U.S. MAGNET DEVELOPMENT PROGRAM

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Vancouver, Canada | 2019

Development and First Test of the US-MDP 15 T Nb_3Sn Dipole Demonstrator MDPCT1

MT-26, September 24, 2019

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Outline

In June 2019 the HFM group at Fermilab has tested a new accelerator dipole magnet based on Nb_3Sn superconductor, which produced a world record field of 14.1 Tesla at 4.5 K.

Outline

- Magnet design and analysis
- Magnet technology
- Quench performance (training)
- Conclusions and next steps

Introduction

- The 15 T dipole demonstrator project was initiated in 2015 at Fermilab in response to recommendations of the Particle Physics Project Prioritization Panel (P5) and HEPAP Accelerator R&D subpanel.

- In June 2016, the Office of High Energy Physics at US-DOE created the national MDP to integrate accelerator magnet R&D in the United States and coordinate it with the international effort.

  The project became a key task of the MDP.

- In 2017 this effort received support also by the EuroCirCol program, making it a truly International endeavor.

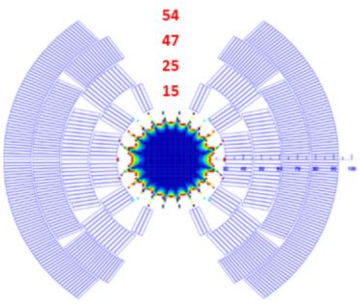
EuroCirCol
A key to New Physics

15 T Dipole Program Goals

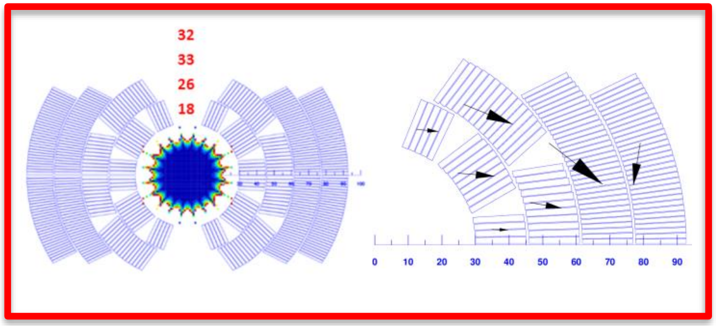
- Demonstration of 15+ T field level in accelerator magnet with Nb_3Sn superconductor
- Study and optimization of:
  - magnet quench performance and mechanics
  - field quality
  - quench protection
  - cost optimization

15 T Dipole Design Selection

Coil geometry:
- 60-mm aperture
- Min conductor volume
- 4-layer graded "block-cos-theta" coil
- Selection criteria:
  B_{max}, FQ, forces, protection

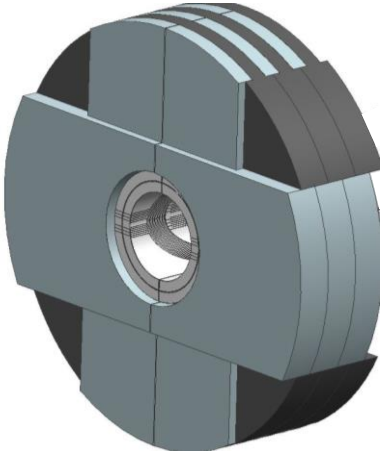


cos-theta

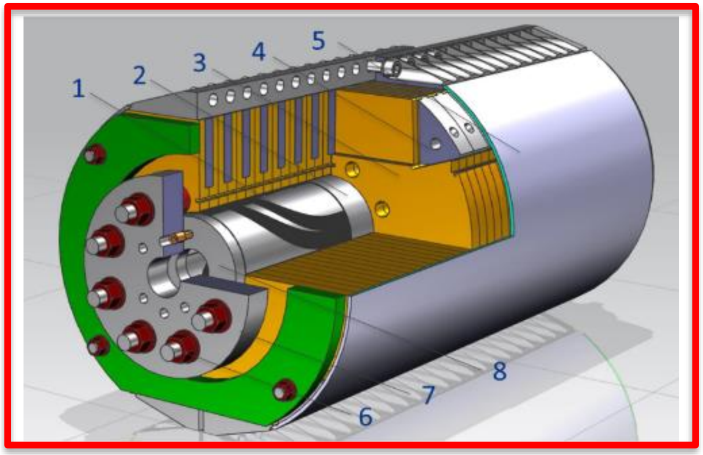


block-cos-theta

Innovative mechanical design:
- Min number of parts
- Widely available materials
- 3D clamp-iron lock
- Aluminum I-clamps
- SS 12.5mm thick welded skin
- Cold mass OD=612mm
- Criteria:
  structural integrity,
  coil stress and deformation

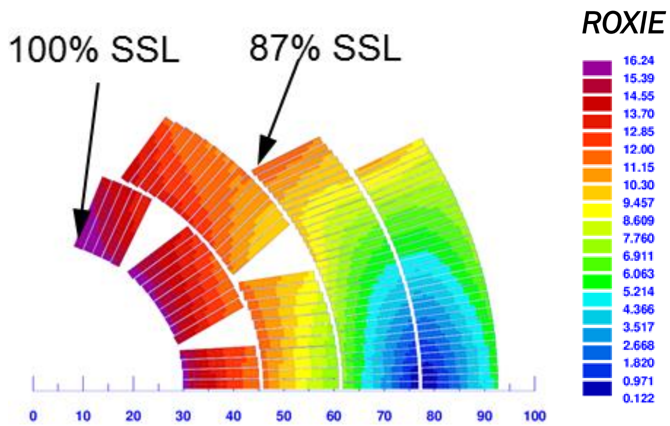


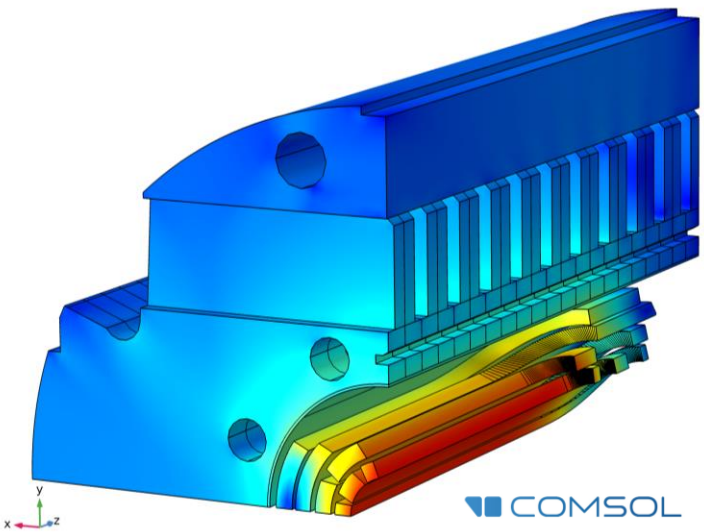
3D clamp-iron lock

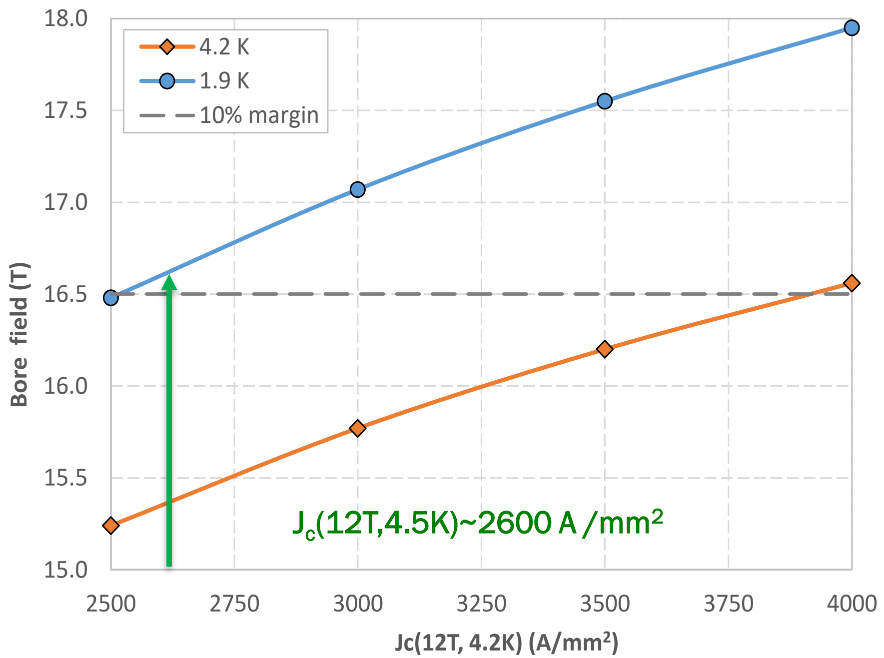


collarless, AL I-clamp, 12.5mm SS skin

Magnet Conductor Limit







Magnet ***conductor limit*** for the wire J_c(12T,4.2K)~2.6 kA/mm^2

- B_{ap}=15.3T @4.5K
- B_{ap}=16.7T @1.9K

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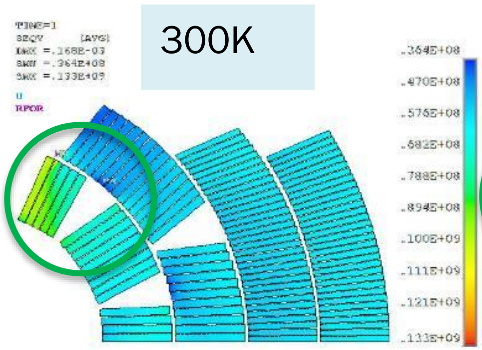
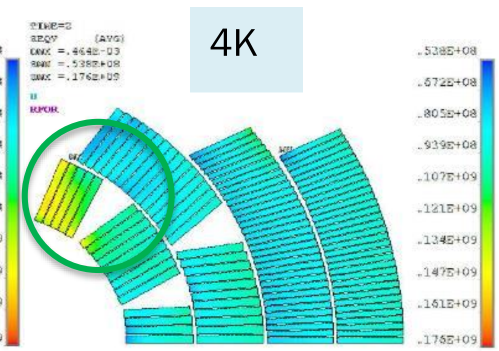
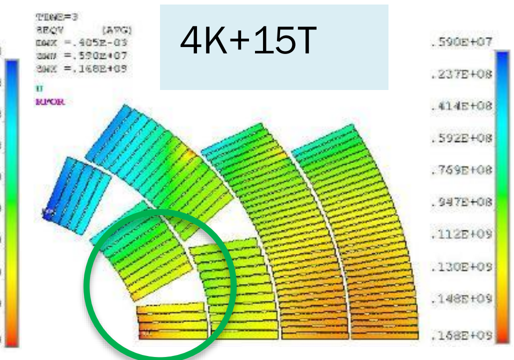
2D Mechanical Analysis



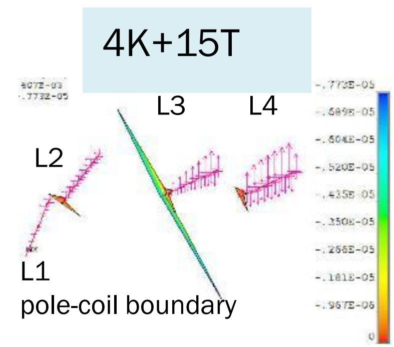
S_{eqv}=133 MPa



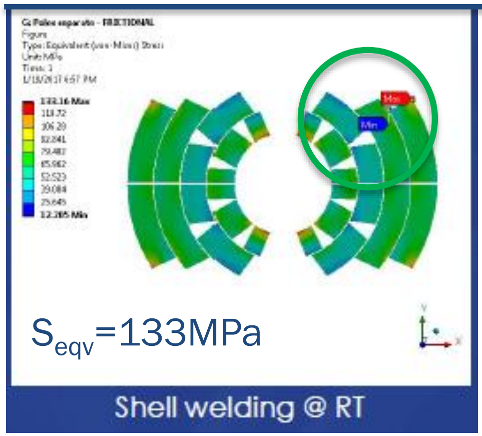
S_{eqv}=176 MPa

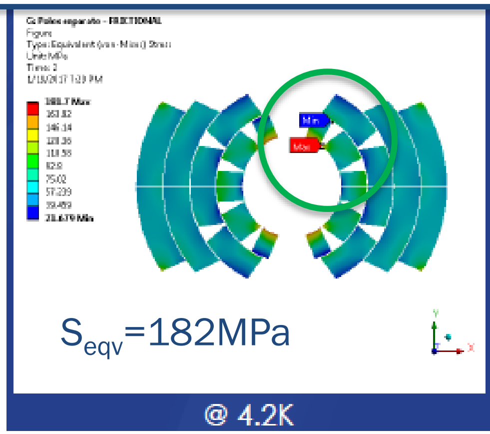


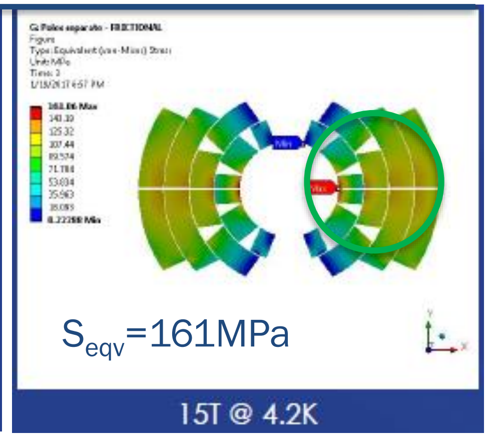
S_{eqv}=168 MPa



Pole Gap < 0.7e-5 mm







ANSYS

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΑΤΡΩΝ
UNIVERSITY OF PATRAS
with the assistance of
FEAC

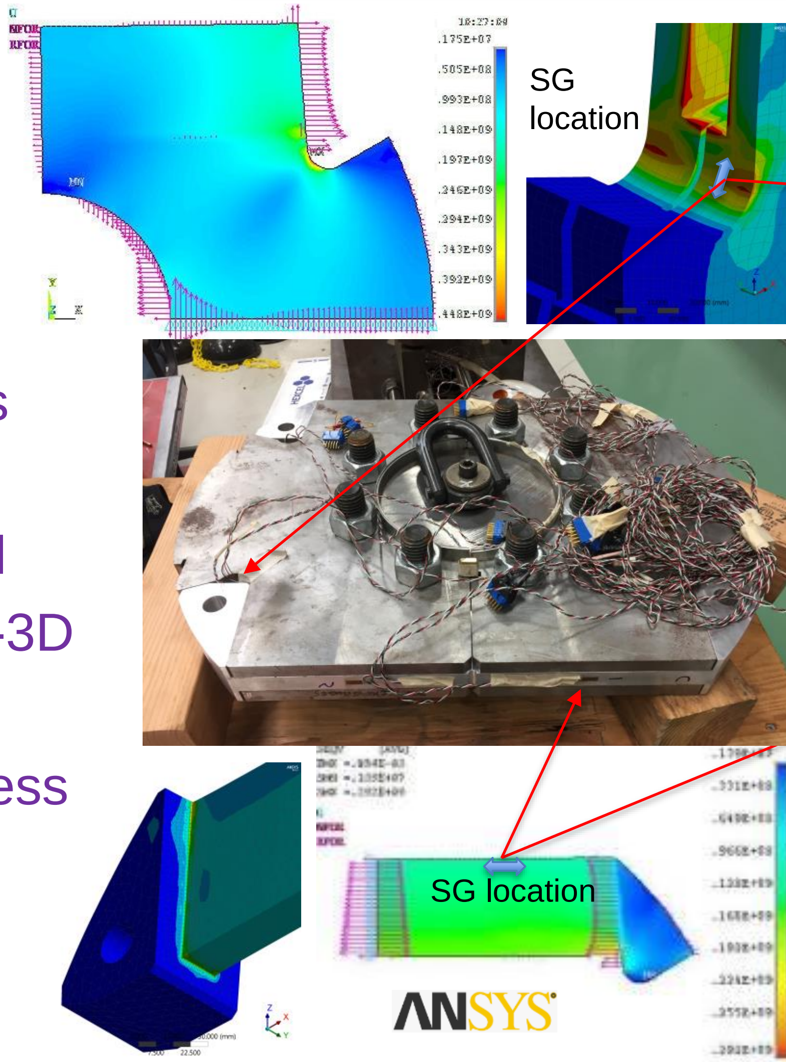
Courtesy C. Kokkinos
work supported by CERN

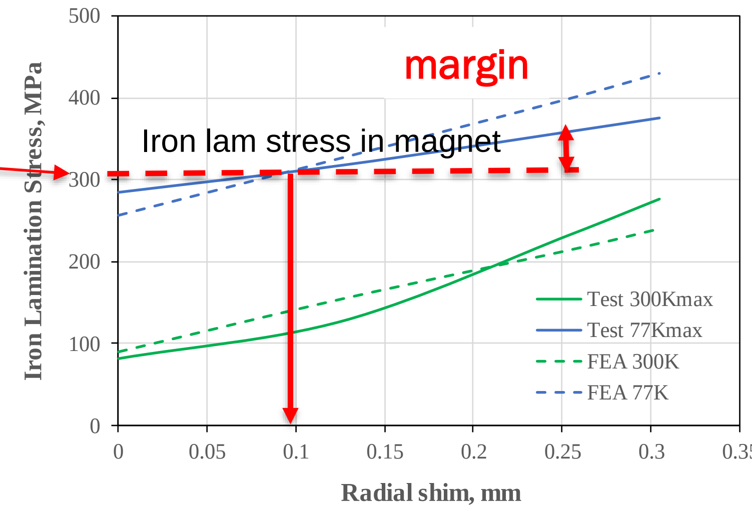
Magnet ***mechanical design limit*** is determined by the coil maximum stress and the coil turn separation from poles at 15T bore field

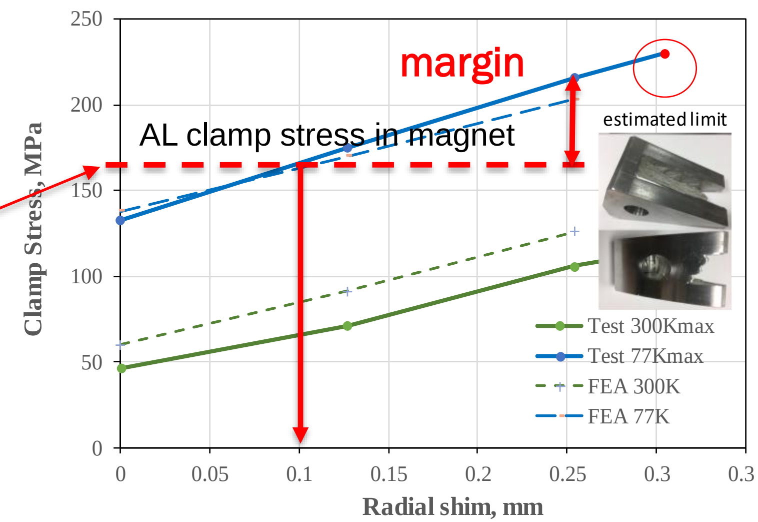
Mechanical Model Tests

MM Goals:

- Test brittle yoke and clamps
- Validate mechanical analysis, 2-3D
- Develop coil pre-stress targets



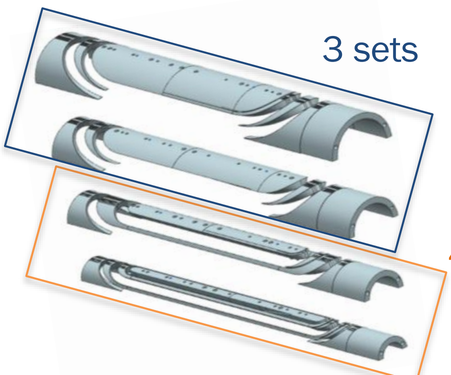




Coil Components

Cable (FNAL)

L3/4 parts (FNAL)



Traces (LBNL/FNAL)

L2

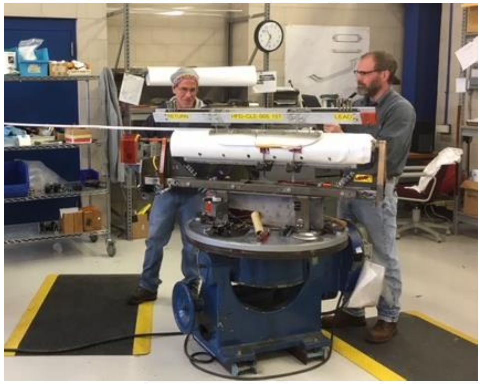
L4

L1/2 parts (CERN contribution)

Ti and Cop Wedges

Ti poles and spacers, SS saddles

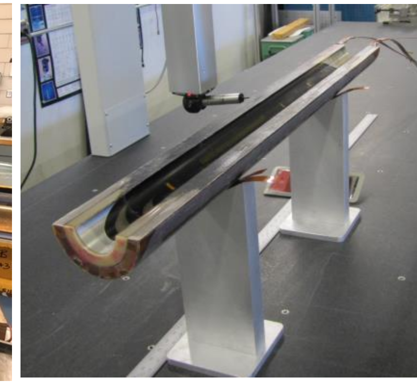
Coil Fabrication Process



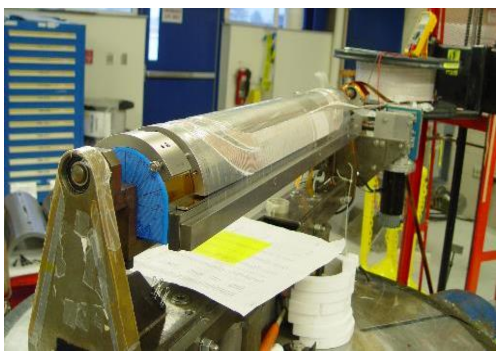
Coil winding and curing using ceramic binder

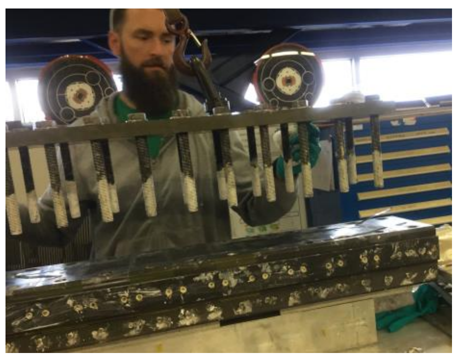
Coil reaction

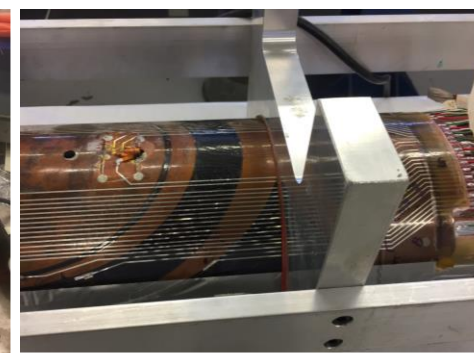
Coil lead splicing, epoxy impregnation



Coil size measurement, instrumentation

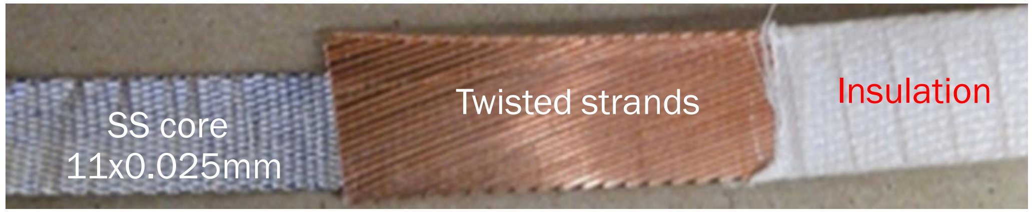




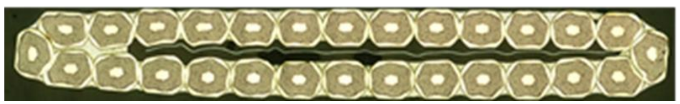


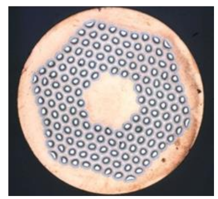
Coil fabrication, measurement and instrumentation time ~3 months

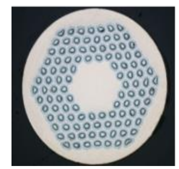
Nb_3Sn Strands and Cables



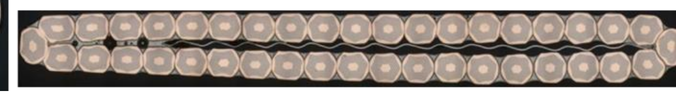
1 mm RRP150/169
28-strand cable with SS core — **IL coils**

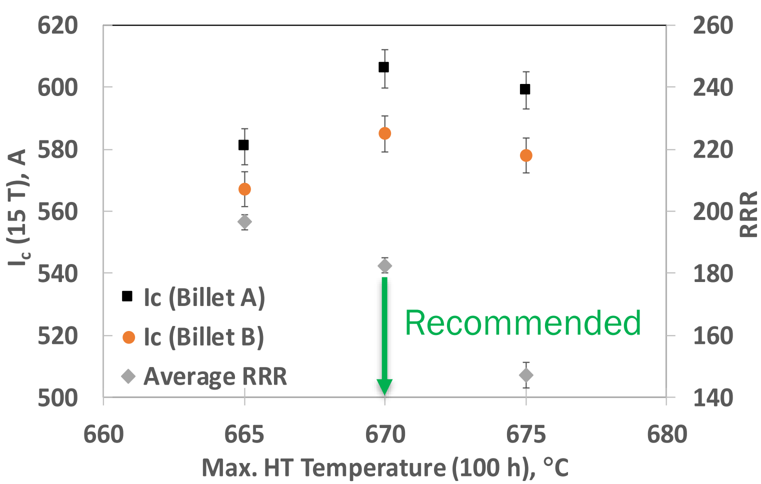


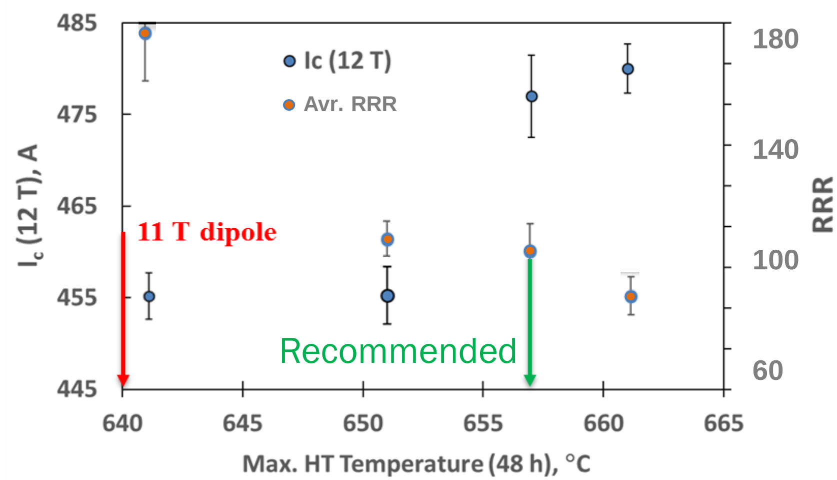




0.7 mm RRP108/127
40-strand cable with SS core — **OL coils**

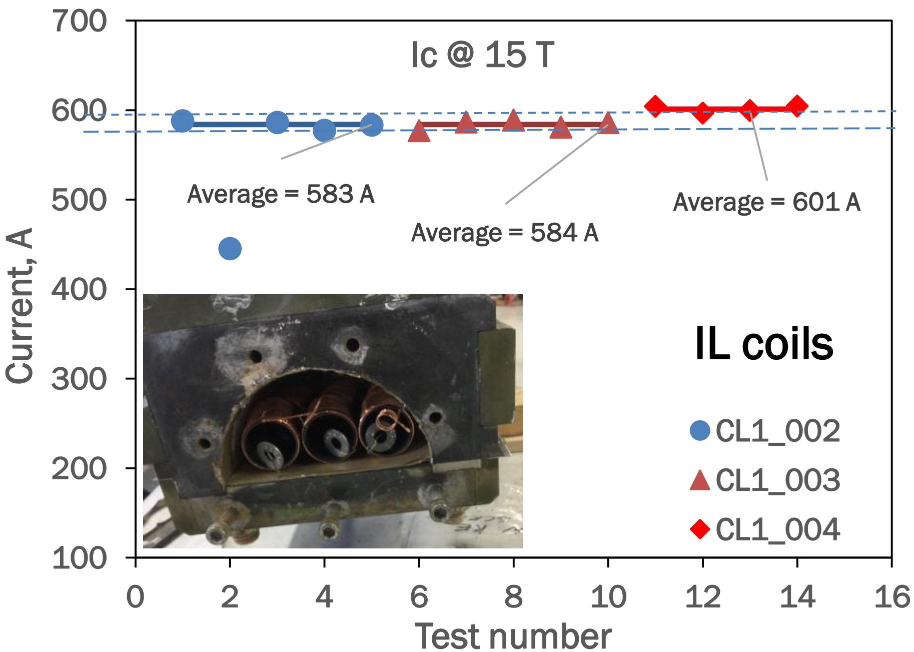


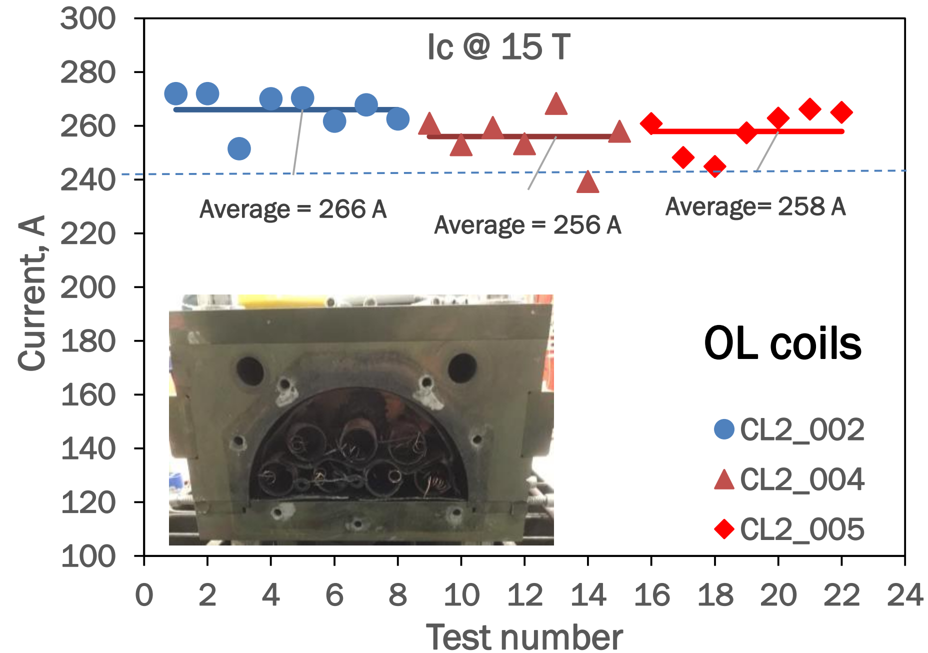




Sensitivity study of I_c and RRR to heat treatment parameters

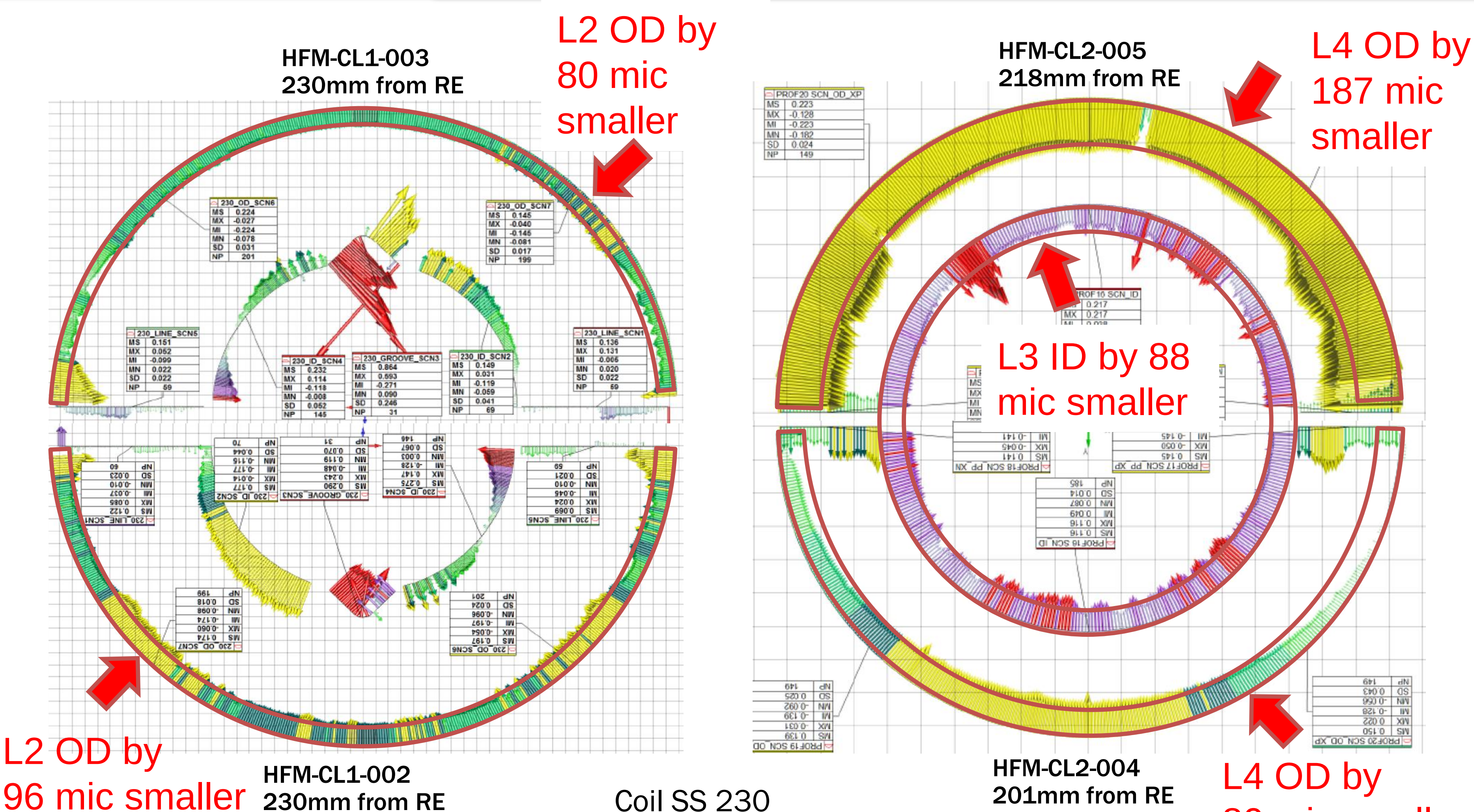
Witness Sample Data and Magnet SSL





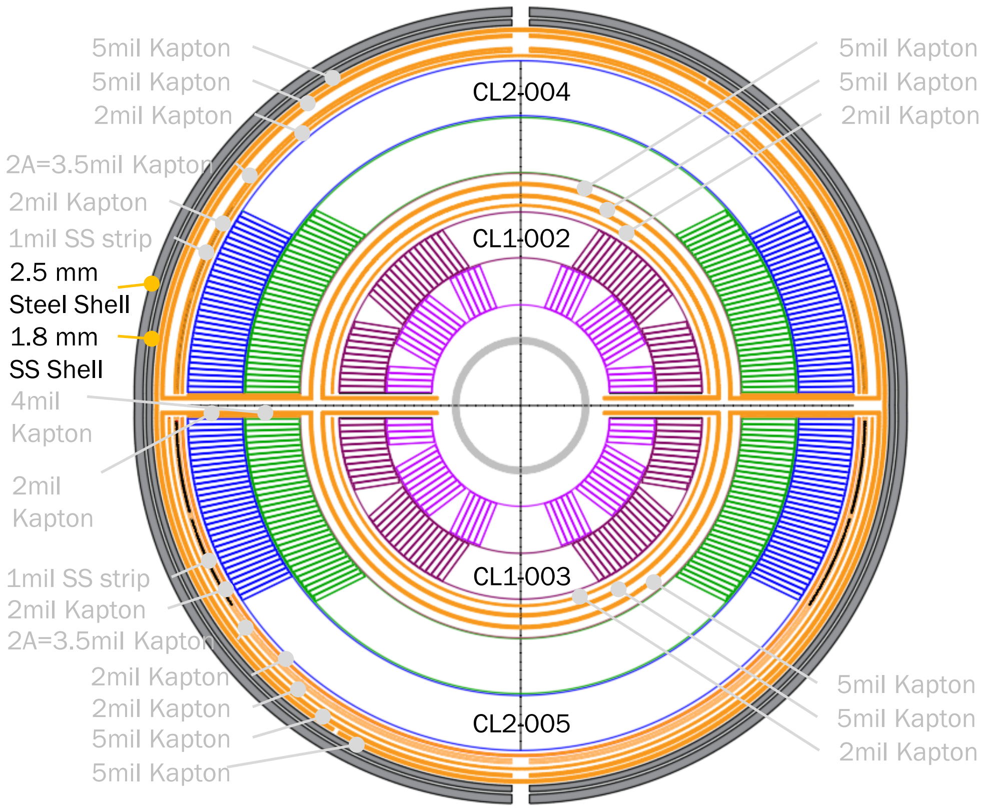
- Witness sample data are close to the target I_c
- Good reproducibility of witness sample data for IL and OL coils
- Magnet ***short sample limit***: 15.16 T @4.5K and 16.84 T @1.9K

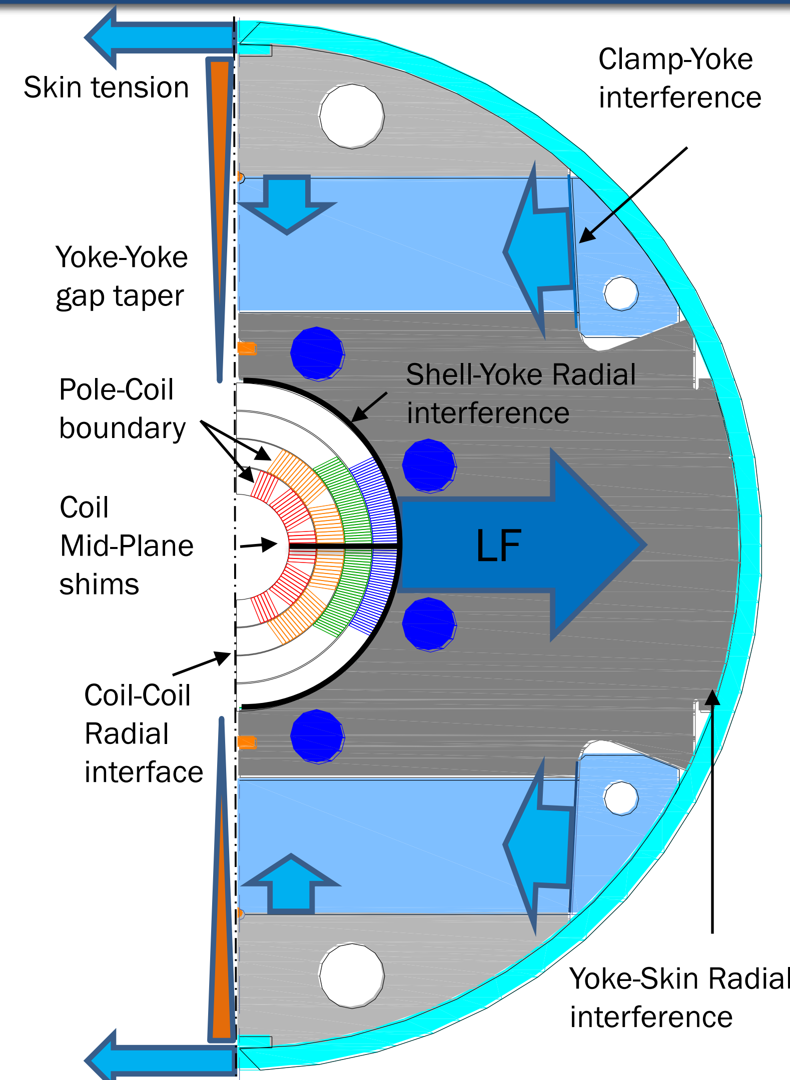
Coil Interfaces Analysis and Optimization



Coil SS 230

Coil Assembly and Preload Scheme





TAC Recommendations

Report of the Technical Advisory Committee for the U.S. Magnet Development Program

February 22, 2019

Recommendations:

- Maintain as the priority for the cos-theta approach using the clamped mechanical structural design to realize a field of about 14 T, with special attention to mechanical stress management and control.
- Continue with demonstration of 15 T cos-theta performance only after the review of the 14 T magnet test results and feedback from the international workshop.

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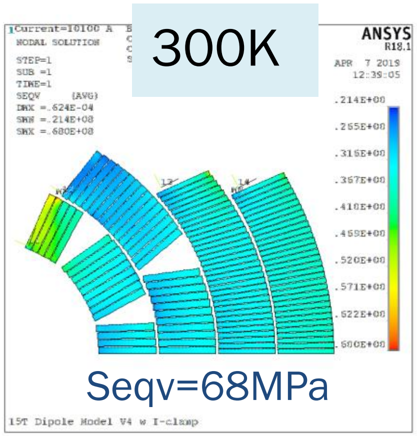
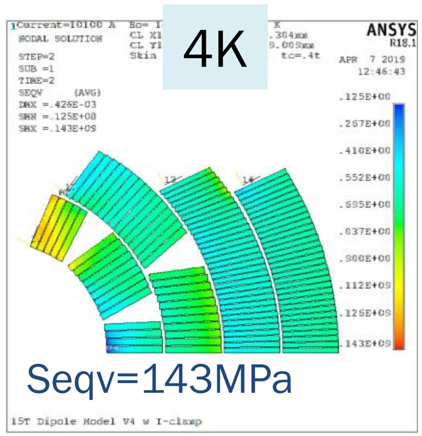
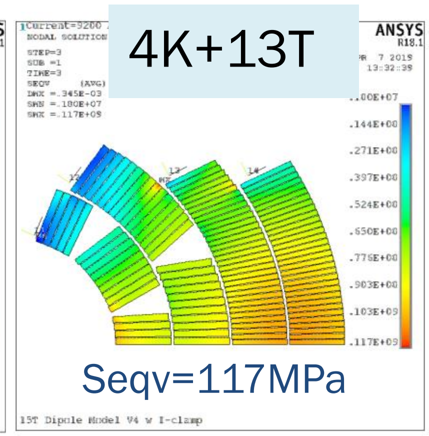
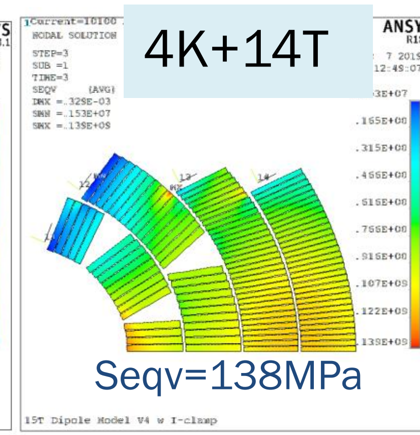
Target Coil Prestress for the First Assembly





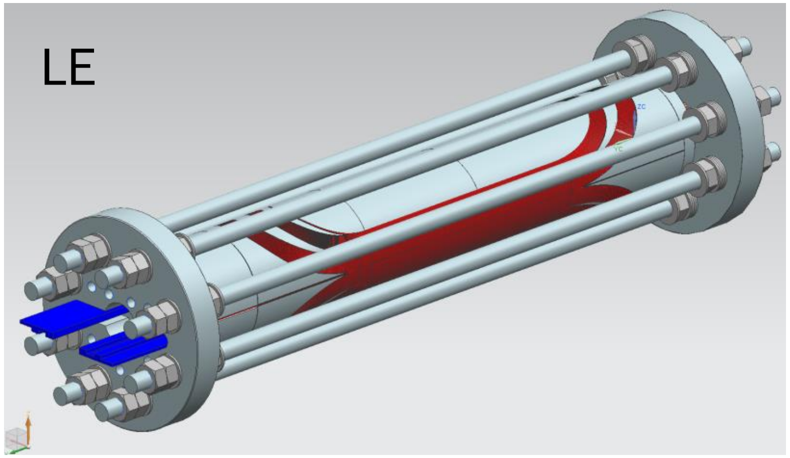


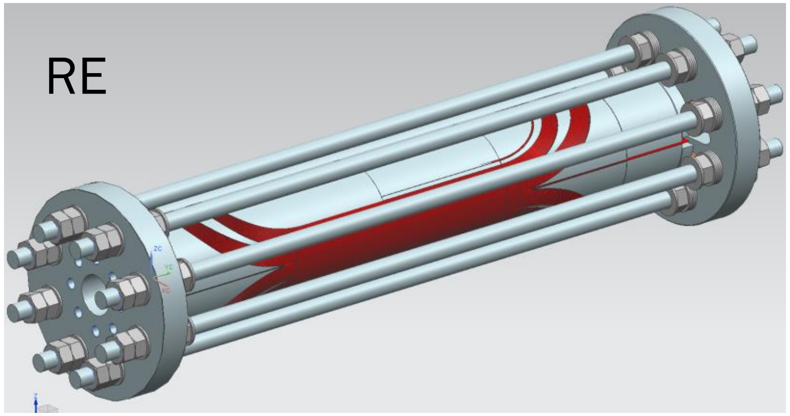


- Coil stress diagrams reconstruction based on the assembly data
- Conservative coil pre-stress: S_{max} at all steps <150 Mpa
- 13T - tension starts to develop between poles and coil turns
- 14T - max tension < 30MPa

Magnet End Mechanics

- 8 30mm stainless steel rods and 2 50mm thick end plates constrain combined load from the inner and outer coils
- Axial load at 300K ~40kN per end
- Major end load at 4K applied to the inner coils
- Calculated LF_{axial} per end at 14T 1250kN



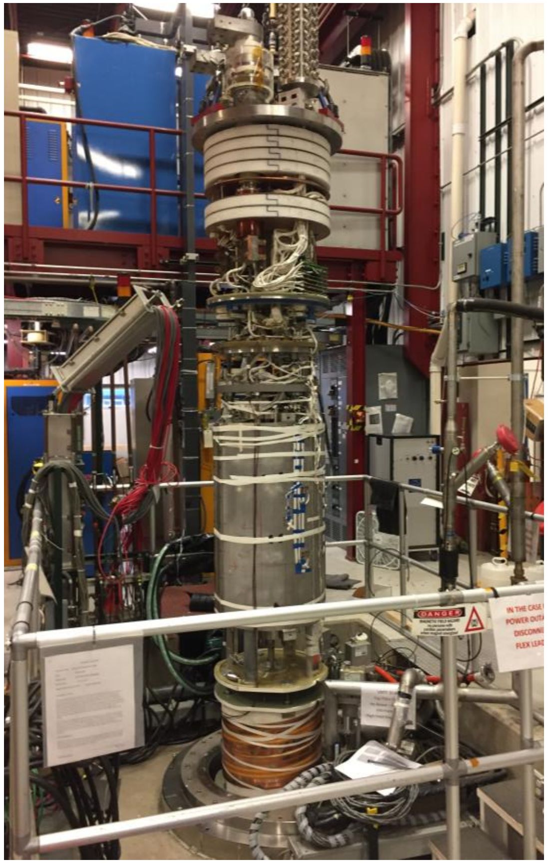


Coil Assembly, Yoking and Skinning

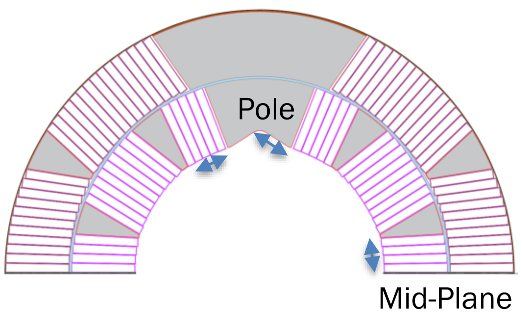
Magnet assembly~3 months

Magnet Test Preparation

Test preparation ~1.5 months



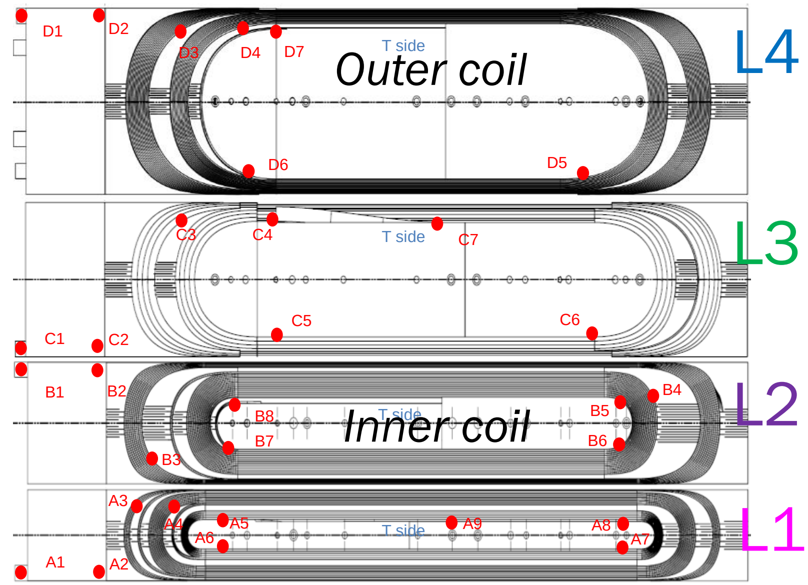
Instrumentation



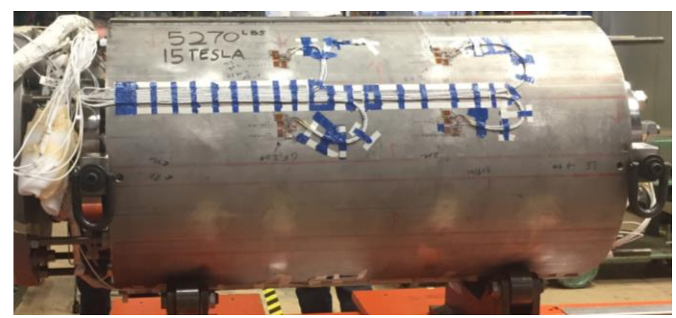
SG on inner coil ID

Traces on outer coil OD

- Voltage taps
- Strain Gauges
  - skin, clamps
  - bullets, poles, coils
- Quench antennas
- Acoustic sensors
- Thermometers

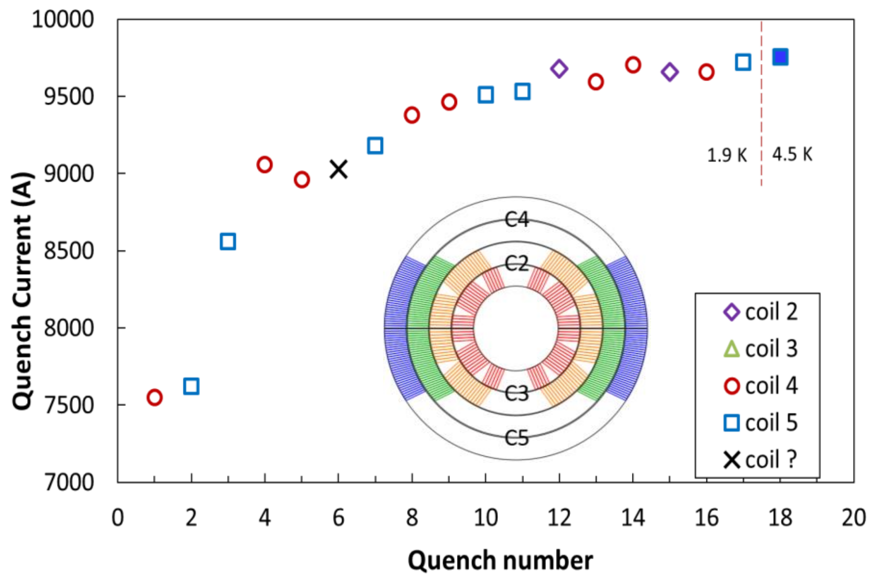


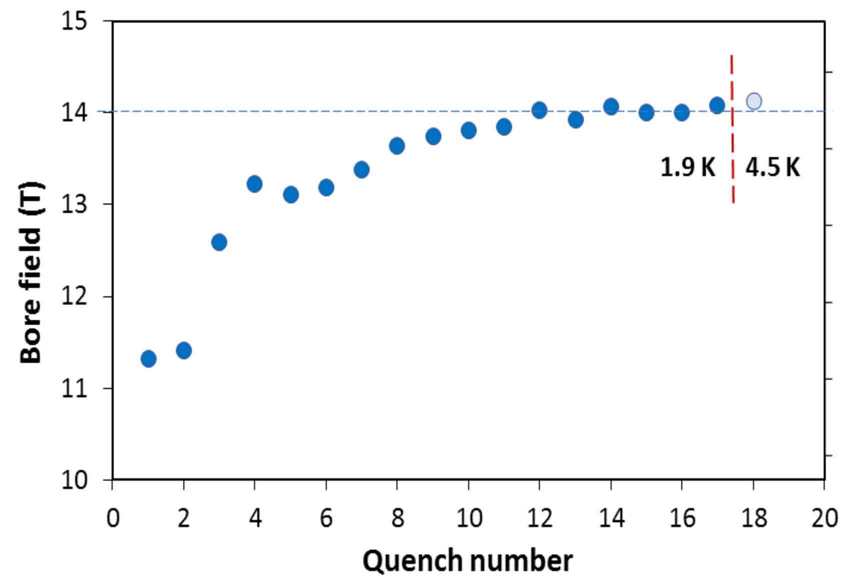
VT location



Skin gauges location

Magnet Training Goal - 14T





- Magnet was trained at 1.9K
- Training plateau after 11 quenches
- IL quenches: 2 in coil 2
- OL quenches: 8 in coil 4
  7 in coil 5

- First quenches above 11 T
- Last quench at 4.5K :
  $B_{measured}$ -14.10±0.04 T
  $B_{calculated}$ -14.112 T

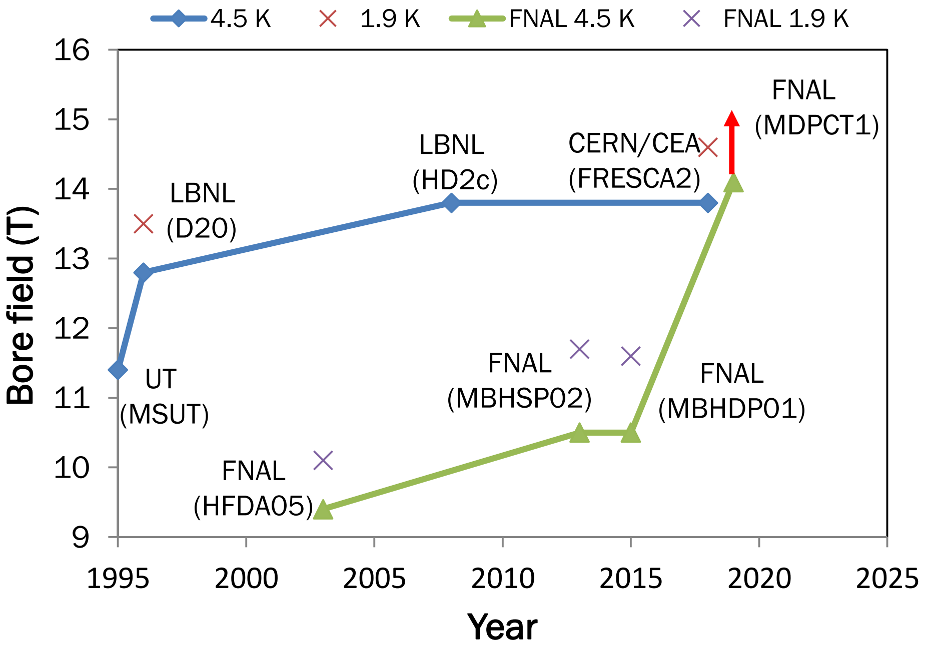
Summary and Next Steps

- 1-m long dipole model MDPCT1 has been developed, fabricated and first tested at Fermilab (June 2019)
- The goals of the first test have been achieved

B_{max} = 14.10±0.04 T *record field at 4.5 K for accelerator magnets*!

Next steps:

- Magnet re-assembly
  - increase coil pre-load to achieve the goal of 15 T
  - improve instrumentation
- Magnet second test in January of 2020



Acknowledgment

FNAL: A. Zlobin, I. Novitski, E. Barzi, J. Carmichael, G. Chlachidze, J. DiMarco, V.V. Kashikhin, S. Krave, C. Orozco, S. Stoynev, T. Strauss, M. Tartaglia, D. Turrioni, G. Velev, A. Rusy, S. Jonhson, J. Karambis, J. McQueary, L. Ruiz, E. Garcia

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FEAC/UPATRAS: C. Kokkinos

US-MDP: G6 and TAC

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