U.S. MAGNET DEVELOPMENT PROGRAM

MT 26 International Conference on Magnet Technology
Vancouver, Canada | 2019

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

MDP meeting, September 11, 2019

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US Magnet Development Program
Fermi National Accelerator Laboratory

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

Acknowledgment

FNAL: A. Zlobin, 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

LBNL: S. Caspi, M. Juchno, M. Martchevskii

CERN: D. Schoerling, D. Tommasini

FEAC/UPATRAS: C. Kokkinos

US-MDP: G6 and TAC

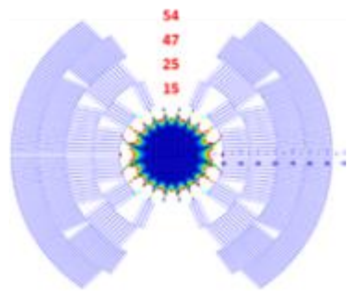
This work was supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy and the US-MDP.

15 T Dipole Program Goals

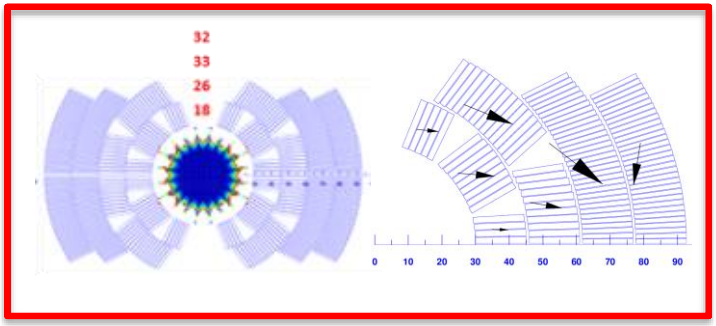
- Demonstration of 15+ T field level in accelerator magnet with Nb_3Sn superconductor
- Study and optimization of:
  - magnet quench performance and mechanics
  - field quality
  - quench protection
  - cost optimization

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

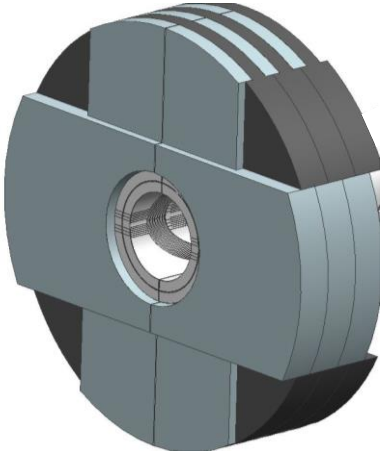


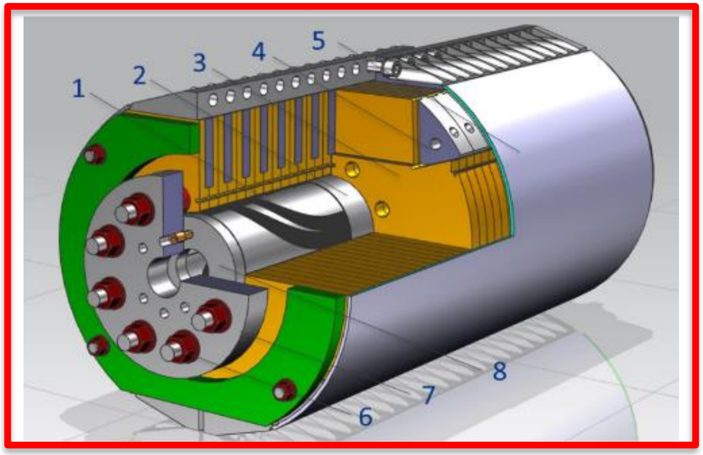
classic cos-theta



block-cos-theta

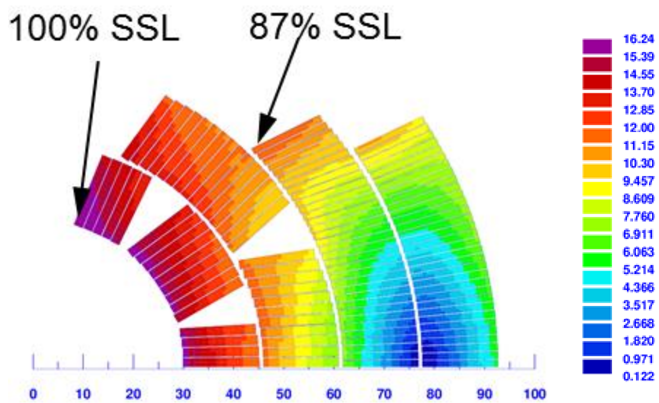
Innovative mechanical design:
- **min number of parts**
- **widely available materials**
- **3D clamp-iron lock**
- **stronger clamp**
- **thinner welded skin**
- **smaller OD**
- Criteria:
  structural integrity,
  coil stress and deformation

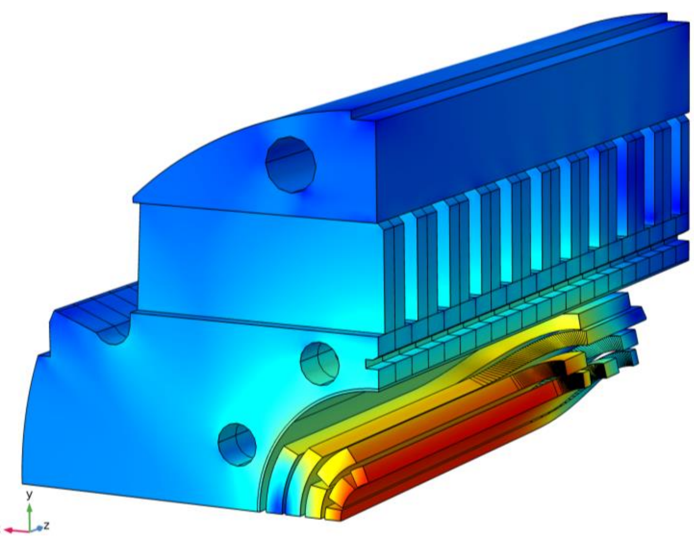




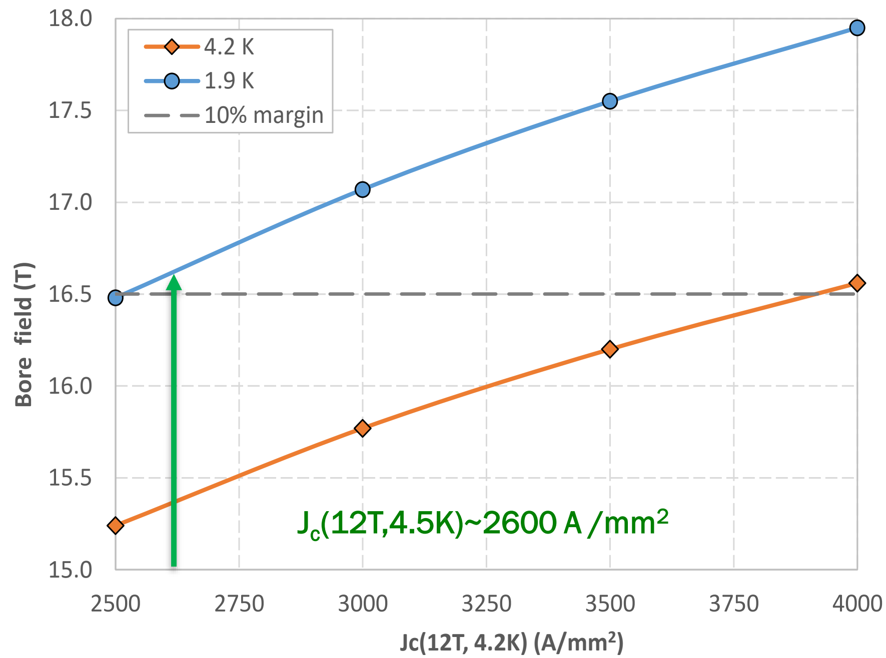
collarless, AL I-clamp, 12mm SS skin

Magnet Conductor Limit





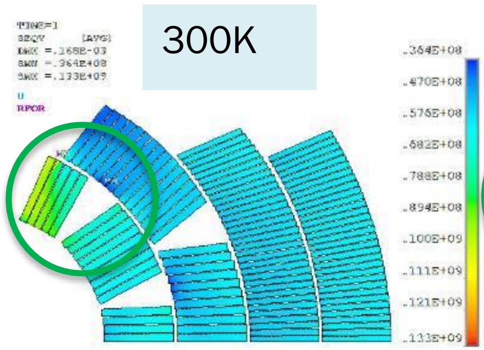
Courtesy V.V. Kashikhin



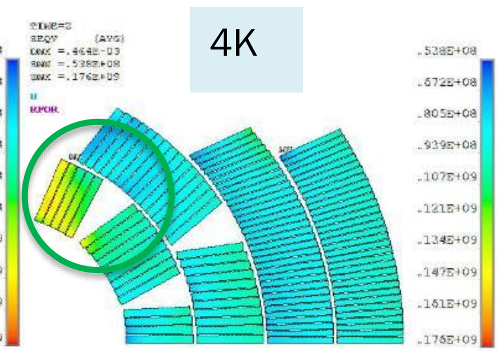
Magnet ***conductor limit*** for the wire $J_c(12T,4.2K)$~$2.6\ kA/mm^2$

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

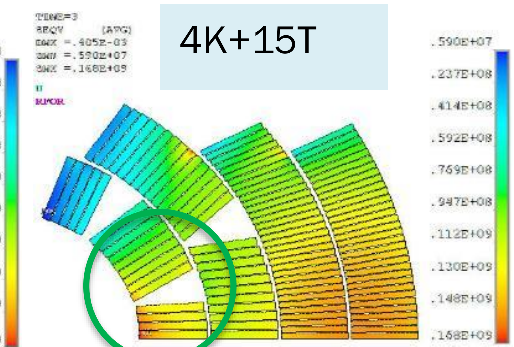
2D Mechanical Analysis



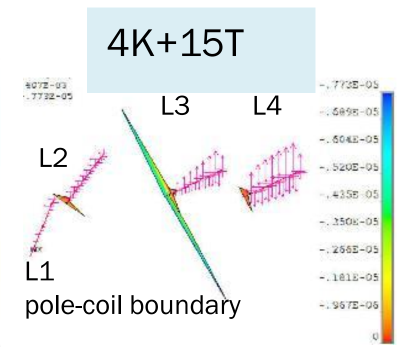
S_{eqv}=133 MPa



S_{eqv}=176 MPa



S_{eqv}=168 MPa

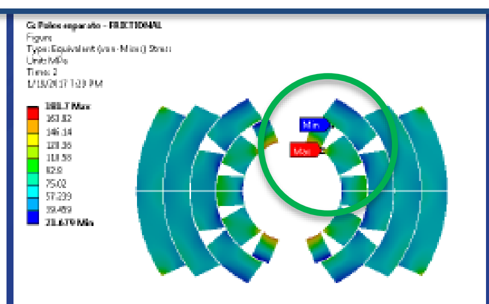


Pole Gap < 0.7e-5 mm

Courtesy I. Novitski

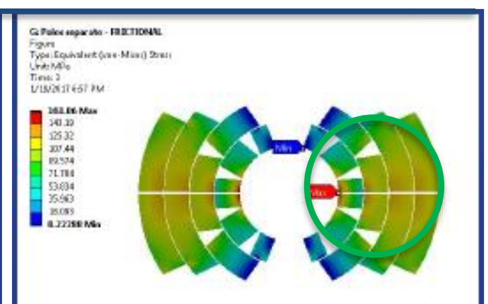
S_{eqv}=133MPa

Shell welding @ RT



S_{eqv}=182MPa

@ 4.2K



S_{eqv}=161MPa

15T @ 4.2K

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΑΤΡΩΝ UNIVERSITY OF PATRAS
with the assistance of FEAC

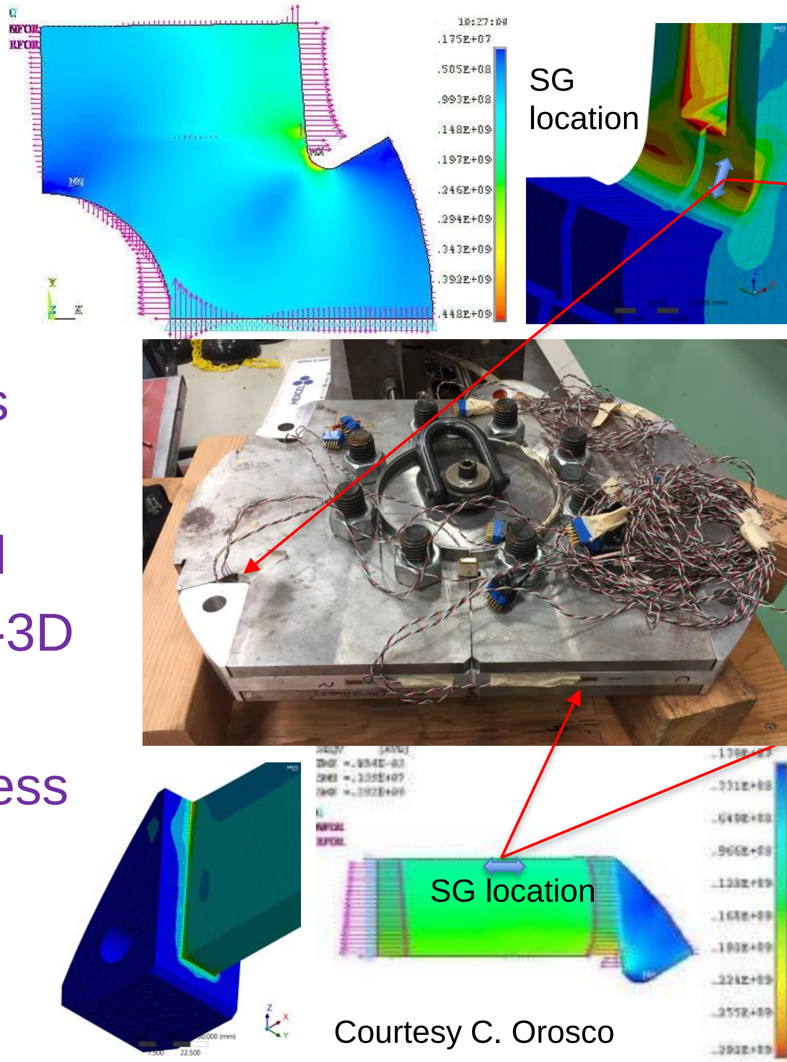
Courtesy C. Kokkinos
Work supported by CERN

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

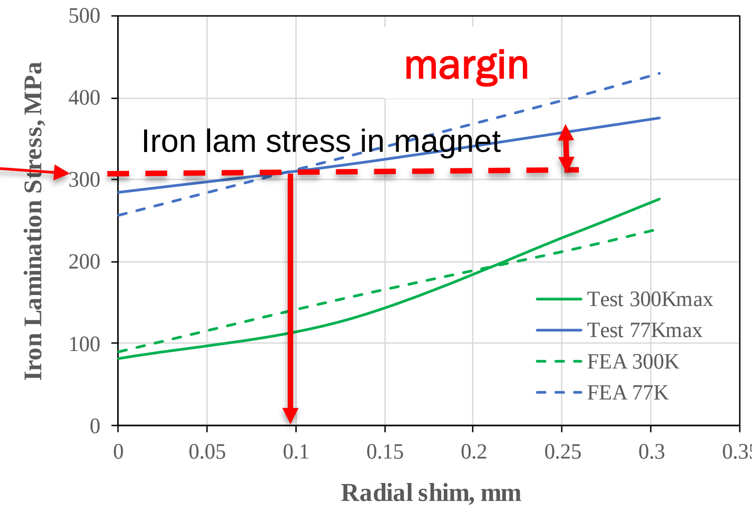
Mechanical Model Tests

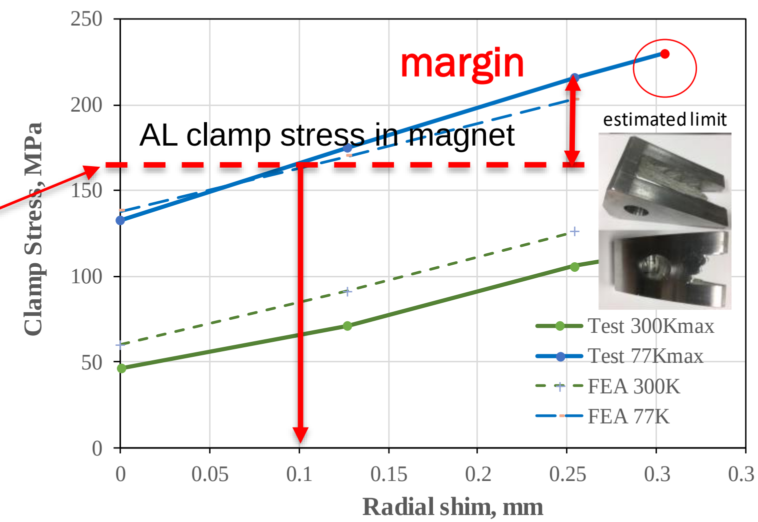
MM Goals:

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



Courtesy C. Orosco

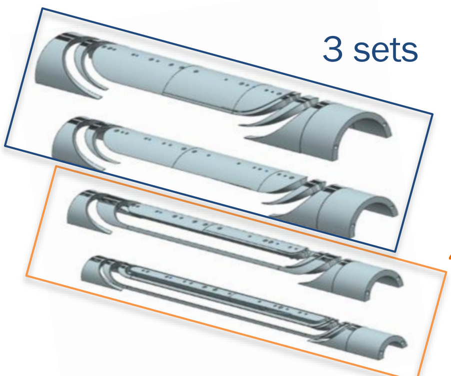




Coil Components

Cable (FNAL)

L3/4 parts (FNAL)



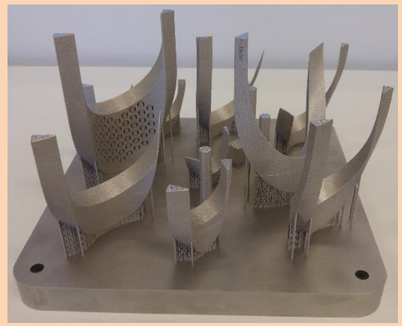
4 sets

Traces (LBNL/FNAL)

L2

L4

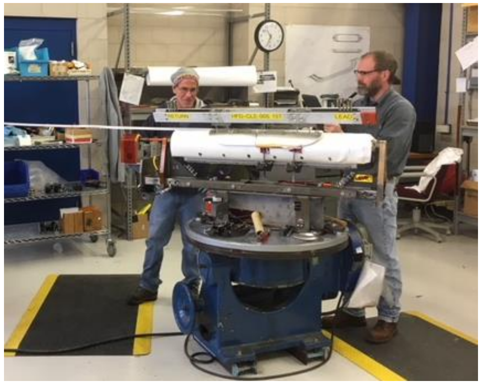
L1/2 parts (CERN contribution)



Ti and Cop Wedges

Ti poles and spacers, SS saddles

Coil Fabrication Process



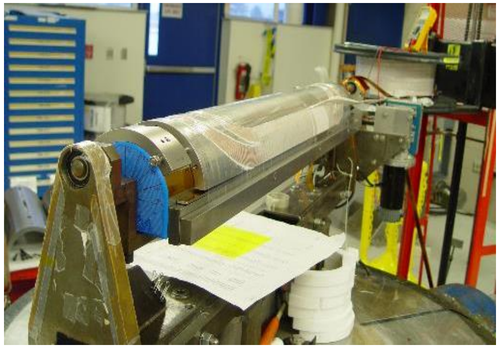


Coil winding and curing using ceramic binder

Coil reaction

Coil lead splicing, epoxy impregnation

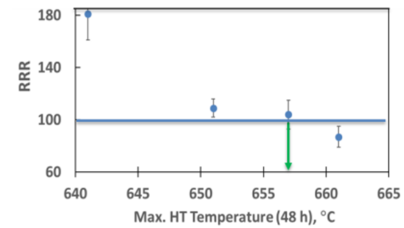
Coil size measurement, instrumentation




Coil fabrication, measurement and instrumentation time ~3 months

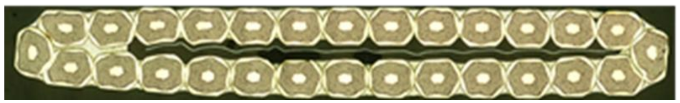
Nb_3Sn Strands and Cables

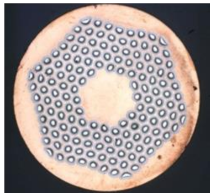
Courtesy E. Barzi and D. Turrioni



1 mm RRP150/169
28-strand cable with SS core

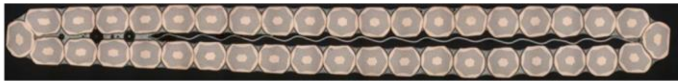
IL coils

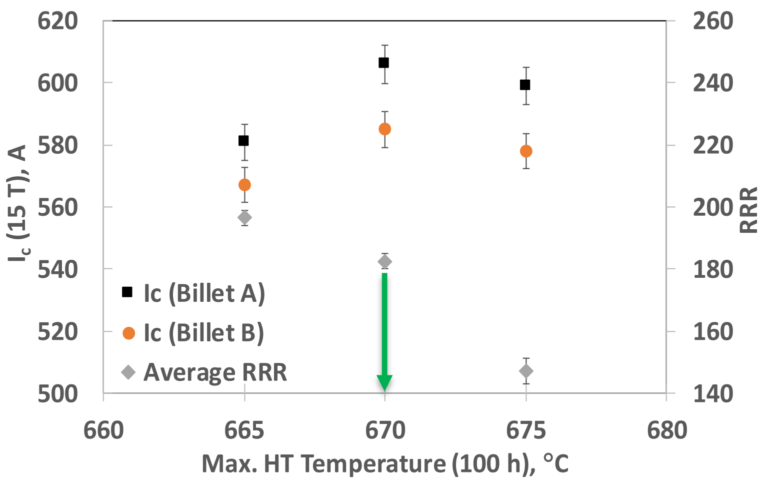


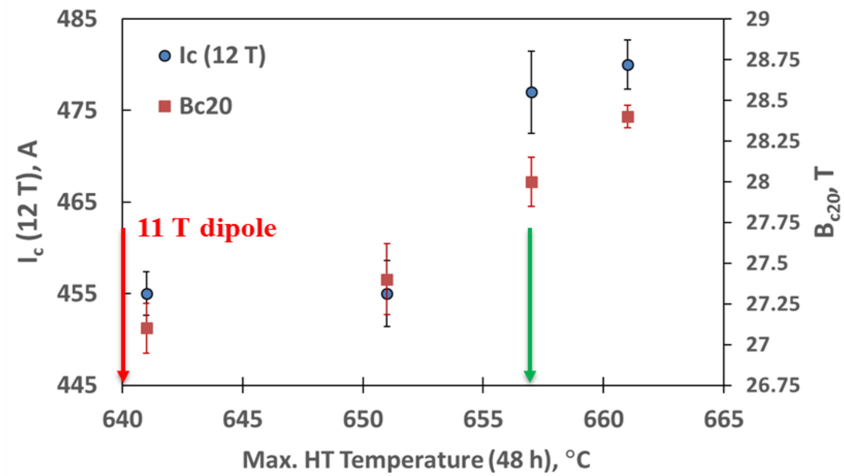


0.7 mm RRP108/127
40-strand cable with SS core

OL coils



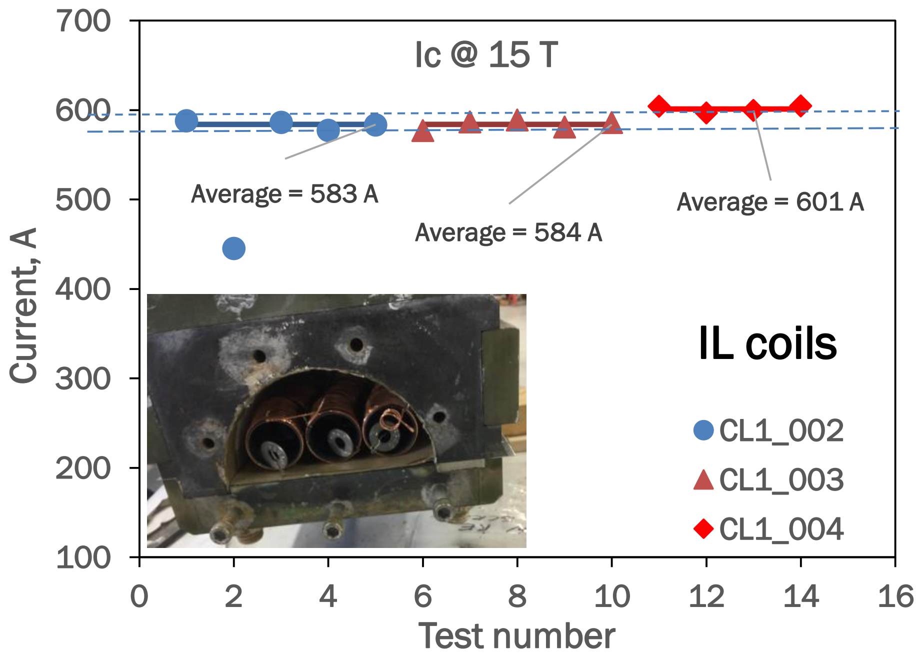


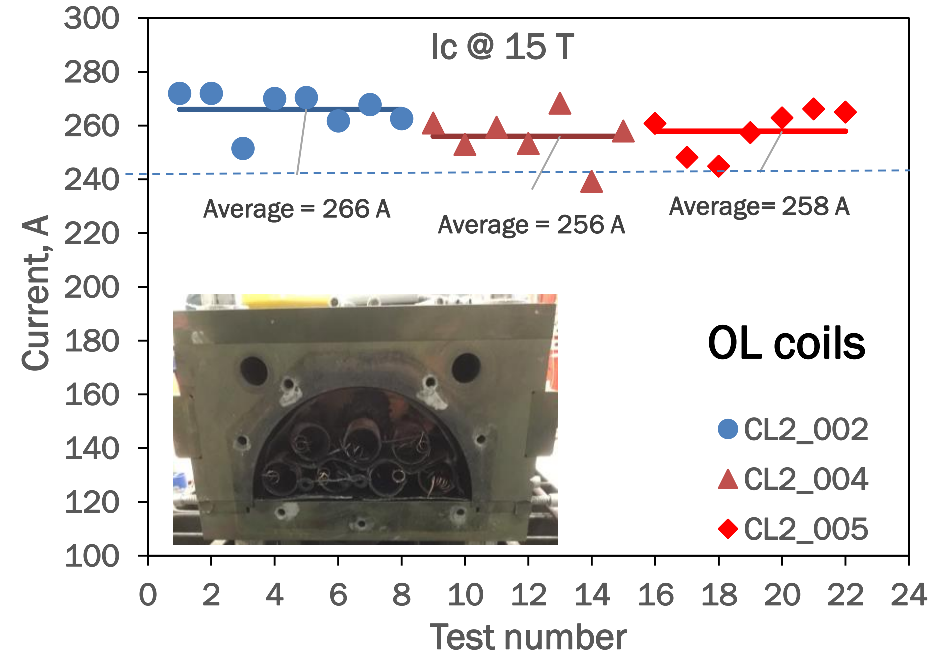


Sensitivity study of I_c and RRR to heat treatment parameters

Witness Sample Data and Magnet SSL

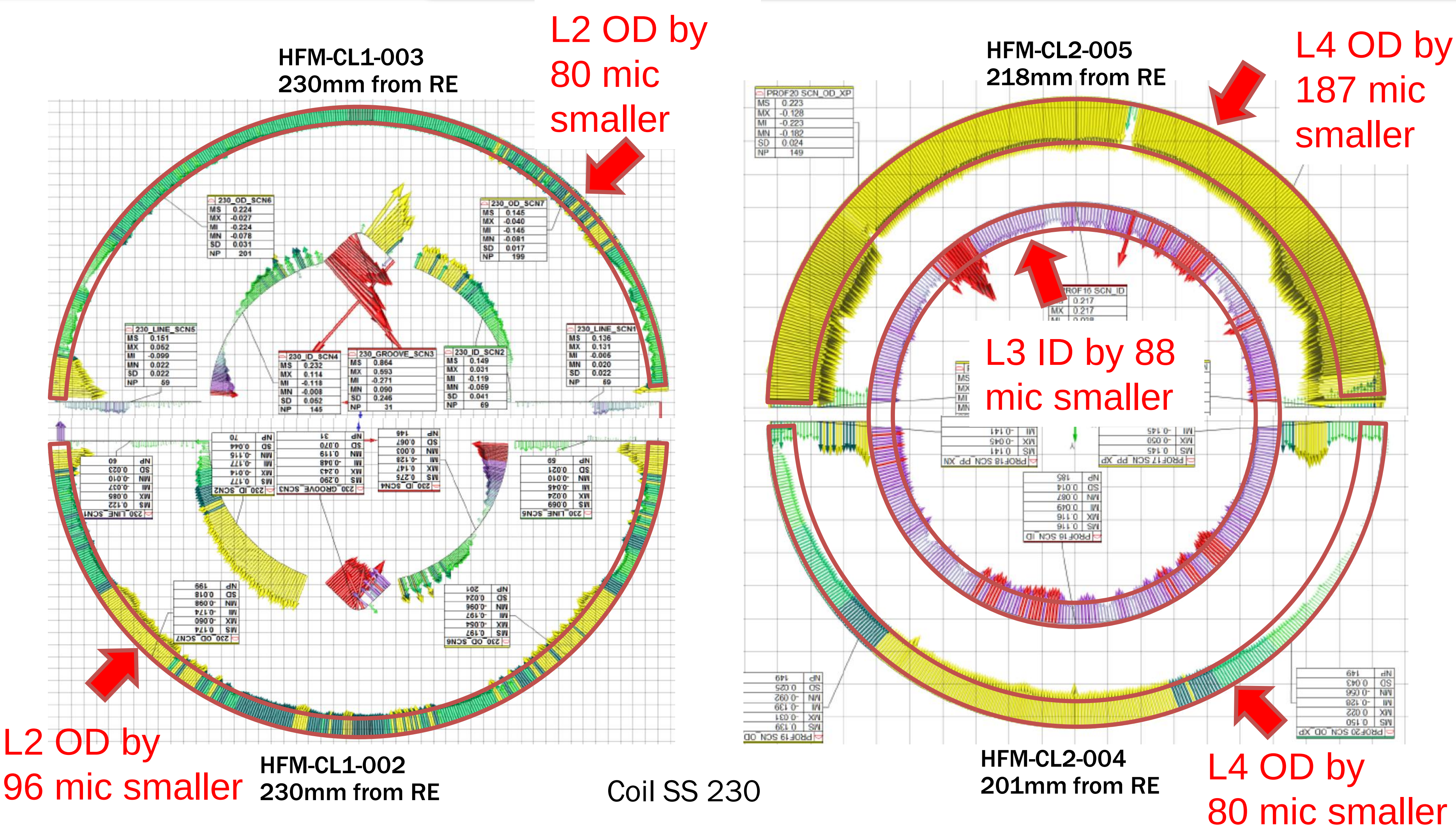
Courtesy E. Barzi and D. Turrioni





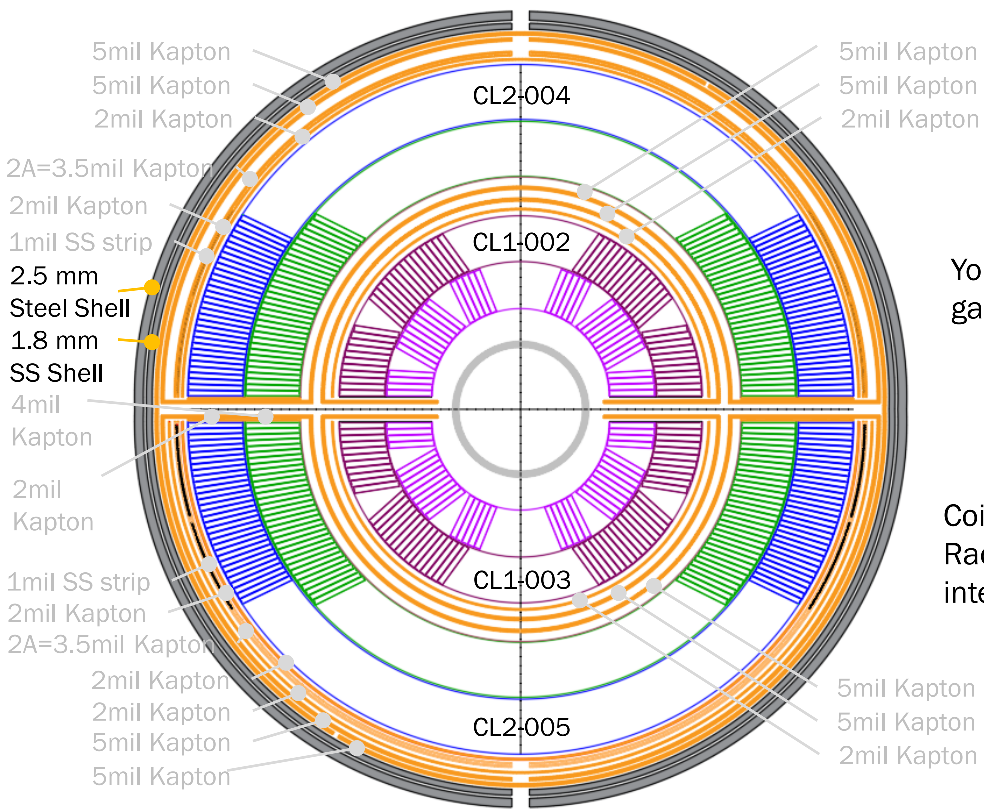
- Witness sample data are close to the target I_c
- Good reproducibility of witness sample data for IL and OL coils
- Magnet short sample limit: 15.16 T @4.5K and 16.84 T @1.9K

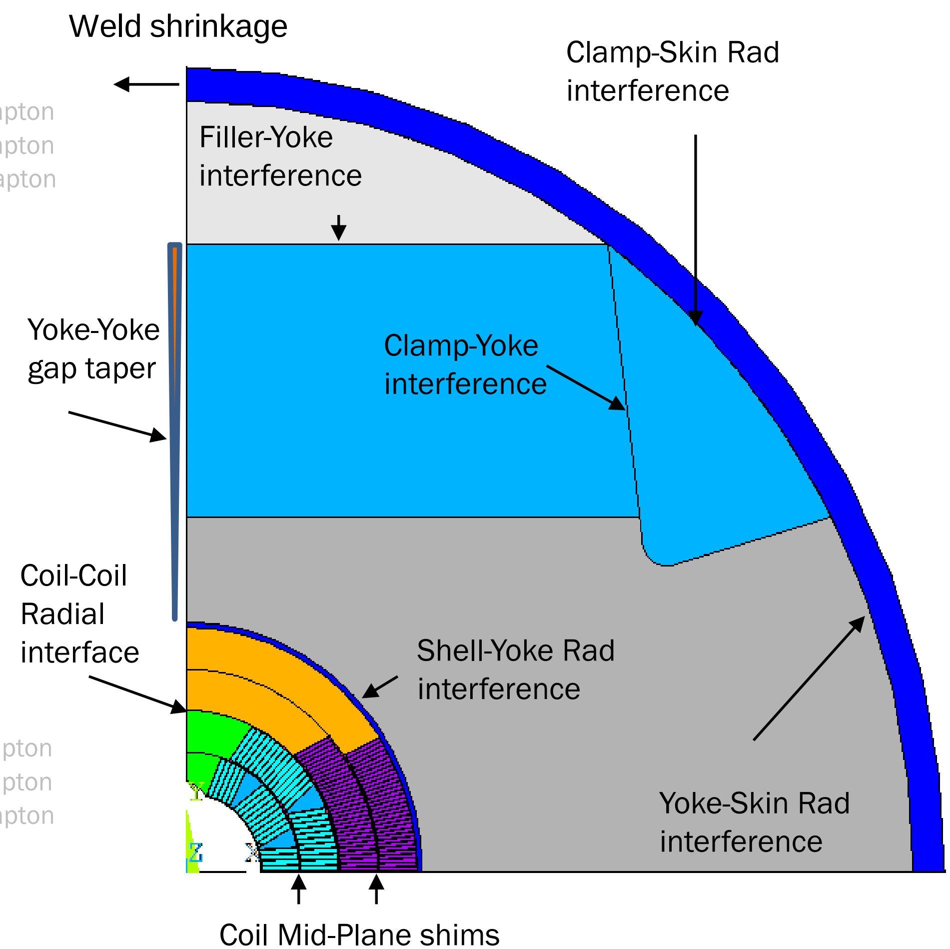
Coil Interfaces Analysis and Optimization



Coil SS 230

Coil Assembly and Preload Scheme





TAC Recommendations

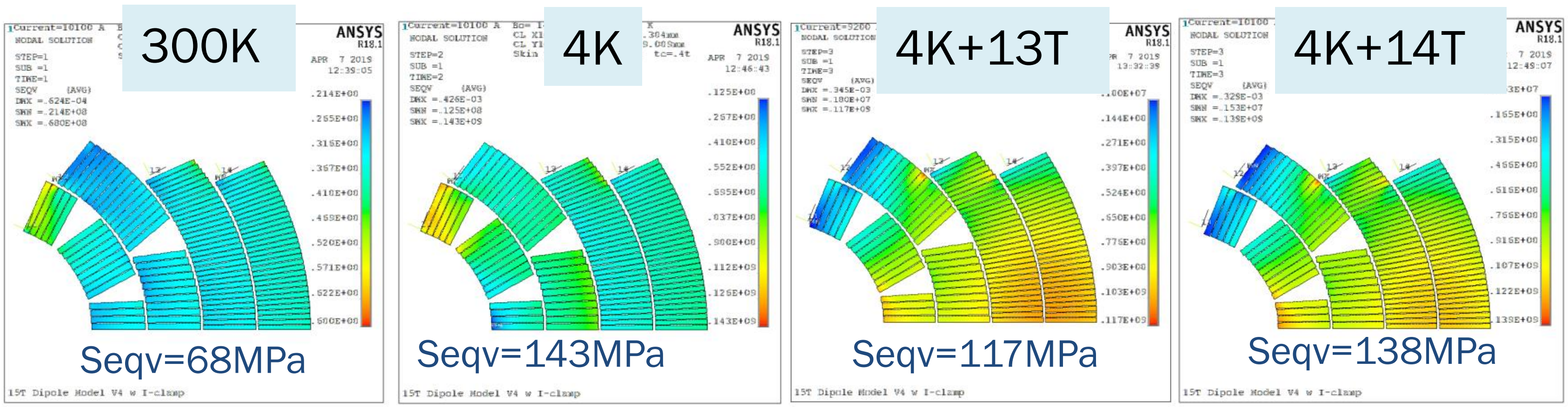
Report of the Technical Advisory Committee for the U.S. Magnet Development Program

February 22, 2019

Recommendations:

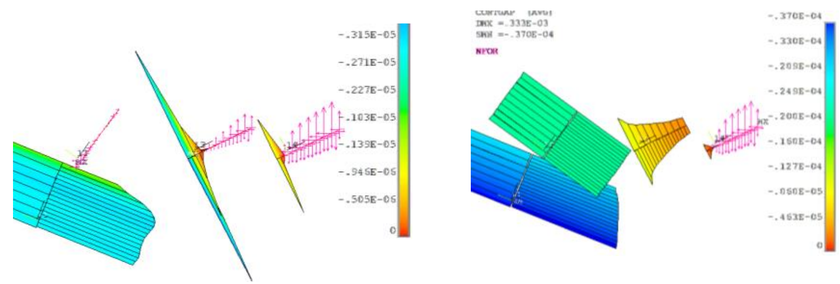
- Maintain as the priority for the cos-theta approach using the clamped mechanical structural design to realize a field of about 14 T, with special attention to mechanical stress management and control.
- Continue with demonstration of 15 T cos-theta performance only after the review of the 14 T magnet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

Target Coil Prestress for the First Assembly



Conservative pre-stress:

S_{max} at all steps <150 MPa

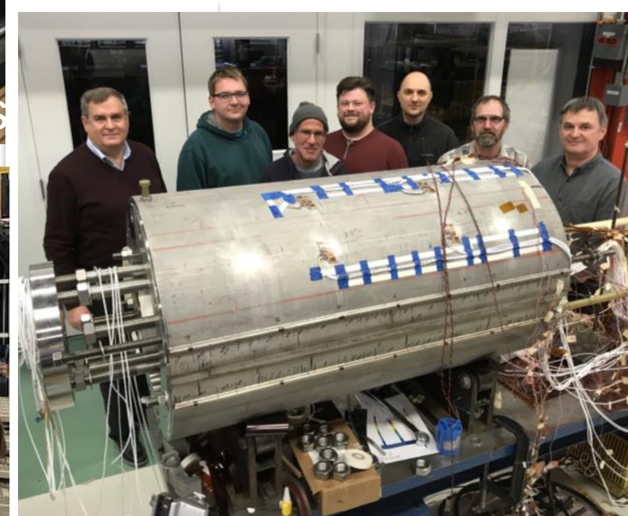


Inner Pole at 13T
Gap=0.003mm

Inner Pole at 14T
Gap=0.037mm

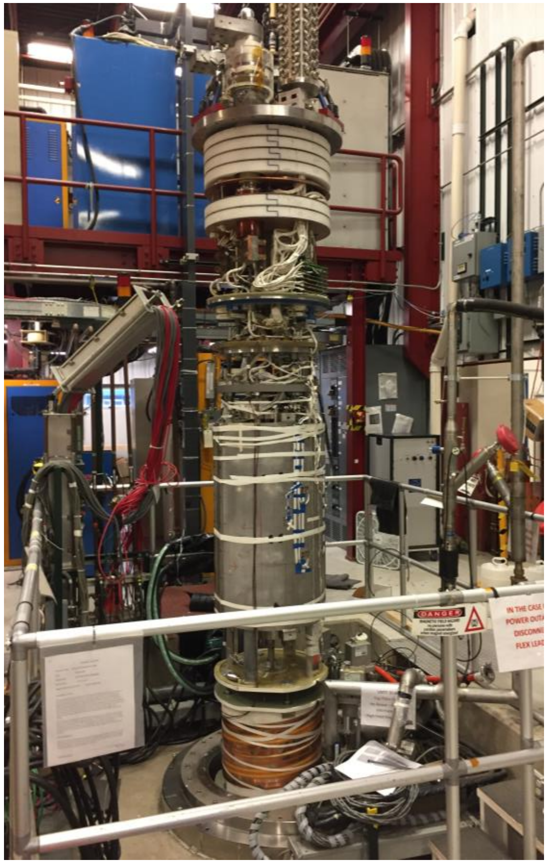
Coil Assembly, Yoking and Skinning

Magnet assembly~3 months

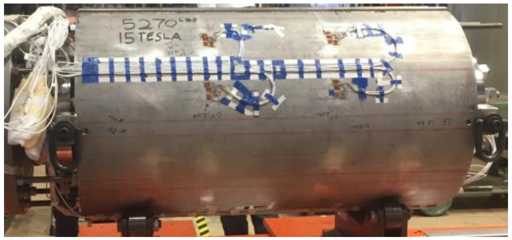


Magnet Test Preparation

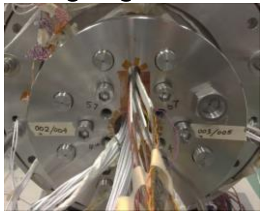
Test preparation
~1.5 months

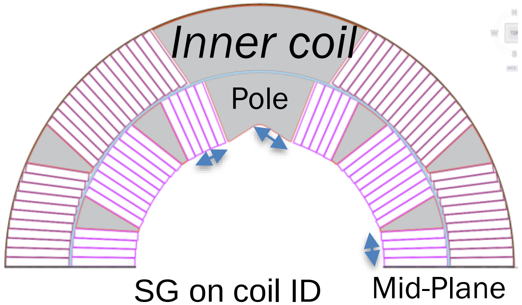


Instrumentation

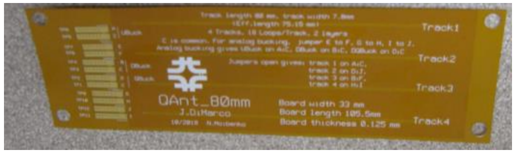


Skin and bullet gauges



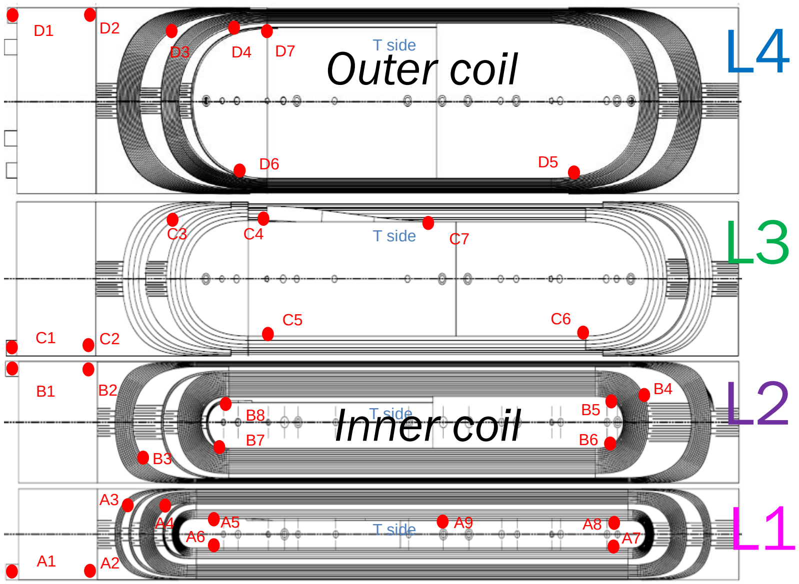


SG on coil ID

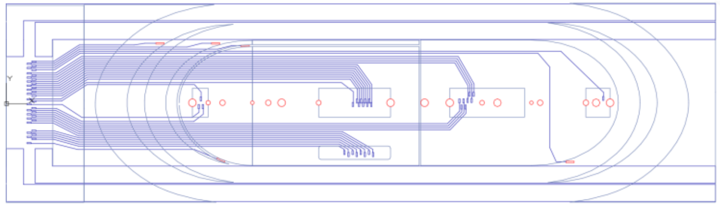


Flexible “Trace” QA

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



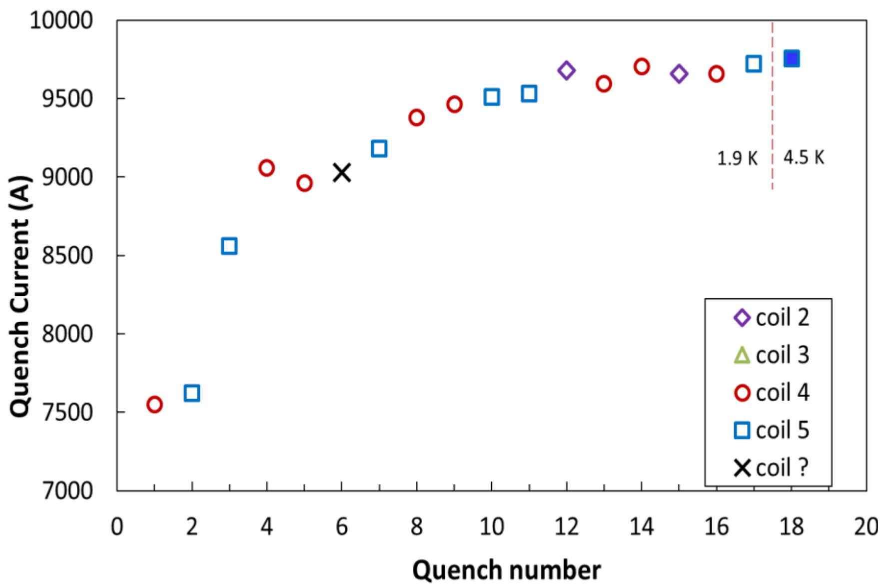
VT location

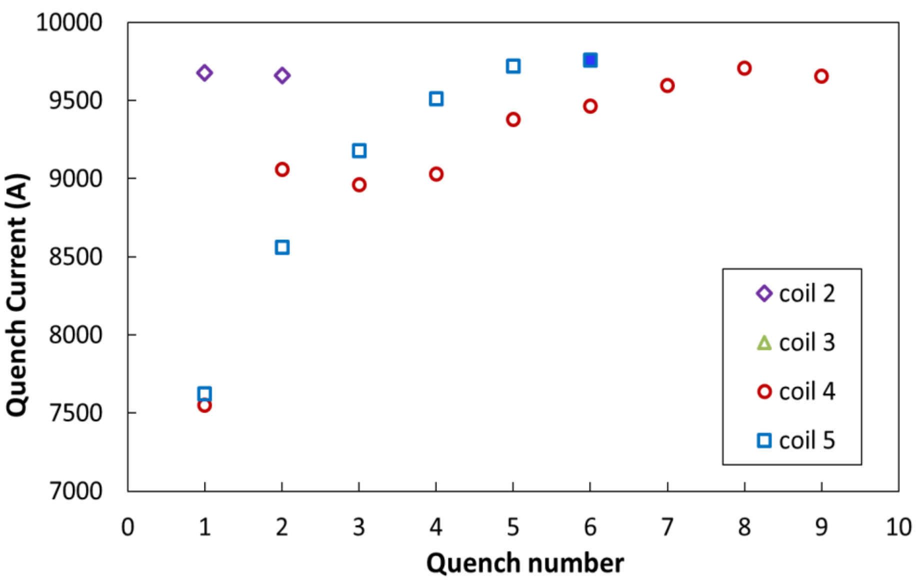


Layer 4 Traces

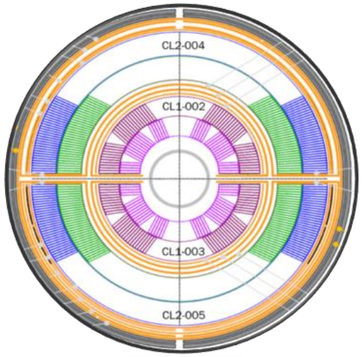
Magnet Training

Courtesy S. Stoynev and G. Chlachidze



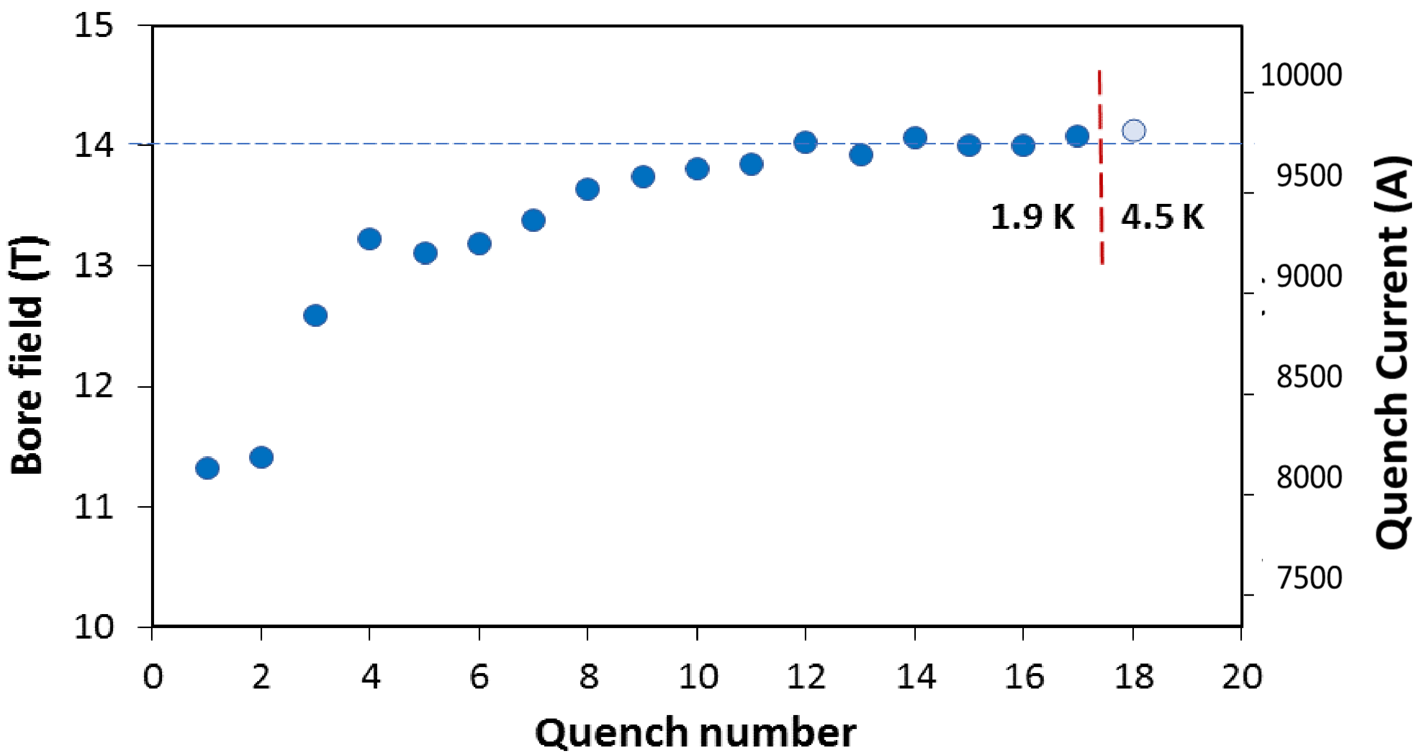


- Magnet was trained at 1.9K
- Highest achieved quench current 9758 A at 4.5 K
- Only 2 quenches in IL
- OL quenches are equally distributed between coil 4 and coil 5
- Magnet quenching was stopped after reaching the goal of ~14 T to avoid coil damage



Layers: 4 3 2 1

Maximum Field Achieved



First quenches above 11 T

Maximum bore field at 4.5K

measured 14.10±0.04 T

calculated 14.112 T

Summary and Next Steps

- 1-m long 15 T 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 the fall-winter of 2019