U.S. MAGNET DEVELOPMENT PROGRAM

US-MDP Collaboration Meeting 2021
1-5 March 2021

AREA II: HTS MAGNETS

Bi-2212 SMCT accelerator magnets

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March 2, 2021

OUTLINE

- Introduction
- Milestones
- Present Status:
  - Bi2212 Conductor
  - Bi2212 Dipole Insert
- Next Steps
- Summary
- References

Introduction

- A major goal of the US-MDP SC magnet program is that of developing HTS inserts producing fields larger than 5 T within 15 T Nb_3Sn outserts to generate 20 T or higher fields for future high energy colliders.

- With the existing Bi2212 composite wires, there is the potential of reaching a maximum field of up to 16-17 T in Bi2212 coils using a 6-layer hybrid dipole design when using stress management concepts.

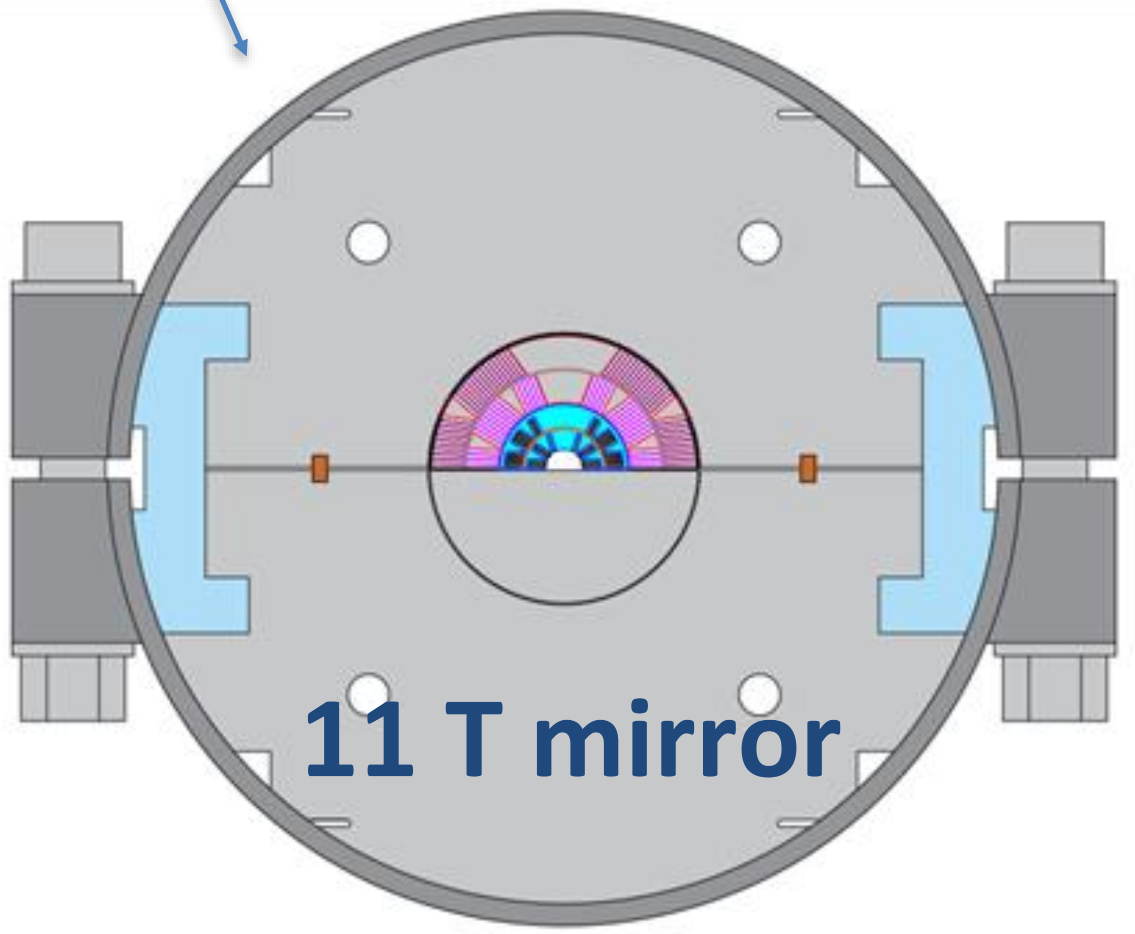
- The maximum field in the coil bore will be ~2% lower, or within 15.7-16.6 T.

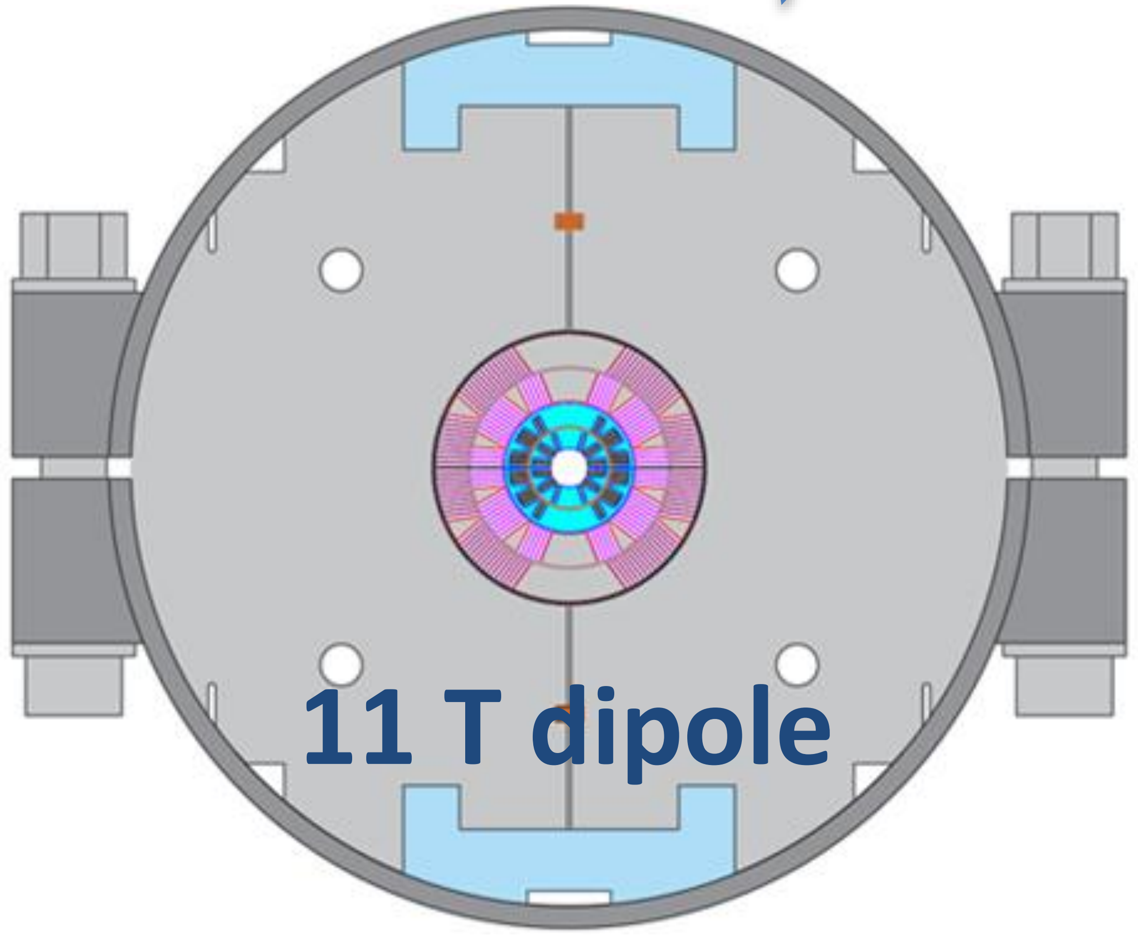
Bi2212 Stress-Managed Dipole Insert Milestones

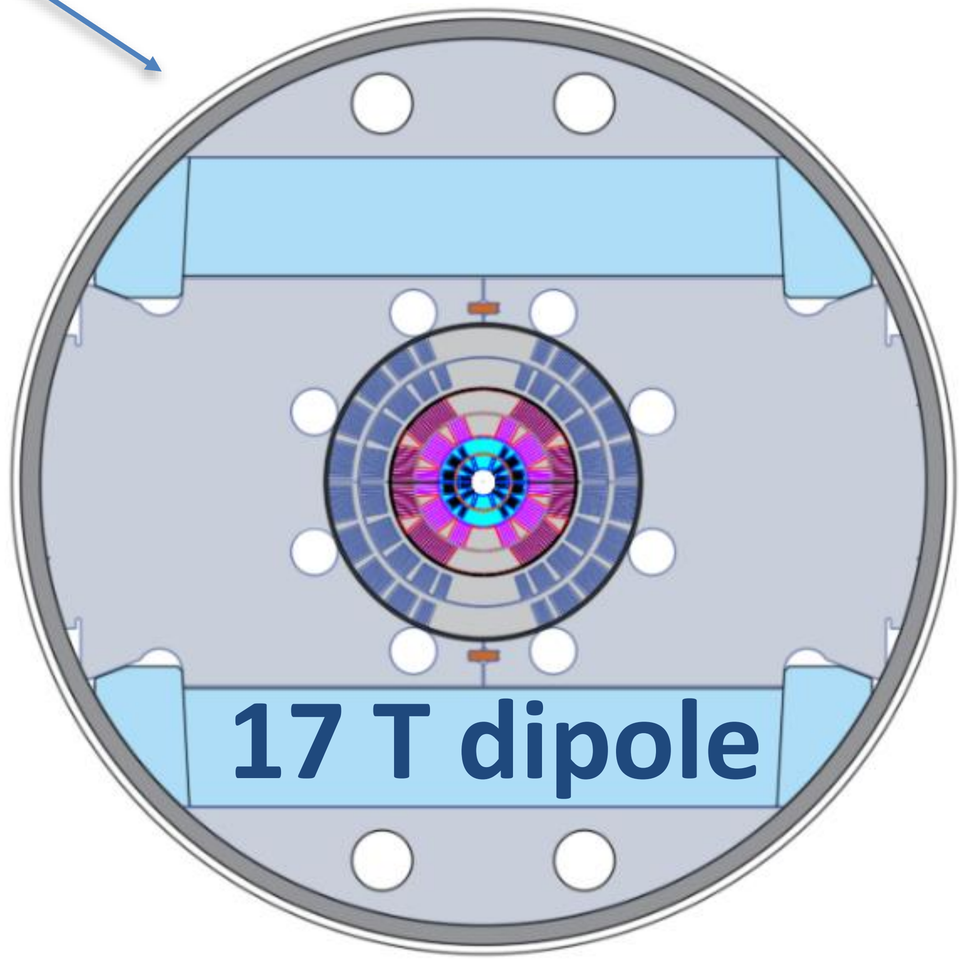
Table 5. Milestones for the Stress-Managed Cosine-Theta (SMCT) effort within the Bi-2212 area of the MDP.

Milestone #	Description	Target
AIIa-M1b	Study strand damages due to cabling, transverse pressure dependence	April 2022
AIIa-M2b	Fabricate the first 2-layer 17-mm aperture Bi-2212 coil using LBNL cable. Coil test independently and inside a 60-mm aperture 2-layer Nb_3Sn dipole coil in mirror configuration.	July 2022
AIIa-M3b	Fabricate the 2nd 2-layer 17-mm aperture Bi-2212 coil using optimized Bi-2212 cable, coil structure, materials and technologies. Coil test independently and inside a 60-mm aperture 4-layer Nb_3Sn dipole coil in mirror configuration.	December 2022
AIIa-M4b	Fabricate another 2-layer Bi-2212 coil using optimized Bi-2212 cable and coil structure. Bi-2212 coil test independently and inside a 60-mm aperture 4-layer Nb3Sn dipole coil.	September 2024

OBJECTIVE:
Study Bi2212 dipole inserts in hybrid configurations with available (11 T) and future (SM) Nb_3Sn coils.



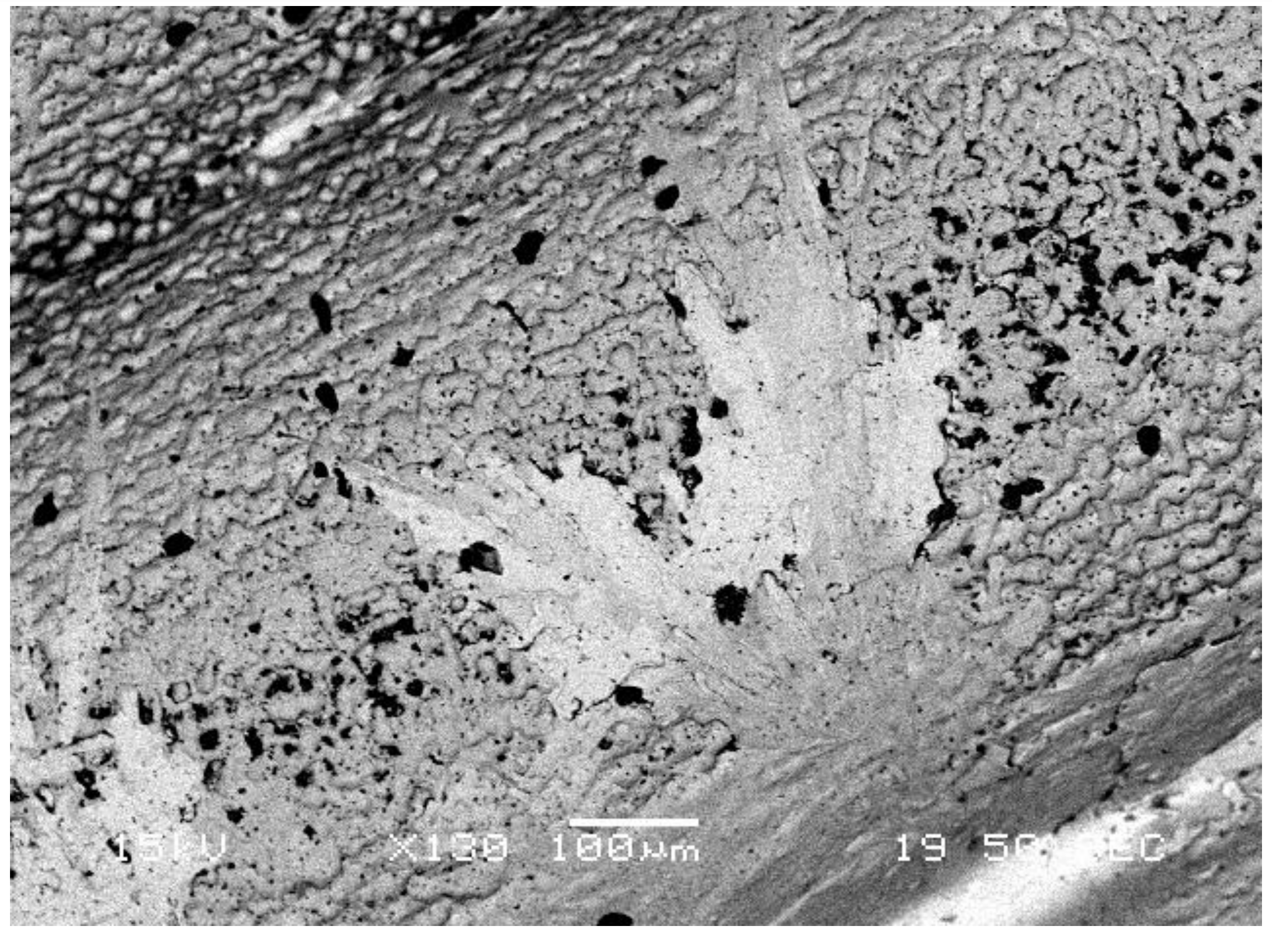




Conductor Challenges in Magnet Structures

Why is the coil performance inferior to the short sample limit calculated on the wire ➔ Study the technology of insulated Bi2212 Rutherford cables when wound inside a mechanical support structure, as in the CCT and the SMCT.

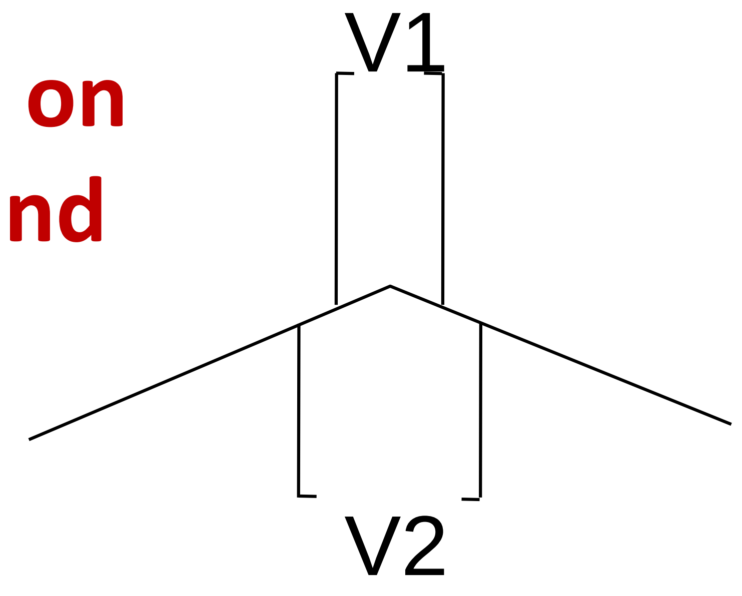
- Fabricate Rutherford cable with minimal current reduction
- Eliminate Bi2212 leakage during heat treatment in oxygen
- Ensure homogenous oxygen diffusion to conductor wound inside mechanical structure
- Understand Bi2212 cable strain behavior, and especially under azimuthal pressure in magnets
- Reduce Bi2212 magnet processing costs

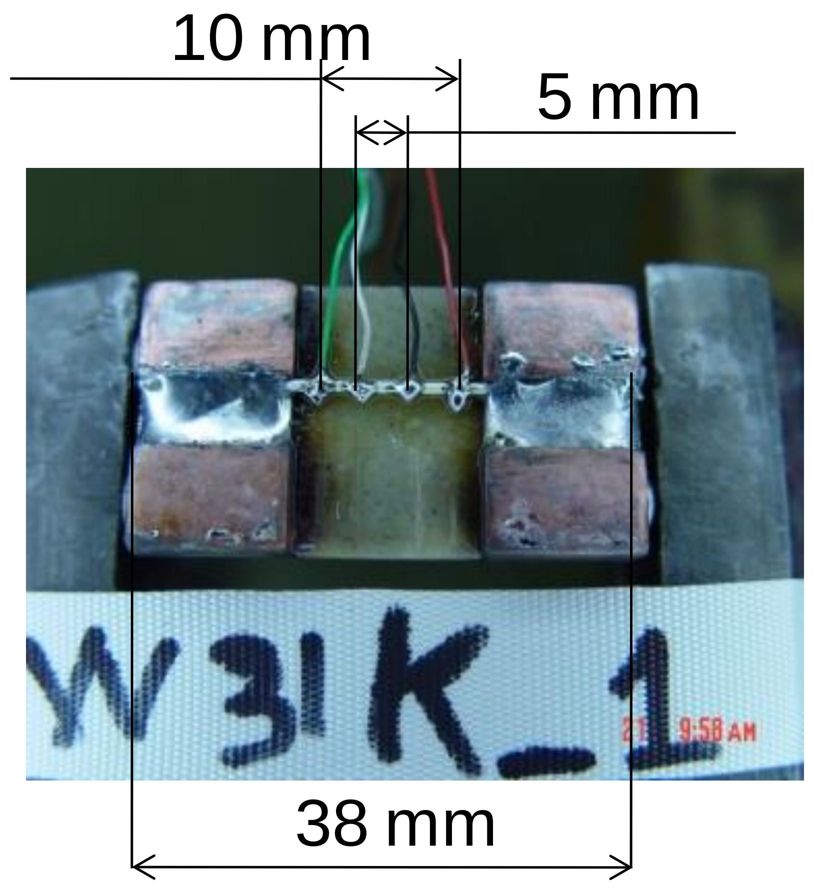


Spectrum No.	1	2	3
Element	At. %	At. %	At. %
Ag (L)	0	100	0
Bi (M)	14.91	0	3.59
Sr (L)	9.04	0	2.21
Ca (K)	5.53	0	0.78
Cu (L)	11.49	0	5.80
Mg (K)	0	0	29.33
O (K)	59.03	0	58.28
Totals	100.00	100.00	100.00

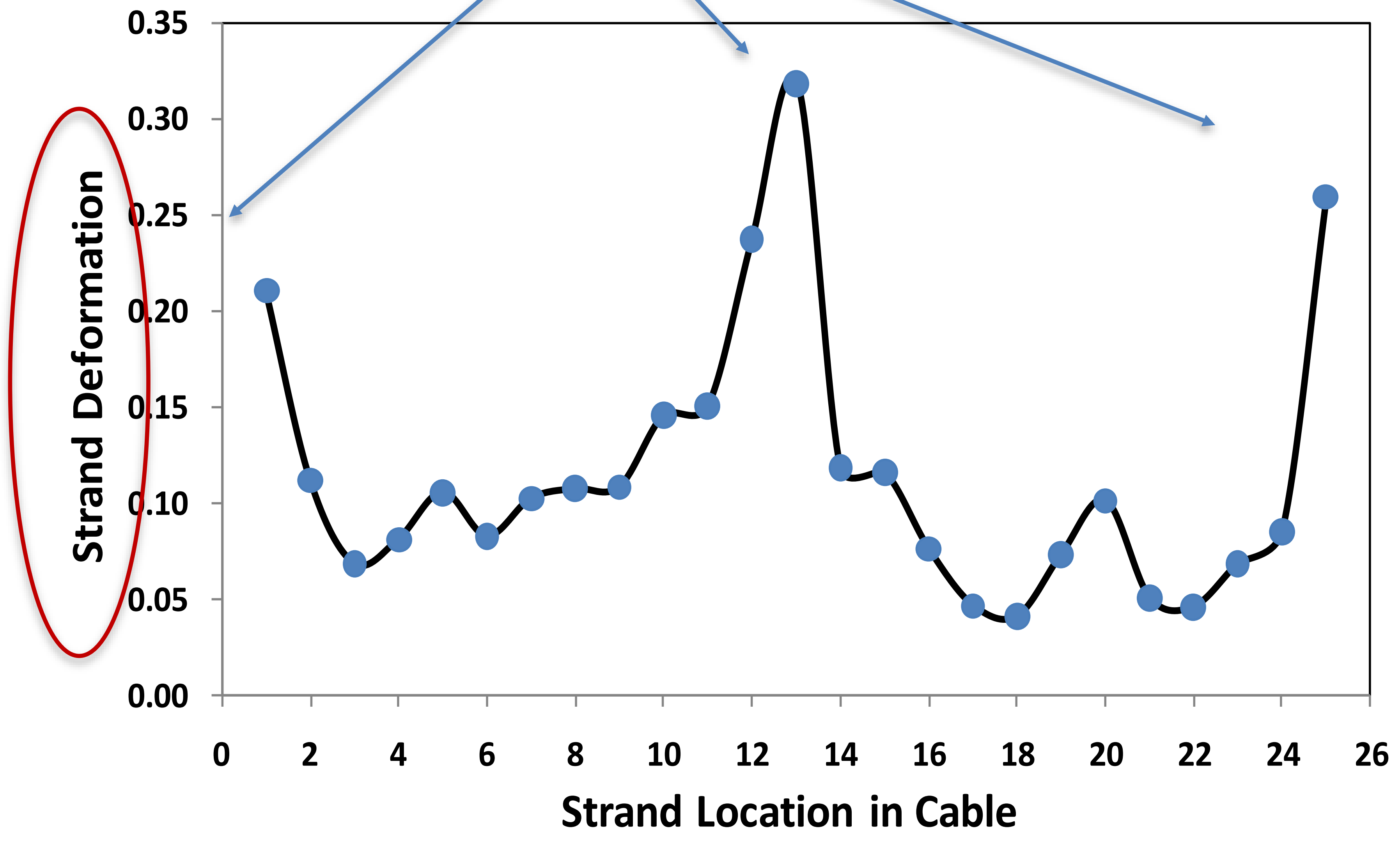
Bi2212 Strands Extracted from Rutherford Cable

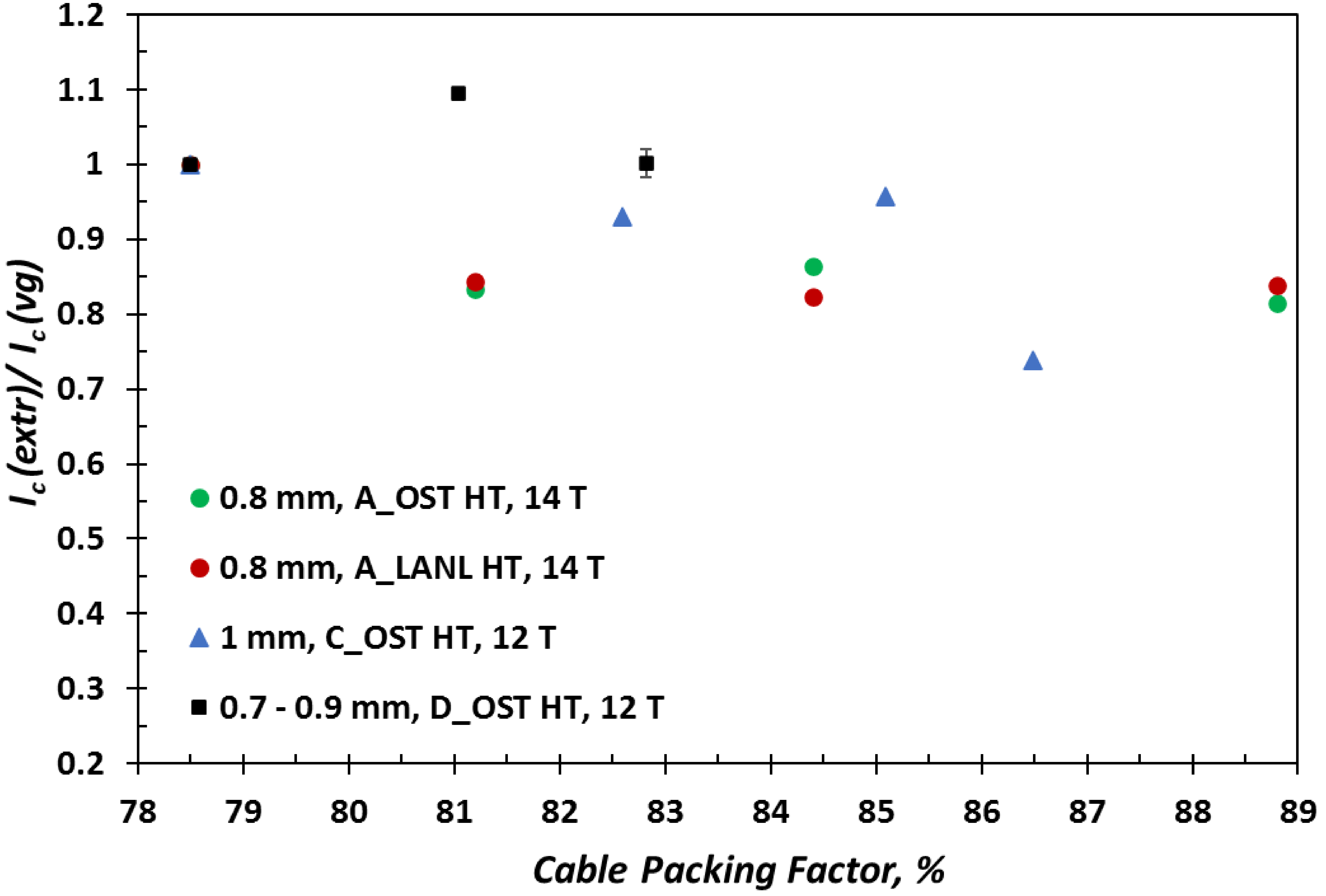
I_c measured on edge of strand sample





Cable edges



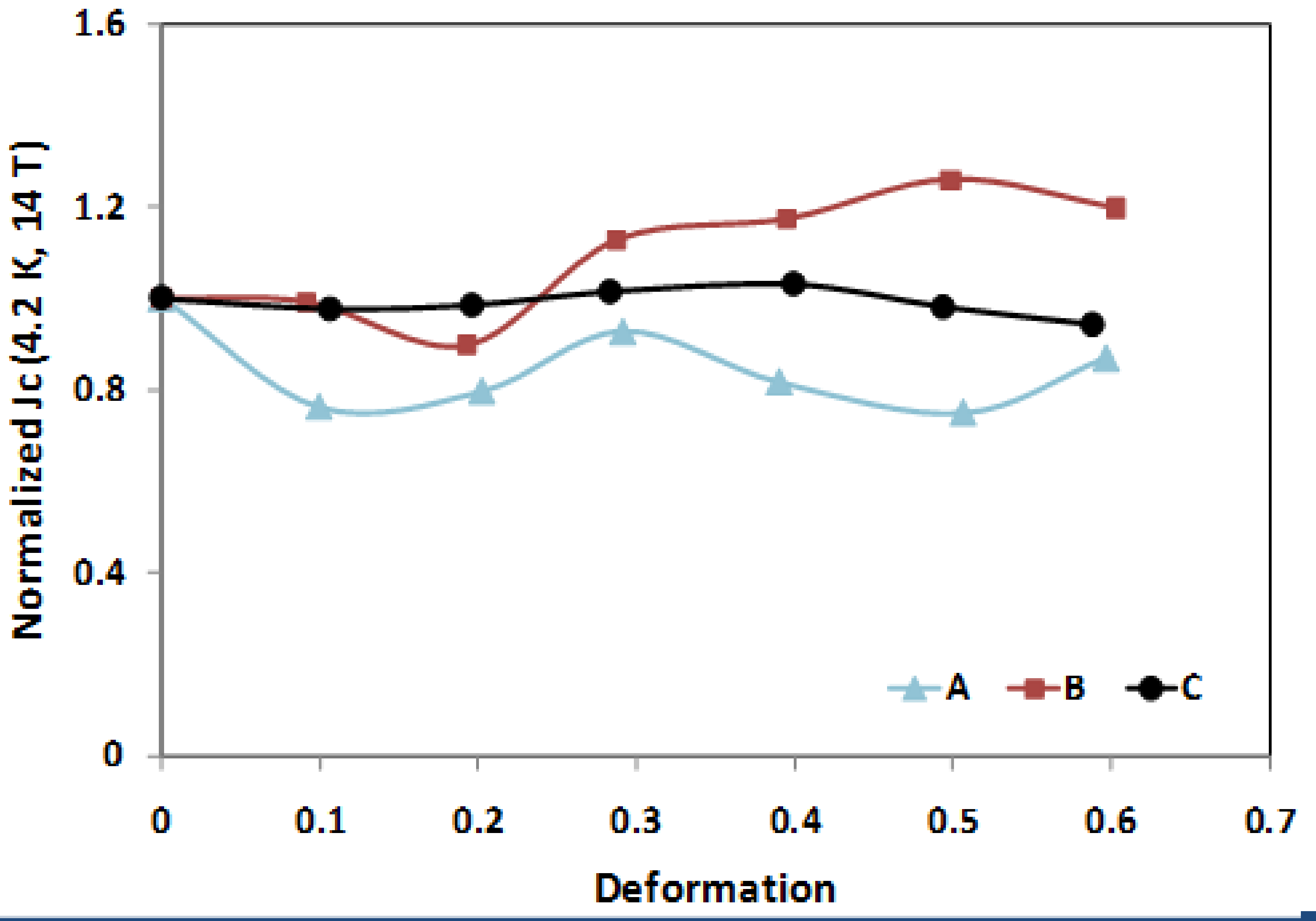


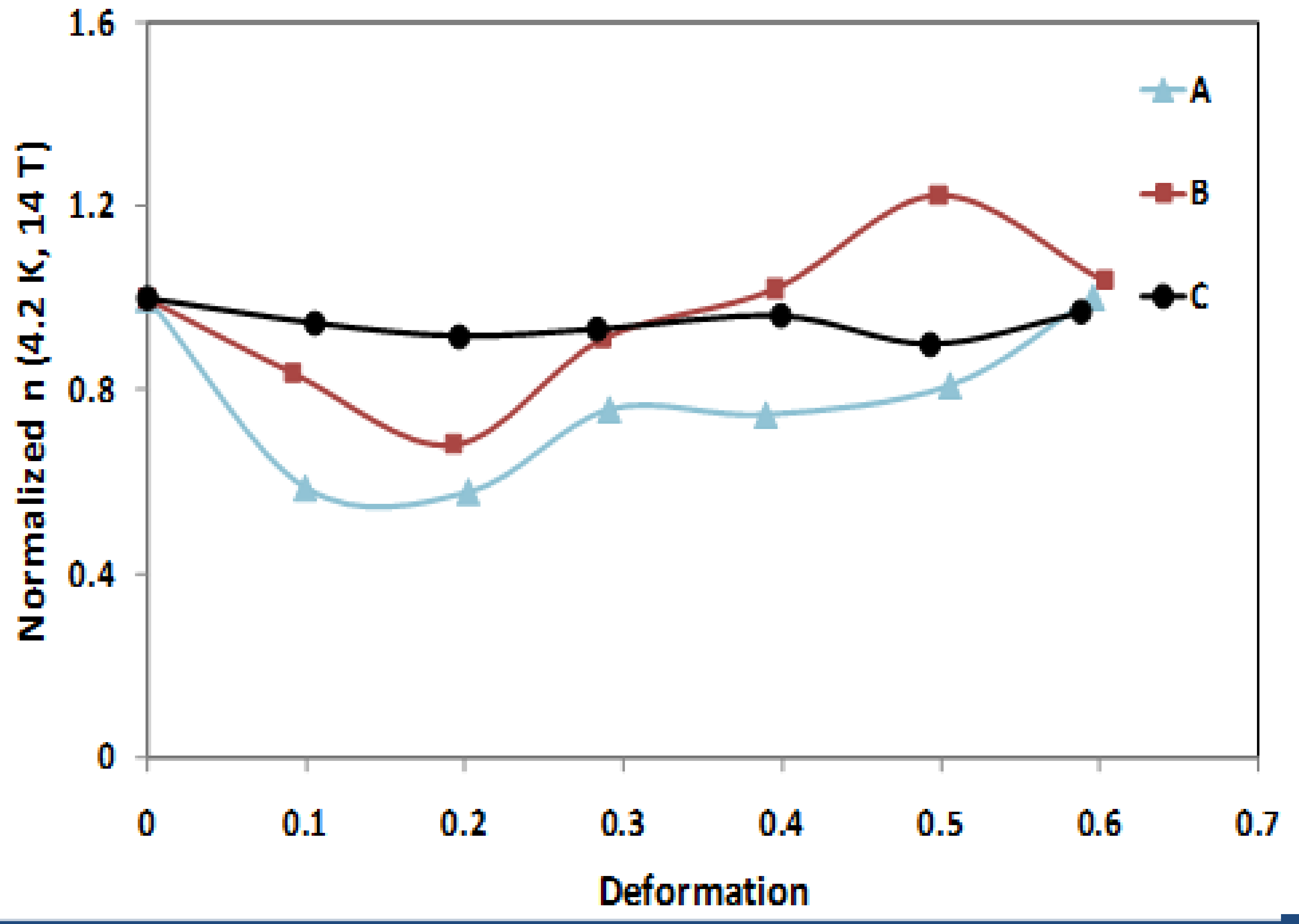
[1] See REFERENCES slide

Dependence of Superconducting Properties on Strand Deformation

Systematic studies are performed through homogenous flat-rolling of wire.

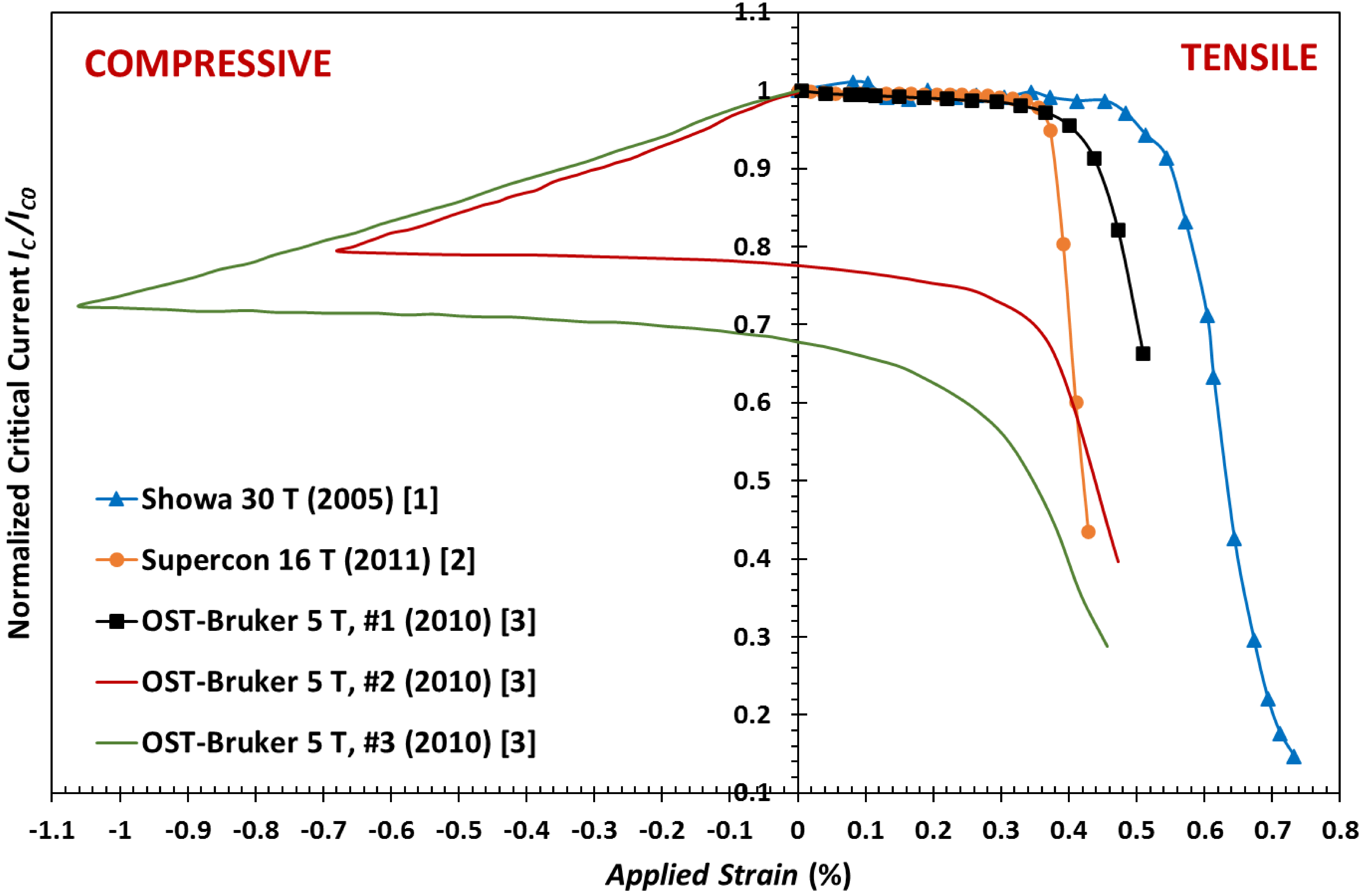
The example below is from the times of the U.S. Very High Field Superconducting Magnet Collaboration (VHFSMC). When processed in oxygen at 1 bar, at the highest tested deformation of 60%, the I_c and n-value of all three Bi2212 wires had exceeded or recovered their original values, as if filament separation self-corrected as the wire was further rolled to smaller thicknesses. Also, wire C made with Nexans granulate precursor vs. Nexans powder, was the most homogenous wire at all deformation levels [1].





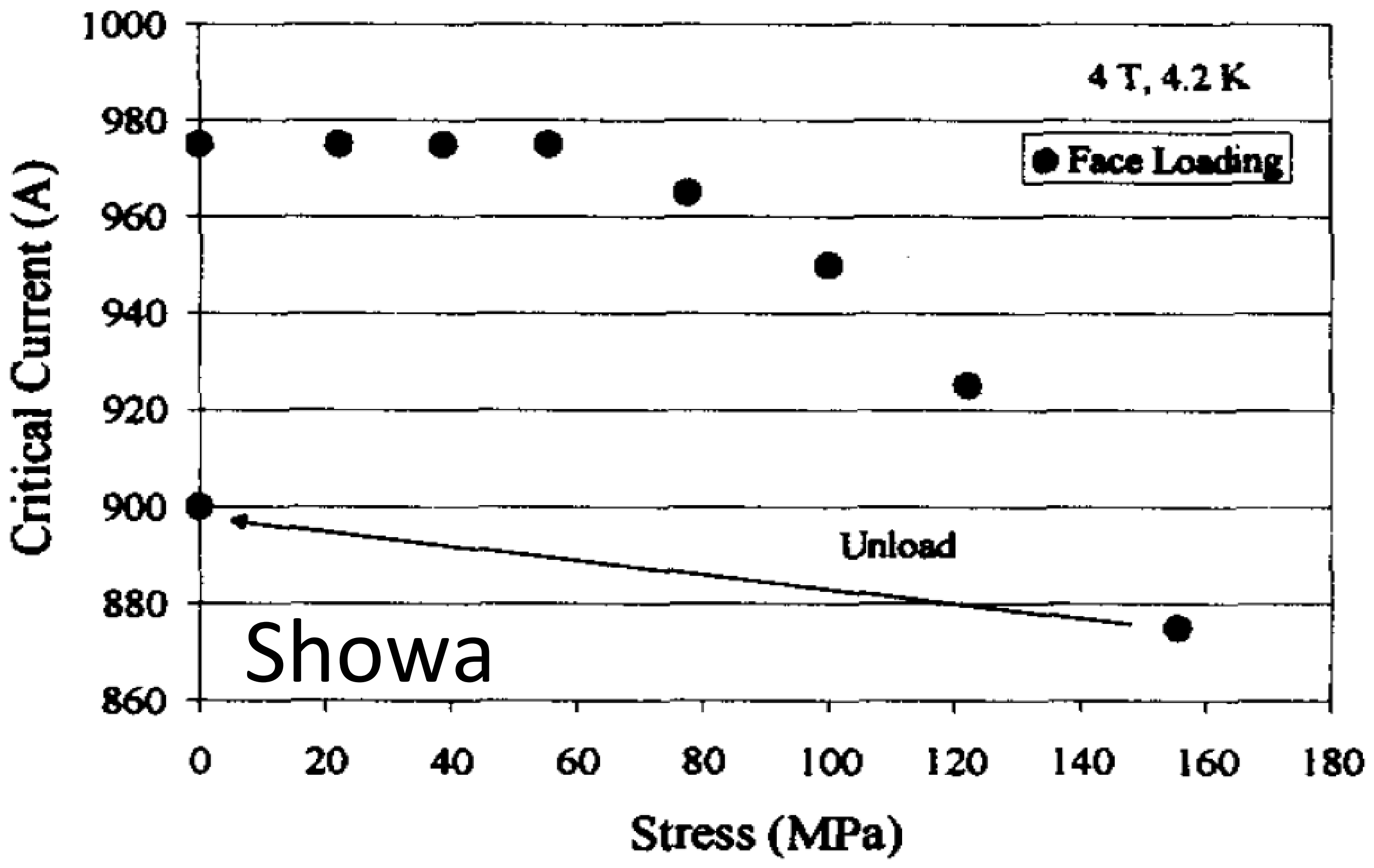
Bi2212 Strain Sensitivity

Although all Bi-2212 is made with the Powder-in-Tube technique, this plot indicates that strain behavior depends on the specific technology used by each manufacturer.



Cable Transverse Pressure Sensitivity

Use FNAL Transverse Pressure Insert (TPI) measurement system to test critical current sensitivity of impregnated superconducting cables to uniaxial (plane stress) transverse pressures up to about 200 MPa. This produces larger strain values on the cable sample than for instance on a laterally constrained one.



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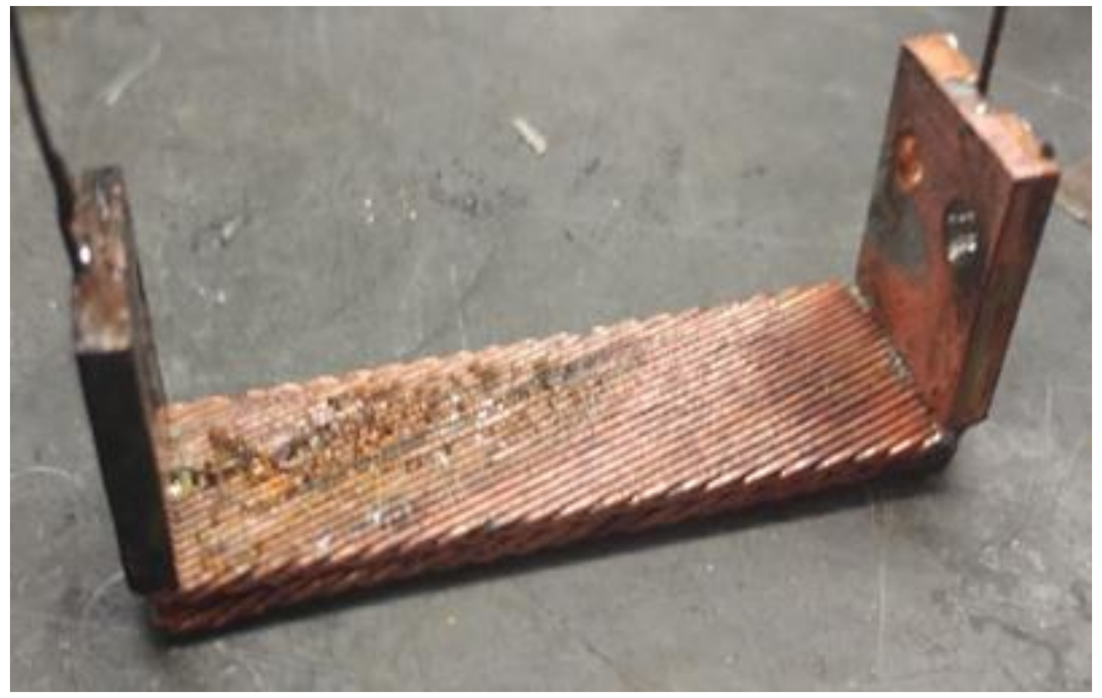
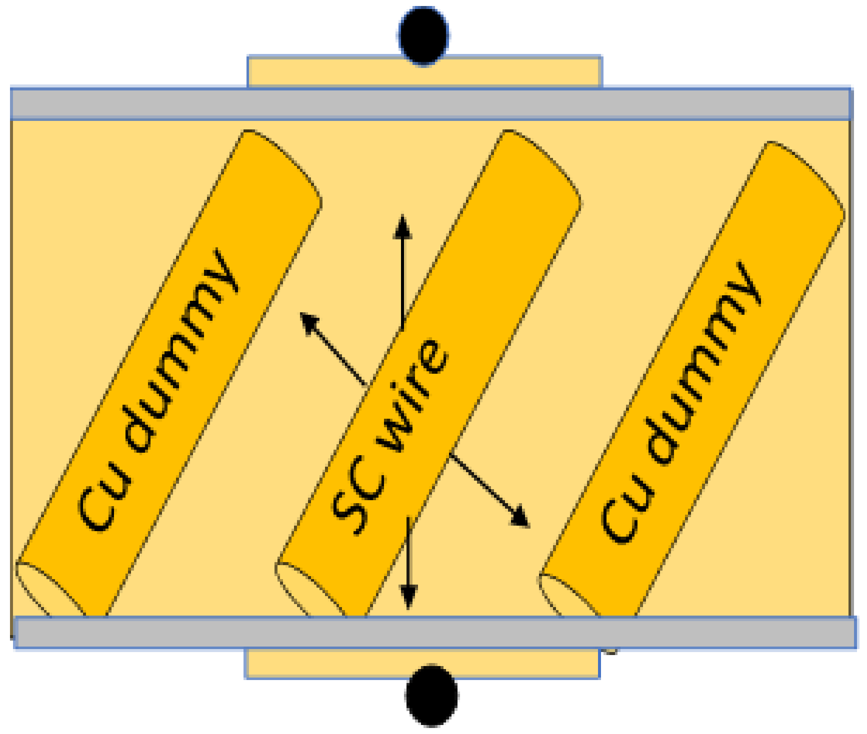
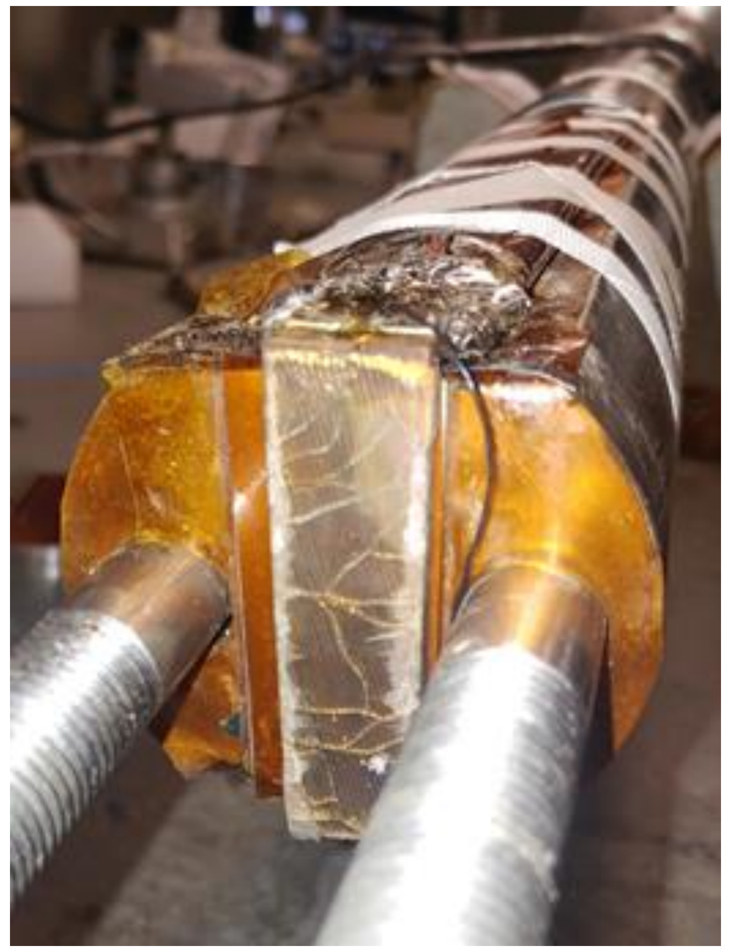


Sample before impregnation



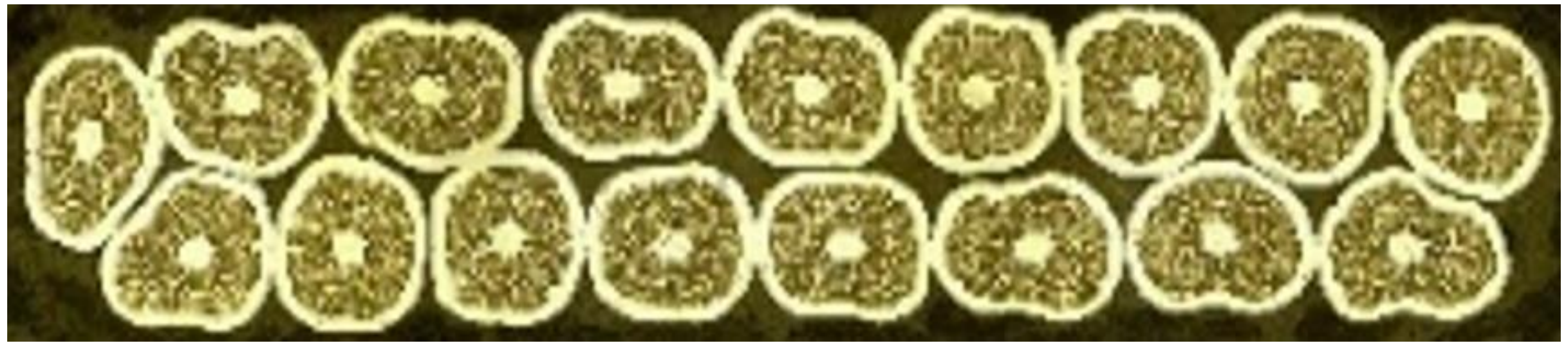
Current carrying wire in between adjacent Cu dummy wires in the cable package



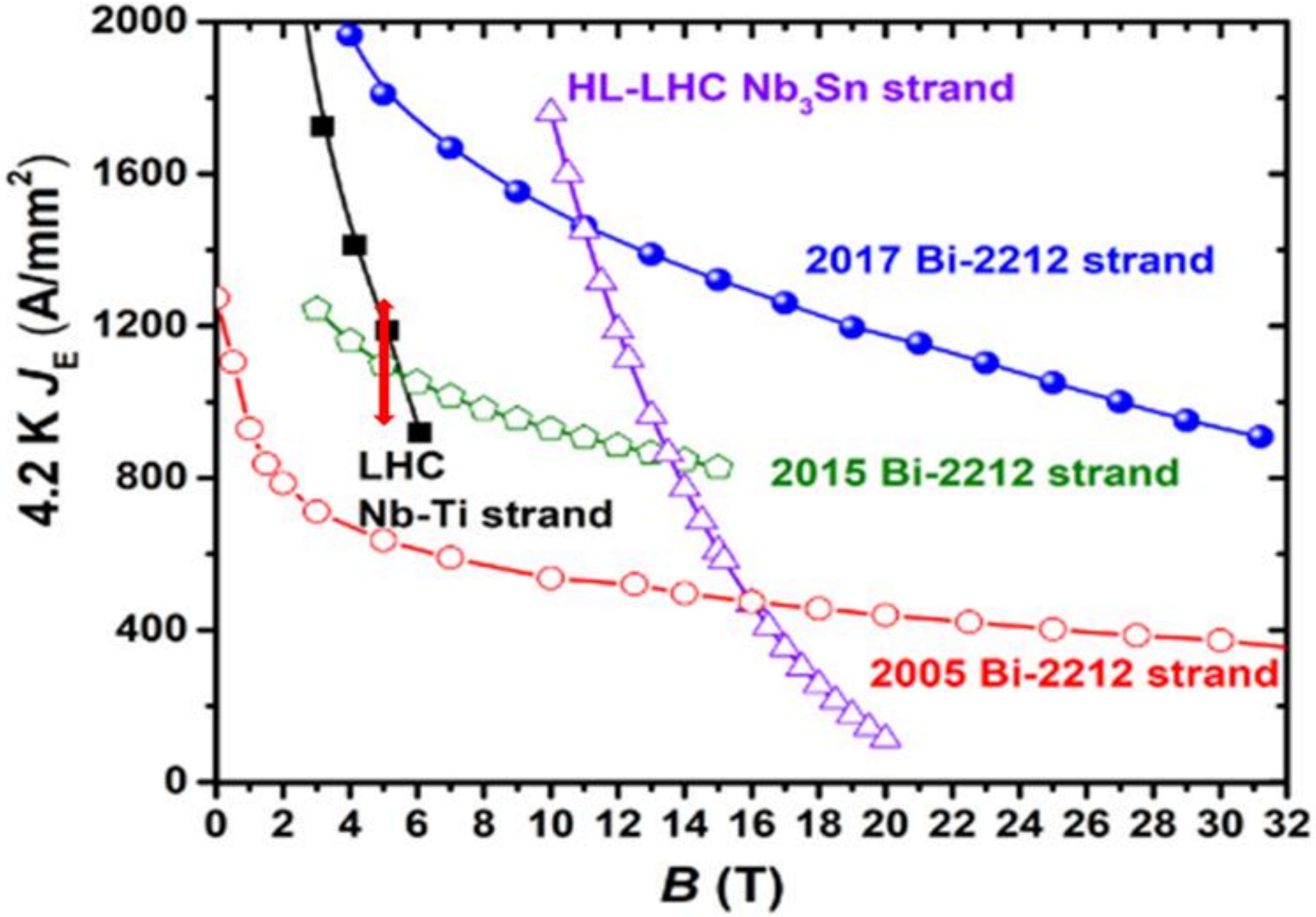
Sample after testing, as mounted to the fixture with the bottom pressure plate removed

Bi2212 Insert Cable and Strand

Parameter	Value
Cable ID	LBNL-1110
Number of strands	17
Bare cable width, mm	7.8
Bare cable thickness, mm	1.44
Cable transposition pitch, mm	58
Billet ID	PMM180207-2
Strand diameter before/after reaction, mm	0.80/0.778
Strand architecture	55 x 18
Strand fill factor, %	23
Strand twist pitch, mm	25
Strand I_c*(4.2K,5T)* after NHMFL 50 bar OPHT, A	460-640*

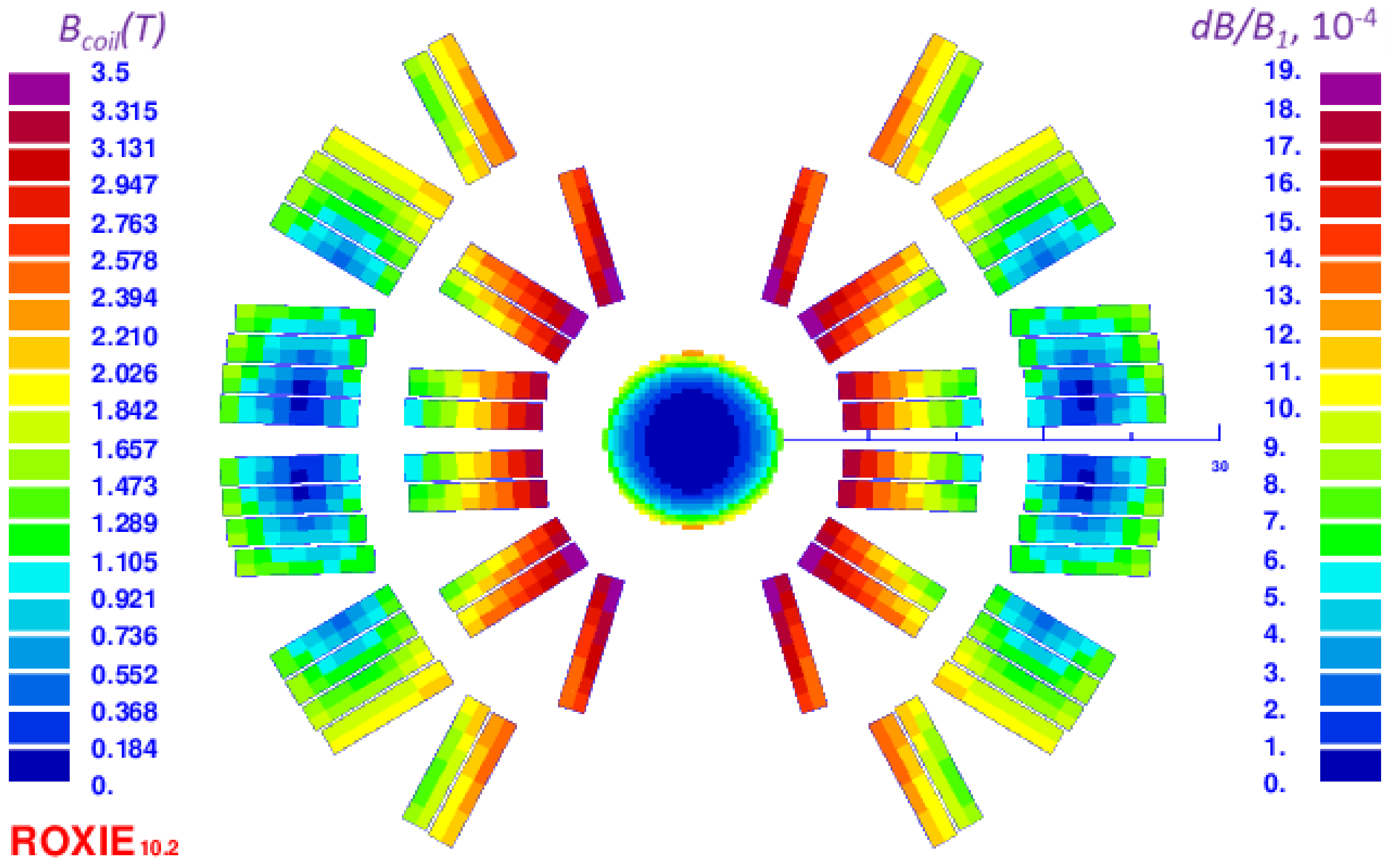


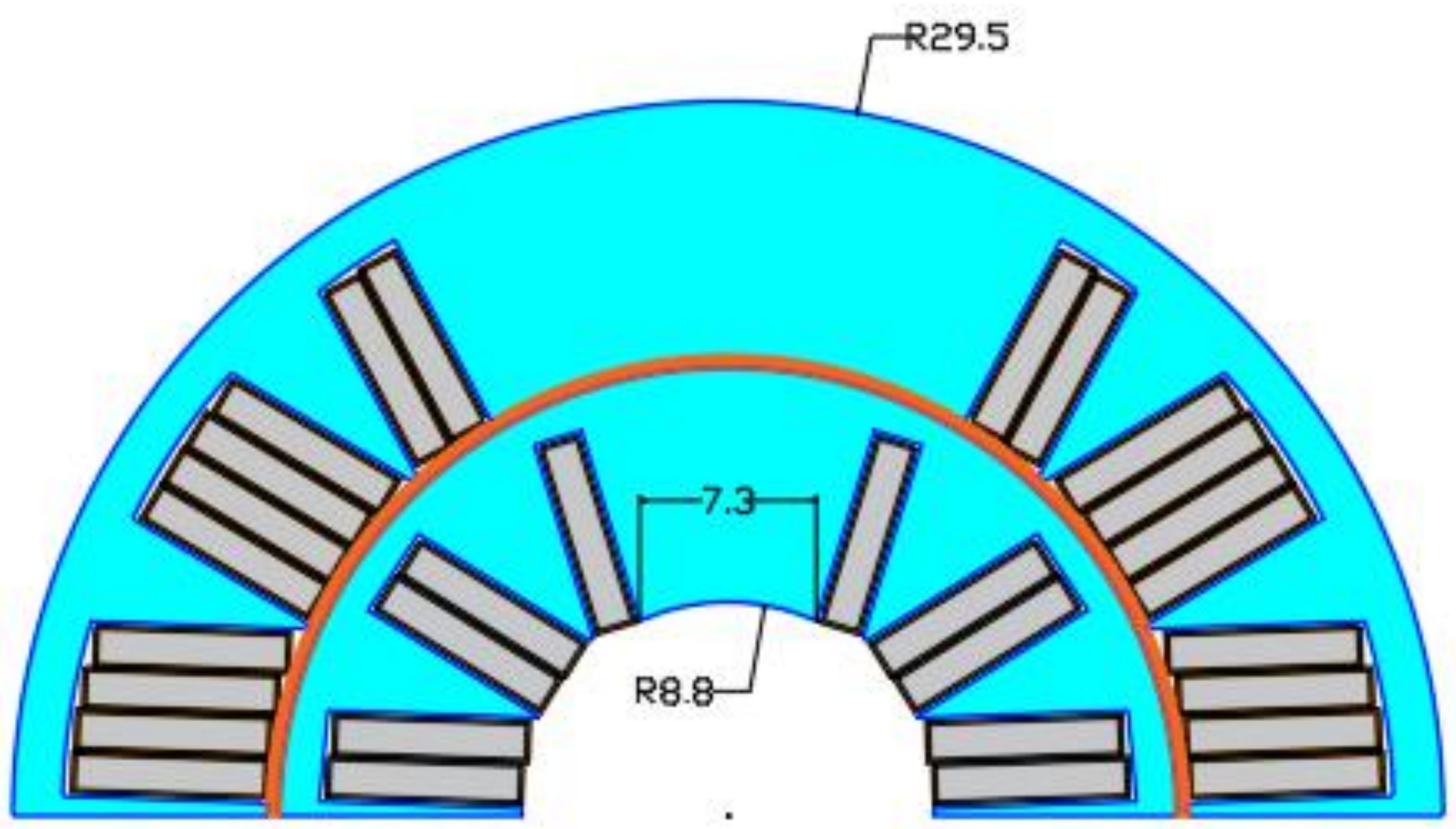
LBNL cable

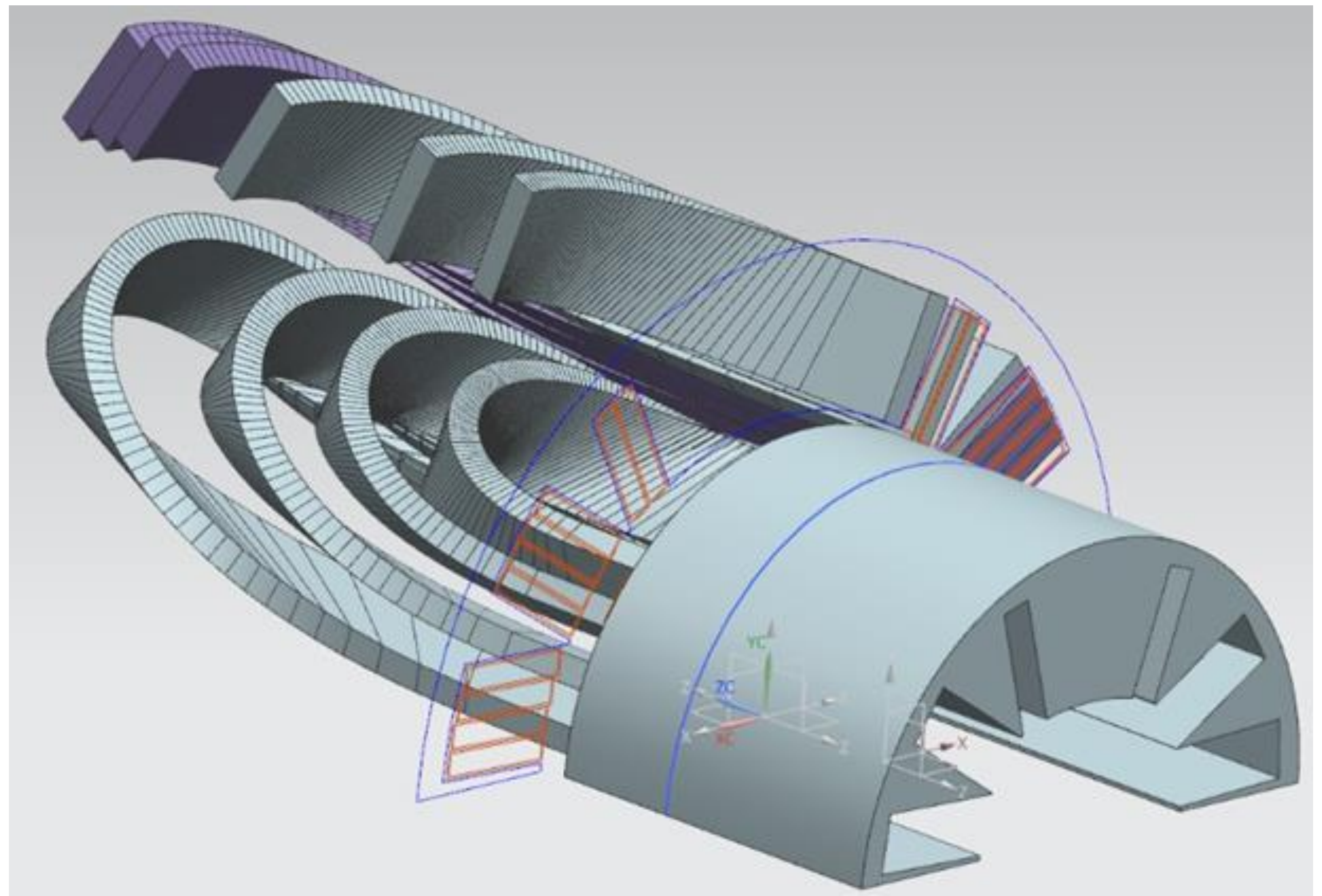


[1] See REFERENCES slide

Magnetic and Structural Designs







- The first Bi2212 coil design was done for an iron yoke of 100 mm ID and constant iron permeability of 1000 [1]
- Coil length = 450 mm
- Stress managed coil structure controls turn positioning and stress on Bi2212 cable in windings
- Concern about small winding radius on inner-layer pole

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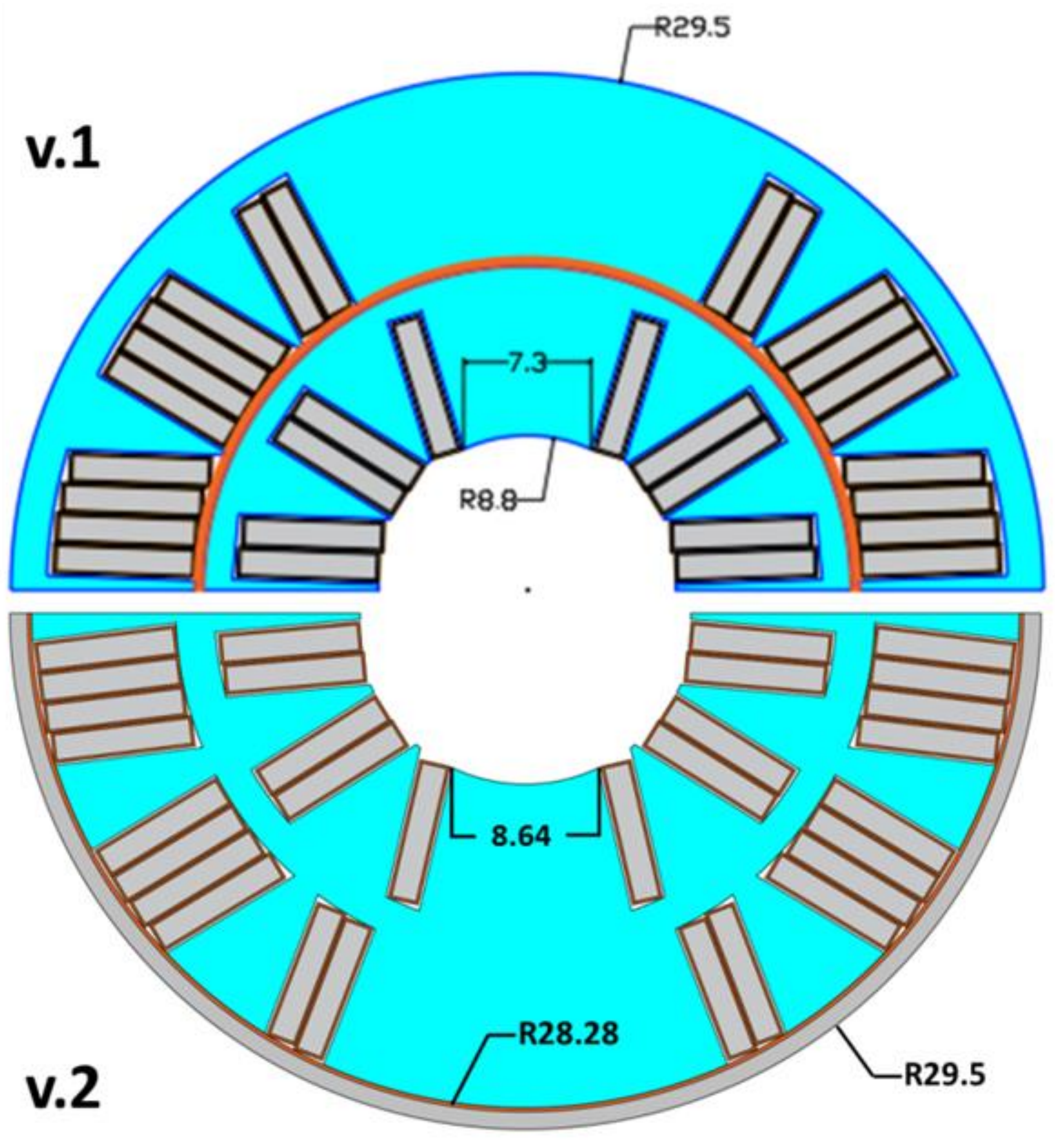
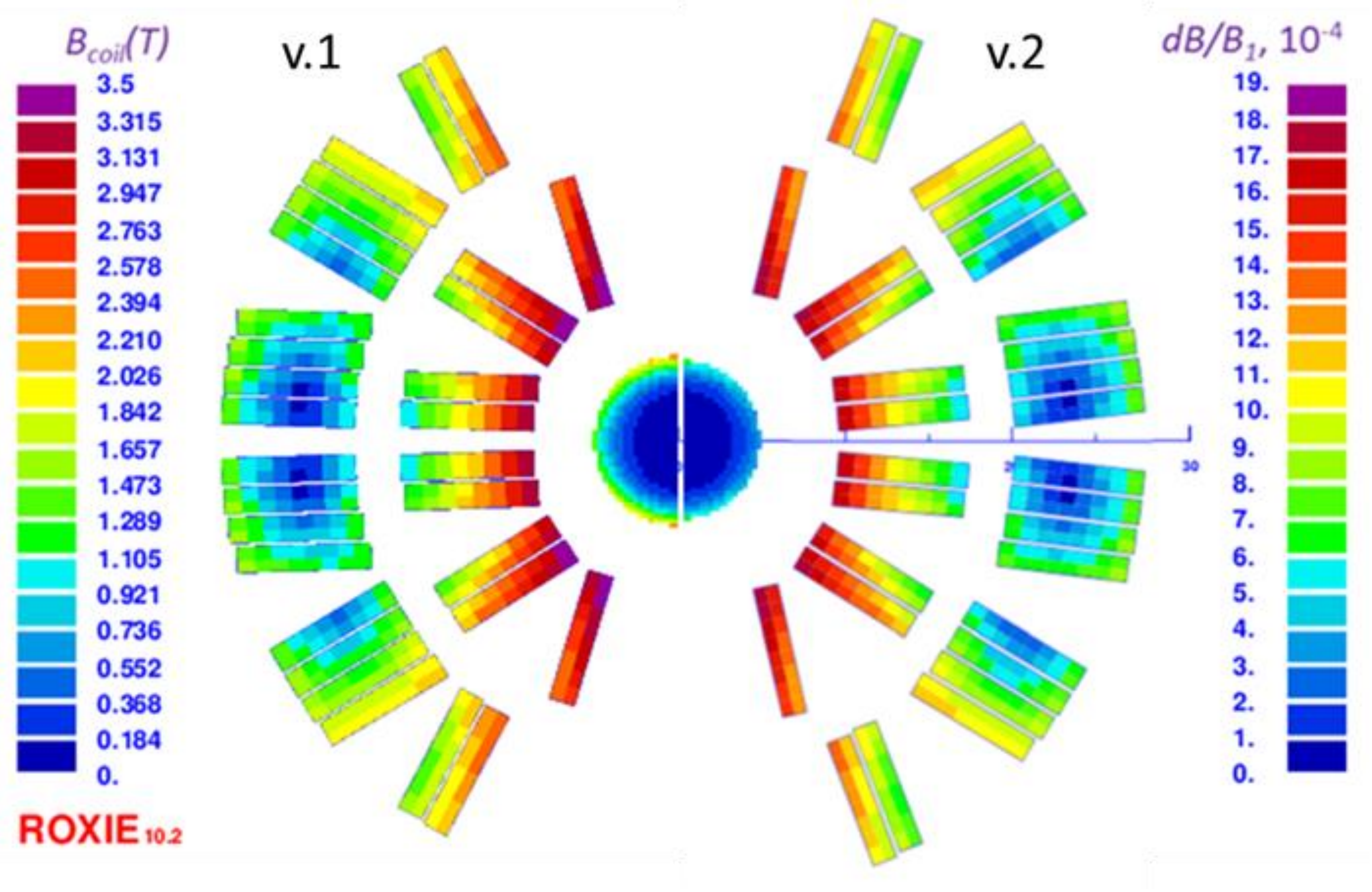
A New and Better Version

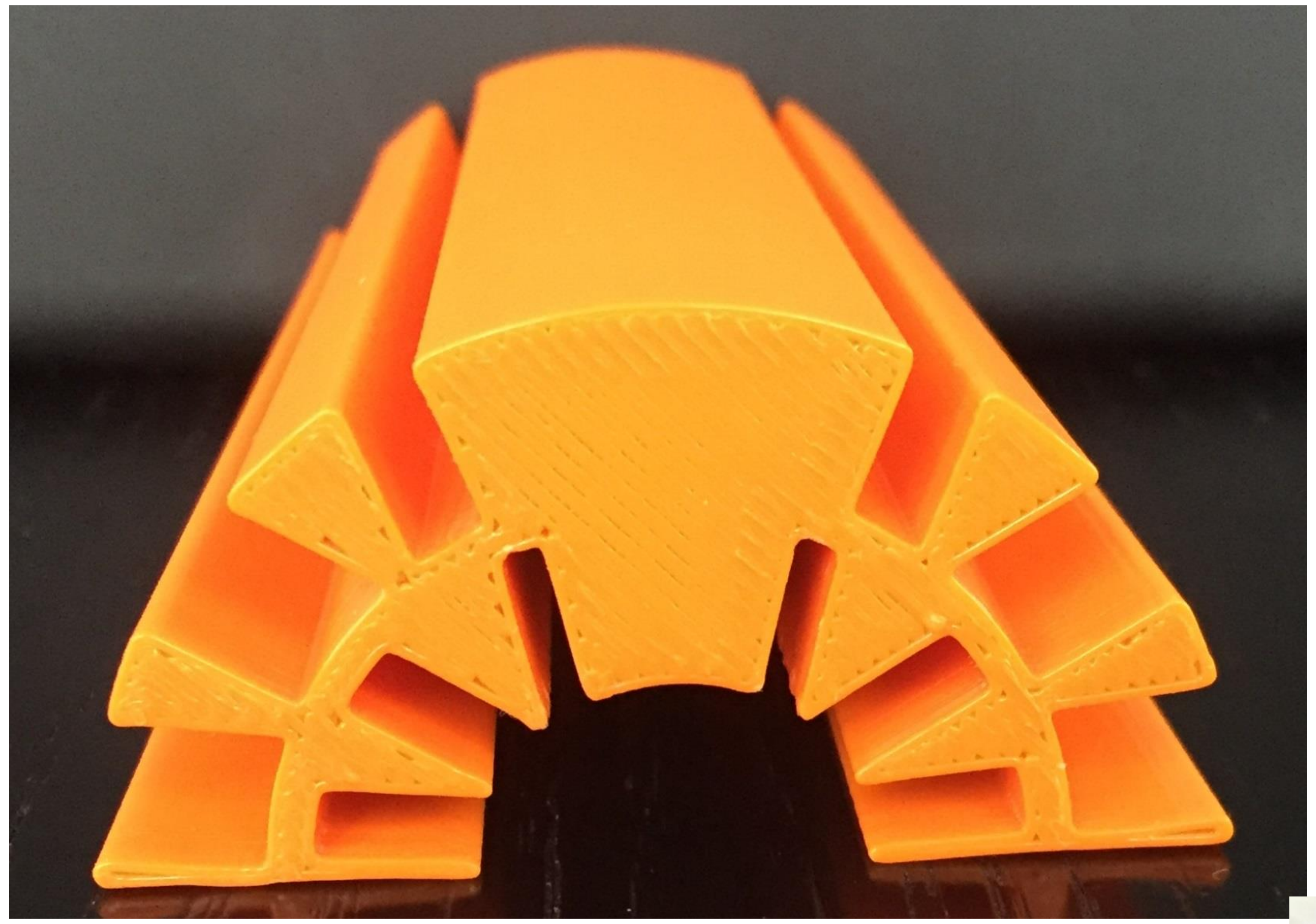
- One single support structure rather than two
- Aperture from 17 mm to 19 mm
- Both inner surface of inner coil and outer surface of outer coil accessible for installation of instrumentation
- Larger radius on inner-layer pole
- Better field quality

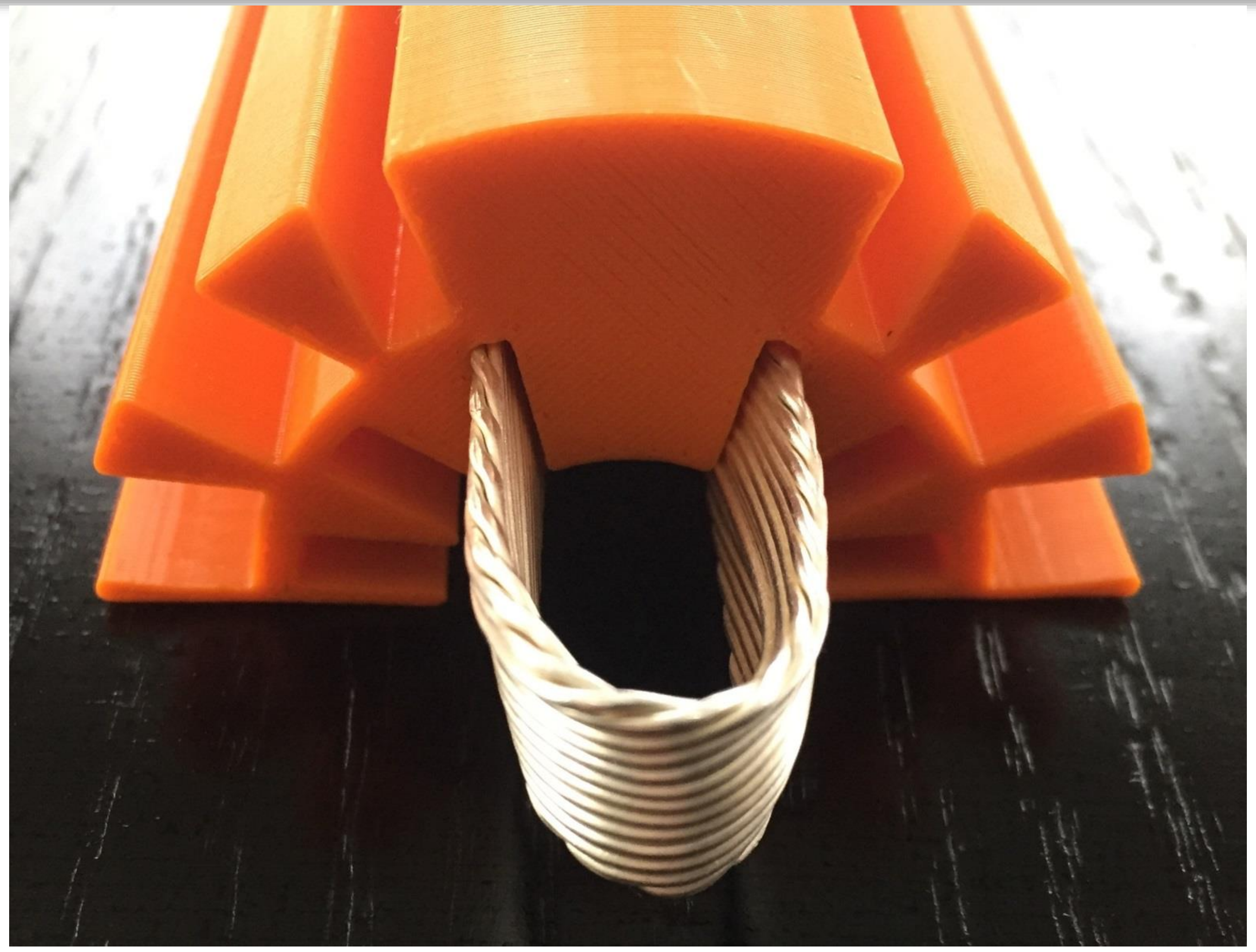
n	Design	3	5	7	9	11
b_n, 10^{-4}	v.1	-0.76	-9.6	3.43	-0.23	0.03
	v.2	**0.015**	**-5.12**	**1.46**	**0.003**	0.05

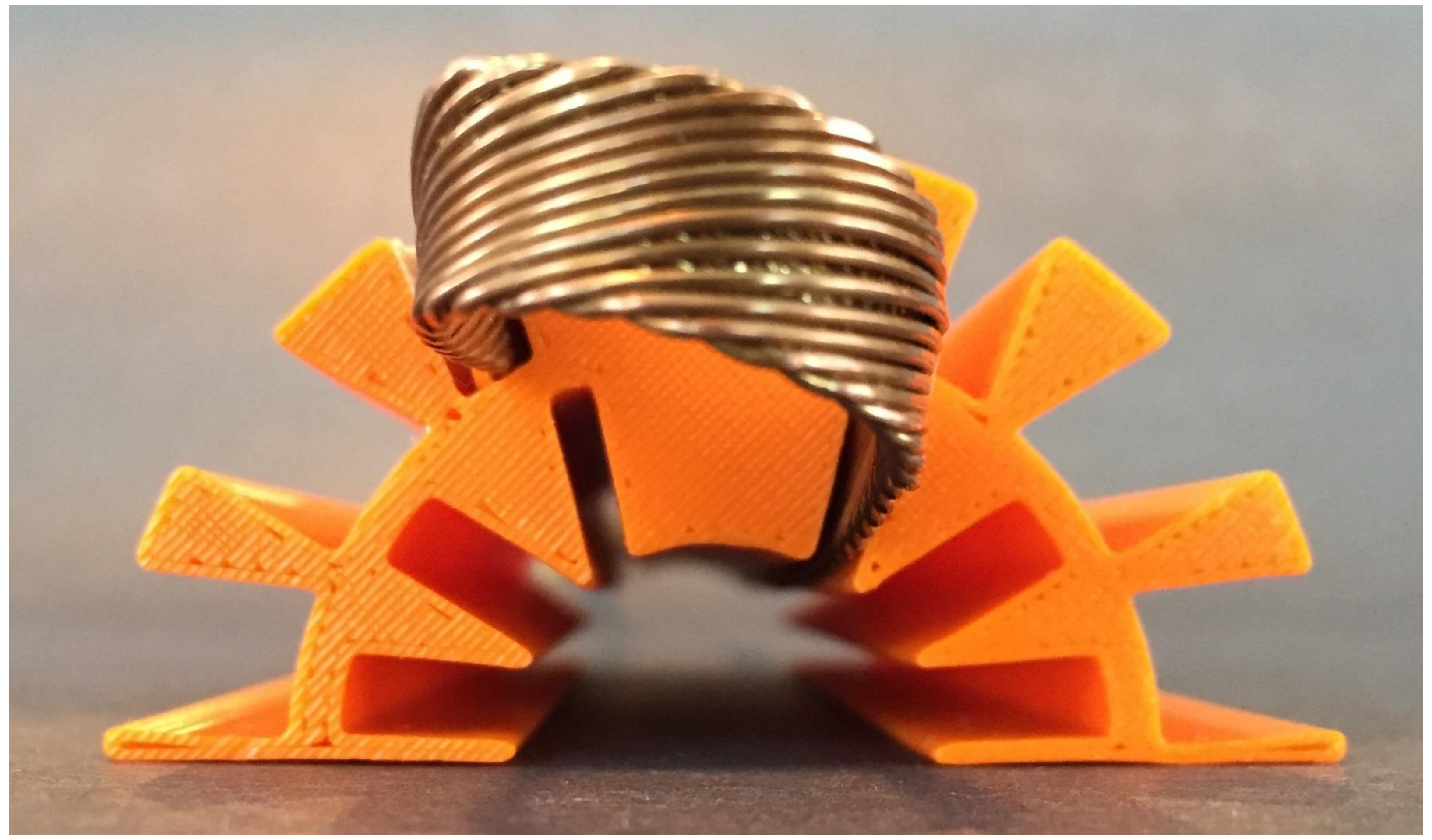




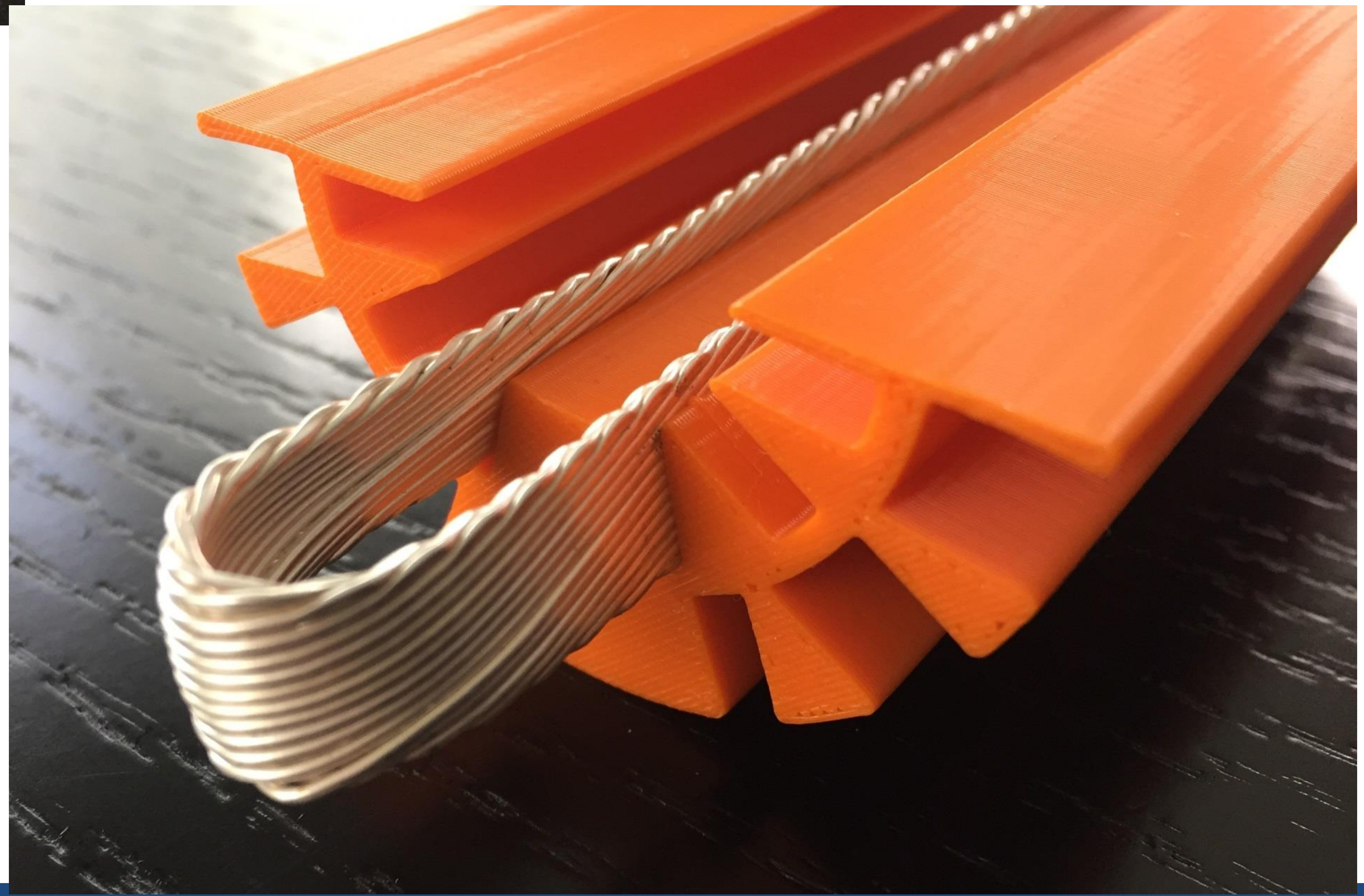
Bi2212 Coil Insert Structure and Winding Demonstration

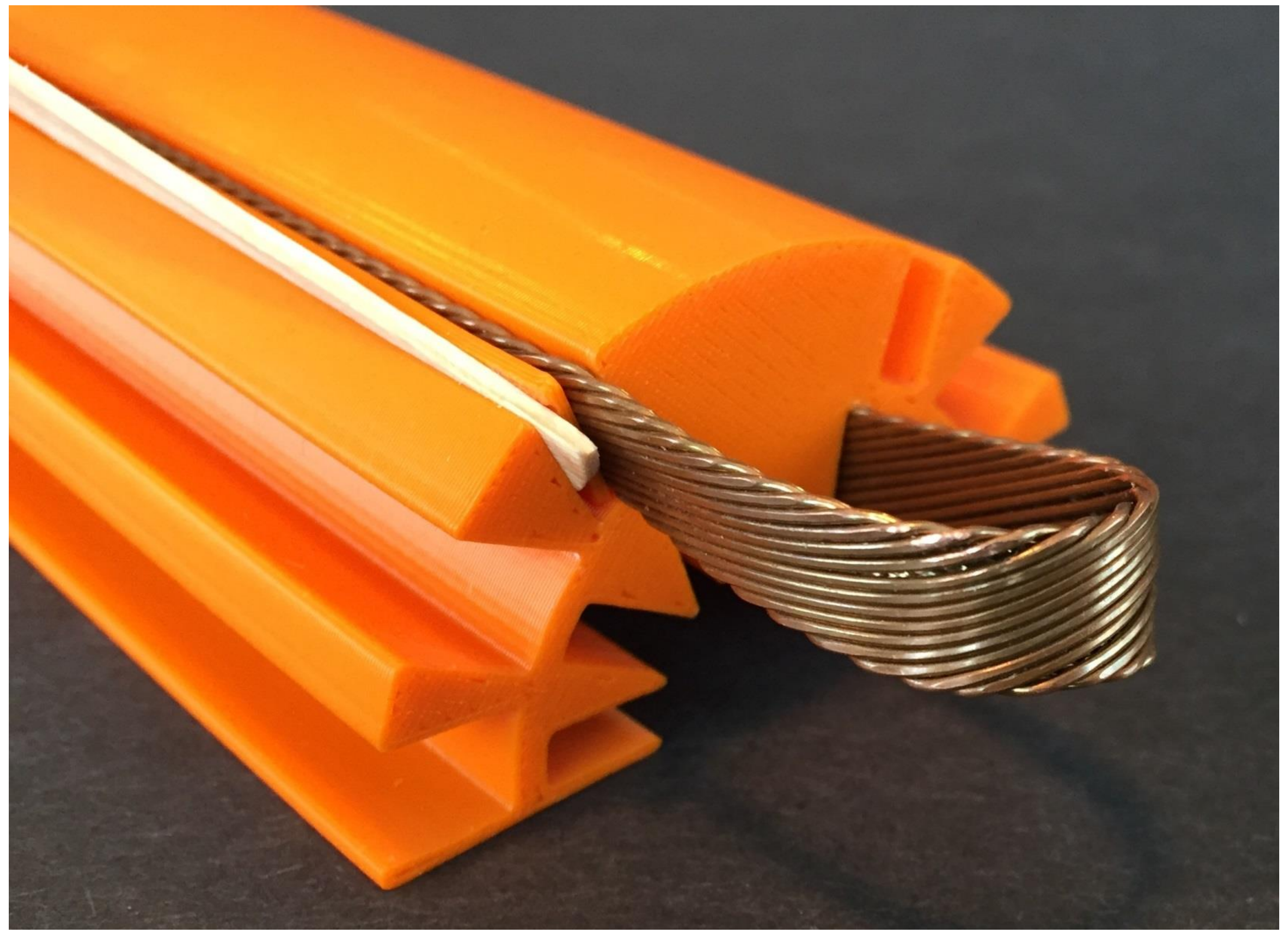






Nb_3Sn LBNL cable ~10 m long with same width as Bi2212 cable and slightly smaller thickness was used for practice winding.

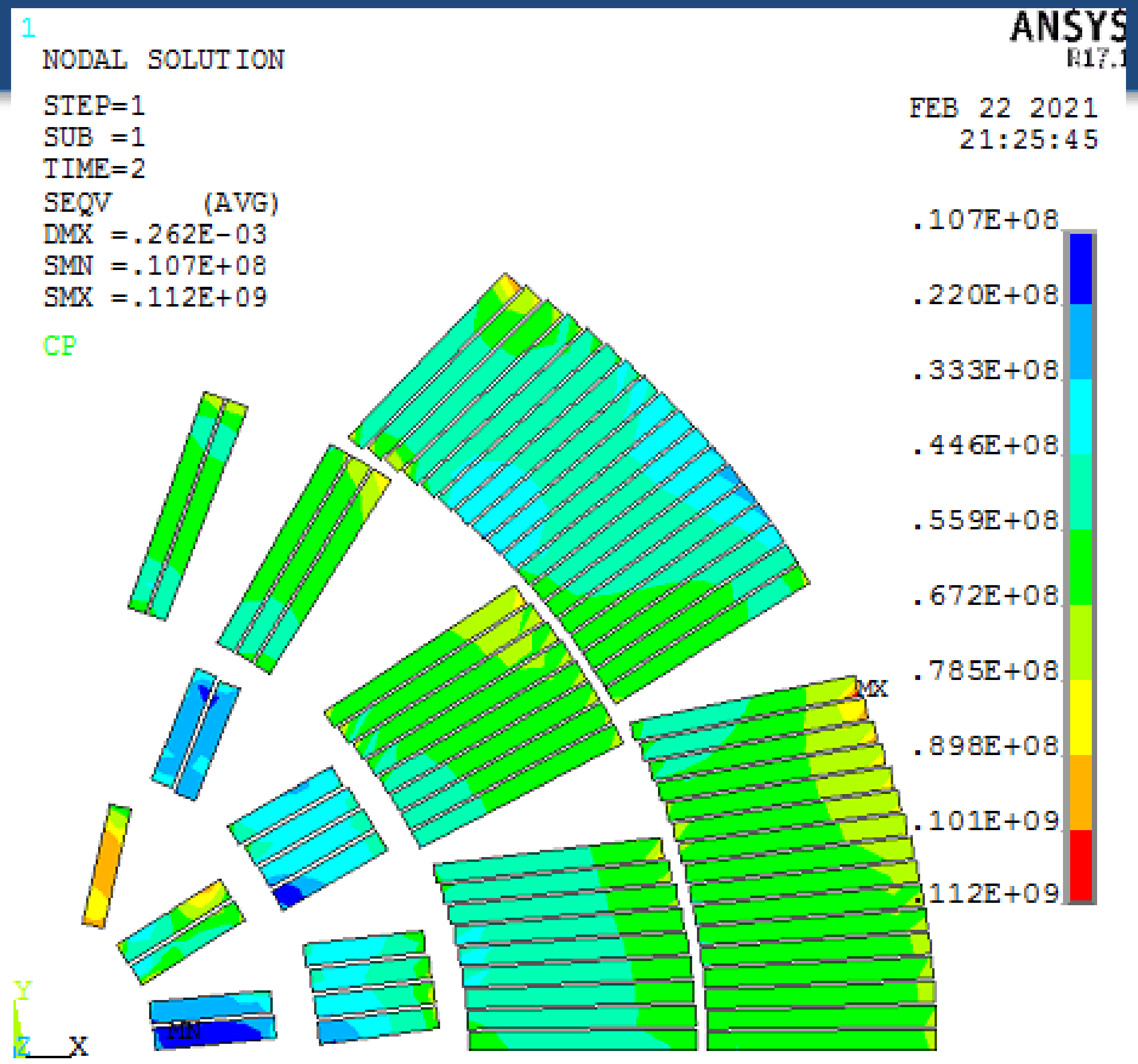


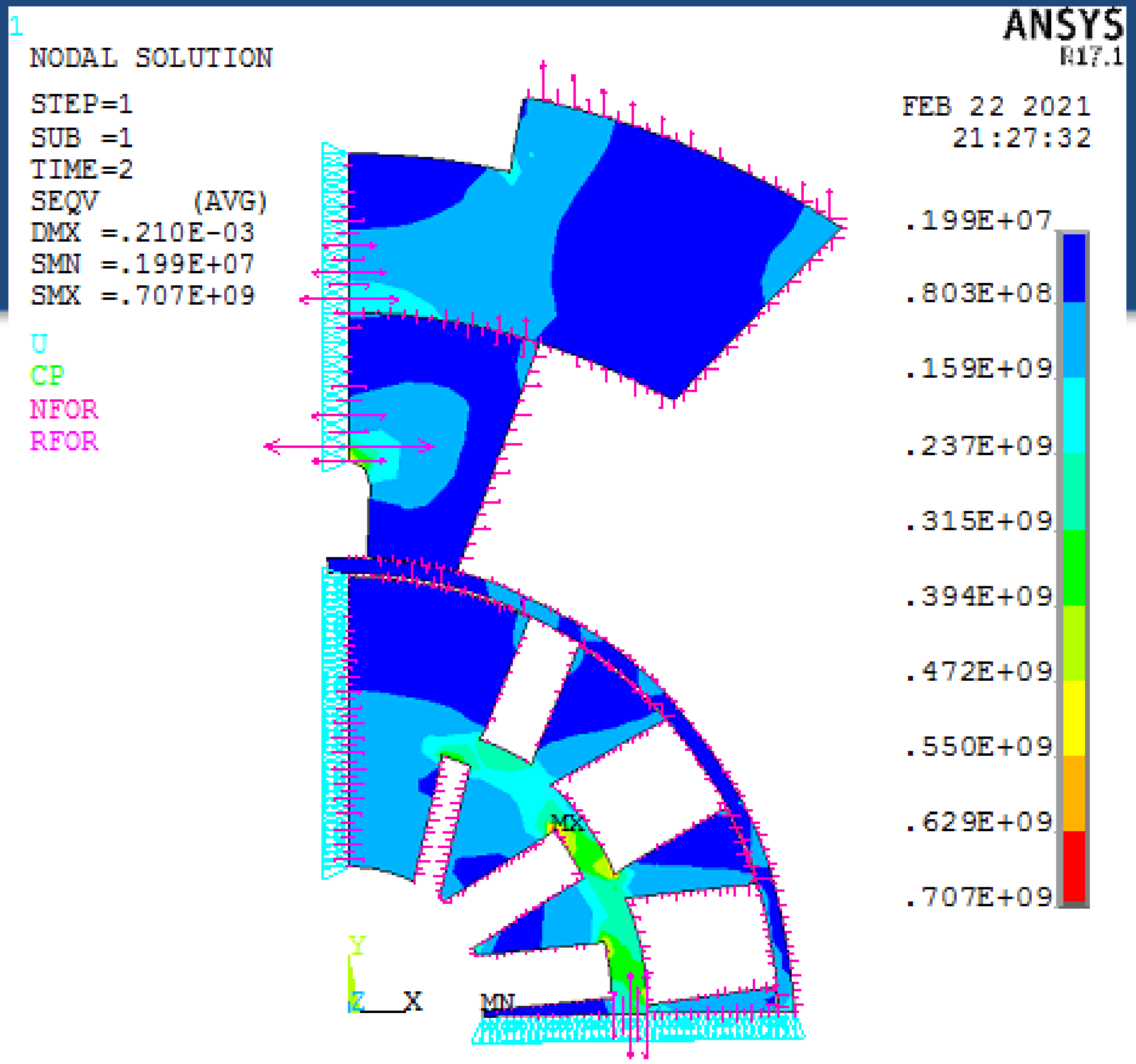


Mechanical Analysis in 11 T Dipole

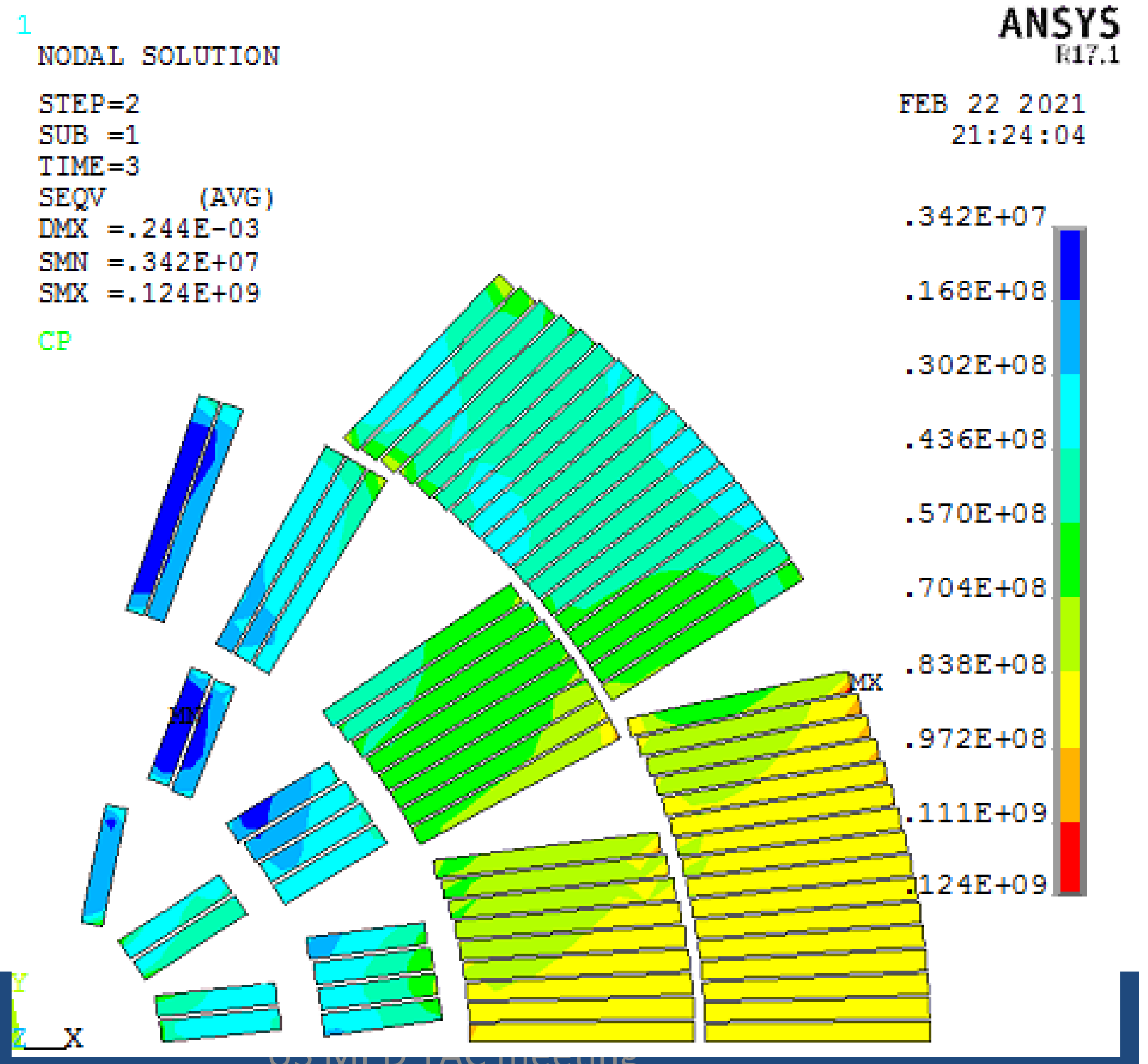
Von Mises Stress in coil < 100 MPa
Von Mises Stress in structure < 600 MPa

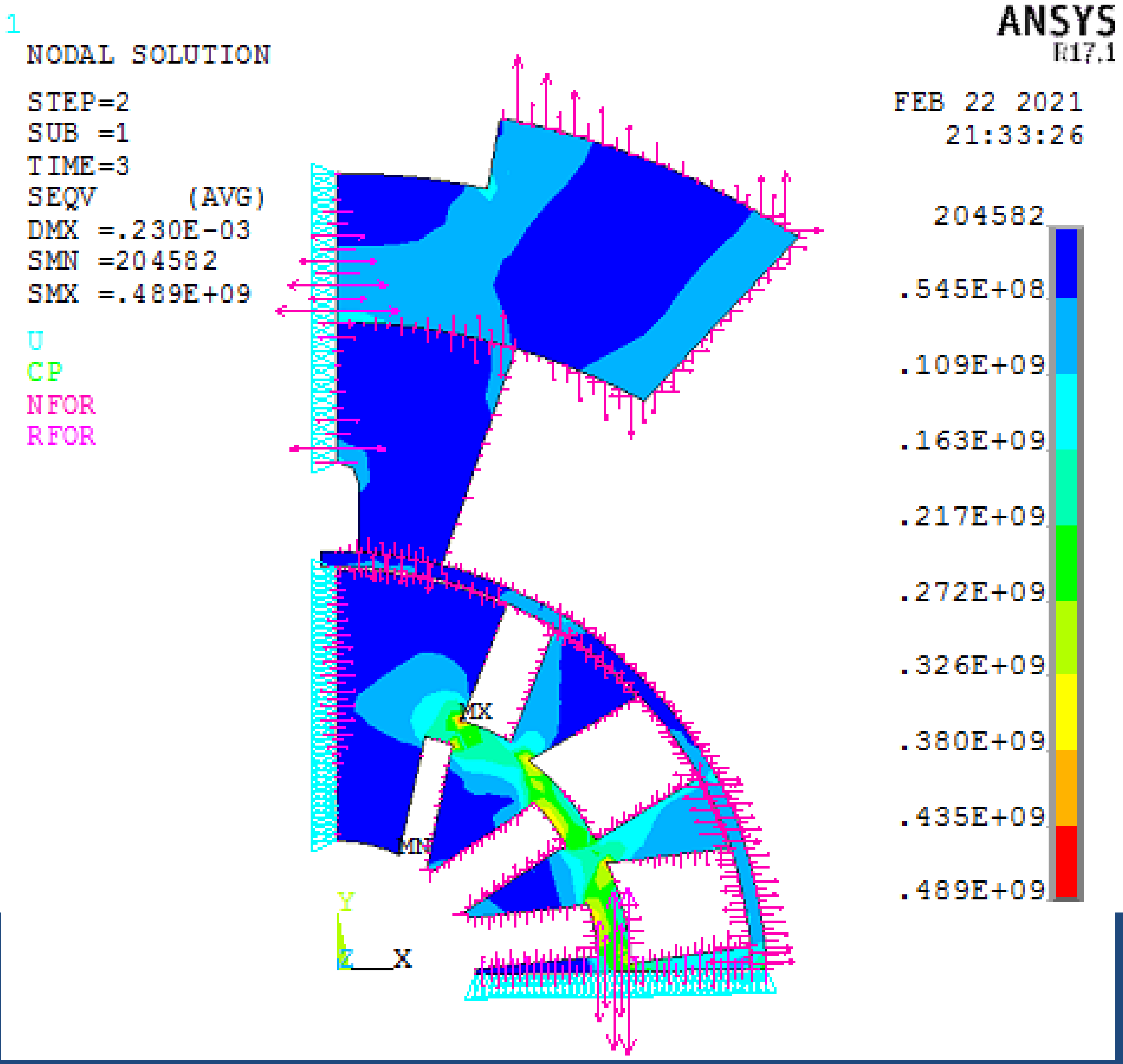
4.2 K, no current





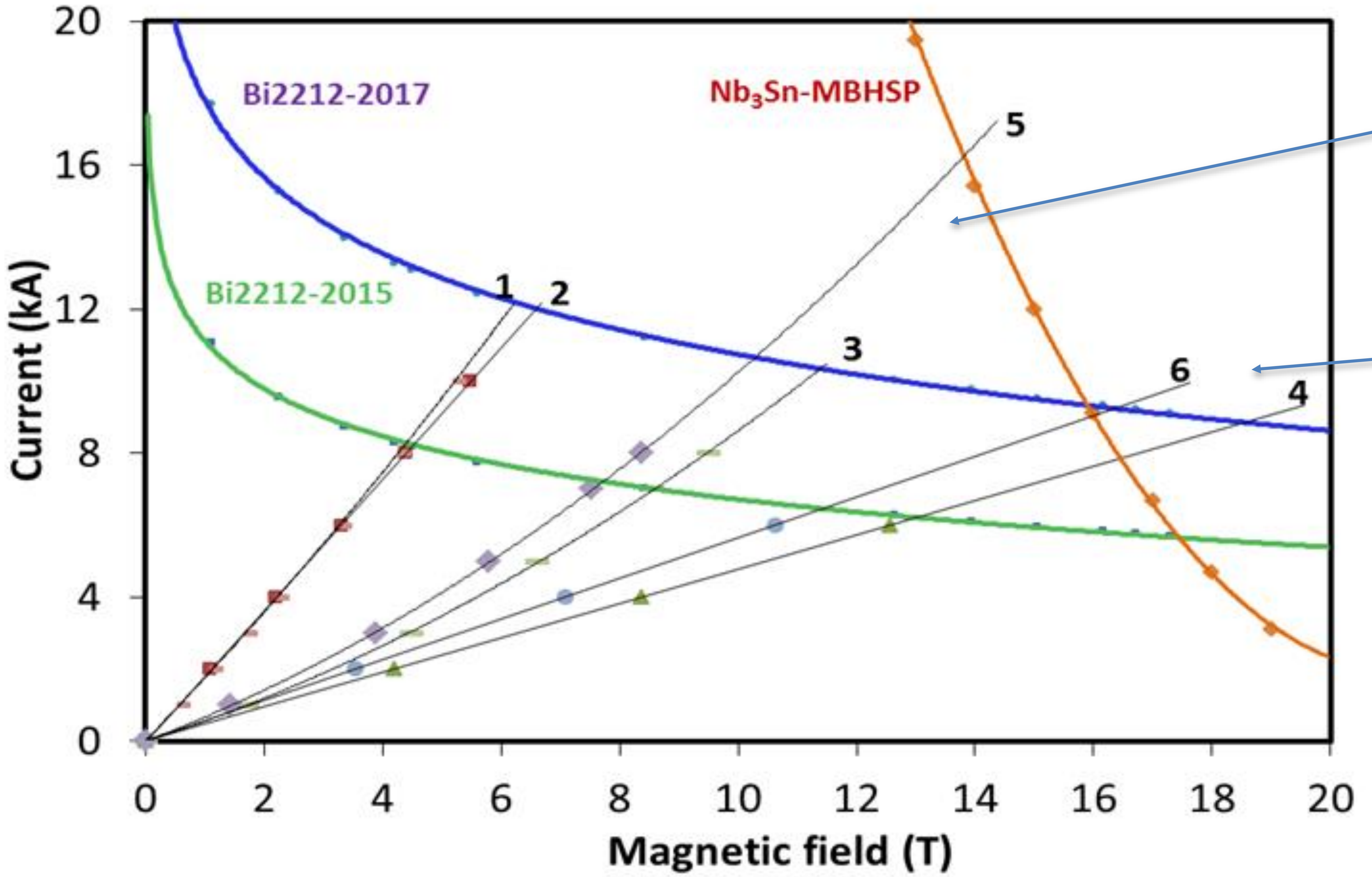
4.2 K, 8 kA, B_{max} = 12 T

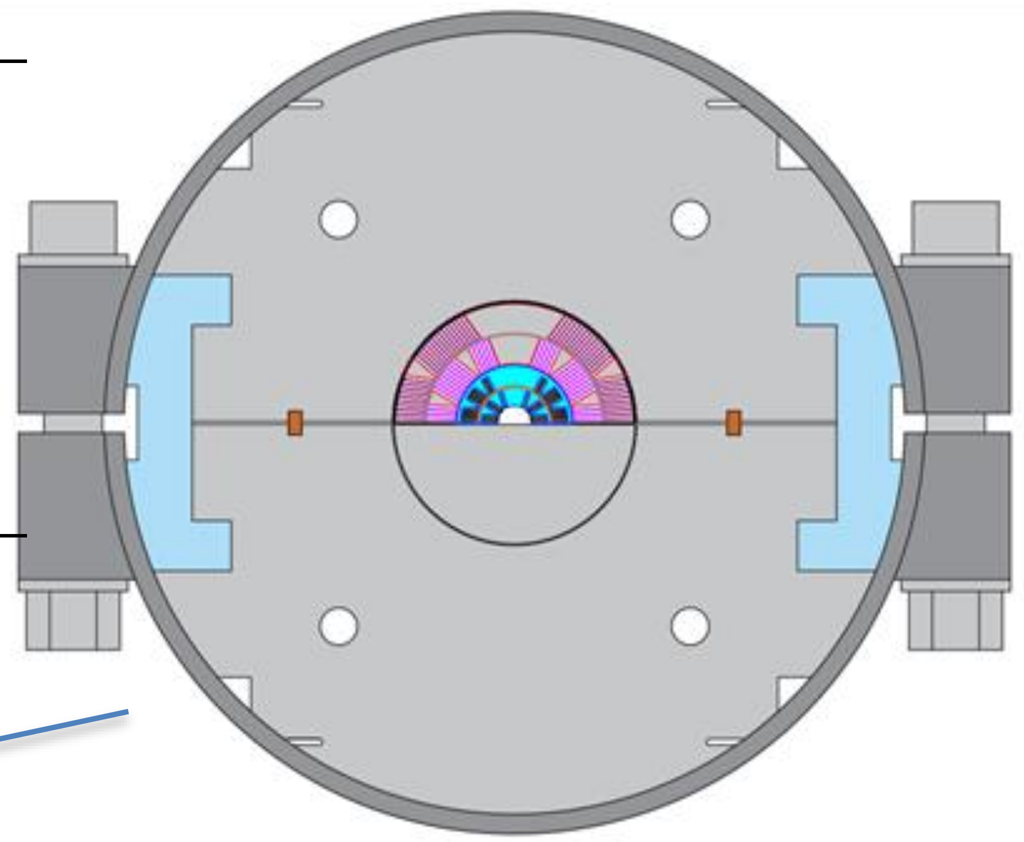


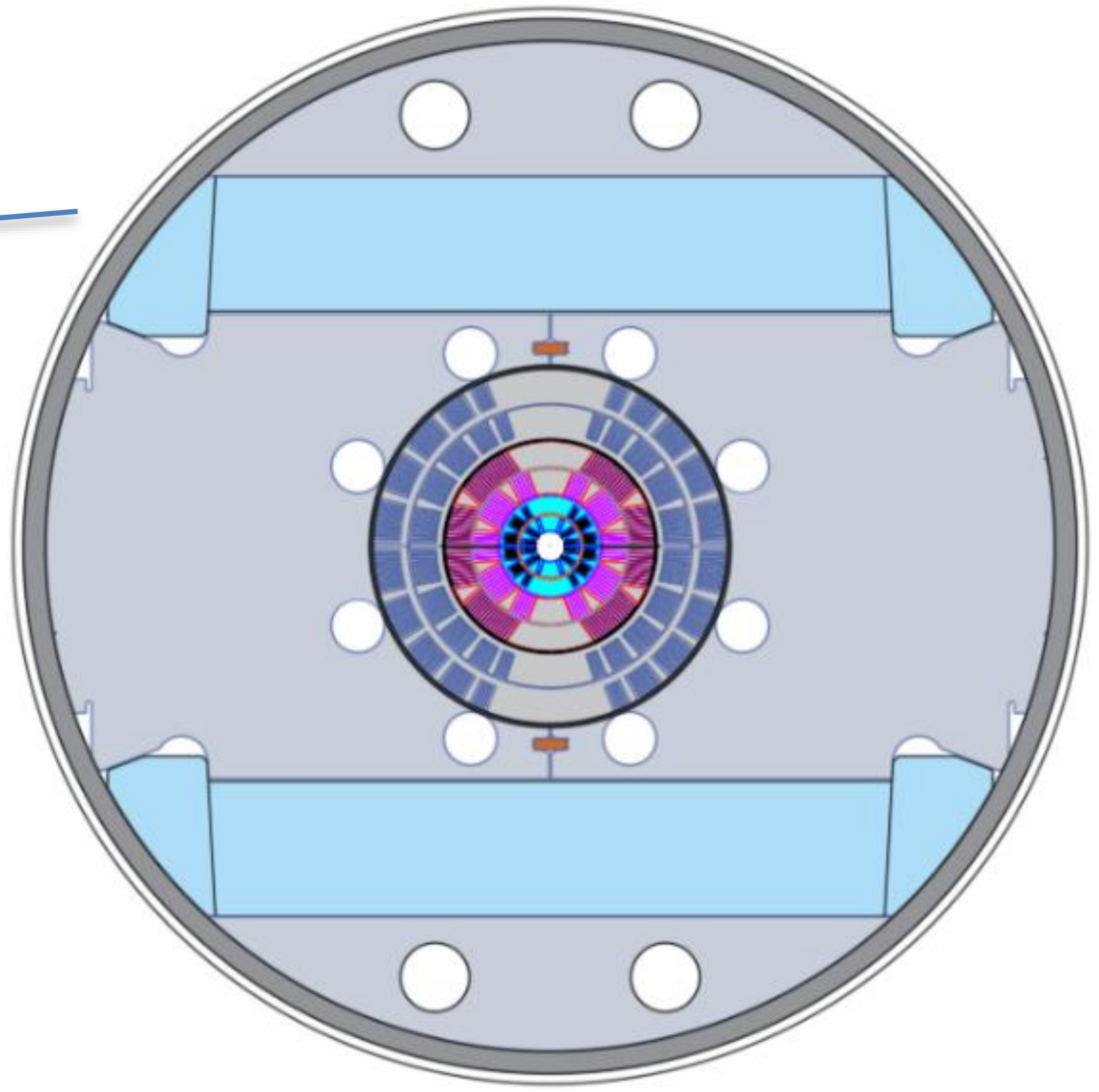


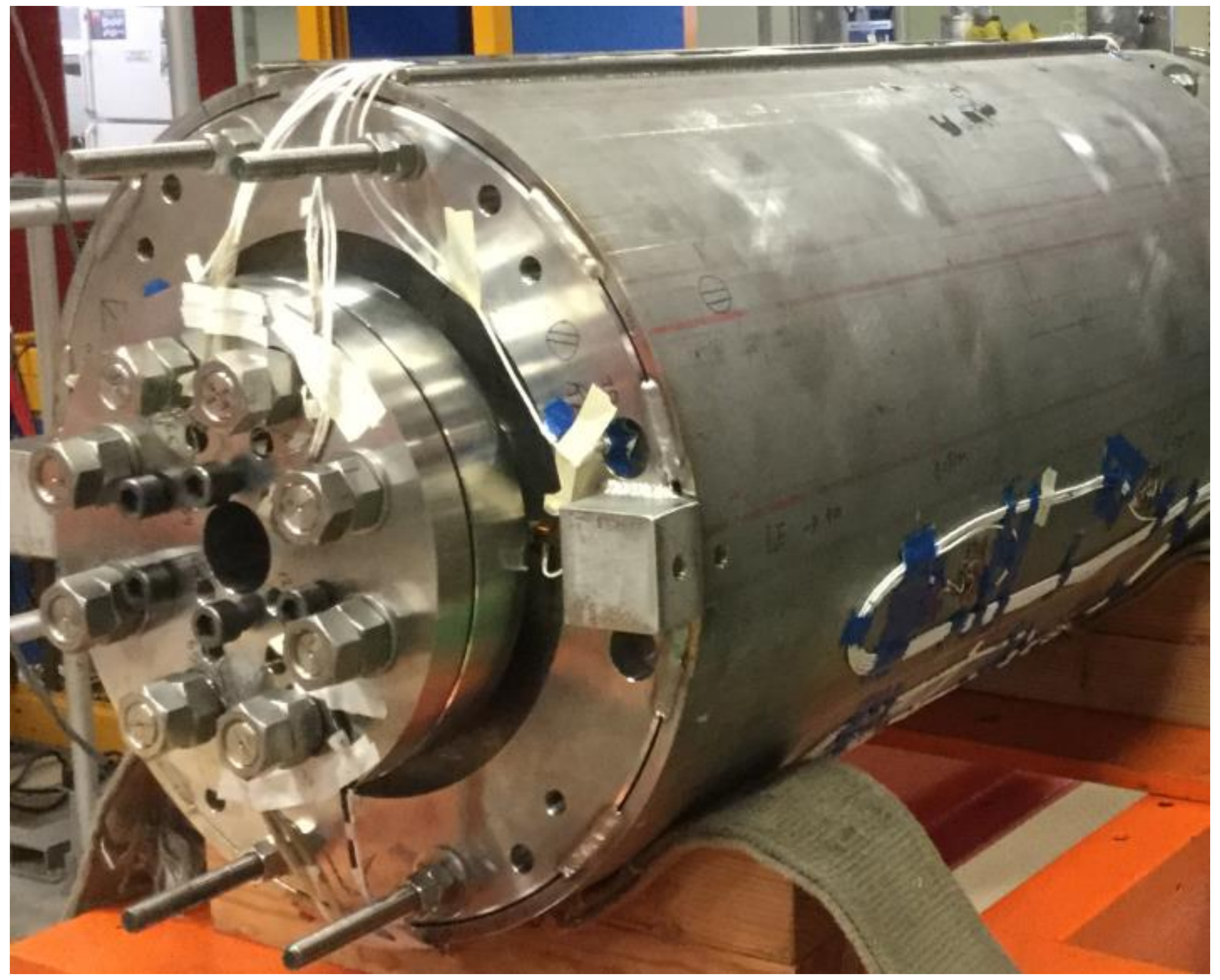
Expected Performance of Hybrid Test Configurations

Parameter	4-layer dipole mirror	6-layer dipole
Coil inner diameter, mm	17.0	17.0
Coil outer diameter, mm	122.3	206.5
Number of layers	4 (2 Bi2212+2 Nb_3Sn)	6 (2 Bi2212+4 Nb_3Sn)
Iron yoke outer diameter, mm	400	587
Maximum transverse size, mm	545	613









Bi2212 Conductor Needs

- By FY21 - 1250 m, 50 m minimum piece length, 0.8 mm diameter, J_e of 1000 A/mm^2 at 5 T after 50 bar OP HT as a standard. Standard Engi-Mat powder composition, twist, restack No. and insulation.
- By FY22 - 2050 m, 0.8 mm, 120 m minimum piece length, 0.8 mm diameter, J_e > 1000 A/ mm^2 at 5 T after 50 bar OP HT (as high as achievable by then), same as above for other parameters.
- By FY23 - 2050 m, 0.8 mm, 120 m minimum piece length, 0.8 mm diameter, Je > 1000 A/mm^2 at 5 T after 50 bar OP HT (as high as achievable by then), same as above for other parameters.

Next Steps

- Conductor studies for milestone (Milestone AIIa-M1b, April 2022)
- Coil structure engineering design - March-April, 2021
- Coil reaction/impregnation tooling design - May-June, 2021
- Structure and tooling procurement/inspection - May-July, 2021
- Coil winding/reaction at 50 bar in 1 m long Renegade furnace at FSU/ impregnation/instrumentation - August-October, 2021
- Mirror assembly – Q1 FY22
- Mirror test - Q2 FY22 (Milestone AIIa-M2b, July 2022)

Summary

- The HEP global community has been ushering in a new era of high-tech accelerator development through the strong endorsement of the European Strategy for Particle Physics of “high-field superconducting magnets, including high-temperature superconductors”.
- Area II on HTS Magnets within US-MDP will sustain the U.S. world leadership position in accelerator magnets.
- The 2-layer dipole coil design with stress-management allows extensive and cost-effective ways of developing and testing the technology of HTS inserts based on Bi2212 cable and the cos-theta coil geometry.
- The development of the Bi2212 coil engineering design is in progress. Tests of the first Bi2212 coil in dipole mirror configuration could start by end of 2021.

Involvement in the Snowmass HEP Planning Process

Snowmass 2021, Letter of Interest

High field superconducting accelerator magnet technologies based on Bi-2212 high-temperature superconductor for future accelerator facilities

Emanuela Barzi[1], Ernesto Bosque[2], Daniel Davis[2], Laura Garcia Fajardo[3], Paolo Ferracin[3], Youngjae Kim[2], David Larbalestier[2], Igor Novitski[1], Soren Prestemon[3], Tengming Shen[3,*], Ulf Trociewitz[2], Alexander Zlobin[1]

1. Fermilab, 2. National High Magnetic Field Lab, 3. Lawrence Berkeley National Lab, *tshen@lbl.gov.

[Why Bi-2212?] The development of high-temperature superconducting magnets for frontier particle physics colliders was endorsed by the 2014 P5 report and its 2015 accelerator R&D subpanel report and recently again by the 2020 update of European strategy for particle physics. High temperature superconductors (HTS) can generate magnetic fields of 45 T at 4.2 K, nearly two times of the ~23 T limit of two Nb-based superconductors; they also have many applications in other fields of science. Since the early 2000s, progress have been made with developing accelerator magnet technologies with two HTS, REBCO coated conductors and Bi-2212 round wires. Using REBCO coated conductors, CERN has pursued an aligned block dipole design based on a ROEBEL cable assembled from cut REBCO tapes [1], whereas LBNL, within the US magnet development program (MDP) [2], has been developing a canted cosine theta

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SLIDE 6

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[1] Zlobin, A.V.; Novitski, I.; Barzi, E. "Conceptual Design of a HTS Dipole Insert Based on Bi2212 Rutherford Cable", Instruments 2020, 4, 29.