U.S. MAGNET DEVELOPMENT PROGRAM

15 T dipole demonstrator MDPCT1 – development, tests, lessons learned and next steps

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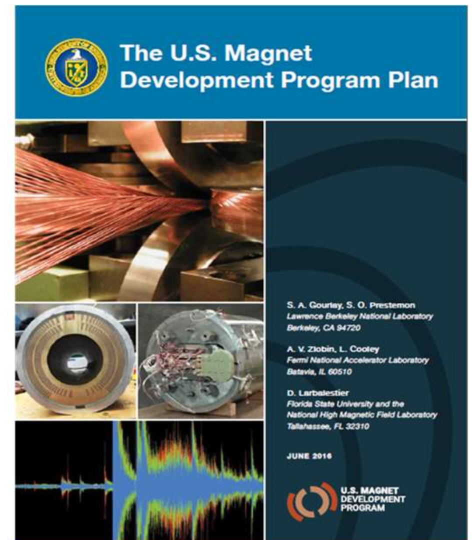
US Magnet Development Program
Fermi National Accelerator Laboratory

TE-MSC seminar, 7 April 2022

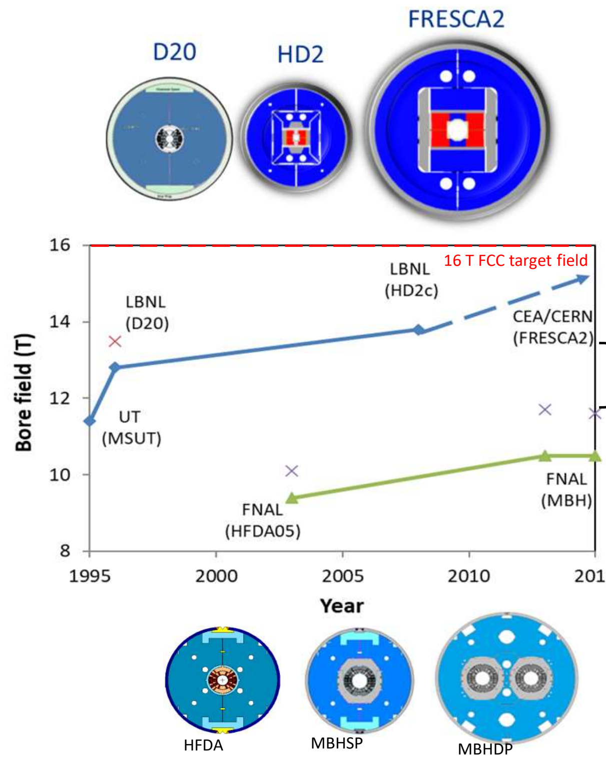
Program Goal

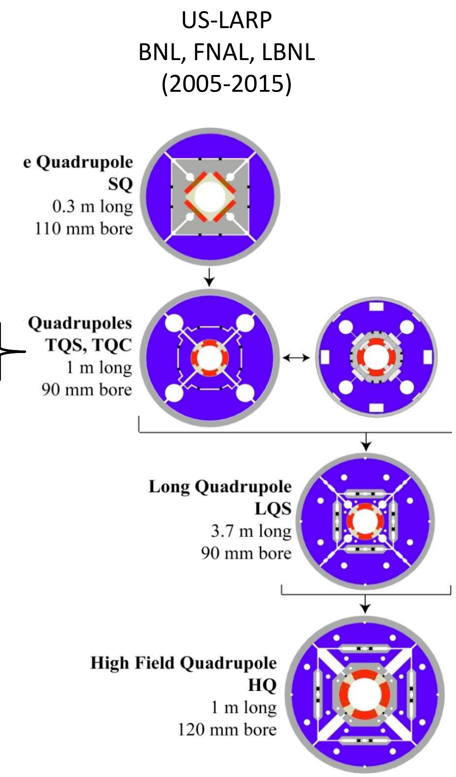
- In 2015 Fermilab in response to recommendations of the Particle Physics Project Prioritization Panel (P5) and HEPAP Accelerator R&D subpanel has initiated a program *to demonstrate the 15 T field in a Nb_3Sn accelerator dipole*
- In 2016, US-DOE Office of High Energy Physics created the national Magnet Development Program (MDP) to integrate accelerator magnet R&D in the U.S. and coordinate it with the international effort
  - –the project became a key task of the USMDP
- In 2017 this effort received support also by the EuroCirCol program, making it a truly international endeavor.



Program background

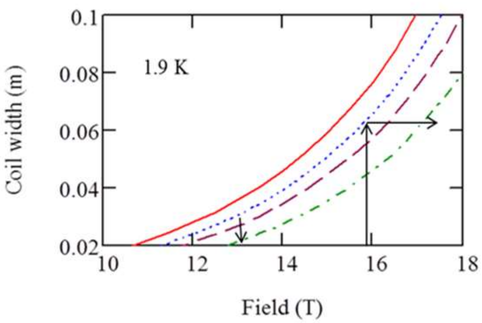
- By 2015 Nb_3Sn accelerator magnet technology has made significant progress
  - LBNL: highest field B_{max}= 13.8 T @4.5K
  - LARP: 11-12 T large-aperture quadrupoles with ~15-20% margin
  - FNAL-CERN: 60-mm aperture 11 T MBH dipole demonstrator for the LHC
- Future needs
  - FCC: affordable for mass production 16 T dipole
- Open questions
  - long training, conductor degradation, cost





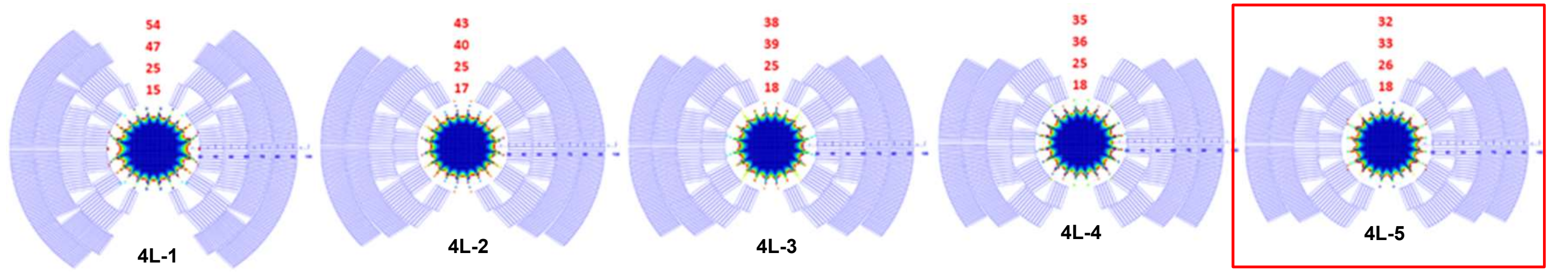
Coil design studies and selection

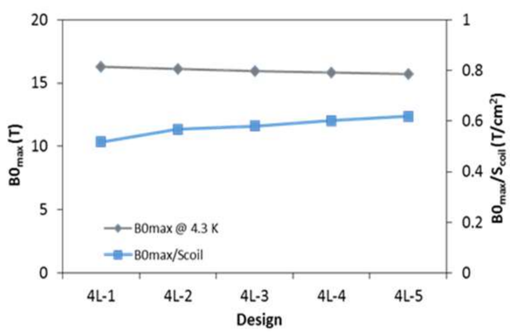
V. Kashikhin



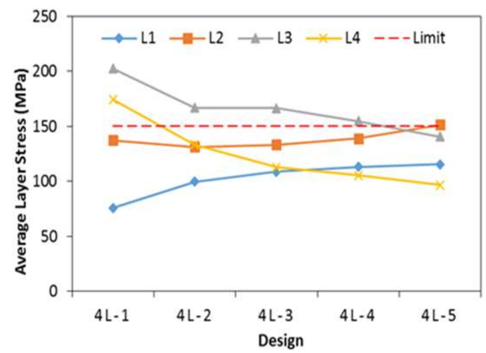
$$B0_{max} = \frac{\sqrt{3}\,\mu_0}{\pi} \cdot \lambda J_c\left(B_{max\_coil}\right) \cdot w$$

Parameter	Cable 1	Cable 2
Number of strands	28	40
Mid-thickness, mm	1.870	1.319
Width, mm	15.10	15.10
Keystone angle, degree	0.805	0.805

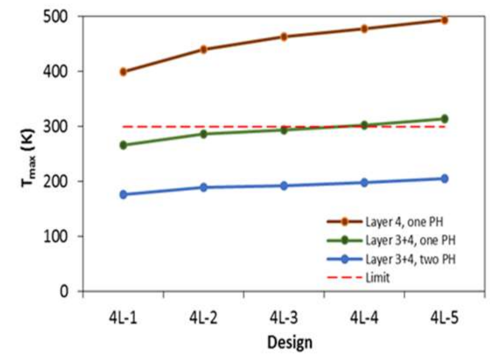




Parameter	Coil design				
	4L-1	4L-2	4L-3	4L-4	4L-5
N_{tot} coil	141	125	120	114	109
S_{coil}, cm^2	31.4	28.4	27.5	26.3	25.4
$B0_{max}$(4.3K), T	16.3	16.1	16.0	15.8	15.7
I_{max}(4.3K), kA	9.9	10.3	10.5	10.8	11.1
L, mH/m	40	34	32	29	27
W(B_{max}), MJ/m	1.95	1.81	1.74	1.69	1.63



$$\sigma_{av} = \frac{1}{w_L} \cdot \sum_{n=1}^{N_L} F_{\theta n}$$



$$W_m = N_{qt} \cdot \int_{T_{cs}}^{T_{max}} C_{pt}\,(T)\,dT$$

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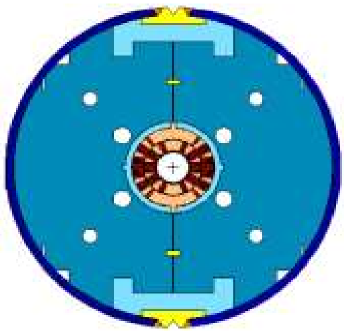
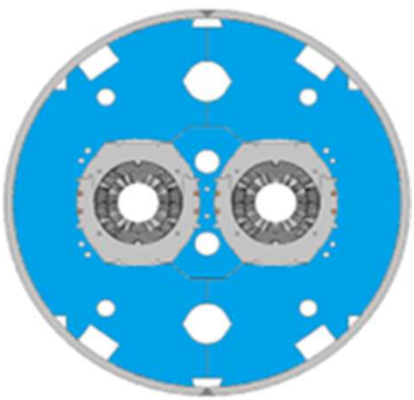
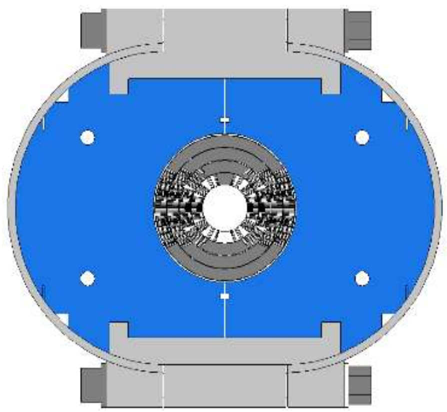
Mechanical structure studies and selection

HFDA

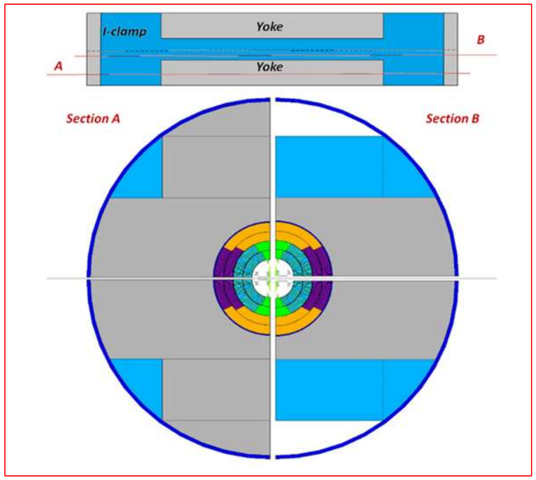


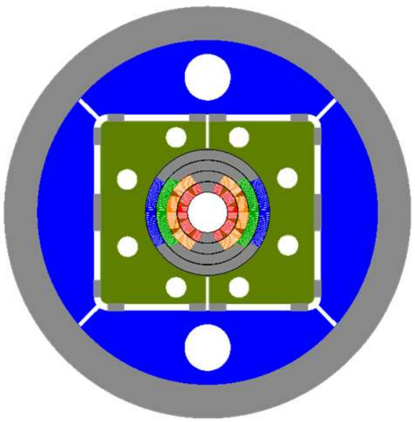
MBHDP

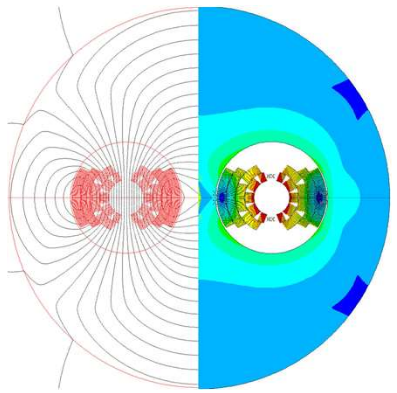




I. Novitski





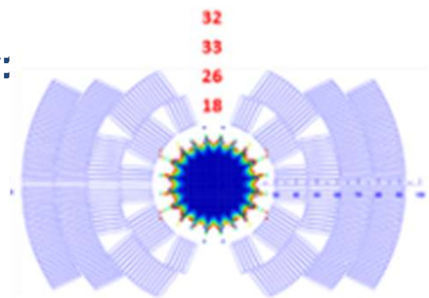


Mechanical structure selection:

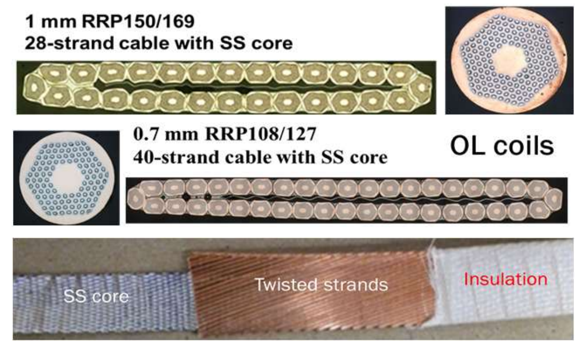
- Design 1: SS C-clamps and 20-mm thick SS skin
- Design 2: Al I-clamps and 12-mm thick SS skin
- Design 3: 50-mm thick Al shell

15 T Dipole Demonstrator (MDPCT1) design

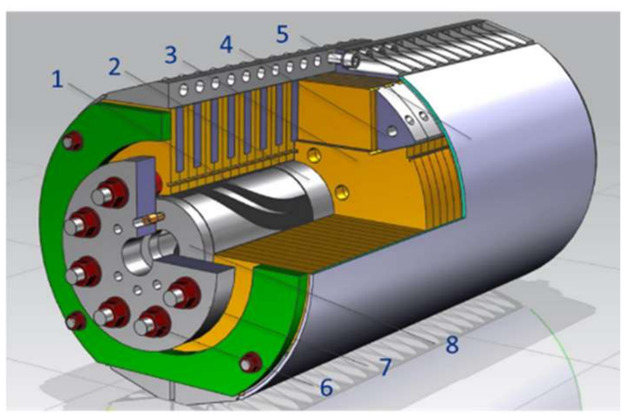
Optimized coil geometry:
- 60-mm aperture
- Min conductor volume
- 4-layer graded shell-type coil

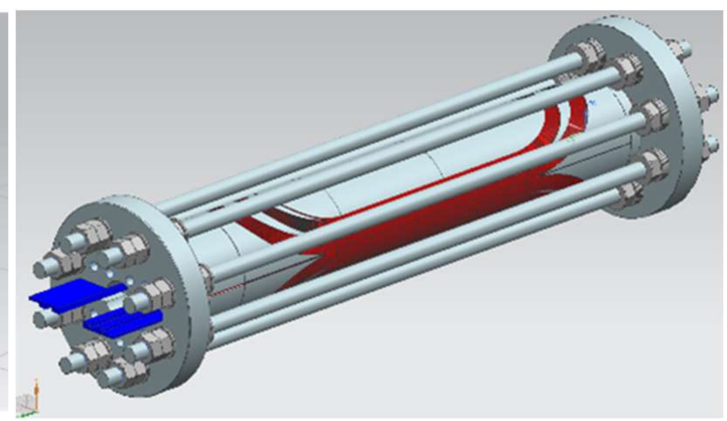


Cable:
- L1-L2: 28 strands, 1 mm RRP150/169
- L3-L4: 40 strands, 0.7 mm RRP108/127
- 0.025 x 11 mm^2 stainless steel core



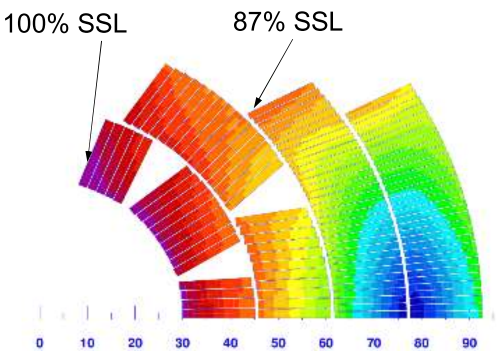
Innovative mechanical structure:
- Vertically split iron yoke
- Aluminum I-clamps
- 12.5-mm thick stainless-steel skin
- Cold mass OD=612mm
- Axial coil support with 50-mm thick end plates

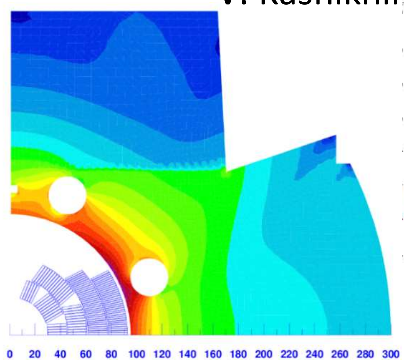


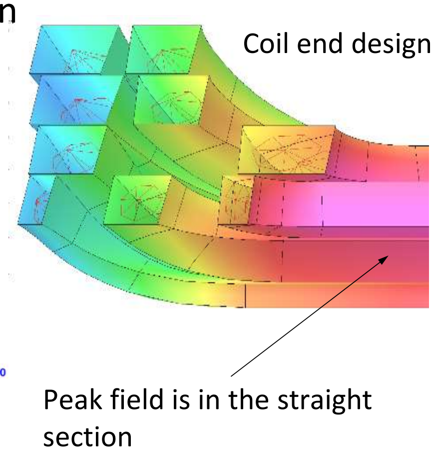


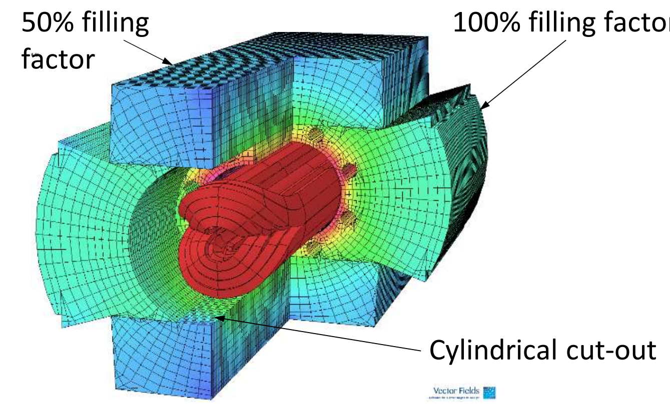
2D and 3D magnetic analysis

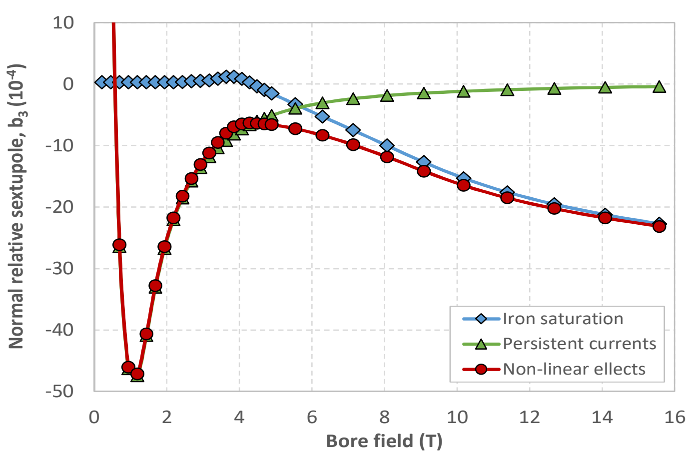
V. Kashikhin



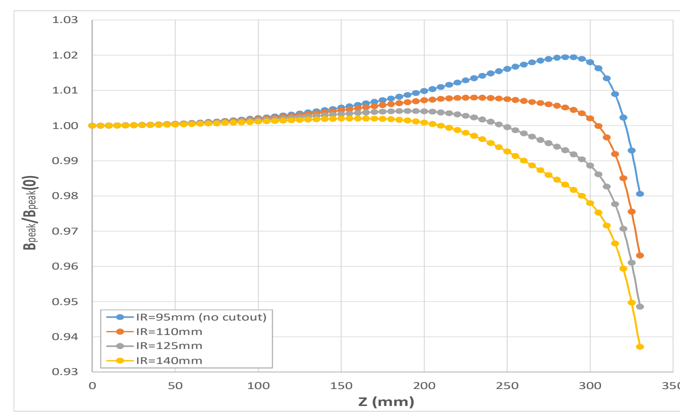




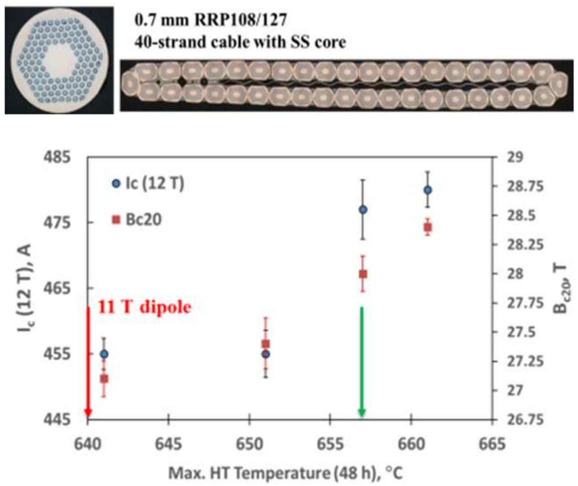


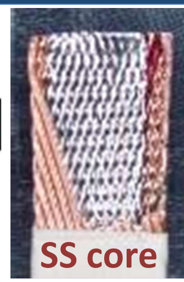


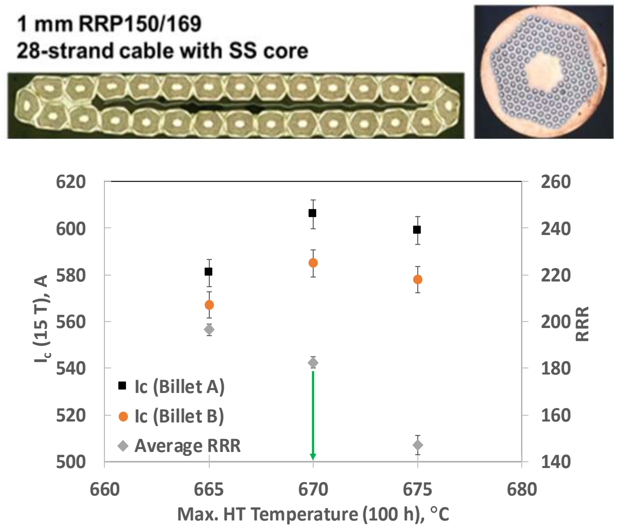
- Coil end were optimized to take into account structural and magnetic considerations
- Without the iron cutout, B_{peak} in the coil end is 2% higher than in the straight section
- Removing ~45 mm of the iron yoke around coil ends reduces end B_{peak} to the level of the straight section B_{peak}



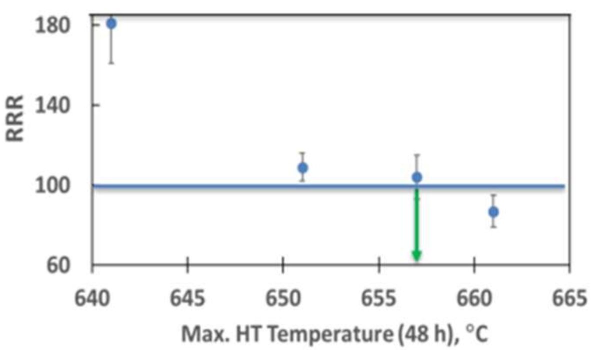
Cable and strand R&D

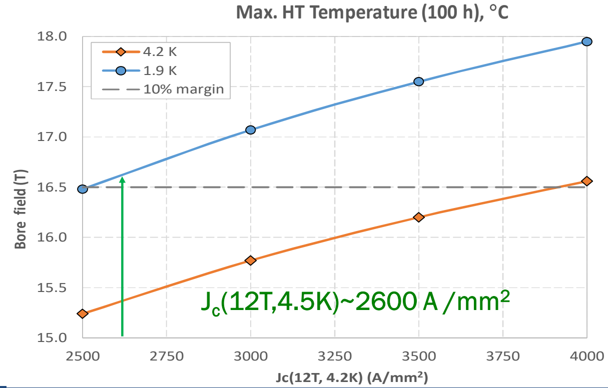






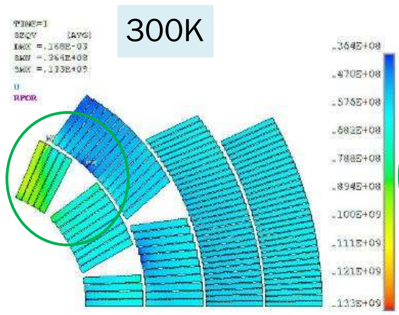
E. Barzi



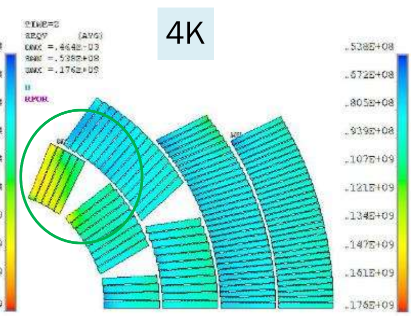


- Outer-layer cable was developed and used in 11 T Dipole
- Inner-layer cable was developed for HFDA dipole:
  - Effect of cable PF on I_c degradation and RRR
  - Final cable cross-section parameters have been selected – PF~87%, Ic degradation <5%, RRR>100
- HT optimization to achieve optimal J_c and RRR
- **Magnet conductor:**
  - B_{ap}=15.3T @4.5K
  - B_{ap}=16.7T @1.9K

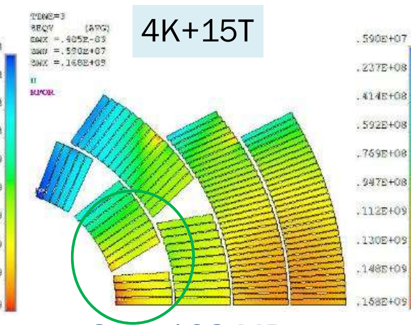
Mechanical limit and target pre-load for the 1st test



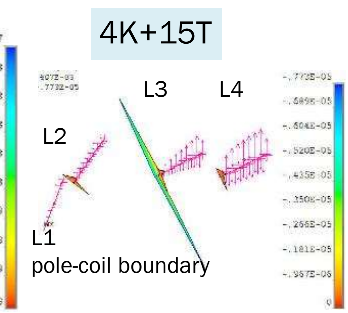
S_{eqv}=133 MPa
S_{eqv}=133 MPa



S_{eqv}=176 MPa
S_{eqv}=182 MPa



S_{eqv}=168 MPa
S_{eqv}=161 MPa



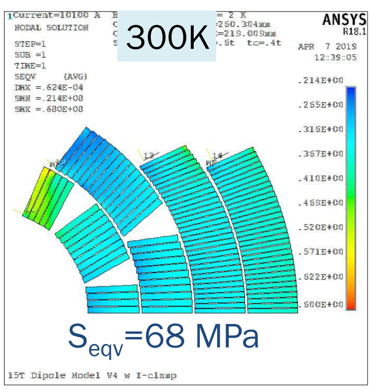
Pole Gap < 7 μm

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

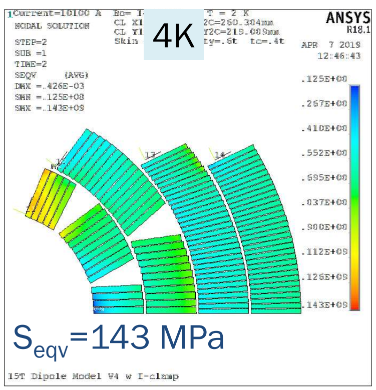
- it determined by the coil maximum stress and the coil turn separation from inner-layer poles
- S_{max} at all steps <180 MPa

I. Novitski, H. Kokinos

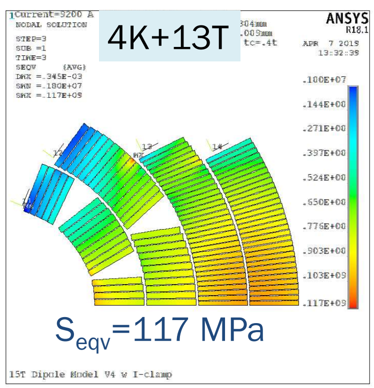
ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΑΤΡΩΝ UNIVERSITY OF PATRAS
with the assistance of FEAC



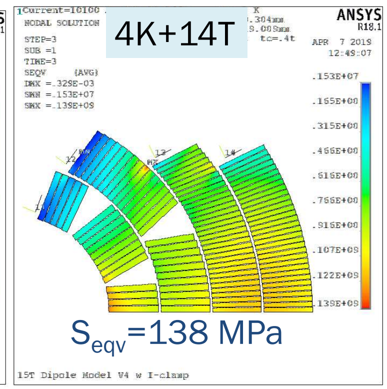
S_{eqv}=68 MPa



S_{eqv}=143 MPa



S_{eqv}=117 MPa



S_{eqv}=138 MPa

Conservative coil pre-stress for the 1st test:

- S_{max} at all steps <150 MPa
- B_{ap}=14 T

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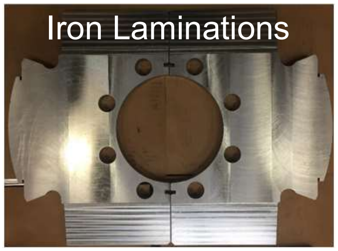
15 T dipole components

Coil parts (FNAL)

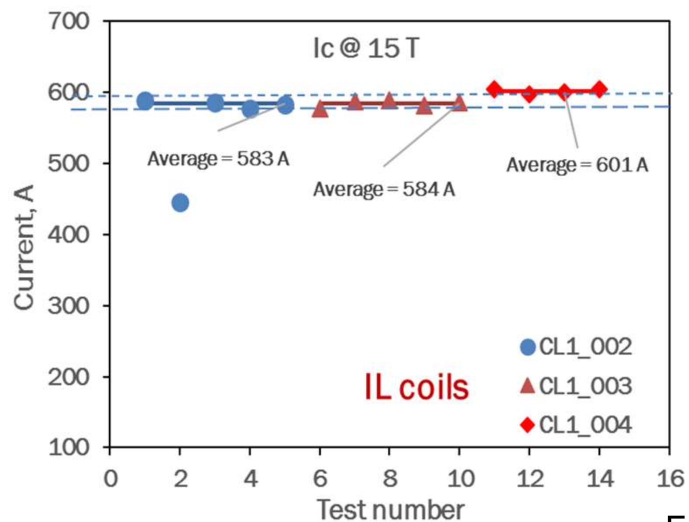
L1/2 parts (CERN)

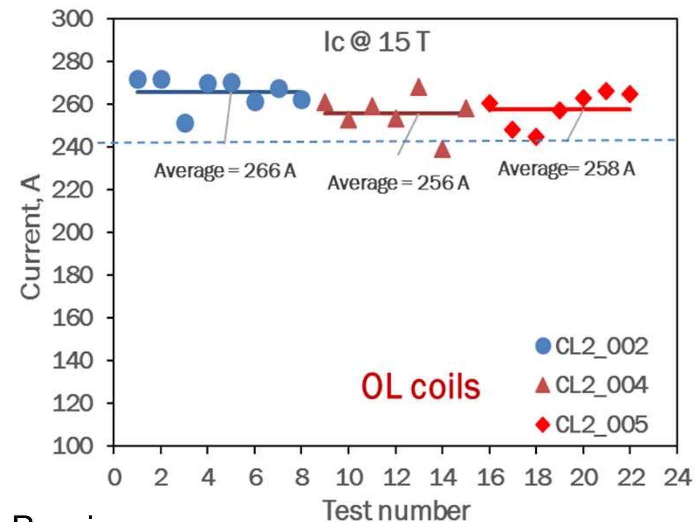
Ti and Glidcop wedges

4 sets: Ti poles and spacers, SS saddles



Witness sample data and magnet SSL





E. Barzi

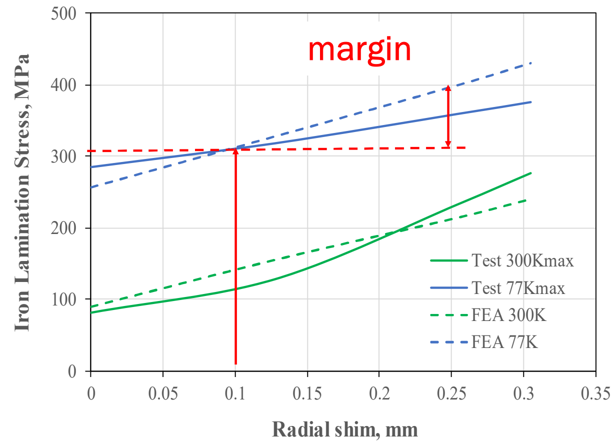
- Witness sample data are close to the target I_c
- Good reproducibility of witness sample data for IL and OL coils

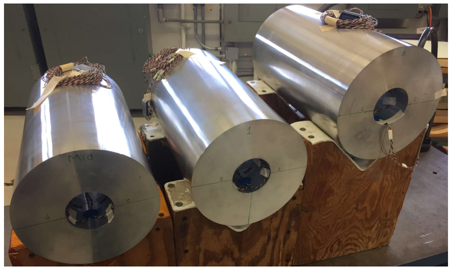
Magnet short sample limit: 15.2 T at 4.5 K and 16.8 T at 1.9 K

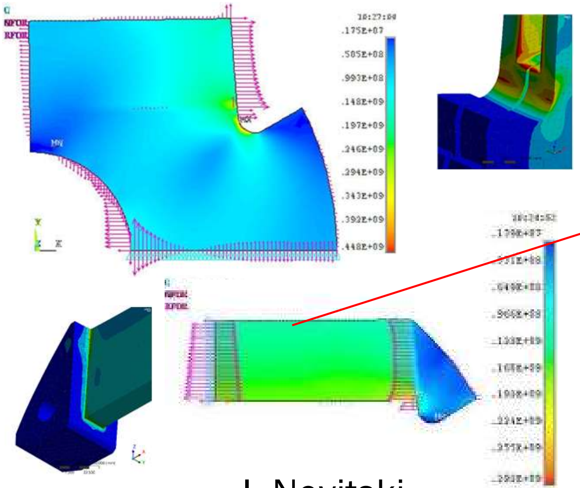
Short and full-scale Mechanical Models

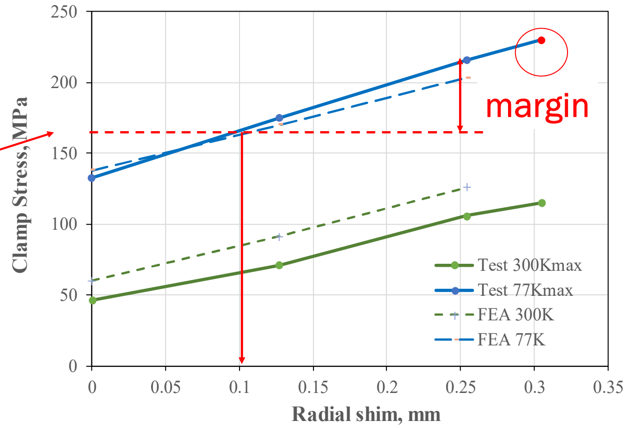
Goals:

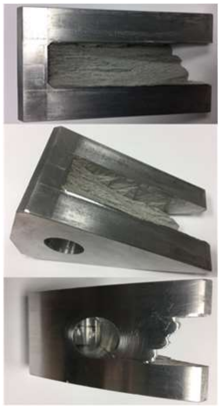
- Test yoke and clamp
- Validate the mechanical analysis
- Develop the coil pre-stress targets





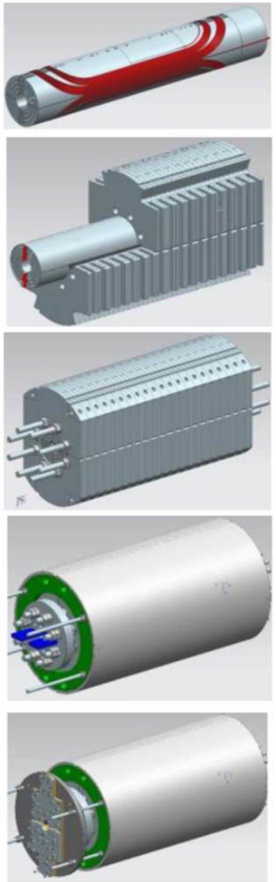


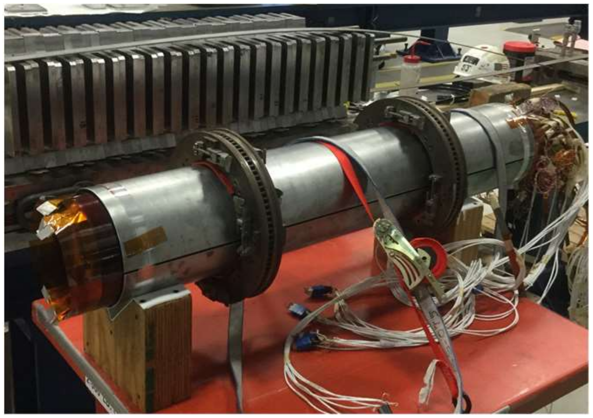


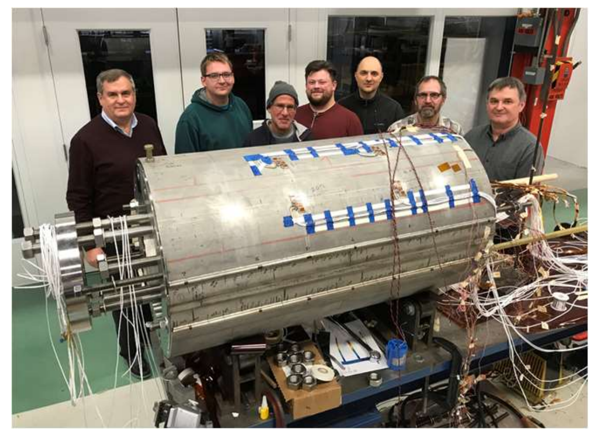


I. Novitski

Magnet assembly



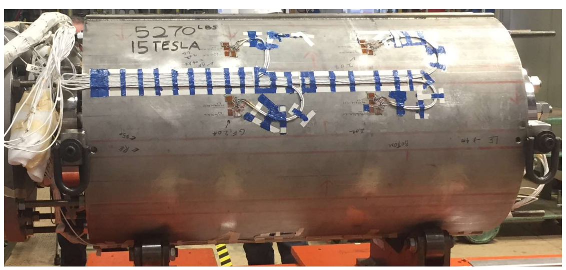




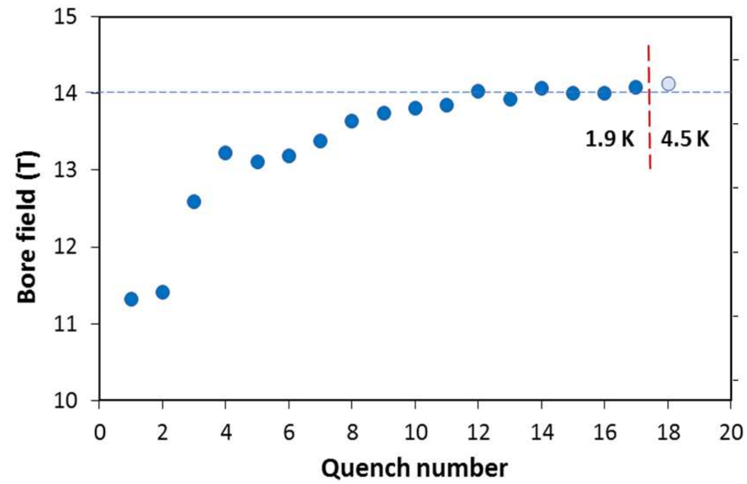
Magnet instrumentation and 1st test (June 2019)

Instrumentation:

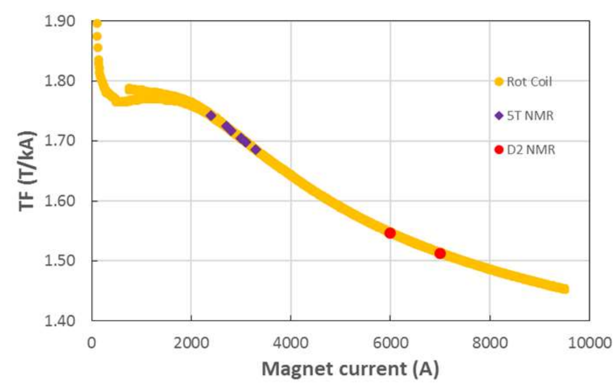
- Voltage taps
- Strain gauges
  - skin
  - clamps
  - bullets
  - poles
  - coils
- Quench antennas
- Acoustic sensors
- Thermometers



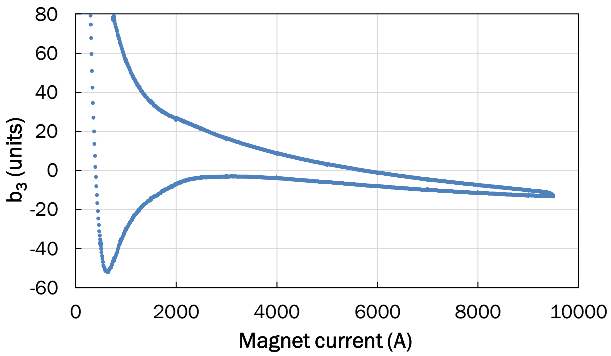
Significant part of instrumentation has been lost.

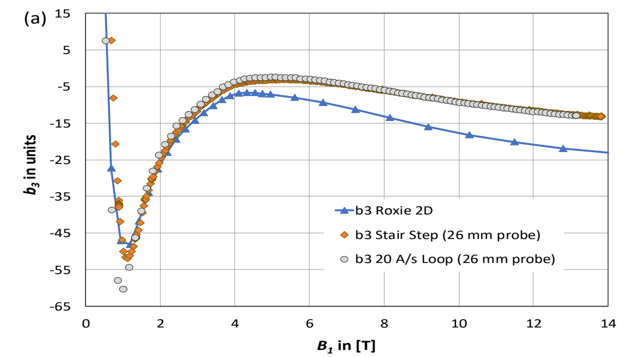


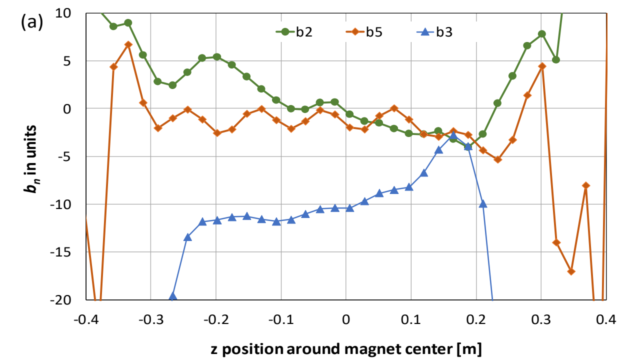
- 11 quenches to plateau
  - IL: 2 quenches in coil 2
  - OL: 8 quenches in coil 4, 7 quenches in coil 5
- Last quench at 4.5 K:
  B_{meas} = 14.13±0.02 T
  B_{calc} = 14.112 T

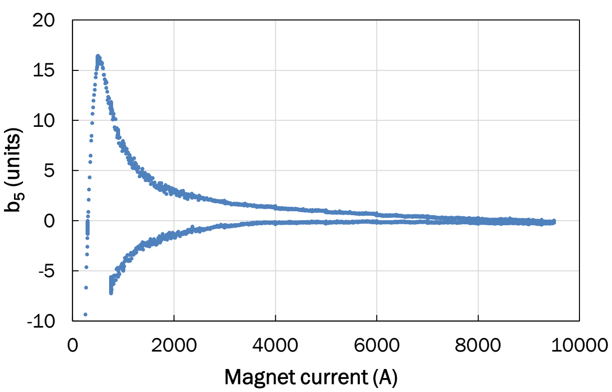


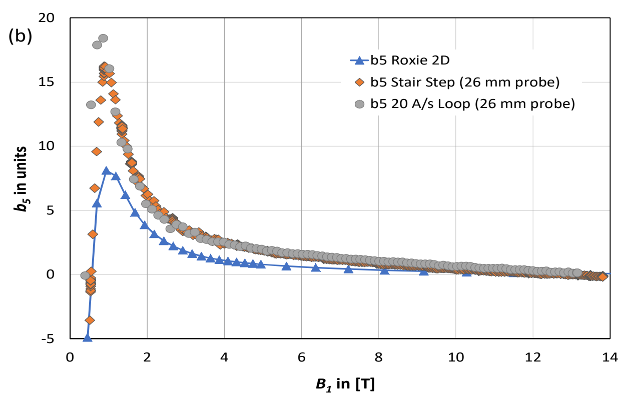
Field harmonics

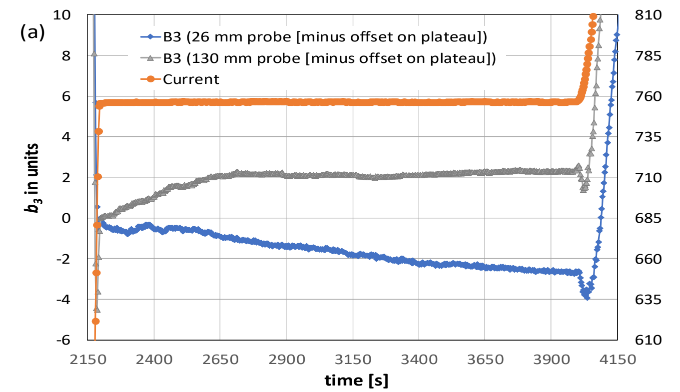












Geometrical harmonics at R_{ref}=17 mm (I=2.5 kA)

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

J. DiMarco, V. Kashikhin

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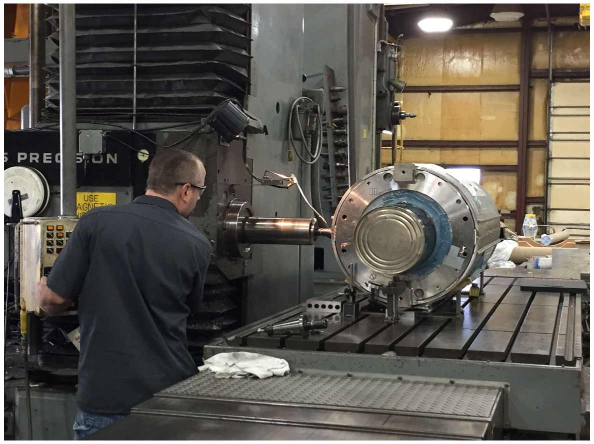
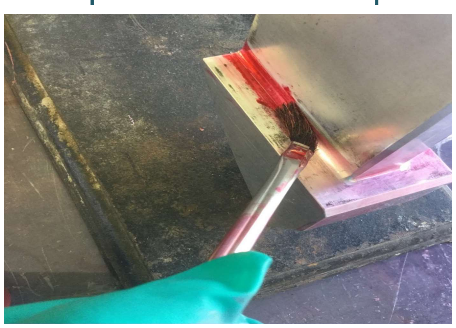
Magnet disassembly and inspection

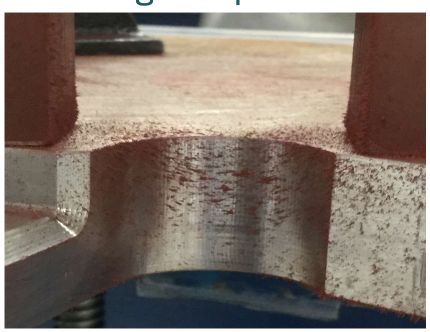


Magnet disassembly

Aluminum clamp test with die penetration technique



Iron lamination test with magnetic powder



Coil inspection

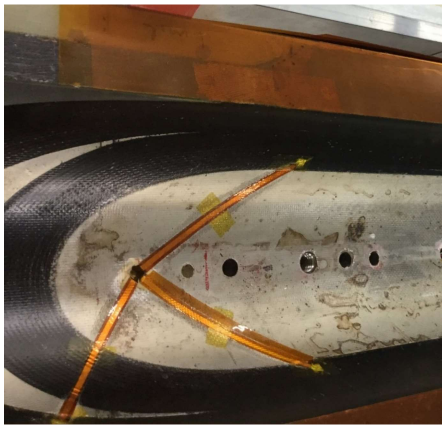
L1/L2:

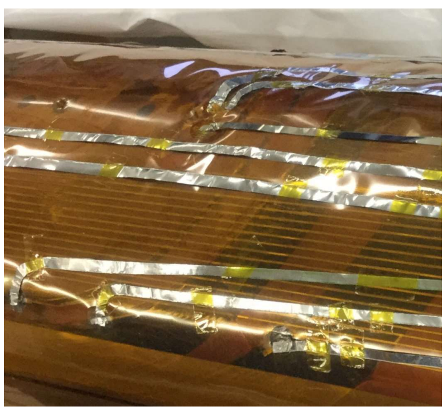
- no coil/pole separation in straight section and ends

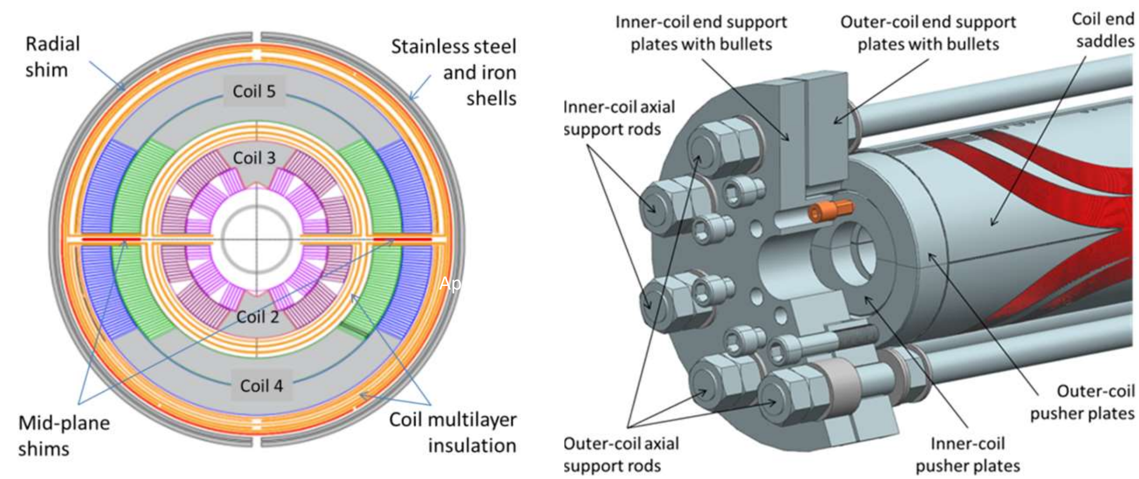
L3/L4:

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

MDPCT1 repair and reassembly

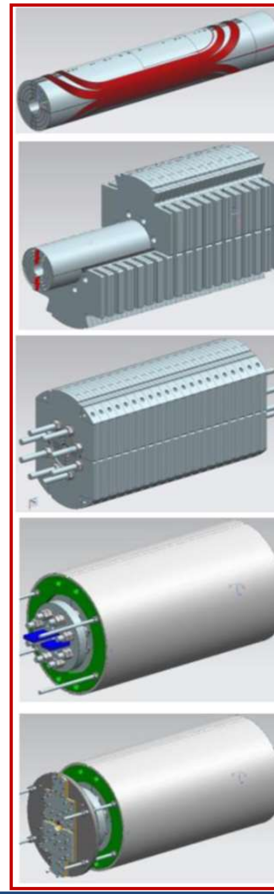




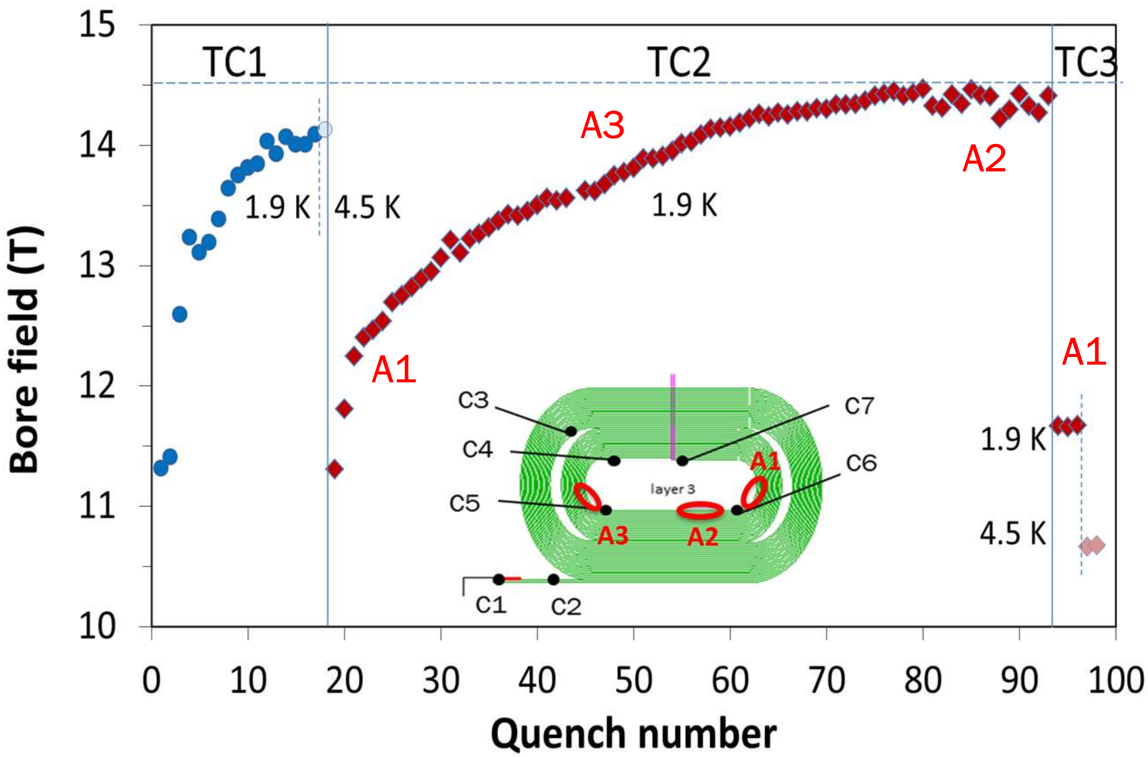


Improvements:

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



MDPCT1 training summary in TC2 and TC3



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

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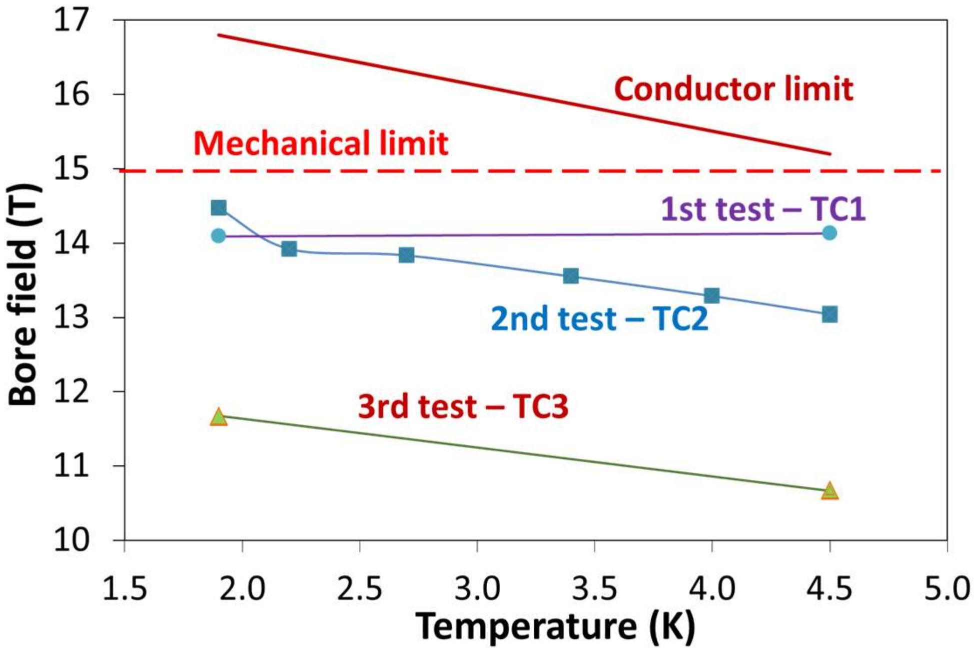
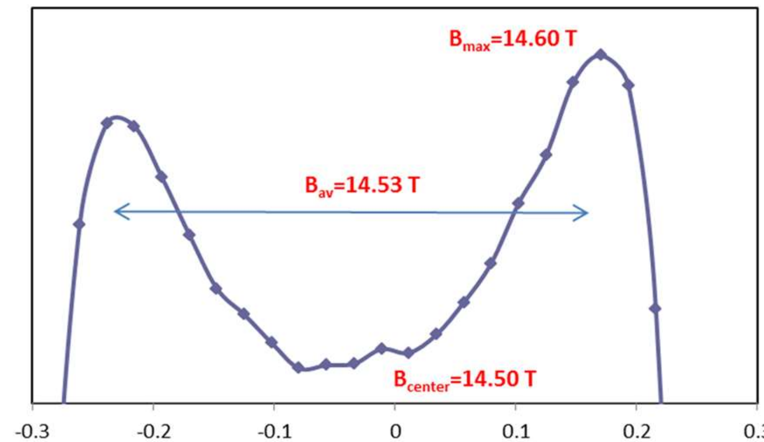
MDPCT1 quench performance summary





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

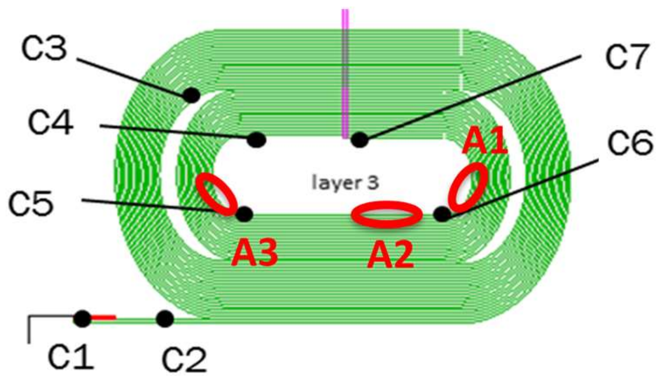
TC2:
- Test target field - 15 T
- B_{max}=14.5-14.6 T @1.9K - ***record field***

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

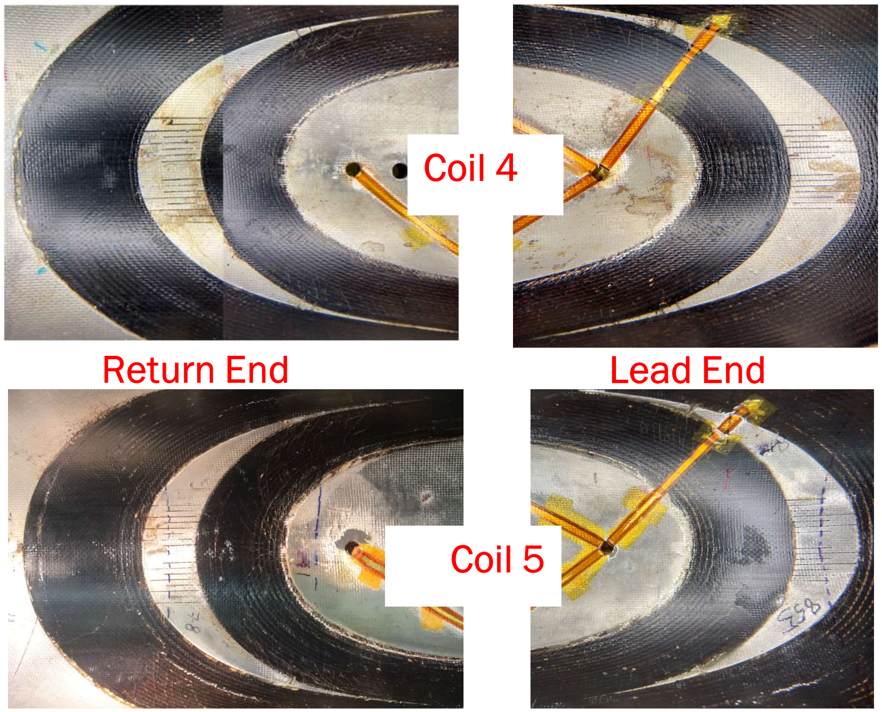
- *$I_q(T)$ data show that the magnet has been trained in TC2 and TC3 to its conductor limit.*
- *Large I_q degradation in TC2 and TC3.*

Post testing disassembly and coil inspection

- 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 (body) and A3 (LE)



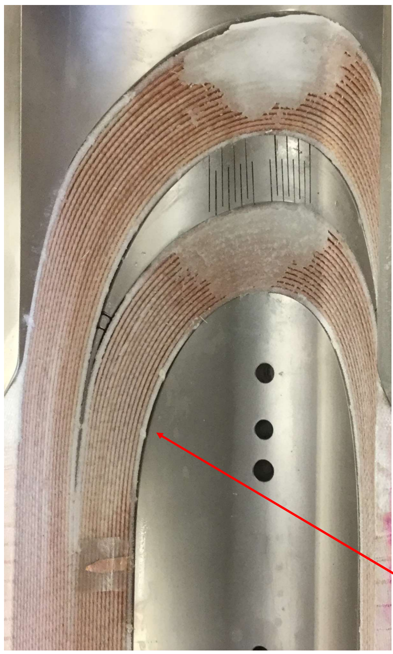
Epoxy cracking and pole turn separation in LE and RE of both coils



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

Inner layer RE view of coil 5 at different stages

After curing



After reaction

Before impregnation

After impregnation

After cold test

glass filler

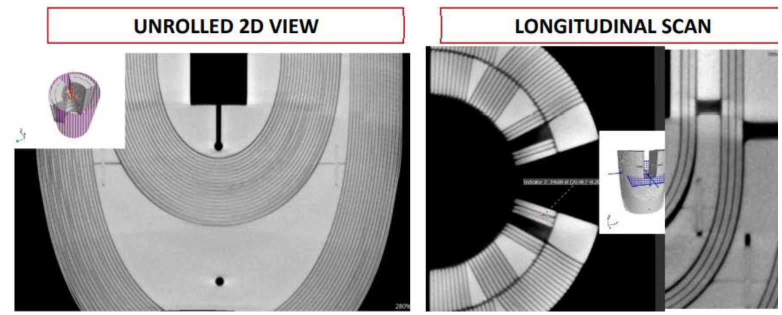
pole turn,
extra insulation

Inner layer was
wound/cured/rewound

No clear evidence why coil 5 limits magnet performance.

Coil 5 CT scan

300 kV CT scan at AlloyWeld Inspection (Illinois)



- It was used at ITER for nondestructive inspection of He inlet welds and of epoxy from vacuum pressure impregnation
- It is used at CERN as an aid to post-mortem inspection of R&D magnets
- A service requisition is being written with Diondo (Germany) for 6 MeV CT scans measurements of coil 5, with crack resolution > 0.4 mm.

diondo x-ray systems and services

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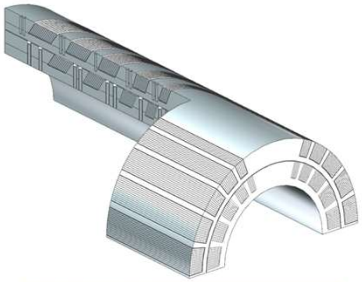
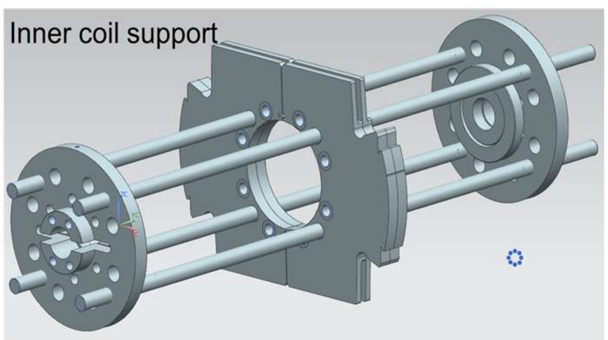
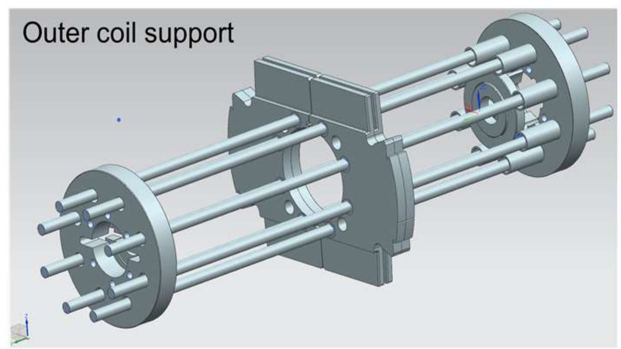
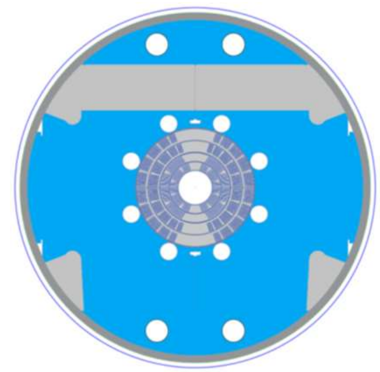
Lessons learned and design modifications

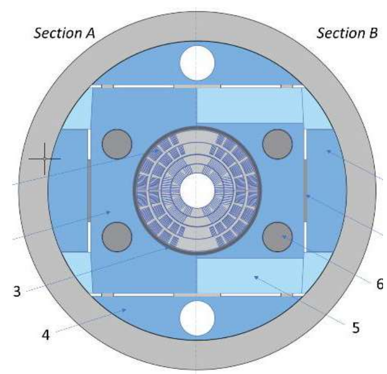


- Stress management (SM) structure to be used in outer layers L3-L4 to improves turn azimuthal and axial support and transfer radial forces
- Since MDPCT structure will be used to test 4-layer magnets with SMCT coils to achieve the fields up to 17 T, skin thickness and axial support system will be reinforced
  - 4 new rods for inner coils and 6 old rods for outer SMCT coils
  - SMCT coil rod anchoring









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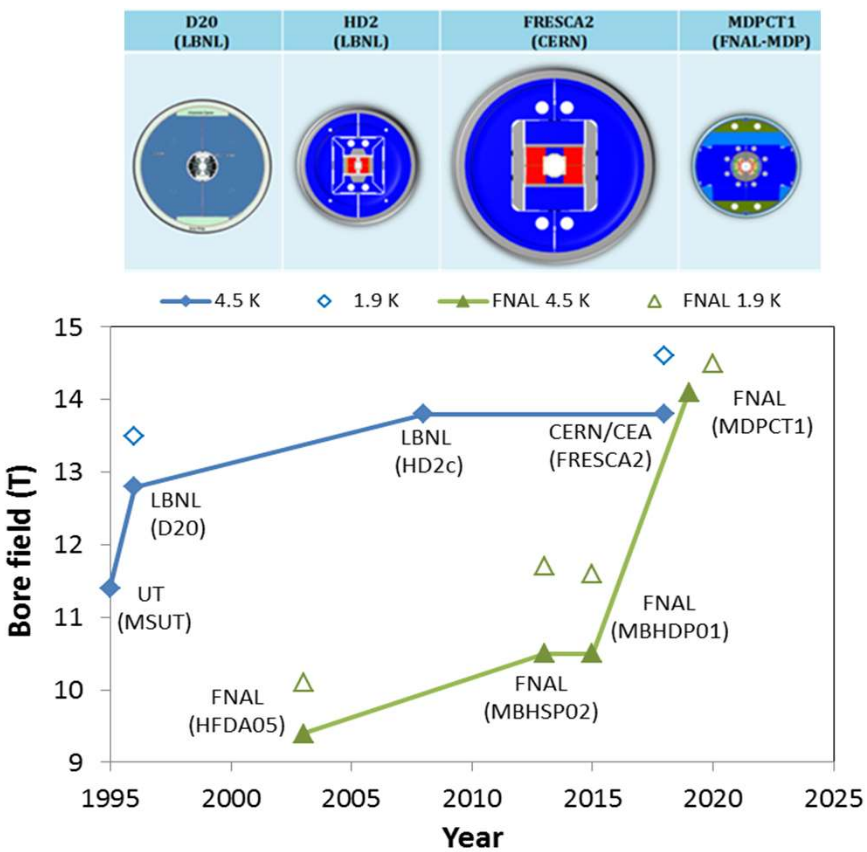
MDPCT program summary



- **The goals of the MDPCT1 program have been achieved**
  - **graded 4-layer coil, innovative support structure, magnet technologies have been developed**
  - **magnet performance parameters were tested**
  - **maximum bore field of 14.5 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**

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Publications

1. A.V. Zlobin et al., “Design concept and parameters of a 15 T Nb_3Sn dipole demonstrator for a 100 TeV hadron collider”, IPAC2015, Richmond, VA, USA, p.3365.
2. V.V. Kashikhin et al., “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 et al., “Development of a 15 T Nb_3Sn Accelerator Dipole Demonstrator at Fermilab”, IEEE TAS, Vol. 26, Issue 3, June 2016, 4001007.
4. E. Barzi et al., “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”, NAPAC2016, Chicago, IL, USA, p.137
6. E. Barzi et al., “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 et al., “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 et al., “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 et al., “Quench performance and field quality of the 15 T Nb_3Sn dipole demonstrator MDPCT1 in the first test run”, NAPAC2019, September 2019.
10. A.V. Zlobin et al., “Development and First Test of the 15 T Nb_3Sn Dipole Demonstrator MDPCT1”, IEEE TAS, Volume 30, Issue 4, 2020
11. T. Strauss et al., “First field measurements of the 15 T Nb_3Sn Dipole Demonstrator MDPCT1”, IEEE TAS, Volume 30, Issue 4, 2020,
12. A.V. Zlobin et al., “Reassembly and Test of High-Field Nb3Sn Dipole Demonstrator MDPCT1”, IEEE TAS, Vol. 31, Issue 5, 2021.
13. J. DiMarco et al., “Field Measurement Results of the 15 T Nb3Sn Dipole Demonstrator MDPCT1b,” IEEE TAS, Vol. 31, Issue 5, 2021.

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A. Rusy, S. Jonhson, J. Karambis, J. McQueary, L. Ruiz, E. Garcia

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CERN: D. Schoerling, D. Tommasini

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