U.S. MAGNET DEVELOPMENT PROGRAM

Assembly and First Test of the US-MDP Nb_3Sn Dipole Demonstrator (MDPCT1)

June 27, 2019

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Acknowledgment

FNAL: 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

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

CERN: D. Schoerling, D. Tommasini

FEAC/UPATRAS: C. Kokkinos

US-MDP: G6 and TAC

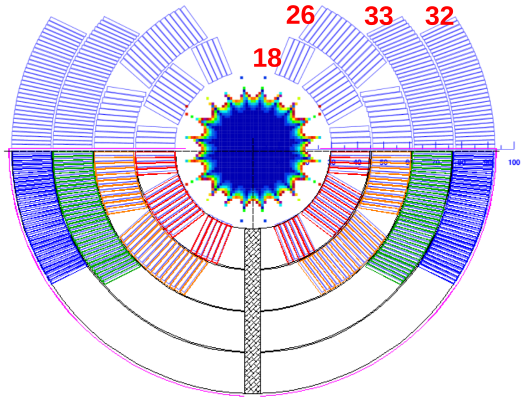
This work was supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy and the US-MDP.

Program goals

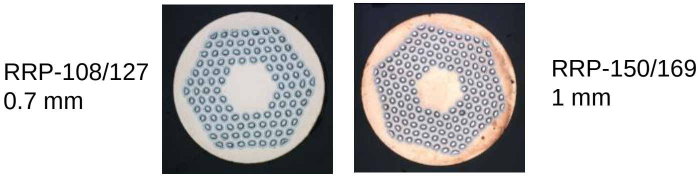
- Demonstration of 15 T field level
  - Record Nb_3Sn dipole magnets:
    - D20 (LBNL, 1997): B_{max}=13.5 T @1.9K, 12.8 T @4.4K
    - HD2 (LBNL, 2008): B_{max}=13.8 T @4.5K
    - FRESCA2 (CERN, 2018): B_{max}=14.6 T @1.9K, 13.9 T @4.5K
- Study and optimization of
  - magnet quench performance and mechanics
  - quench protection
  - field quality
- The development and test of the 15 T dipole demonstrator is a key milestone of the US Magnet Development Program
  - coordinated with EuroCirCol program and supported by CERN

15 T Dipole design

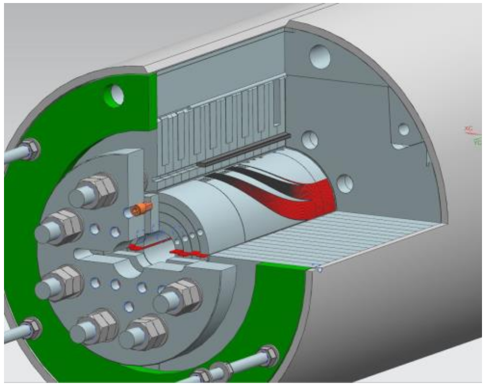
- **Coil** (V.V. Kashikhin et al.)**:**
  - 60-mm aperture, 4-layer graded coil
  - W_{sc} = 68 kg/m/aperture

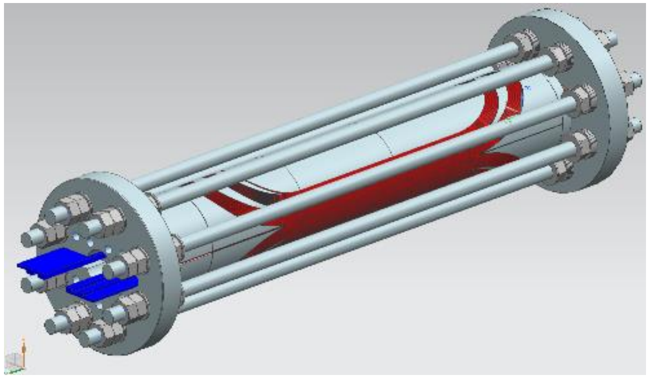


- **Cable** (E. Barzi et al.)**:**
  - L1-L2: 28 strands, 1 mm RRP150/169
  - L3-L4: 40 strands, 0.7 mm RRP108/127
  - 0.025 mm x 11 mm SS core
  - Insulation: E-glass tape

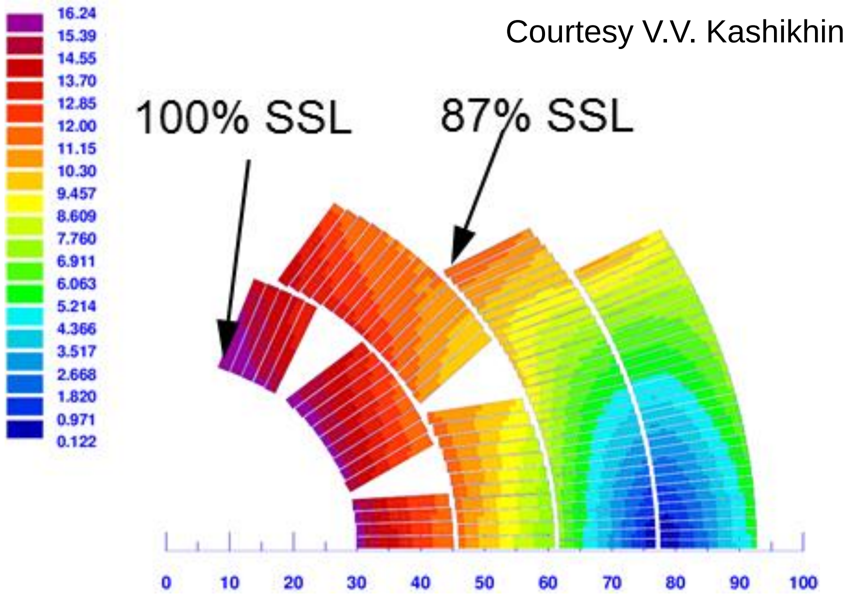


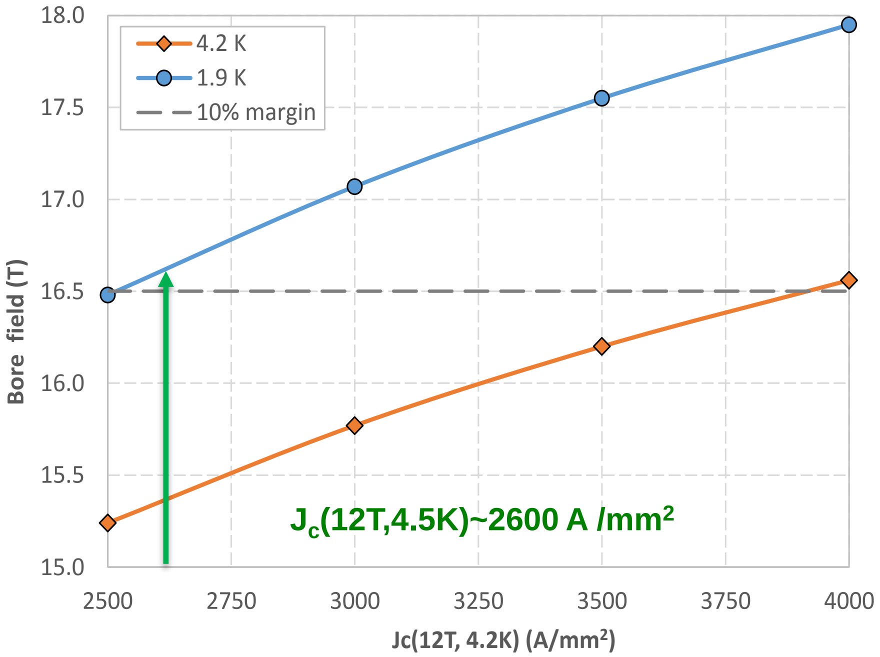
- **Innovative mechanical structure** (I. Novitski et al.)**:**
  - Thin StSt coil-yoke spacer
  - Vertically split iron laminations
  - Aluminum I-clamps
  - 12-mm thick StSt skin
  - Thick end plates and StSt rods
  - Cold mass OD<610 mm





Magnet conductor limit



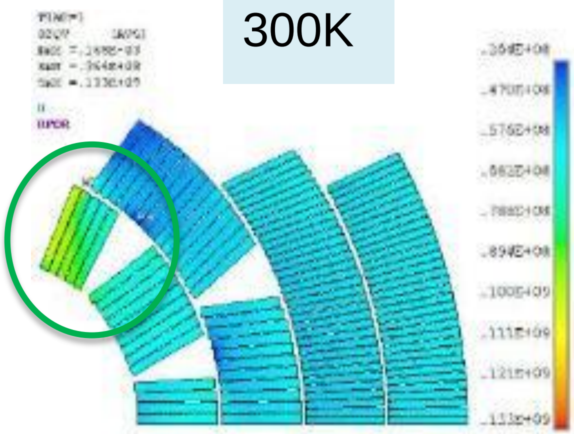


Magnet conductor limit for the wire J_c(12T,4.2K)~2.65 kA/mm^2

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

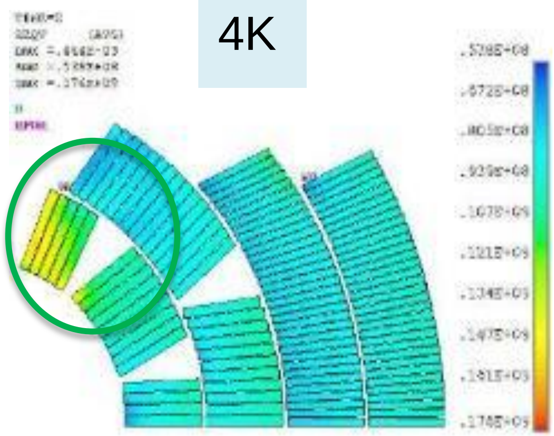
Magnet mechanical limit

300K



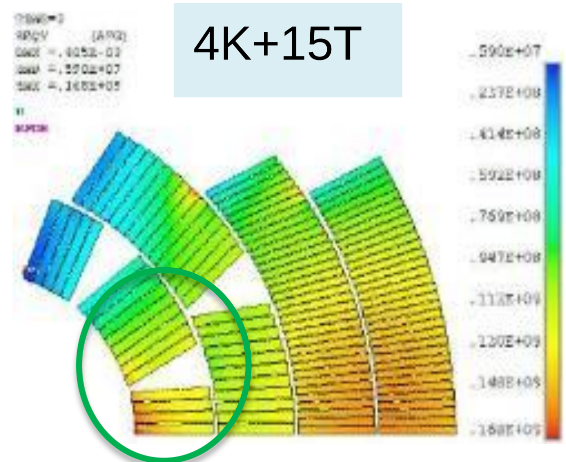
S_{eqv}=133 MPa
Limit 150 MPa

4K



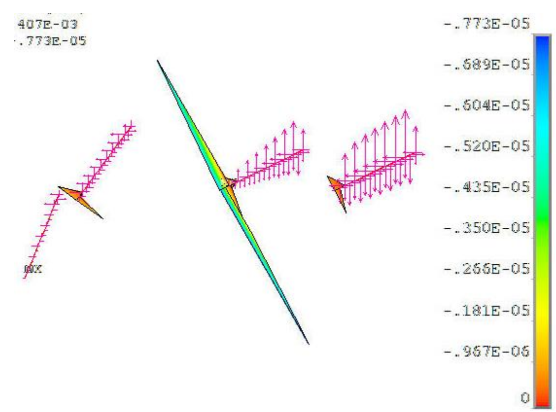
S_{eqv}=176 Mpa
Limit 200 MPa

4K+15T



S_{eqv}=168 Mpa
Limit 200 MPa

- **Magnet *design limit* is determined by the coil maximum stress and the pole turn separation from poles**
  - **independent FNAL and FEAC analysis**



Courtesy I. Novitski

Mechanical limit for this design is 15 T!

TAC recommendations

TAC members:

- Andy Lankford (UCI, Chair), Giorgio Apollinari (Fermilab), Joe Minervini (MIT), Mark Palmer (BNL), Davide Tommasini (CERN), Akira Yamamoto (KEK & CERN)

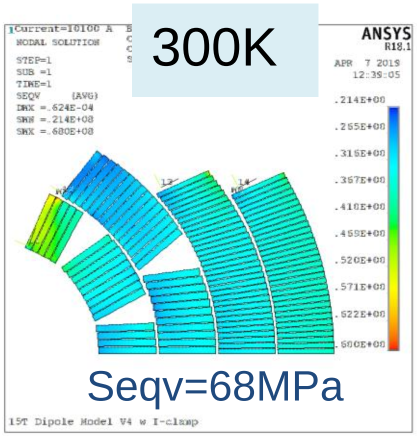
Report of the Technical Advisory Committee for the U.S. Magnet Development Program

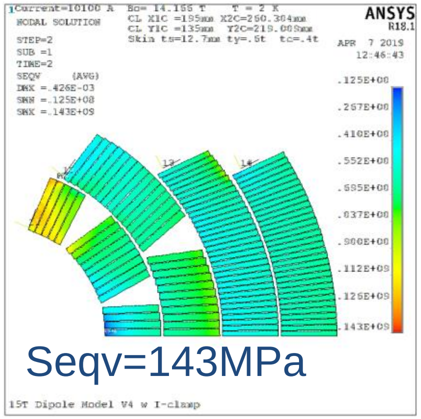
February 22, 2019

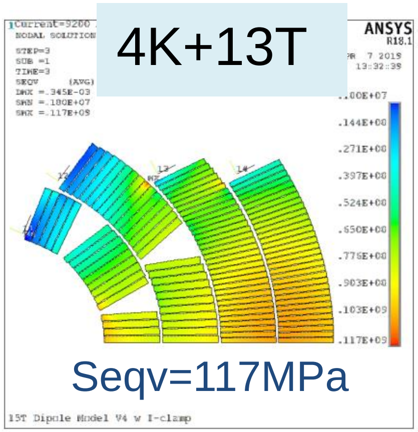
Recommendations:

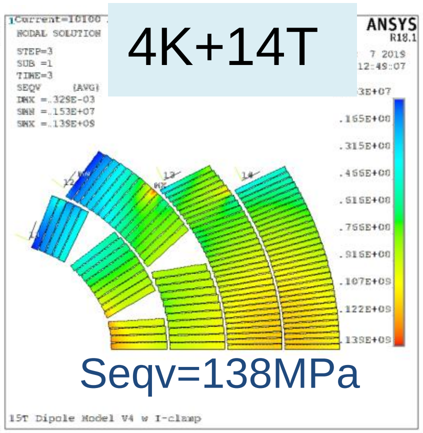
- Maintain as the priority for the cos-theta approach using the clamped mechanical structural design to realize a field of about 14 T, with special attention to mechanical stress management and control.
- Continue with demonstration of 15 T cos-theta performance only after the review of the 14 T magnet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

Target coil prestress for the first assembly



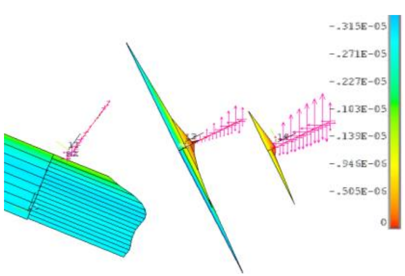




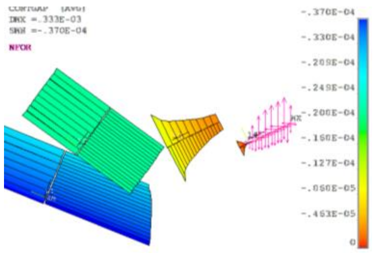


Conservative pre-stress:

- **S_{max} at all steps <150 MPa**



Inner Pole at 13T
Gap=0.003mm



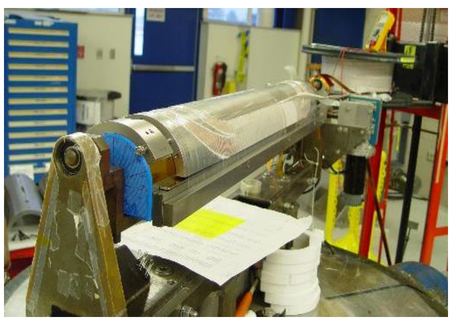
Inner Pole at 14T
Gap=0.037mm

Courtesy I. Novitski

U.S. MAGNET DEVELOPMENT PROGRAM

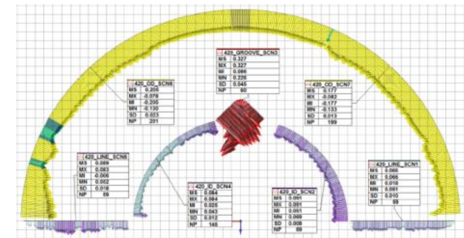
Coil fabrication, measurements and instrumentation

Coil winding and curing using ceramic binder



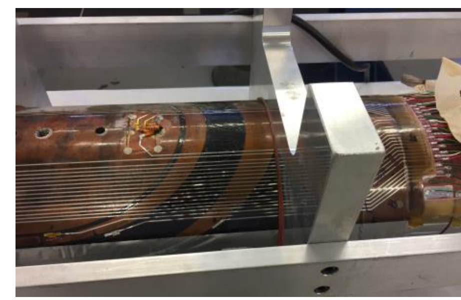
Coil reaction

Coil lead splicing and epoxy impregnation



Coil size control, accuracy ~10 microns

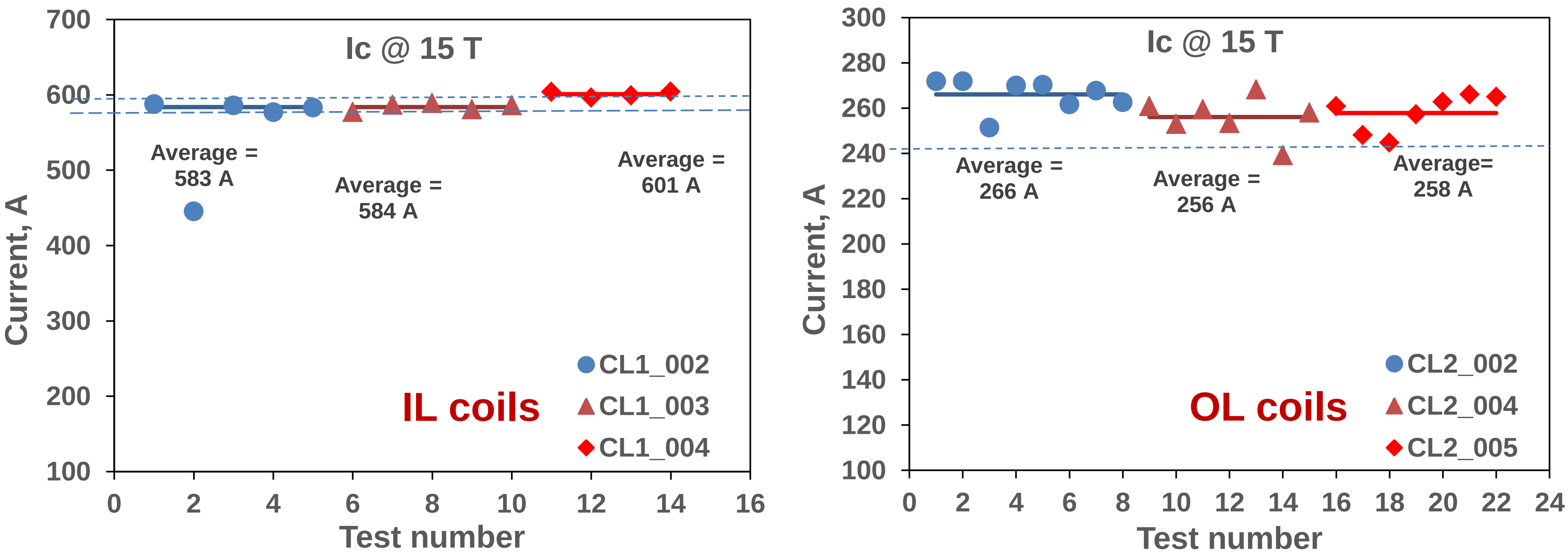
Coil instrumentation



- **Coil fabrication, measurement and instrumentation time ~3 months**
  - **IL spare coil was wound, reacted and impregnated**
  - **OL spare coil – the cable and coil parts are available**

Witness sample data

Courtesy E. Barzi and D. Turrioni



- HT cycle optimized for the 28-starnd and 40-strand cable
- 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

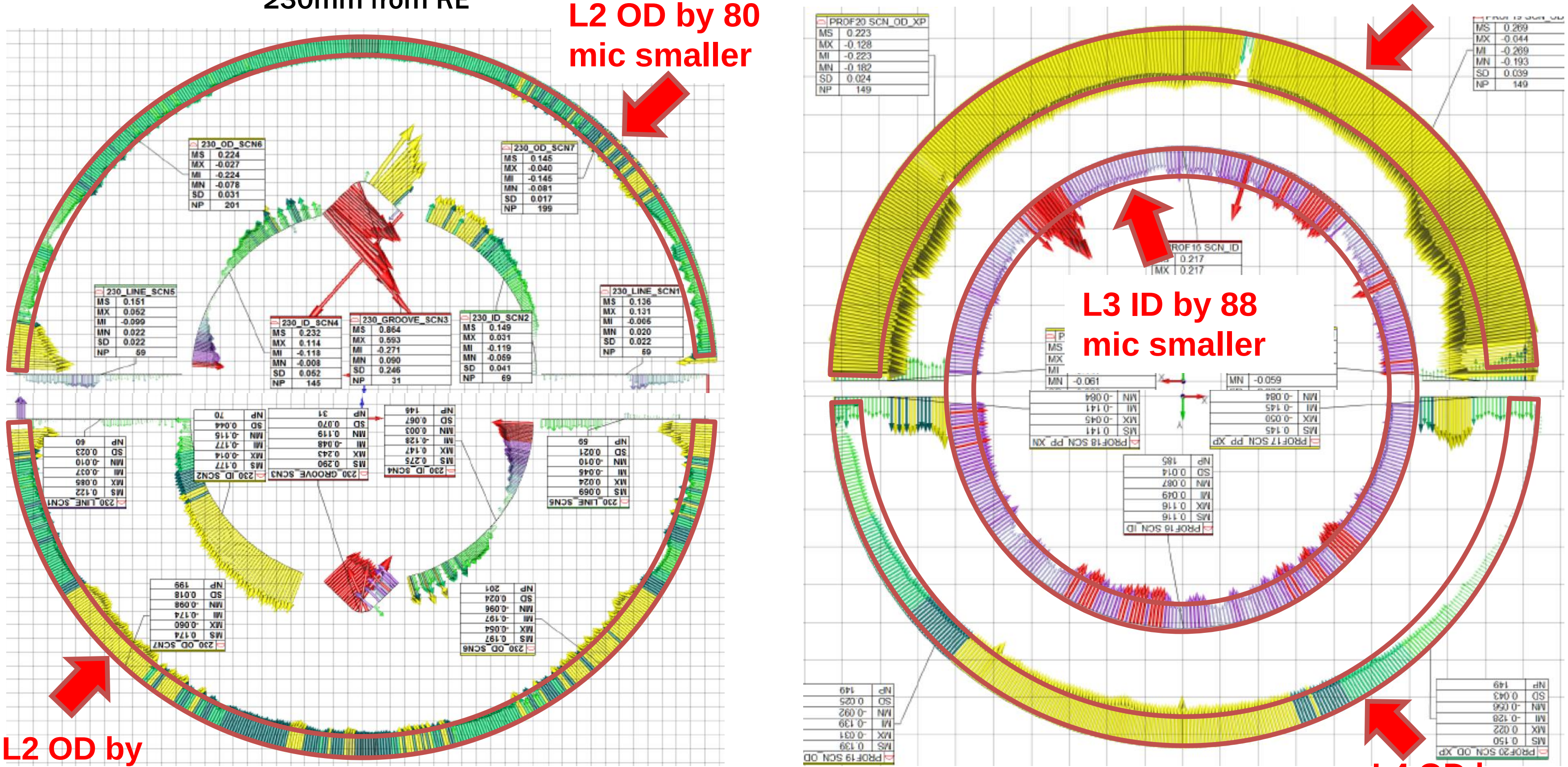
Coil interfaces analysis and optimization

HFM-CL1-003
230mm from RE

L2 OD by 80 mic smaller

HFM-CL2-005
218mm from RE

L4 OD by 187 mic smaller



L3 ID by 88 mic smaller

L2 OD by 96 mic smaller

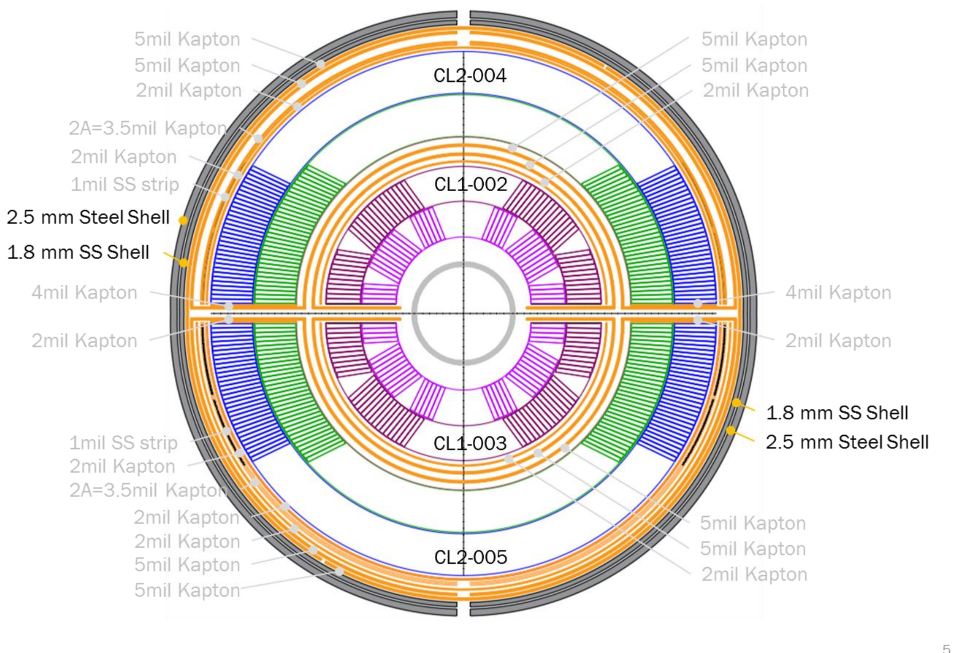
HFM-CL1-002
230mm from RE

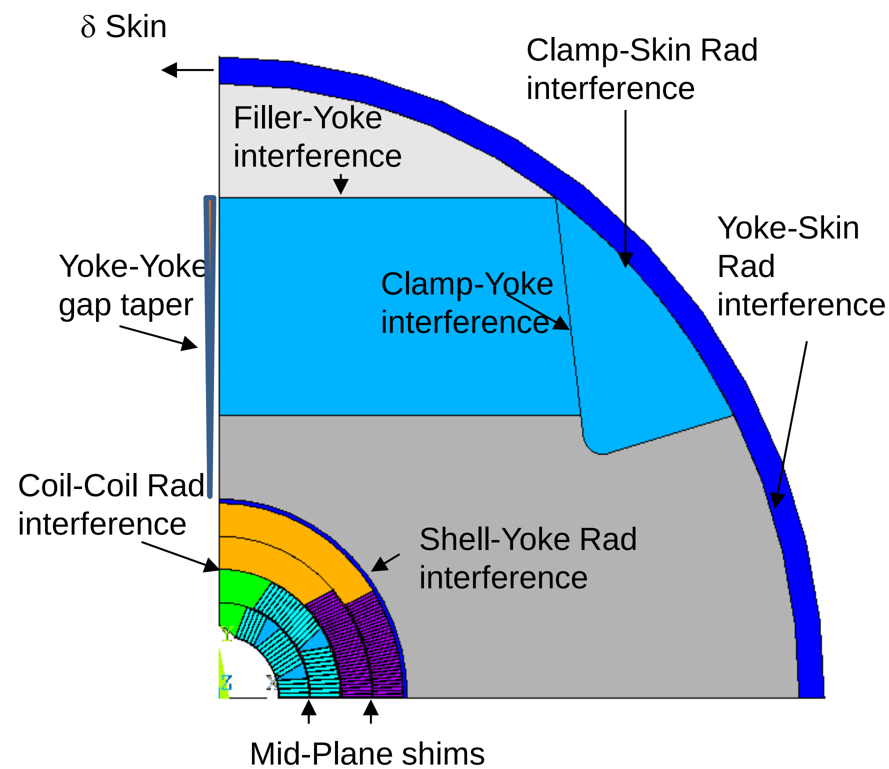
Coil SS 230

HFM-CL2-004
201mm from RE

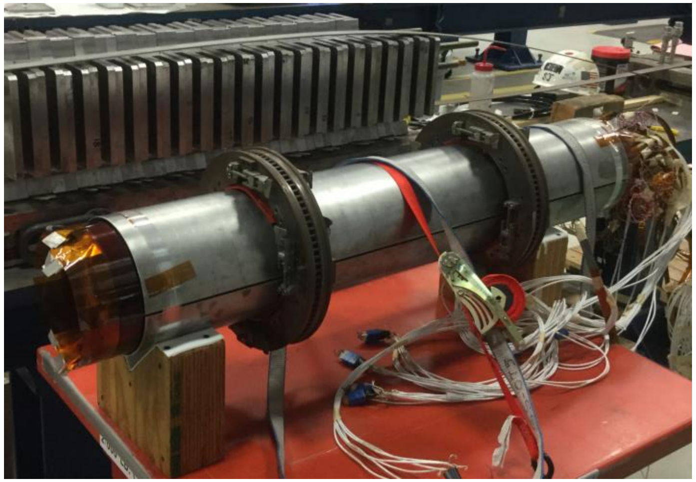
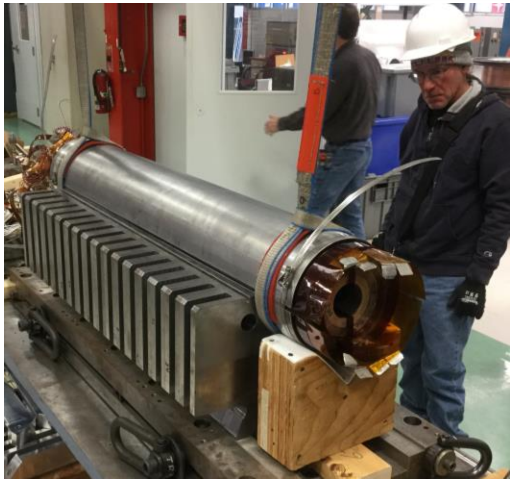
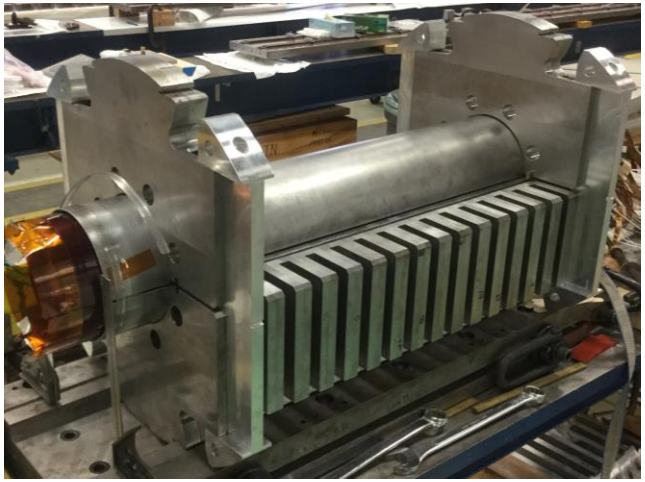
L4 OD by 80 mic smaller

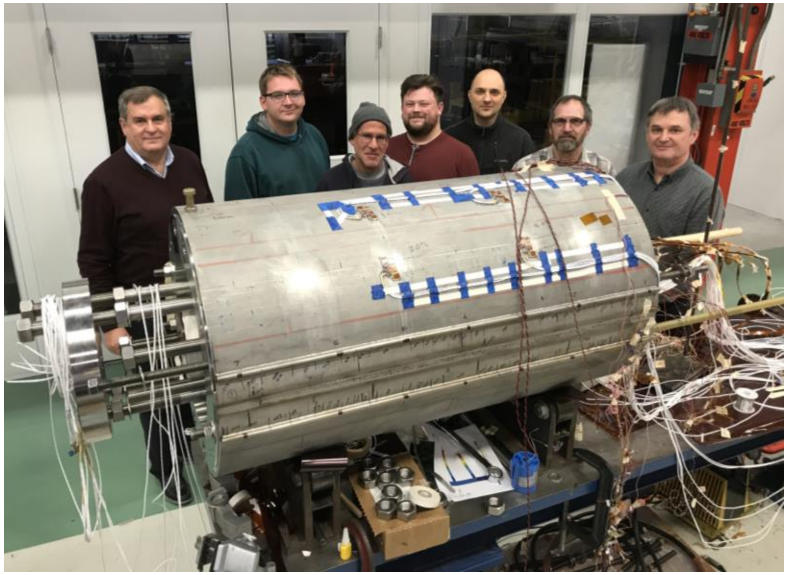
Coil assembly and preload scheme



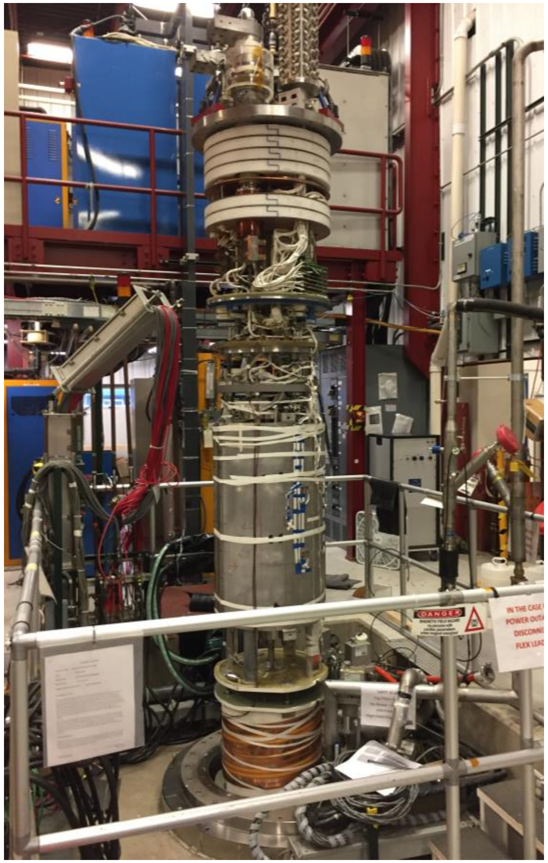


Coil assembly, yoking and skinning

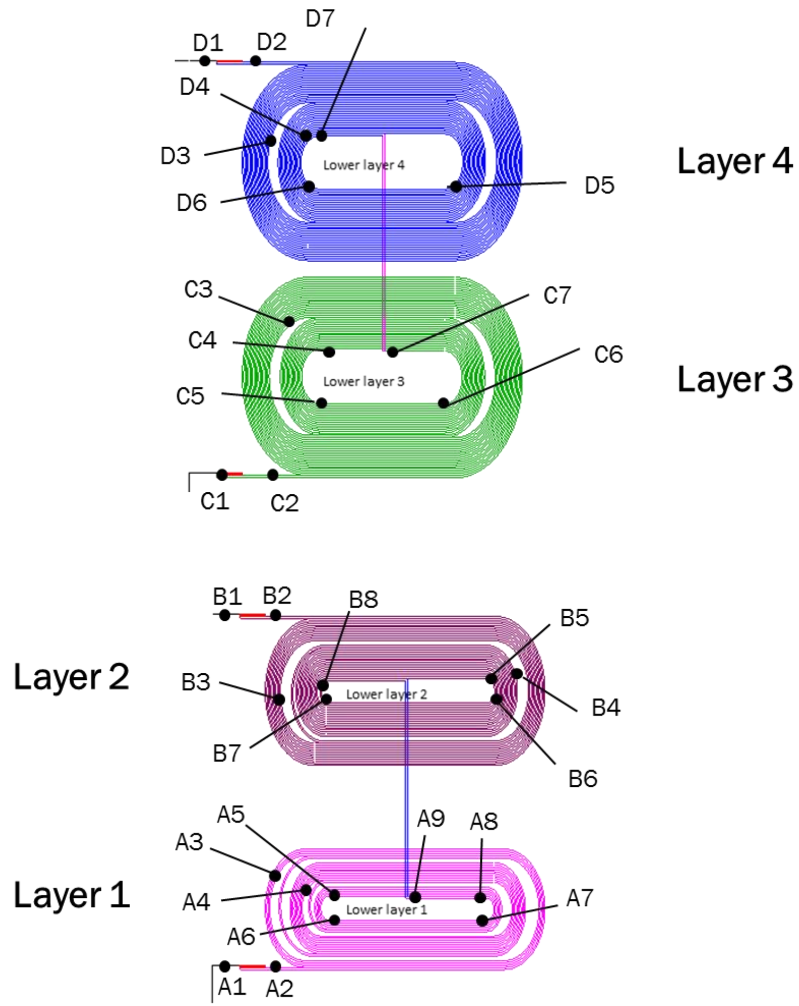


Magnet transportation and test preparation



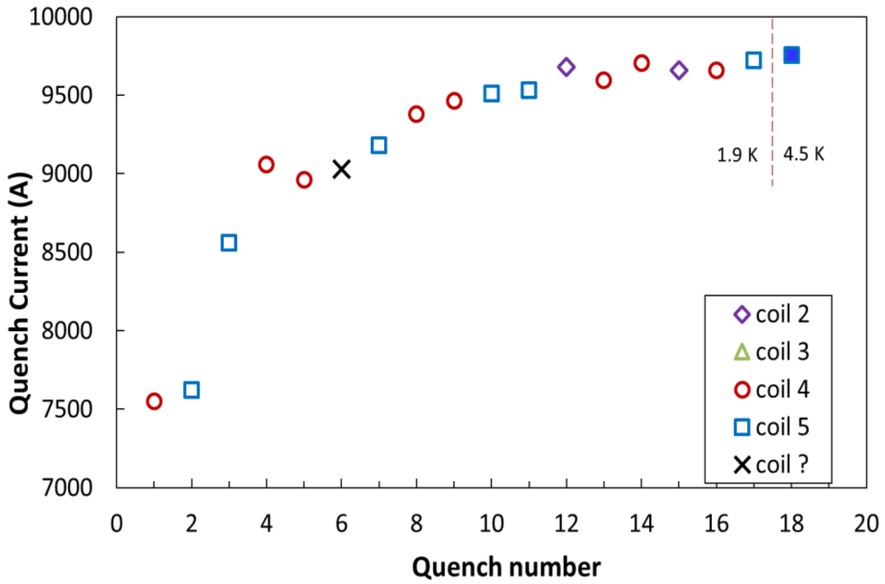
Instrumentation

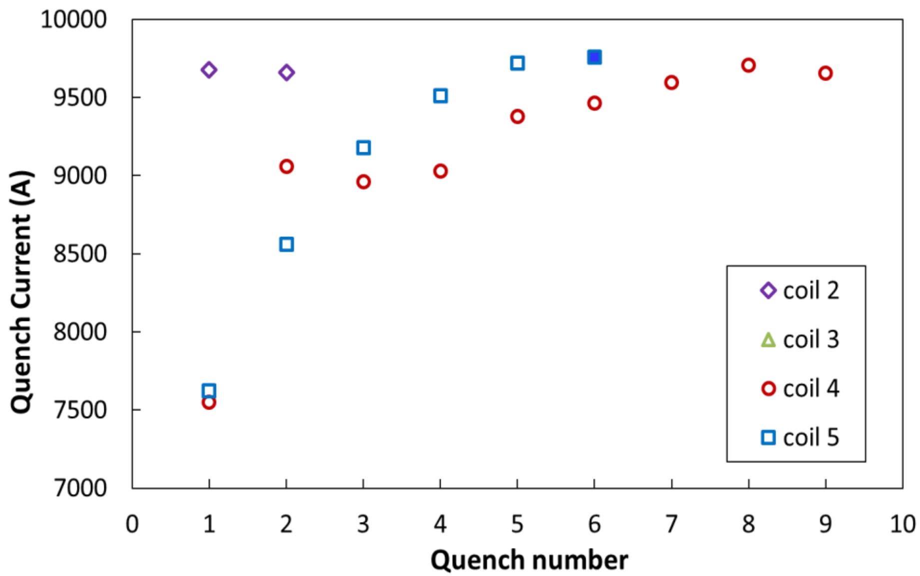
- Voltage taps on all coil layers
  - one dead and one inactive (both by-passed by using longer segments)
- Strain Gauges
  - skin gauges: OK
  - bullet gauges: two (on different bullets) dead
  - pole gauges: layer 3 and 4 all gone or inactive, layer 1 are OK
  - coil gauges: one switched off (problems during ramp up), another off for technical reasons (could be recovered if needed)
- Quench antennas
  - only sensitive to quenches in Layer 1 (didn't happen yet)
- Acoustic sensors
  - not useful data (very noisy signal)



Magnet training

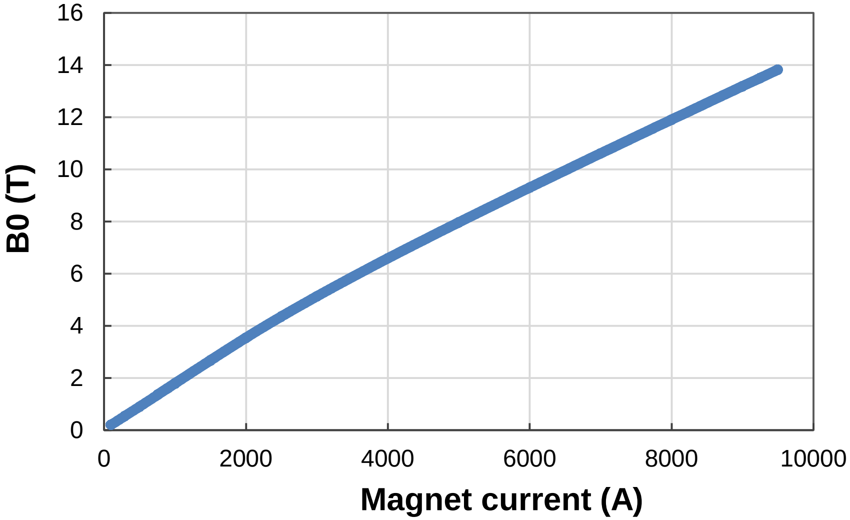
Courtesy S. Stoynev

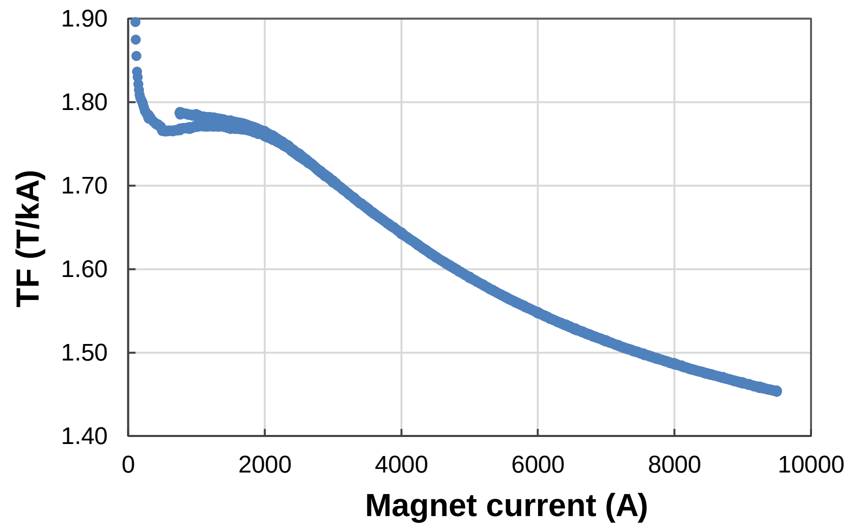


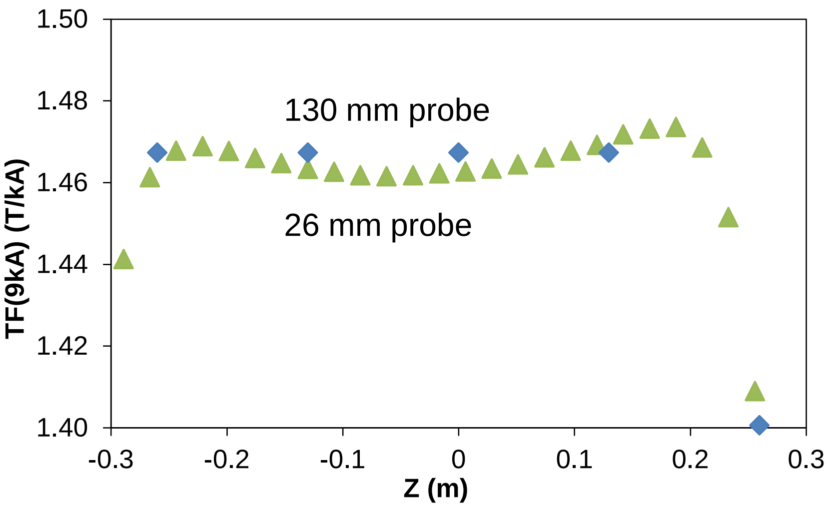


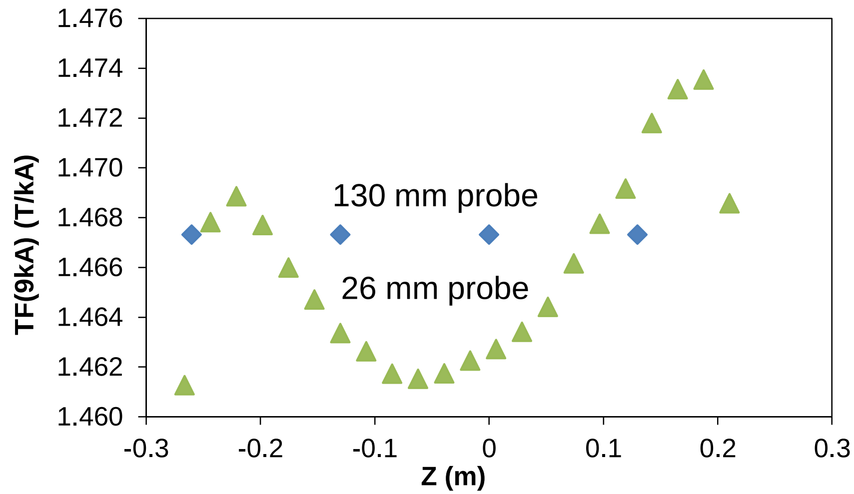
- Only 2 quenches in IL coil 2
- No quenches in coil 3
- OL quenches are equally distributed between coil 4 and coil 5
- Quenches are in both layers 3 and 4 mostly in the LE
- Highest achieved quench current 9758 A at 4.5 K
- Magnet quenching was stopped to avoid coil damage

Magnetic field measurements



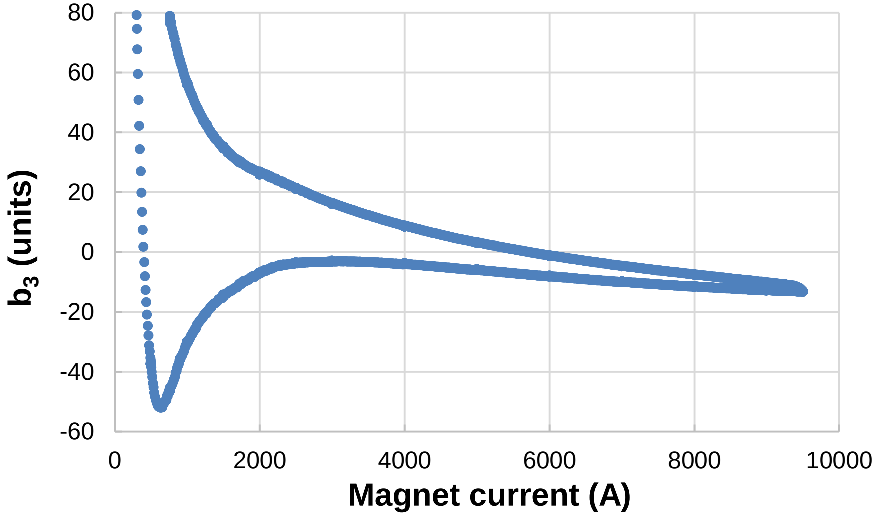


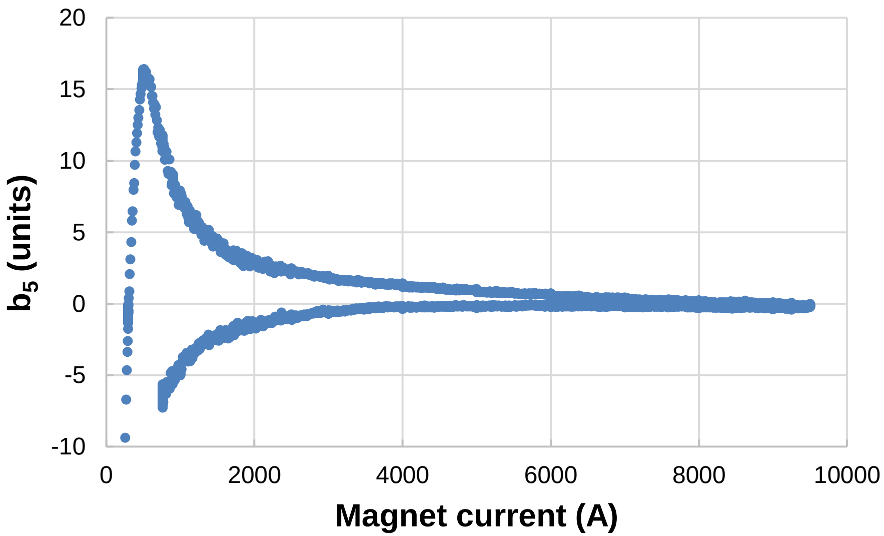




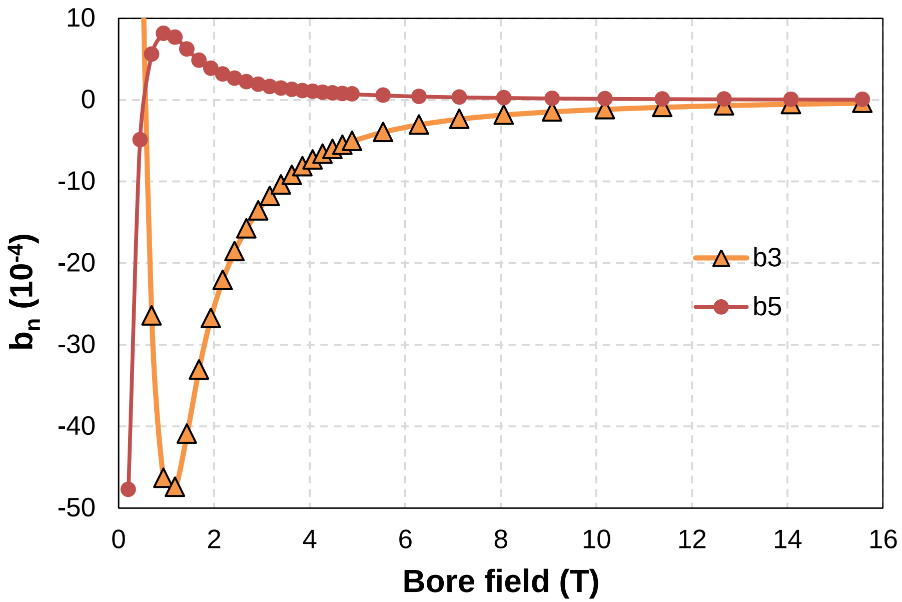
Courtesy J. DiMarco and T. Strauss

Low-order field harmonics



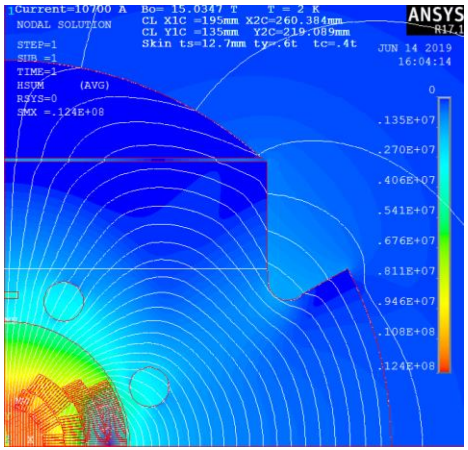


V.V. Kashikhin and A.V. Zlobin, NAPAC2016

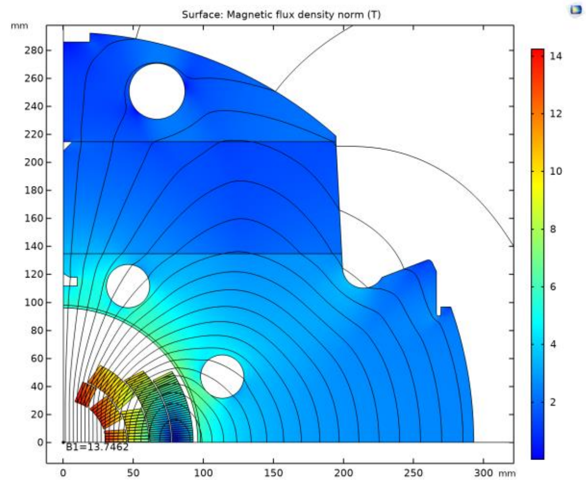


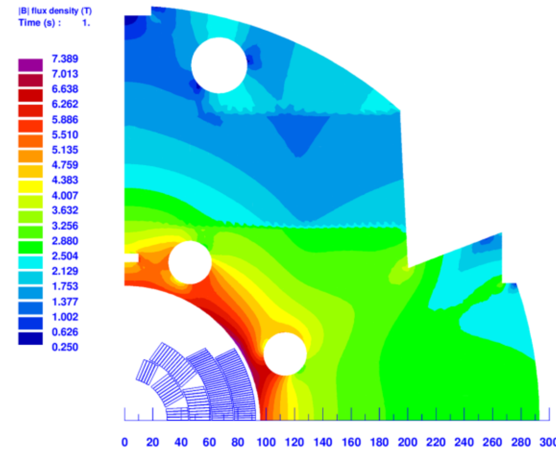
- **Good correlation of measurements with theoretical predictions**

TF analysis



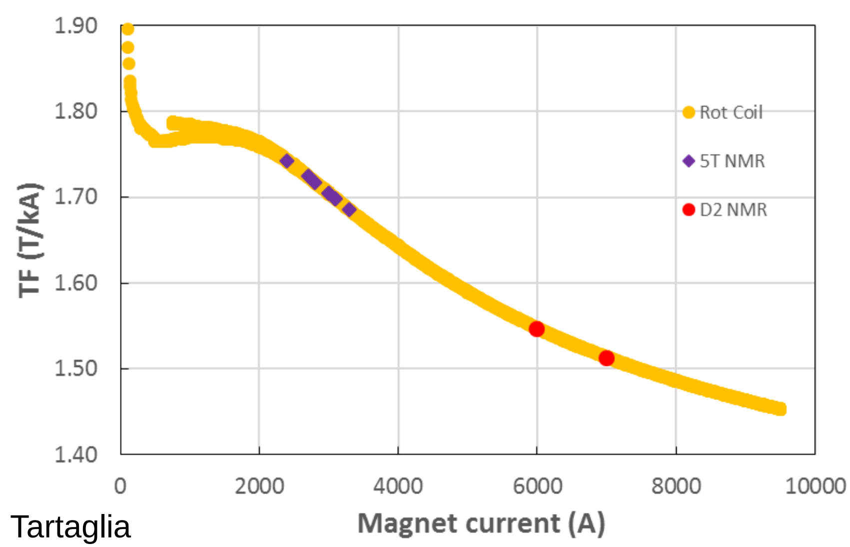
Courtesy I. Novitski





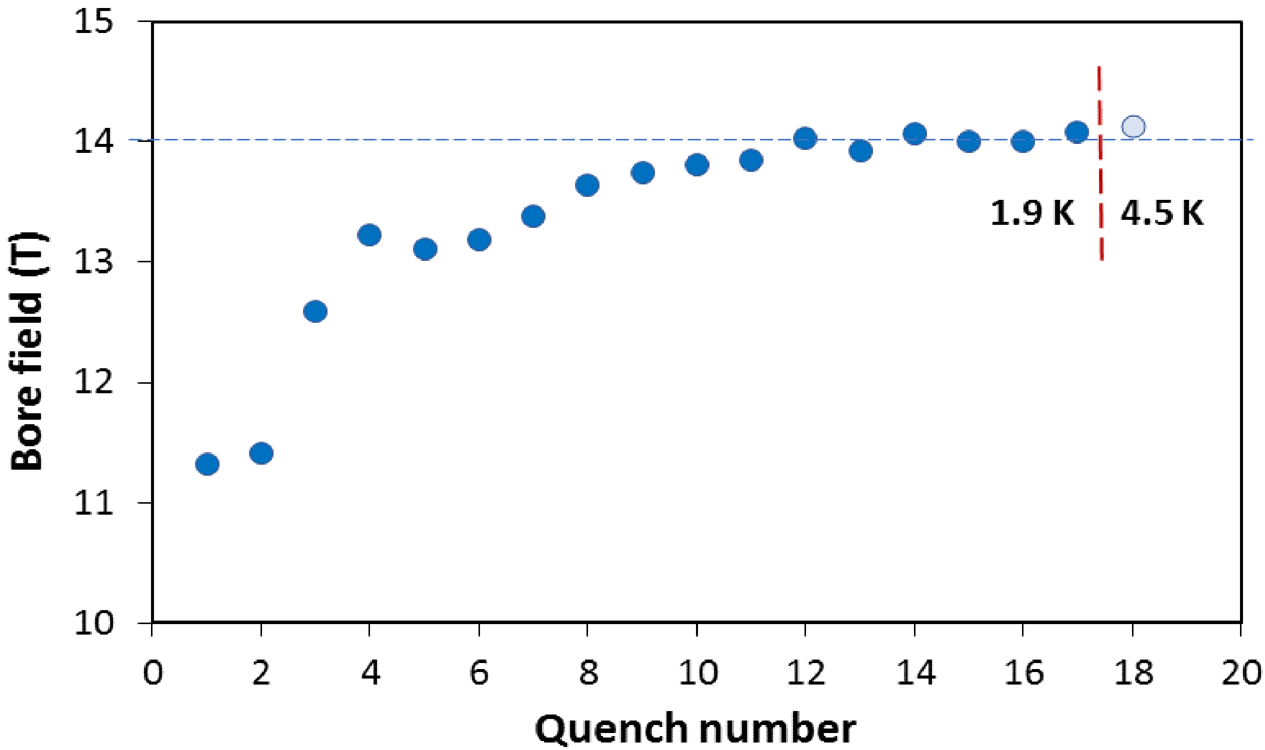
Courtesy V.V. Kashikhin

- **2D analysis has been updated based on the actual yoke material properties and the final magnet geometry**
- **3D calculations are in progress**
- **Measurements have been verified with NMR probes (provided by GMW)**



Courtesy M. Tartaglia

Maximum field achieved



- First quenches above 11 T
- Maximum bore field at 4.5 K
  - measured **14.10±0.04 T**
  - calculated (COMSOL, V.V. Kashikhin) **14.112 T**

Summary and next steps

- 15 T cos-theta dipole is a challenging and important MDP milestone to understand limits of Nb_3Sn accelerator magnet technology
  - integrated international effort with EuroCirCol
- 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 at 1.9 and 4.5 K – *record field at 4.5 K for accelerator magnets*!
  - graded 4-layer coil design, innovative support structure and magnet fabricated procedure tested
- Next steps
  - Magnet re-assembly
    - coil pre-load increase to the level sufficient to achieve the goal of 15 T
    - improve instrumentation
  - Magnet second test in the fall of 2019