U.S. MAGNET DEVELOPMENT PROGRAM

Nb_3Sn cos-theta magnets: program status and next steps

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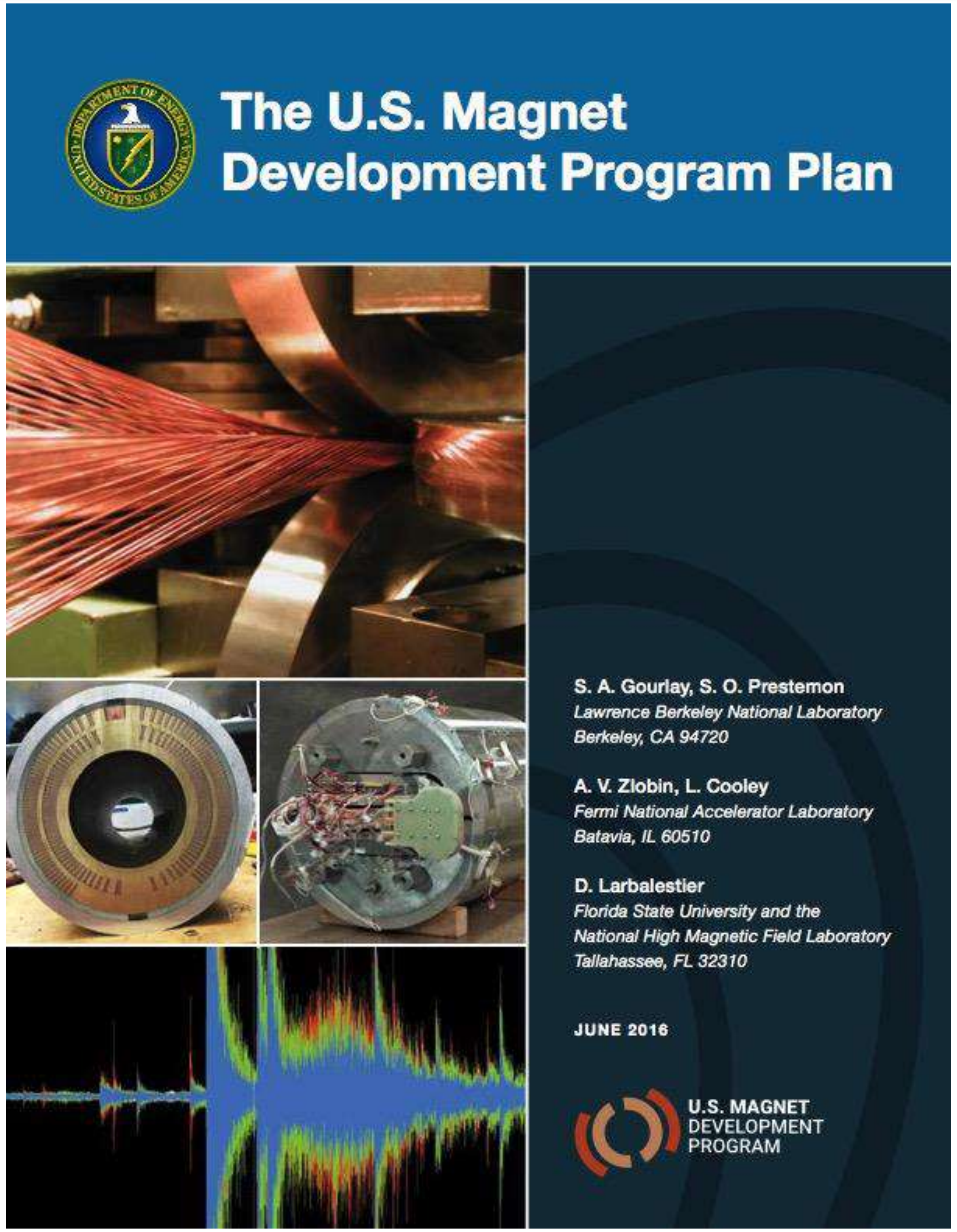
Outline

- 2016-2019 Nb_3Sn cos-theta magnet R&D plan and results
  - Step 1: 15 T dipole demonstrator (MDPCT1) development and test
  - Step 2: MDPCT1 preload optimization
  - Step 3: Magnet design studies
- 2020-2023 Nb_3Sn cos-theta dipole program proposal



Nb_3Sn cos-theta magnets: 2016-2019 plan and work status

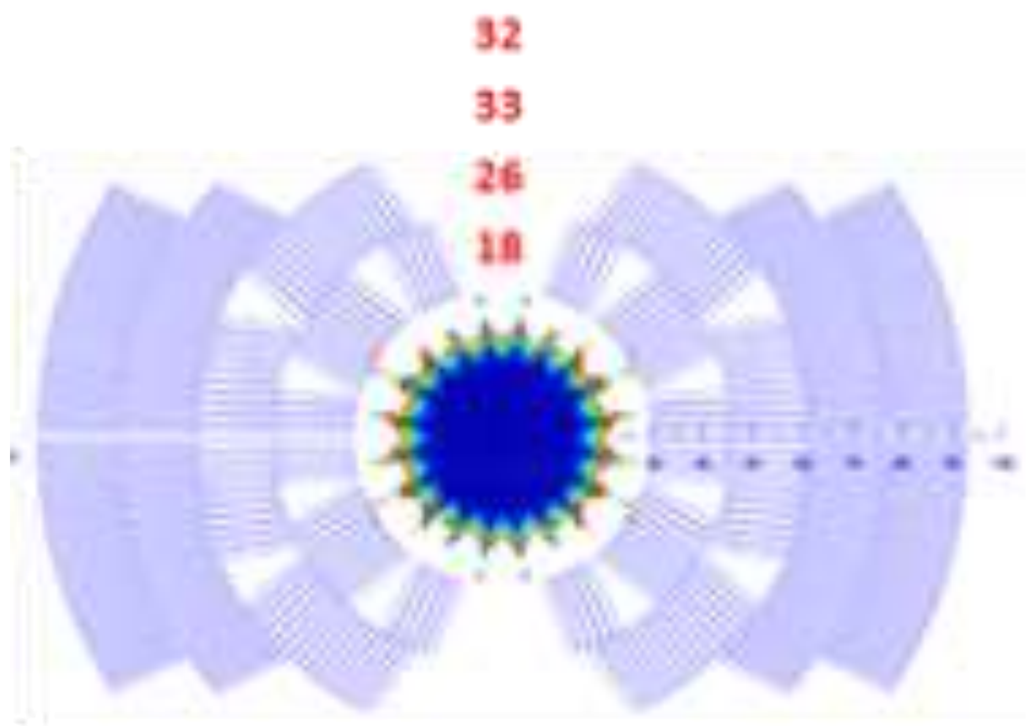
2016	2017	2018	2019
Push traditional Cos-theta technology to its limit with newest conductor and structure			

Cos-theta 4 layer 15 T	Preload mods	15 T with improvements	4-layer 16 T Cos-theta
Leverage latest Nb_3Sn and Bladder and Key structure	Impact of preload on training		Optimized 16 T design as baseline

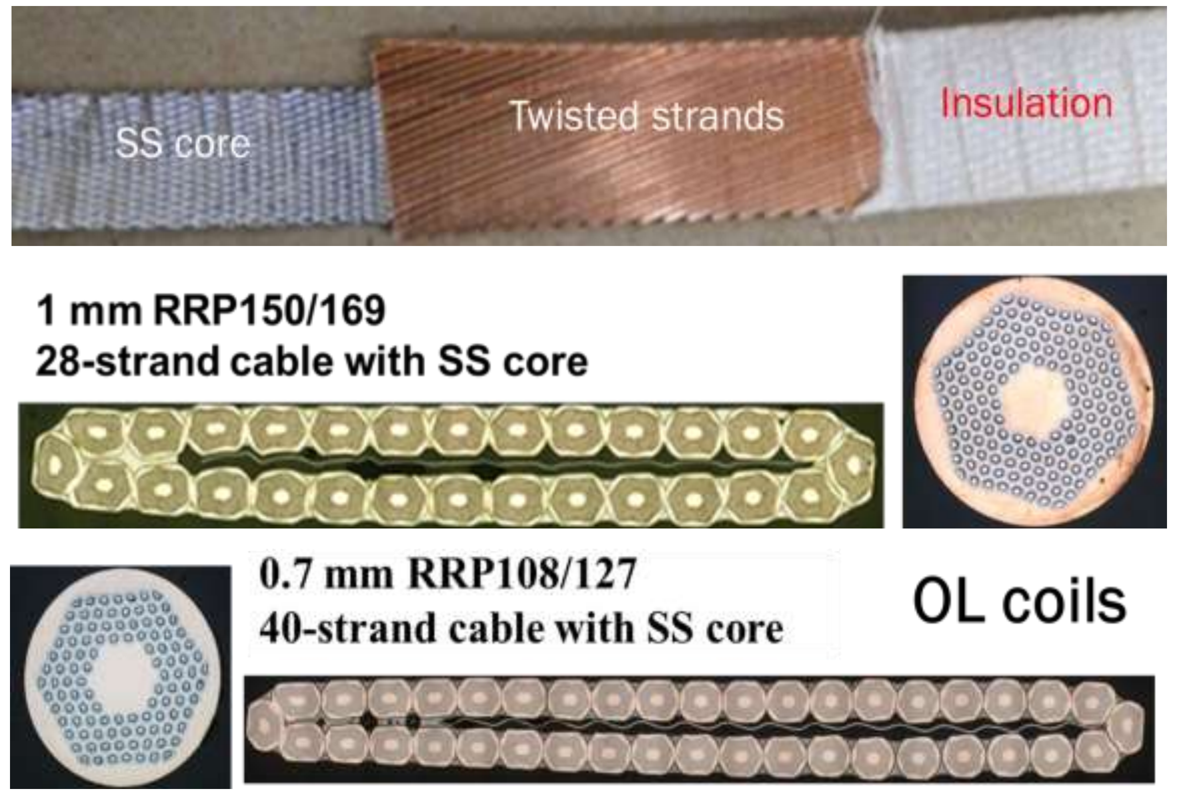
- ***Step 1***: 15 T dipole demonstrator design – the field target has been changed to 14 T - *done, the magnet was tested up to 14 T in June 2019.*
  - explore the target field and force range
  - serve as a technical and cost basis for comparison with new concepts
  - opportunity for program integration, particularly in the area of support structure design, and for exploration of various support structures.
- ***Step 2***: A successful series of magnets will provide a platform for performance improvement by integrating the outcomes of the Technology Development program – focus on achieving 15 T - *in progress, the 2nd test with optimized azimuthal and axial coil preload for 15 T is in January-February 2020.*
- ***Step 3***: 16 T cos-theta design to explore the limit of Nb_3Sn in this geometry – *done, 17 T 60-mm aperture and 11- 15 T 120-mm aperture coil designs with stress management and two mechanical structures have been developed.*

Step 1: 15 T Dipole Demonstrator (MDPCT1)

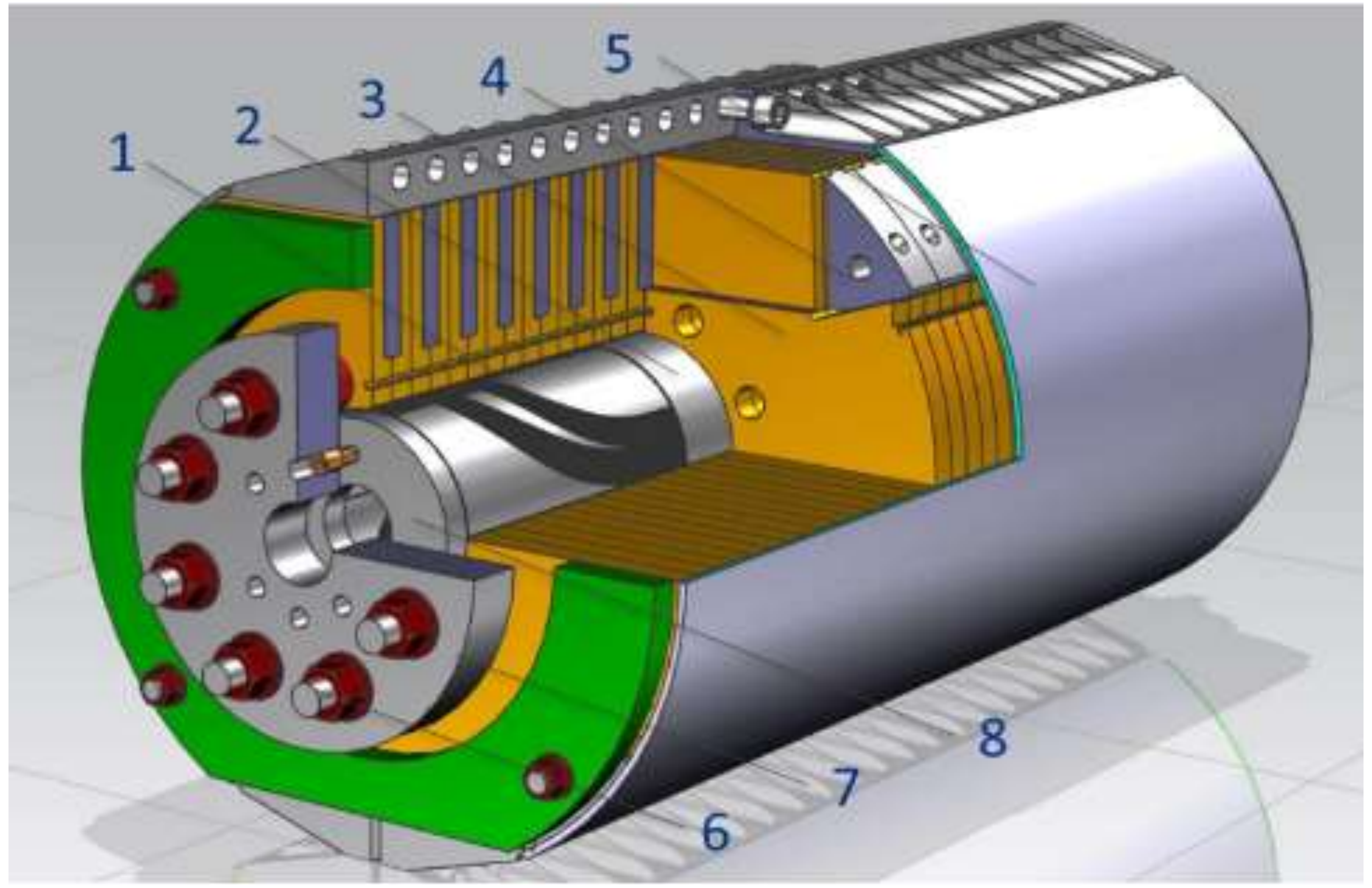
Optimized coil geometry:
- 60-mm aperture
- Min conductor volume
- 4-layer graded shell-type coil
- Optimization criteria: B_{max}, FQ, FL, QP

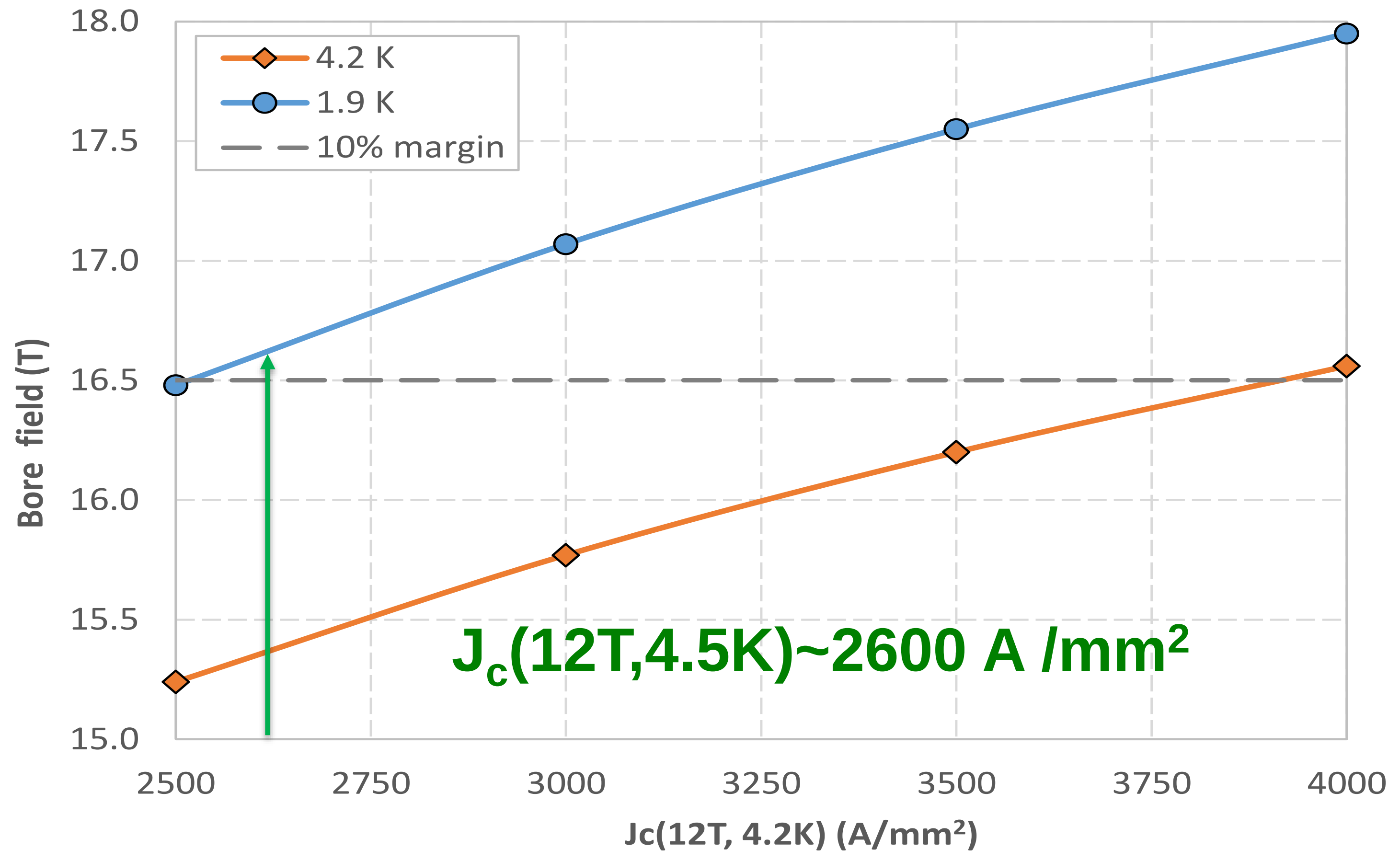


Cable:
- L1-L2: 28 strands, 1 mm RRP150/169
- L3-L4: 40 strands, 0.7 mm RRP108/127
- 0.025 x 11 mm^2 stainless steel core



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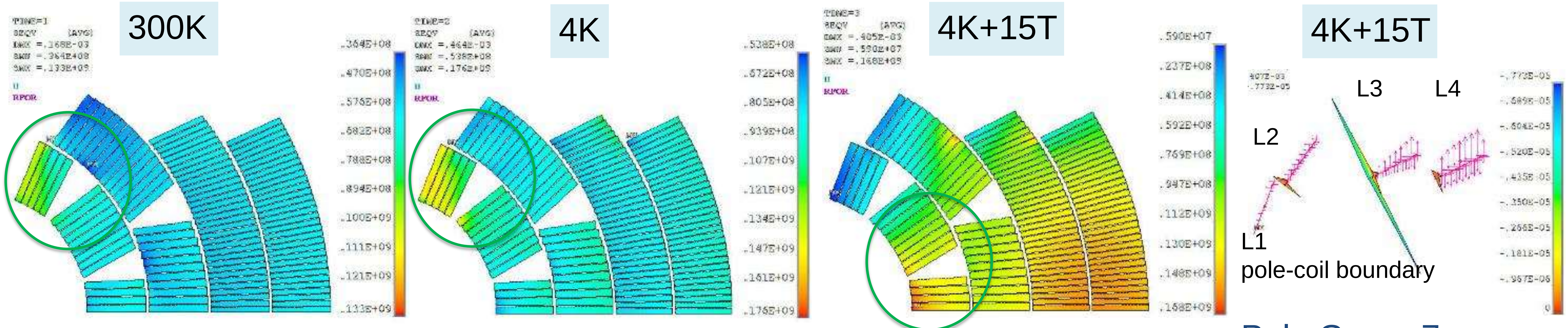
Mechanical limit and target pre-load for the 1st test



S_{eqv}=133 MPa

S_{eqv}=176 MPa

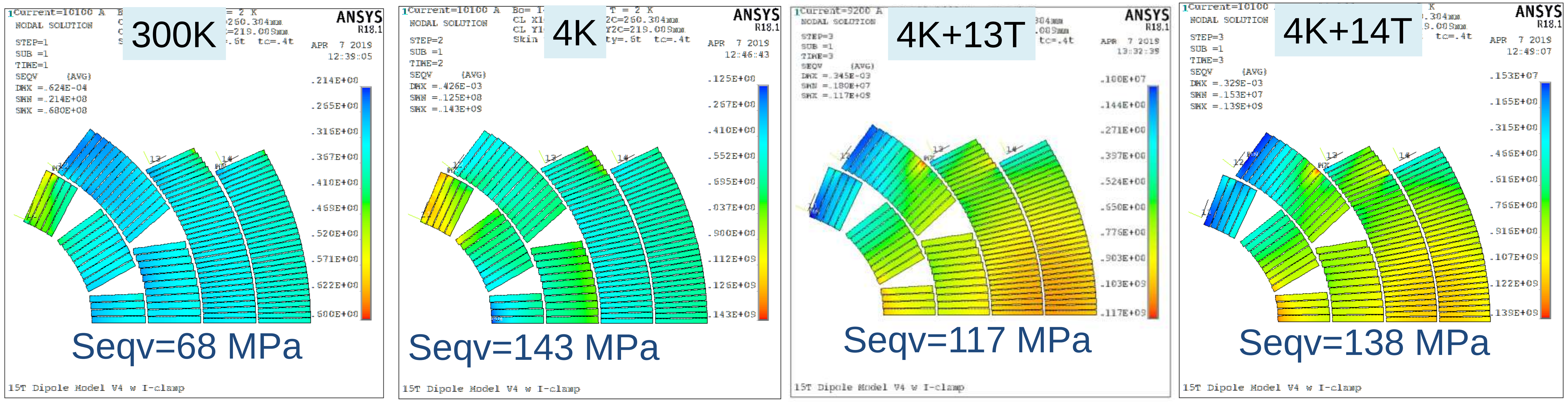
S_{eqv}=168 MPa

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



Seqv=68 MPa

Seqv=143 MPa

Seqv=117 MPa

Seqv=138 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

Coil and Support Structure components

Cable (FNAL)

L3/4 parts (FNAL)

L1/2 parts (CERN contribution)

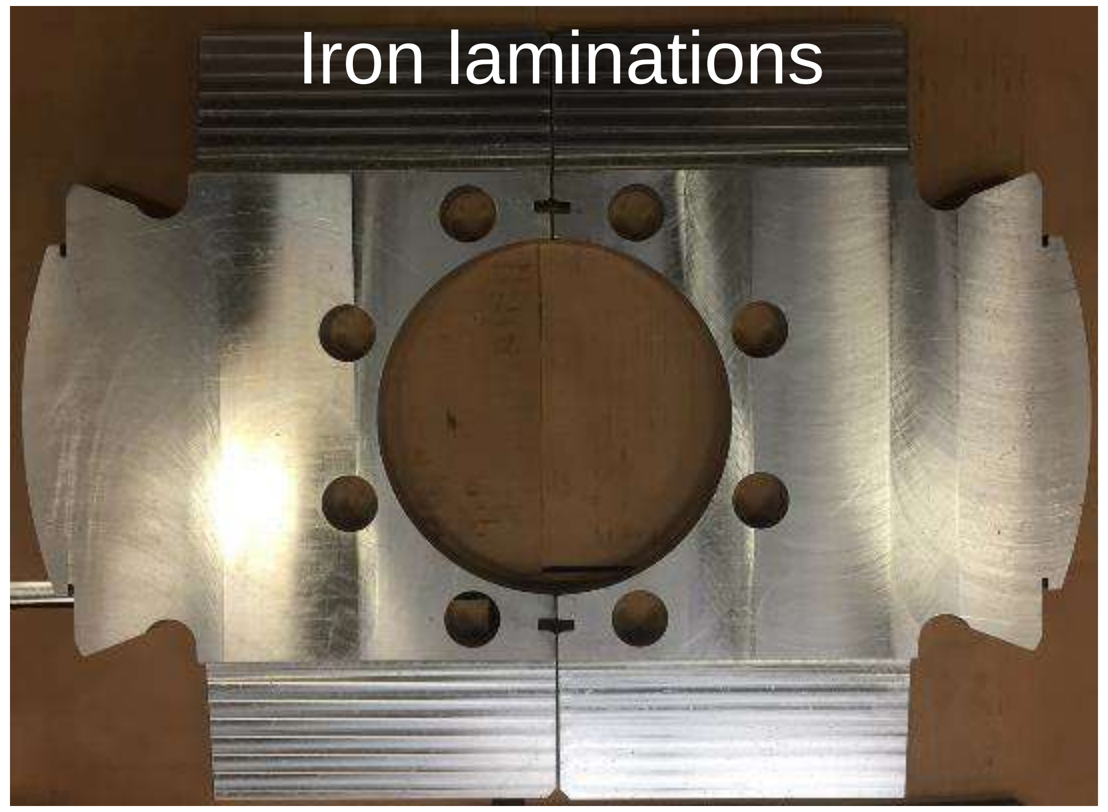
Ti and Cu wedges, Ti poles & spacers, SS saddles

Traces (LBNL/FNAL)

Layer 2

Layer 4

End plates and rods



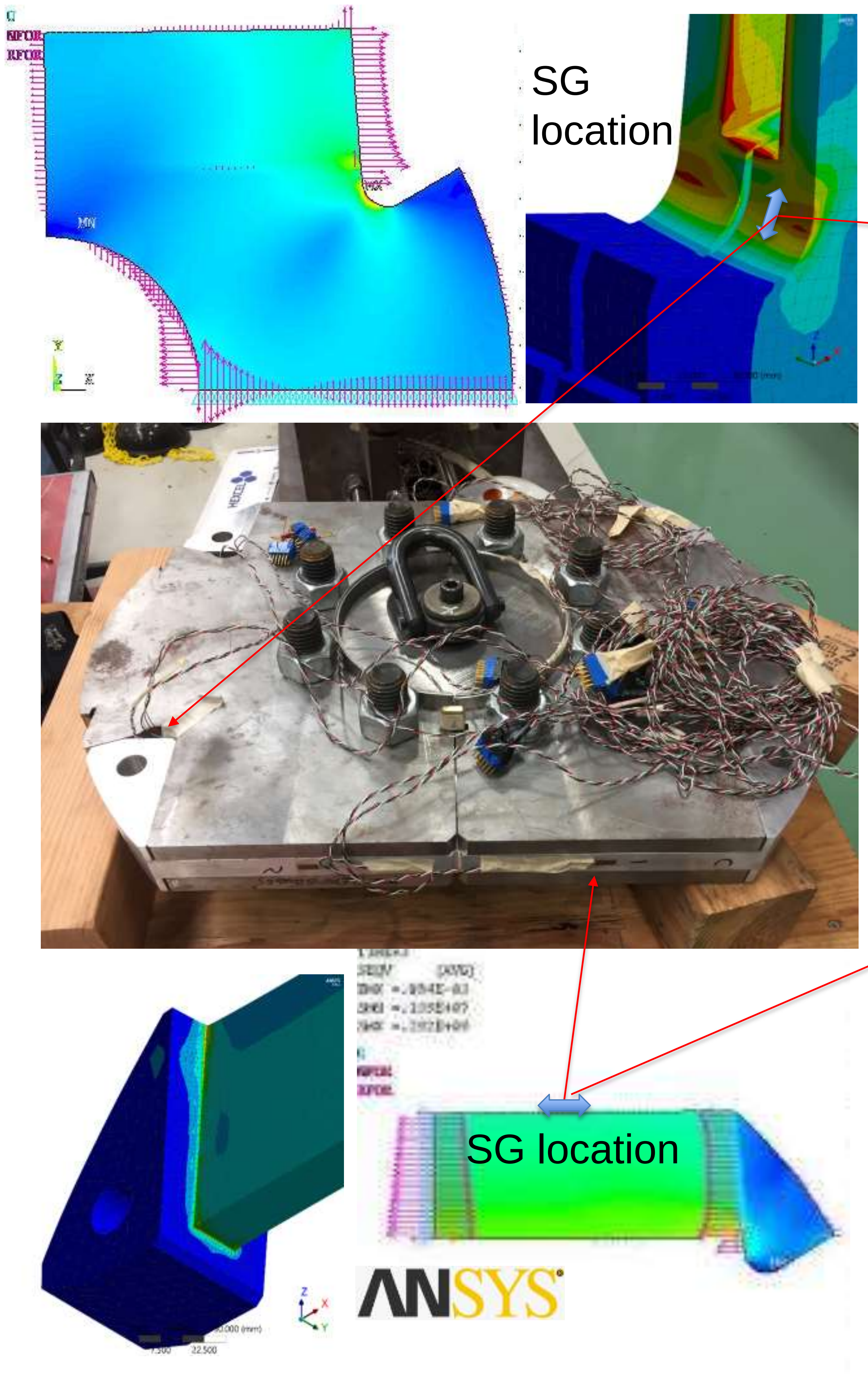
Iron laminations

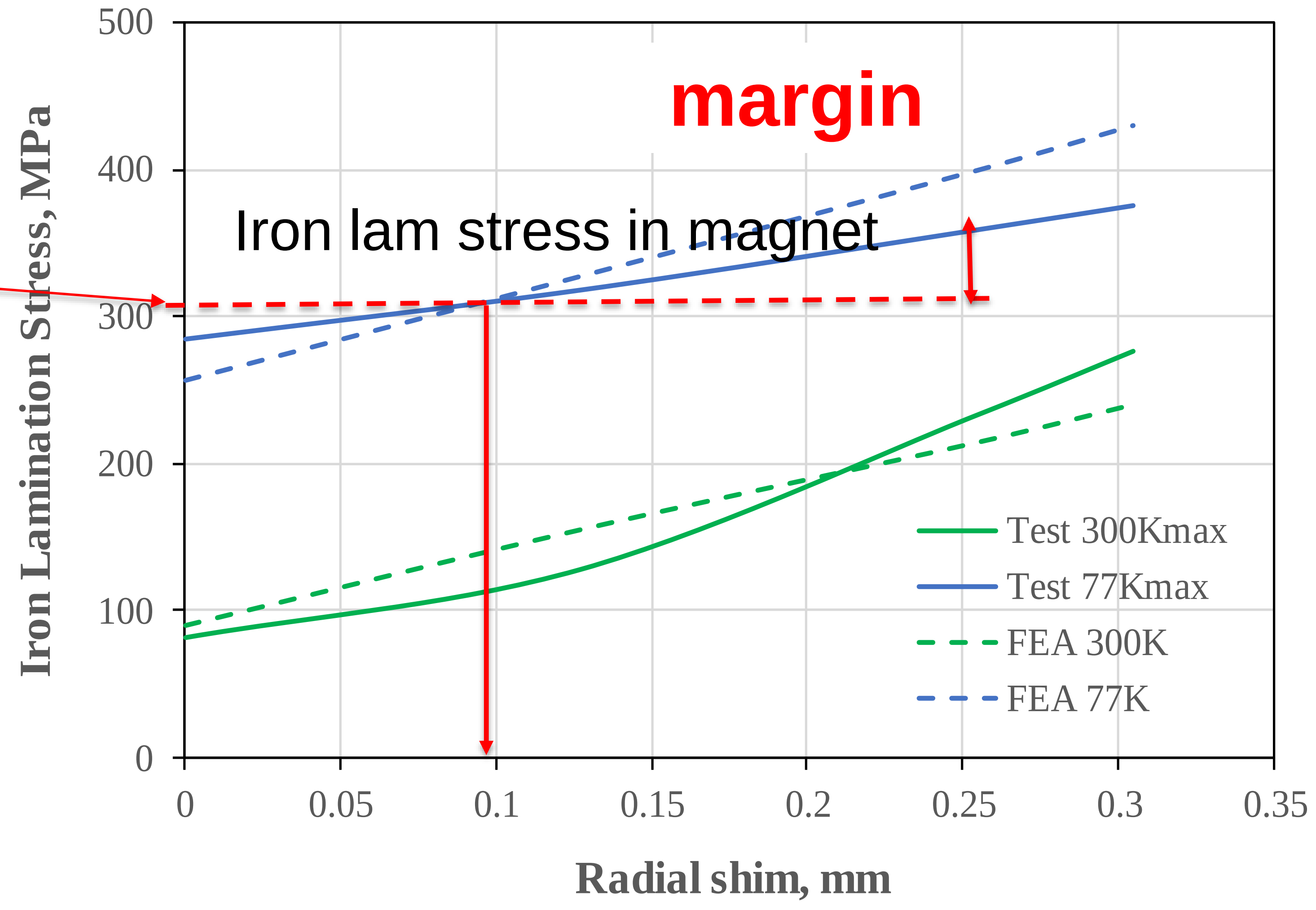
Iron blocks

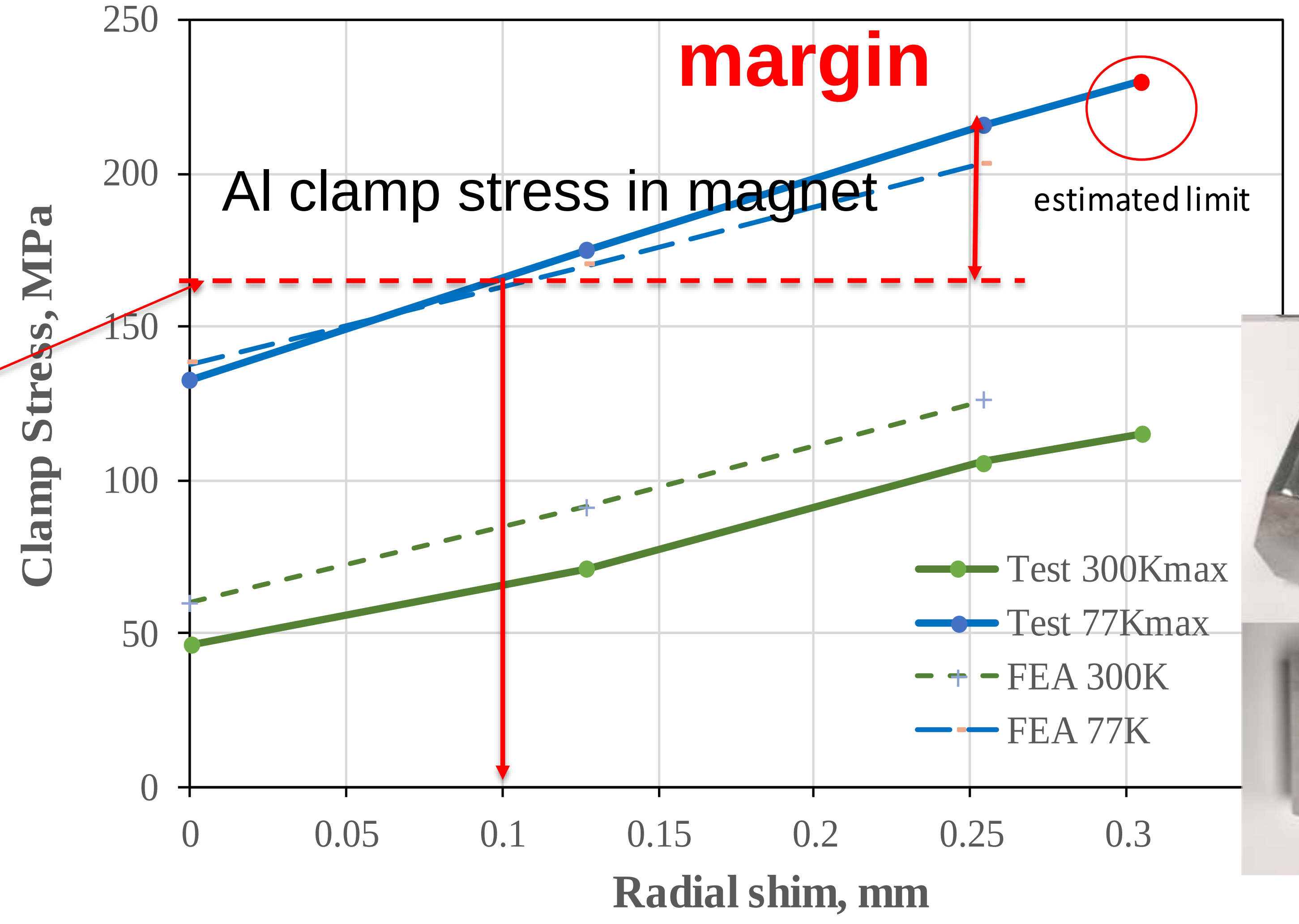
Skin half-shels

Al clamps

Mechanical Model & Structure tests







MM & structure goals:

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

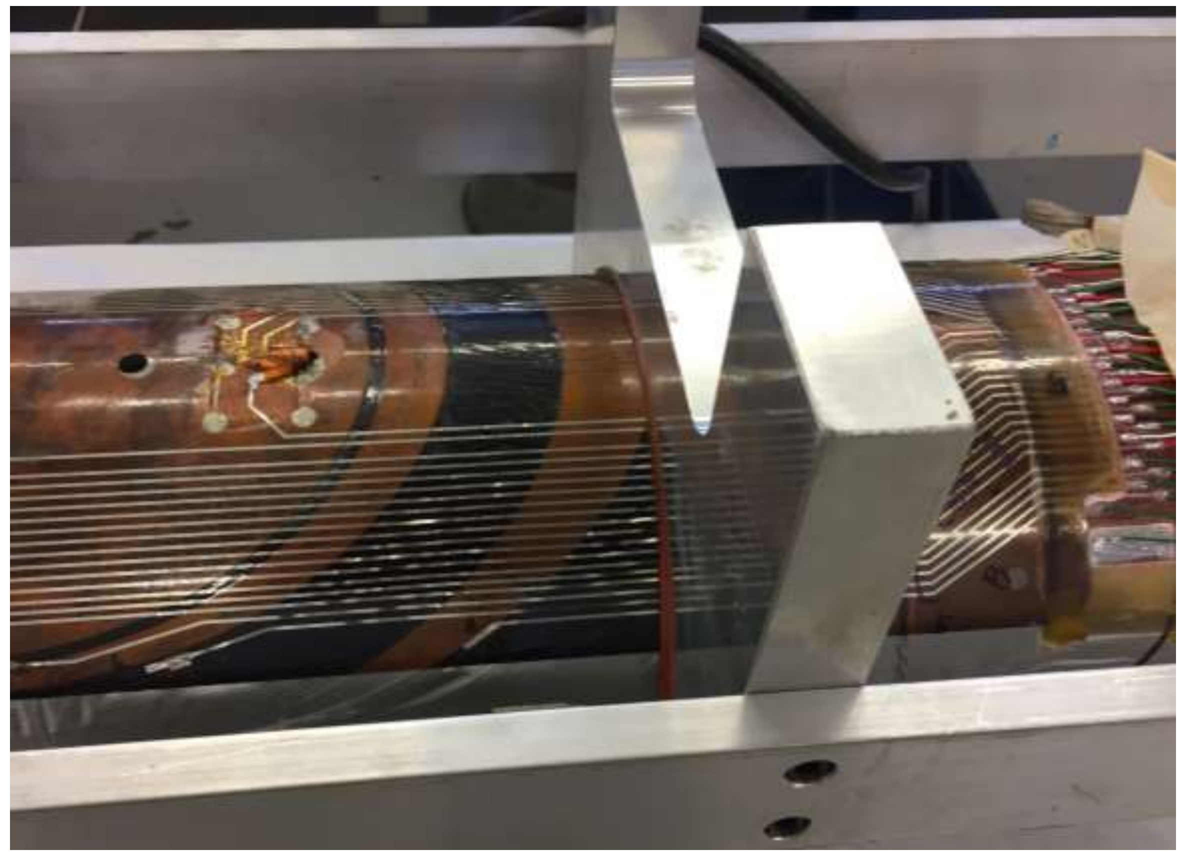
Coil fabrication, measurements and instrumentation

Coil winding and curing using ceramic binder

Coil reaction

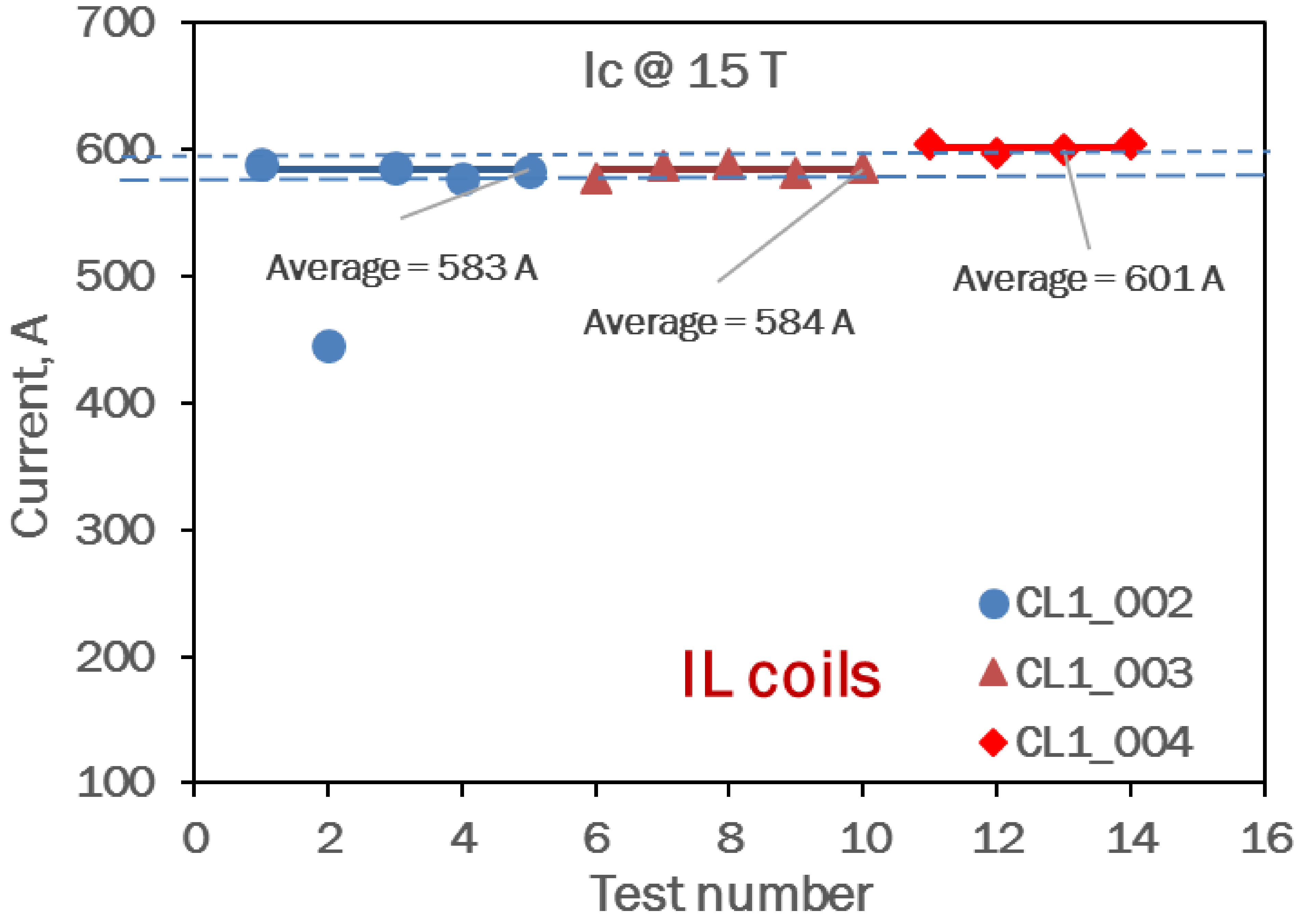
Coil lead splicing, epoxy impregnation

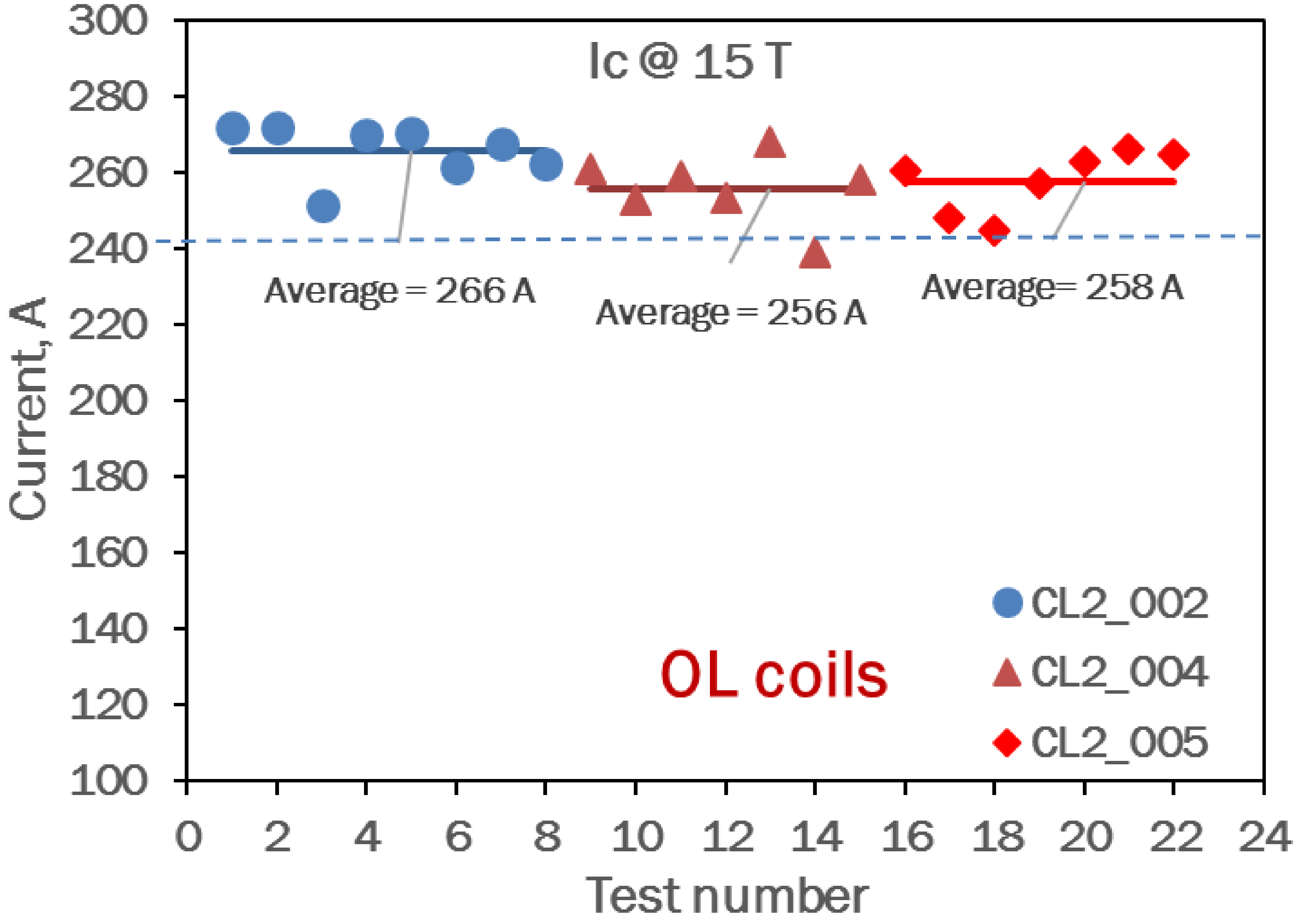
Coil size measurement, instrumentation



Coil fabrication, measurement and instrumentation time ~3 months

Witness Sample Data and Magnet SSL

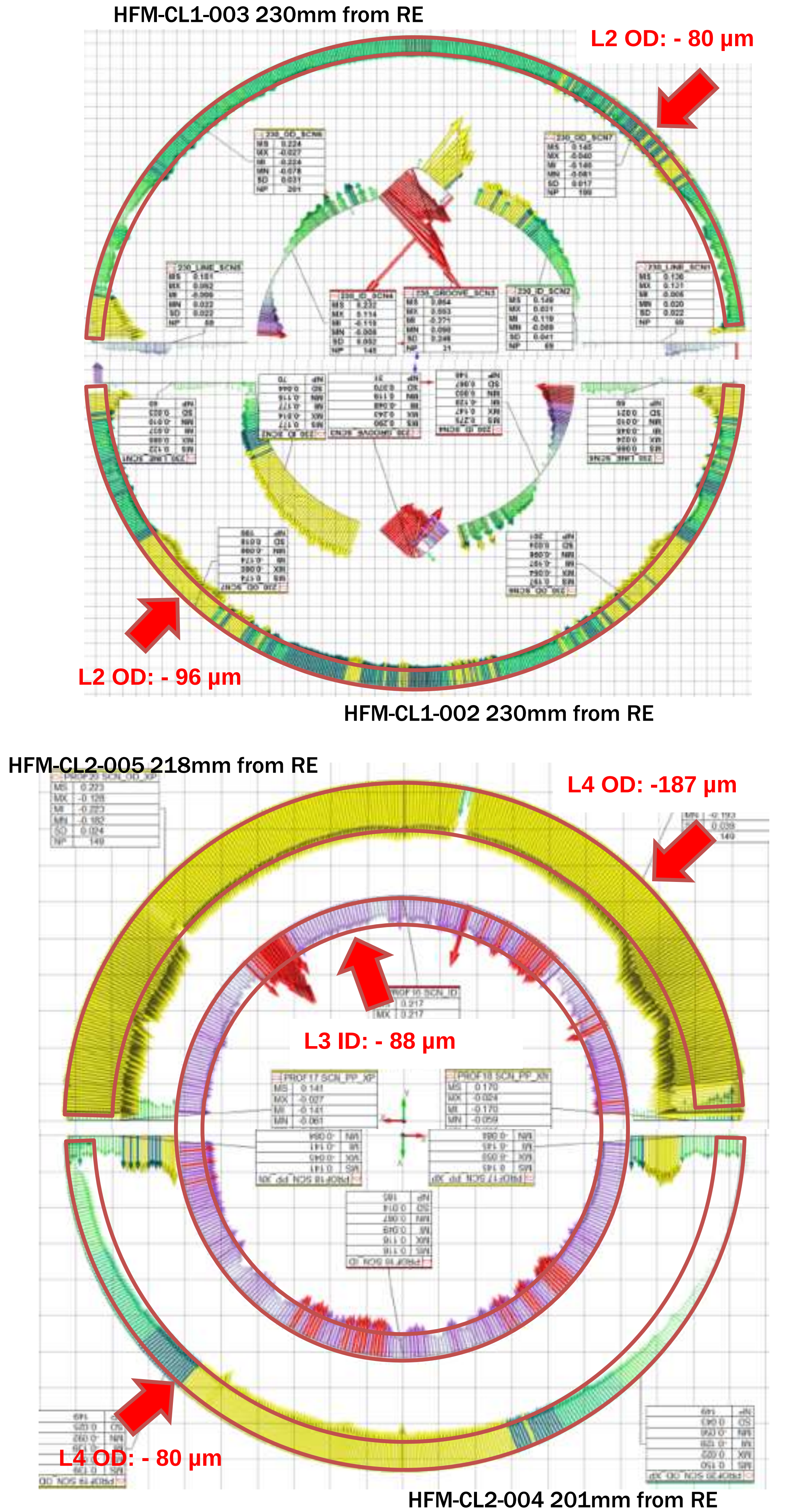


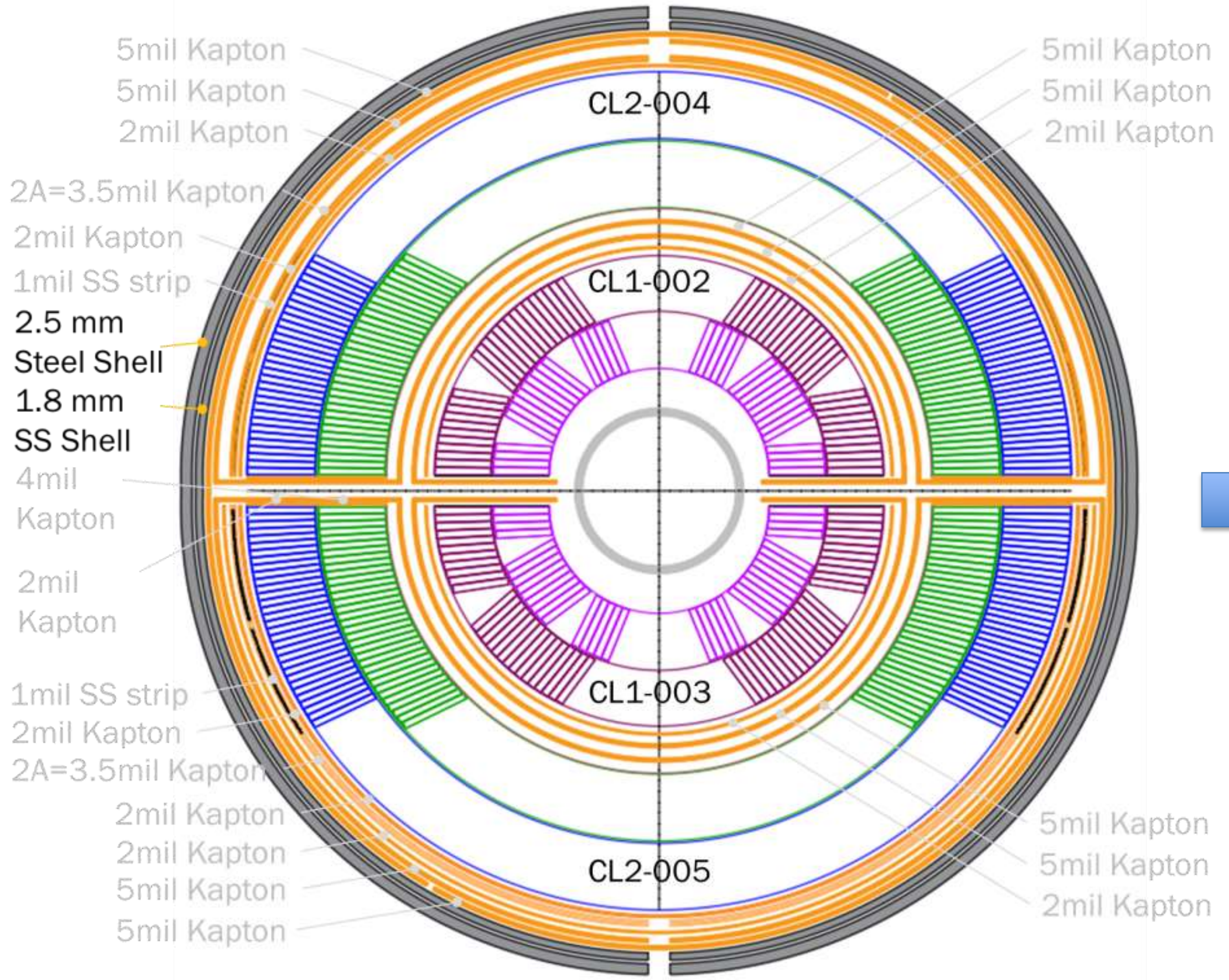


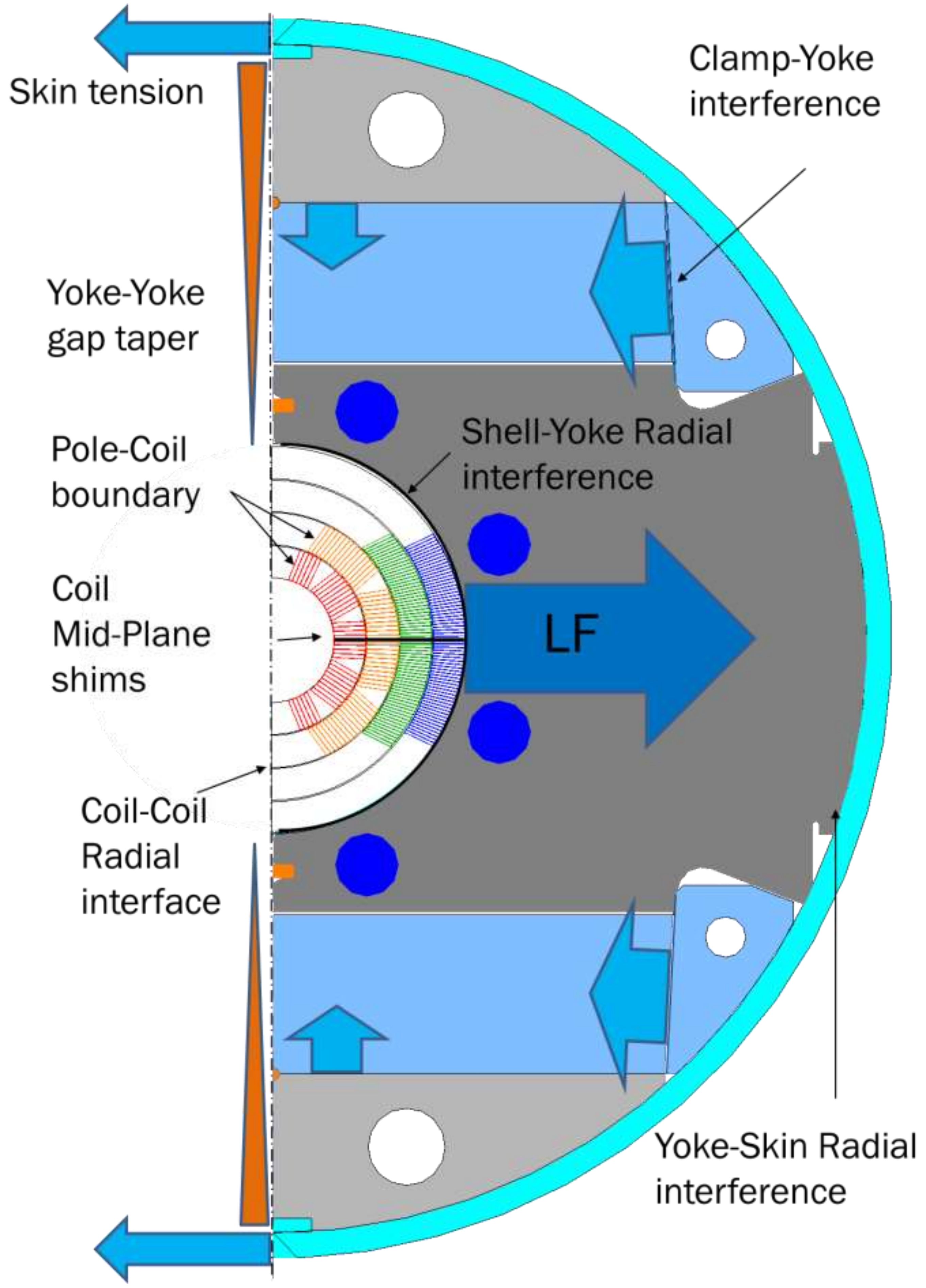
- Witness sample data are close to the target I_c
- Good reproducibility of witness sample data for IL and OL coils

Magnet ***short sample limit***: 15.2 T at 4.5K and 16.8 T at 1.9K

Coil Assembly and Preload Scheme

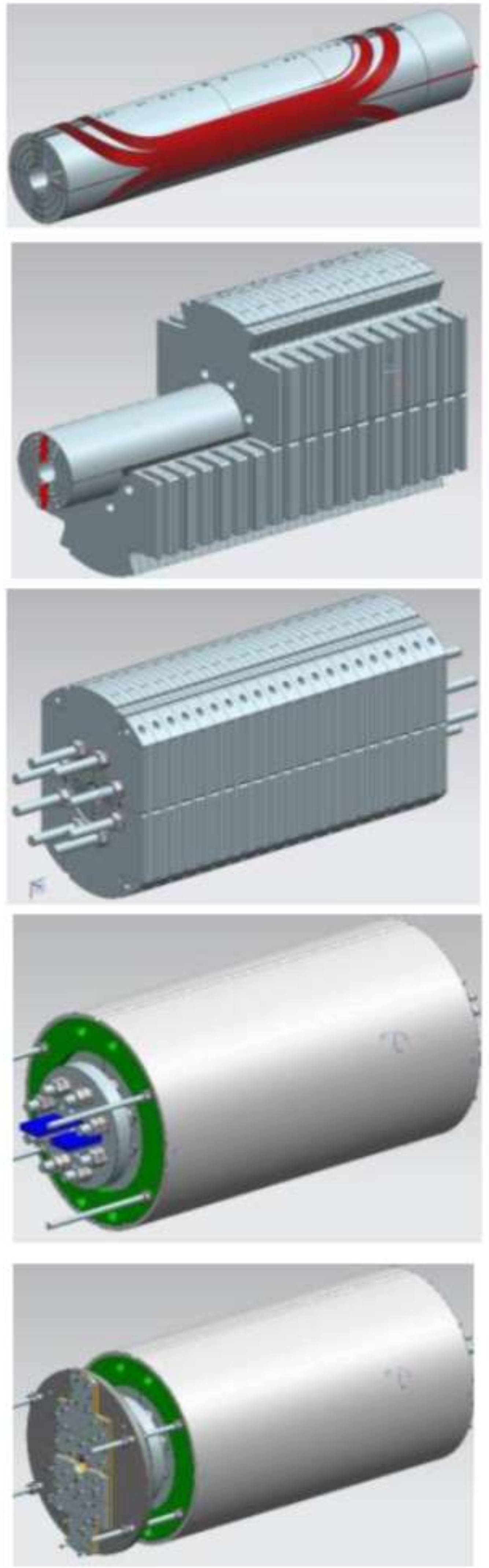


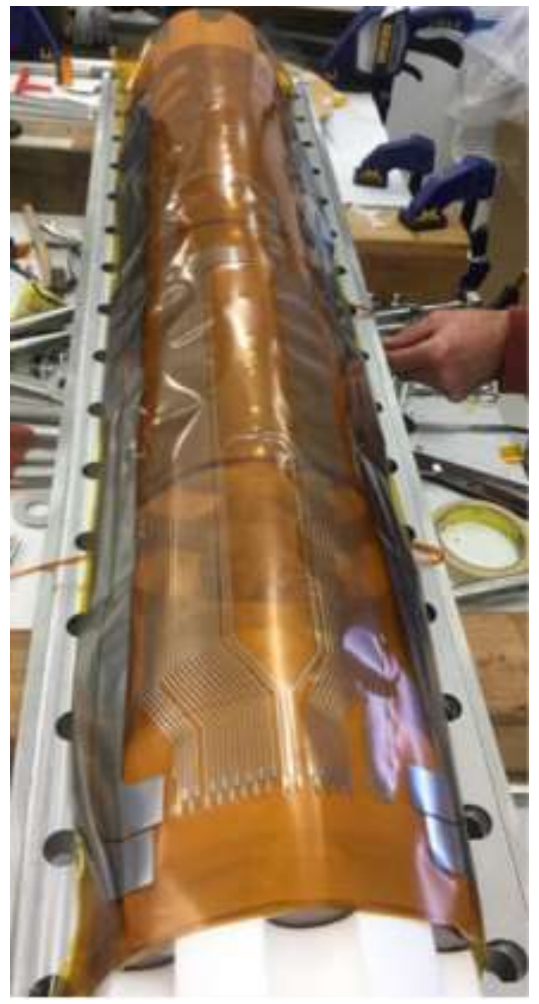


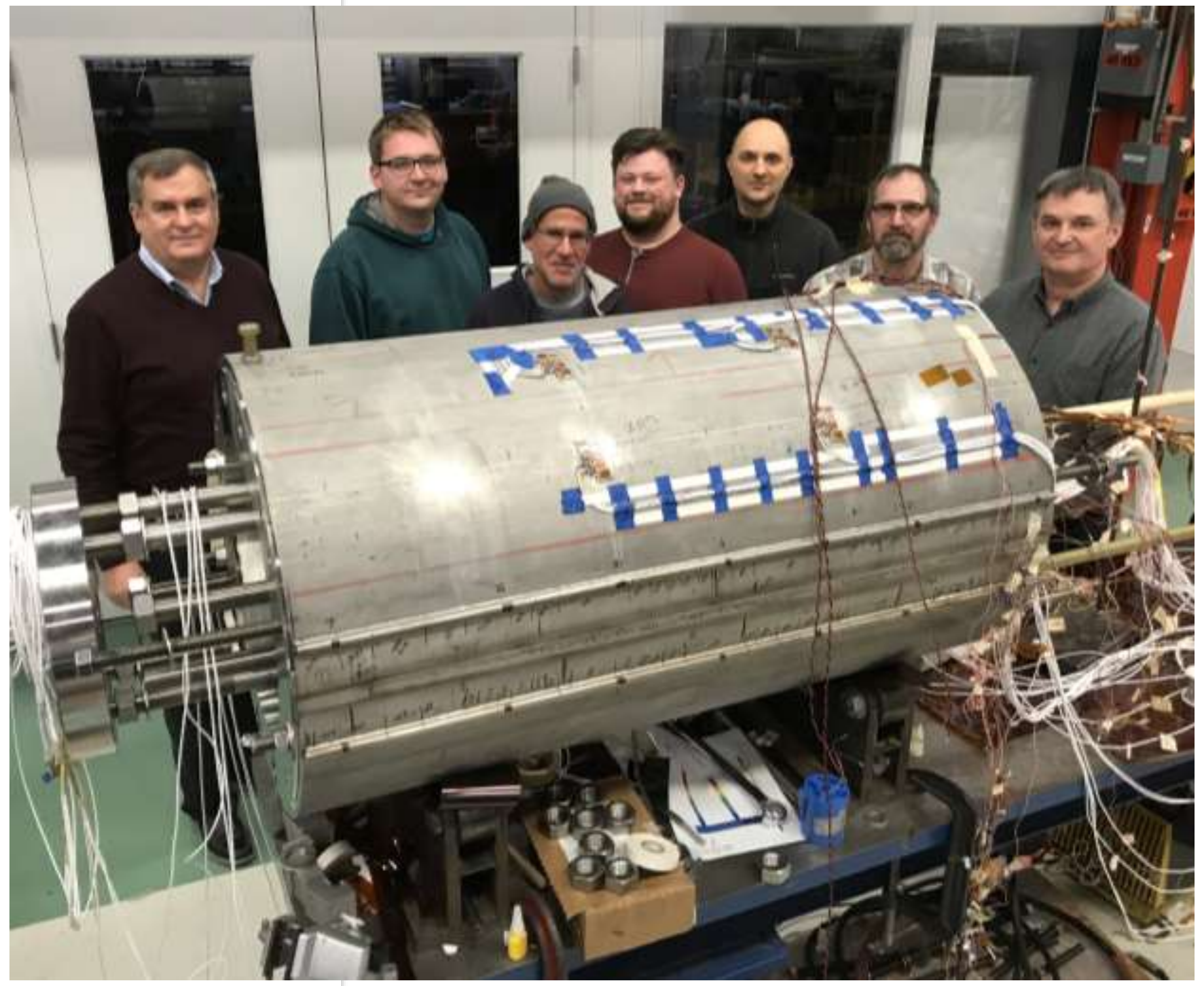


<u>L2-L3 interface was accurately matched (not glued)!</u>

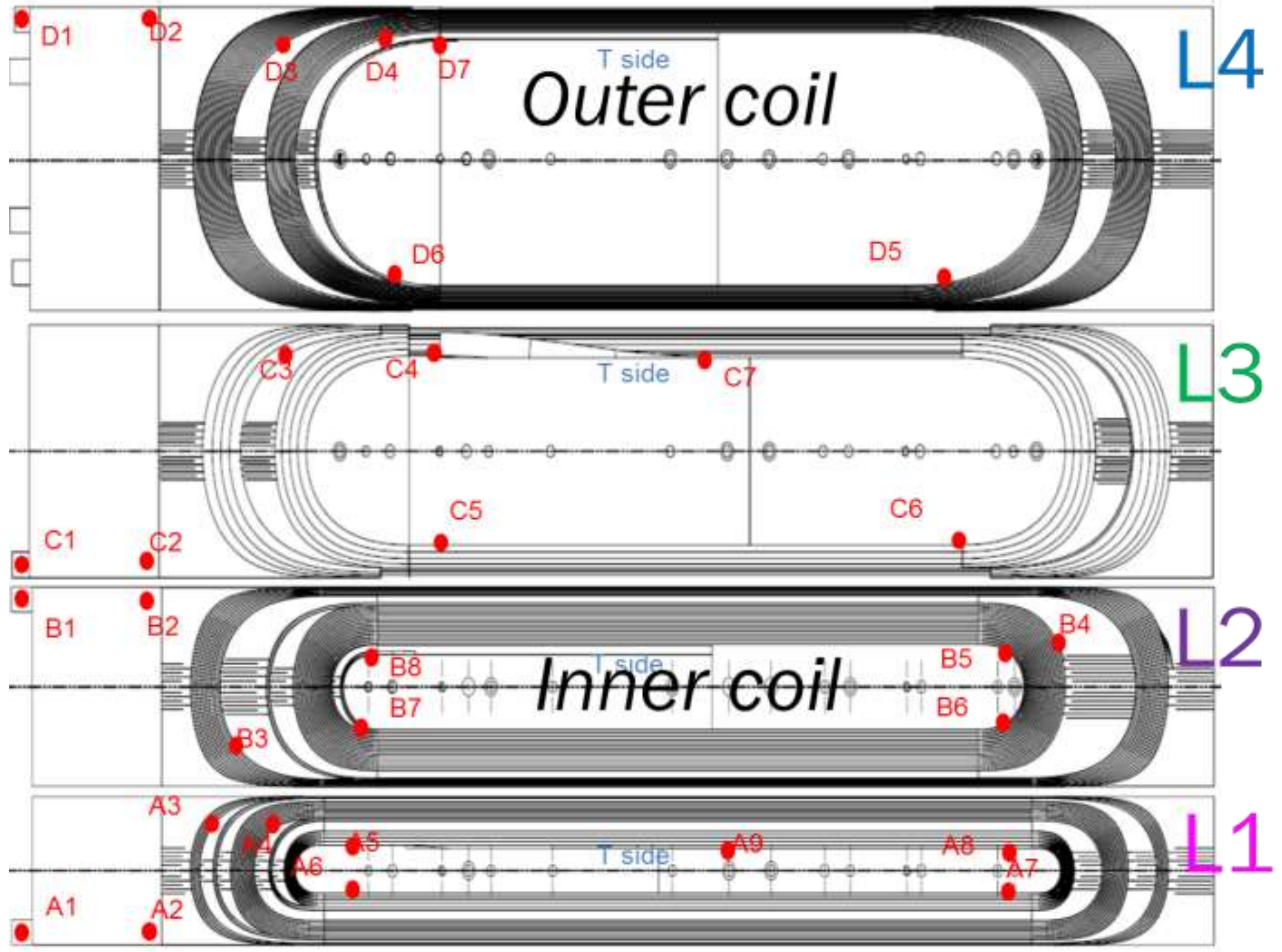
Coil Assembly, Yoking and Skinning



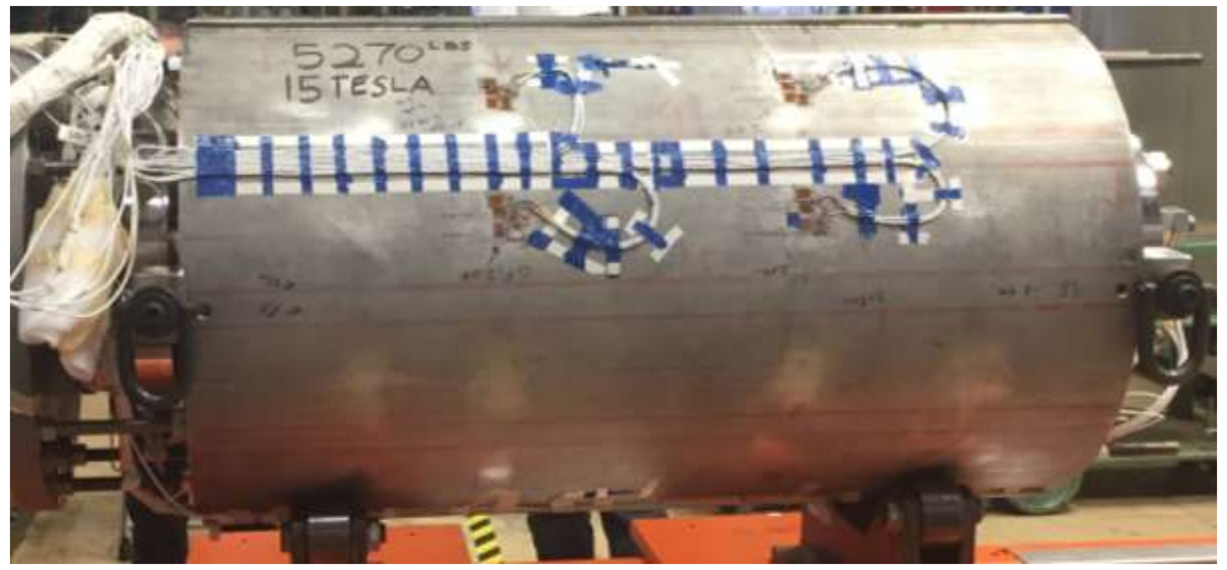




Magnet instrumentation and test preparation



VT location



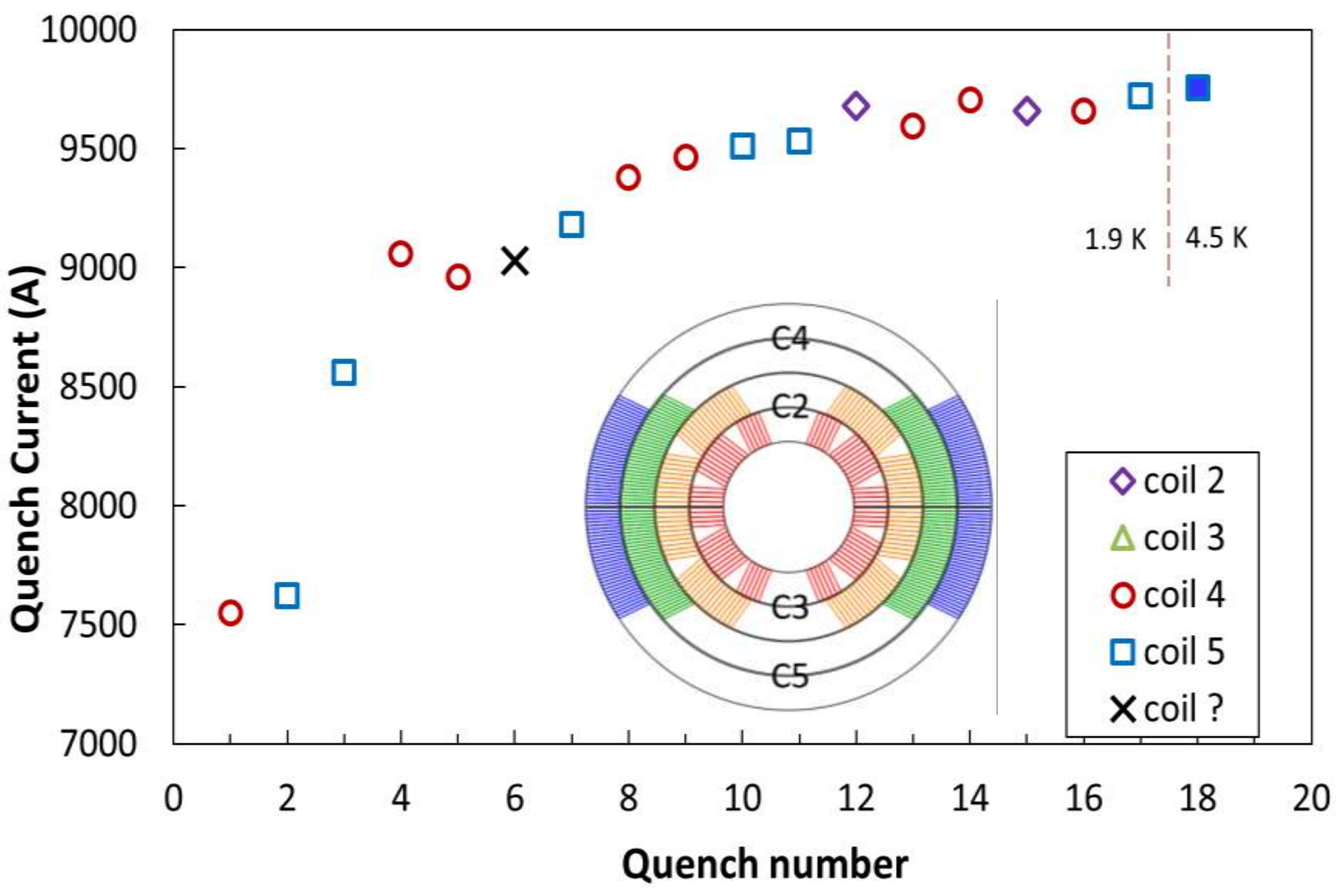
Skin gauges location

Test preparation ~1.5 months

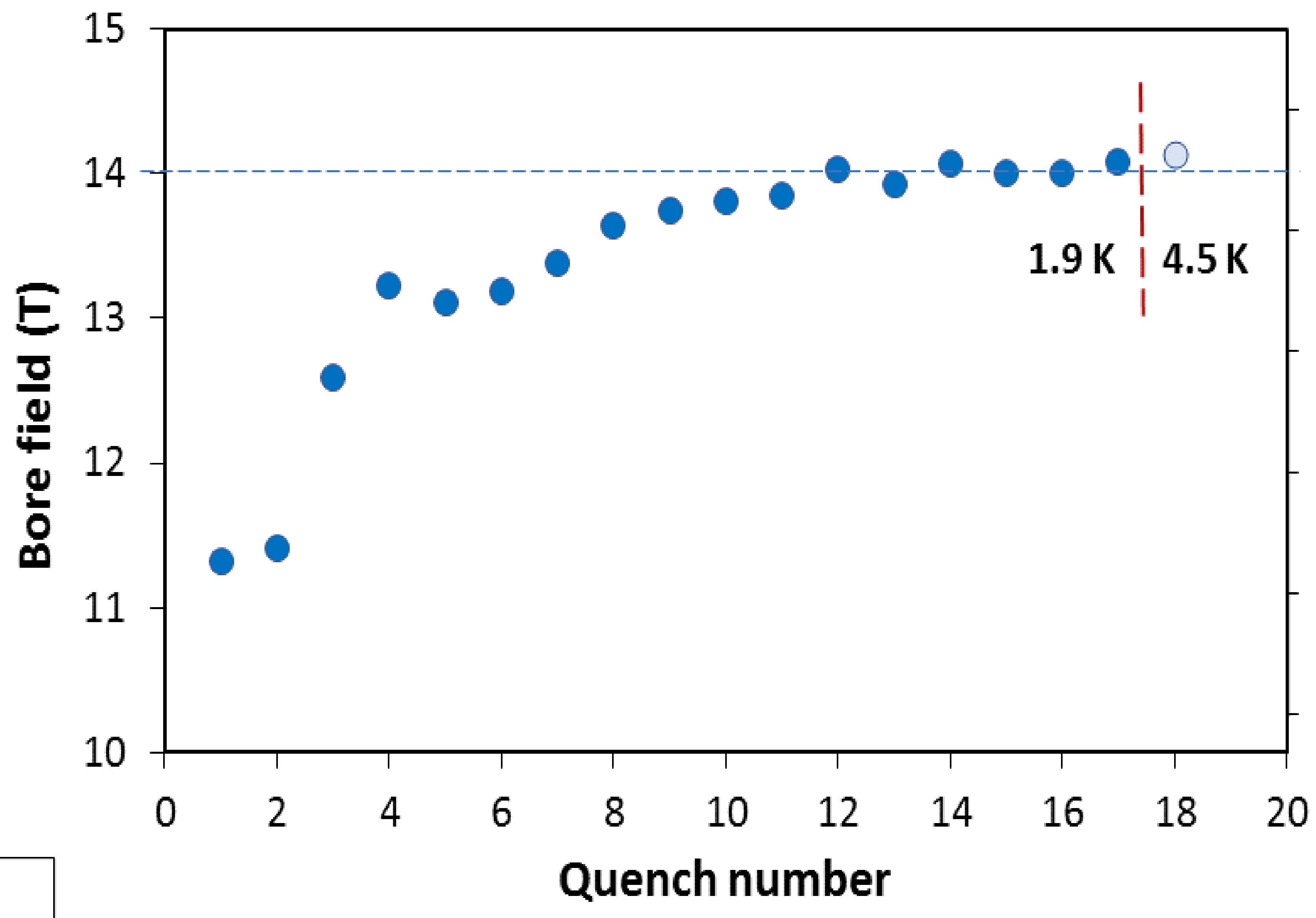
- Instrumentation:
  - Voltage taps (VT)
  - Strain Gauges (SG)
    - skin, clamps, bullets, poles, coils
  - Quench antennas (QA)
  - Acoustic sensors (AS)
  - Thermometers (T)

Significant part of instrumentation was lost.

Magnet Training

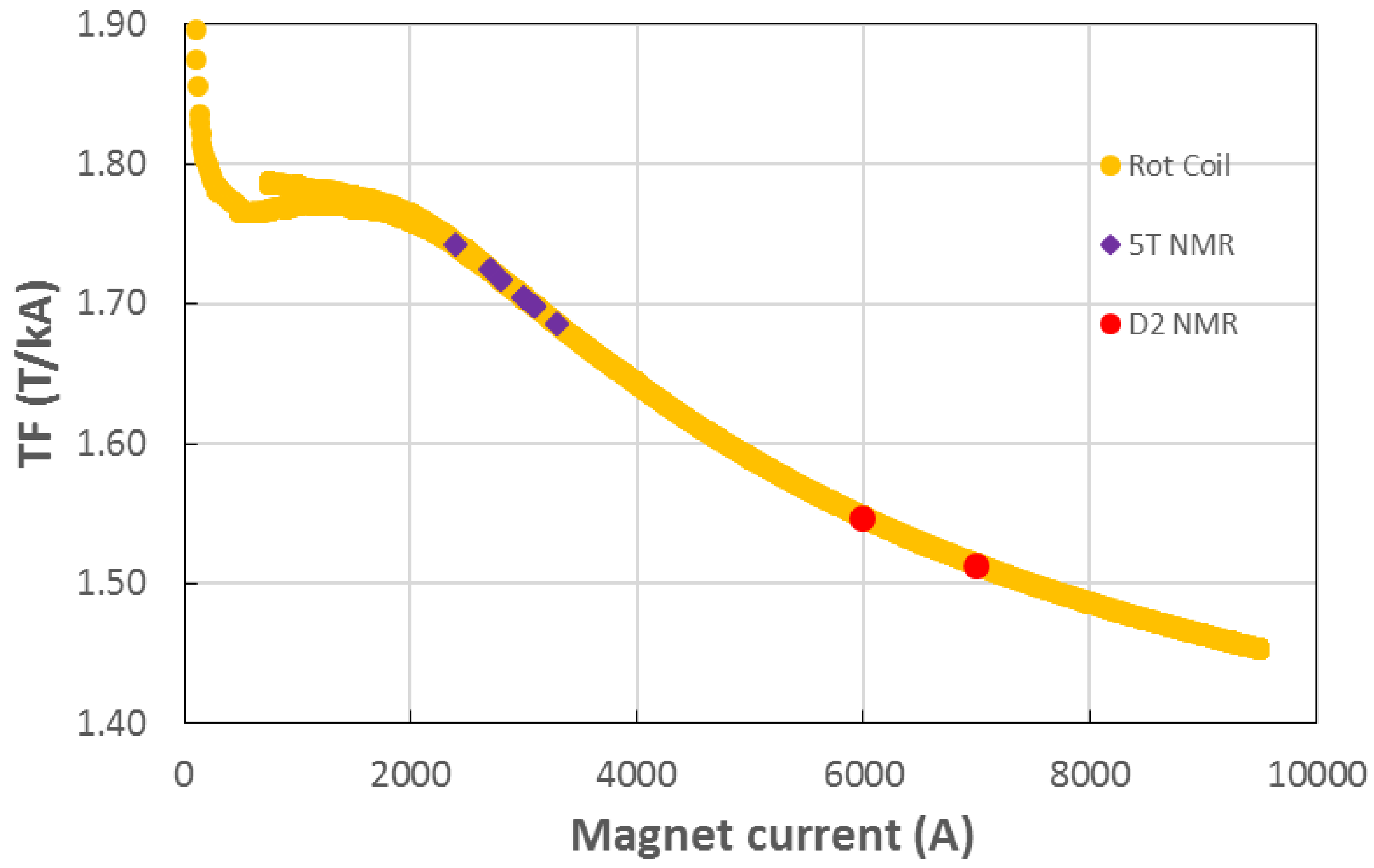


- 2D and 3D analysis based on the actual yoke material properties and the final magnet geometry
- Measurements have been verified with NMR probes (provided by GMW)



- 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

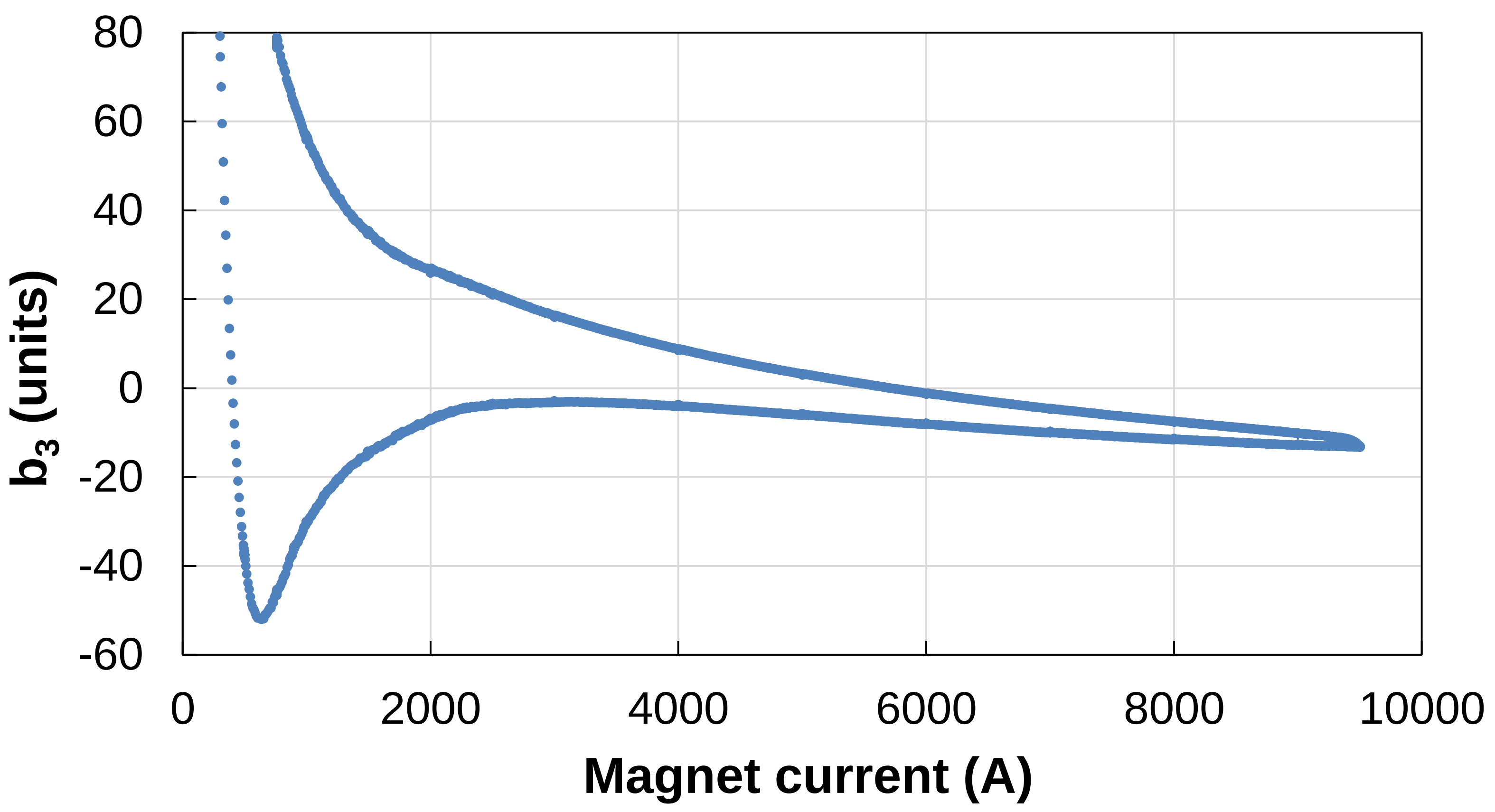


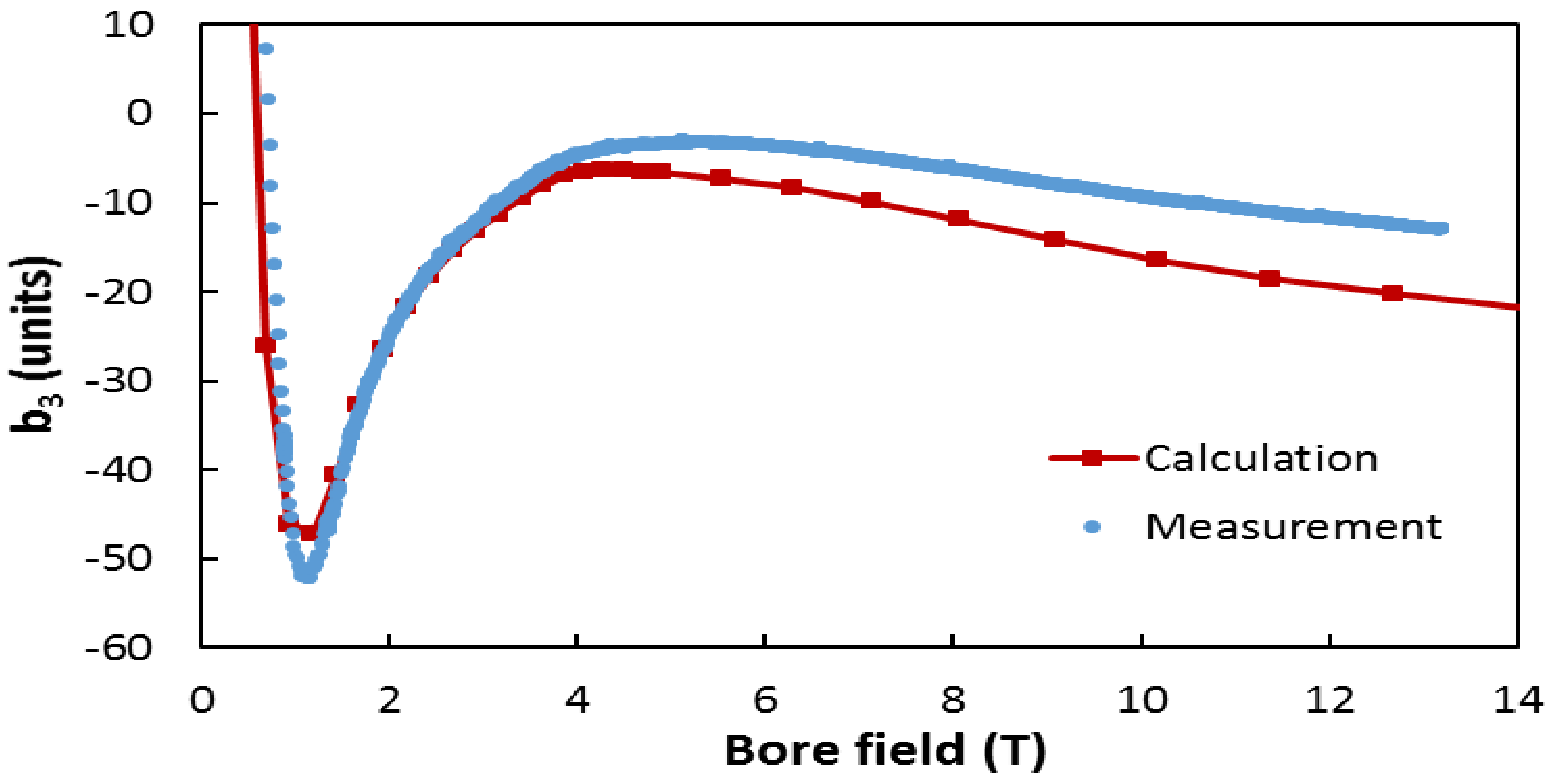
- First quenches above 11 T
- Last quench at 4.5 K :

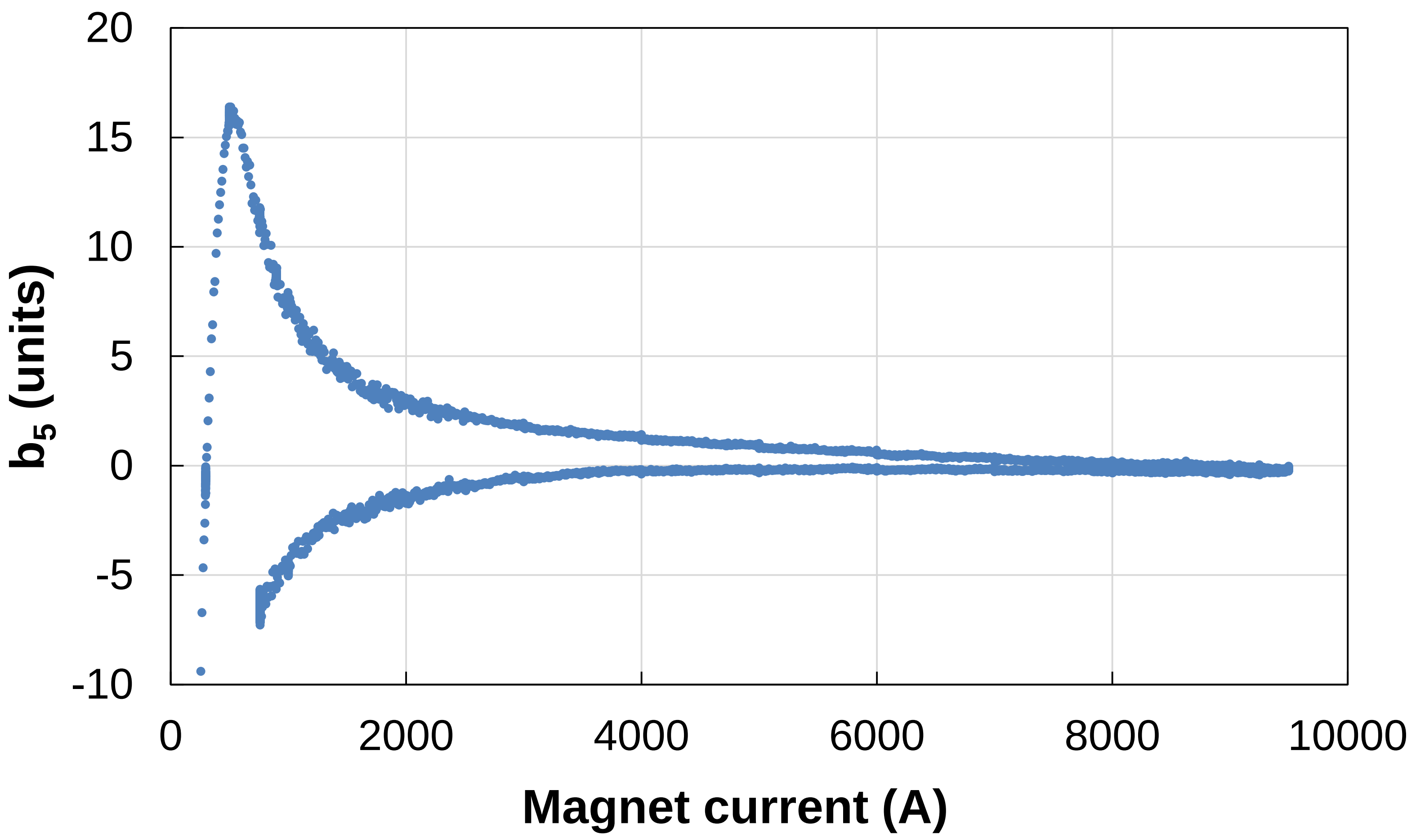
  B_{meas} = 14.10±0.04 T

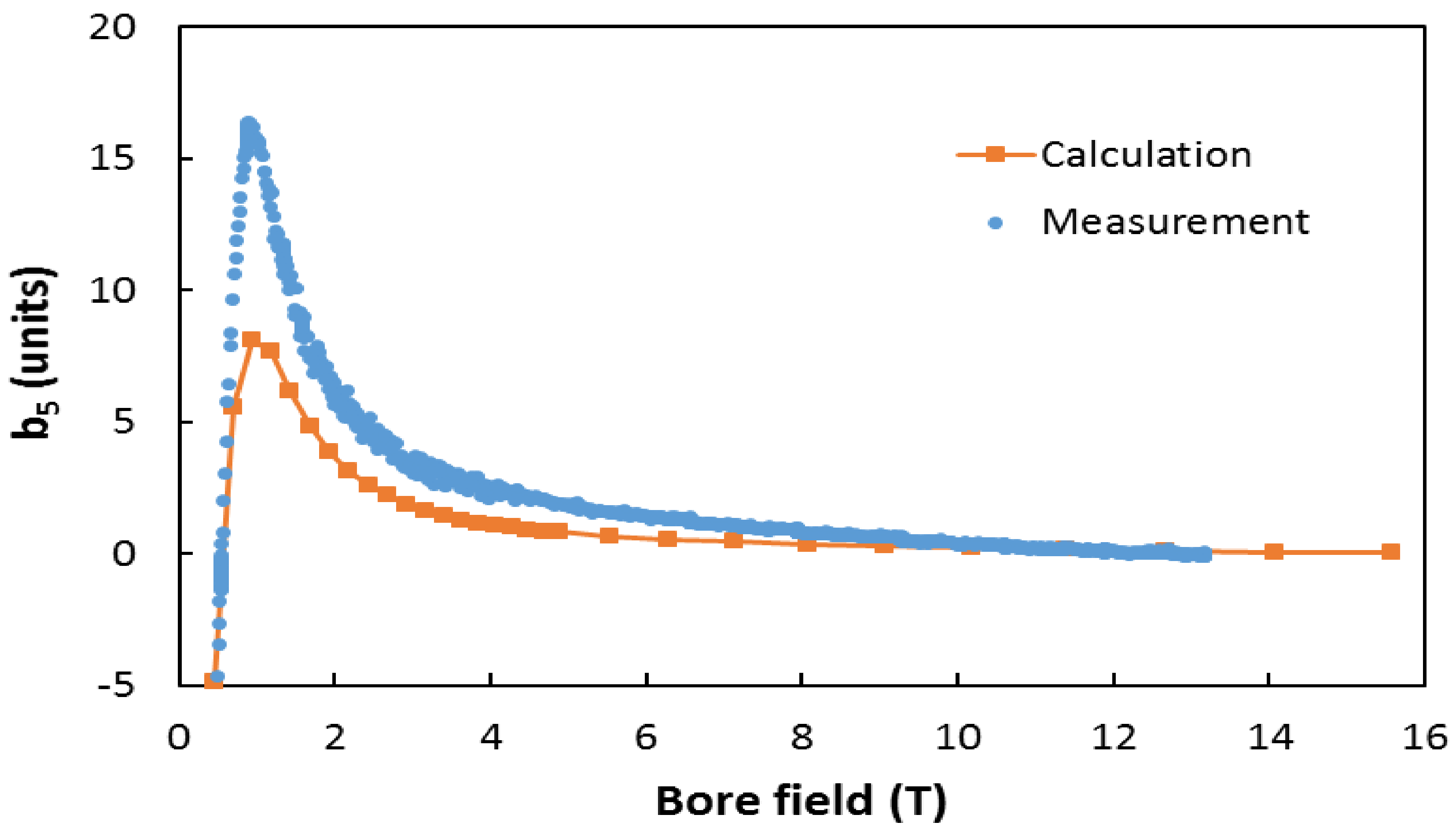
  B_{calc} = 14.112 T

Field harmonics









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

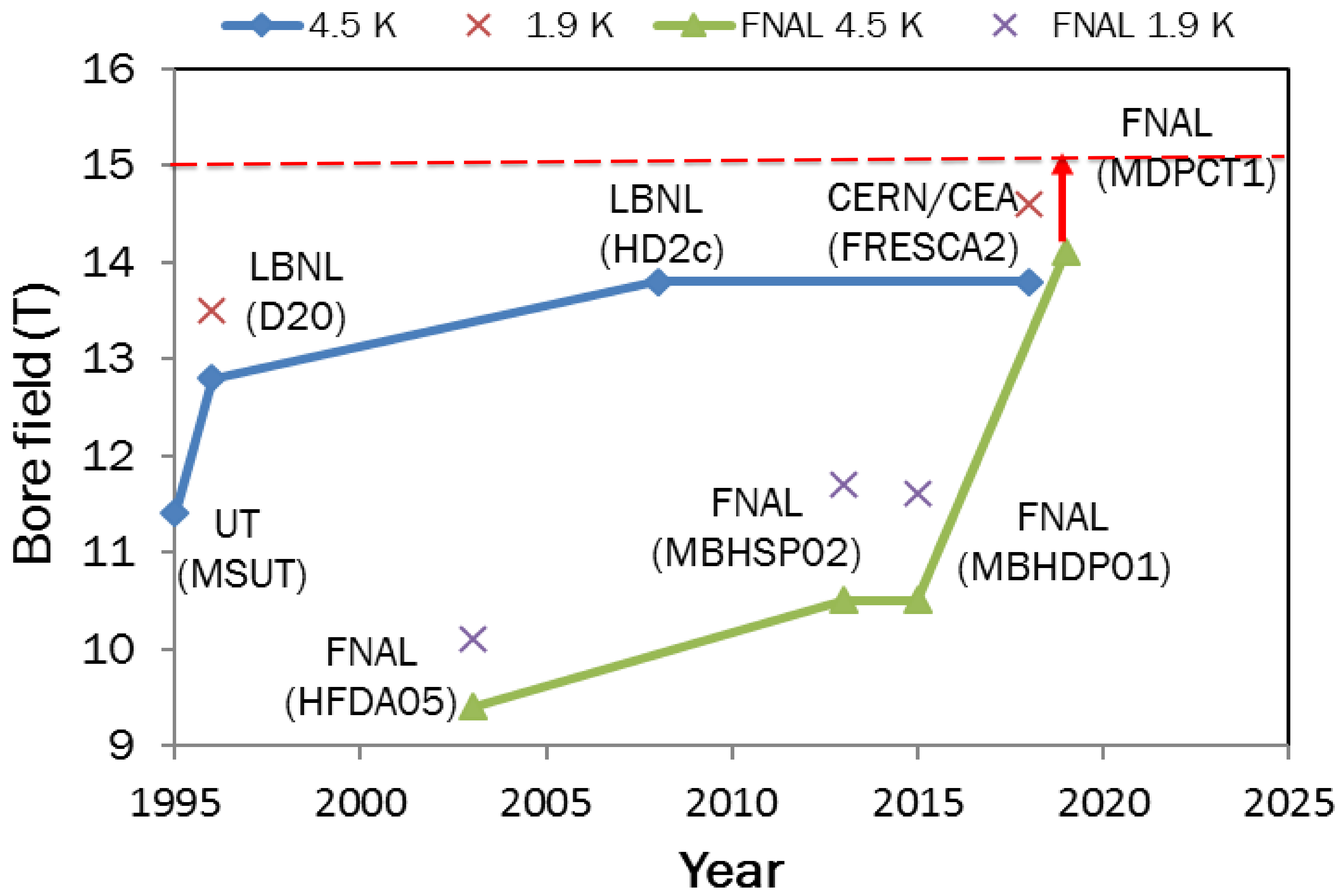
n	2	3	4	5	6	7	8	9	10
b_n	0.8	8.8	-0.4	0.7	0.1	1.0	0.0	0.2	-0.4
a_n	-2.2	-3.5	0.3	0.1	0.1	0.1	-0.1	0.2	-0.3

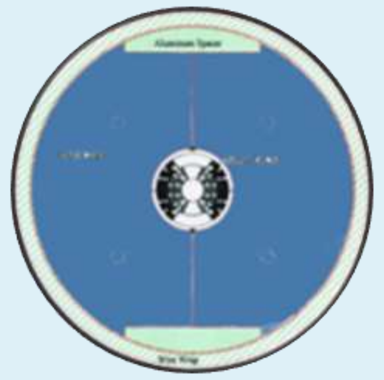
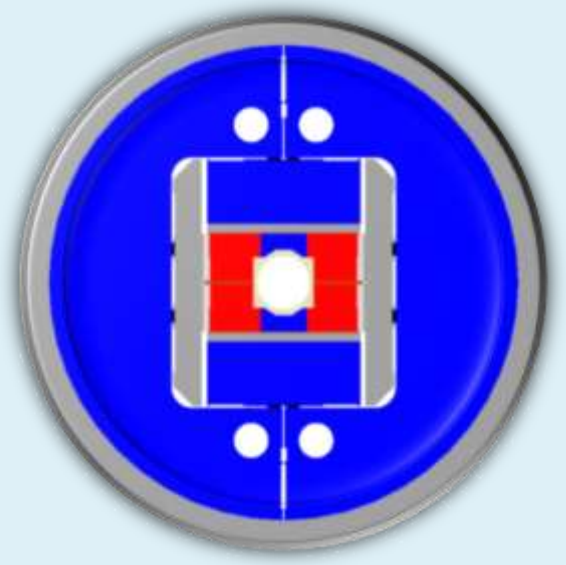
MDPCT1 Summary and next step

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

Next step - magnet re-assembly

- increase azimuthal coil pre-load and axial support to achieve the goal of 15 T
- improve instrumentation



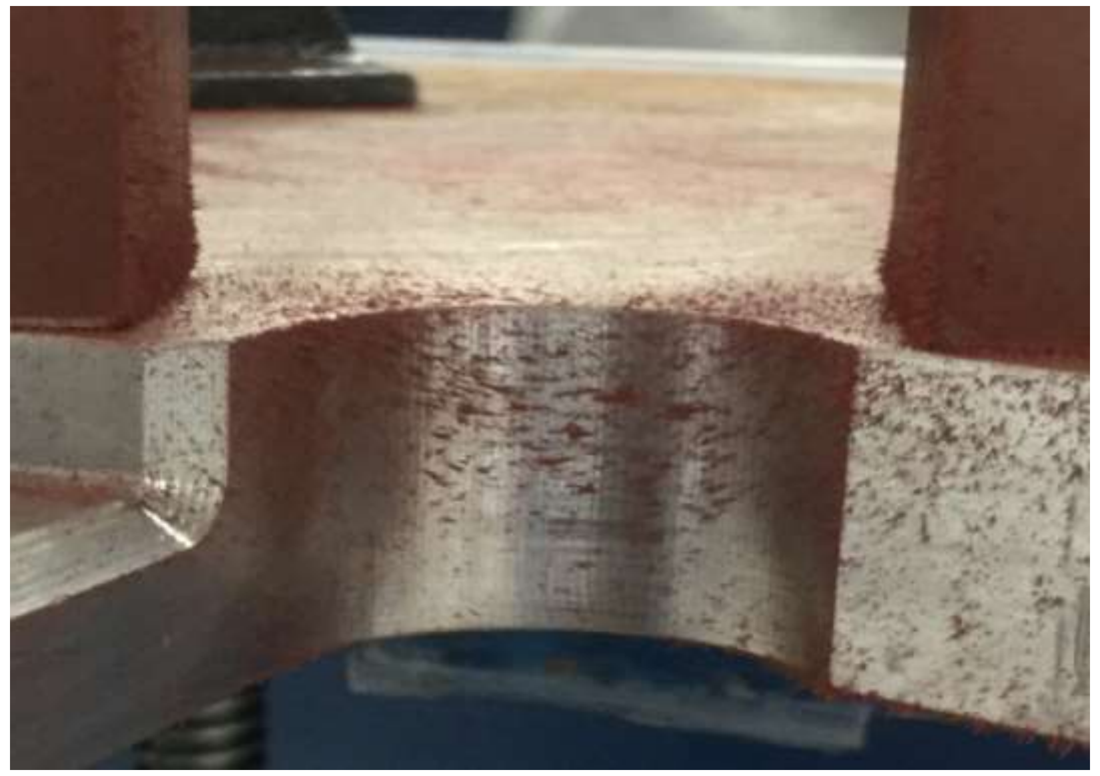
Parameter	D20 (LBNL)	HD2 (LBNL)	FRESCA2 (CERN)	MDPCT1 (FNAL-MDP)
				
Test year	1997	2008	2017	2018 (plan)
Max bore field [T]	13.35 (14.7*)	15.4	16.5 (18*)	15.2 (16.5*)
Design field B_{des} [T]	13.35	15.4	13	15
Design margin B_{des}/B_{max}	1.0 (0.9*)	1.0	0.8 (0.7*)	0.96 (0.89*)
Achieved B_{max} [T]	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)

Step 2: Magnet disassembly and inspection

Magnet disassembly

Al clamps test with die penetration technique

Iron lams test with magnetic powder

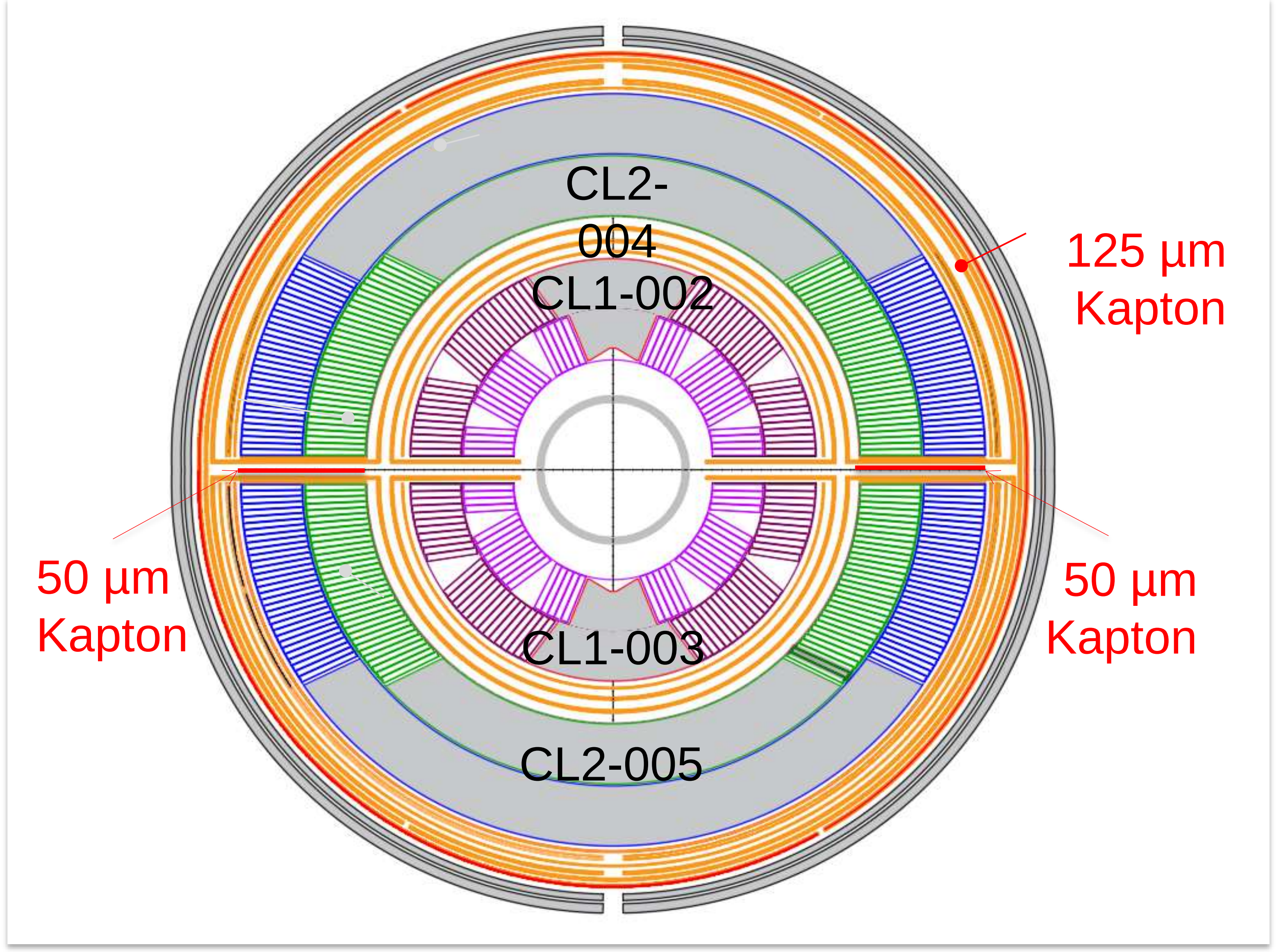


Coil inspection

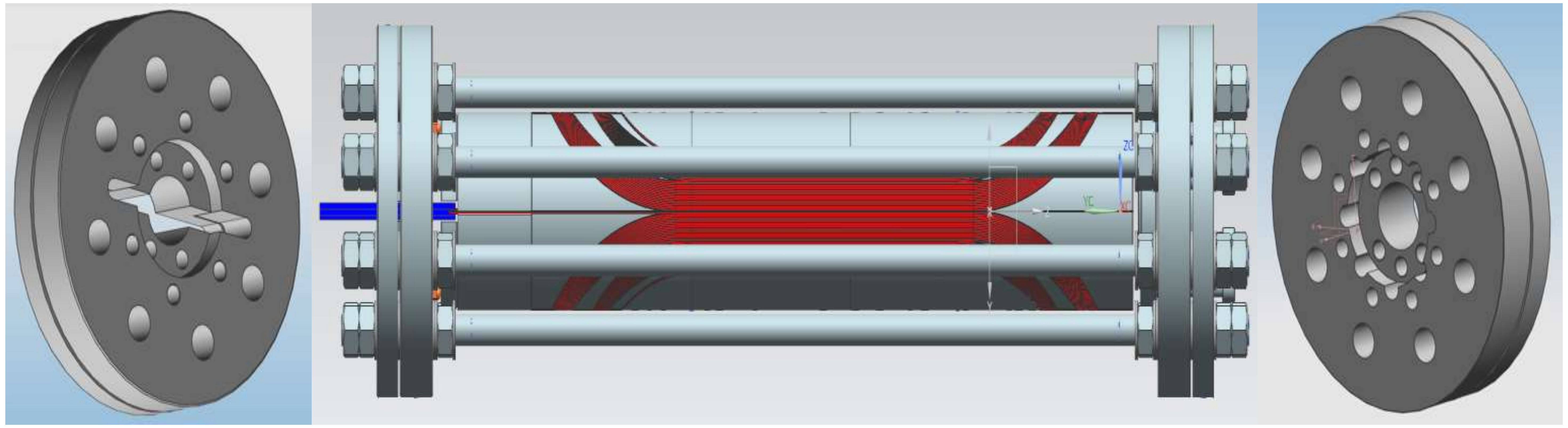
L1/L2:
- no coil/pole separation in straight section and ends

L3/L4:
- lost SG and VTs
- no coil/pole separation in straight sections
- coil/pole separation in coil ends

Coil shimming and modified end support



Azimuthal pre-stress increases by ~20 MPa



Separate end plates to preload and support inner and outer coils

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

Magnet status:

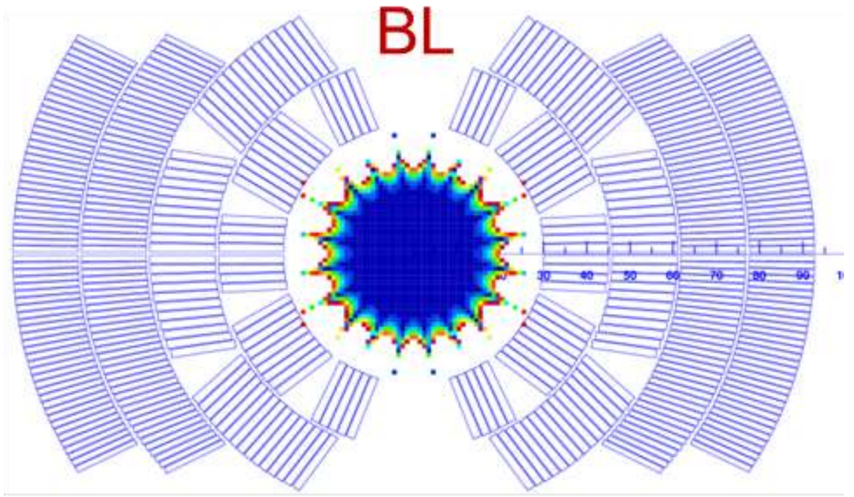
- Prepared for skin welding

Magnet second test in Jan-Feb 2020

Step 3: Conceptual design and analysis of 4-layer 16 T cos-theta dipole

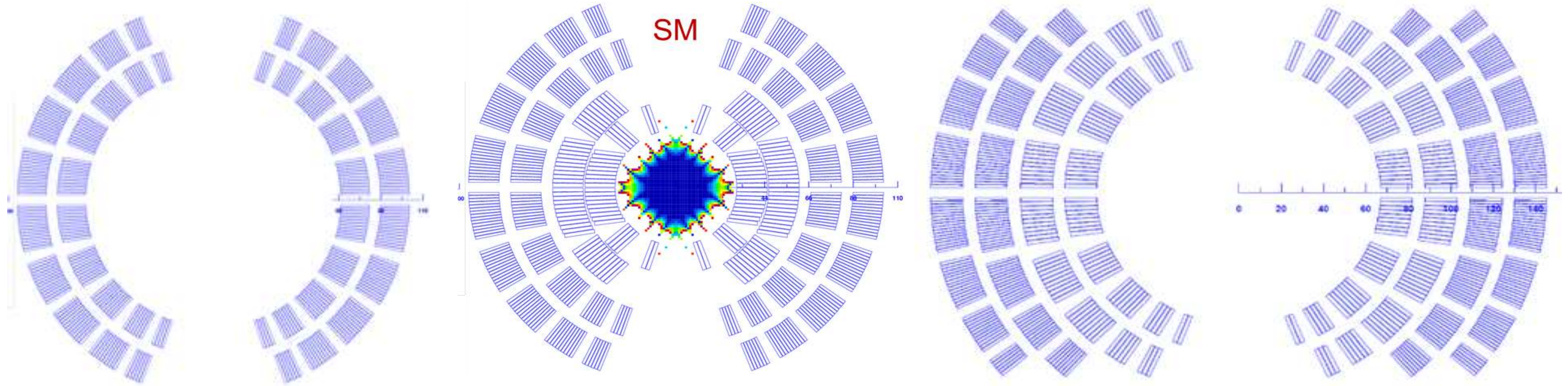
1. Coil conceptual design with stress management

60 mm bore, B_{des}~15 T



Coil SM is needed

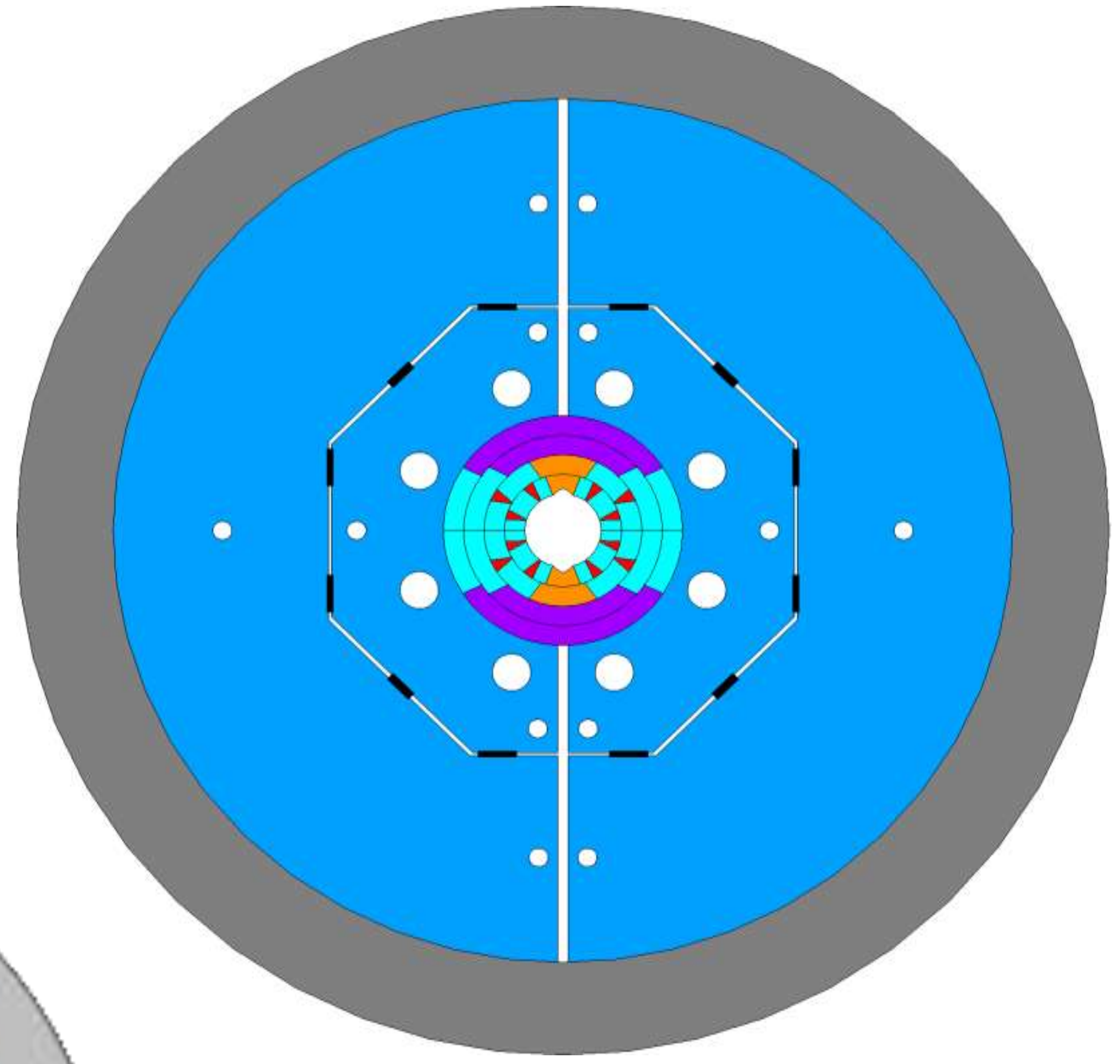
120 mm bore, B_{des}~11 T | 60 mm bore, B_{des}~17 T | 120 mm bore, B_{des}~15 T

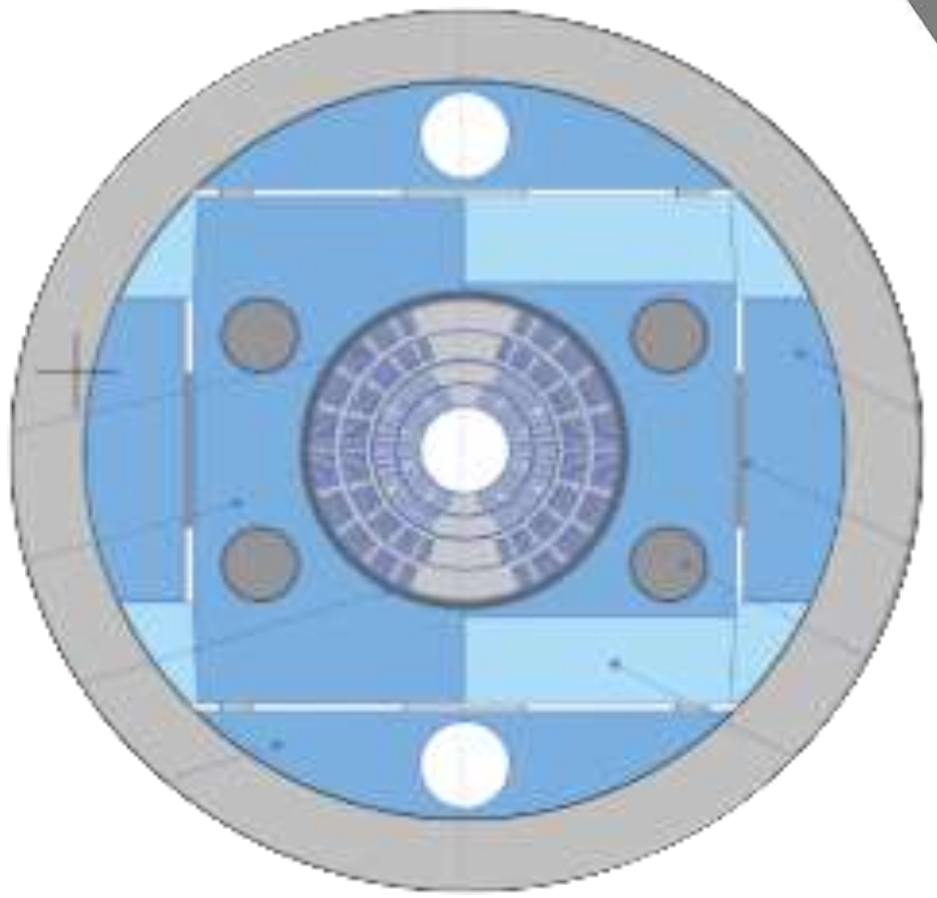


2-layer 120-mm aperture and 4-layer 60-mm and 120 mm aperture cos-theta dipole coils with stress management

2. Mechanical structures

- Utility structure (LBNL/FNAL)
  - Cold mass OD=750 mm
  - 75 mm thick Al shell





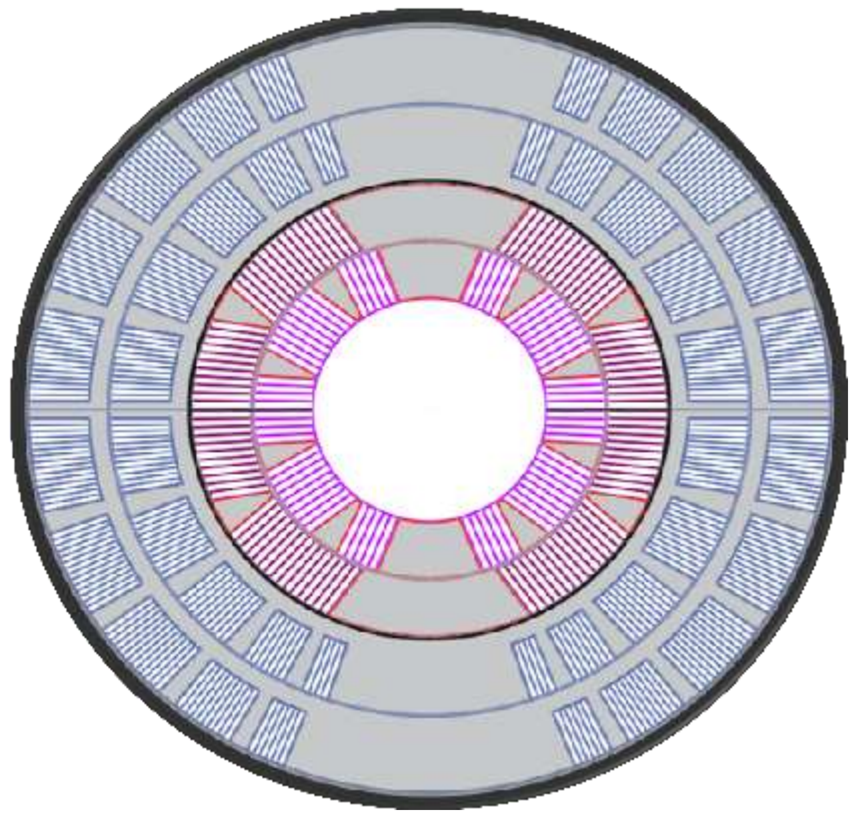
- Compact structure for VMTF (FNAL)
  - Cold mass OD=630 mm
  - 55 mm thick Al shell
  - Al or stainless steel clamps

Baseline for the next step of cos-theta Nb_3Sn magnet R&D program

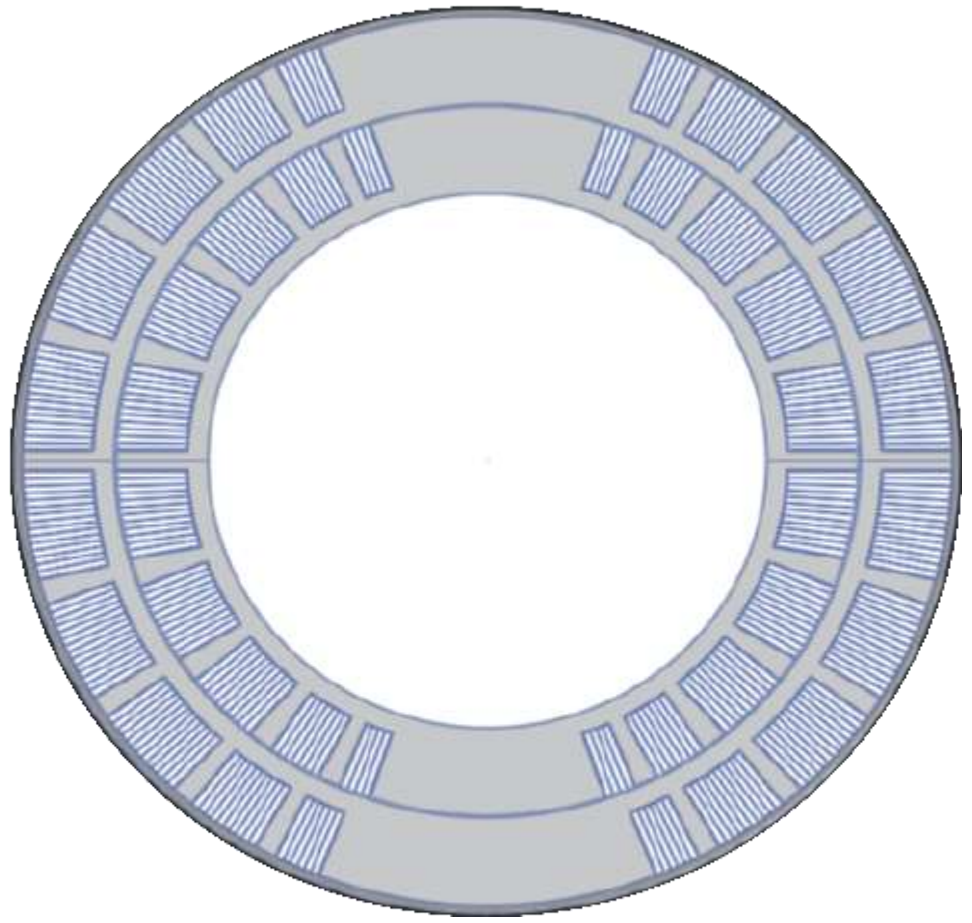
2020-2023 Nb_3Sn cos-theta magnet program

Goals
Continue addressing MDP driving questions 1-9, special attention to magnet training and degradation
Develop and demonstrate stress management (SM) approach (designs, materials, technologies) for shell-type Nb_3Sn and any other brittle, stress/stain sensitive superconducting coils including HTS
Explore and extend the operation parameter space for Nb_3Sn accelerator magnets – B_{max}~15-17T, coil bore 60-120 mm, large Lorentz forces and stored energies
Study and optimize quench performance (training, degradation), field quality and quench protection of high-field accelerator magnets with stress management
Develop and demonstrate strong and efficient mechanical structures for accelerator magnets
Develop capabilities to test cables, HTS coils and inserts, etc. for MDP and other programs
Approach
Integrate technical expertise and capabilities of MDP participating labs - design and analysis, fabrication infrastructure and instrumentation, test facilities
Achieve fast R&D turnaround time - test up to 2 magnets /year
Minimize R&D cost - use available tooling, magnet materials and components, test facilities

Stress management approach for cos-theta coils



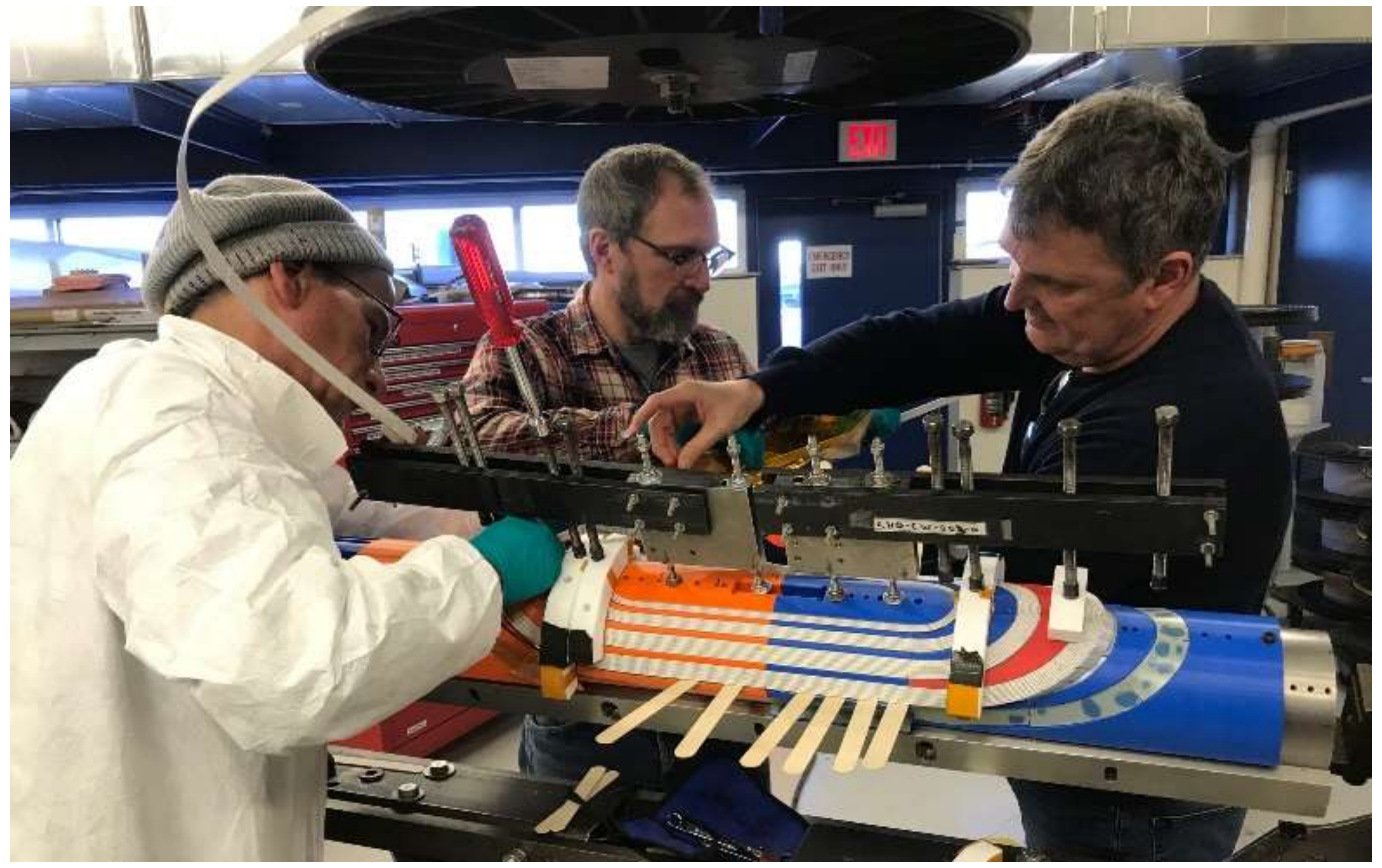
Stress management in outer layers (small aperture)

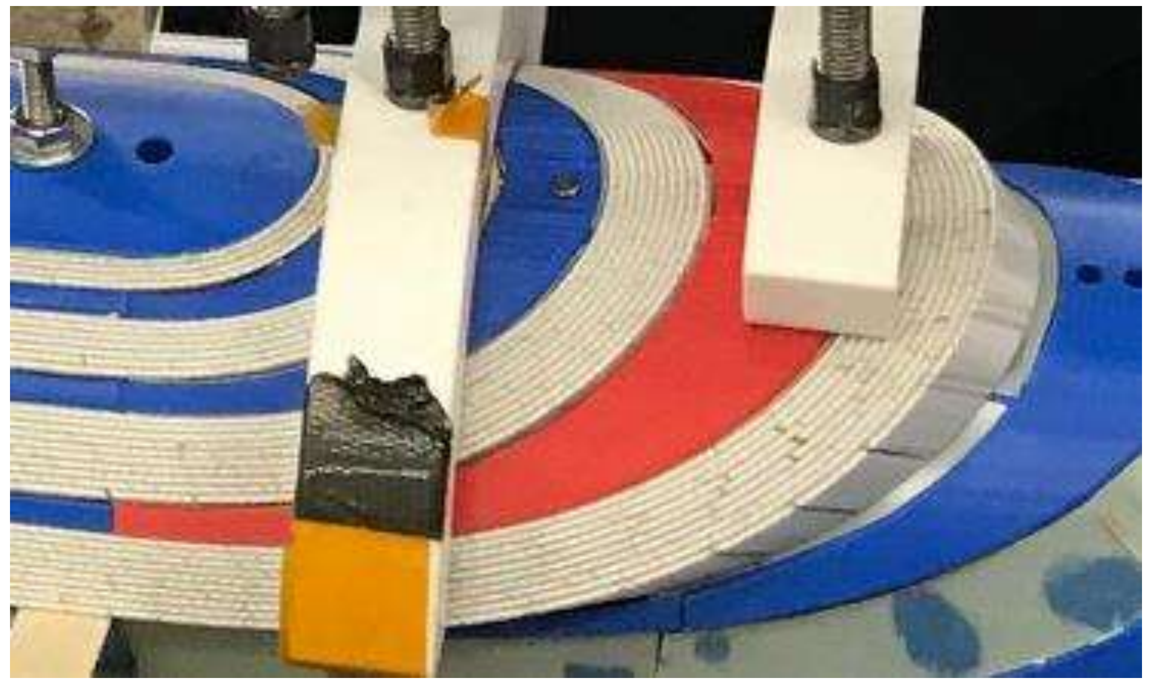


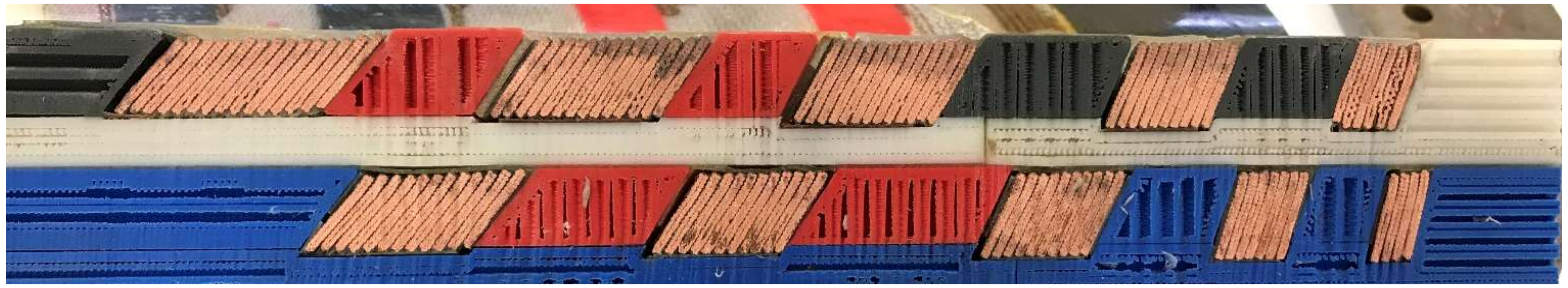
Stress management in whole coil (large aperture)

Category	SMCT vs CCT
Design	• Use of wide cables • Smaller coil volume, shorter coil ends • Use stress management in selected layers • Simpler and less costly coil support structure • Simpler and more reliable coil ground insulation • Use collar in the coil straight section
Fabrication	• Faster coil winding • No coil curing • Better axial and transverse control of cable expansion • Minimized epoxy volume (coil ends and straight section)
Instrumentation	• Use of voltage taps, acoustic and strain gauges • Traditional strip heaters for protection
Assembly and preload	• Simpler assembly of multilayer coils • Better control of azimuthal and radial preload, and end support
Tests	• Test of half-coils in magnetic mirror configuration
Scale up	• Simpler and less expensive coil scale up

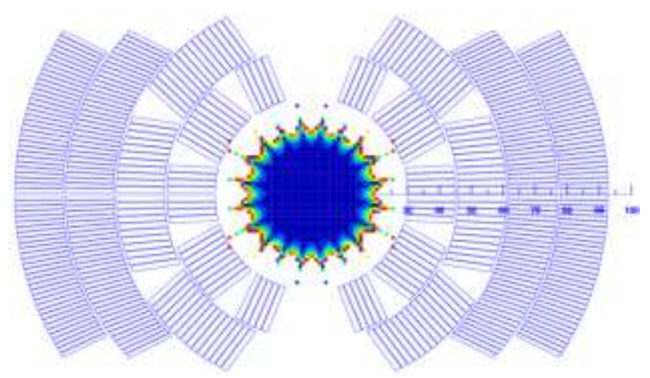
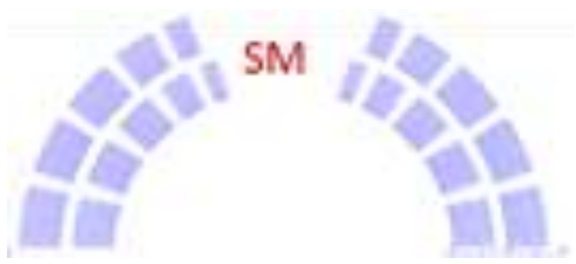
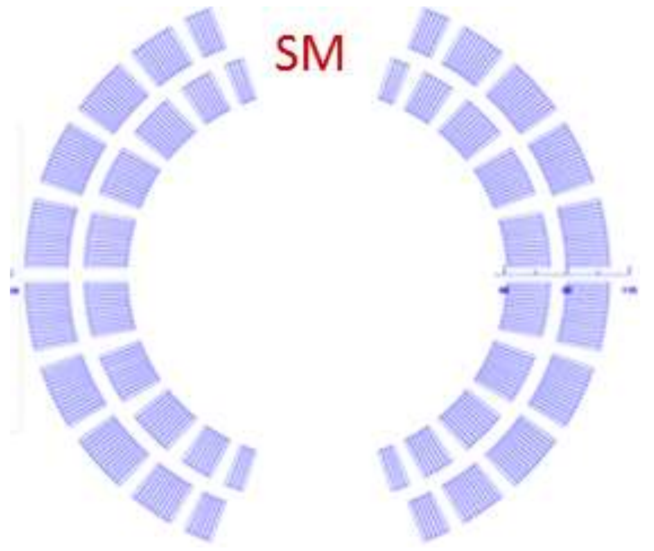
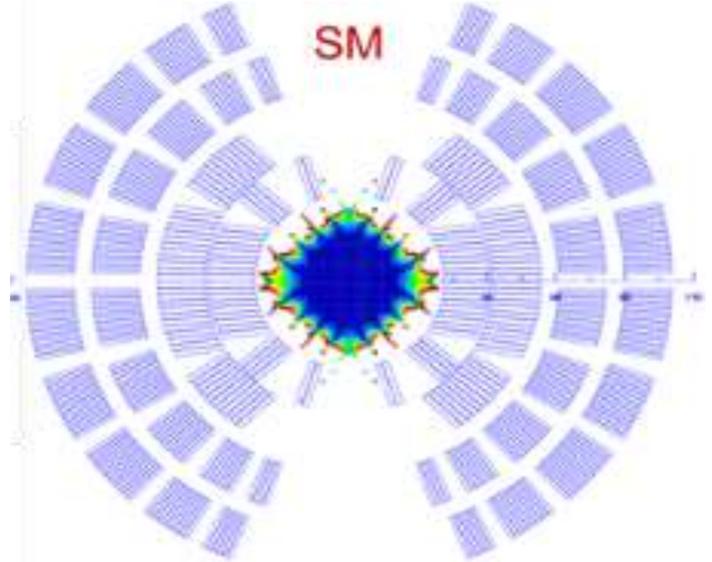
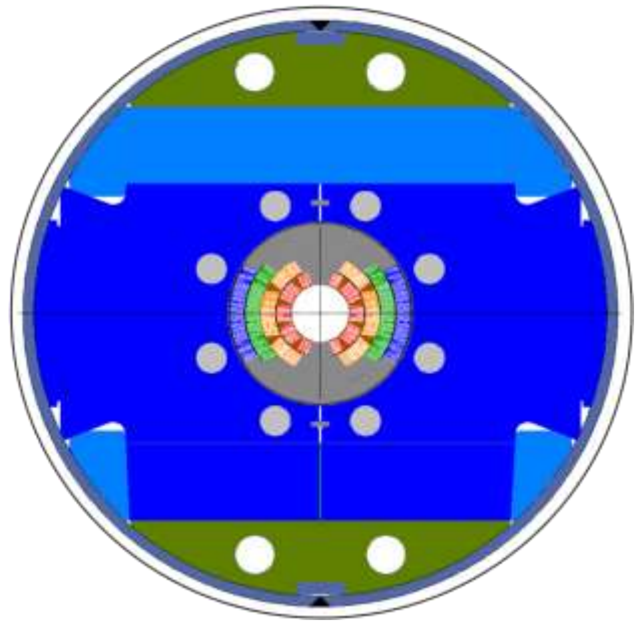
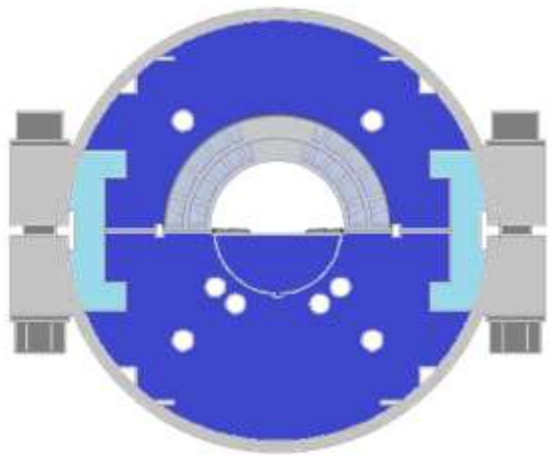
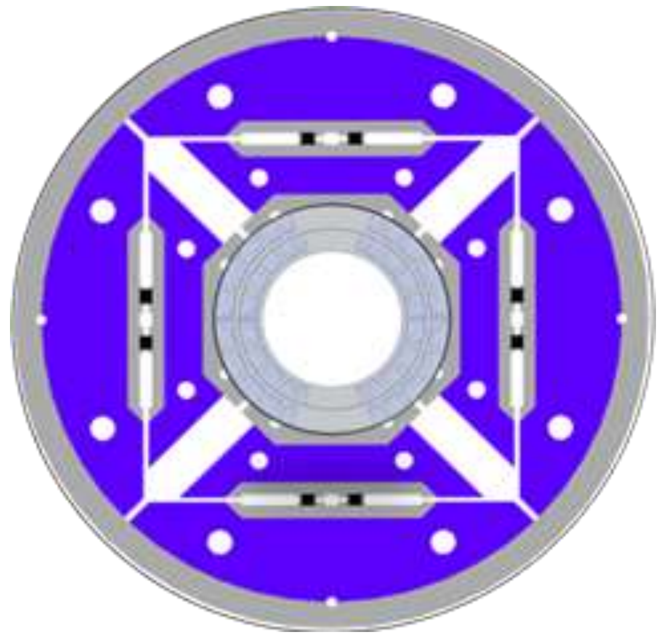
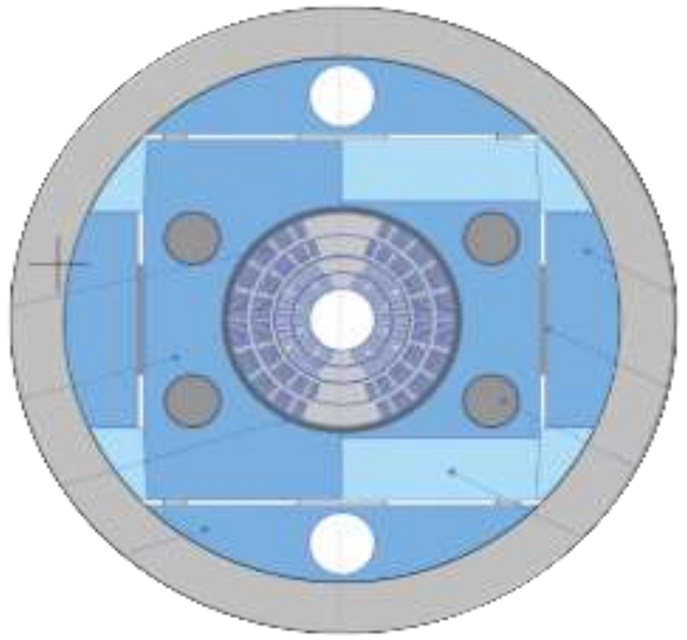
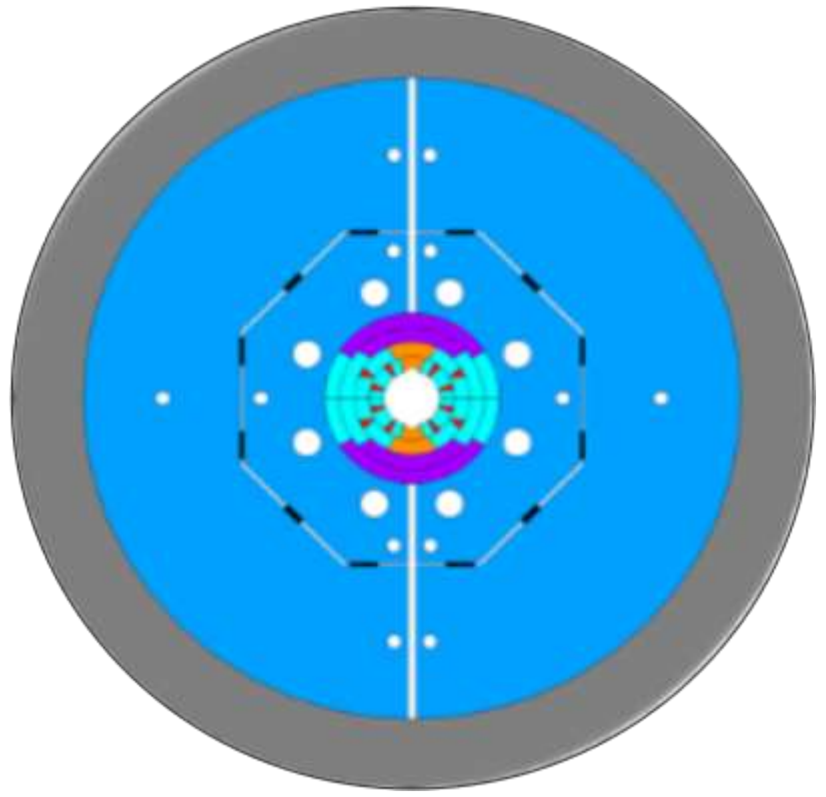
Cos-theta SM coil design and technology demonstration



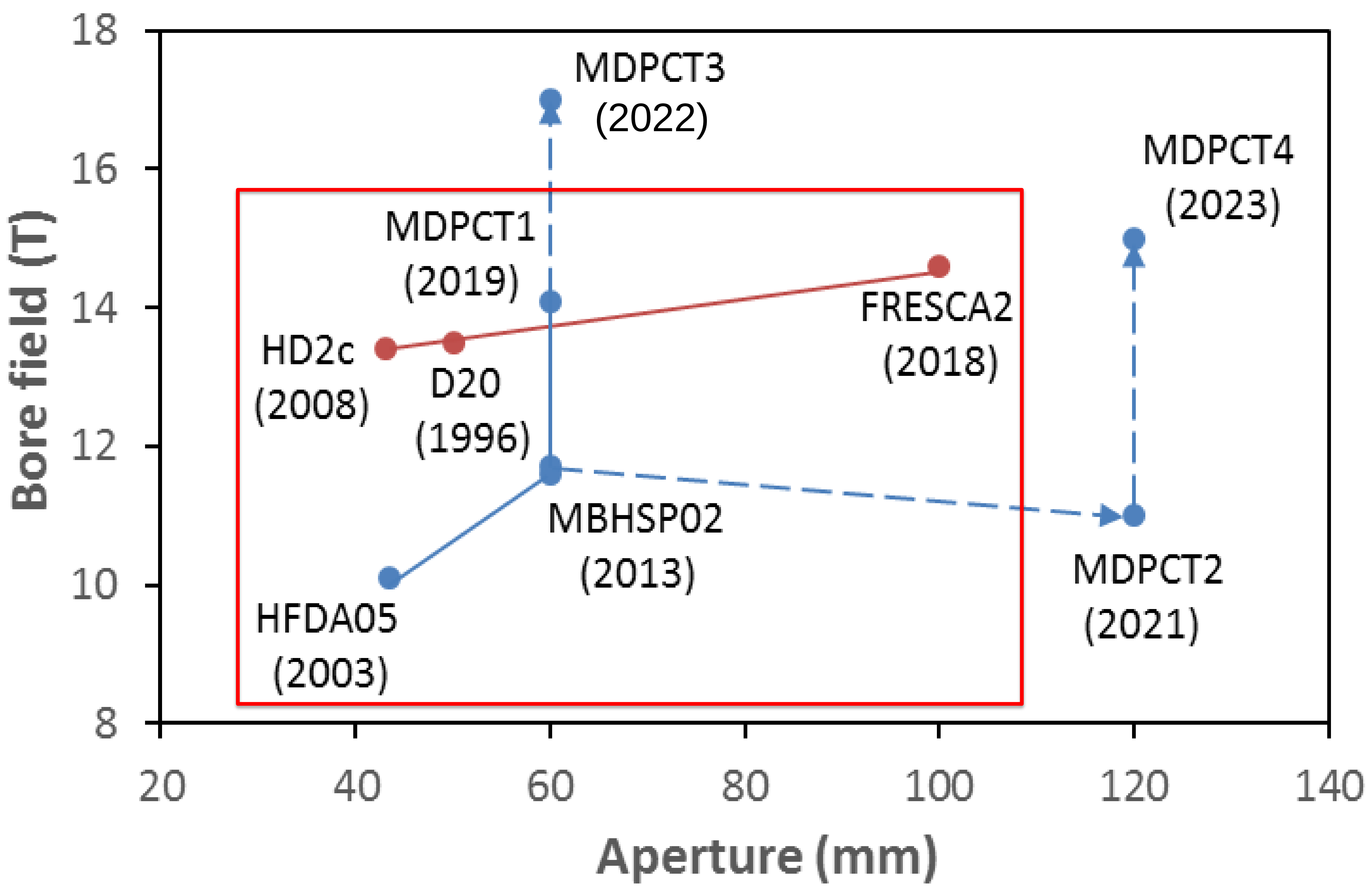




2020-2023 R&D plan and outcomes

Task 1	Task 2	Task 3	Task 4	Task 5
MDPCT1 reassembly and test	2-layer 120-mm SM coil in dipole mirror structure	2-layer 120-mm 11 T dipole in HQ2 structure	4-layer 60-mm 17 T dipole in modified MDPCT1 structure	4-layer 120-mm aperture 15 T SM dipole
				
				
Testing HTS coils up to 50-mm OD and cable samples in fields up to ~13 T	Testing HTS half-coils 120 mm OD in background fields up to 11 T	Testing HTS inserts up to 120 mm OD in background fields up to 11 T	Testing HTS half-coils up to 60-mm OD up to ~15 T background field	Testing HTS inserts up to 120-mm OD in 15 T field

Program target parameters and milestones



- Magnet designs and target parameters are innovative and challenging
- Schedule is ambitious but realistic

Summary

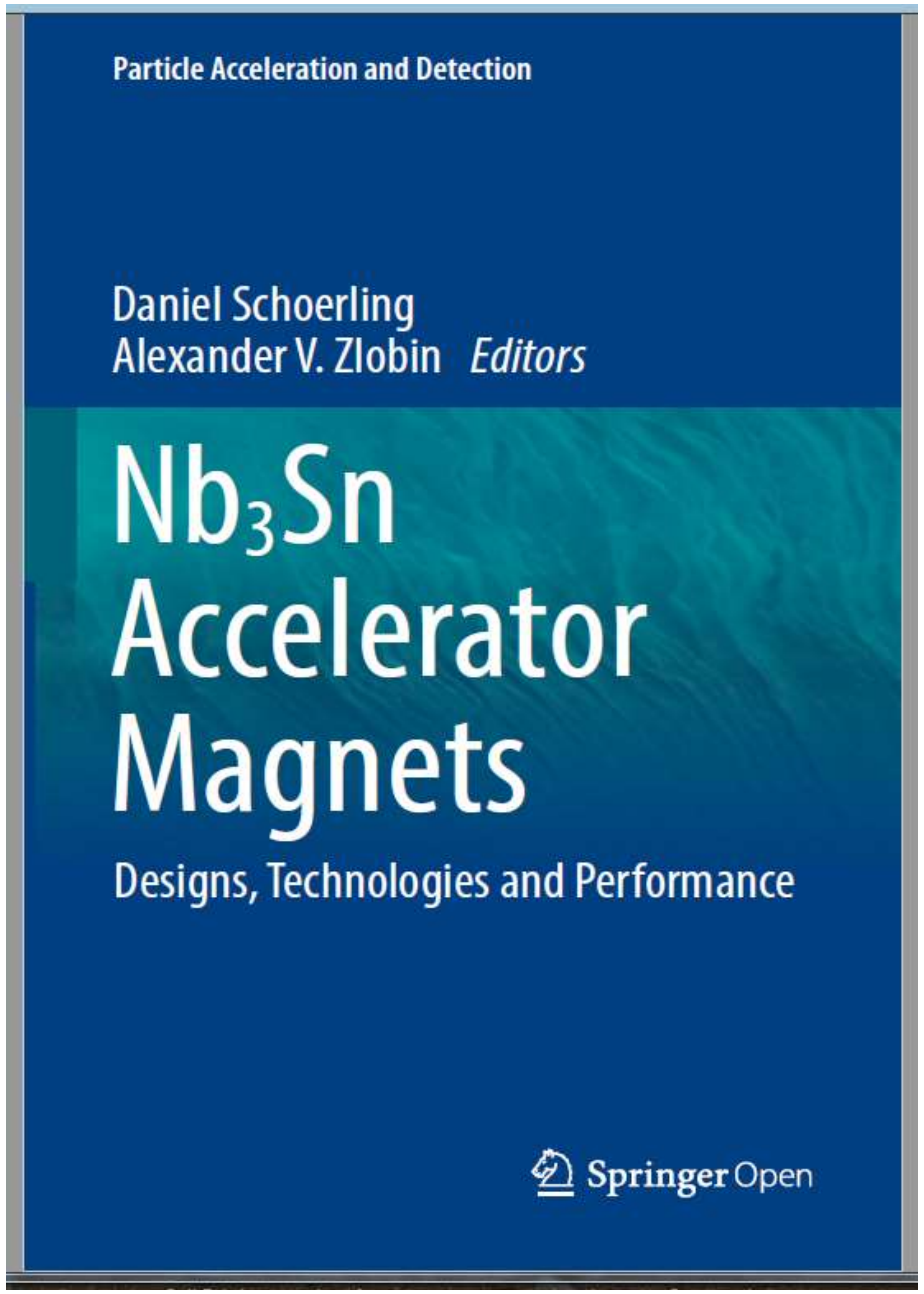
- The original 2016-2019 plan for Nb_3Sn cos-theta magnets is practically complete
  - collaborative effort with LBNL and EuroCirCol
- Step 1 is complete
  - the magnet was tested in June 2019.
  - the goals of the first test have been achieved
    - graded 4-layer coil design, innovative support structure and magnet fabricated procedure have been developed and tested
    - B_{max} = 14.10±0.04 T - *record field at 4.5 K for accelerator magnets*!
- Step 2 is almost complete
  - magnet reassembly with azimuthal and axial coil preload, optimized for 15 T bore field, by the end of December 2019
  - the 2nd test is in January-February 2020
- Step 3 is complete
  - 17 T 60-mm aperture and 11- 15 T 120-mm aperture coil designs with stress management and two mechanical structures for magnet tests have been developed and analyzed
- The results are reported in a book and 24 publications, and widely discussed by media
- The plan for Nb_3Sn cos-theta magnet R&D in 2020-2023 has been developed
  - the new plan to be discussed and approved at MDP CM4 in February 2020

Backup slides

The book

- Nb_3Sn Accelerator Magnets – Designs, Technologies and Performance, Springer 2019
- ~450 pages on Nb_3Sn accelerator magnet (dipoles) designs, technologies and performance covering the period of time from 1967 to 2019
- written by world experts in Nb_3Sn accelerator magnet technologies
- open access, available online

https://link.springer.com/book/10.1007/978-3-030-16118-7



Nb_3Sn cos-theta magnets: publications

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2. V.V. Kashikhin et al., “Magnetic and structural design of a 15 T Nb_3Sn accelerator dipole model”, CEC/ICMC2015, v.101, issue 1, 2015, p.012055.
3. I. Novitski et al., “Development of a 15 T Nb_3Sn Accelerator Dipole Demonstrator at Fermilab”, TAS, Vol. 26, Issue 3, June 2016, 4001007.
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7. S. Stoynev, K. Riemer. A. V. Zlobin, “Quench Training Analysis of Nb_3Sn Accelerator Magnets”, NAPAC2016, Chicago, IL, USA, p. 155
8. I. Novitski, J. Carmichael, V.V. Kashikhin, A.V. Zlobin, “High-Field Nb_3Sn Cos-theta Dipole with Stress Management,” FERMILAB-CONF-17-340-TD,
9. E. Barzi et al., “Heat Treatment Optimization of Rutherford Cables for a 15 T Nb_3Sn Dipole Demonstrator”, TAS, Vol. 27, Issue 4, June 2017, 4802905
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12. Pei Li, S. Krave, A. Zlobin, “Study of Thermomechanical Properties of The Epoxy-Impregnated Cable Composite for a 15 T Nb_3Sn Dipole Demonstrator,” IOP Conf. Series: Materials Science and Engineering 279 (2017) 012020
13. C. Kokkinos et al., “FEA Model and Mechanical Analysis of the Nb_3Sn 15 T Dipole Demonstrator,” TAS, Vol. 28, Issue 3, April 2018, 4007406
14. A.V. Zlobin, V.V. Kashikhin, I. Novitski, “Large-aperture high-field Nb_3Sn dipole magnets,” IPAC2018, 2018, p.2738.
15. A.V. Zlobin, J. Carmichael, V.V. Kashikhin, I. Novitski, “Conceptual design of a 17 T Nb_3Sn accelerator dipole magnet,” IPAC2018, 2018, p.2742.
16. D. Tommasini et al.,“Status of the 16 T dipole development program for a future hadron collider,” TAS, Vol. 28, Issue 3, April 2018, 4001305
17. C. Orozco et al., “Assembly and Tests of Mechanical Models of the 15 T Nb_3Sn Dipole Demonstrator,” TAS, Vol. 29, Issue 5, August 2019, 4003404
18. M. Juchno et al., “Mechanical Utility Structure for Testing High Field Superconducting Dipole Magnets,”, TAS, Vol. 29, Issue 5, August 2019, 4001604
19. S. Stoynev et al., “Analysis of Nb_3Sn Accelerator Magnet Training,” TAS, Vol. 29, Issue 5, August 2019, 4001206
20. D. Schoerling et al., “The 16 T Dipole Development Program for FCC and HE-LHC,” TAS, Vol. 29, Issue 5, August 2019, 4003109
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U.S. MAGNET DEVELOPMENT PROGRAM

International news on MDPCT1 1st test

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2. https://cerncourier.com/a/dipole-marks-path-to-future-collider/
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14. https://cryogenicsociety.org/37208/news/fermilab_achieves_world-record_field_strength_for_accelerator_magnet/?utm_source=newsletter&utm_medium=email&utm_campaign=ft-191003
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2016-2019 Program justification

- The 15 T dipole demonstrator project was initiated at Fermilab in 2015 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

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US-MDP: G6 and TAC

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