U.S. MAGNET DEVELOPMENT PROGRAM

MDPCT1 re-assembly and test preparation

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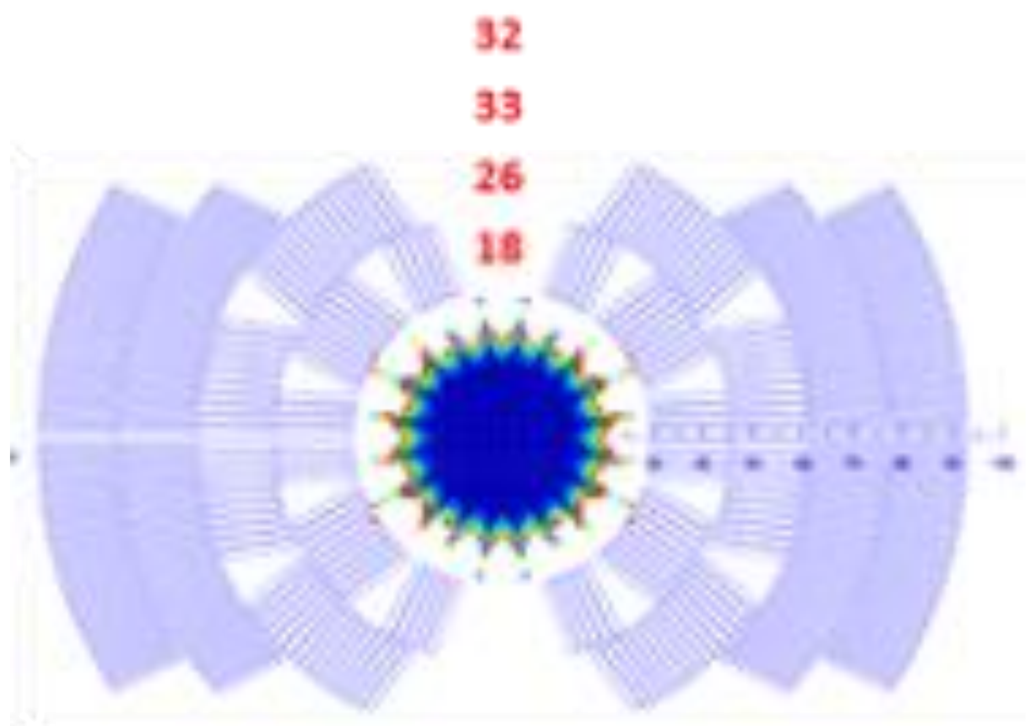
Outline

- Magnet design and program goal
- First test summary and open questions
- Magnet dis-assembly and findings
- Magnet re-assembly summary
- Magnet test plan

15 T Dipole Demonstrator (MDPCT1) Design

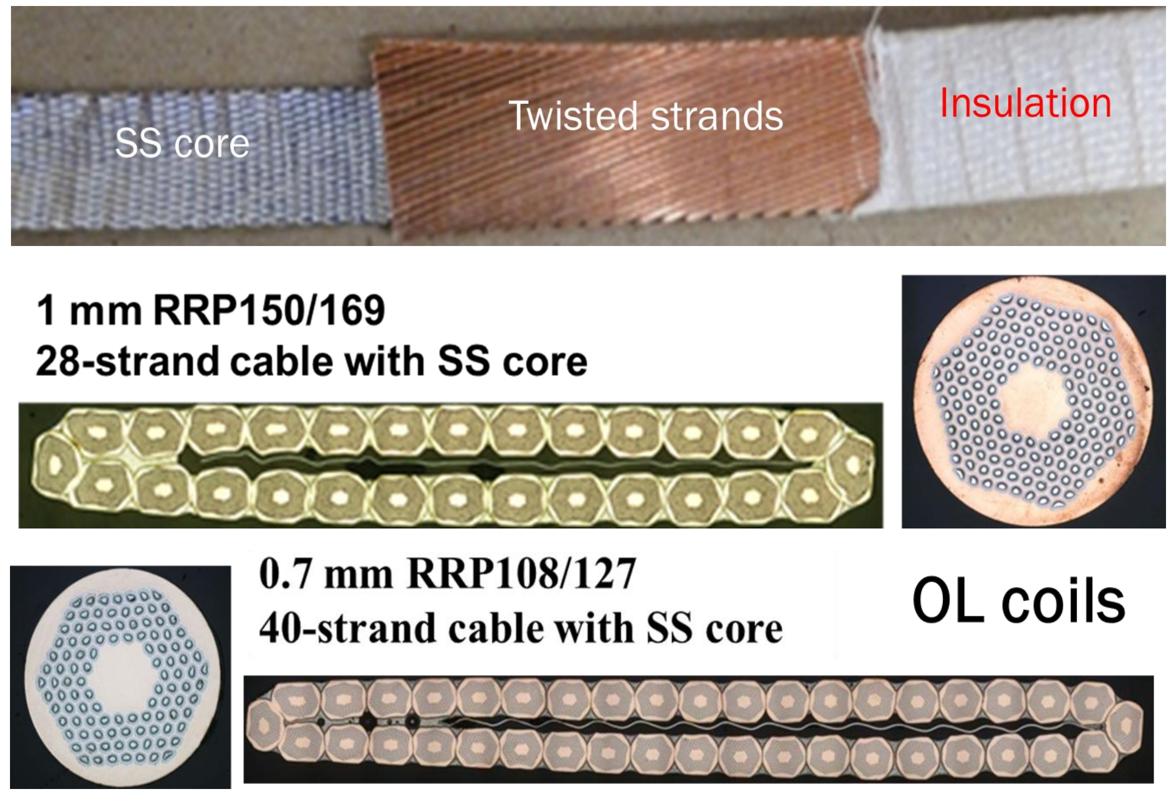
Optimized coil geometry:

- 60-mm aperture
- Min conductor volume
- 4-layer graded shell-type coil
- Optimization criteria:
  B_{max}, FQ, FL, QP



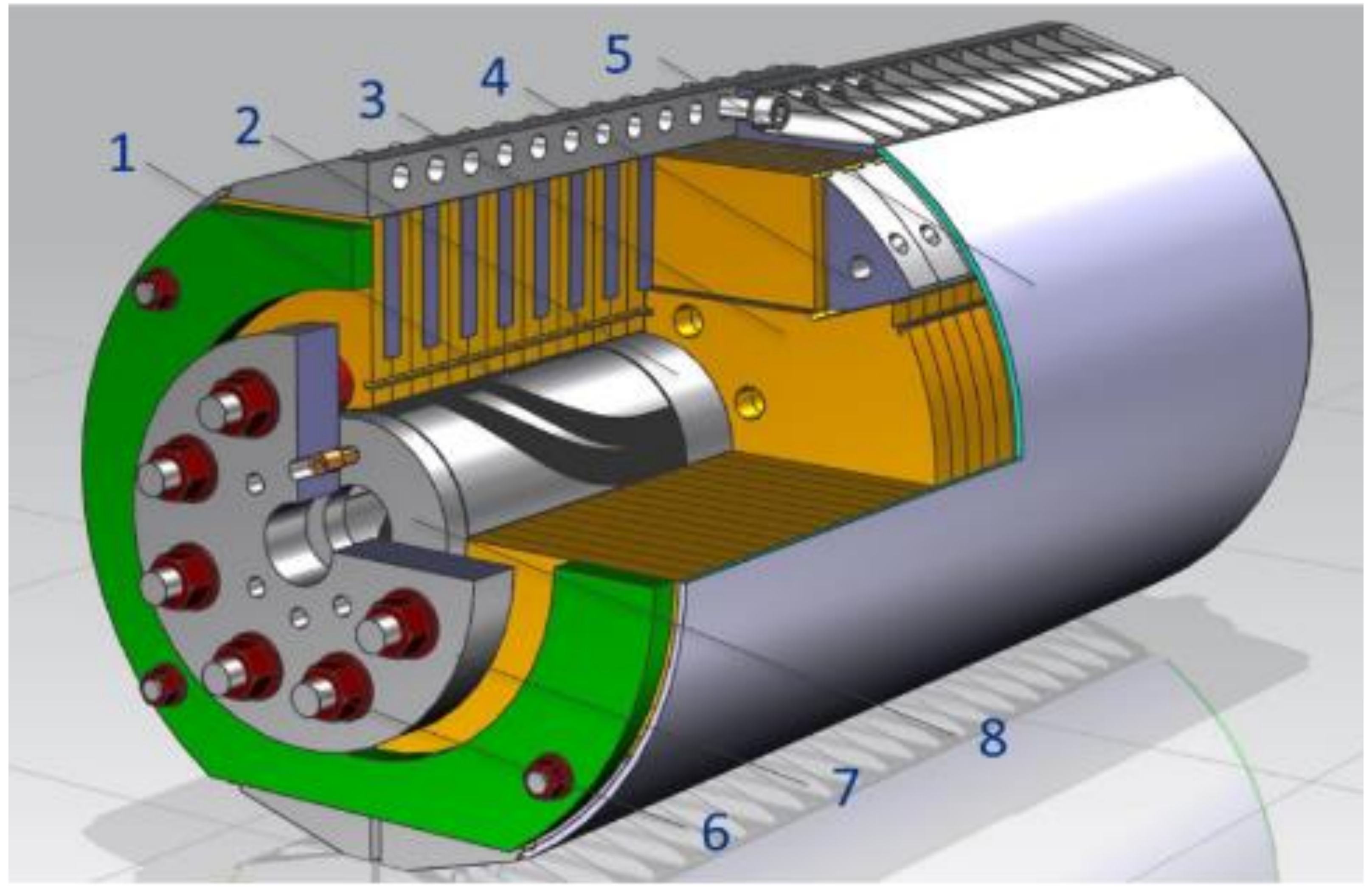
Cable:

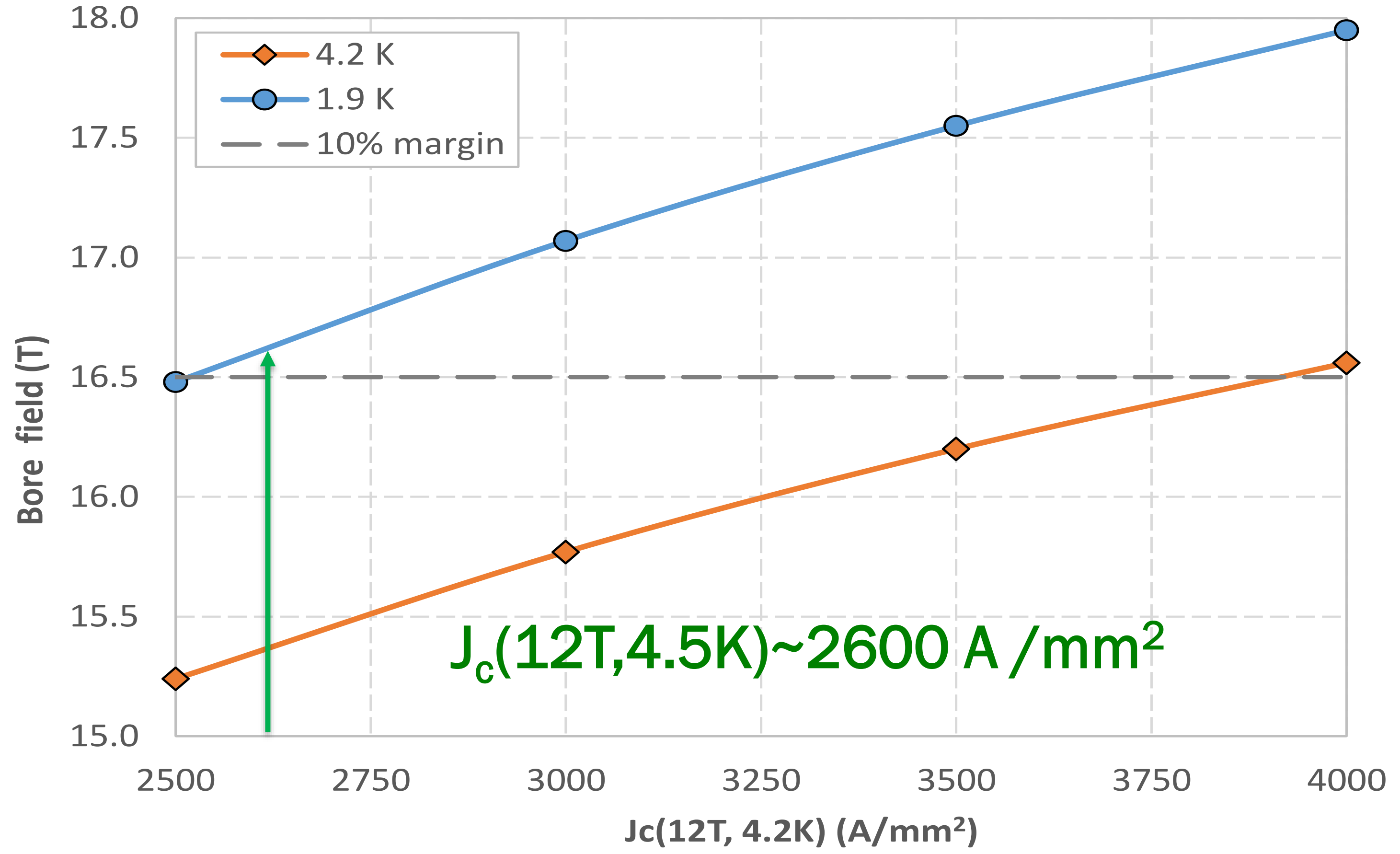
- L1-L2: 28 strands, 1 mm RRP150/169
- L3-L4: 40 strands, 0.7 mm RRP108/127
- 0.025 x 11 mm^2 stainless steel core



Innovative mechanical design:

- Vertically split iron yoke
- Aluminum I-clamps
- 12.5-mm thick stainless steel skin
- Cold mass OD=612mm
- Axial coil support with 50-mm thick end plates
- Optimization criteria:
  coil stress and deformation





Magnet *conductor limit*

- B_{ap}=15.3(16.7)T at 4.5(1.9) K

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Program Goals

- Demonstration of 15 T field level
- Study and optimization of
  - magnet quench performance and mechanics
    - training, degradation, memory, effect of coil pre-load
    - ramp rate sensitivity
    - operation margin
  - field quality
    - geometrical harmonics
    - coil magnetization
    - iron saturation
    - dynamic effects
  - quench protection

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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

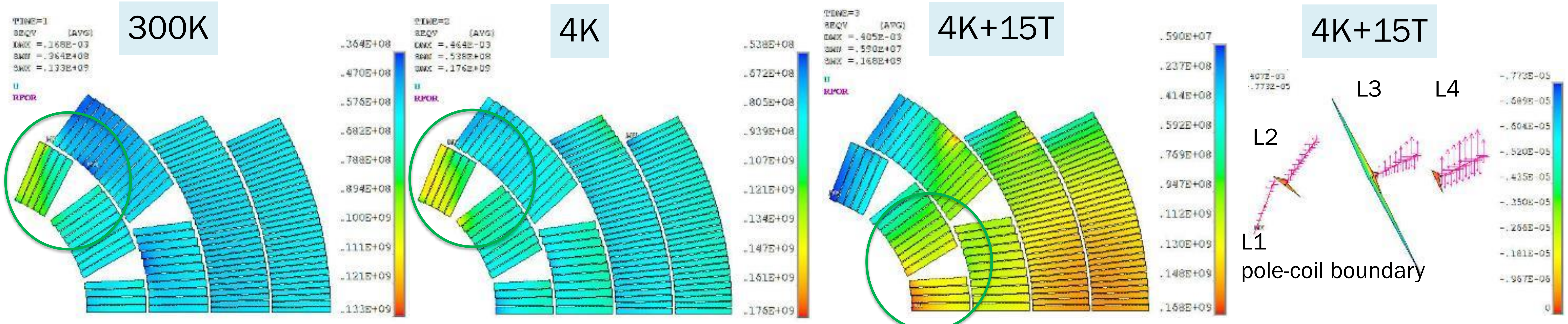
Comments:

- Regarding the cos-theta prototype, the TAC strongly supports and encourages a gradual approach to a target field ~ 14 T. Special care must be paid to mechanical stress management and quench protection, in order not to damage the magnet during prestress assembly and to enable extending the effort for realizing higher field. Due to this concern, the TAC believes that magnet testing should pause following the first test and before increasing prestress, in order to carefully evaluate the results of the first test and to deliberate on the best next steps.

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.
- Hold the international workshop recommended by the GARD review after first 14 T magnet tests and before increasing prestress to try to reach 15 T.
- 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.

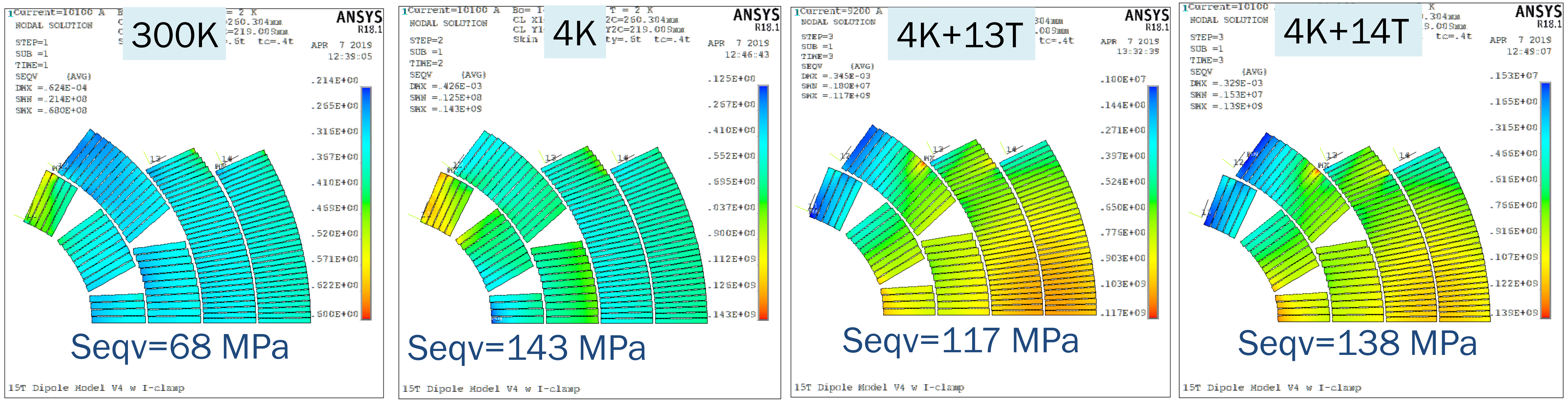
Mechanical limit and target pre-load for the 1st test



S_{eqv}=133 MPa | S_{eqv}=176 MPa | S_{eqv}=168 MPa | Pole Gap < 7 μm

Magnet *mechanical limit*
B_{ap}~15T

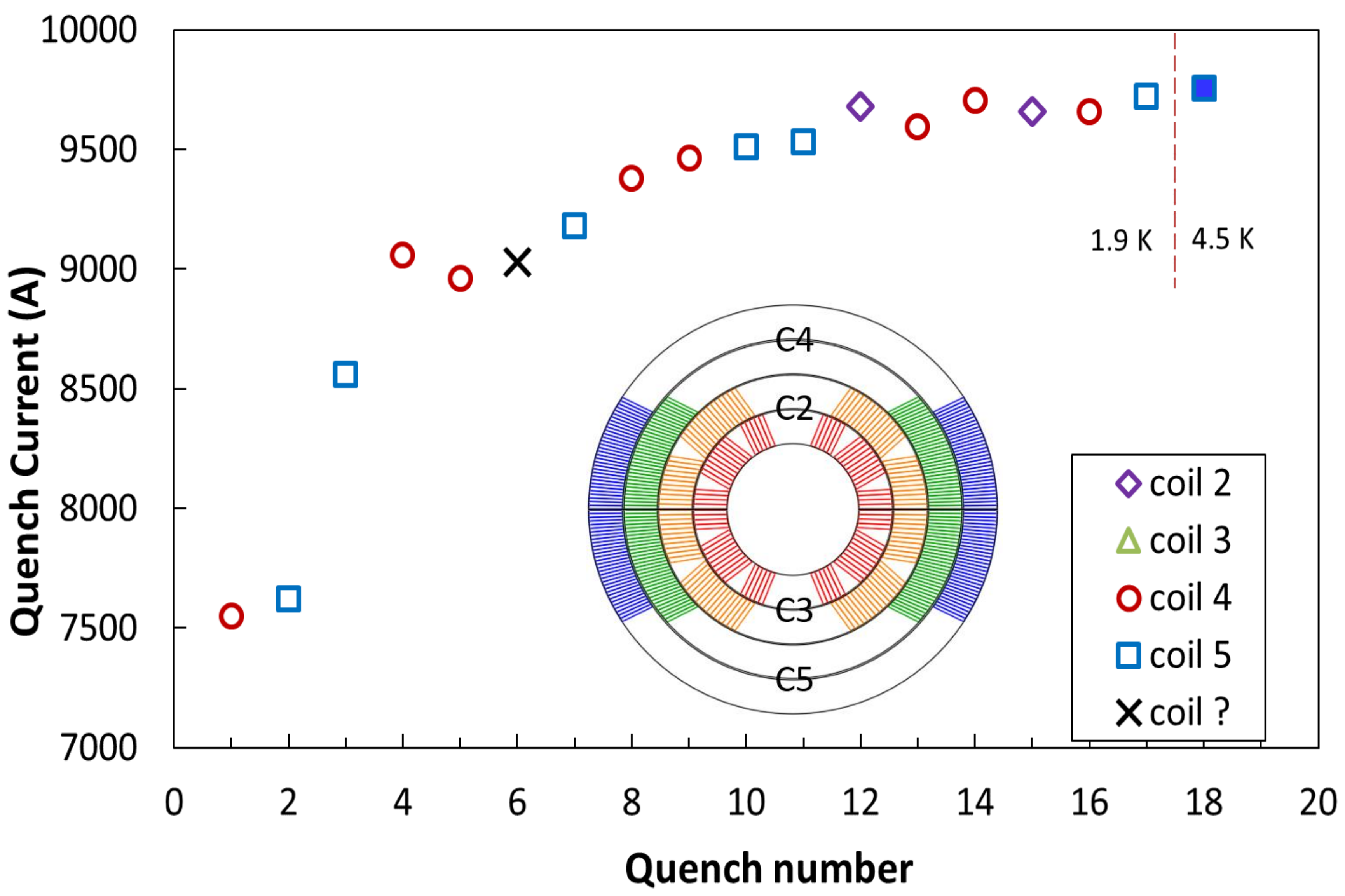
- it determined by the coil maximum stress and the coil turn separation from inner-layer poles
- S_{max} at all steps <180 MPa



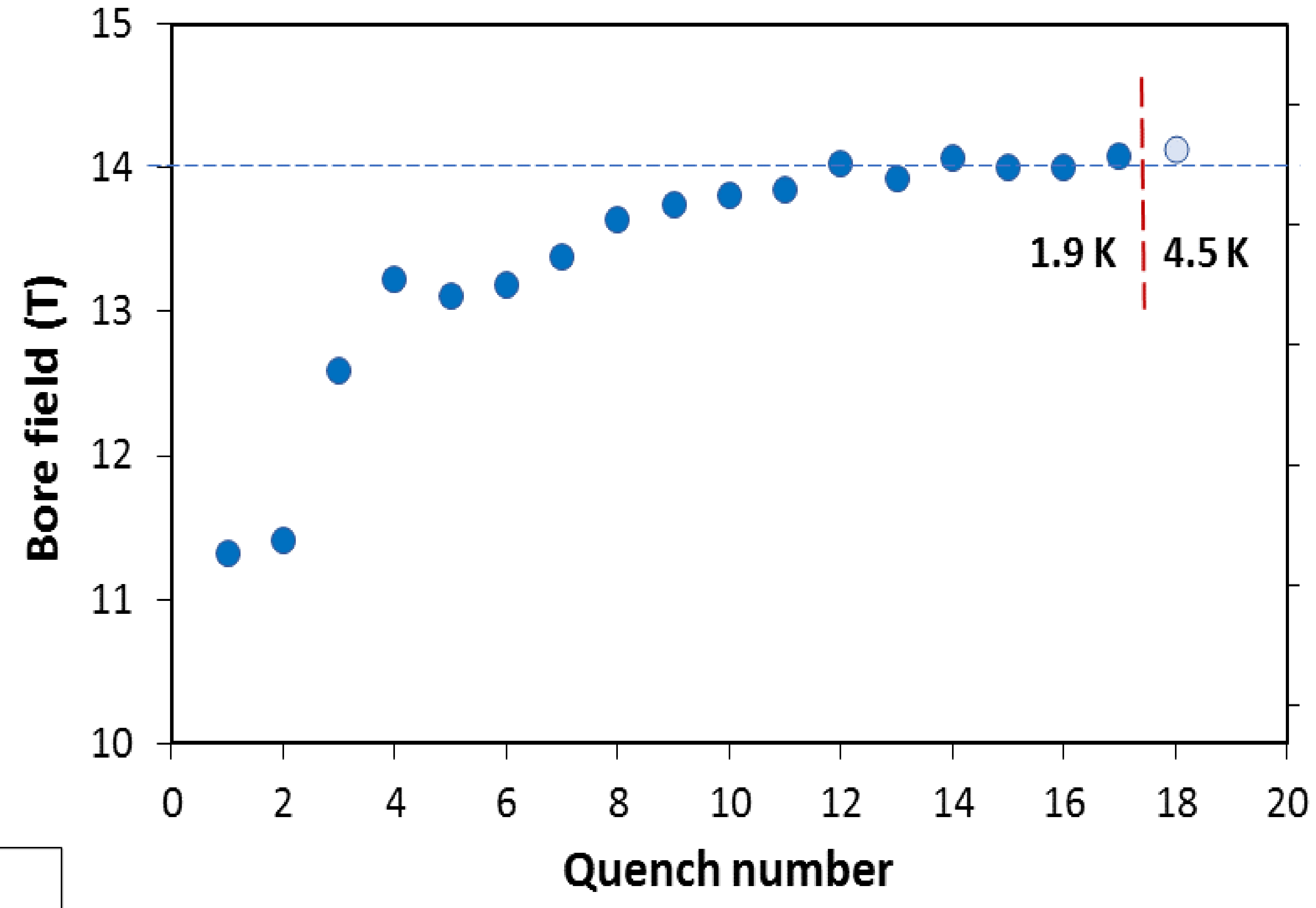
Conservative coil pre-stress for the 1st test:

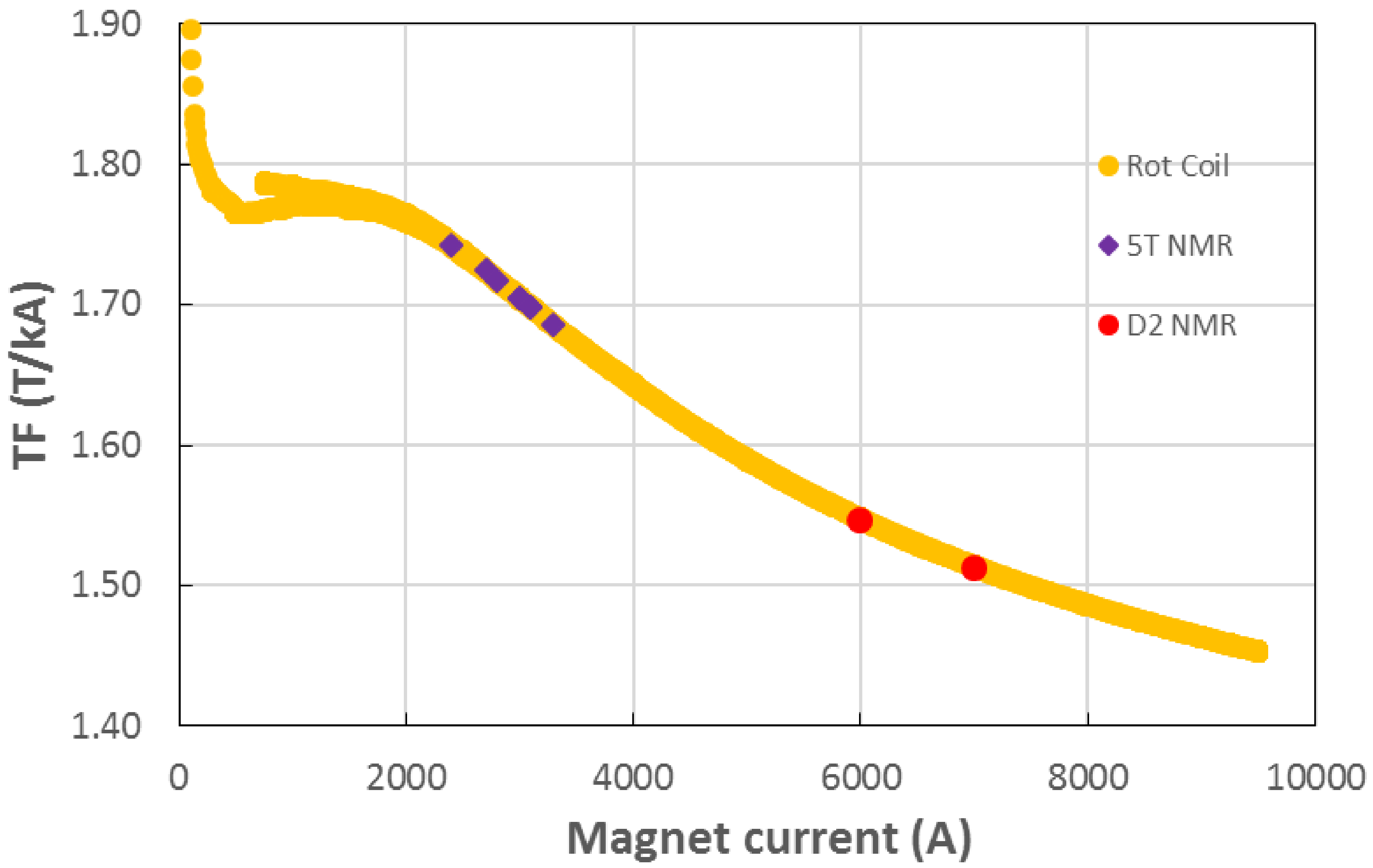
- S_{max} at all steps <150 MPa
- 13T - tension starts to develop between poles and coil turns
- 14T - max tension in poles < 30MPa

Magnet Training



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





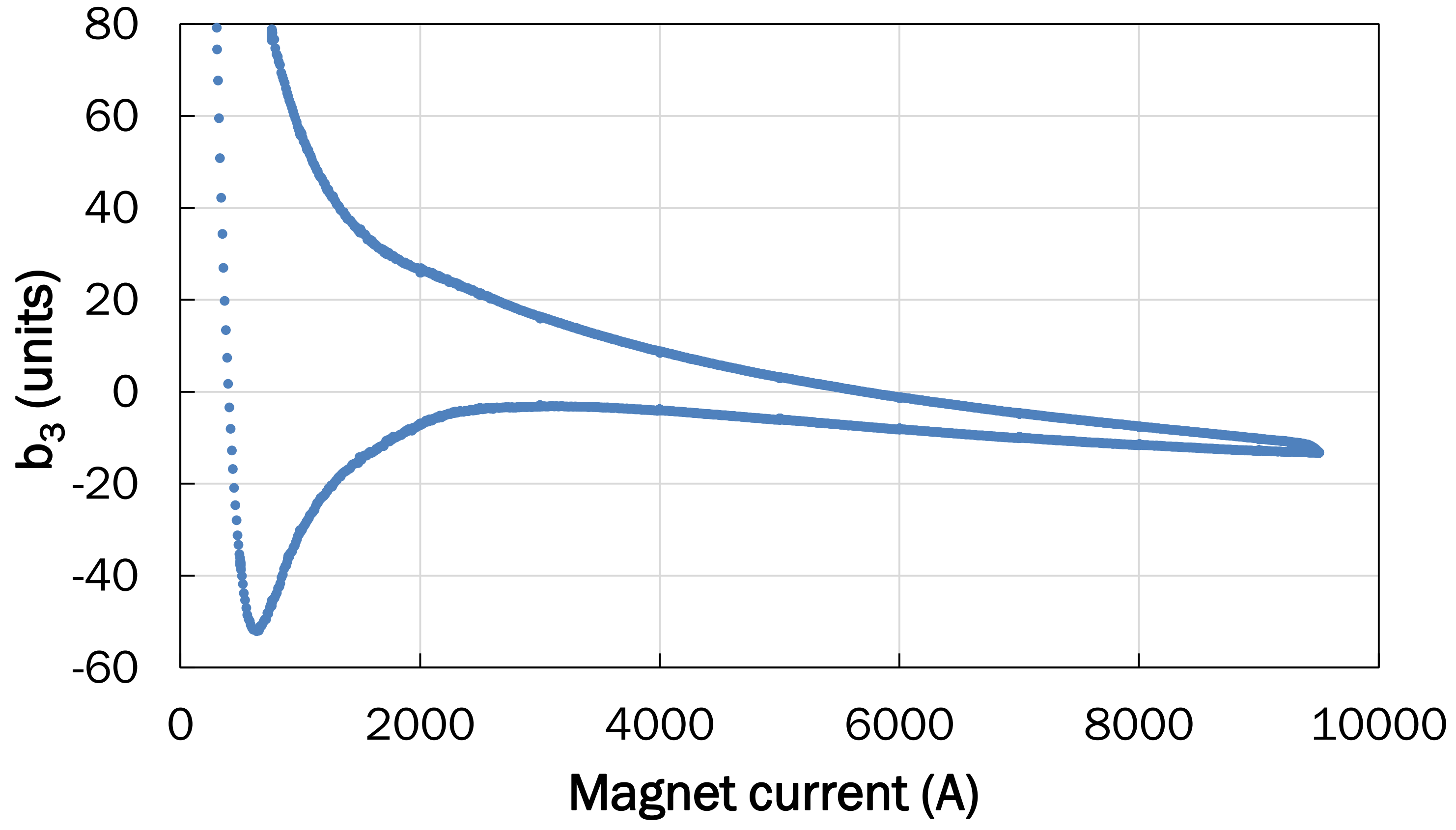
- Magnet was trained at 1.9 K
- Training plateau after 11 quenches
  - IL quenches: 2 in coil 2
  - OL quenches: 8 in coil 4, 7 in coil 5

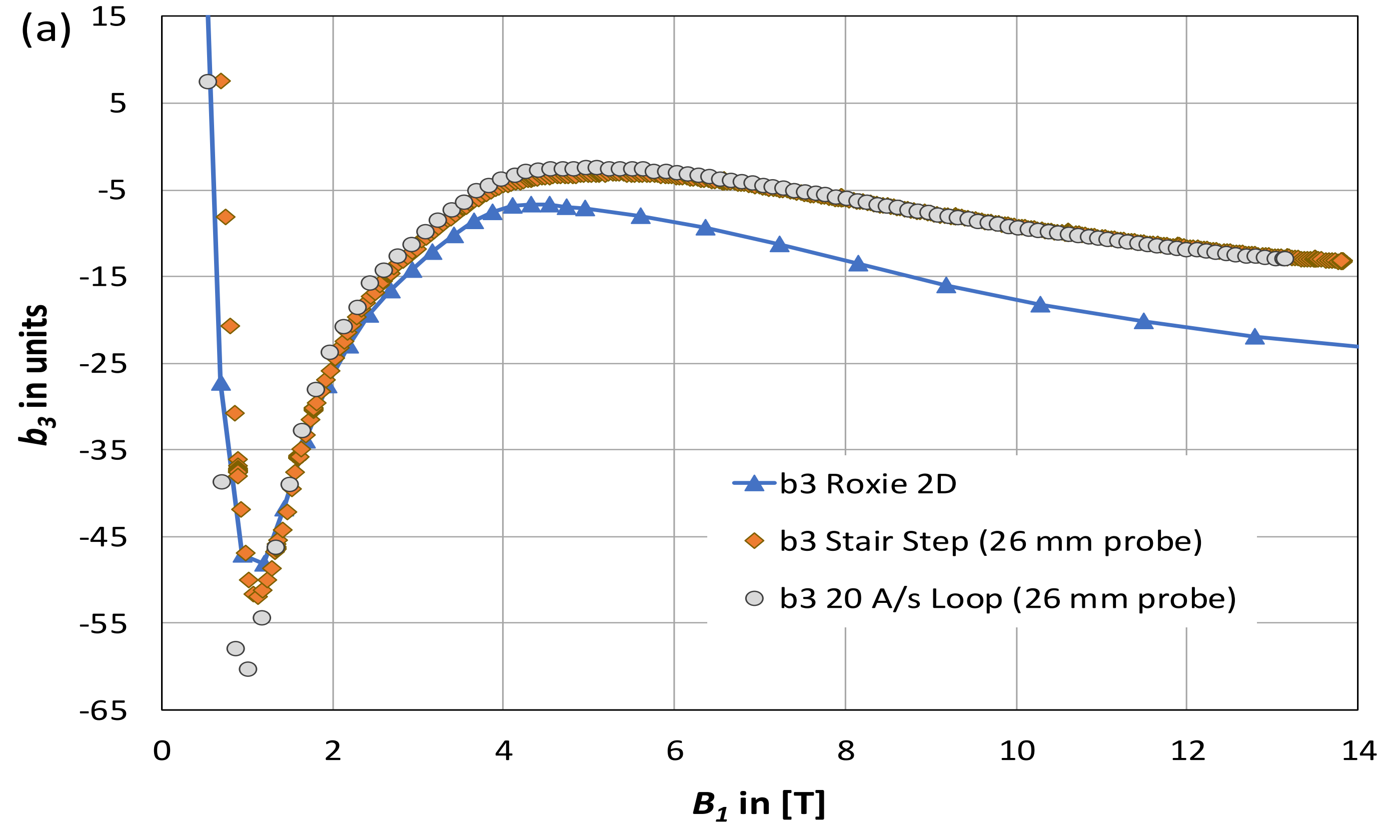
- First quenches above 11 T
- Last quench at 4.5 K :

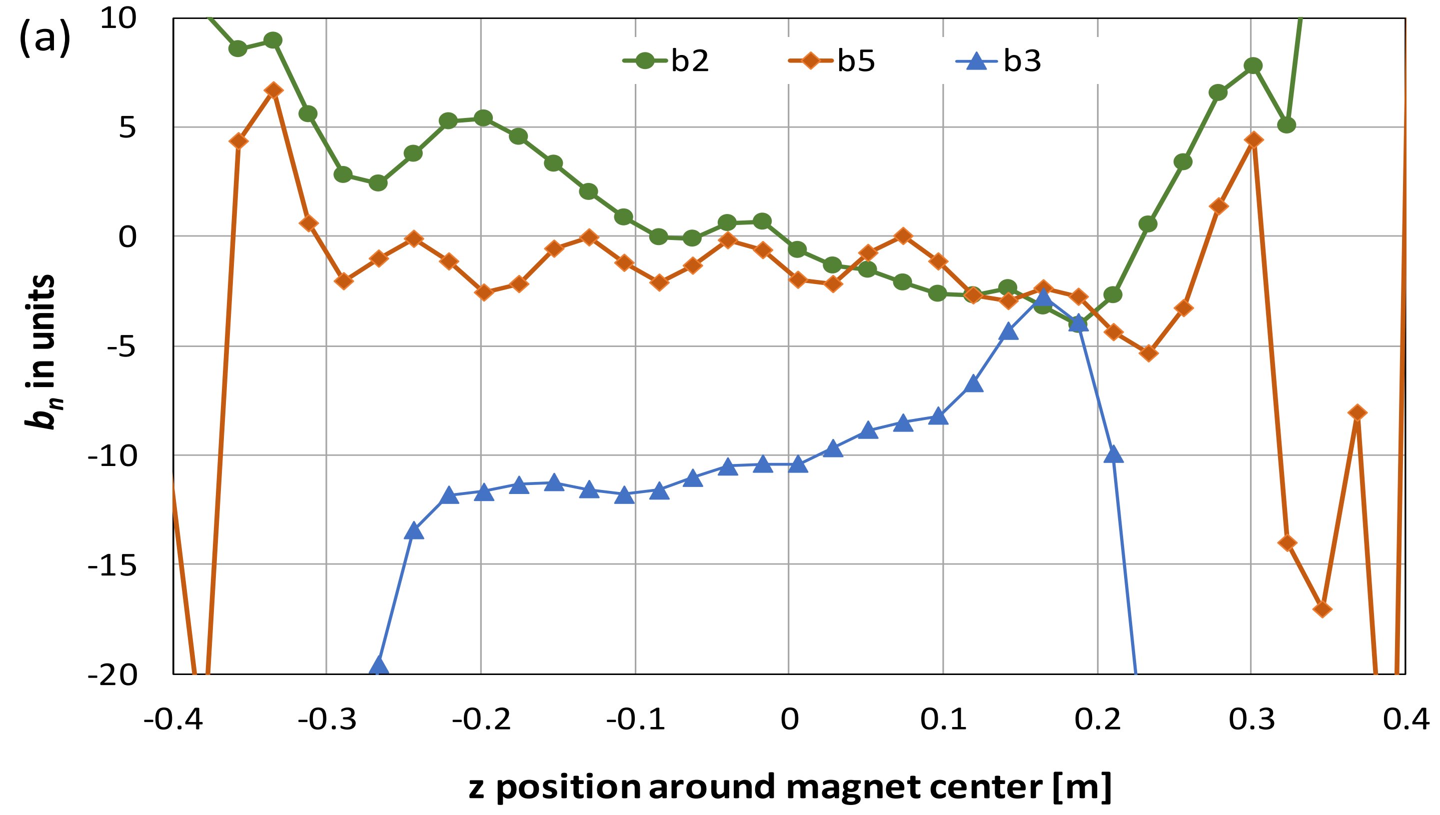
  B_{meas} = 14.13±0.02 T

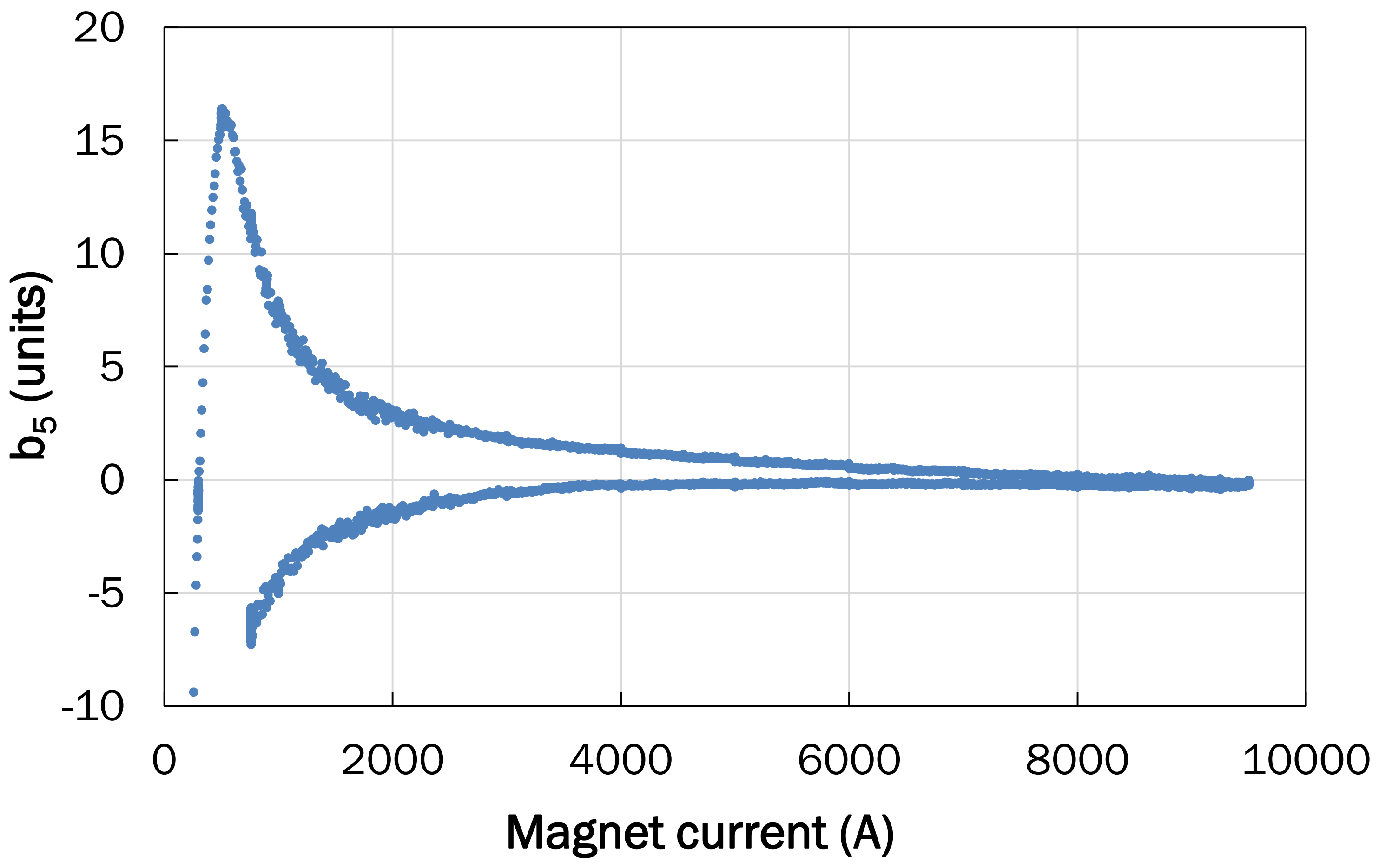
  B_{calc} = 14.112 T

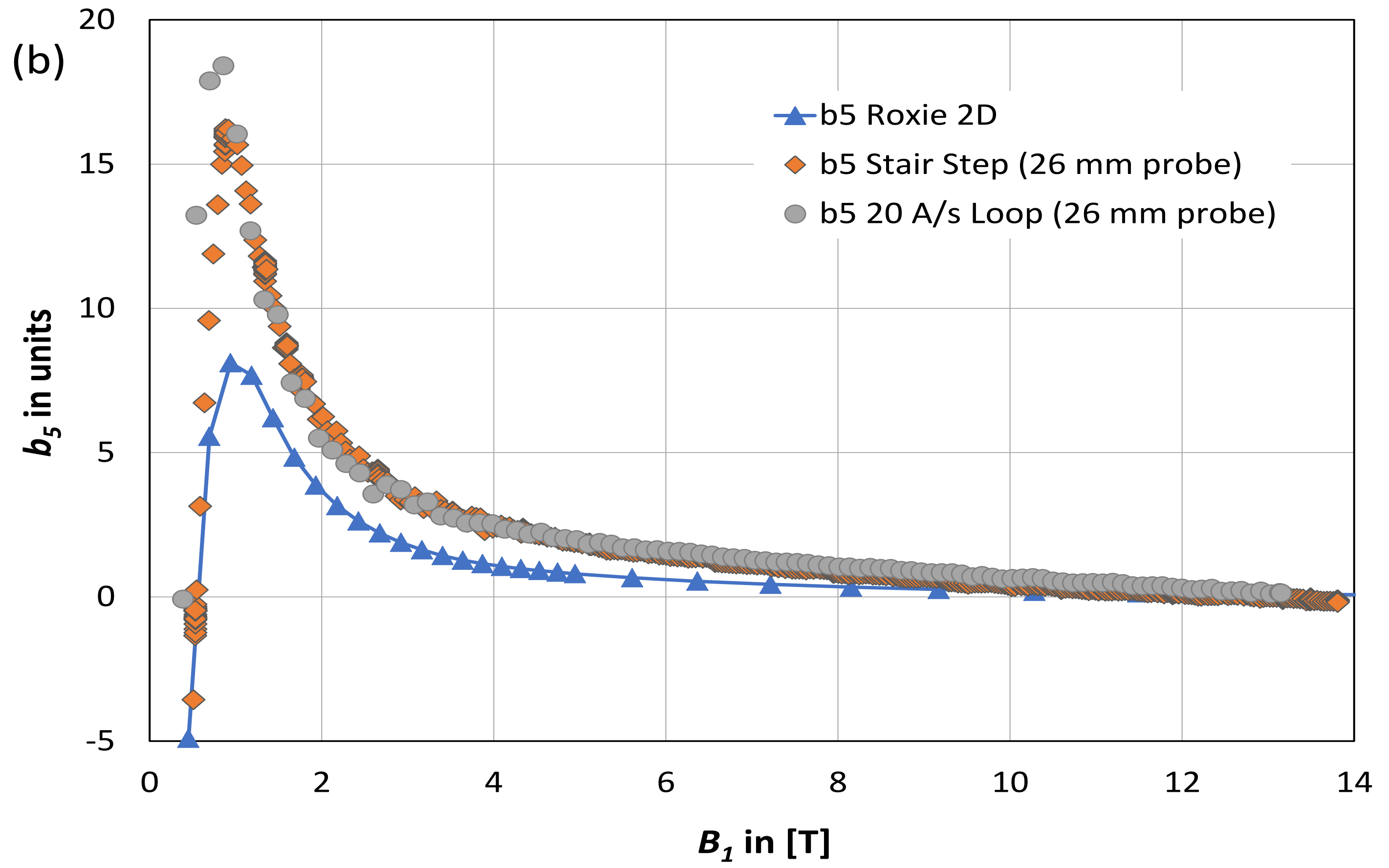
Field Harmonics

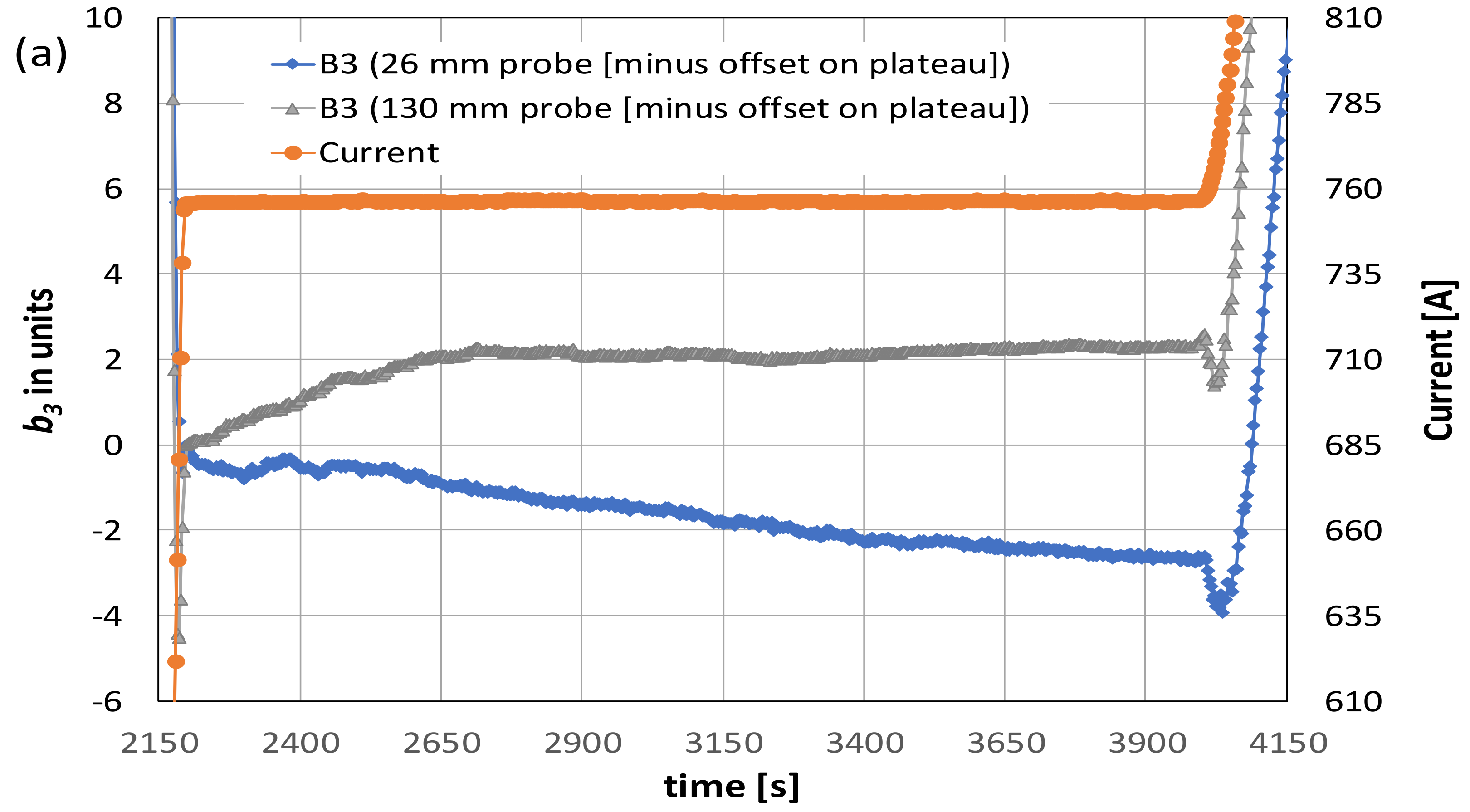












Geometrical harmonics at R_{ref}=17 mm (I=2.5 kA)

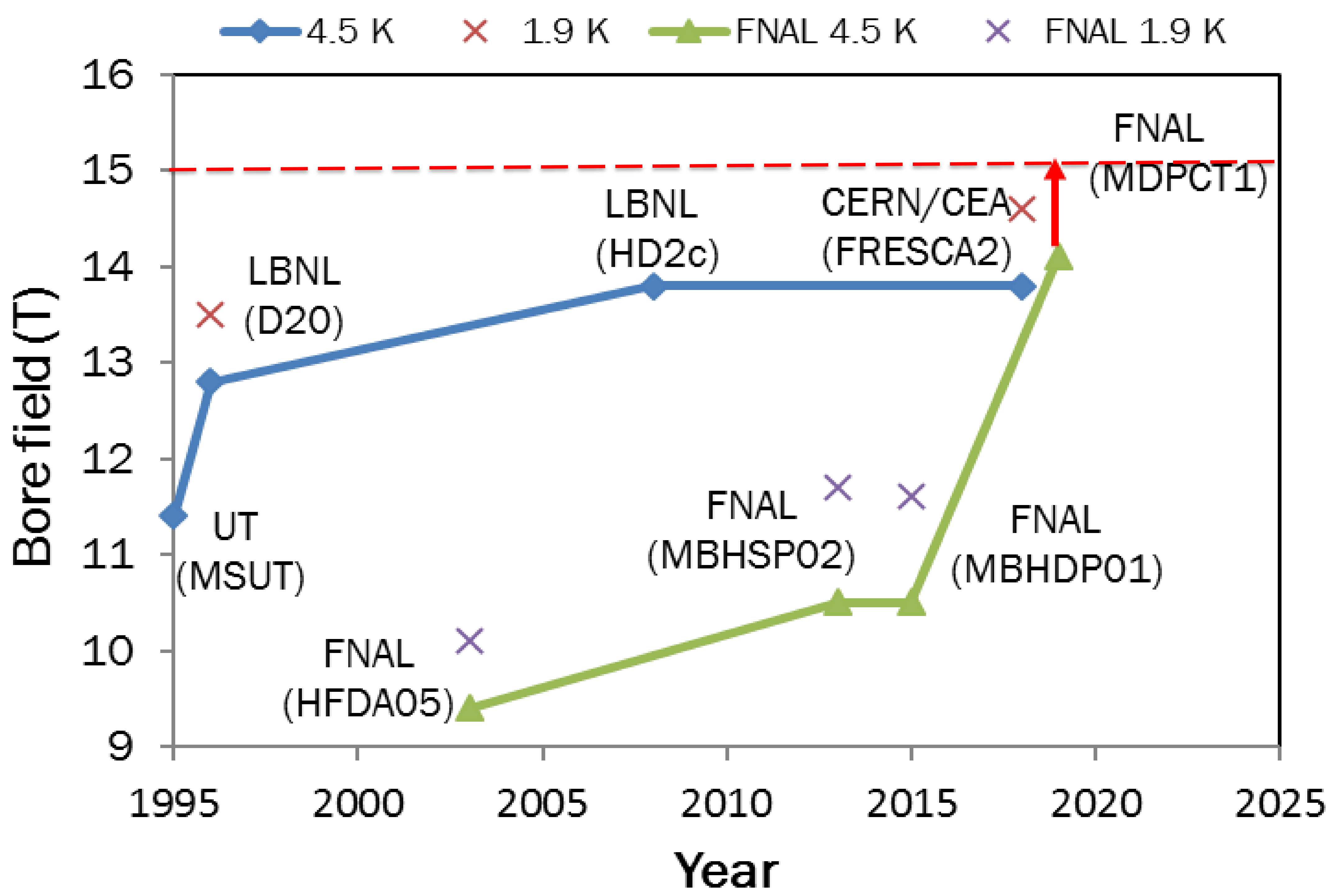
n	2	3	4	5	6	7	8	9	10
b_n	0.8	8.8	-0.4	0.7	0.1	1.0	0.0	0.2	-0.4
a_n	-2.2	-3.5	0.3	0.1	0.1	0.1	-0.1	0.2	-0.3

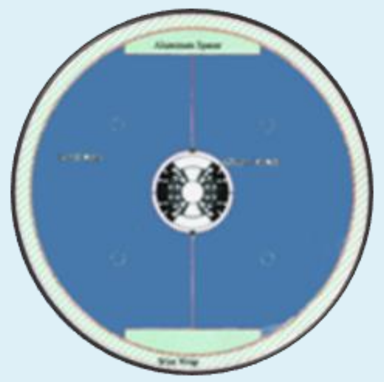
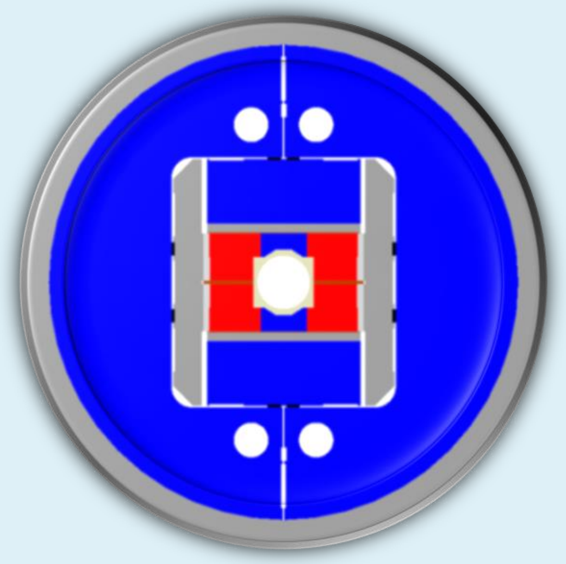
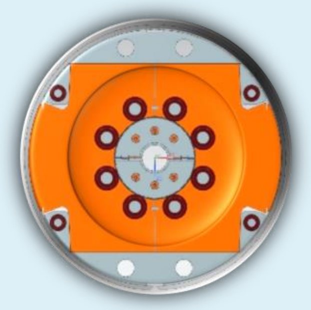
MDPCT1 First Test Summary

The goals of the first test have been achieved

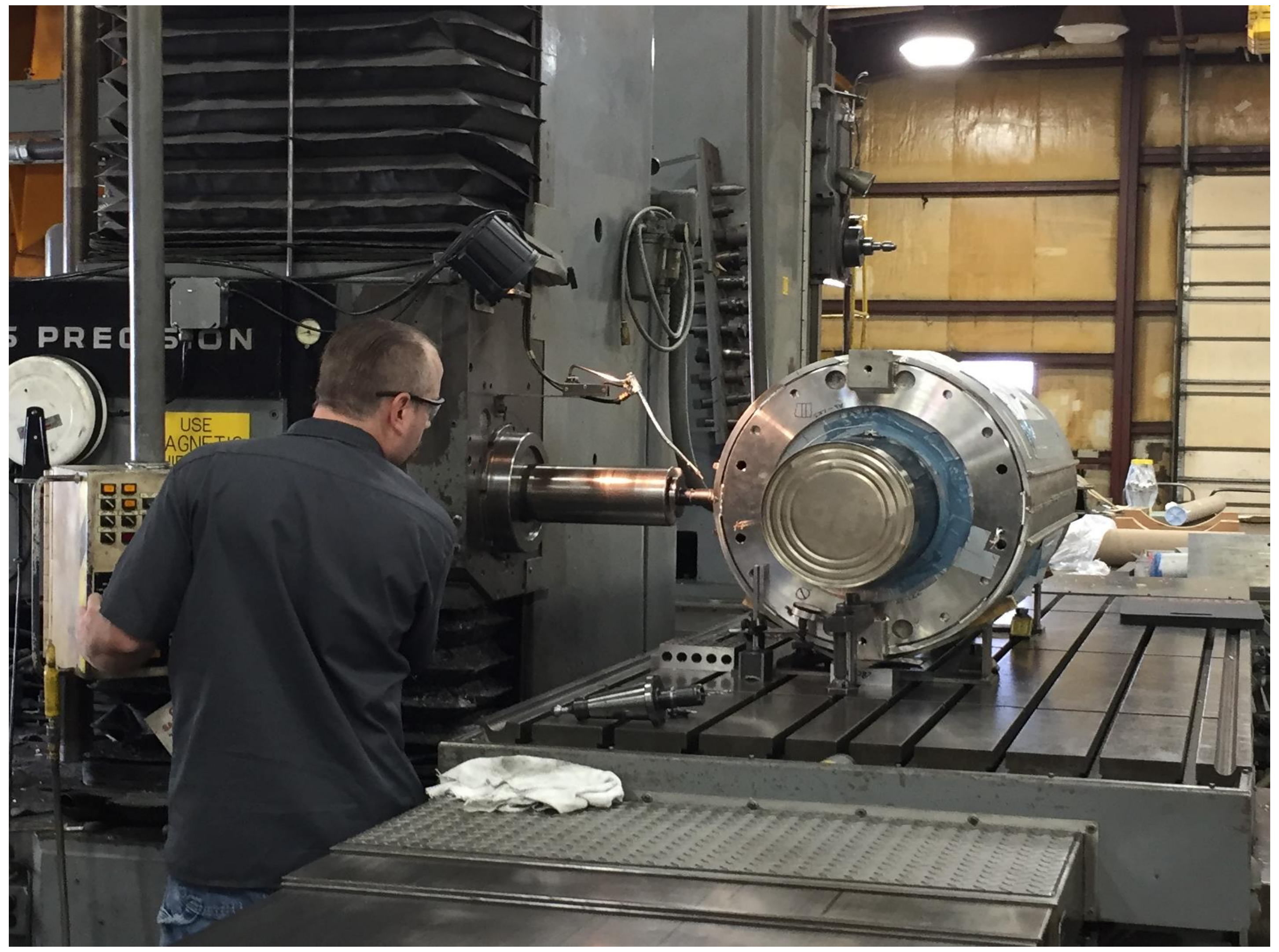
- graded 4-layer coil design, innovative support structure and magnet fabricated procedure have been tested

B_{max} = 14.13 ± 0.02 T - *record field at 4.5 K for accelerator magnets*!

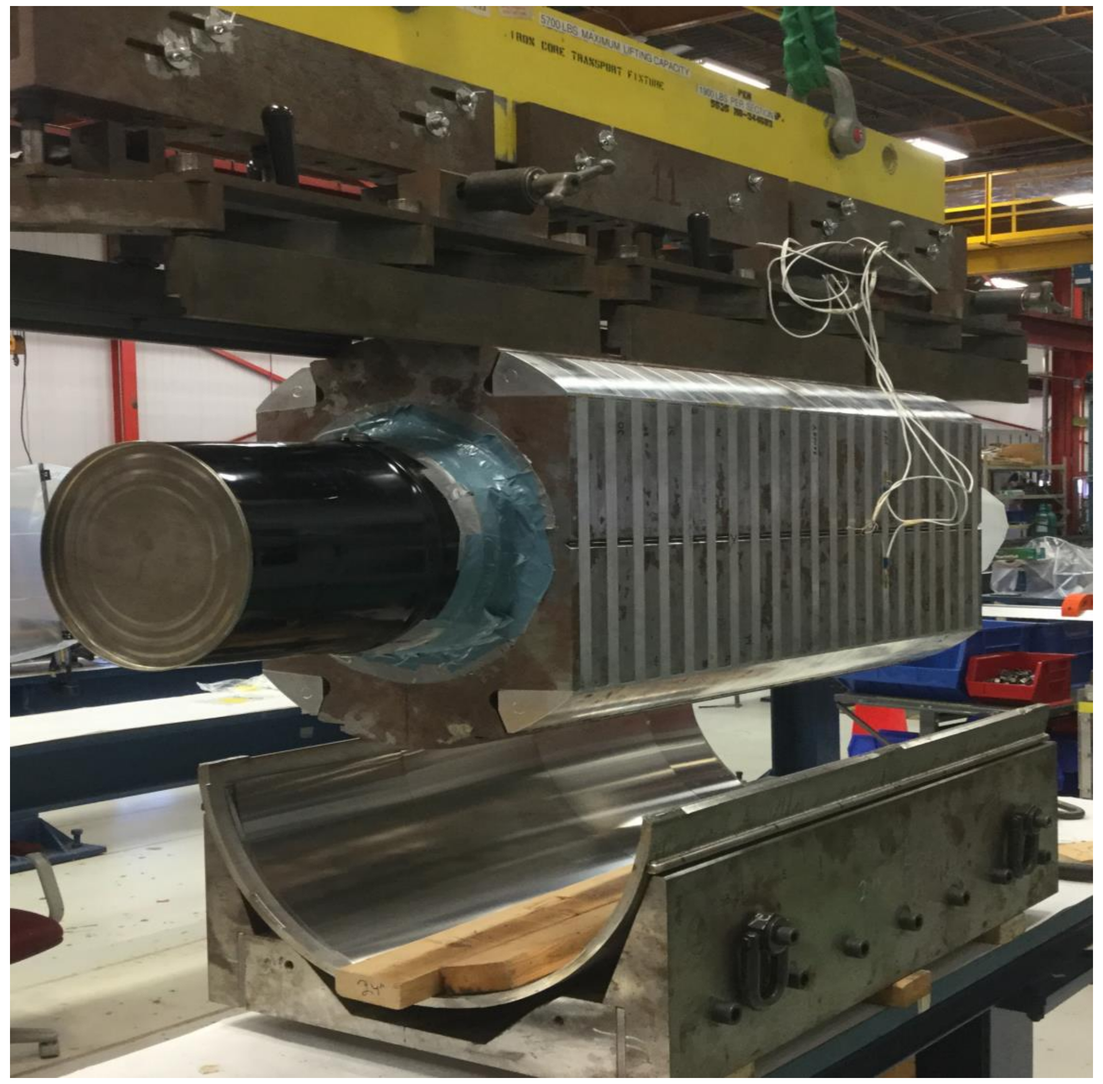


Parameter	D20 (LBNL)	HD2 (LBNL)	FRESCA2 (CERN)	MDPCT1 (FNAL-MDP)
				
Test year	1997	2008	2017	2018 (plan)
Max bore field [T]	13.35 (14.7*)	15.4	16.5 (18*)	15.2 (16.5*)
Design field B_{des} [T]	13.35	15.4	13	15
Design margin B_{des}/B_{max}	1.0 (0.9*)	1.0	0.8 (0.7*)	0.96 (0.89*)
Achieved B_{max} [T]	12.8 (13.5*)	13.8	13.9 (14.6)	14.1
St. energy at B_{des} [MJ/m]	0.82	0.84	4.6	1.7
F_x/quad at B_{des} [MN/m]	4.8	5.6	7.7	7.4
F_y/quad at B_{des} [MN/m]	-2.4	-2.6	-4.1	-4.5
Coil aperture [mm]	50	45	100	60
Magnet (iron) OD [mm]	812 (762)	705 (625)	1140 (1000)	612 (587)

Magnet Disassembly and Inspection

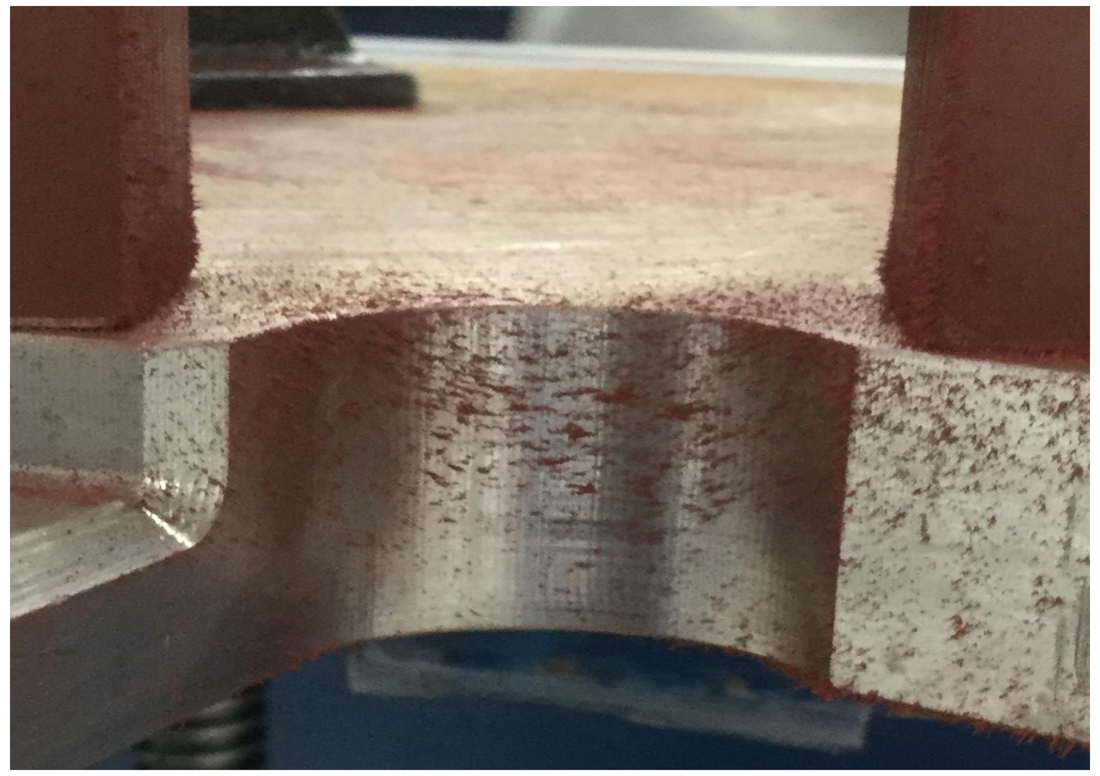


Magnet disassembly



Al clamps test with die penetration technique

Iron lams test with magnetic powder



Coil inspection

L1/L2:

- no coil/pole separation in straight section and ends

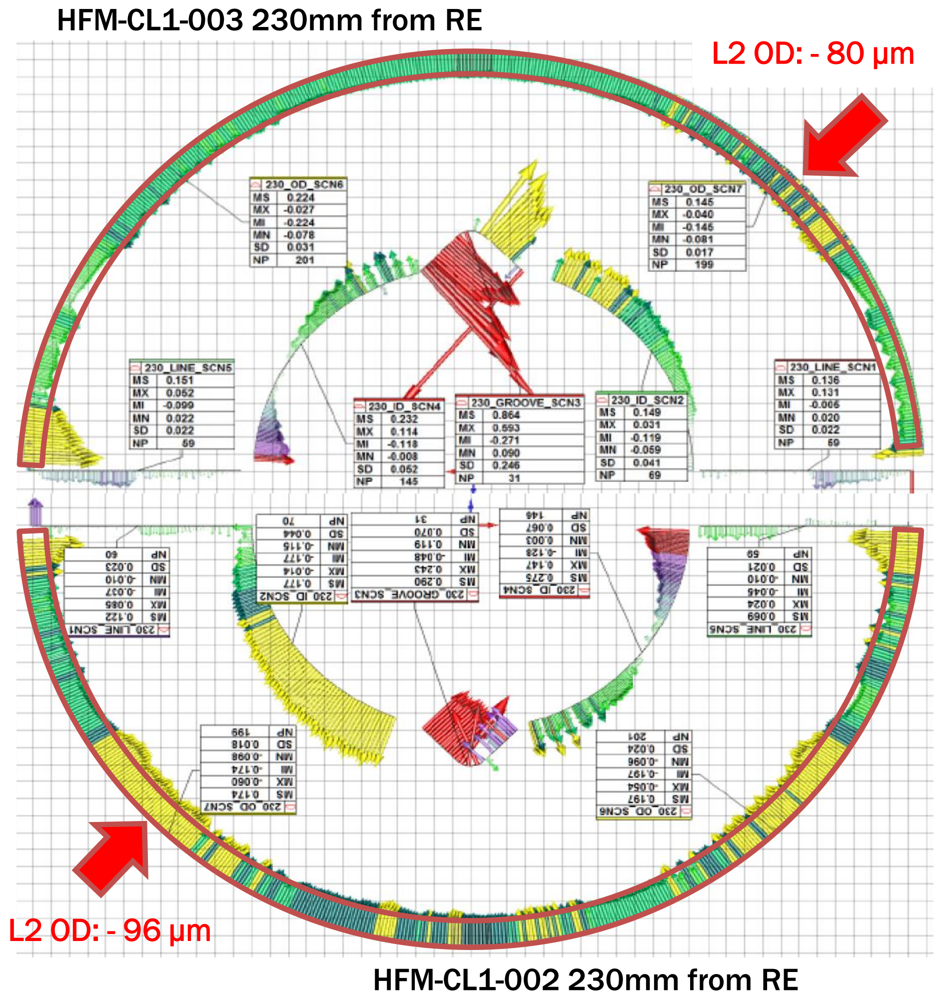
L3/L4:

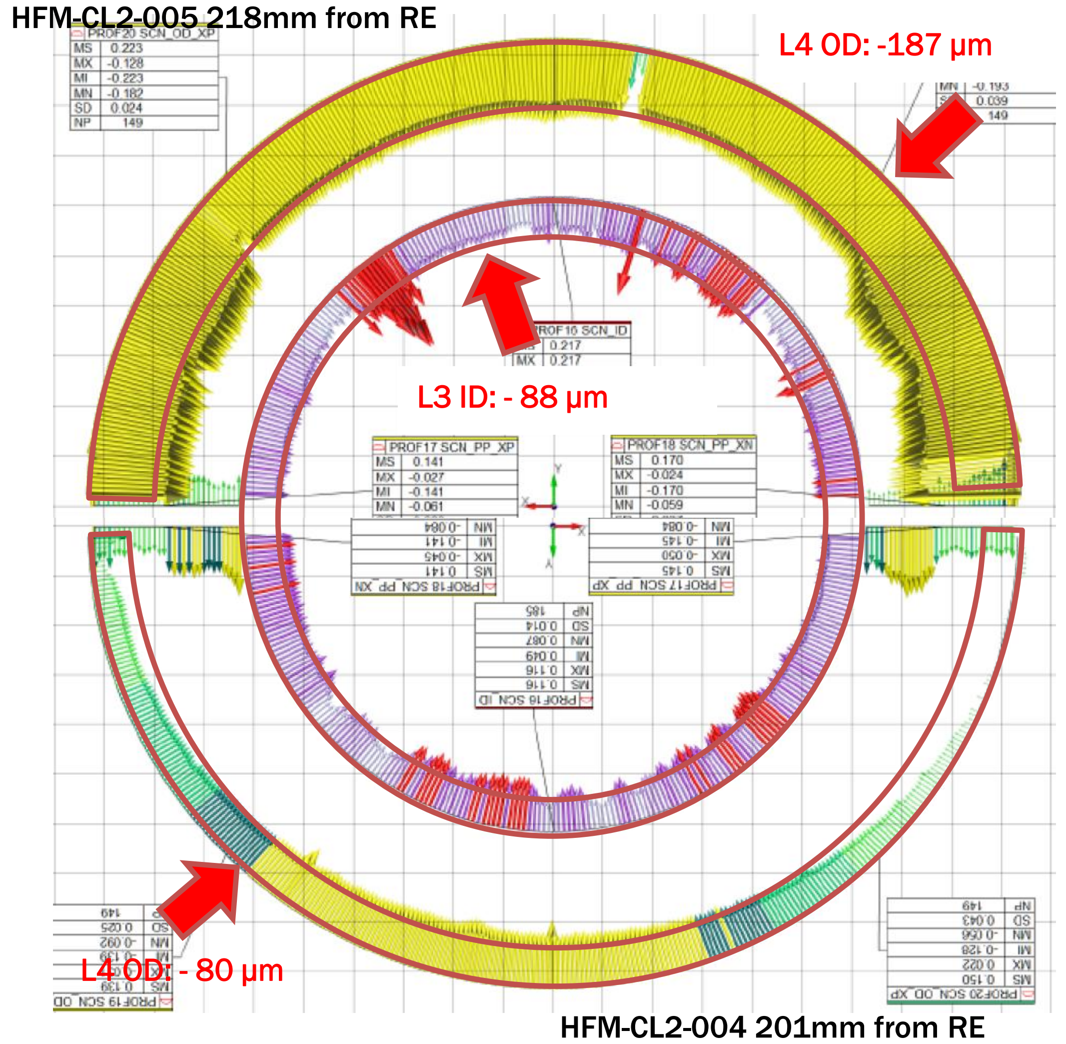
- lost SG and VTs
- no coil/pole separation in straight sections
- coil/pole separation in coil ends

Magnet Re-assembly Goals

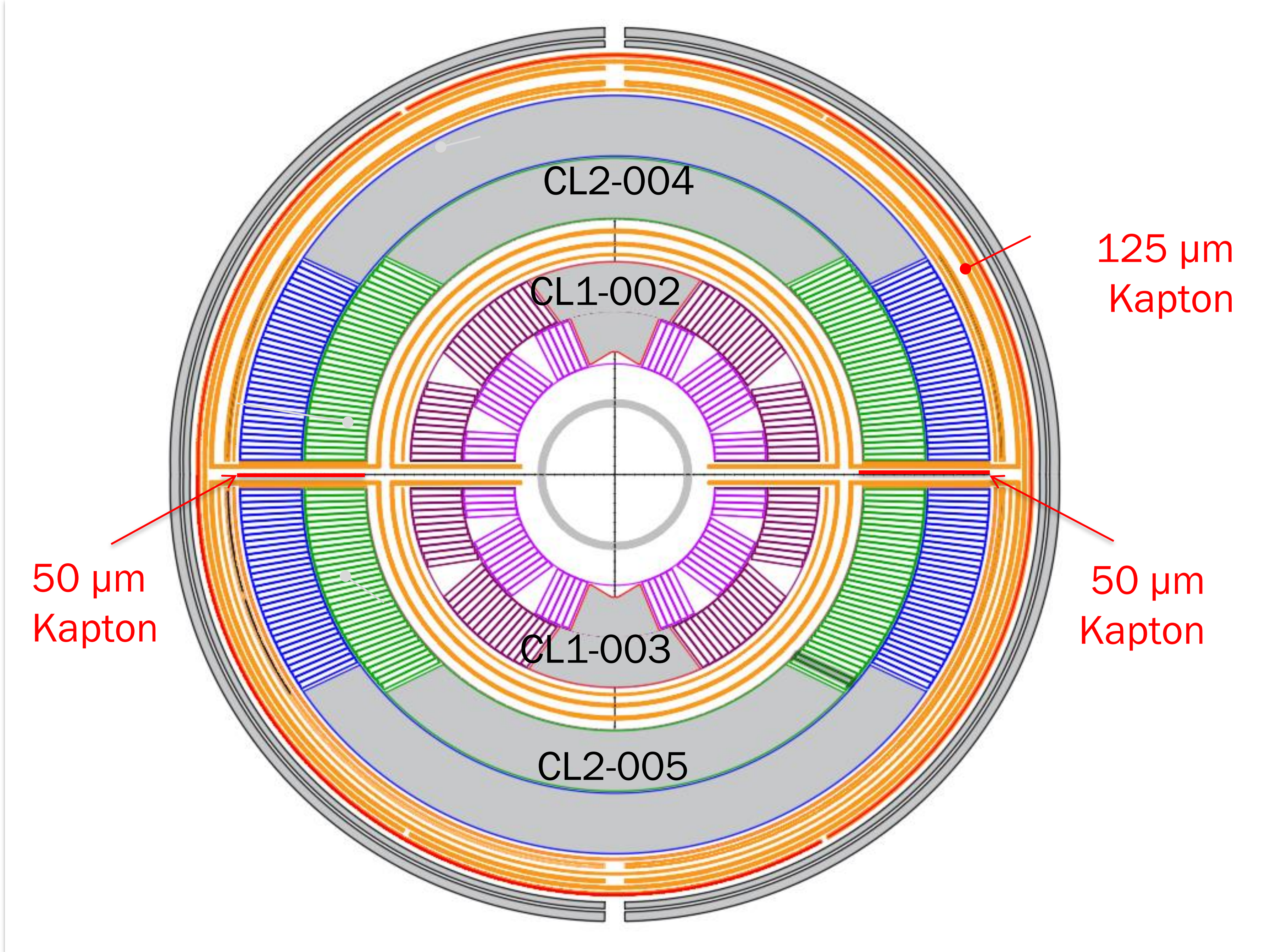
- Increase azimuthal coil pre-load to achieve the goal of 15 T
- Improve axial support
- Improve instrumentation

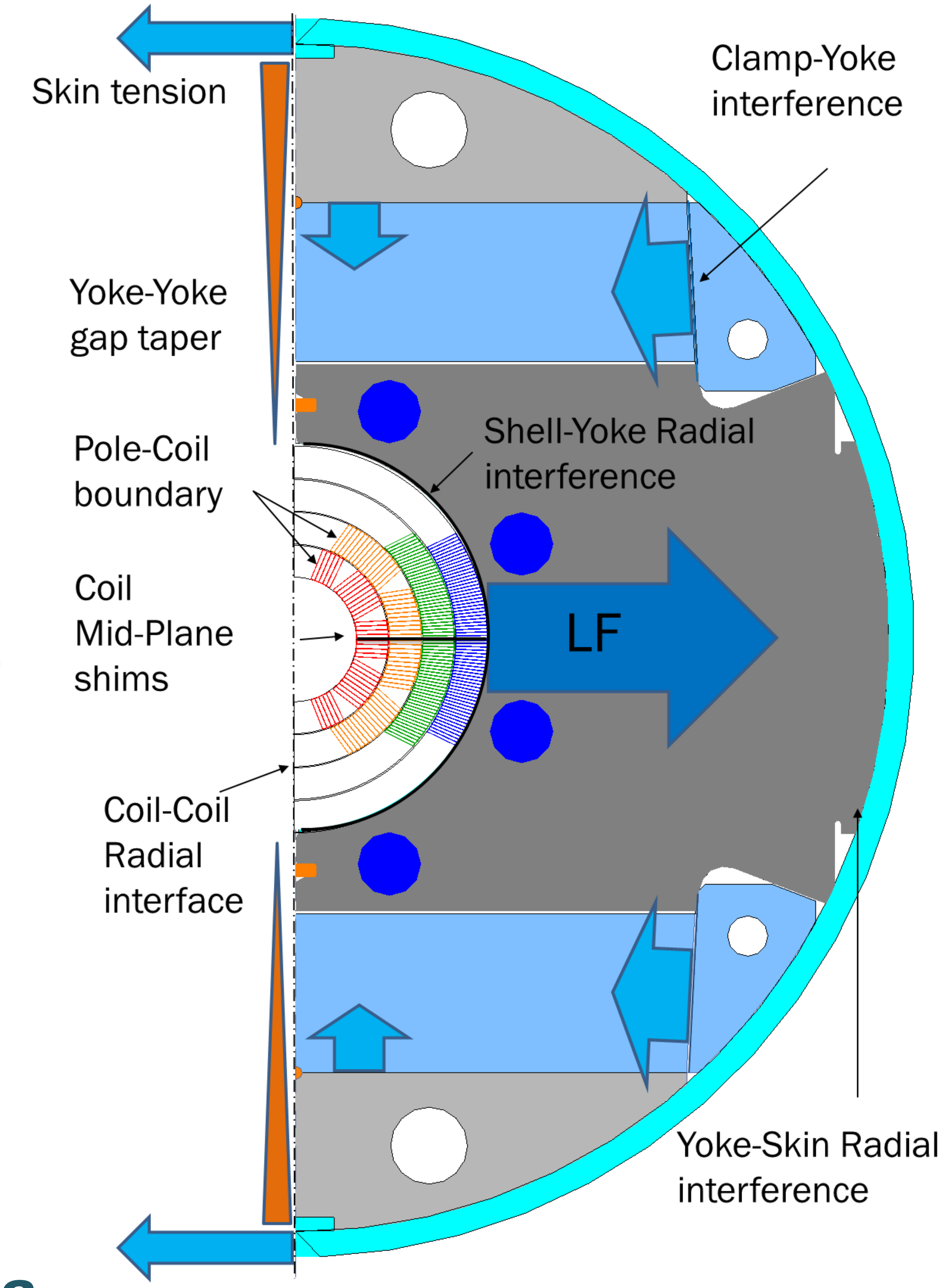
Coil azimuthal pre-load increase





L2-L3 interface was accurately matched (not glued)!



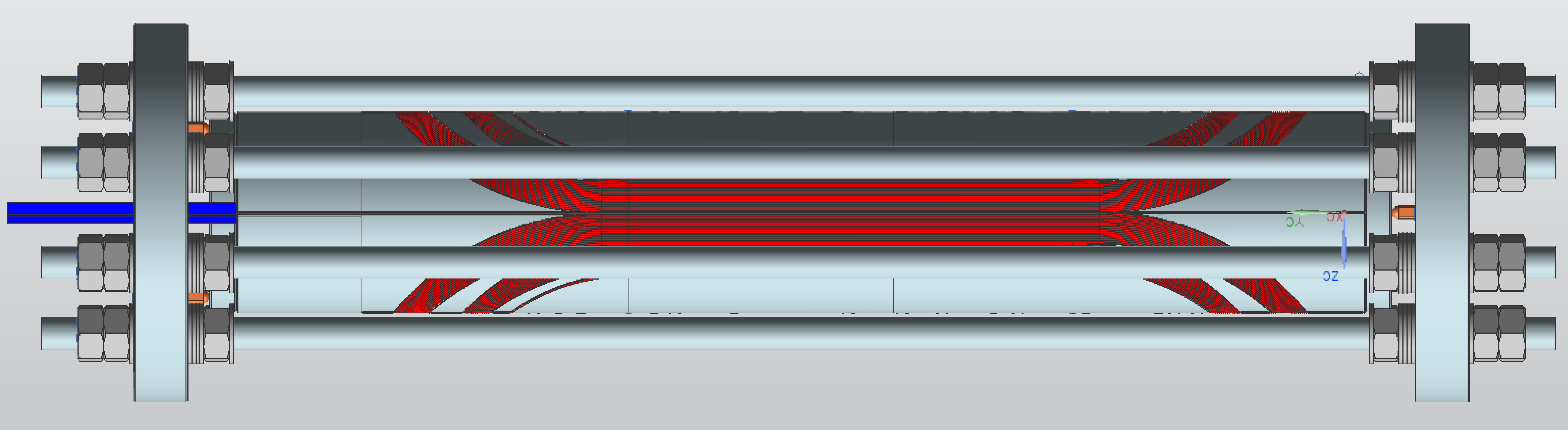


Azimuthal pre-stress increases by ~20 MPa

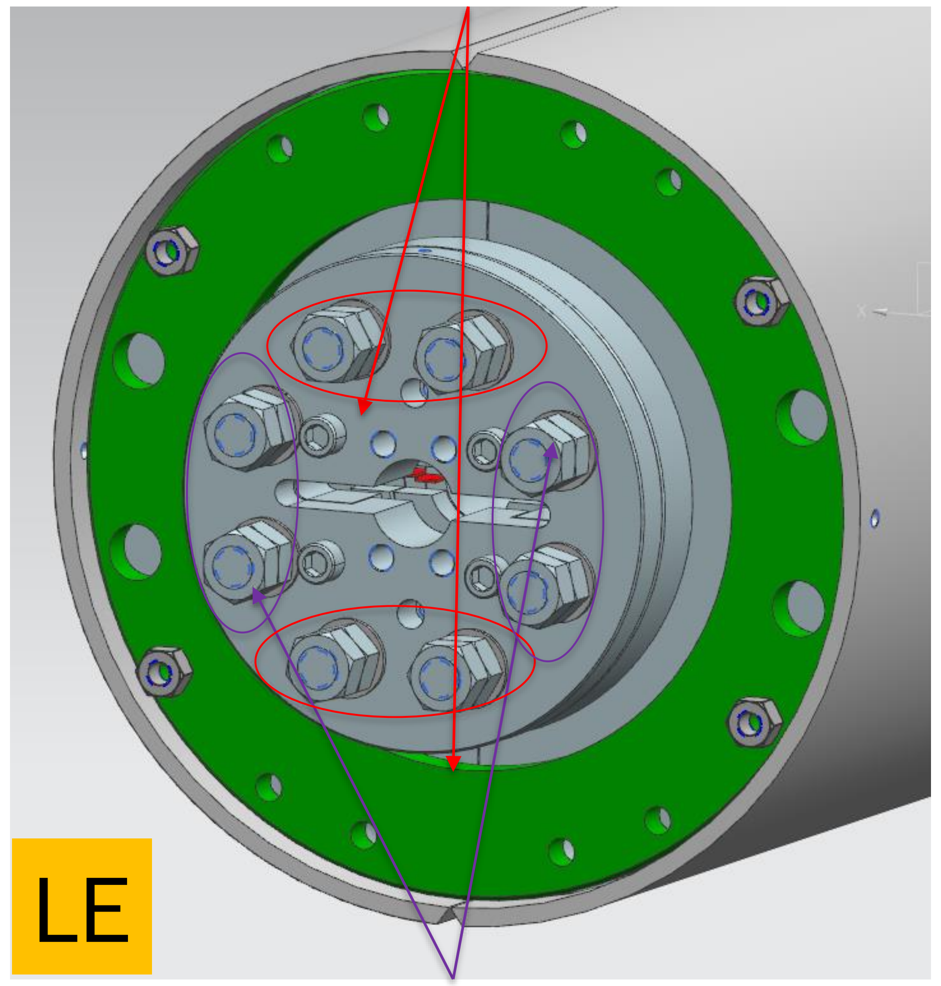
New End Support System

50-mm thick end plates with bullets connected by eight 30 mm OD rods to support the inner and outer coils on each end

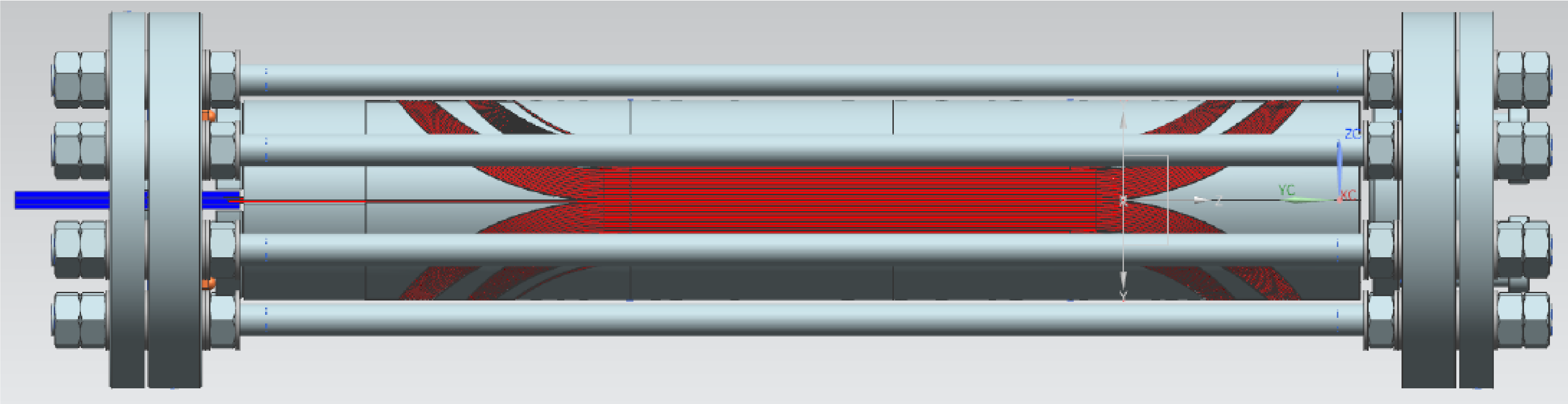
- Test data indicated that the outer coils, due to larger thermal contraction, were not supported by the end plates



Outer coil rods



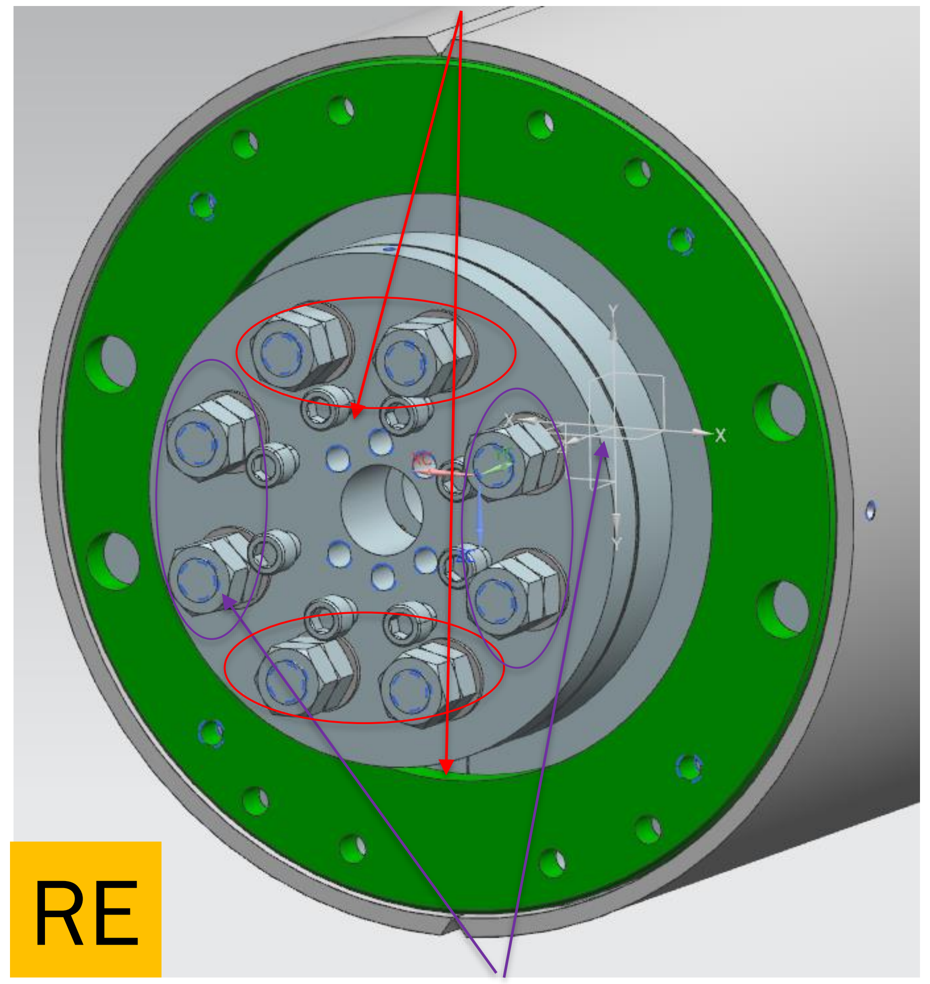
Inner coil rods



Separate 50-mm and 32-mm end plates to support IL and OL coils

- all bullets are in contact with the coil ends at 4K

Outer coil rods



Inner coil rods

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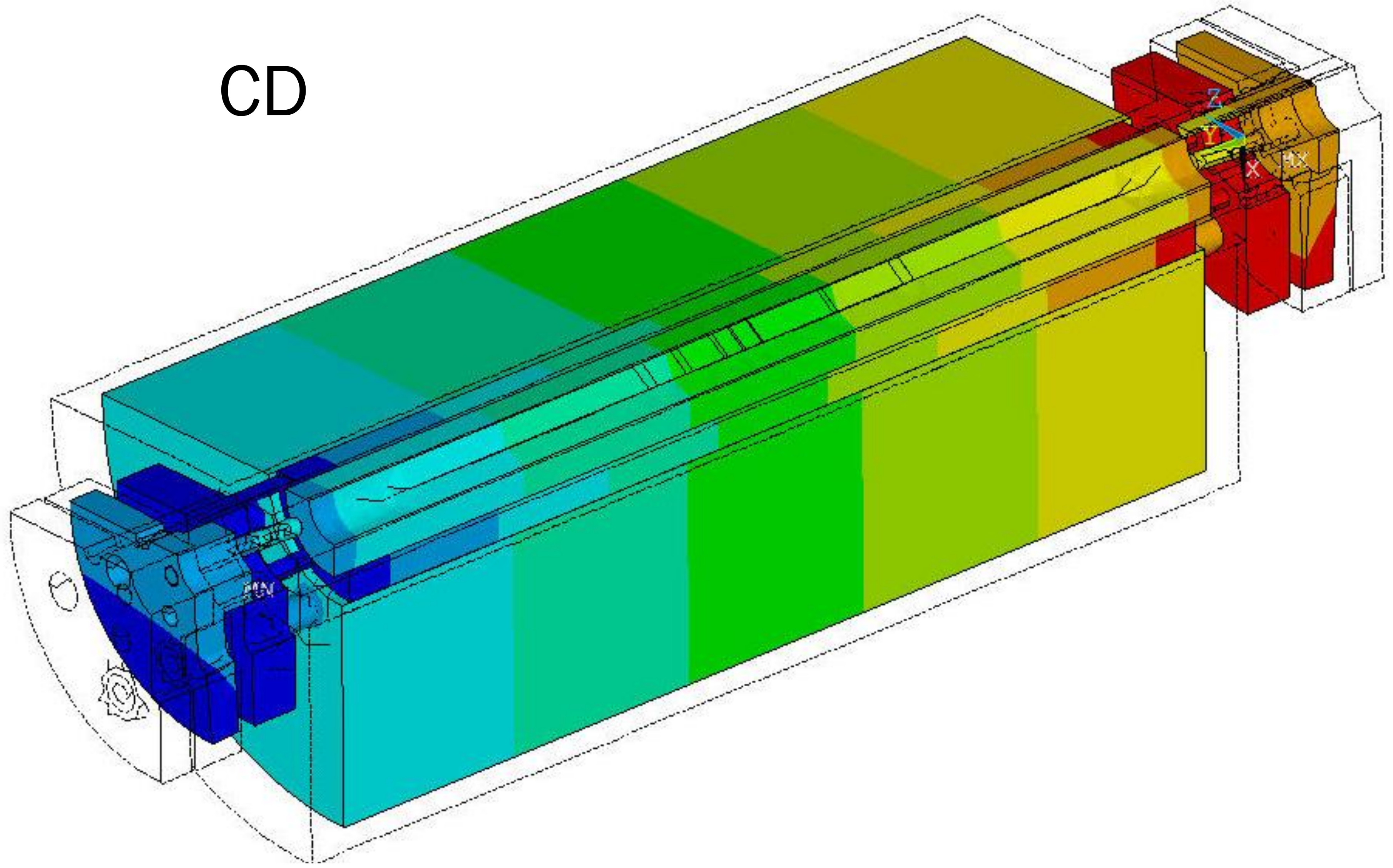
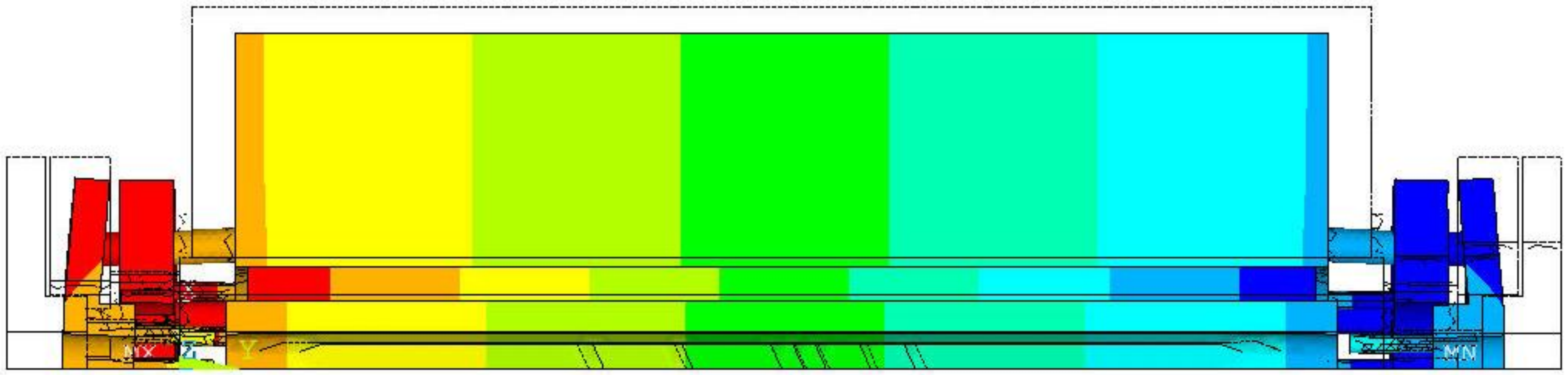
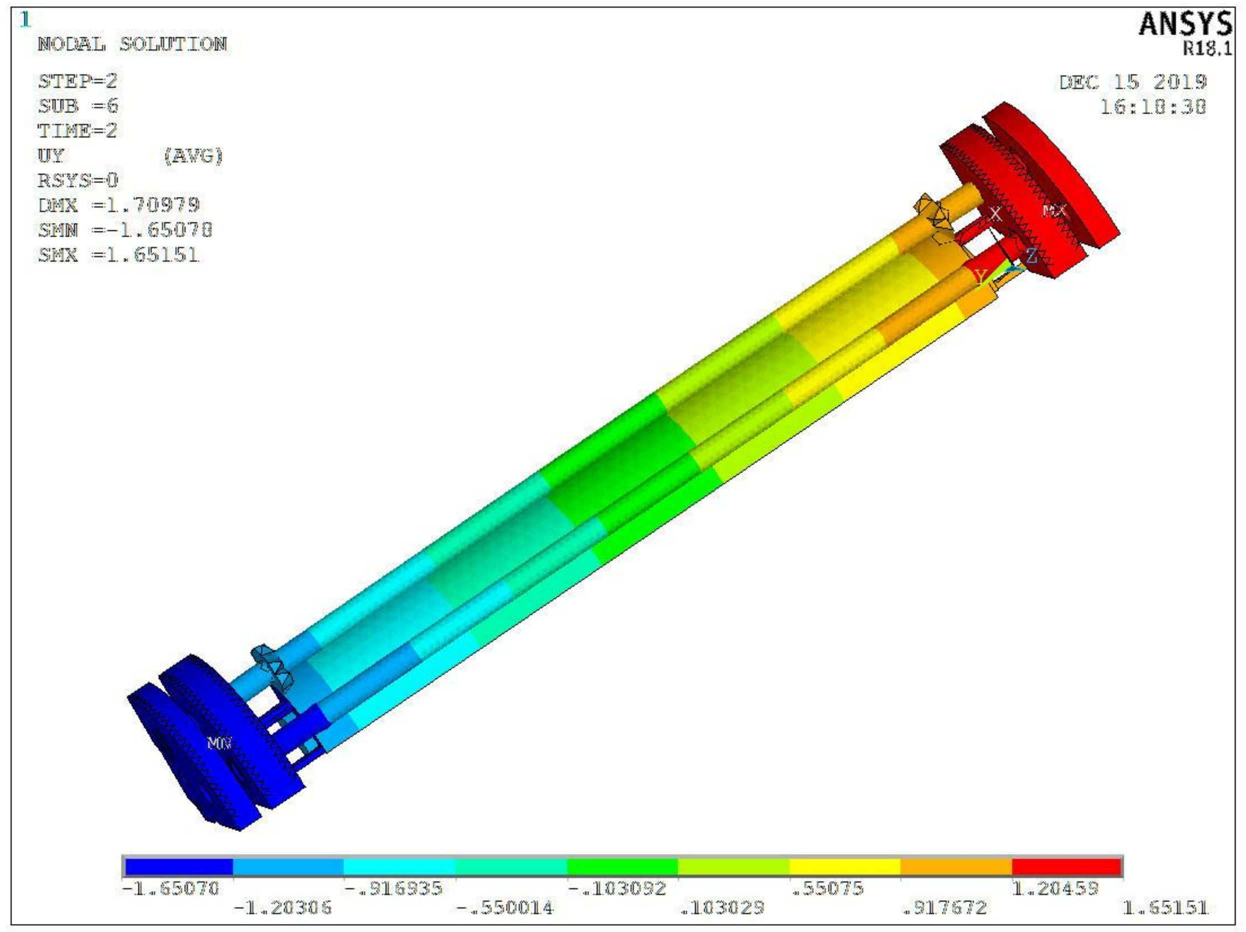
End Plate Deformation Analysis at 15 T

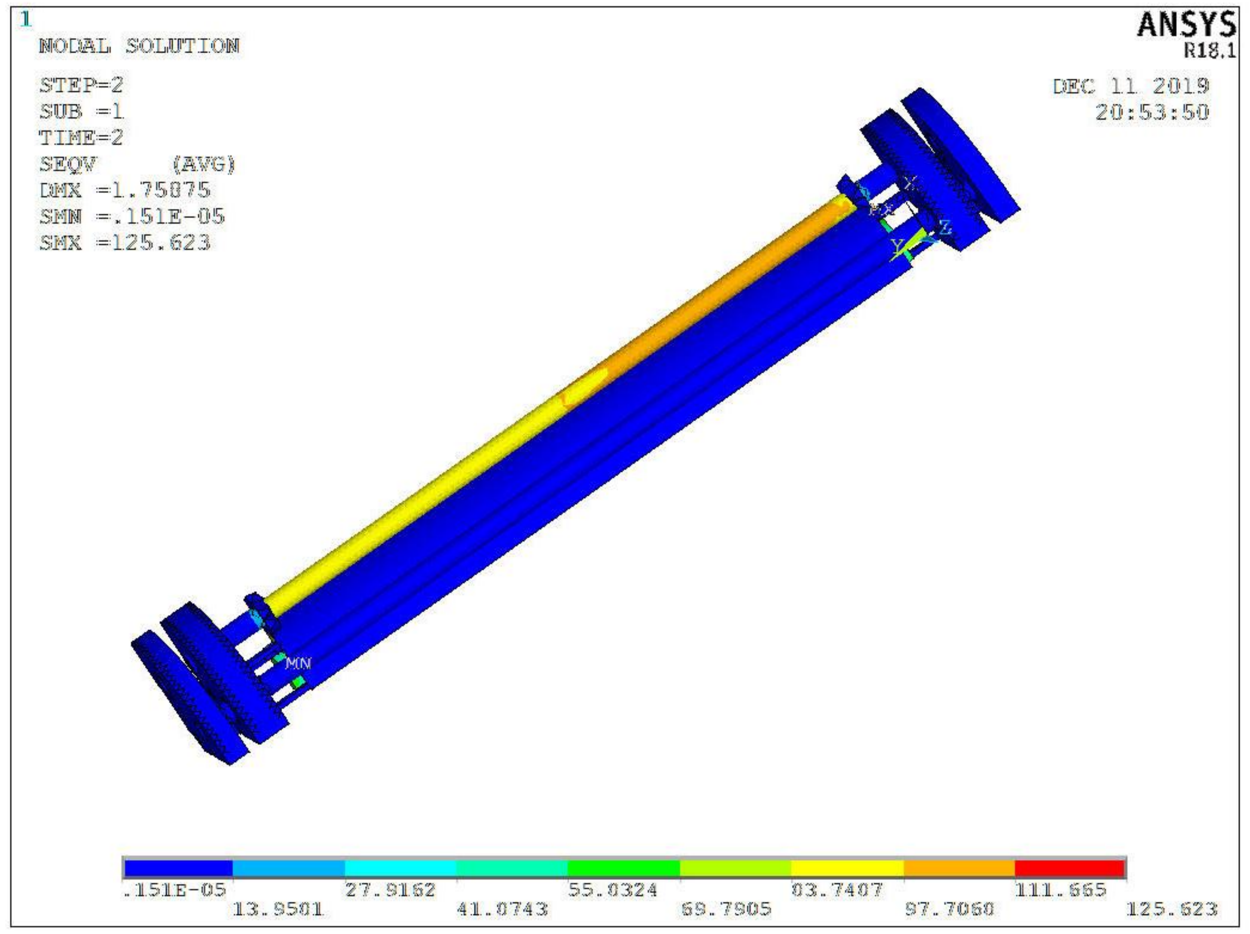
CD



CD+LF





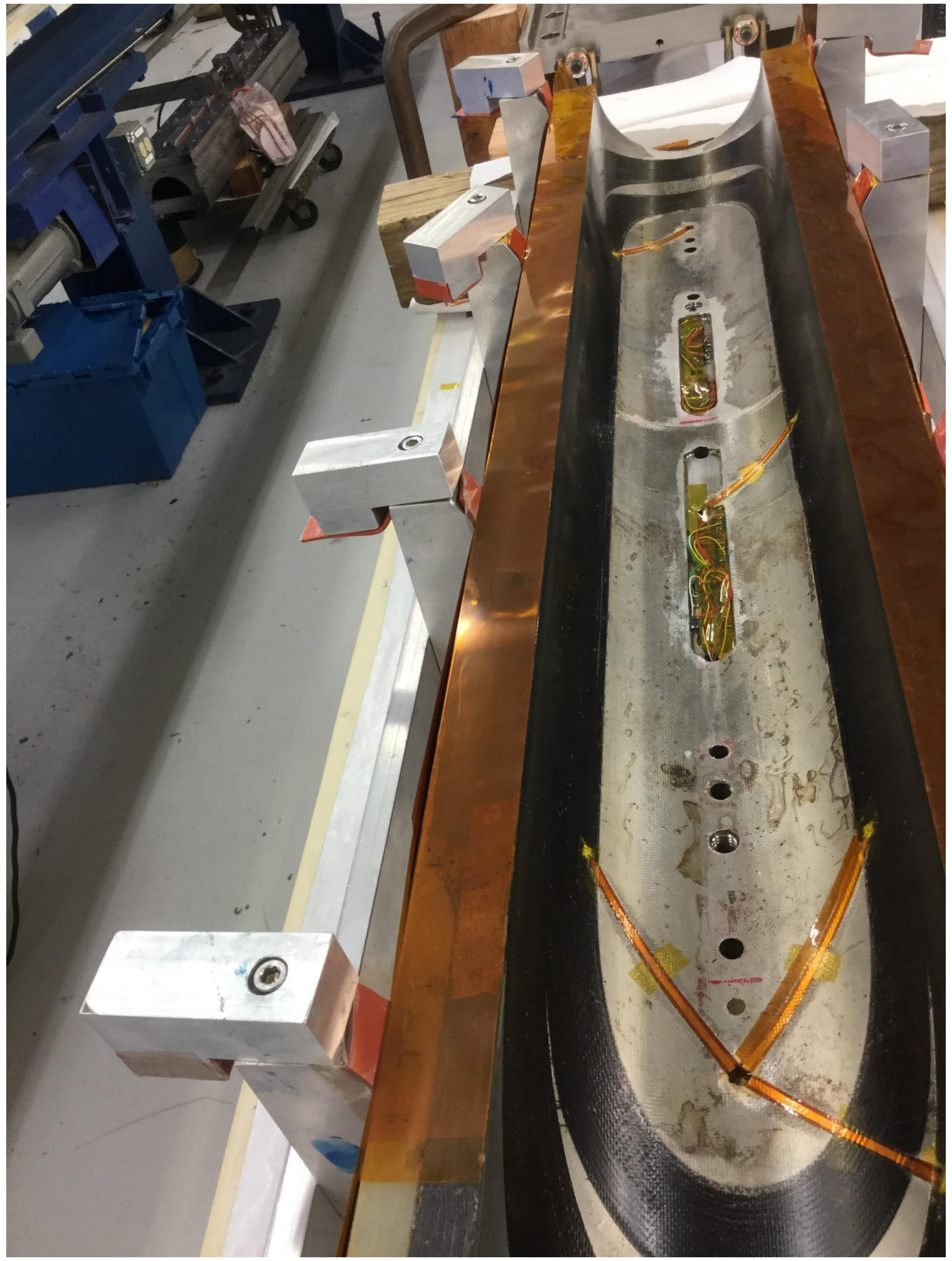


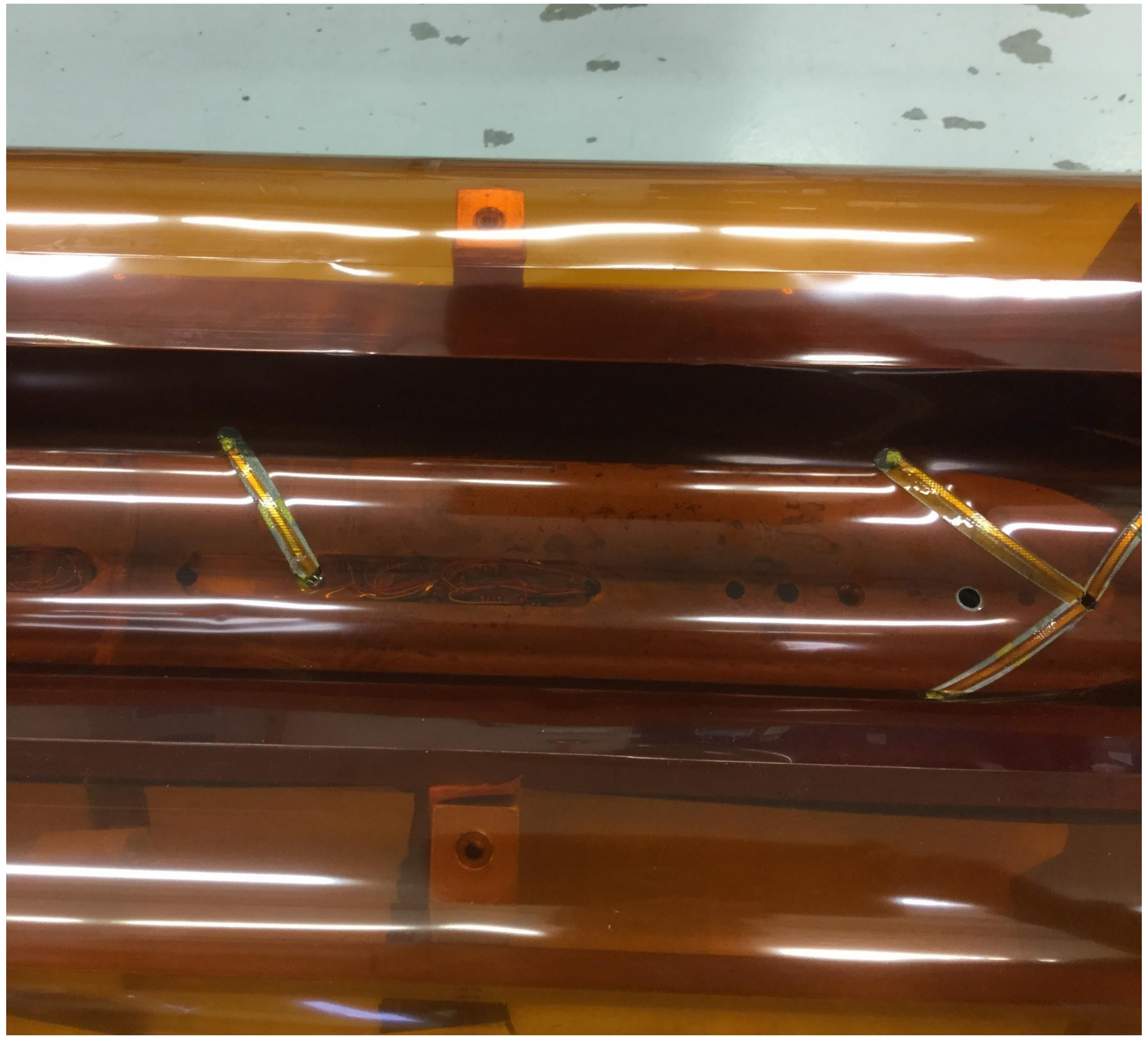
Test 2	Inner coil end	Outer coil end
CD	-0.996 mm	-1.491 mm
LF10%	0.100 mm	0.170 mm

End plate deformation, calculated for MDPCT1 first test for B_{max}=14 T with 10% of LF, is ~0.09 mm

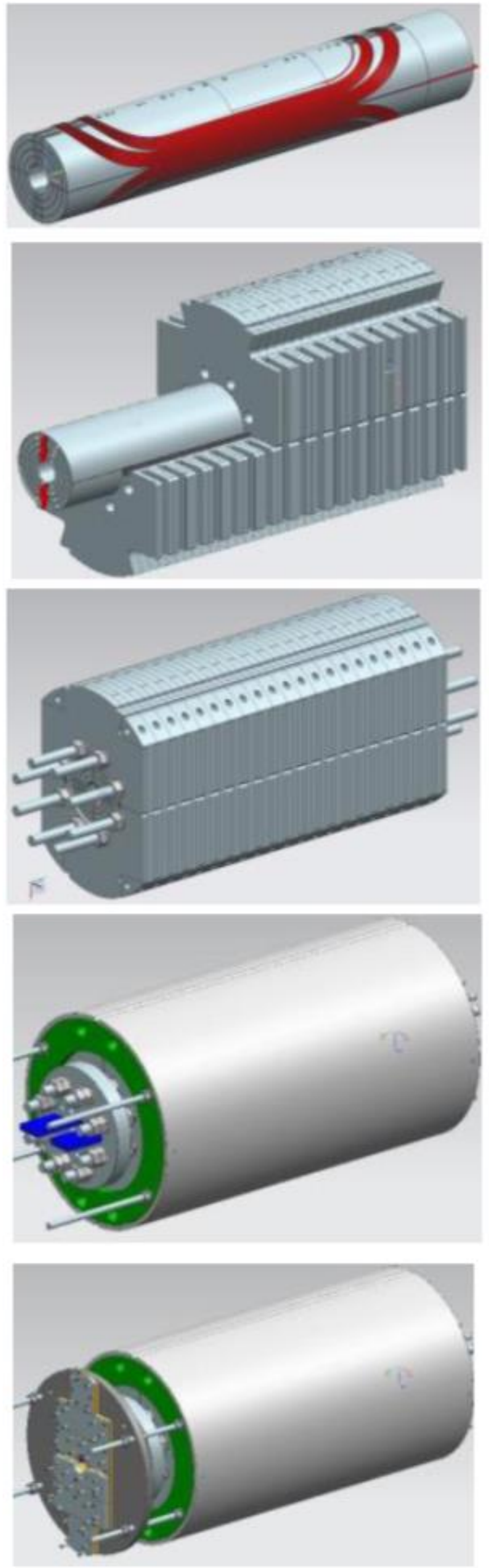
New end support design, performance and assembly procedure were reviewed and approved.

Outer coil VTs



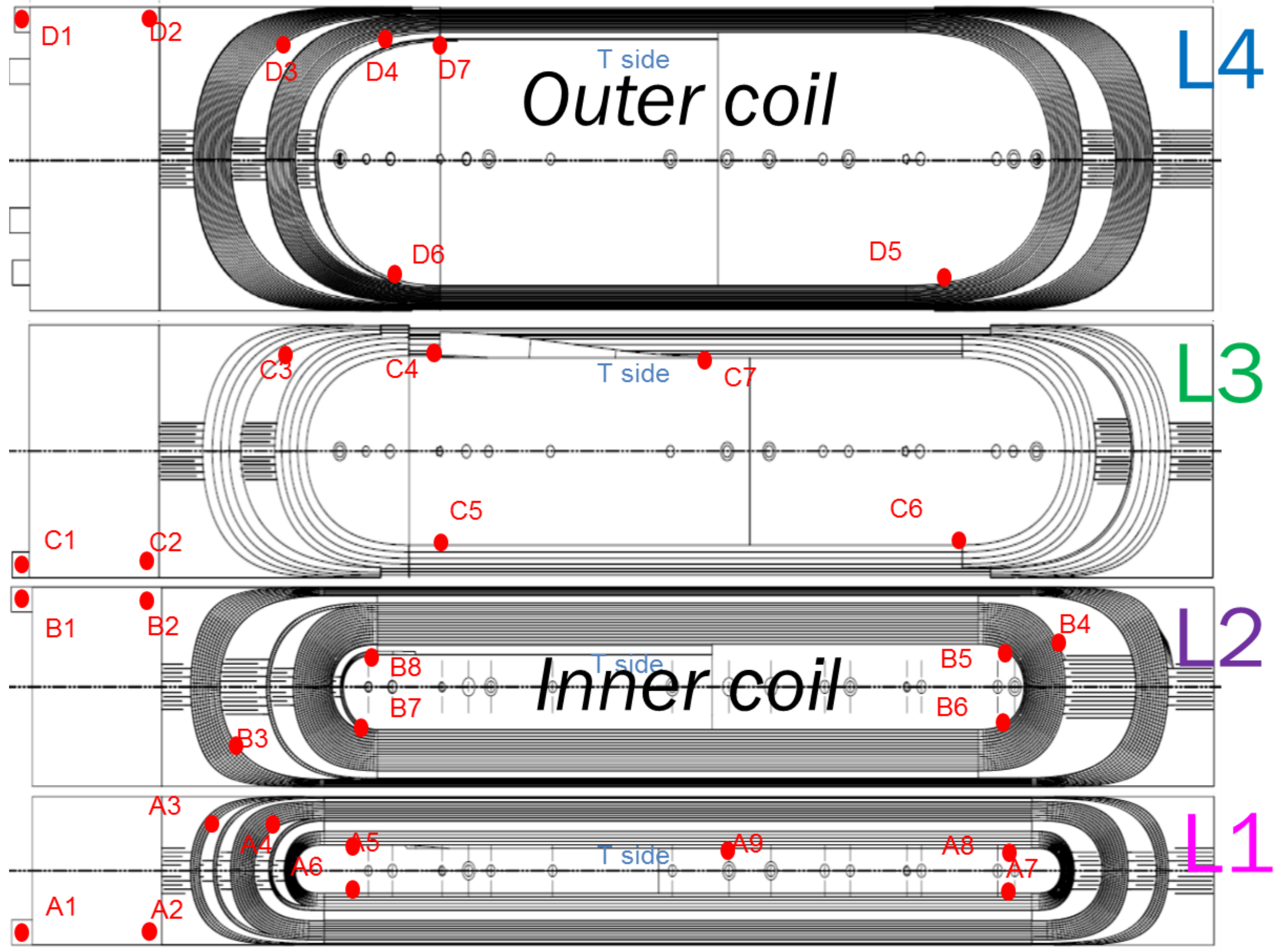


Magnet Assembly



Magnet re-assembly in less than 3 months by 3 people

Magnet Instrumentation



VT location

- Instrumentation:
  - Voltage taps (VT)
  - Strain Gauges (SG)
    - skin, clamps, bullets, IL coils and poles, ~~OL poles~~
  - Quench antennas (QA)
  - Acoustic sensors (AS)
  - Thermometers (T)

Significant part of instrumentation has been restored.

Magnet Status

- The magnet re-assembly is complete
  - The coil azimuthal pre-load has been increased to achieve the test goal of 15 T
  - The end plates have been modified and installed to improve the coil axial support
  - Magnet instrumentation was checked and repaired
- The production tests are complete and the magnet is in IB1
- Magnet test preparation is in progress

Magnet Test Plan

TC1

- **At 1.9 K operation:**
  - Magnetic measurements at 5.0 kA
  - Quench Training at 20/50 A/s to a plateau
  - Ramp rate studies (10/100/200/300/400 A/s)
  - Magnetic measurements in cycles up to I_{max} - 500 A
  - Temperature dependence studies (2.1/2.7/3.4/4.0/4.5 K)
- **At 4.5 K operation:**
  - Inductance measurements at 50 and 300/200 A/s
  - Splice resistance measurements
- **Warm up to 300 K**
  - RRR measurements.

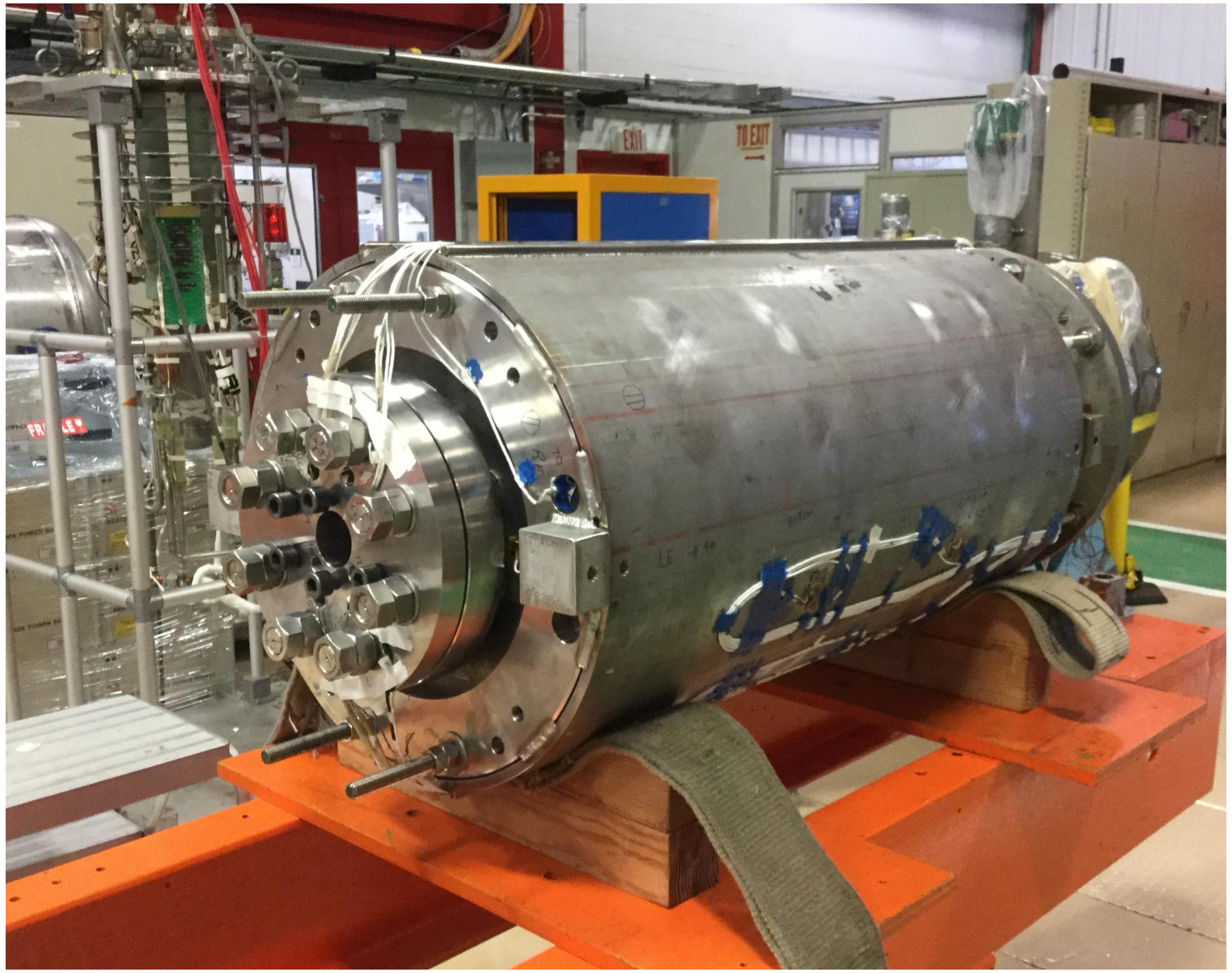
TC2

- **Cool down to 1.9 K (second thermal cycle)**
  - Check training memory
  - Training to plateau if necessary
  - Protection heater studies (if safe)
    - minimum power to quench vs current
    - time delay vs current
    - quench distribution and propagation (L2 PH are in between coils)
- **At 4.5 K operation**
  - 2 training quenches at 20/50 A/s

Test Readiness Review Goal (January 30, 2020)

The review goal is the MDPCT1b test preparation status and the test plan.

1. Are the magnet assembly and production tests complete?
2. Are the results of production tests conclusive to certify the magnet safe operation at cryo temperatures?
3. Are the magnet instrumentation plan and electrical interface compatible with VMTF systems?
4. Is the magnet cold test plan well understood and consistent with the MDPCT1b test goals?
5. Are the main risks identified and their impact understood and mitigated?



Review committee:

- Giorgio Ambrosio
- Guram Chlachidze
- Sandor Feher
- Mike Tartaglia