U.S. MAGNET DEVELOPMENT PROGRAM

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Main results and lessons learned from the MDPCT1 R&D program

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Fermilab

MT-27

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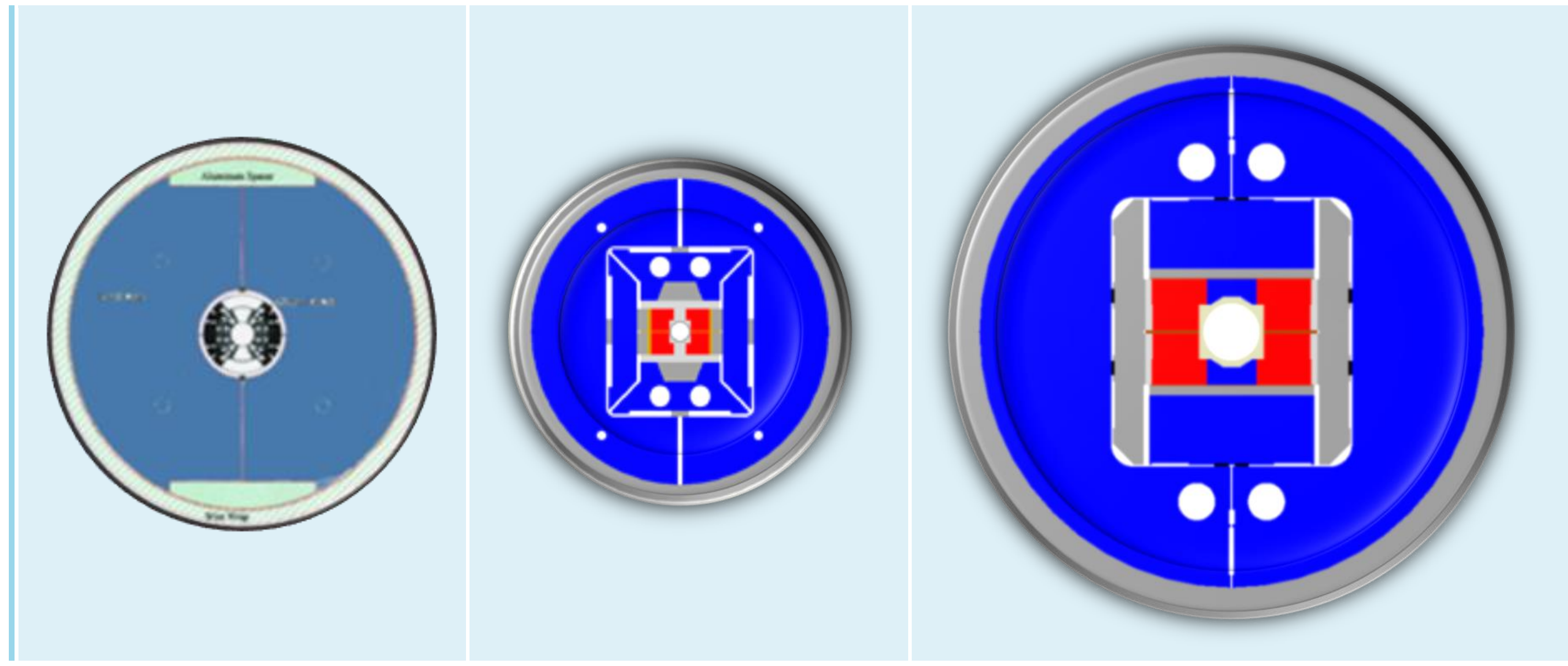
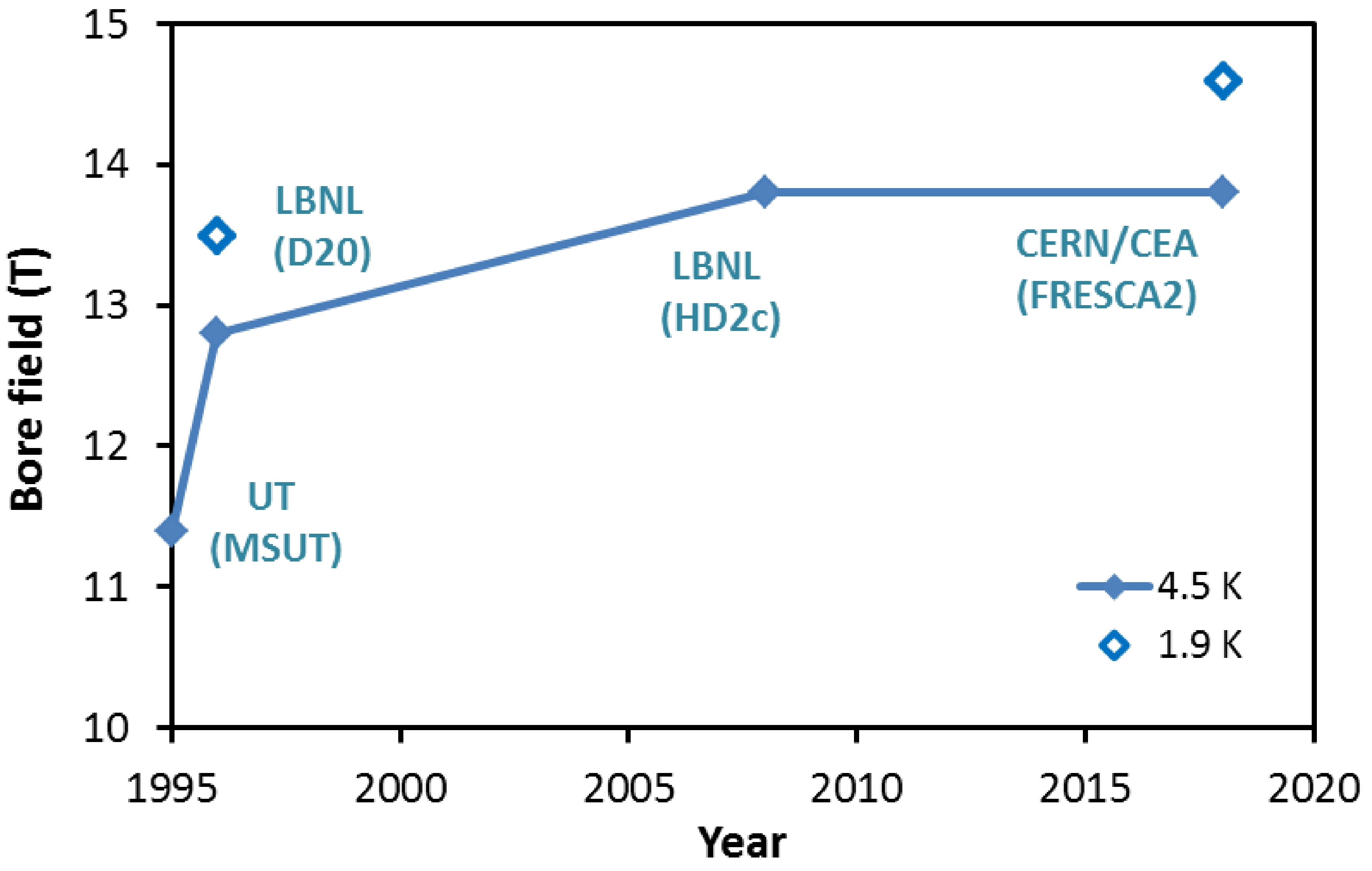
Program goals

- Demonstration of 15 T field level in accelerator dipole magnets
  - 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}= not tested, 13.8 T @4.5K
    - FRESCA2 (CERN, 2018): B_{max}=14.6 T @1.9K, 13.9 T @4.5K
- Study and optimization of
  1. Magnet quench performance and mechanics
  2. Quench protection, field quality, etc.

- The development and test of the 15 T dipole demonstrator was a key milestone of the U.S. Magnet Development Program (US-MDP)
  - the work was coordinated with EuroCirCol program supported by CERN

D20 (LBNL)	HD2 (LBNL)	FRESCA2 (CERN)





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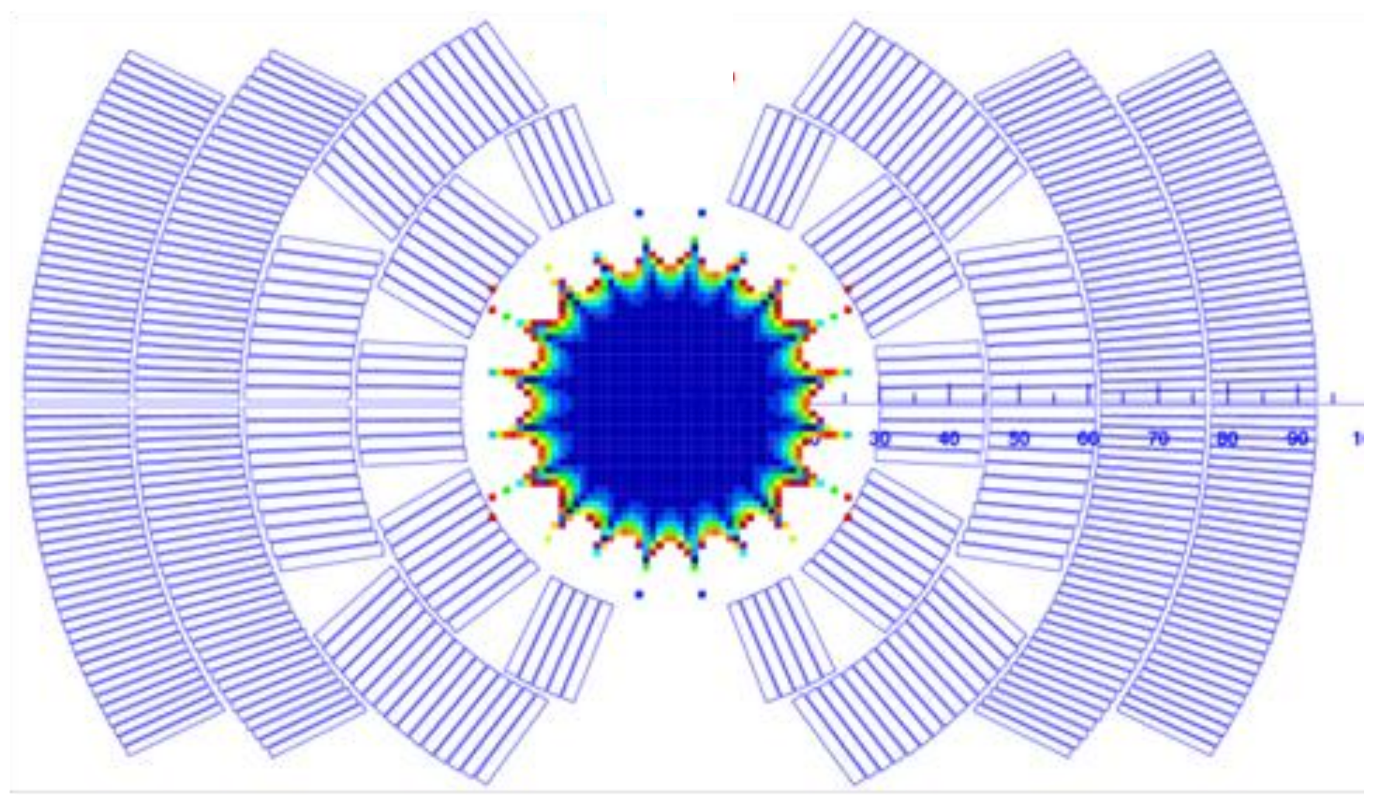
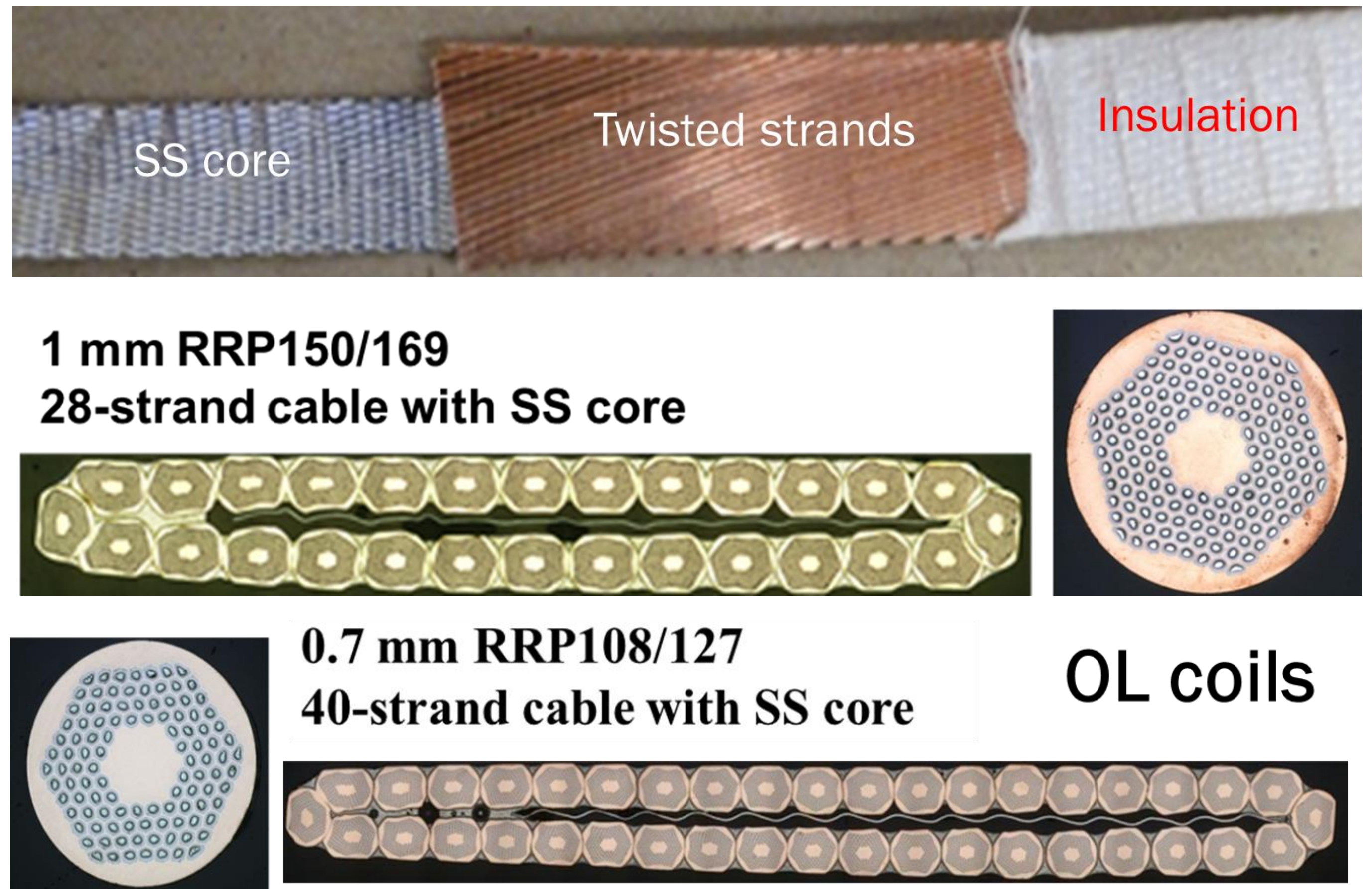
15 T Dipole Demonstrator (MDPCT1) design and parameters

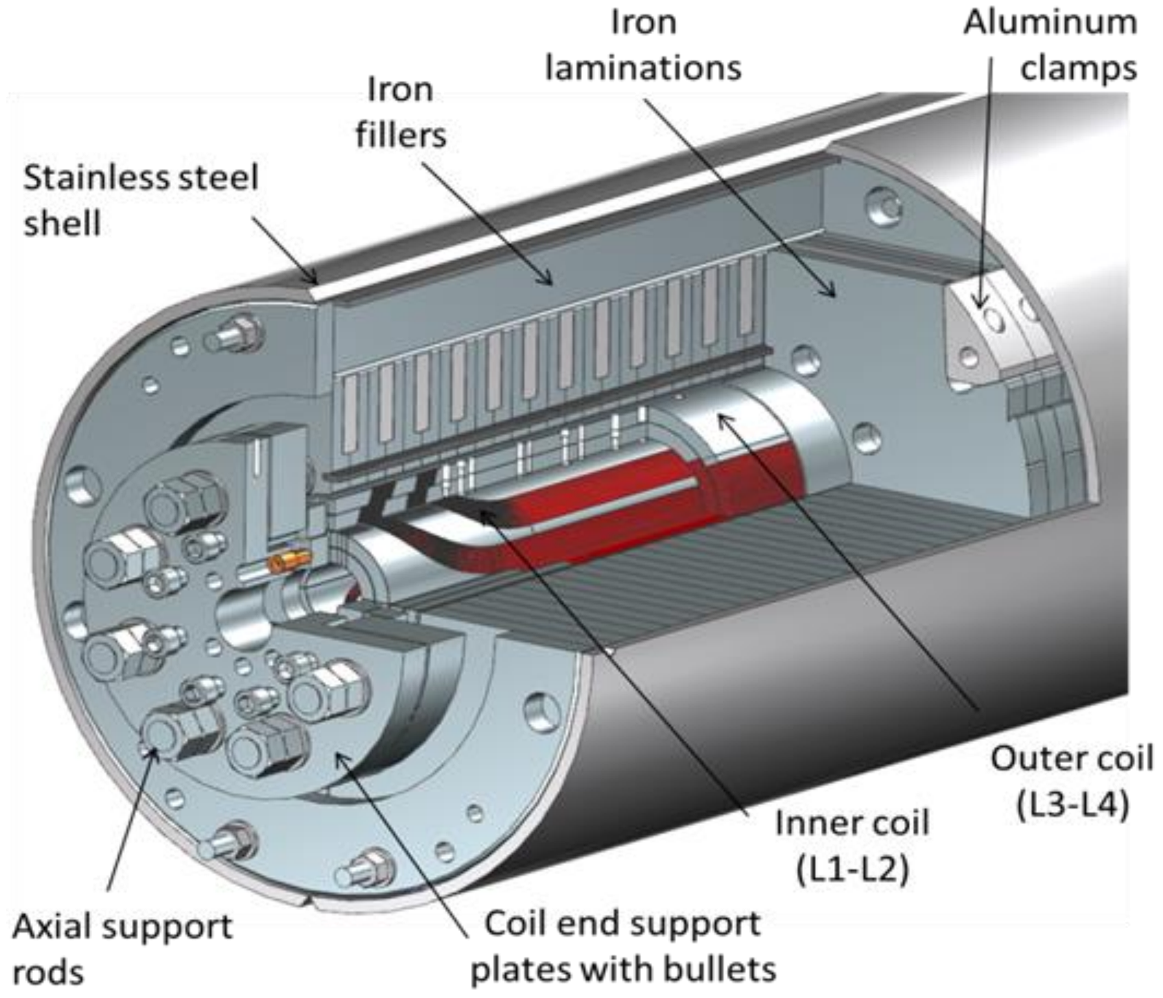
Optimized 60-mm graded coil

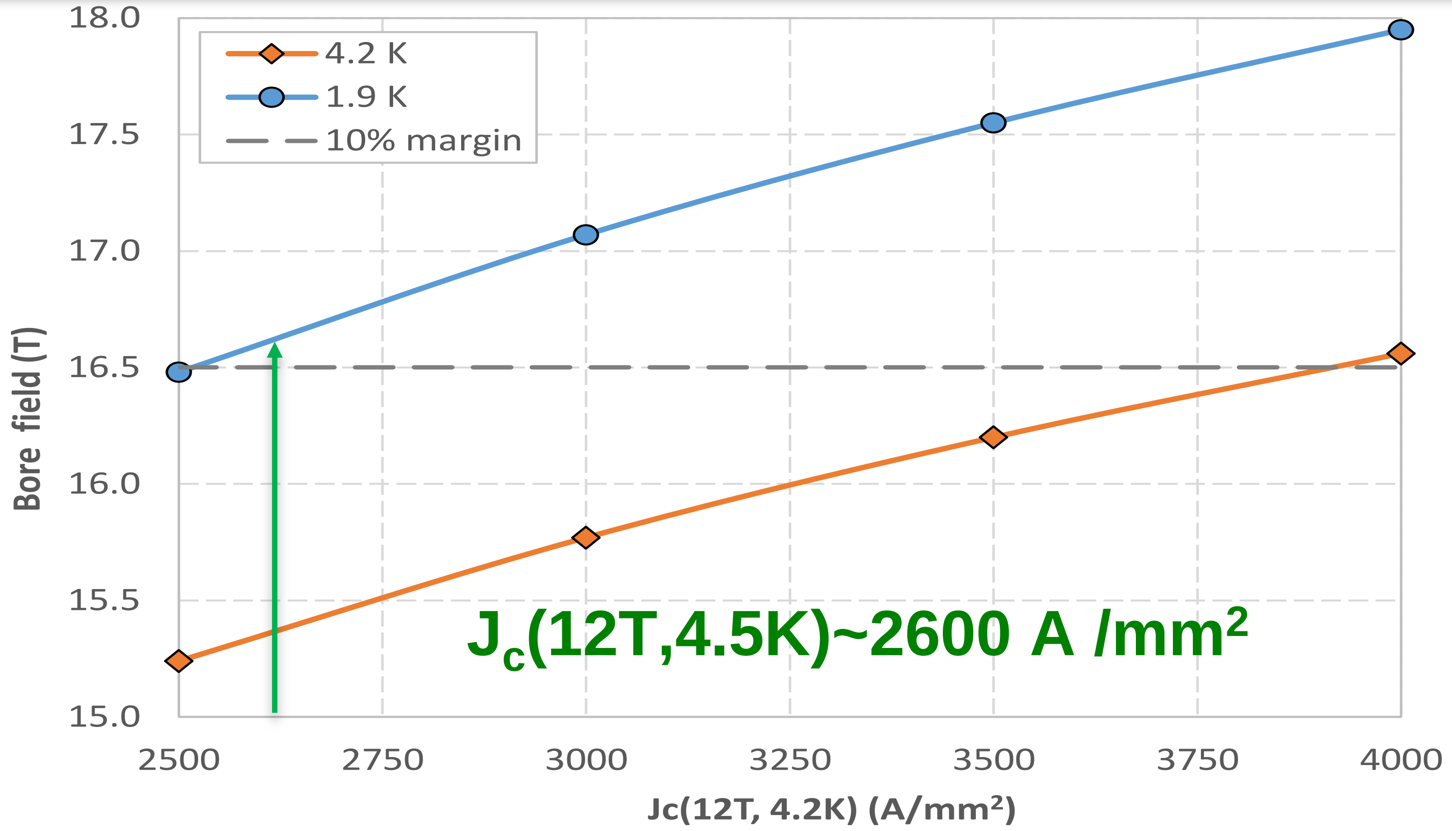


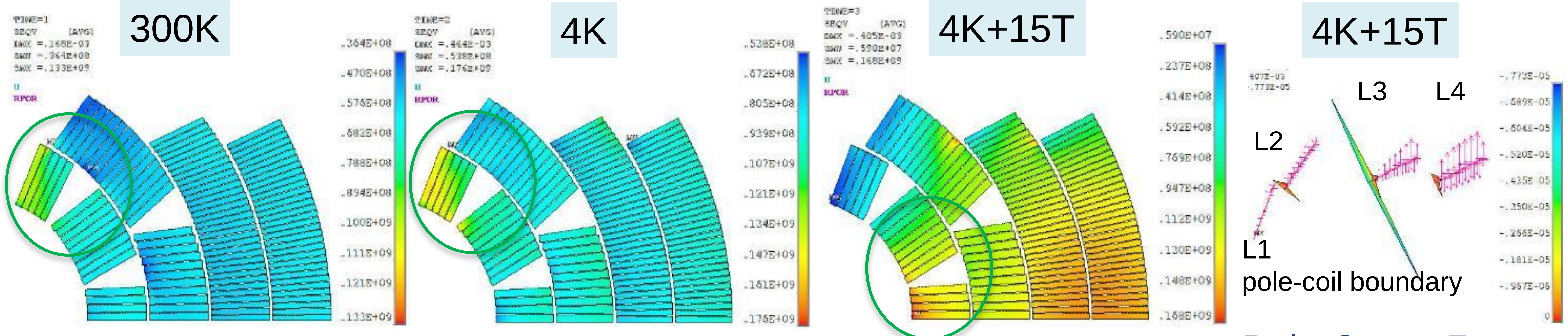
Nb_3Sn strands and cables



Innovative mechanical structure







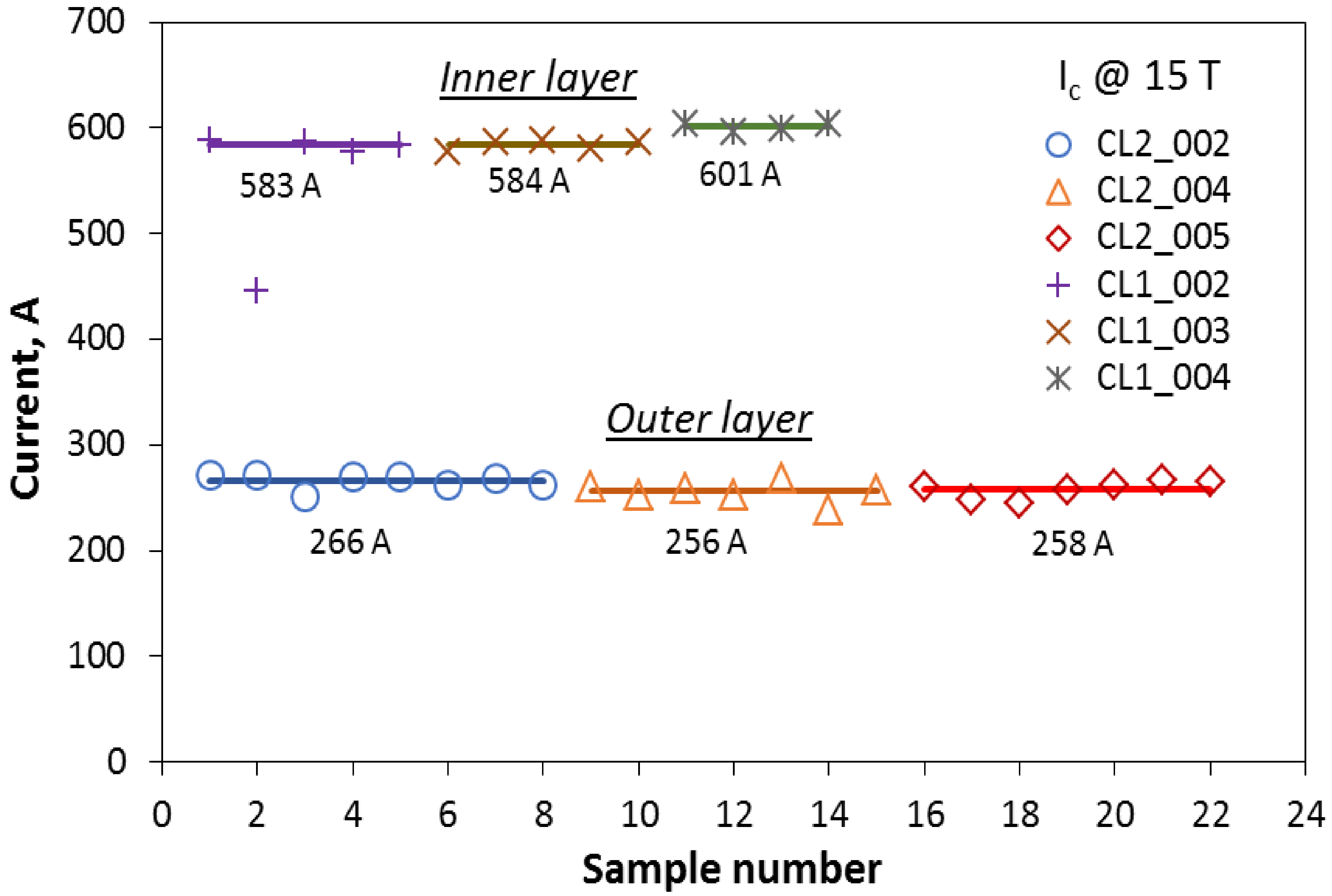
S_{eqv}=133 MPa S_{eqv}=176 MPa S_{eqv}=168 MPa Pole Gap < 7 µm

Conductor limit: **B_{ap}=15.3(16.7)T @ 4.5(1.9)K**

Mechanical limit: **B_{ap}~15T S_{eqv}<180MPa**

Coil fabrication and parameters

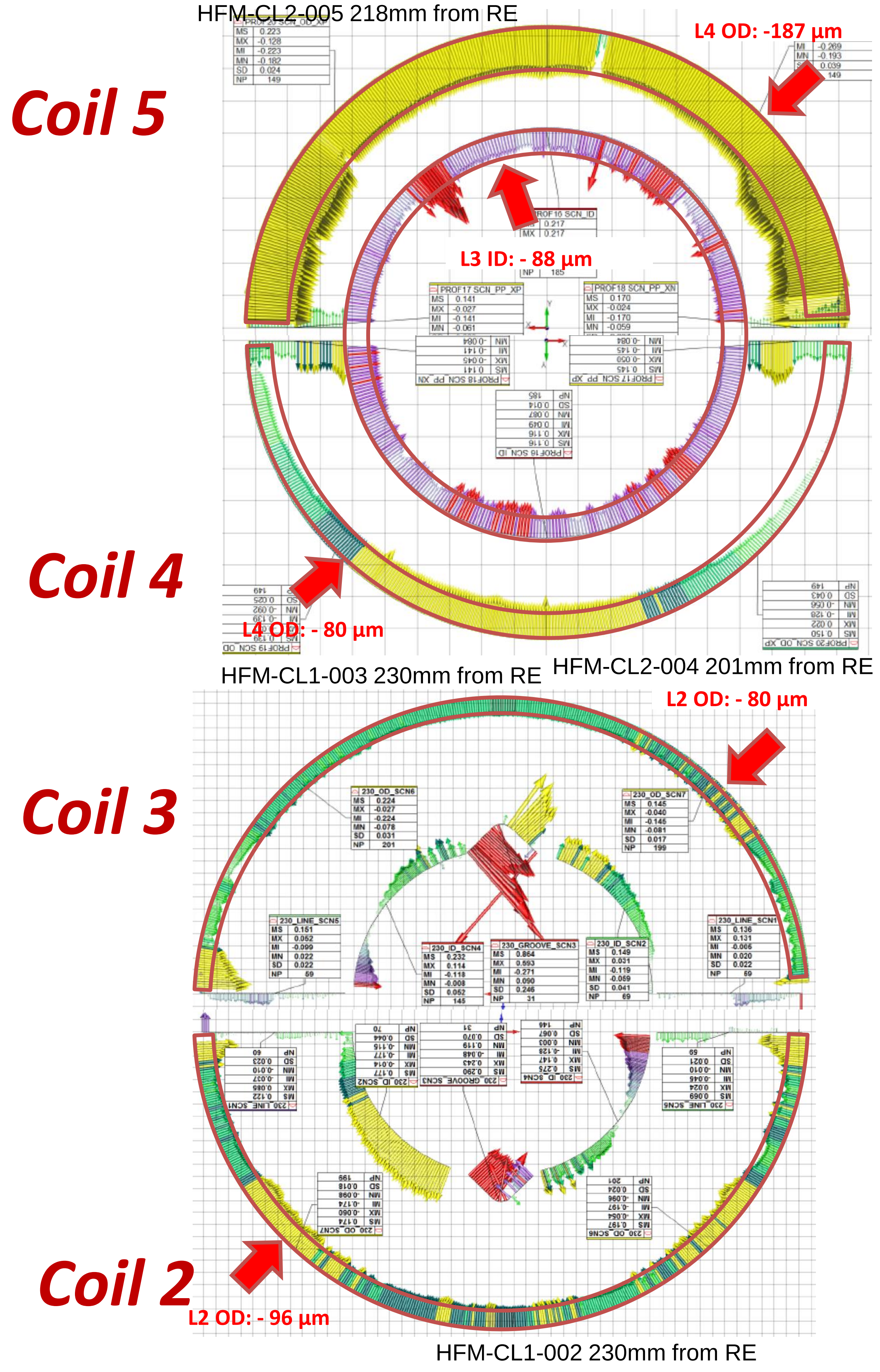
Witness sample test



- **Witness sample data are close to the target I_c**
- **Good reproducibility of witness sample data for IL and OL coils**

Short sample limit: 15.2(16.8)T at 4.5/1.9 K

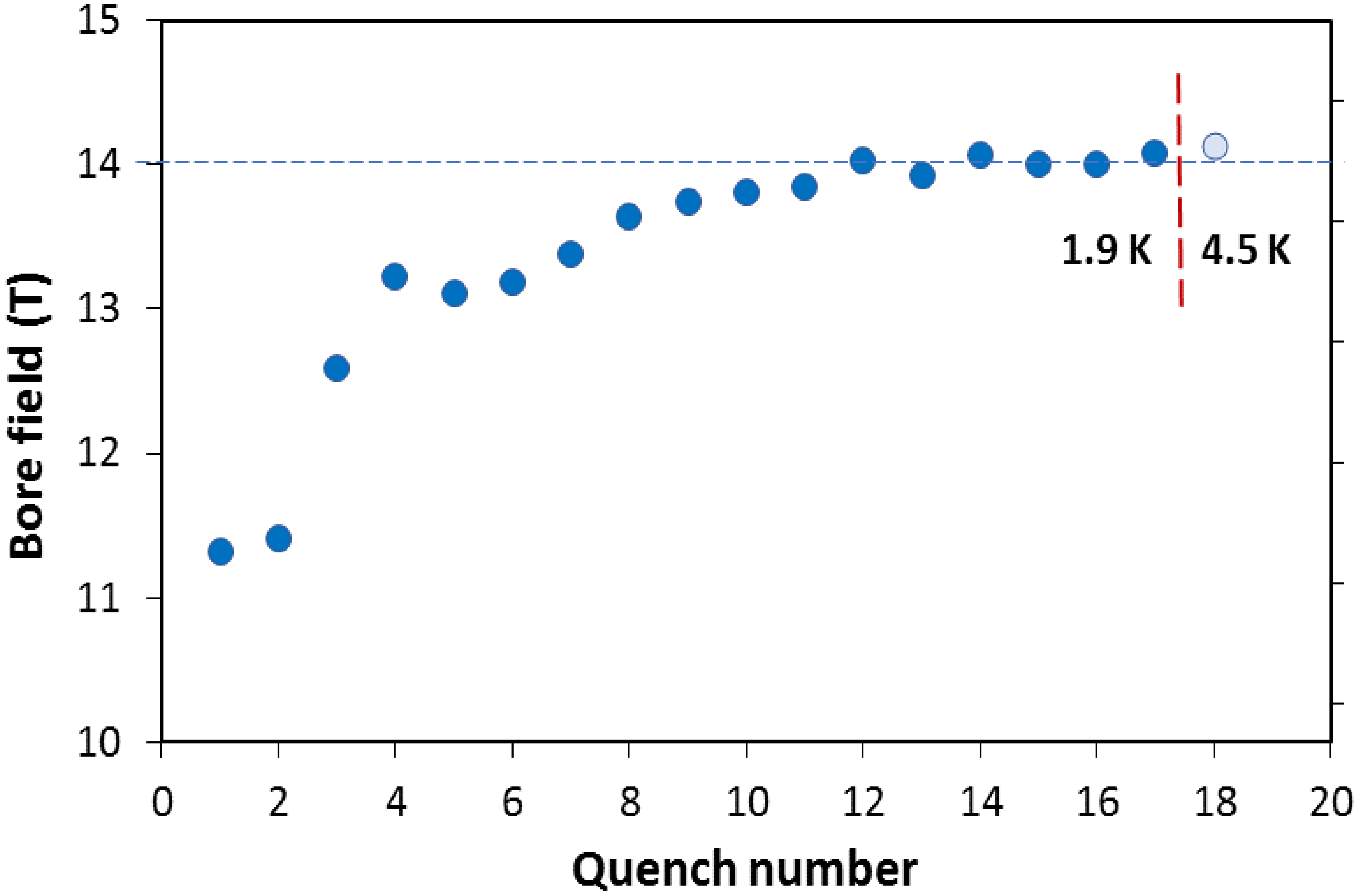
Coil size measurements



Coil interfaces were matched

Magnet assembly and 1st test (June 2019)

Conservative coil pre-stress, σ_{max}<150 MPa at all steps, sufficient to achieve 14 T field



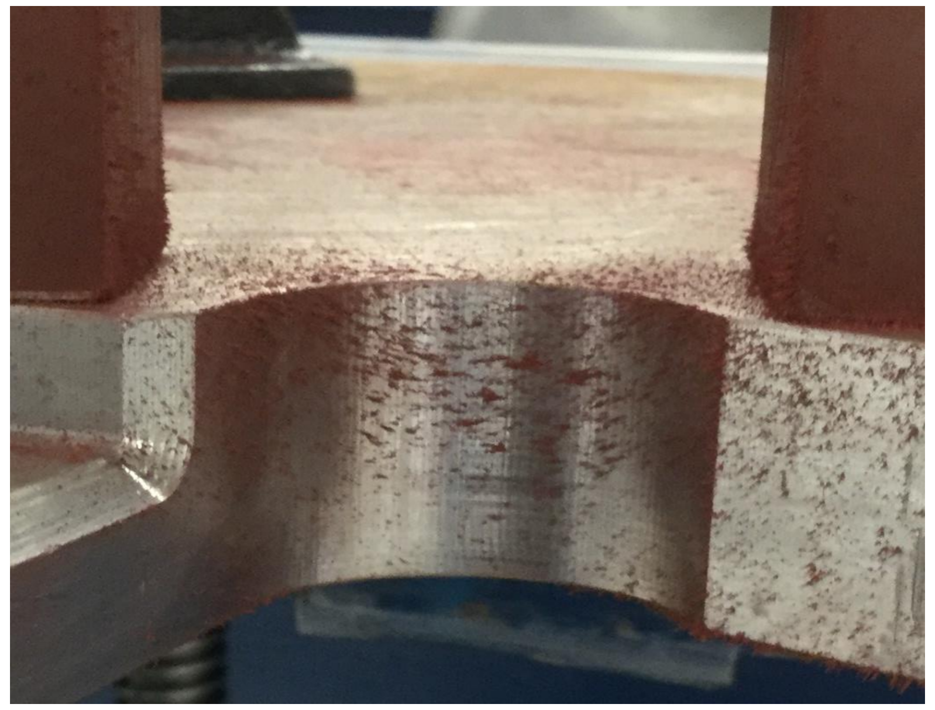
- **11 quenches to plateau**
- **IL: 2 in coil 2**
- **OL: 8 in coil 4 and 7 in coil 5**
- **Last quench at 4.5 K:**

B_{meas} = 14.13±0.02 T

MDPCT1 disassembly, inspection and reassembly

Al clamp test with die penetration technique

Iron lamination test with magnetic powder



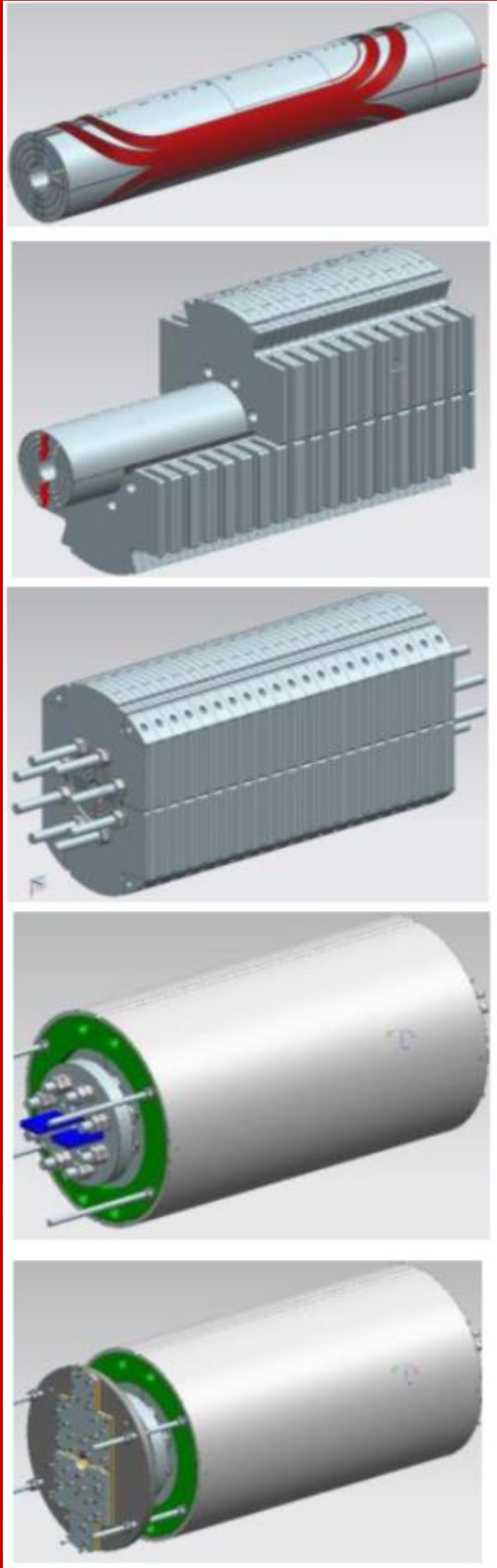
Coil inspection:

L1/L2:

- no coil/pole separation in straight section and ends

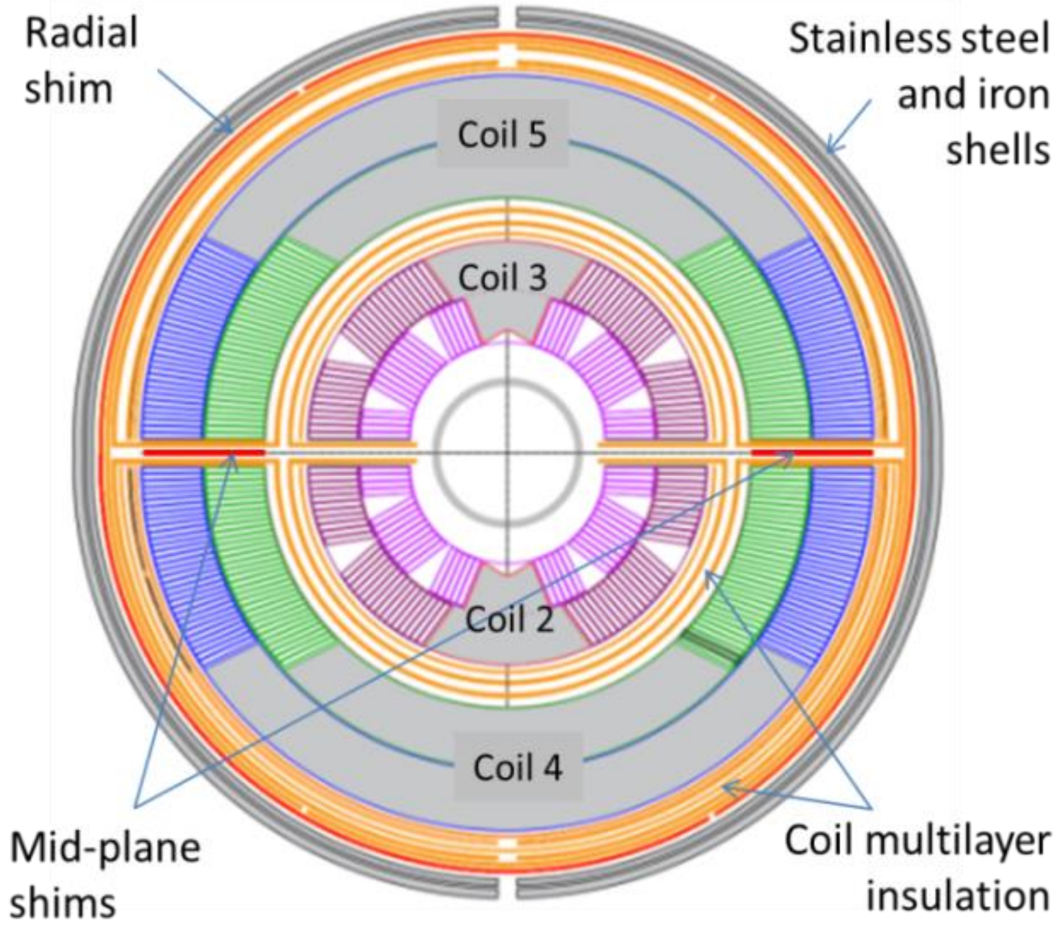
L3/L4:

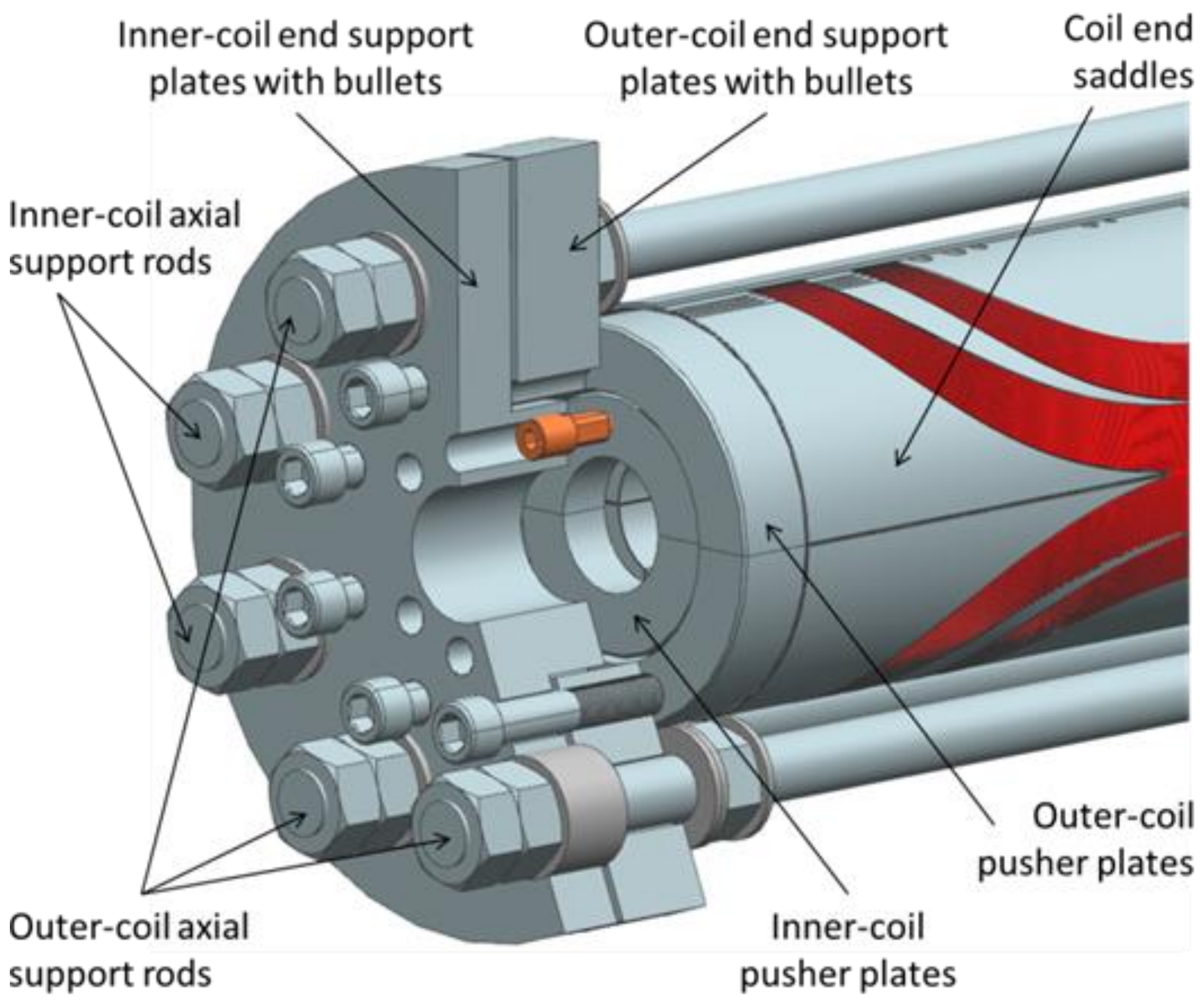
- lost SG and VTs
- coil/pole separation in ends



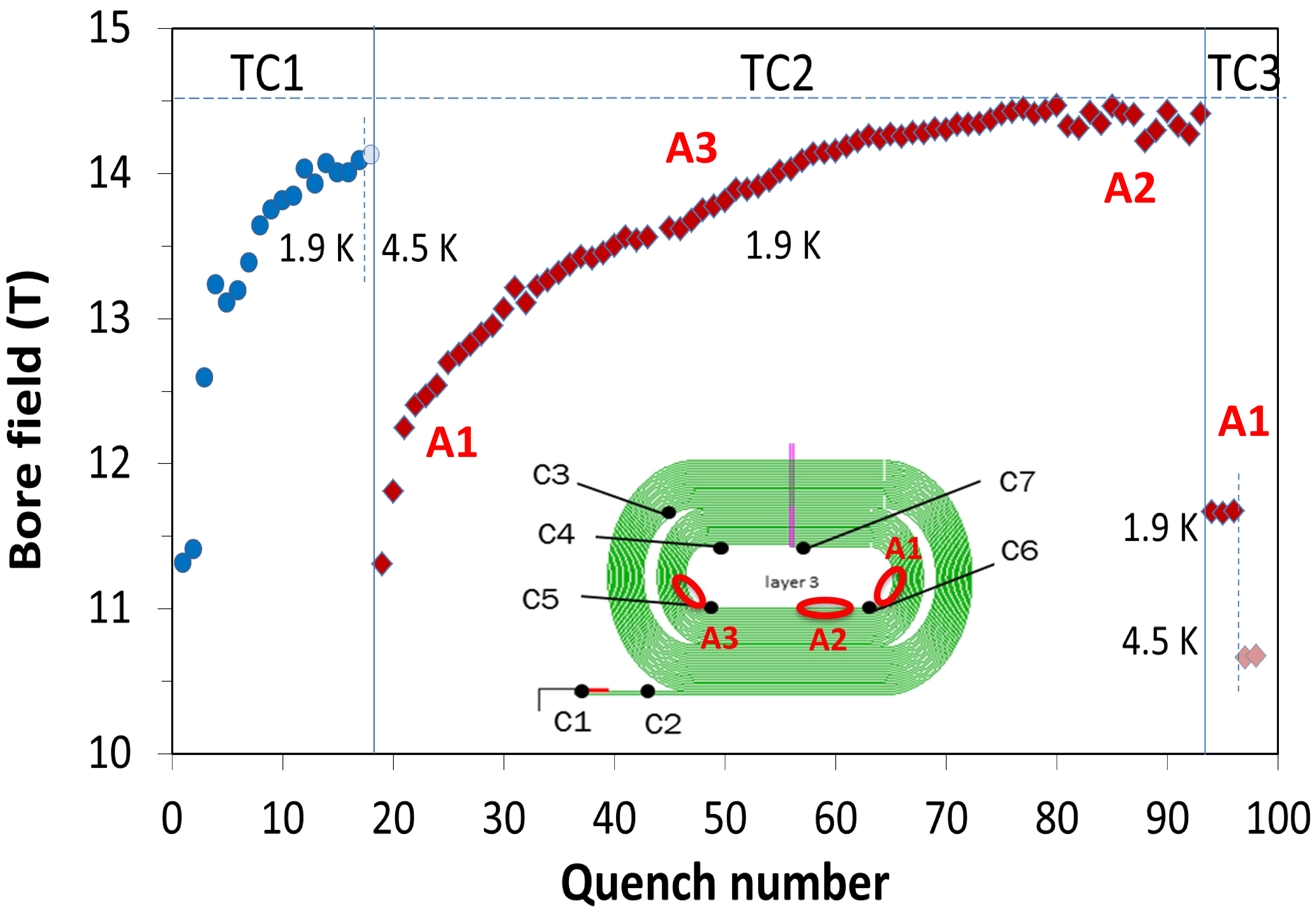
Improvements:

- Outer coil VTs repaired
- The coil azimuthal pre-load increased by ~20 MPa to achieve the test goal of 15 T
- The end plates modified to improve the coil axial support
- Separate 50-mm and 32-mm end plates for IL and OL coils





MDPCT1 training summary in TC1, TC2 and TC3



TC1: May-July 2019

- training stopped after reaching the test target field of 14 T
- all quenches except two were in pole turns of L3-L4 of coils 4 and 5

TC2: May-July 2020

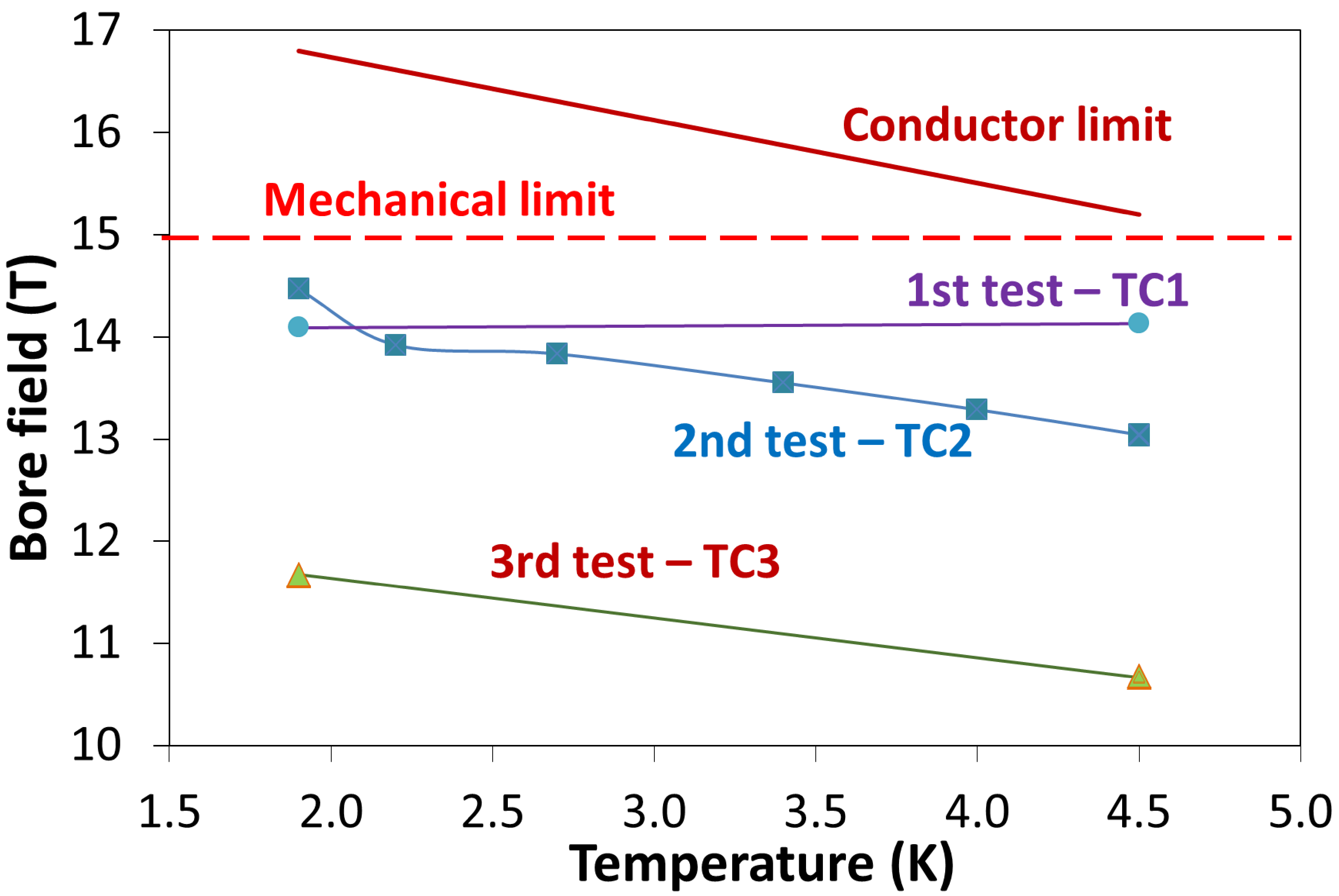
- long training, erratic behavior at plateau, small detraining
- all quenches in pole turns of L3, ~78% in coil 5, area A1 and A3

TC3: August 2020

- no training, large performance degradation
- all quenches in pole turns of L3, in coil 5, area A1

More details on magnet training in the next talk by S. Stoynev

MDPCT1 quench performance summary



TC1:
- **Test target field - 14 T**
- **B_{max} =14.1 T @4.5K, 93% of SSL - *world record field at 4.5 K for accelerator magnets***

TC2:
- **Test target field - 15 T**
- **B_{max}=14.5 T @1.9K *- world record field at 1.9 K for accelerator magnets***

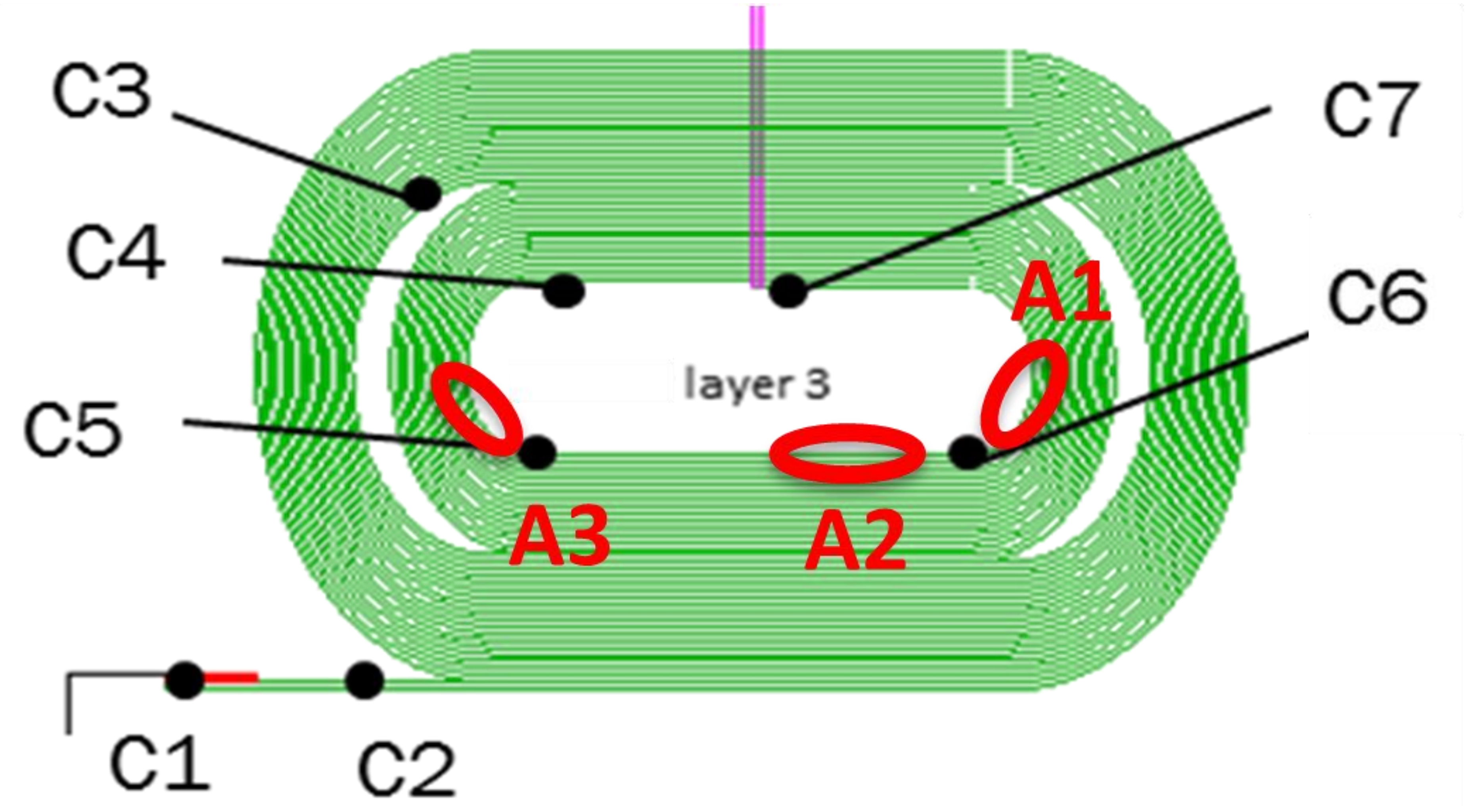
TC3:
- **Test target field - 14.5 T**
- **B_{max}=11.7 T @1.9K**

I_q(T) data show that the magnet has been trained in TC2 and TC3 to its conductor limit.

Large I_q degradation in TC2 and TC3.

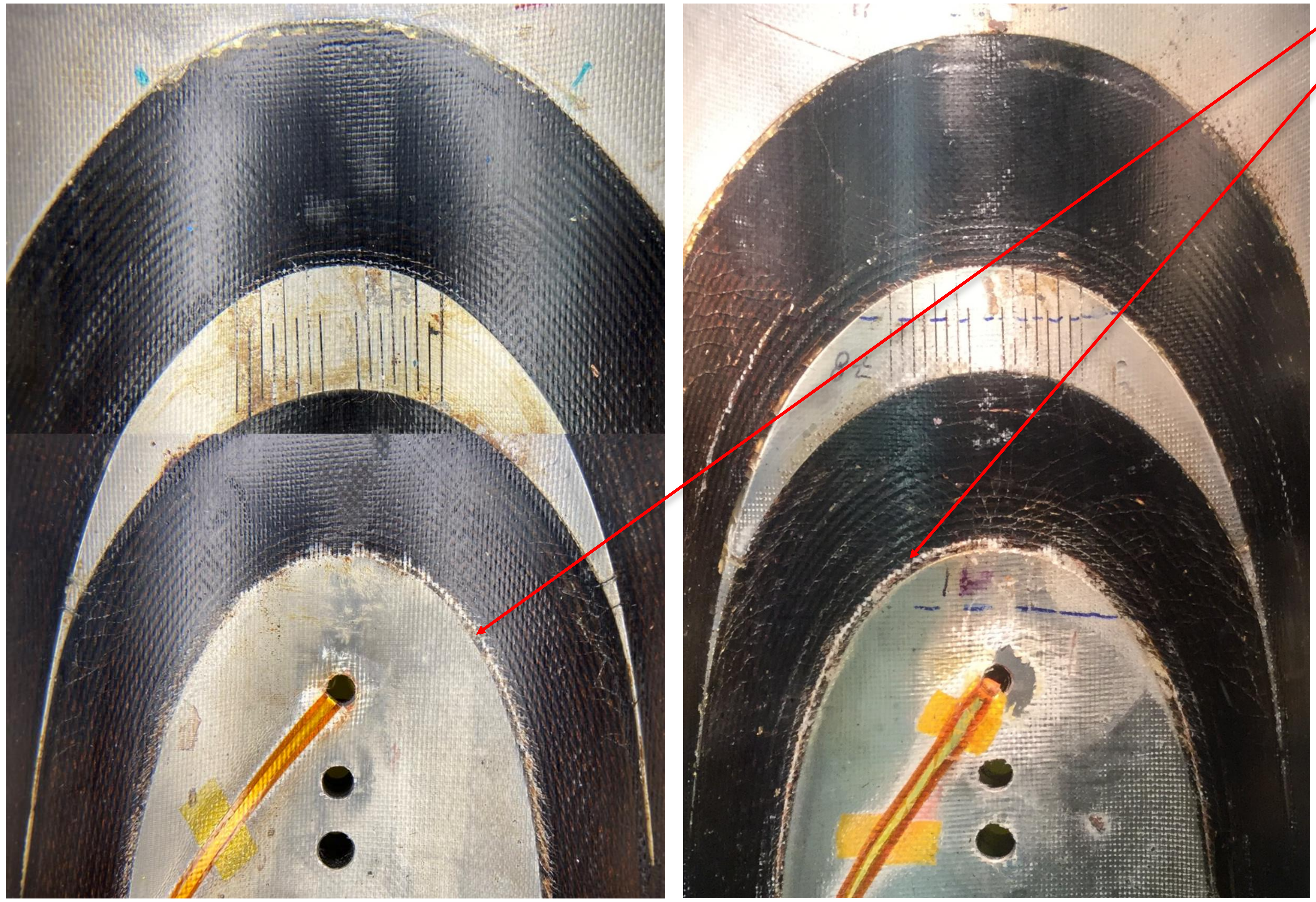
Post testing inspection and analysis

- Magnet disassembly
- Inspection of mechanical structure
  - no visible defects were found
- Inspection of inner and outer coils
  - focus on coils 4 and 5 surface in areas A1 (RE), A2 (straight section) and A3 (LE)

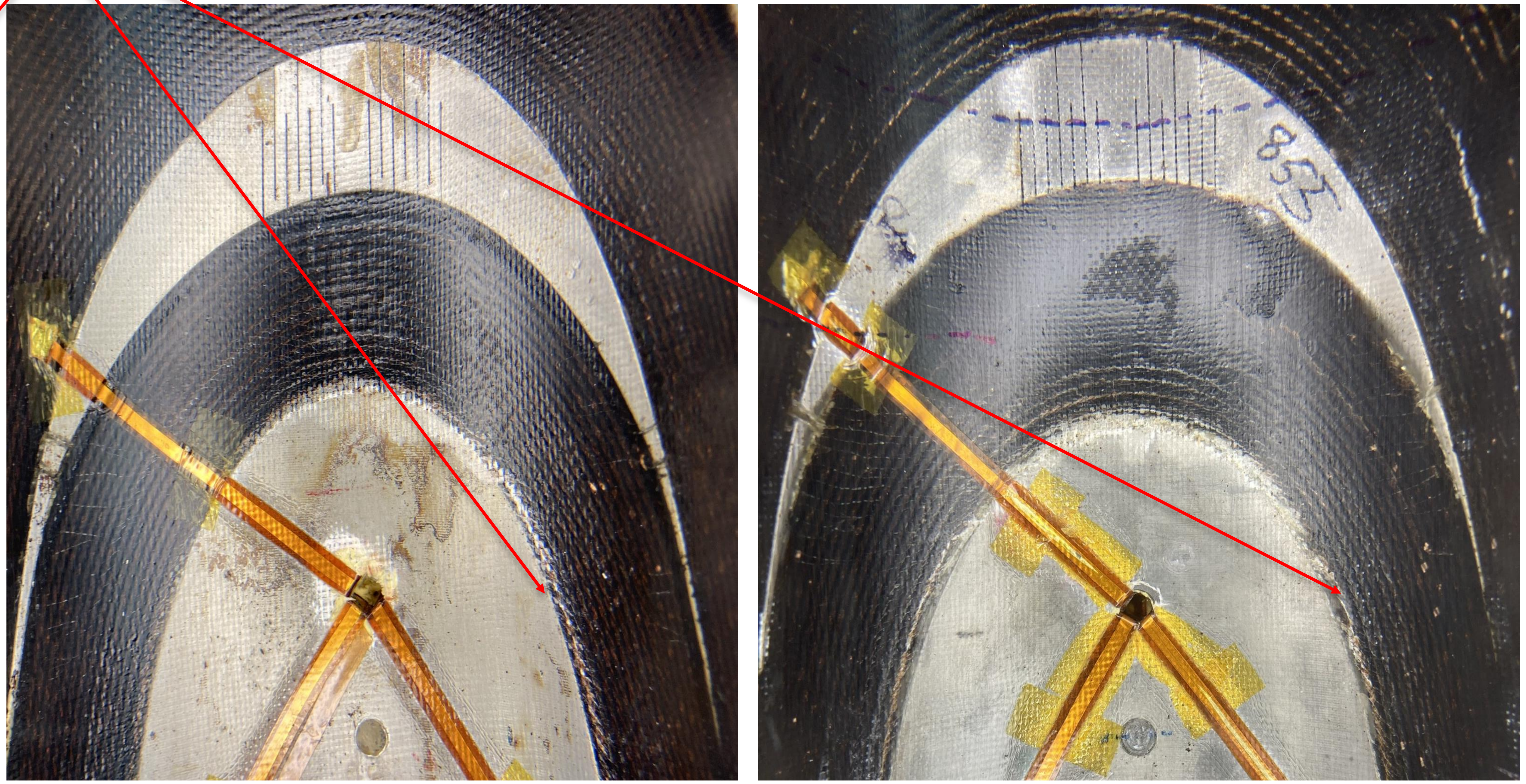


Inner layer of coils 4&5 RE/LE after magnet test

Epoxy cracking and pole turn separation in LE and RE of both coils



Coil 4 Return End Coil 5



Coil 4 Lead End Coil 5

Degradation of coil 4 (smaller than coil 5) is not excluded.

Inner layer RE view of coil 5 at different stages

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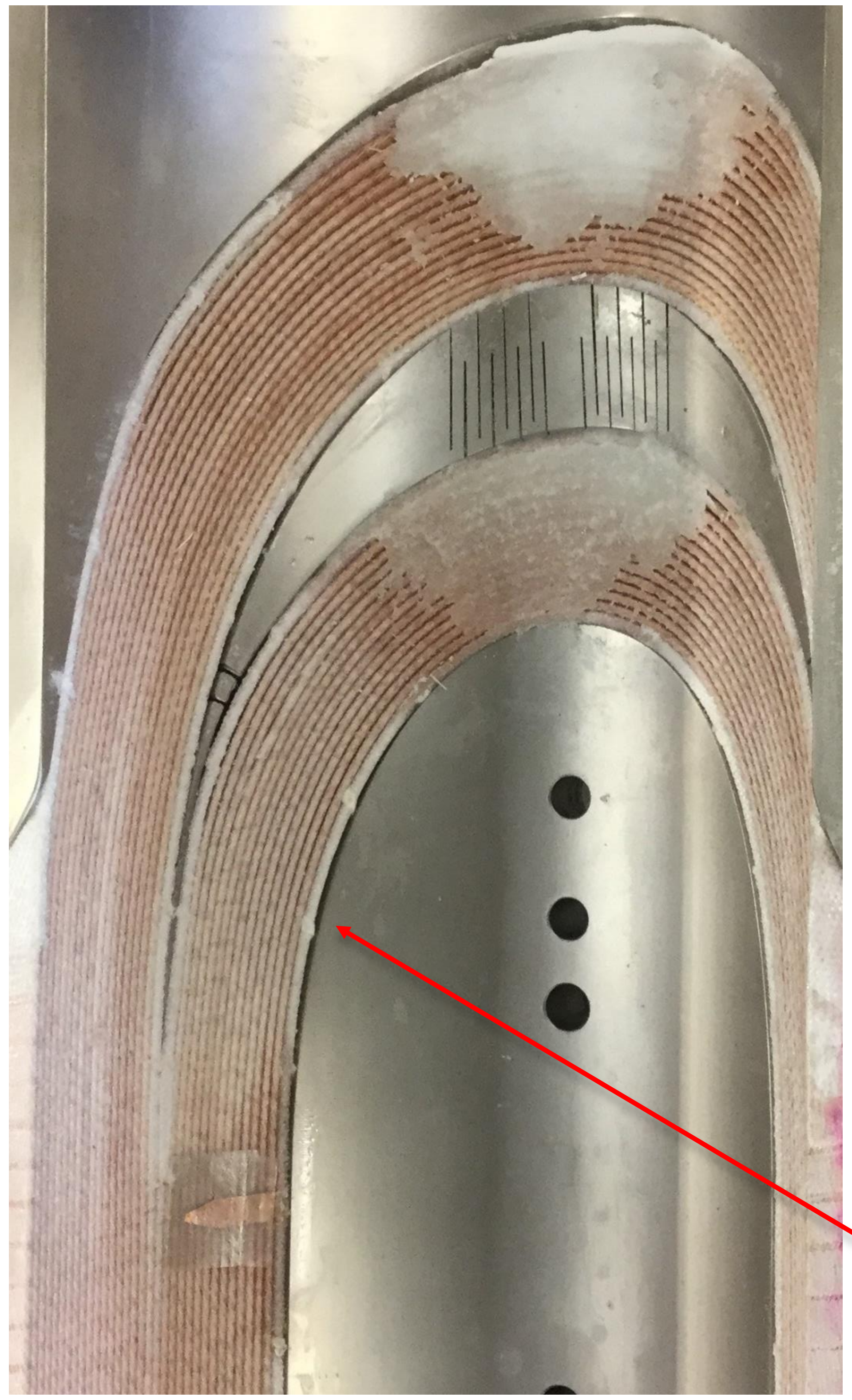
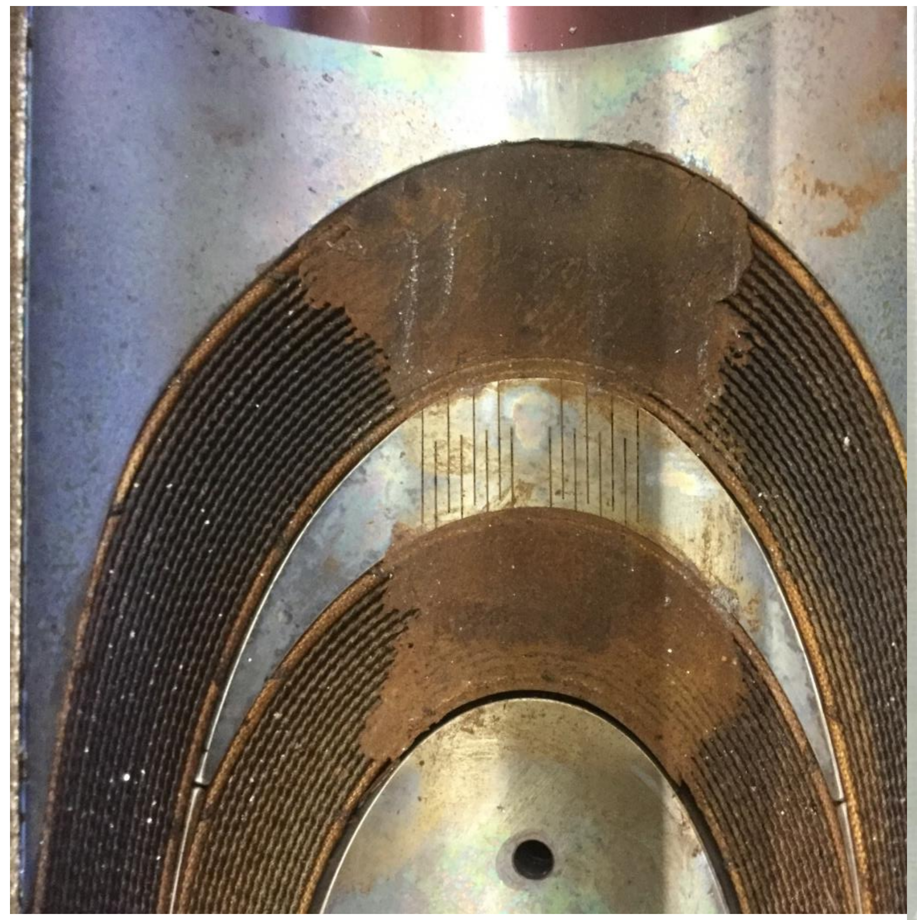
After curing



After reaction



Before impregnation

After impregnation

After cold test

glass filler

pole turn,
extra insulation

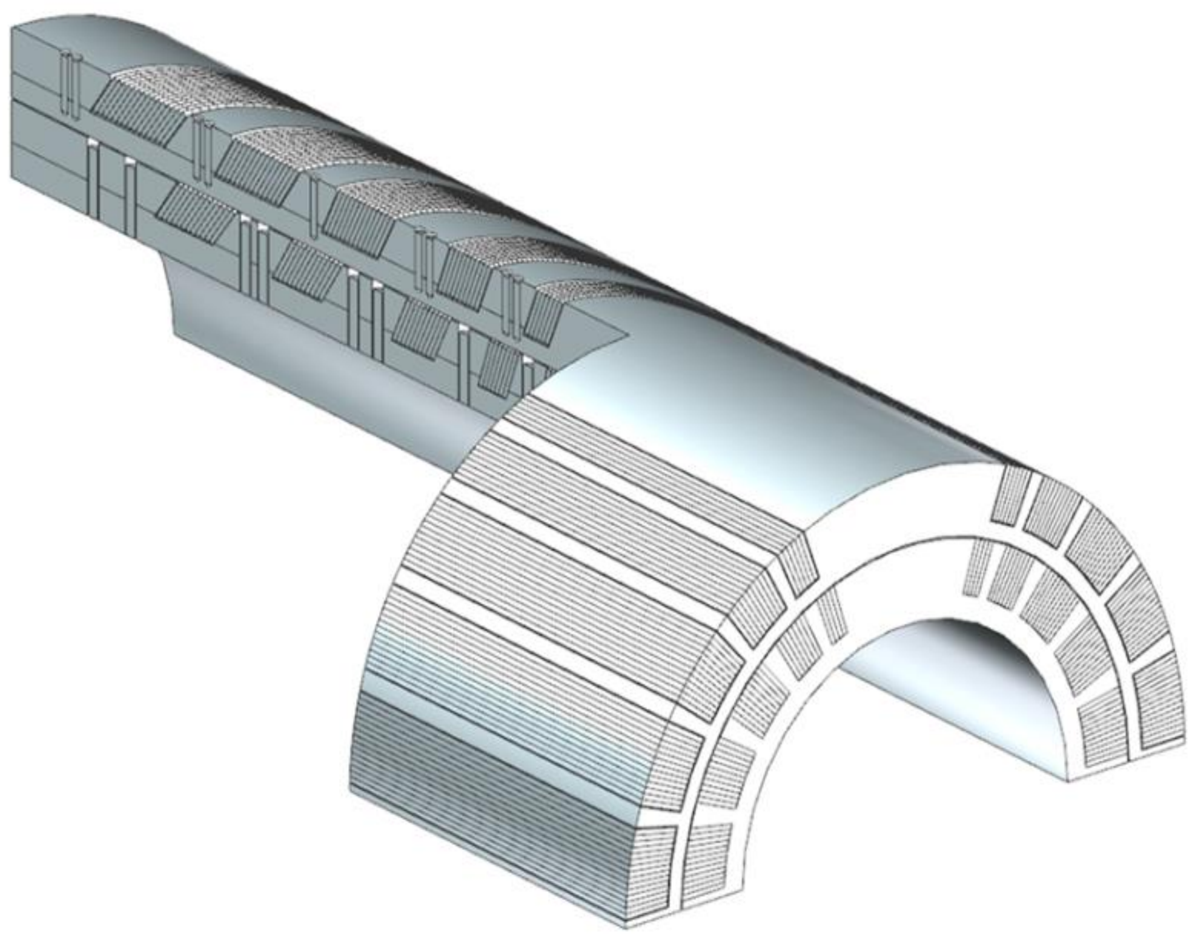
Inner layer was
wound/cured/rewound

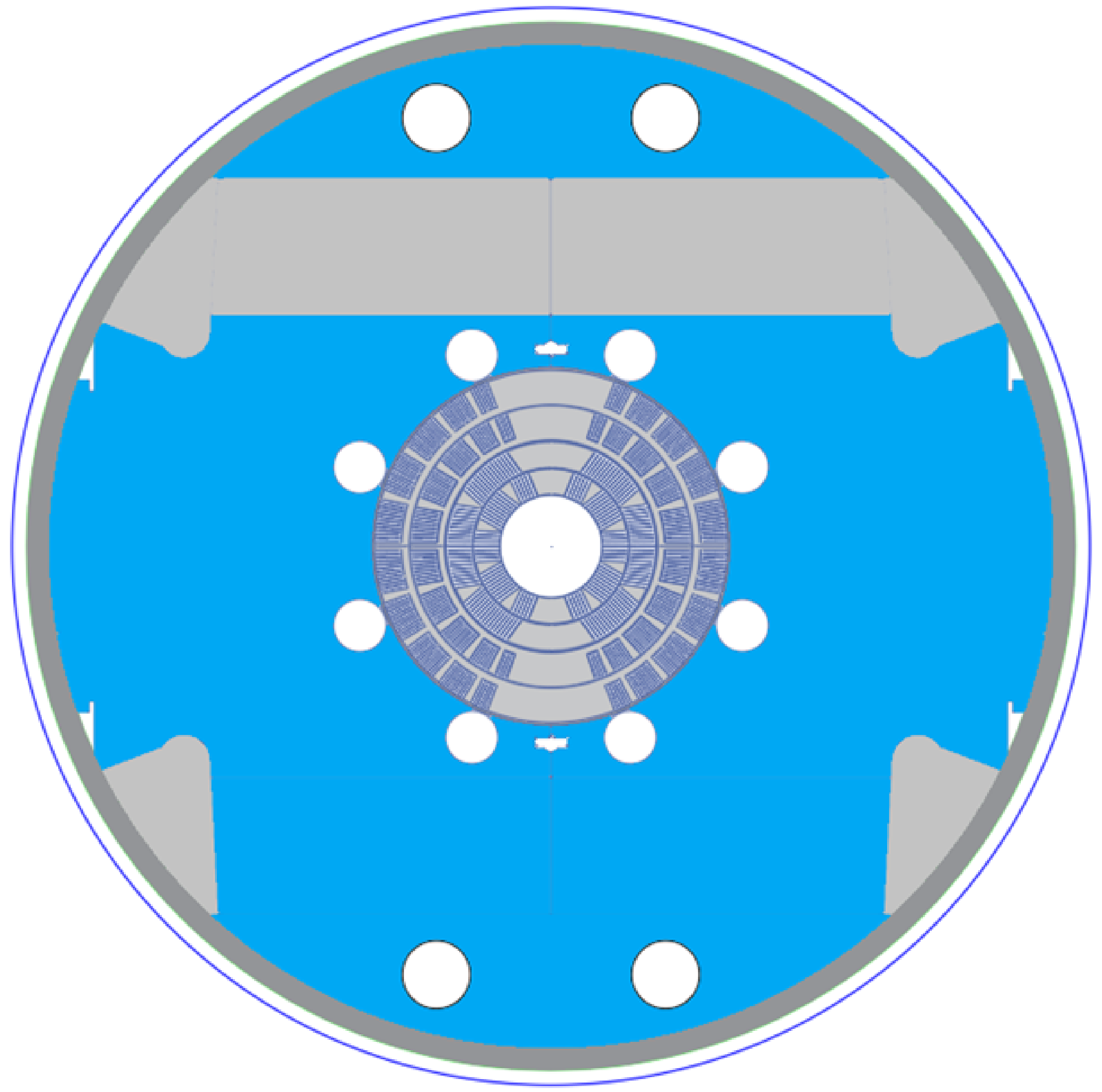
No clear evidence why coil 5 limits magnet performance.

Next step - nondestructive CT scan of coil 5 in Germany.

diondo x-ray systems and services

Lessons learned

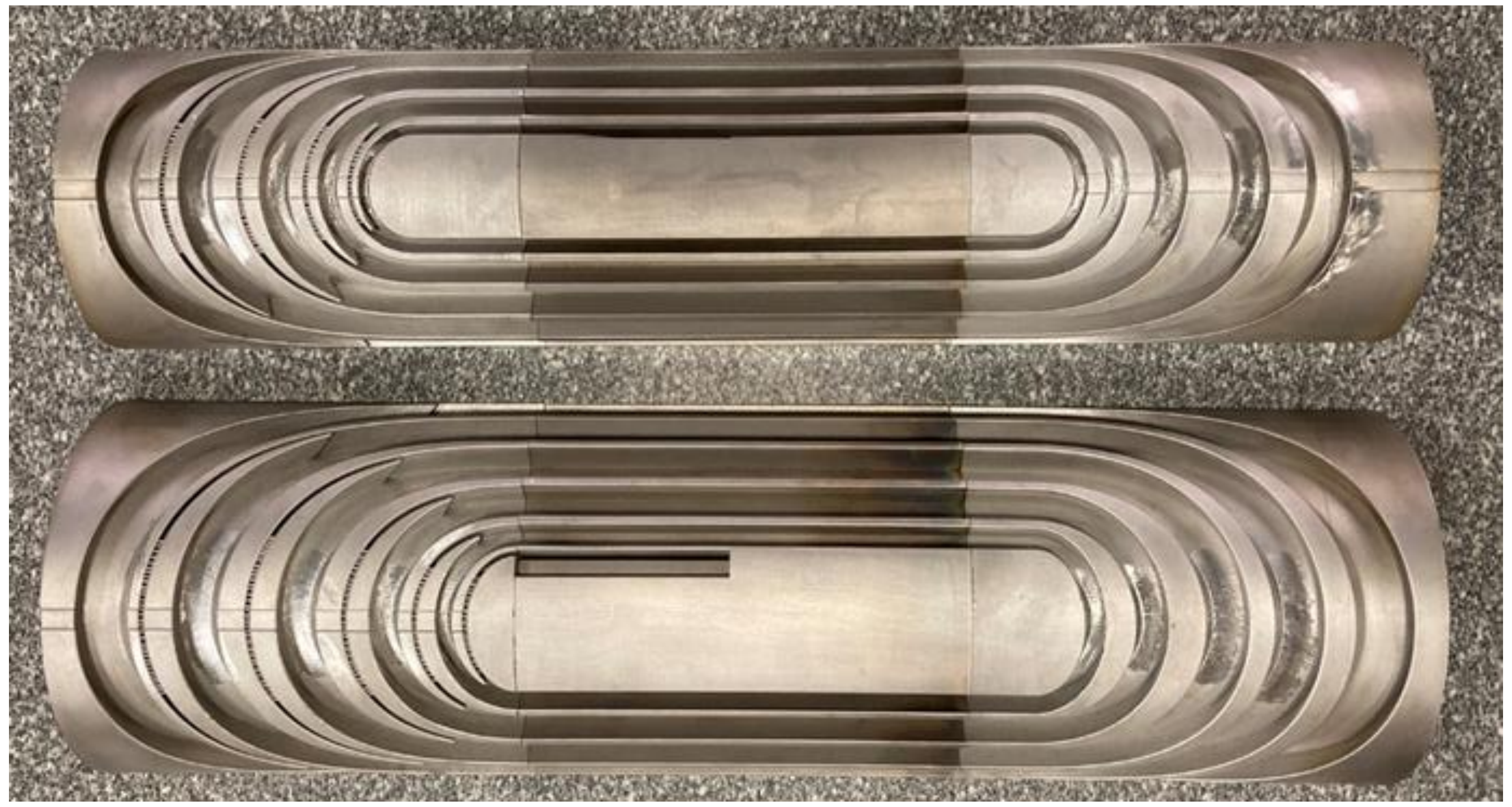


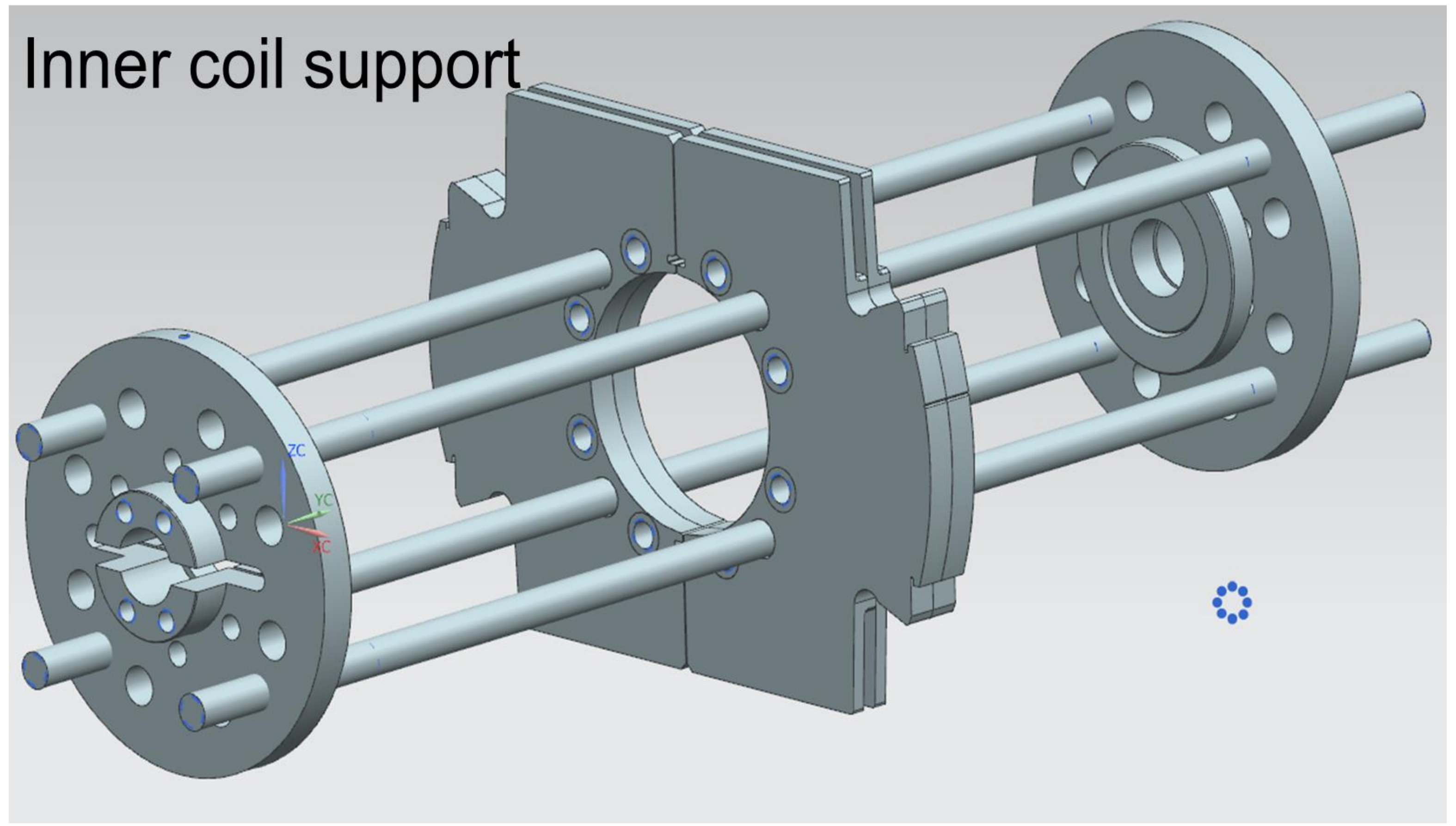


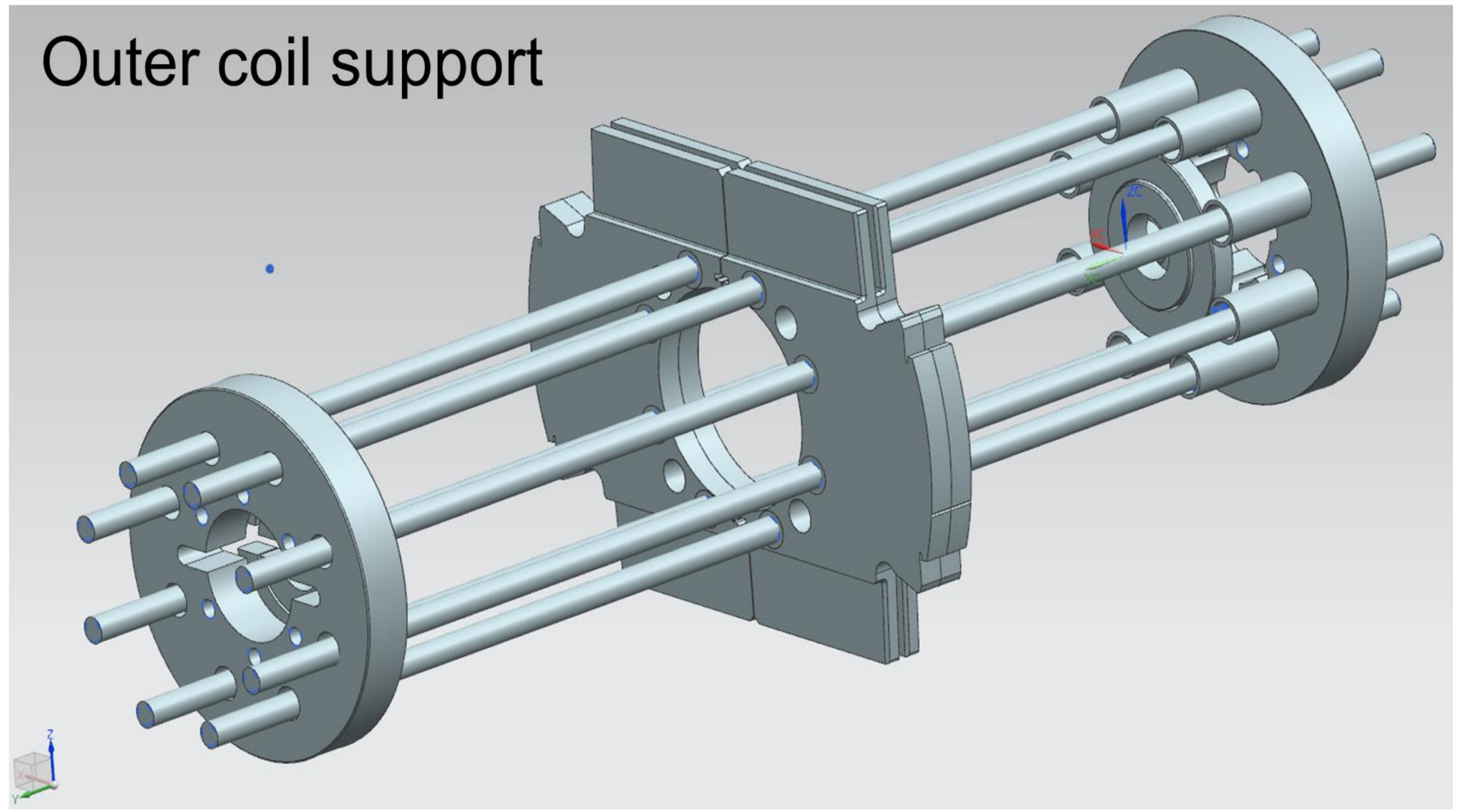
- ***Lesson 1***: Stress management (SM) structure to be used in outer layers L3-L4 to improves turn azimuthal and axial support and transfer radial forces

  (Details are in I. Novitski talk)

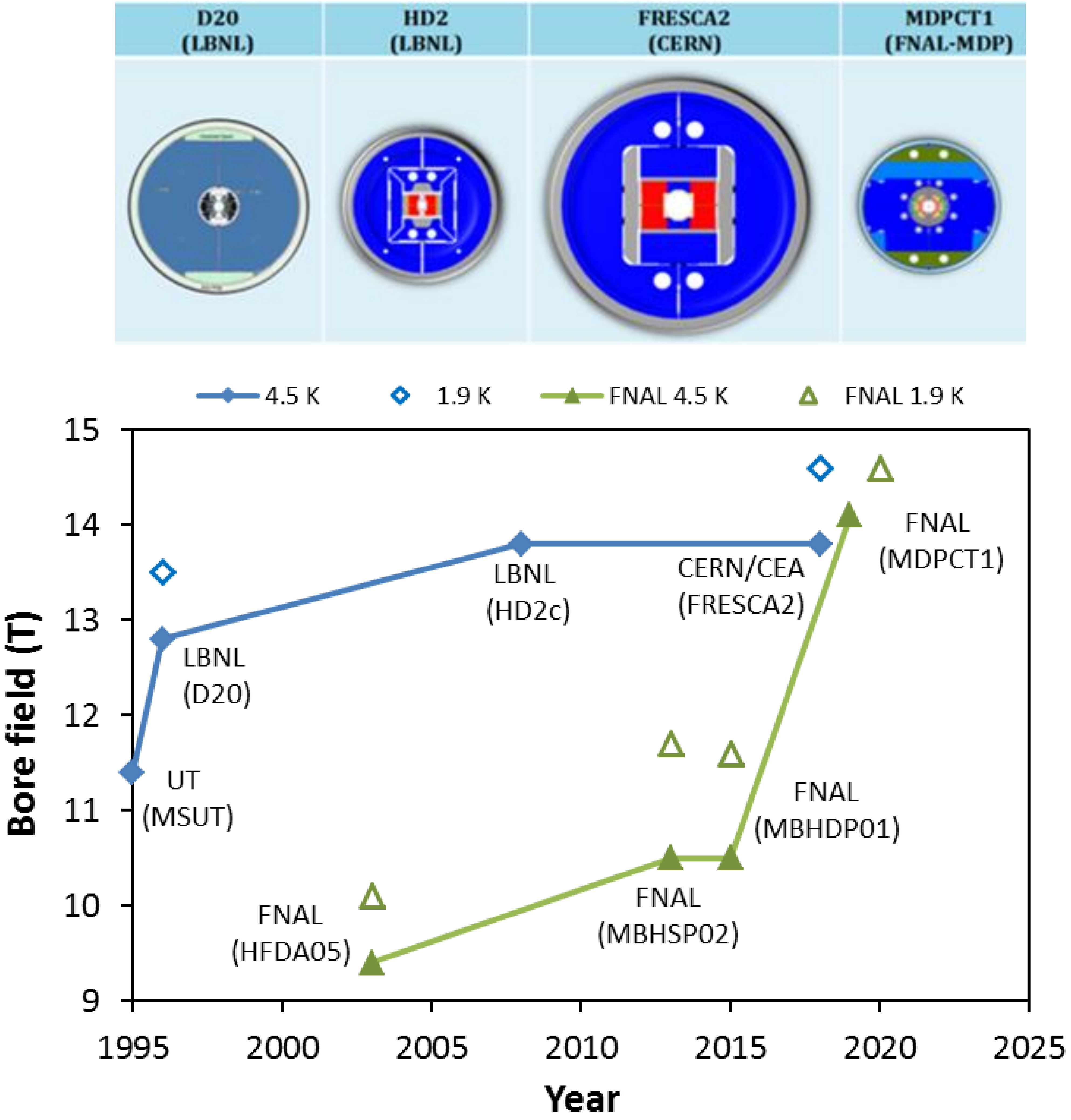
- ***Lesson 2***: Since MDPCT structure will be used to test 4-layer magnets with SMCT and regular coils to achieve the fields up to 17 T, axial support system to be reinforced
  - 4 new rods for inner coils and 6 old rods for outer SMCT coils
  - SMCT coil rod anchoring







MDPCT program summary



- The goals of the MDPCT1 program have been achieved
  - graded 4-layer coil, innovative support structure, magnet technologies were developed
  - magnet performance parameters were tested
  - maximum bore field of 14.5-14.6 T @1.9 K is 97% of the program goal
  - the field levels achieved in MDPCT1 @4.5/1.9 K (with FRESCA2 result at 1.9 K) set ***new world records for Nb_3Sn accelerator magnets***

- The lessons learned from the MDPCT1 program are being implemented in SMCT coils

Result publications

1. A.V. Zlobin, N. Andreev, E. Barzi, V.V. Kashikhin, I. Novitski, “Design concept and parameters of a 15 T Nb_3Sn dipole demonstrator for a 100 TeV hadron collider”, Proc. of IPAC2015, Richmond, VA, USA, p.3365.
2. V.V. Kashikhin, N. Andreev, E. Barzi, I. Novitski, A.V. Zlobin, “Magnetic and structural design of a 15 T Nb_3Sn accelerator dipole model”, CEC/ICMC2015, IOP Conference Series: Materials Science and Engineering, v.101, issue 1, p.012055, 2015
3. I. Novitski, N. Andreev, E. Barzi, J. Carmichael, V. V. Kashikhin, D. Turrioni, M. Yu, and A. V. Zlobin, “Development of a 15 T Nb_3Sn Accelerator Dipole Demonstrator at Fermilab”, IEEE TAS, Vol. 26, Issue 3, June 2016, 4001007.
4. E. Barzi, N. Andreev, P. Li, V. Lombardo, D. Turrioni, and A. V. Zlobin, “Nb_3Sn RRP® Strand and Rutherford Cable Development for a 15 T Dipole Demonstrator,” IEEE TAS, Vol. 26, Issue 3, June 2016, 4001007.
5. I. Novitski, A.V. Zlobin, “Development and Comparison of Mechanical Structures for FNAL 15 T Nb_3Sn Dipole Demonstrator”, Proc. of NAPAC2016, Chicago, IL, USA MOPOB30, p.137
6. E. Barzi, M. Bossert, M. Field, P. Li, H. Miao, J. Parrell, D. Turrioni, A.V. Zlobin, “Heat Treatment Optimization of Rutherford Cables for a 15 T Nb_3Sn Dipole Demonstrator”, IEEE TAS, Vol. 27, Issue 4, 2017, 4802905
7. C. Kokkinos, I. Apostolidis, J. Carmichael, T. Gortsas, S. Kokkinos, K. Loukas, I. Novitski, D. Polyzos, D. Rodopoulos, D. Schoerling, D. Tommasini,.and A.V. Zlobin, “FEA Model and Mechanical Analysis of the Nb_3Sn 15 T Dipole Demonstrator,” IEEE TAS, Vol. 28, Issue 3, April 2018, 4007406
8. C. Orozco, J. Carmichael, I. Novitski, S. Stoynev, A.V. Zlobin, “Assembly and Tests of Mechanical Models of the 15 T Nb_3Sn Dipole Demonstrator,” IEEE TAS, Vol. 29, Issue 5, August 2019, 4003404
9. A.V. 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, “Quench performance and field quality of the 15 T Nb_3Sn dipole demonstrator MDPCT1 in the first test run”, Proc. of NAPAC2019, September 2019. MOPLO20
10. A.V. Zlobin, I. Novitski, V.V. Kashikhin, E. Barzi, J. Carmichael, S. Caspi, G. Chlachidze, S. Krave, C. Oroz-co, D. Schoerling, S. Stoynev, D. Tommasini, D. Turrioni, “Development and First Test of the 15 T Nb_3Sn Dipole Demonstrator MDPCT1”, IEEE TAS, Volume 30, Issue 4, 2020
11. T. Strauss, E. Barzi, J. DiMarco, V.V. Kashikhin, I. Novitski, M. Tartaglia, G. Velev, A.V. Zlobin, “First field measurements of the 15 T Nb_3Sn Dipole Demonstrator MDPCT1”, IEEE TAS, Volume 30, Issue 4, 2020,
12. A.V. Zlobin, I. Novitski, E. Barzi, M. Baldini, J. Carmichael, S. Caspi, V.V. Kashikhin, S. Krave, C. Orozco, D. Schoerling, S. Stoynev, D. Tommasini, D. Turrioni, “Reassembly and Test of High-Field Nb3Sn Dipole Demonstrator MDPCT1”, IEEE TAS, Vol. 31, Issue 5, 2021.
13. J. DiMarco, M. Baldini, E. Barzi, V. Kashikhin, I. Novitski, T. Strauss, M. Tartaglia, G. Velev, A. Zlobin, “Field Measurement Results of the 15 T Nb3Sn Dipole Demonstrator MDPCT1b,” IEEE TAS, Vol. 31, Issue 5, 2021.

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