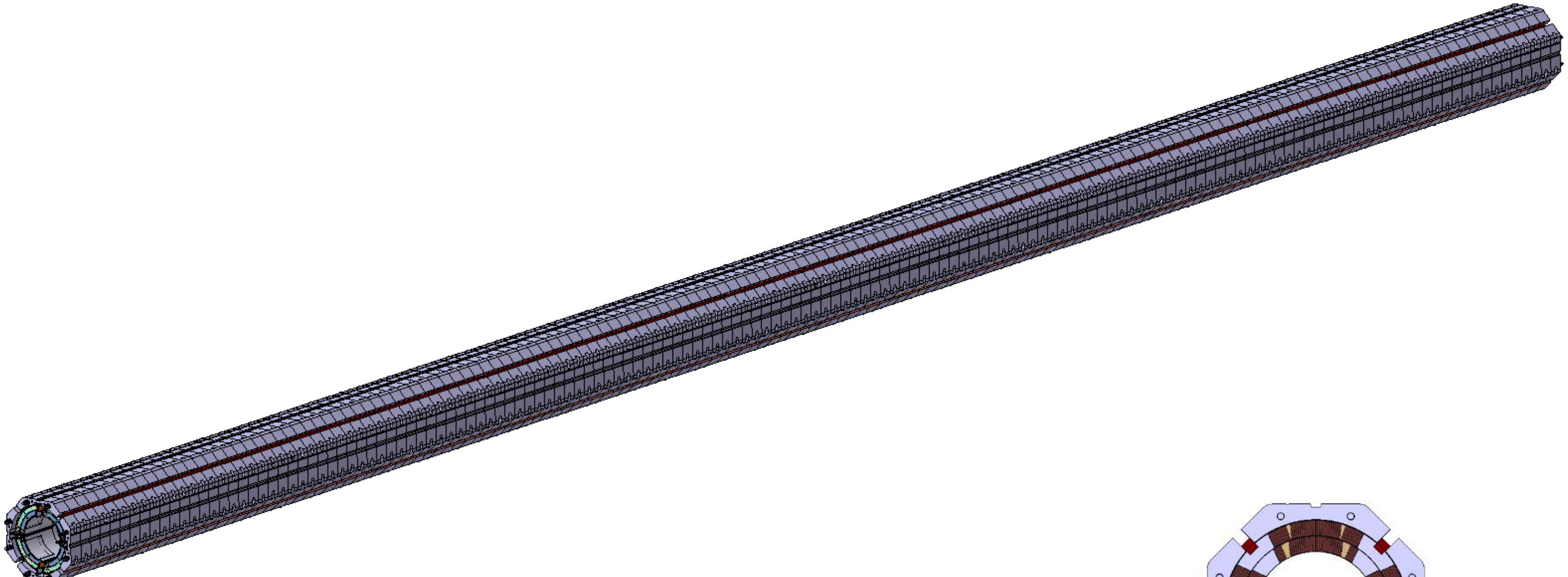
Magnet design
MQXFB

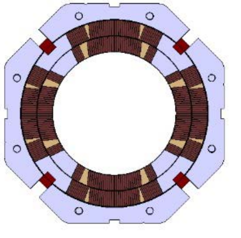




- Pole key for alignment

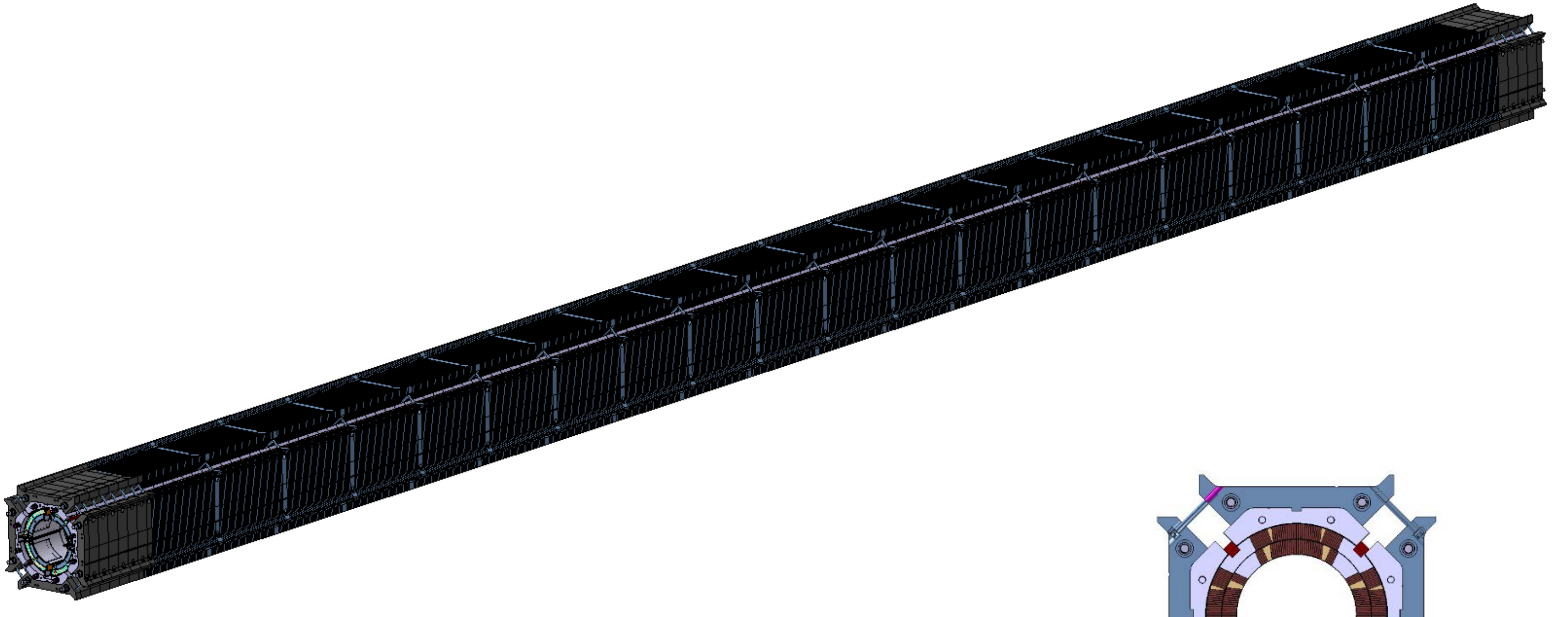
Magnet design
MQXFB

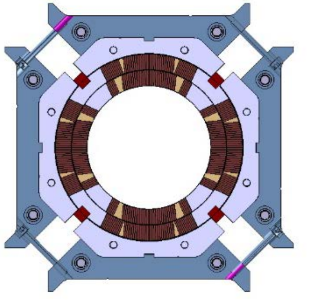




- Bolted aluminium collar
  - No coil pre-load

Magnet design
MQXFB





- Bolted iron pad
  - No coil pre-load

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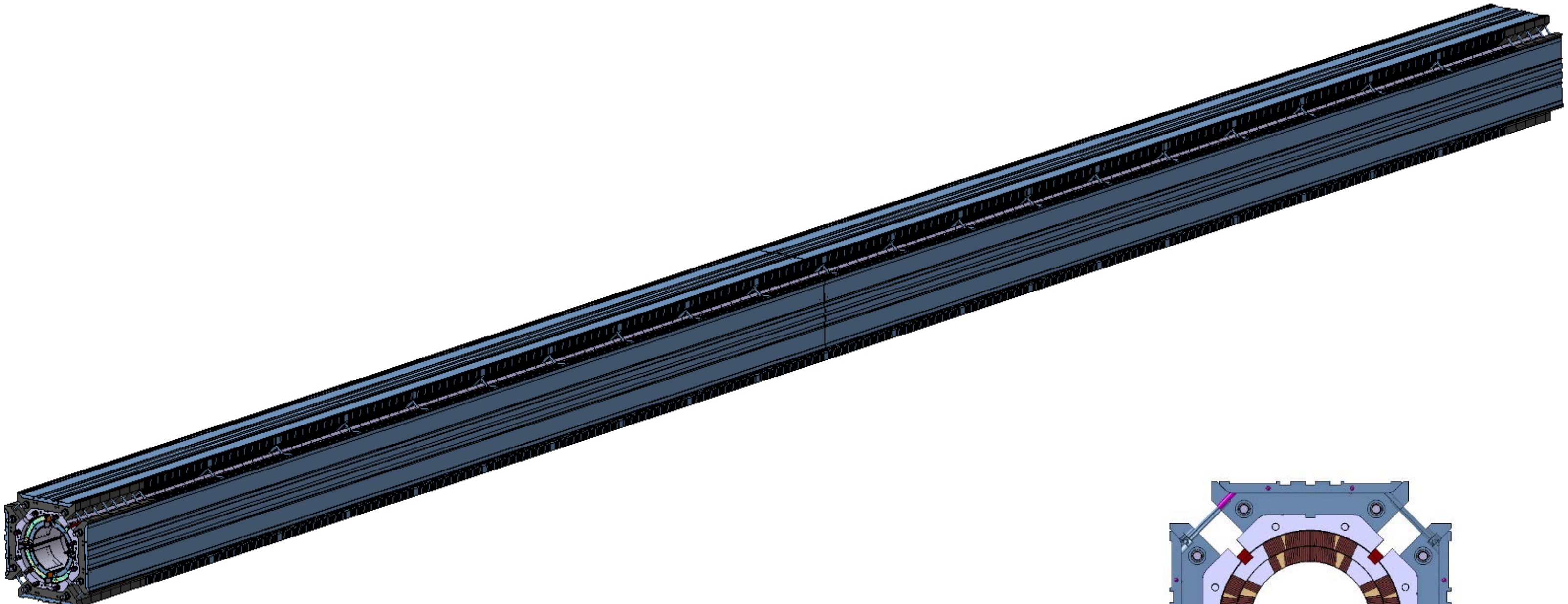
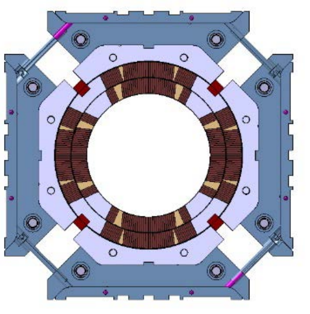
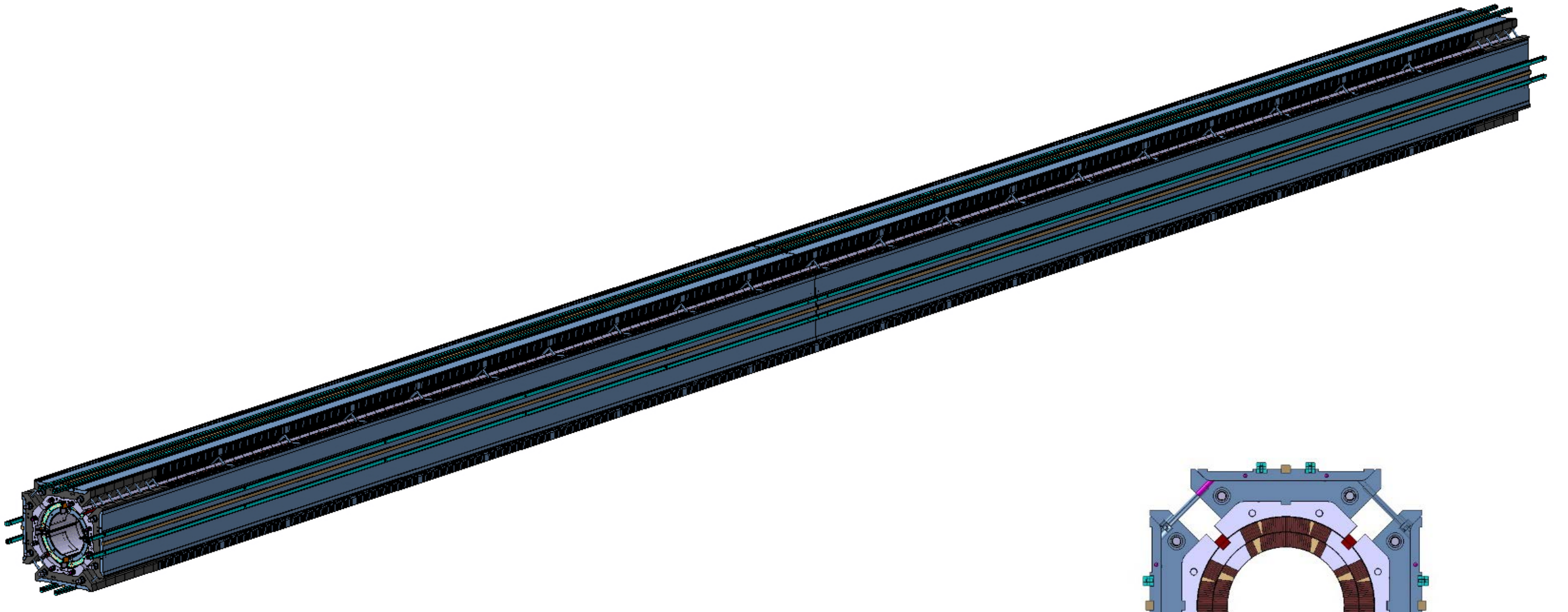
Magnet design
MQXFB

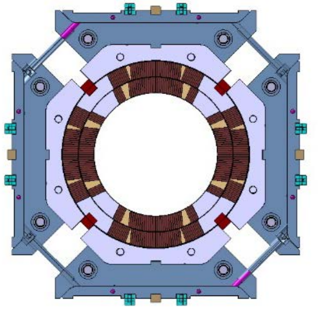




- Iron master
  - Half-length plates for bladders and keys

Magnet design
MQXFB





- Loading and alignment keys

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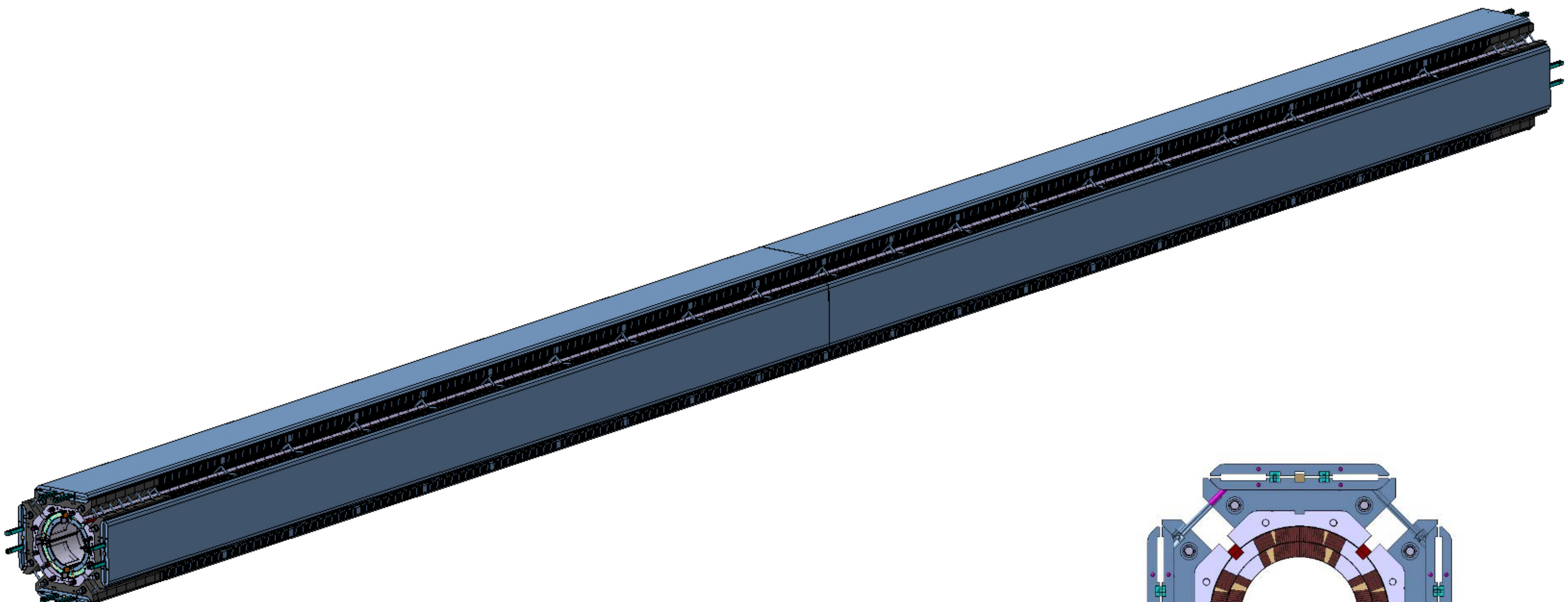
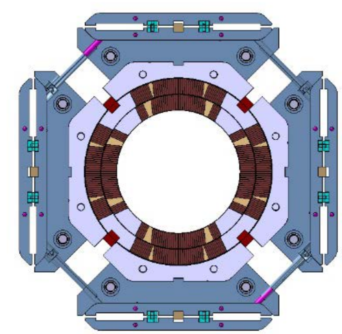
Magnet design
MQXFB





- Second iron master
  - Coil-pack sub-assembly

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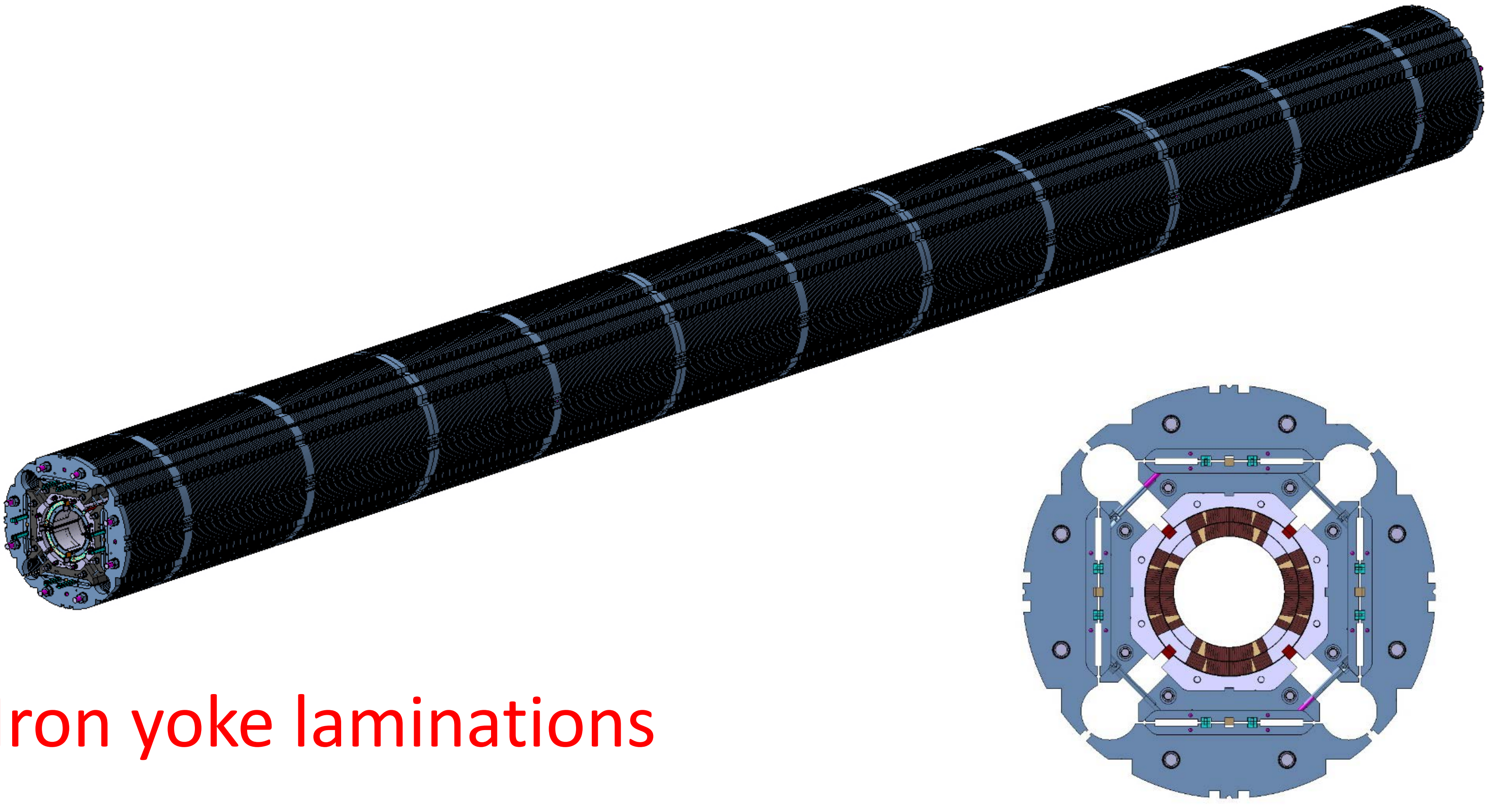
Magnet design
MQXFB



- Iron yoke laminations

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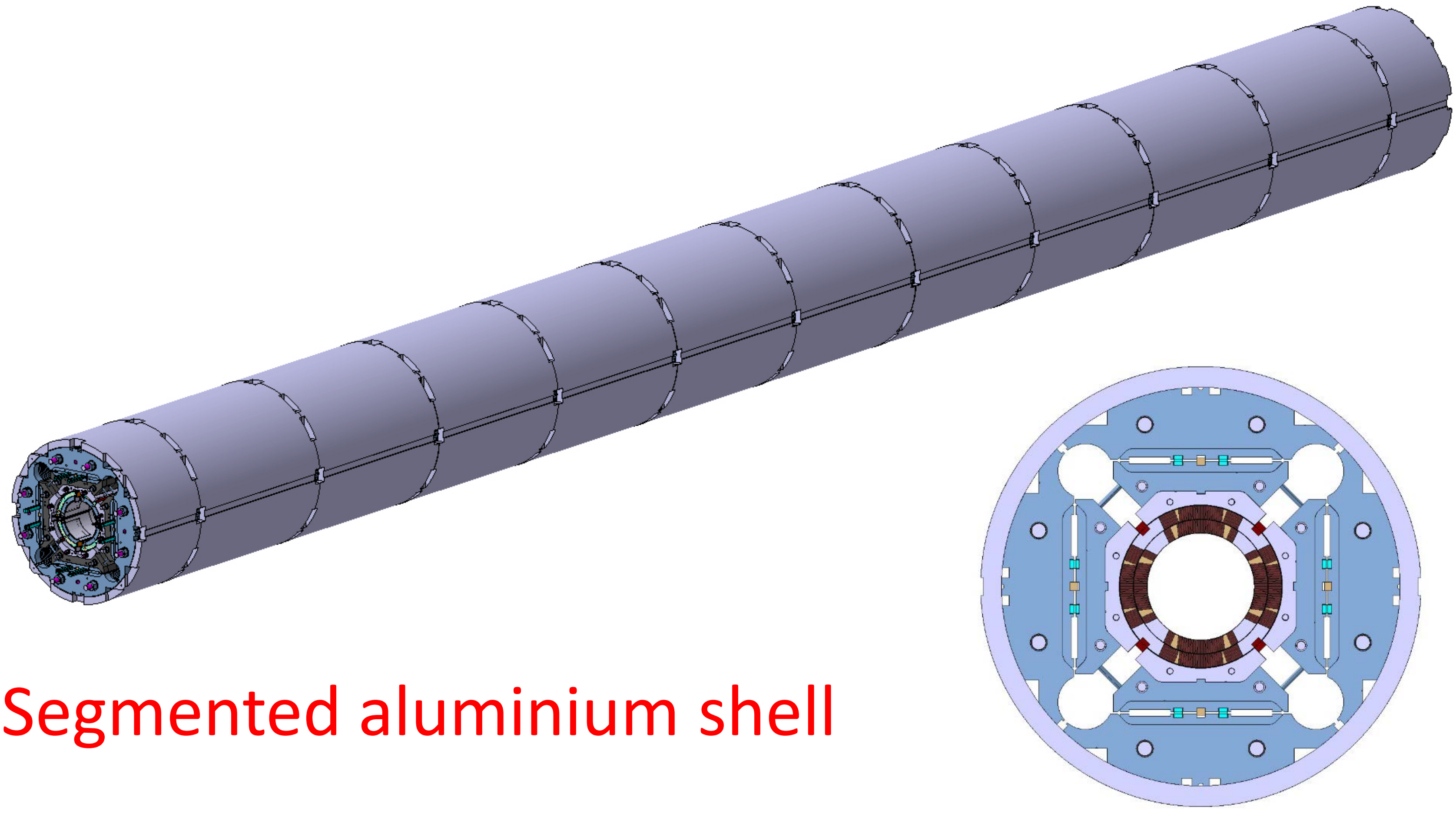
Magnet design
MQXFB



- Segmented aluminium shell

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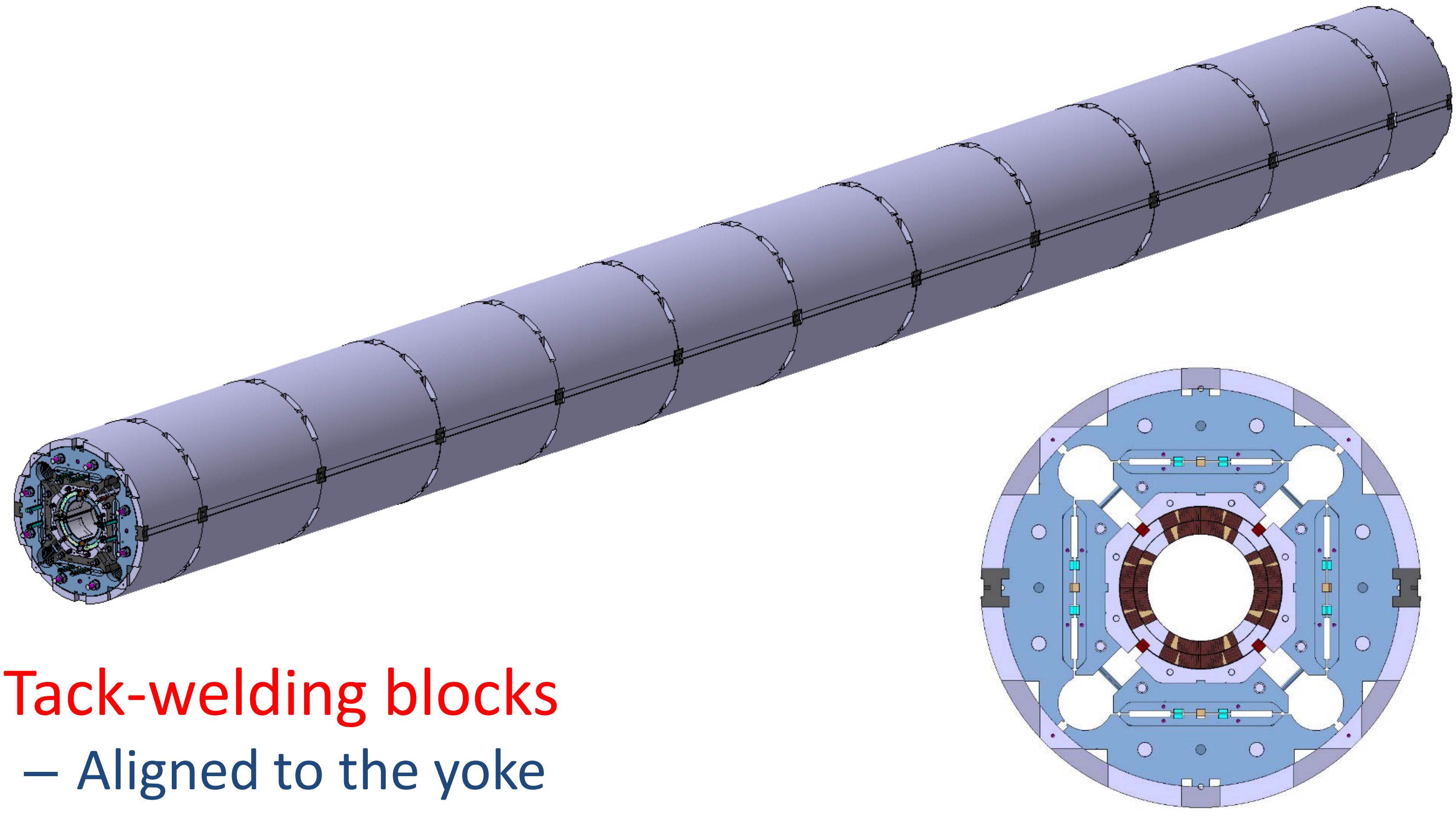
Magnet design
MQXFB



- Tack-welding blocks
  – Aligned to the yoke

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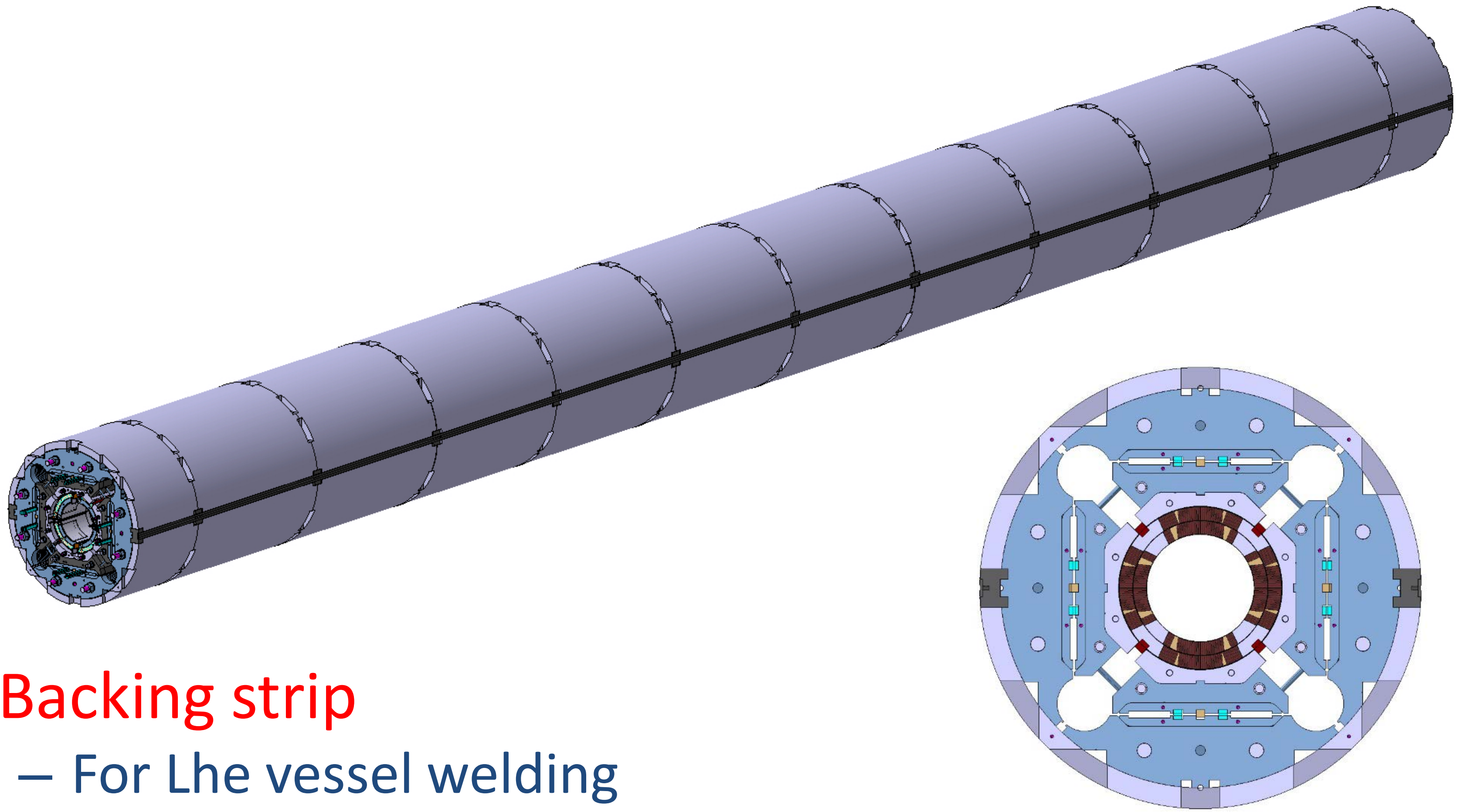
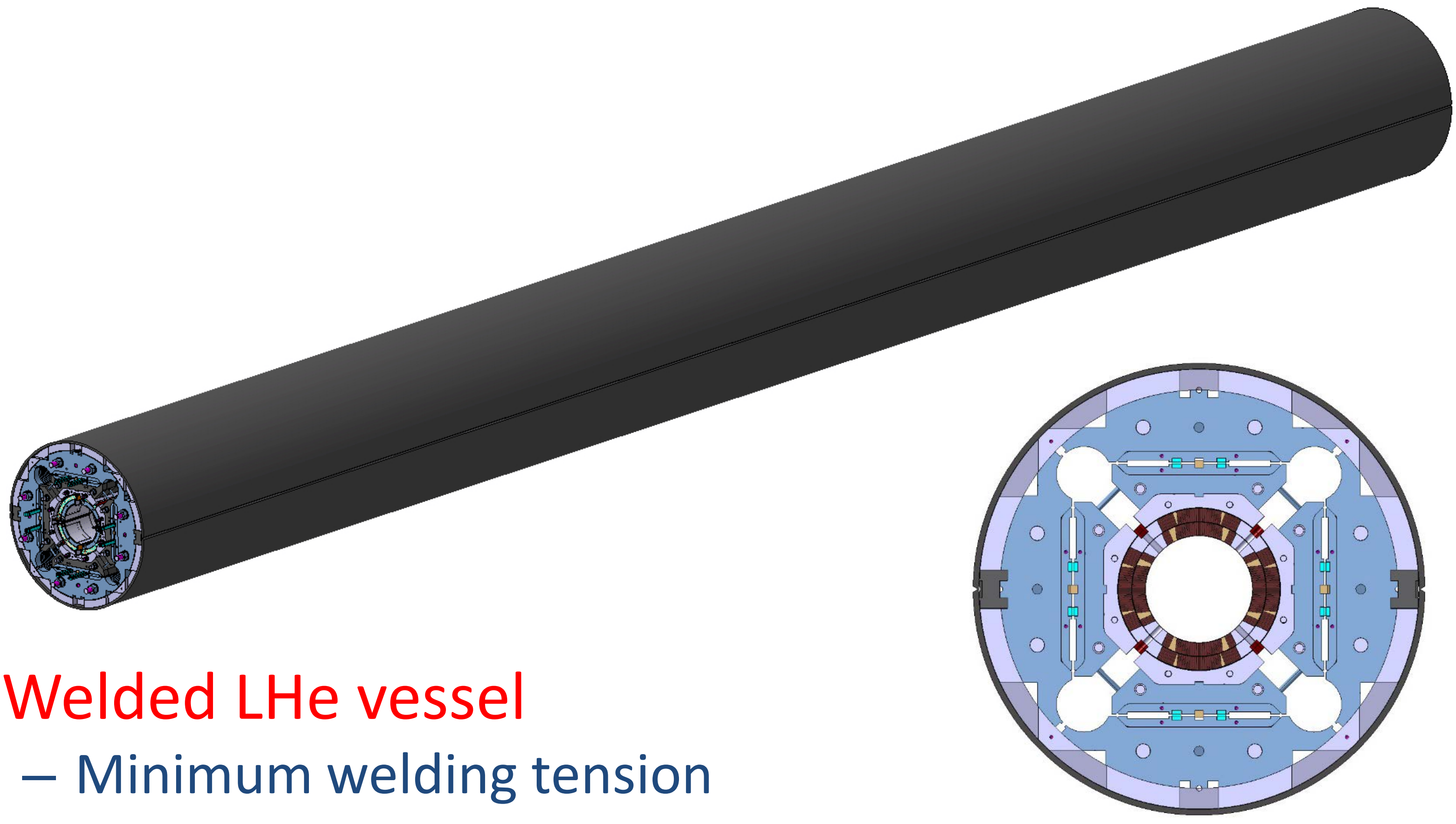
Magnet design
MQXFB



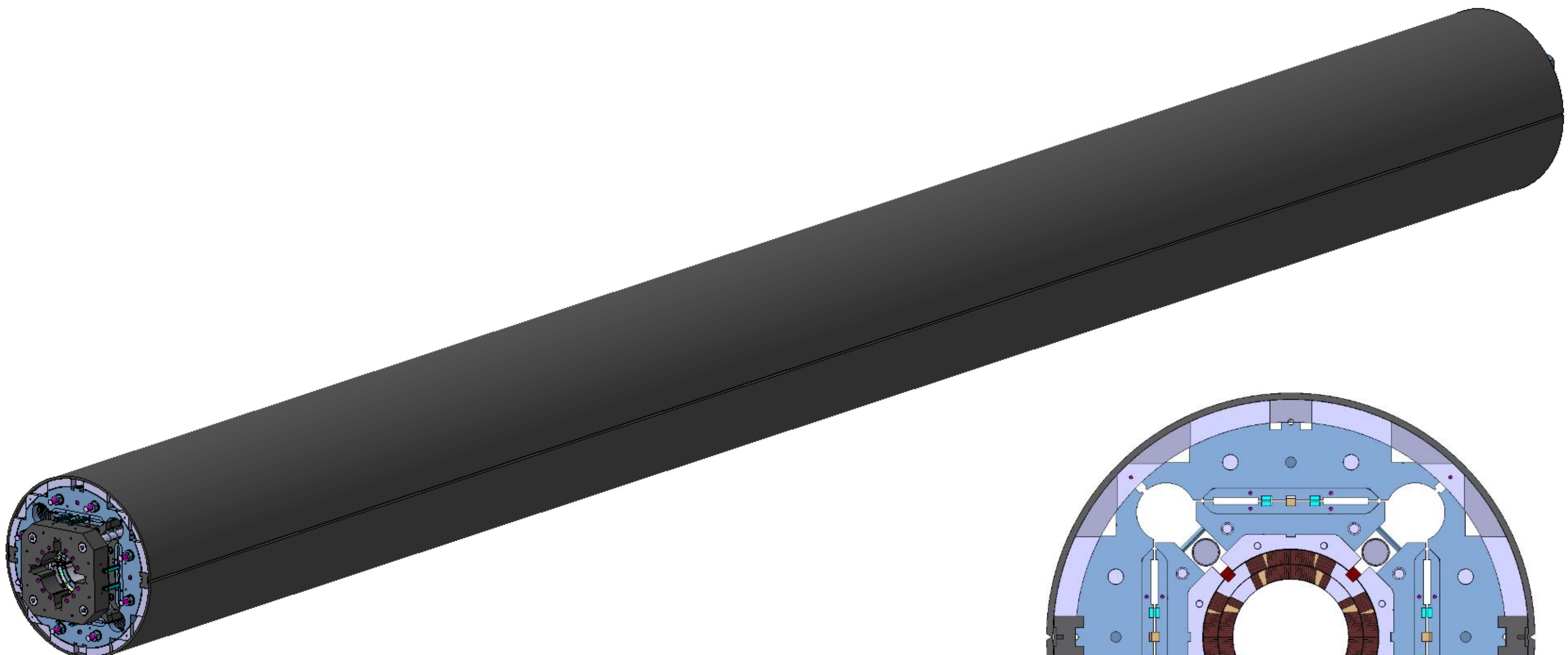
- Backing strip
  - For Lhe vessel welding

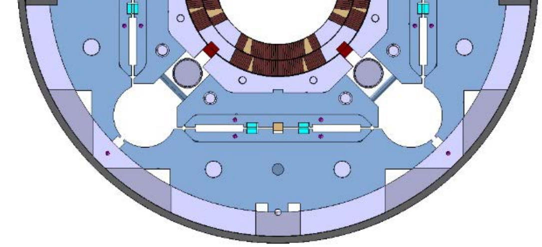
Magnet design
MQXFB



- Welded LHe vessel
  - Minimum welding tension

Magnet design
MQXFB

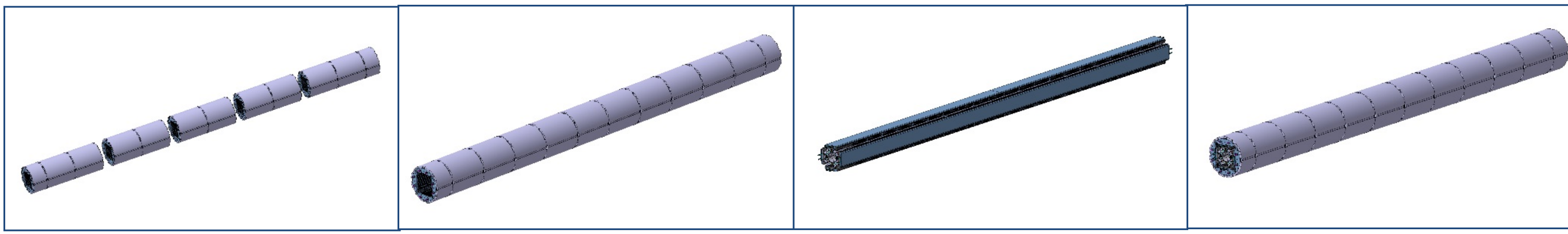




- Axial support system
  - Aluminium rods and end-plates

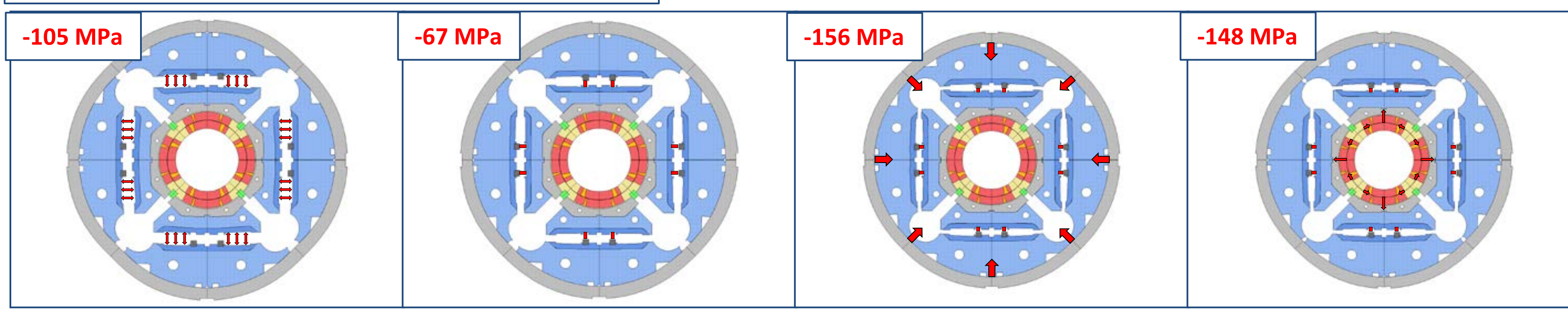
Magnet assembly and pre-loading

- Shell-yoke modules combined
- Insertion of coil-pack sub-assembly



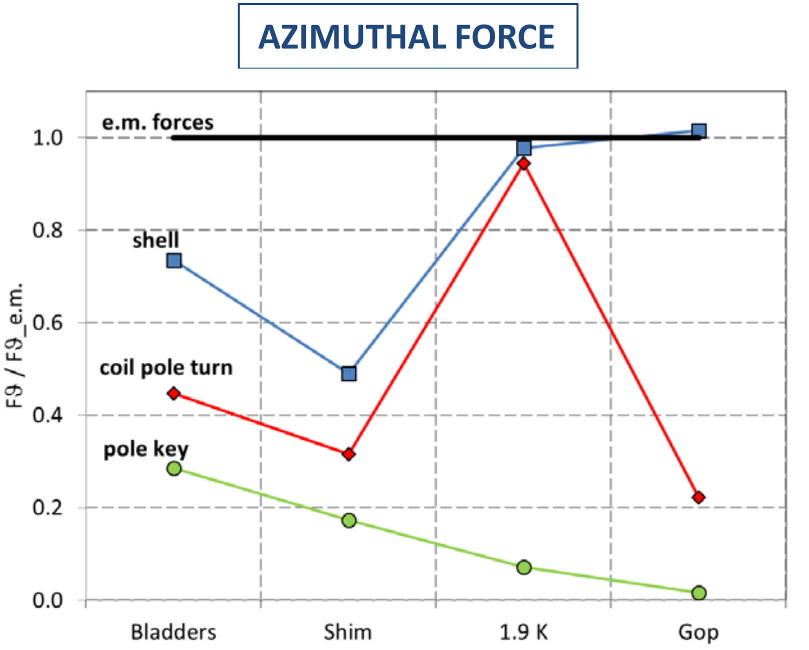
- Then bladder operation

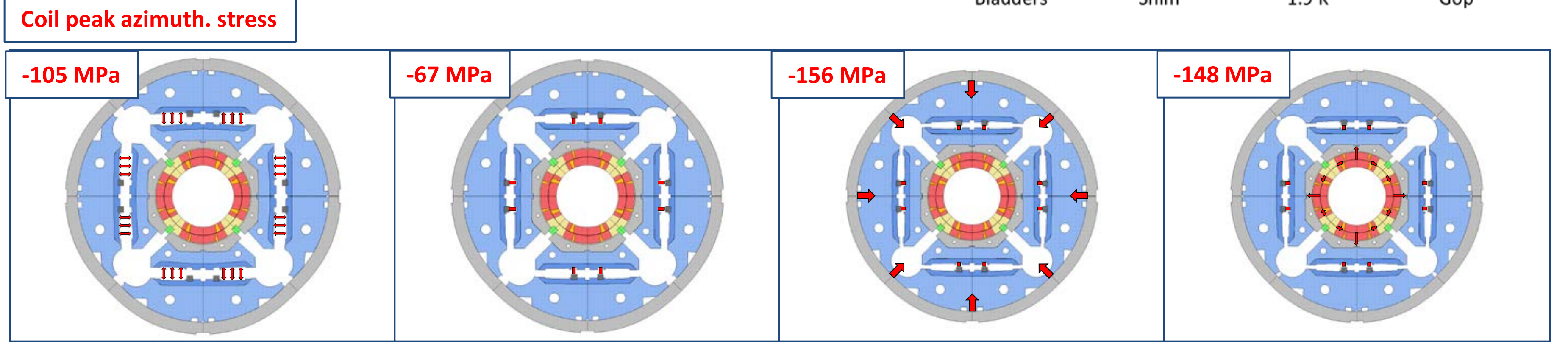
Deformed shape and coil peak azimuth. stress from ANSYS



Mechanical analysis

1. ~30% of shell force intercepted by collars
2. Spring back
3. Full pre-load at 1.9 K
4. Coil still compressed at G_{op}
   – Alignment maintained



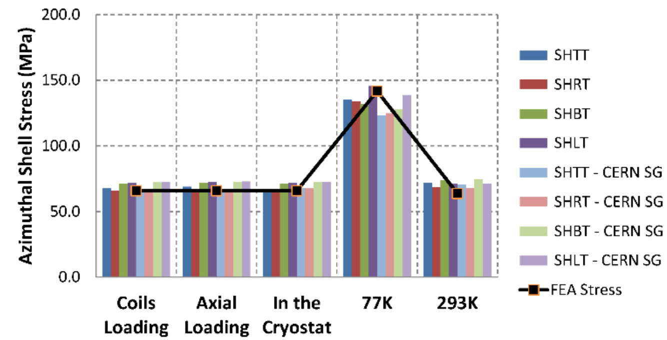


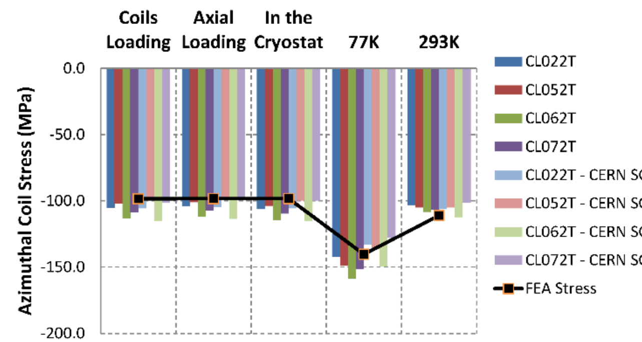
Validation support structure

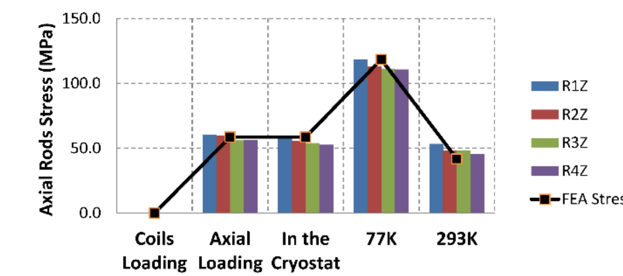
M. Juchno, 3PoBA_04

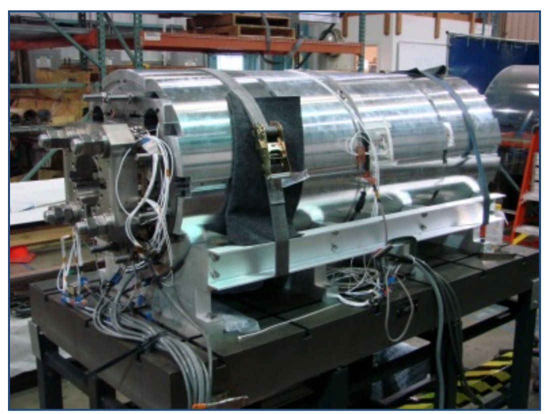
- Two identical structures assembled and pre-loaded with aluminium coils at LBNL and CERN

- Components instrumented with strain gauges
  - Very good agreement









Outline

- Superconducting strand and cable
- Coil design and fabrication, and magnetic analysis
- Magnet design and mechanical analysis
- Quench protection
- Conclusions and plans

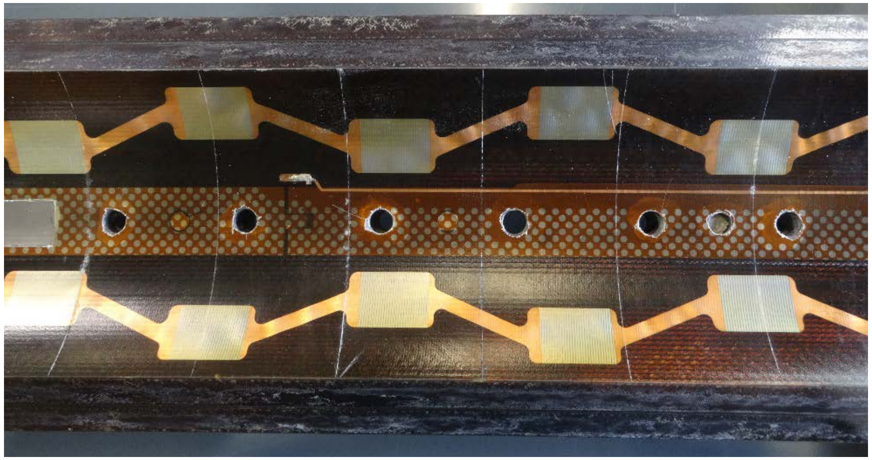
Quench protection

- 50% more stored energy in the coil than LHC dipole
  - Only 5% on dump resistor, due to high inductance of the circuit
- Outer layer trace impregnated with the coil not enough: T_{peak}=340 K
- Outer and Inner layer trace can reduce T_{peak} to 260 K
  - Cooling and detachment issues to be addressed
- Outer layer trace and CLIQ can reduce T_{peak} to 230 K
  - Aspects related to the circuit being analysed
- All strategies being explored

V. Marinozzi, 2PoBA_05

M. Marchevsky, 2PoBA_01

E. Ravaioli, 2PoBA_06



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IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2016.
Invited presentation 3OrCC_01 given at MT-24, Seoul, Korea, October 18-23, 2015.

Conclusions

- HiLumi low-β quadrupole magnet MQXF
  - Into short model phase, start of the prototype phase
- Fine tune of the design: from 1st to 2nd generation
  - Increased margin with longer length and lower gradient
- RRP conductor within spec.
  - R&D on PIT in progress to meet J_c (~5% lower at 12 T)
- New cable geometry for reduced degradation
- Conductor expansion during HT and position under study
  - Corrective strategies for field quality defined and tested
- Support structure qualified at CERN and LBNL
  - Excellent agreement with strain gauges
- Quench protection system with redundancy, T_{peak} < 350K

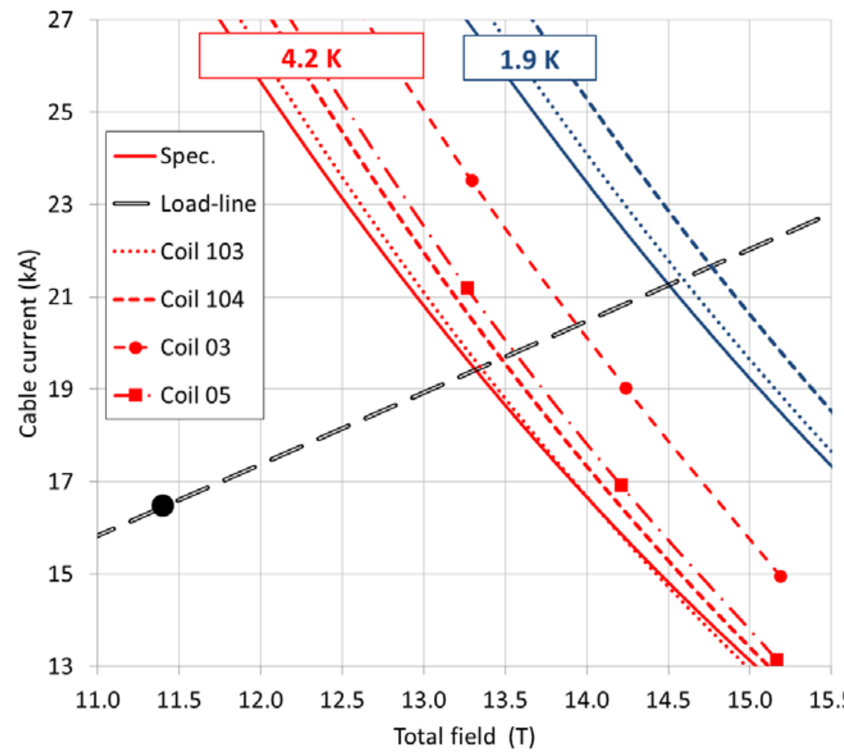
First MQXFS assembly test to be performed at FNAL

H. Pan, 3PoBA_06

G. Ambrosio, 3OrCC_03

Superconducting strand
Operational margin (I)

- G_{op} : 132.6 T/m
- I_{op}: 16.47 kA
- B_{peak_op}: 11.4 T
  - 77% of I_{ss} at 1.9 K (spec.)
- Stored *E*: 1.2 MJ/m
- Induct.: 8.2 mH/m



- From first to second generation design
  - Margin increased