U.S. MAGNET DEVELOPMENT PROGRAM

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Development of a small-aperture cos-theta dipole insert coil based on Bi2212 Rutherford cable and stress management structure

A.V. Zlobin, I. Novitski, E. Barzi, D. Turrioni

Fermilab

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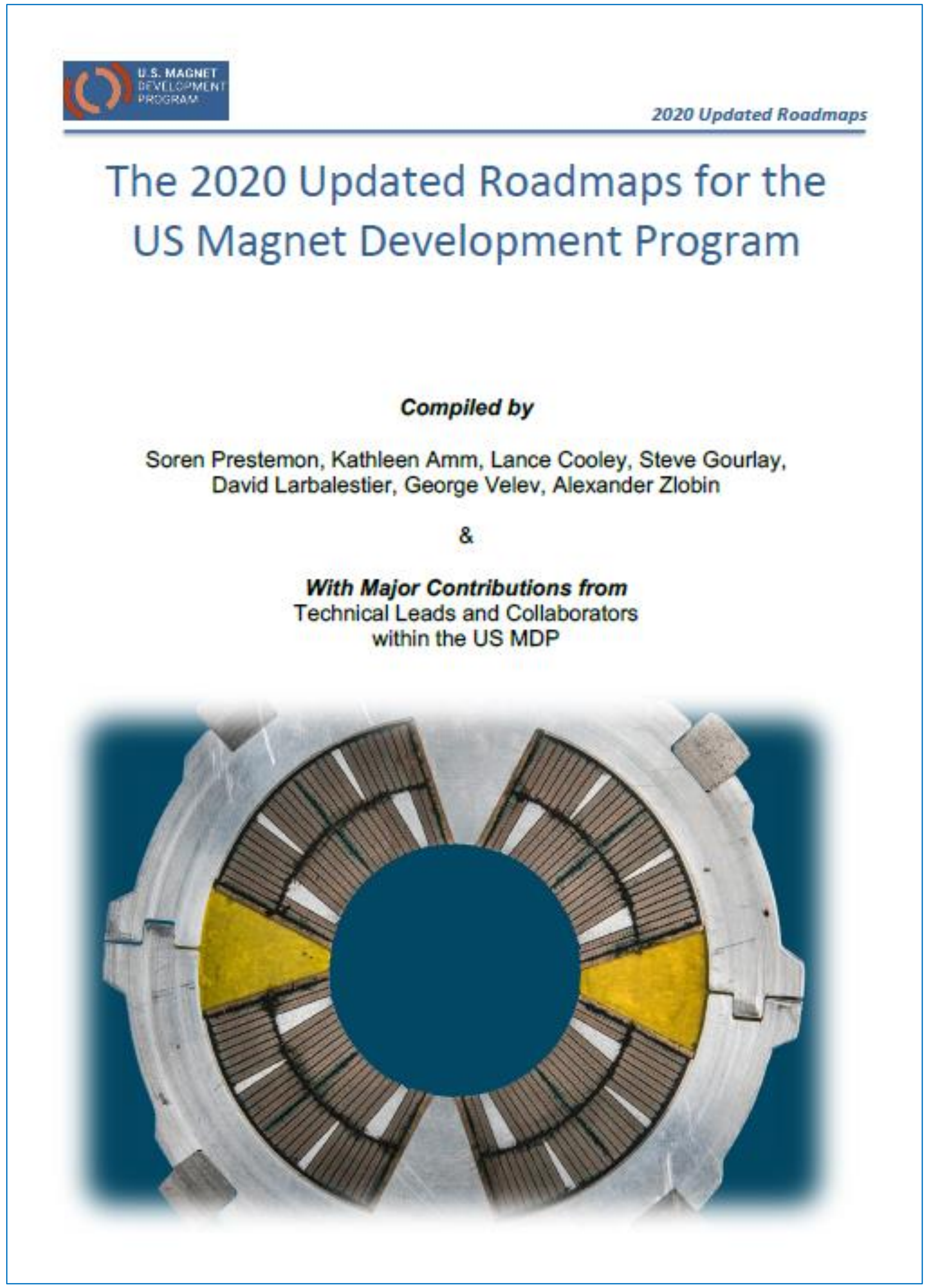
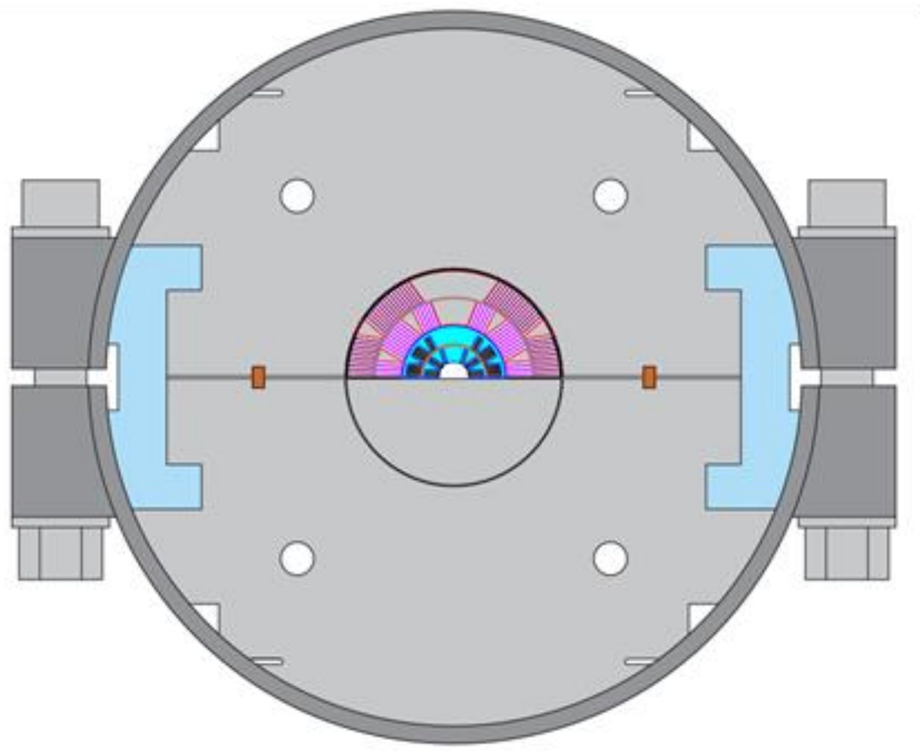
Introduction



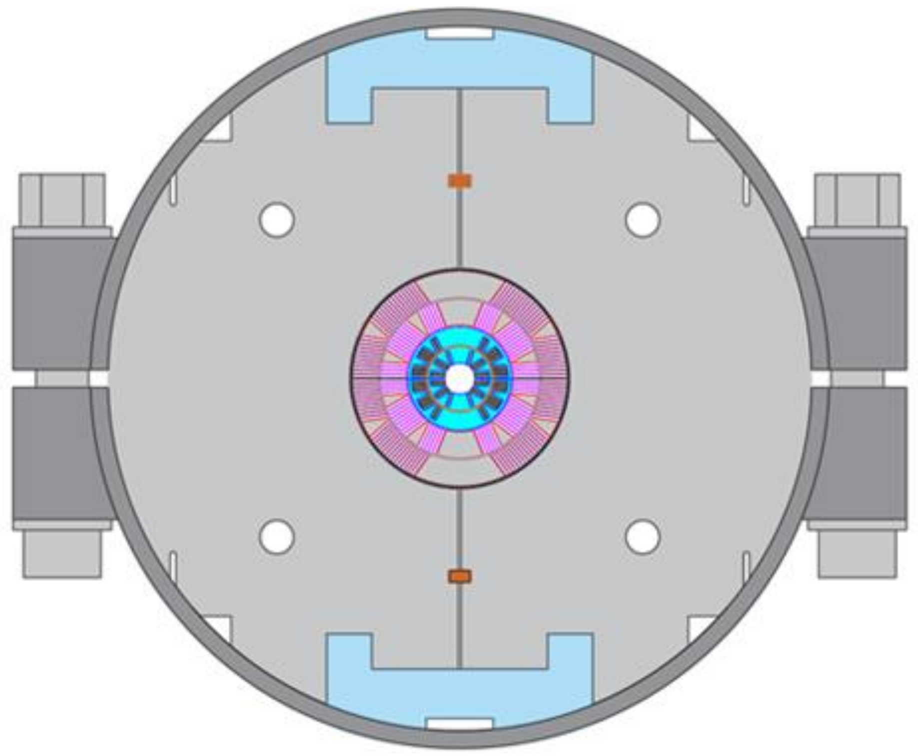
Fermilab in the framework of the US-MDP is developing an insert coil based on Bi2212 superconductor and SM coil structure.

The Bi2212 insert R&D goals:

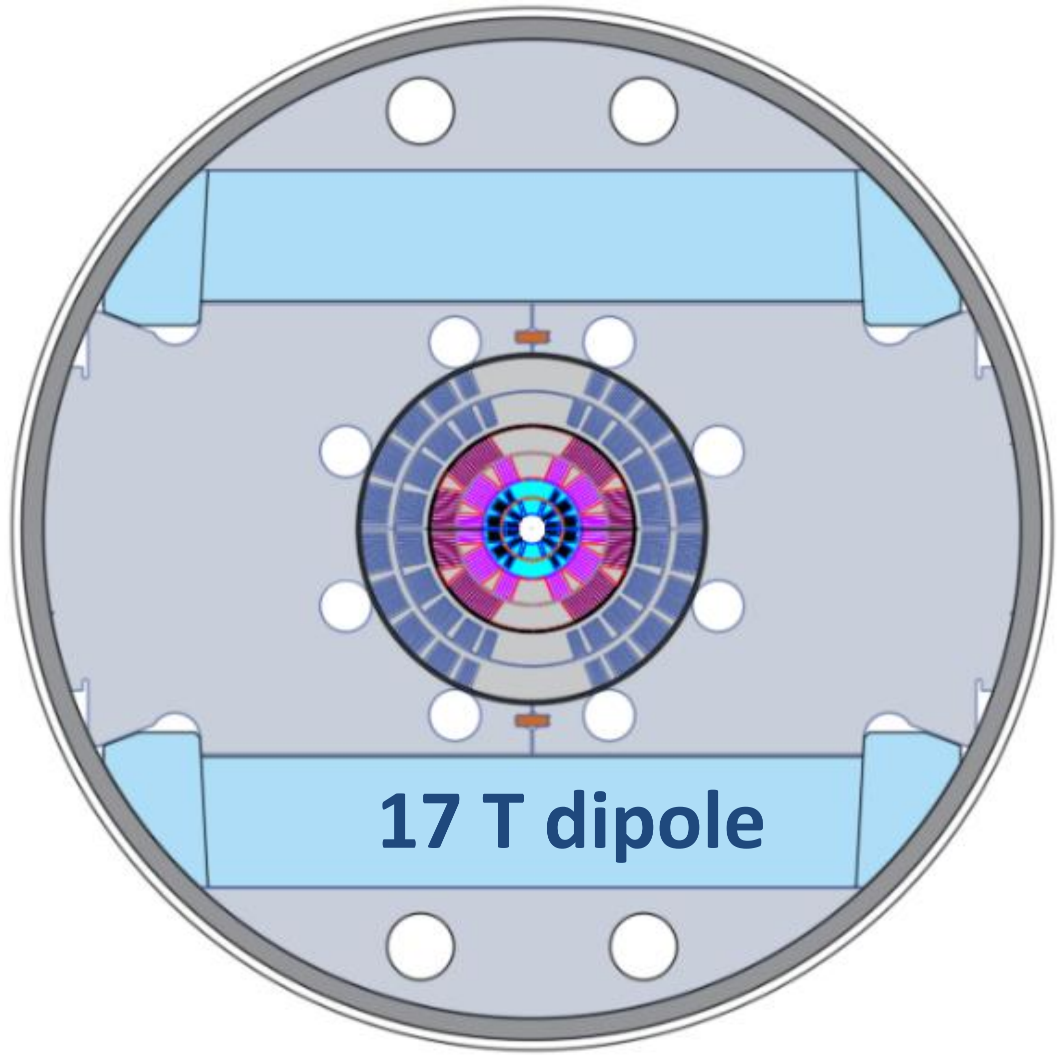
- **development of the small-aperture 2-layer Bi-2212 SMCT dipole coils with the design self-field of 5.5 T**
- **coil testing in the background fields of Nb_3Sn coils being developed within the MDP to understand key questions related to Bi-2212 magnet design and technology**



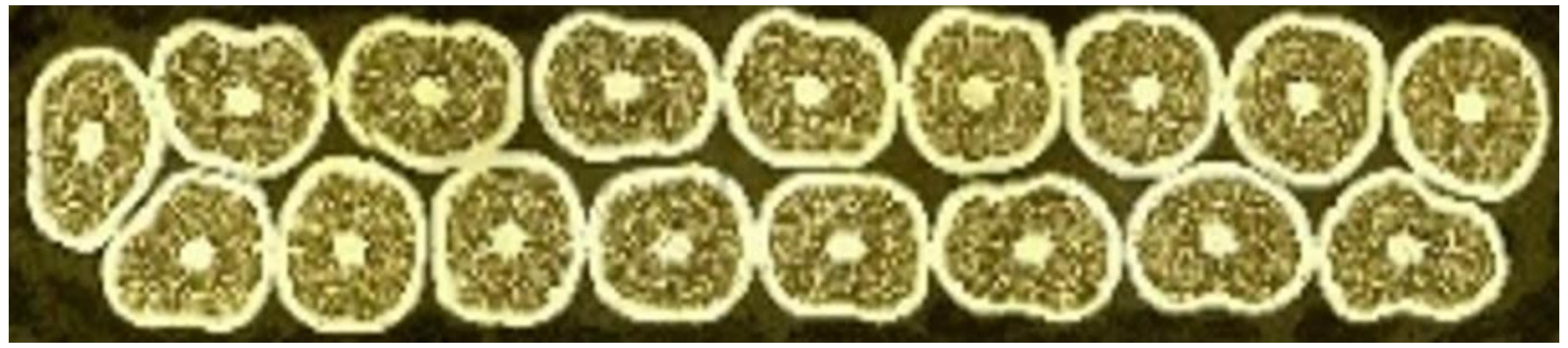
11 T mirror



11 T dipole

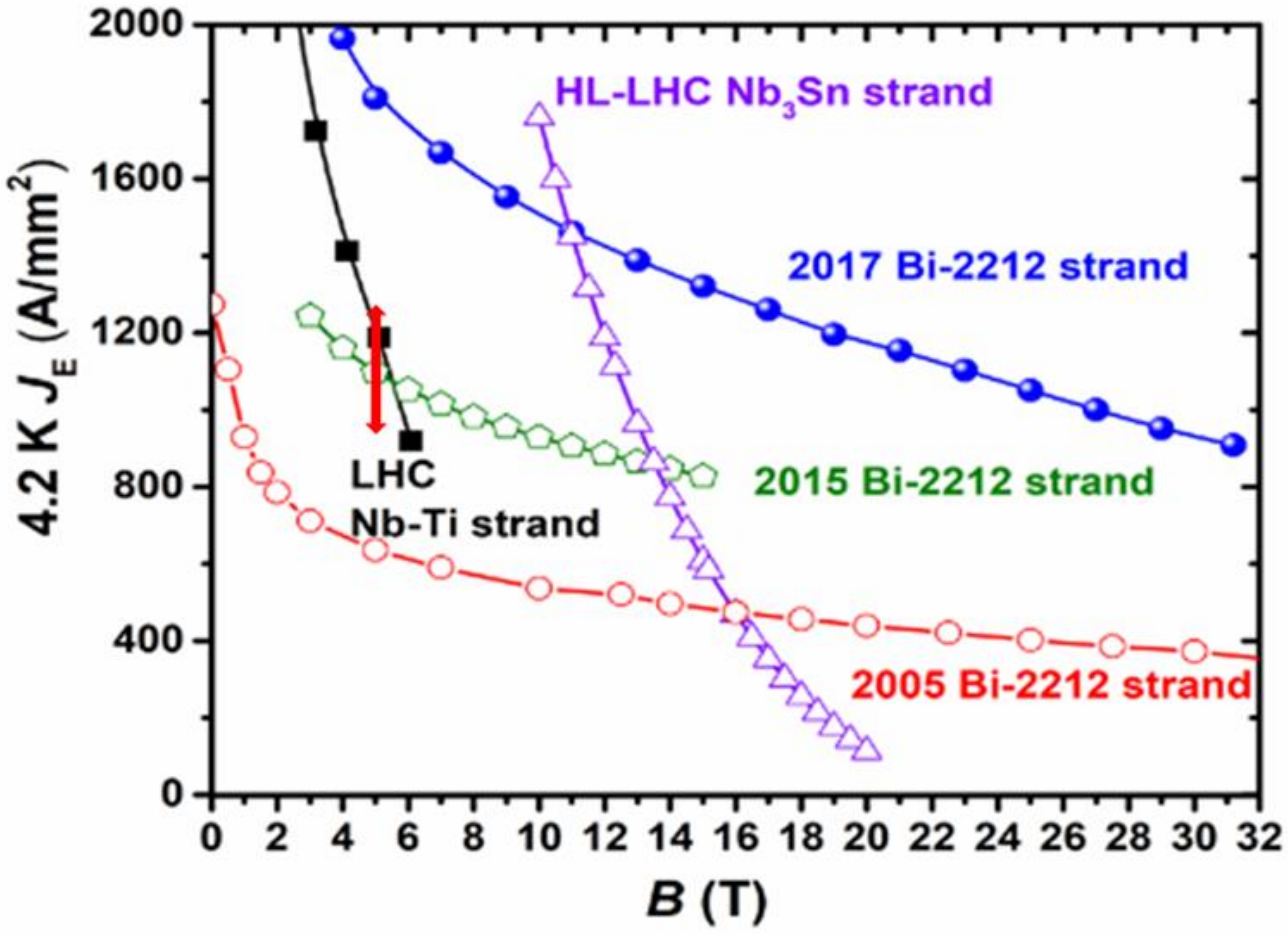


Bi2212 wire and cable



- **0.8 mm Bi2212 wire (BOST)**
- **17-strand cable 7.8x1.44 mm^2 (LBNL)**

Bi2212 round composite wire and Rutherford cable.



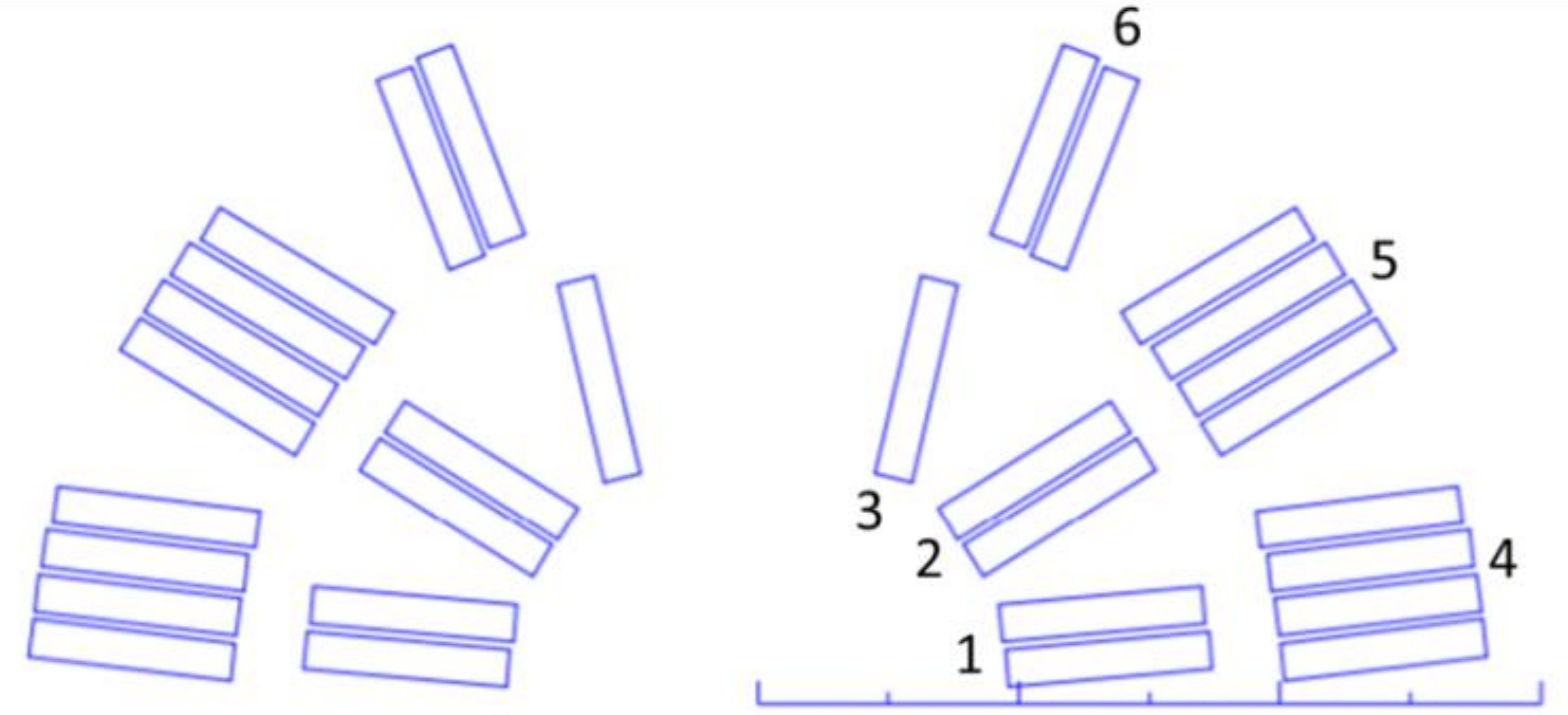
Bi2212 cable and strand parameters.

Parameter	Unit	Value
Number of strands		17
Bare cable width	mm	7.8
Bare cable thickness	mm	1.44
Cable transposition pitch	mm	58
Strand diameter before/after reaction	mm	0.8/0.778
Strand twist pitch	mm	25
Strand $I_c(4.2K,5T)$ after NHMFL 50 bar OPHT	A	460-640*

The target field will be approached gradually by using the "old" 2015 and "new" 2017 generations of Bi-2212 wires.

Magnetic design

Optimized coil cross-section.



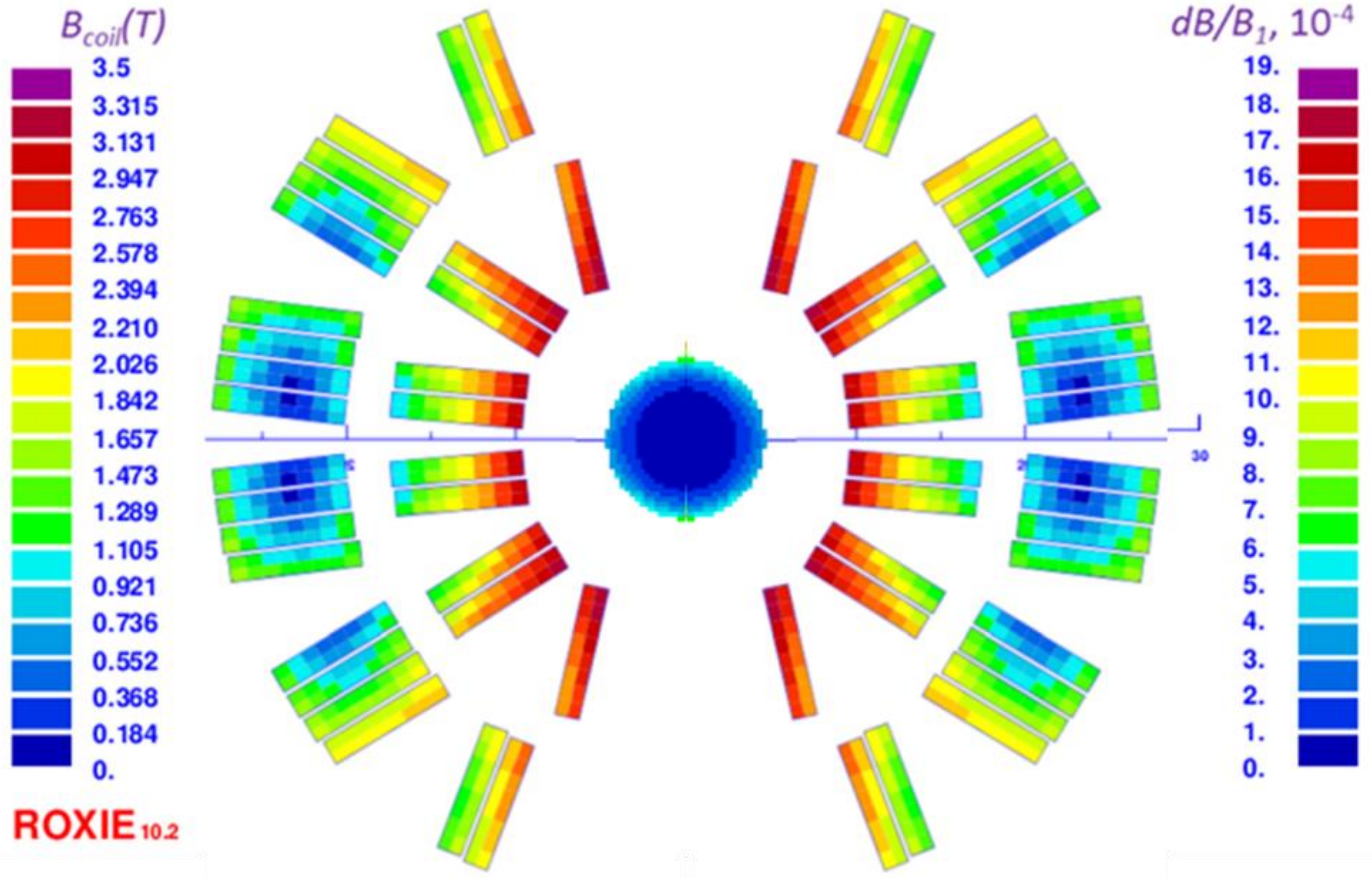
Parameters of Bi2212 insert.

Parameter	Unit	Value
Number of layers		2
Number of turns		15 (5 IL+10 OL)
Coil ID/OD	mm	19/59
Maximum coil $TF=B_{max}/I$	T/kA	0.533
Maximum aperture $TF=B_o/I$	T/kA	0.529
Coil to aperture field ratio B_{max}/B_o		1.008
Coil inductance	mH/m	0.379
Stored energy @ 6 kA	kJ/m	6.82
Lorentz force F_x/F_y @ 6 kA	kN/m/quadrant	97.5/-62.2

Geometrical field harmonics at R_{ref}= 5 mm

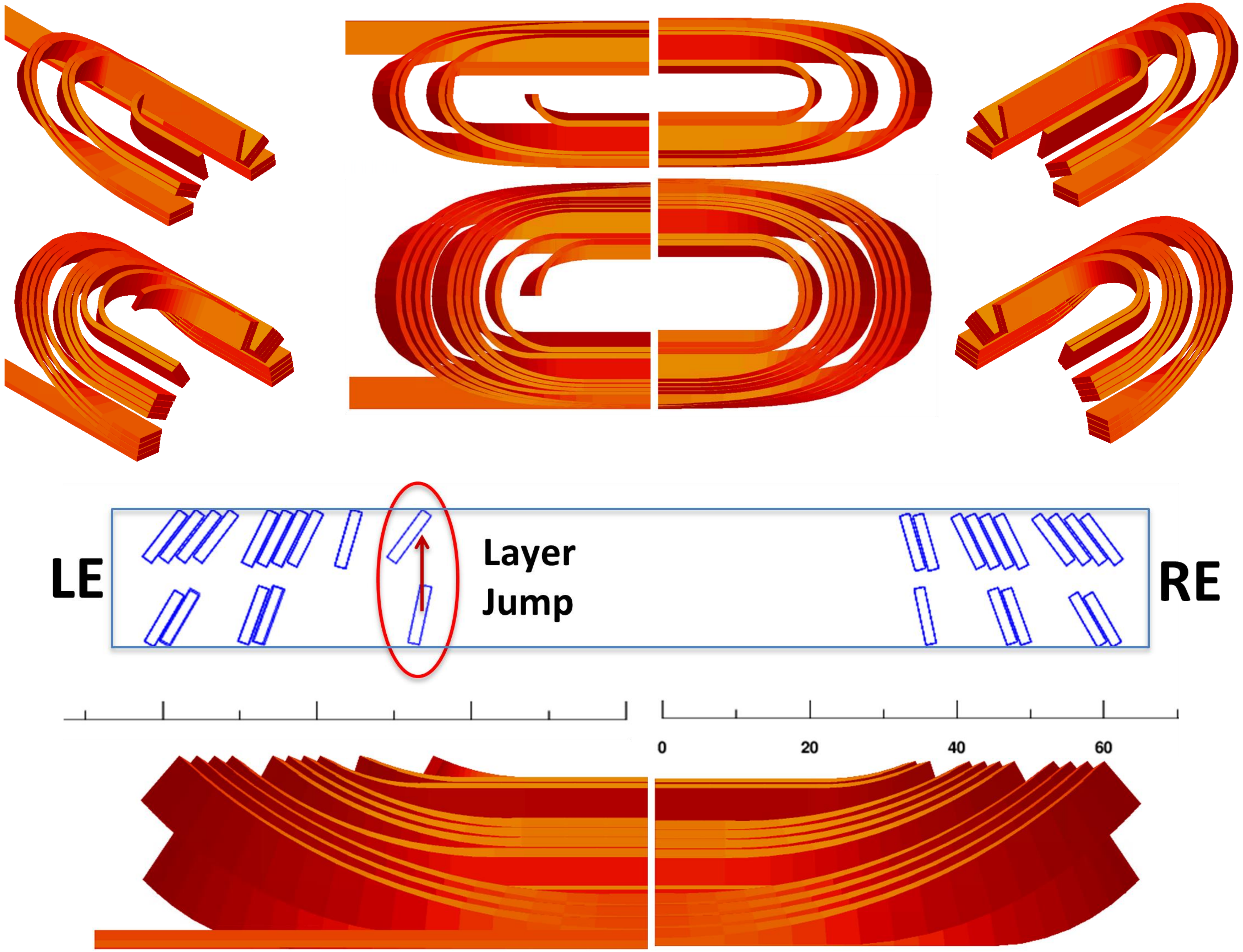
$$B_y(x,y) + iB_x(x,y) = B_1 \sum_{n=1}^{\infty} (b_n + ia_n)\left(\frac{x+iy}{R_{ref}}\right)^{n-1}$$

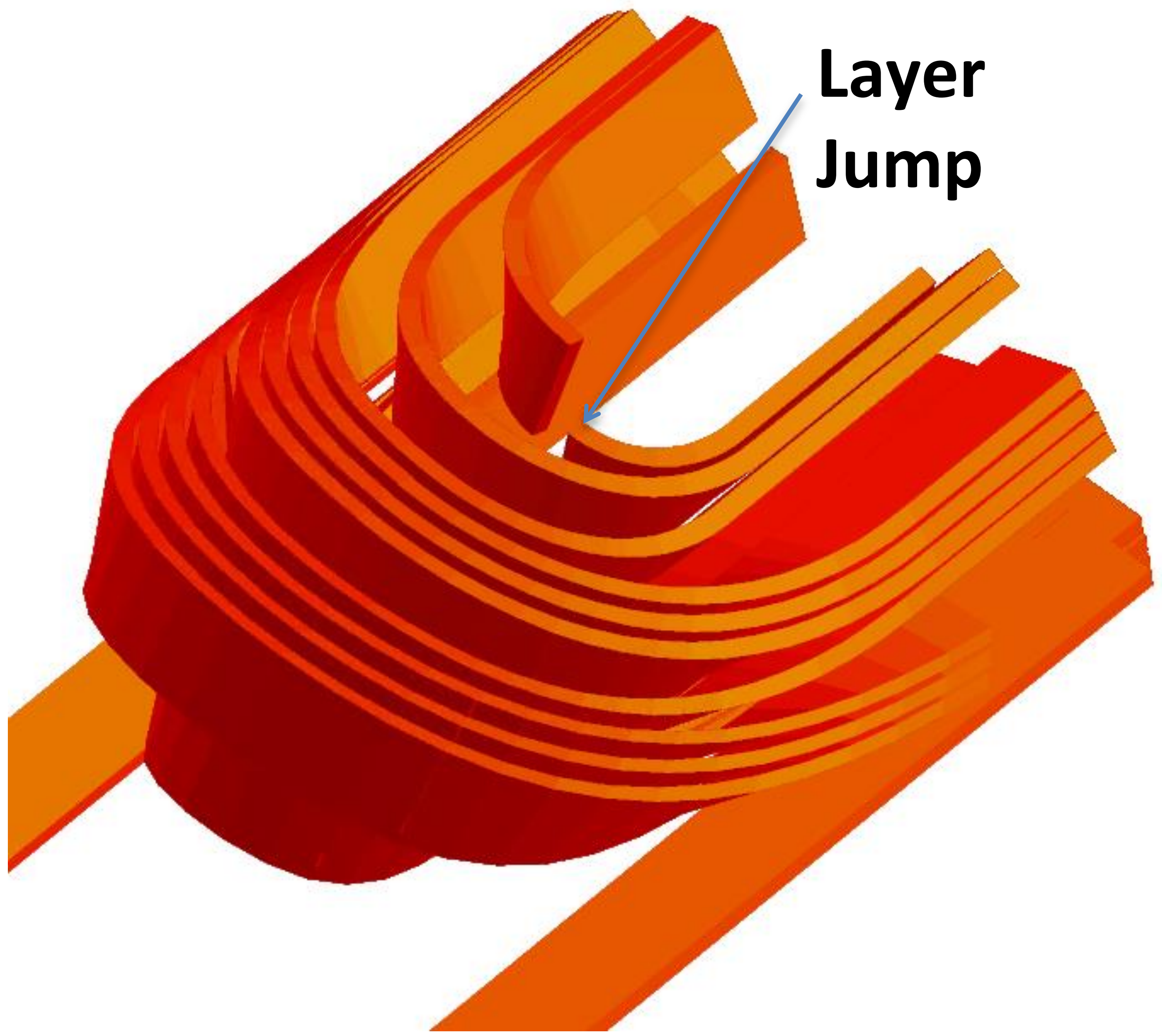
n	3	5	7	9	11
b_n, 10^{-4}	-0.76	-9.6	3.43	-0.23	0.03



The field uniformity diagram in the aperture and the field distribution in the coil at 6 kA current.

Coil ends and layer jump





- Compact symmetric ends with short block transitions in LE
- Smooth turn bends in both layers
- Short layer jump by bending inner cable up to match the outer layer cable angle

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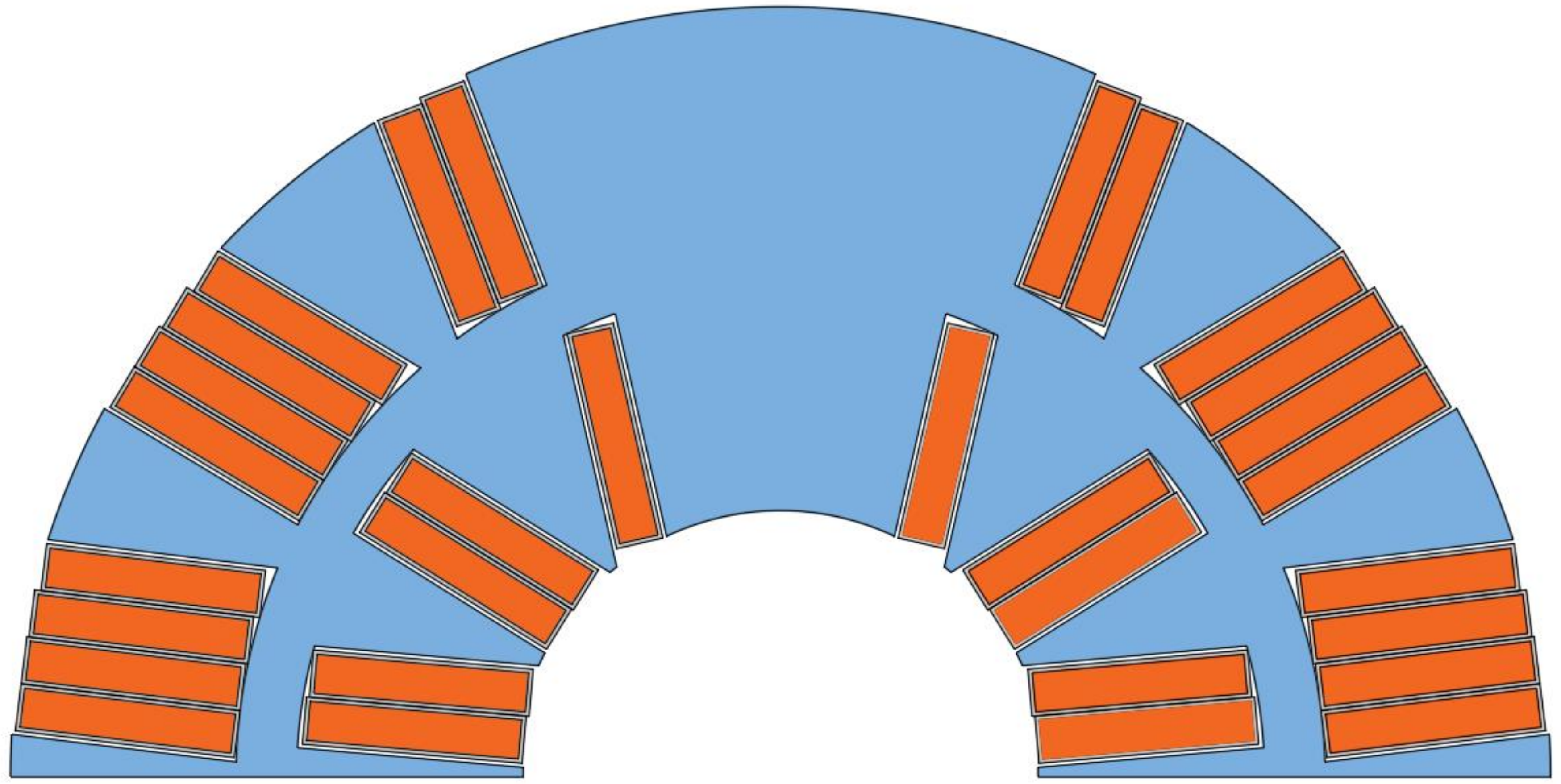
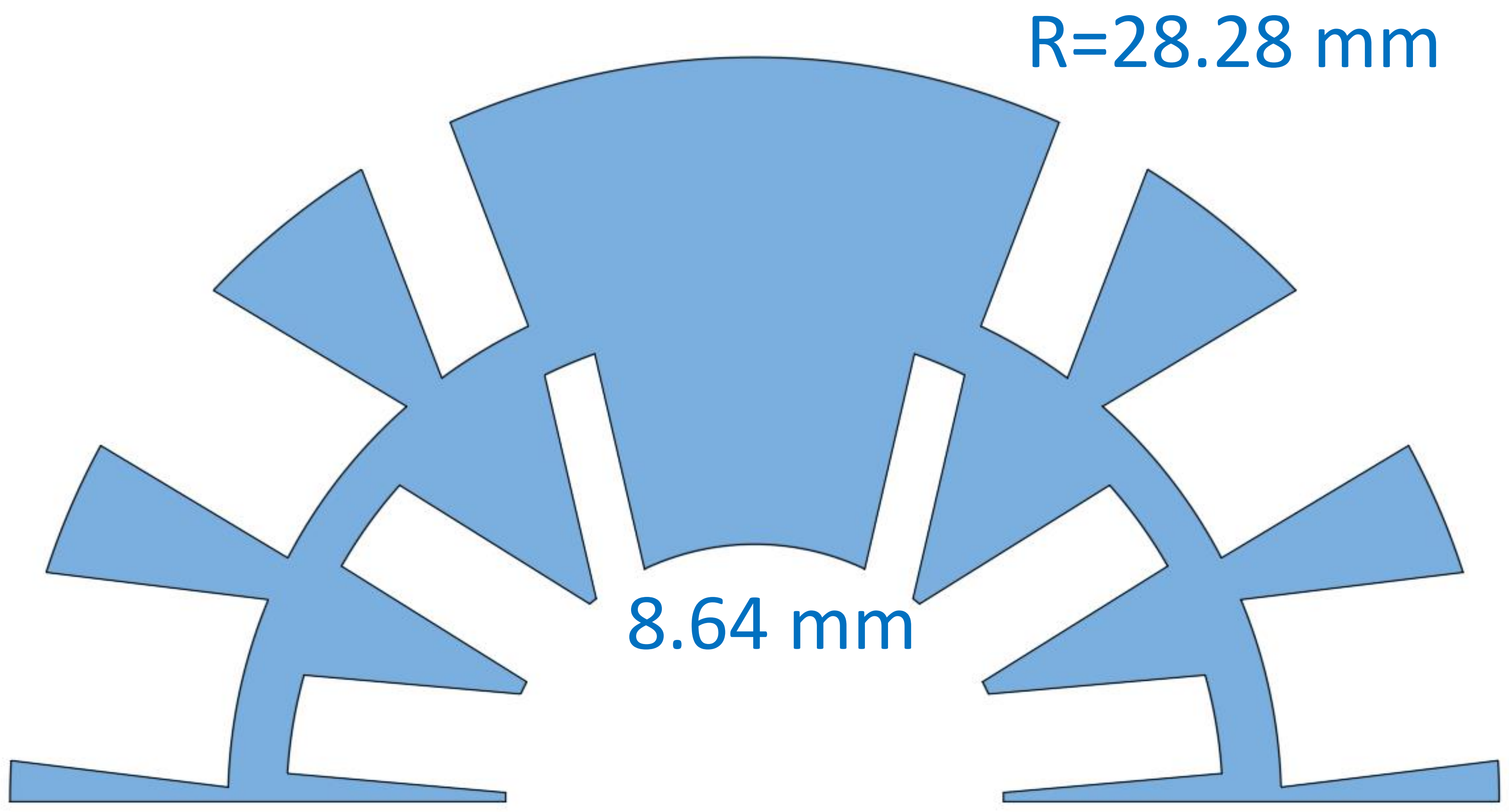
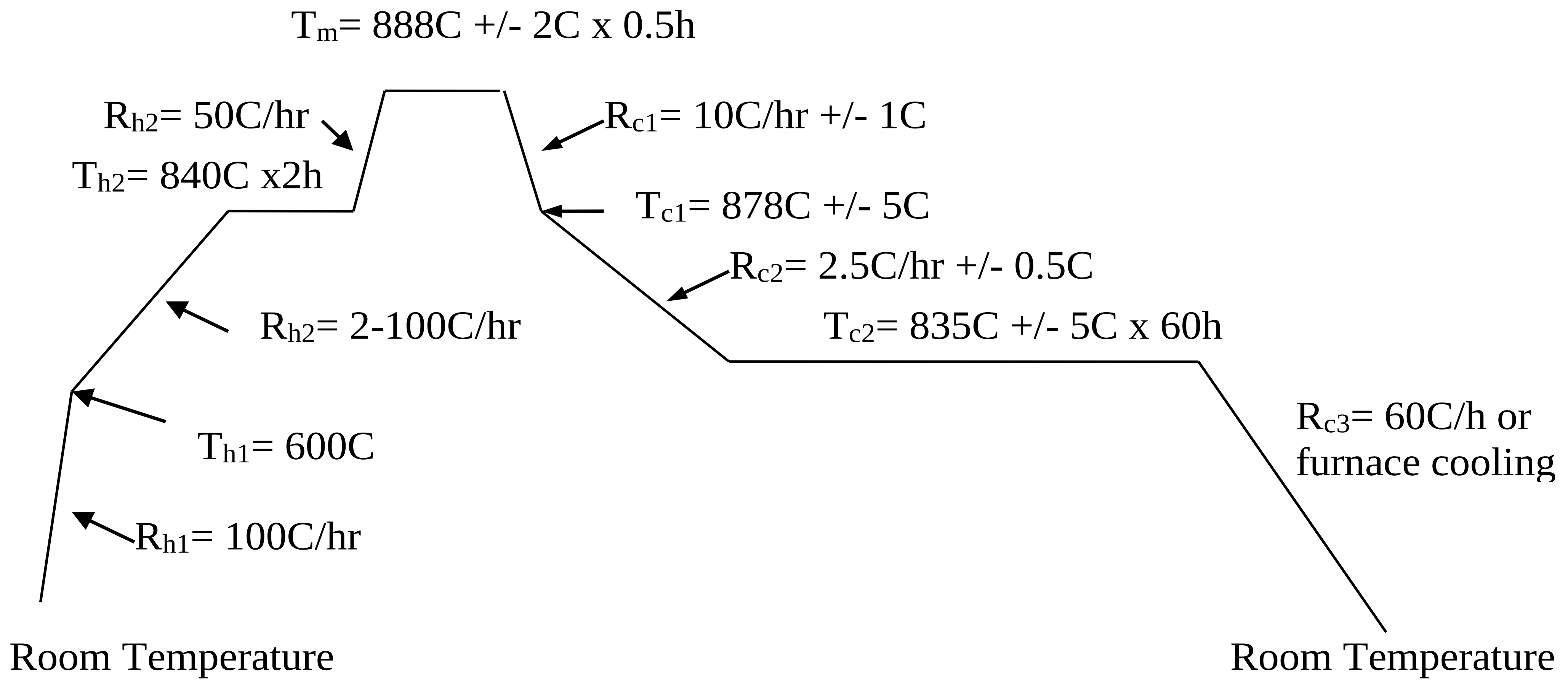
Mechanical design





- One single support structure
- Aperture ID 19 mm
- Coil OD 56.56 mm
- Structure materials to be compatible with HT in Oxygen
- Coil length ~450 mm

Bruker-OST optimized HT for Bi2212 coil at 50 bar O_2 pressure.



Mechanical analysis

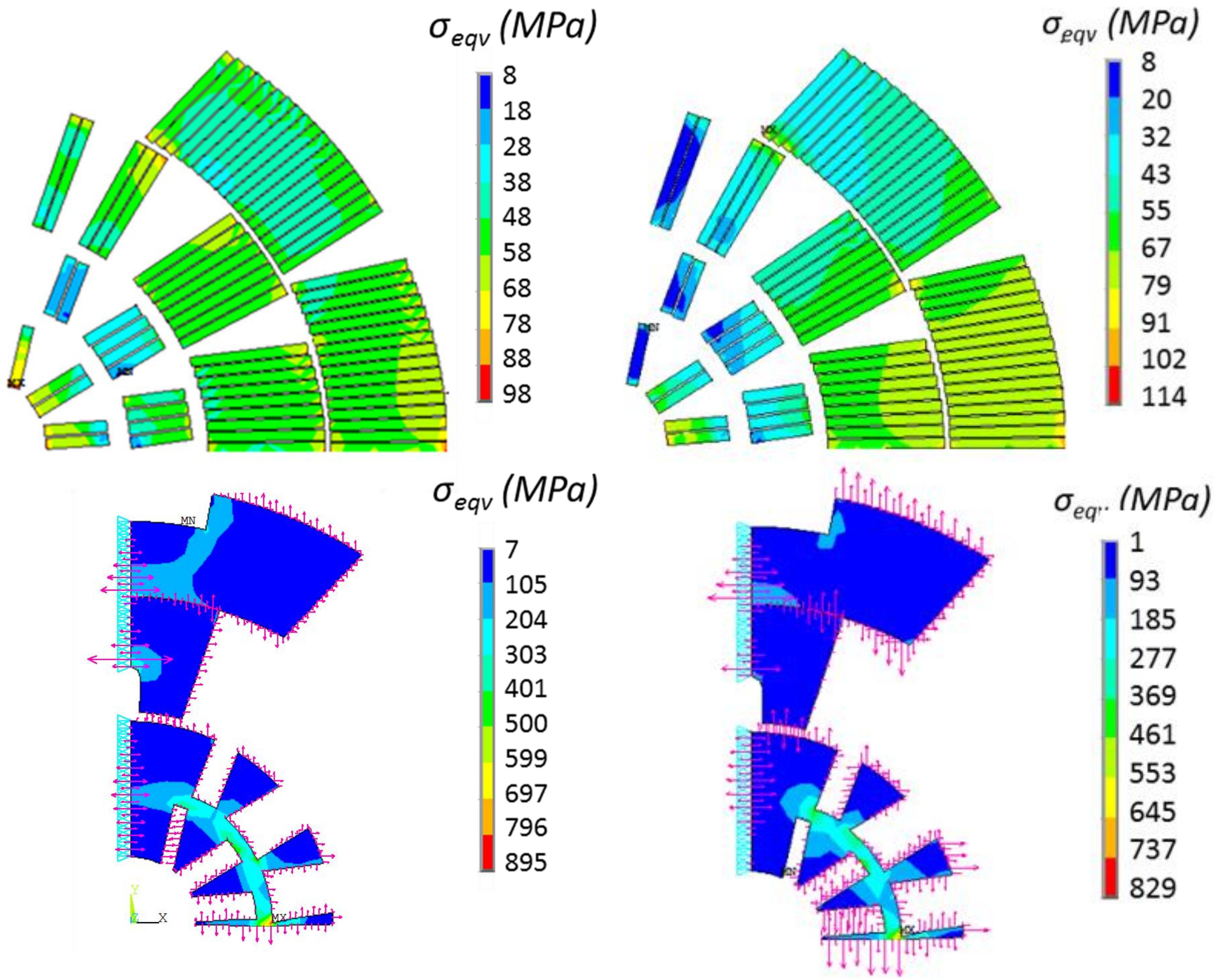
Thermal contraction and cold E-modulus of Bi2212 and Nb_3Sn coil and mirror/dipole structural materials.

	Structural element	Material	Thermal contruct. (300-4K), mm/m	E-modulus (cold), GPa
HTS insert coil	Coil	Bi2212	2.9/3.3*	25/18*
	Structure	Al bronze	3.6	120
		Inconel 718	2.4	219
LTS outsert coil	Coil	Nb_3Sn	2.9/3.3*	40/40*
	Poles/wedge	Ti-6Al-4V	1.7	125
Mirror/dipole structure	Yoke	AISI 1045	2.0	225
	Clamp	Aluminum	4.1	81
	Skin	304L	2.9	210

Max. equivalent stress in Bi2212 and Nb_3Sn coils and coil structural elements in dipole mirror configuration (MPa).

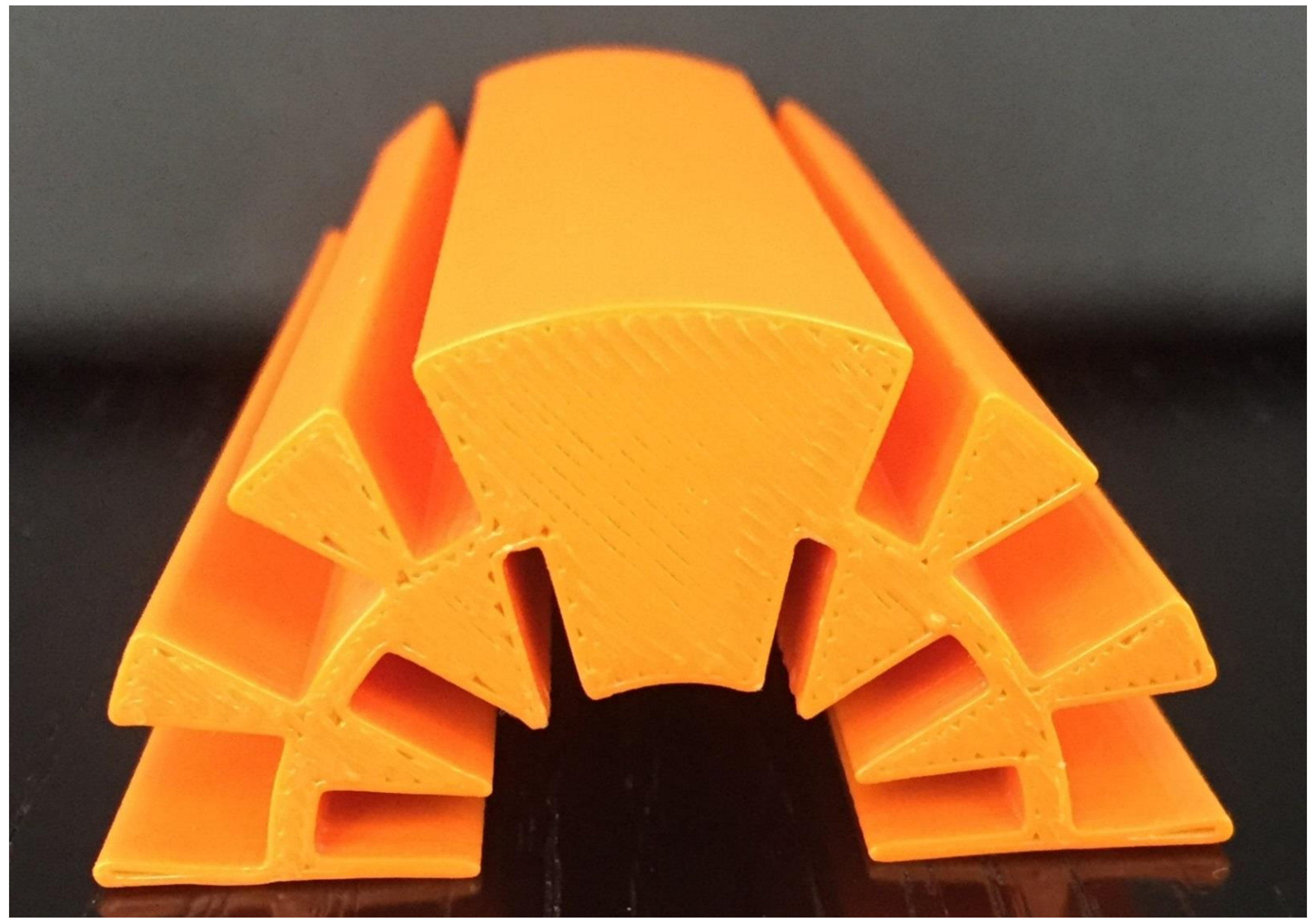
Structural element	Material	Al bronze 0 kA	Al bronze 8 kA	Inconel 718 0 kA	Inconel 718 8 kA
HTS coil structure		283	248	895	829
HTS coil	Bi2212	116	92	96	104
LTS coil	Nb_3Sn	102	121	98	114
LTS pole1	Ti-6Al-4V	487	157	445	131
LTS pole2	Ti-6Al-4V	266	193	269	197

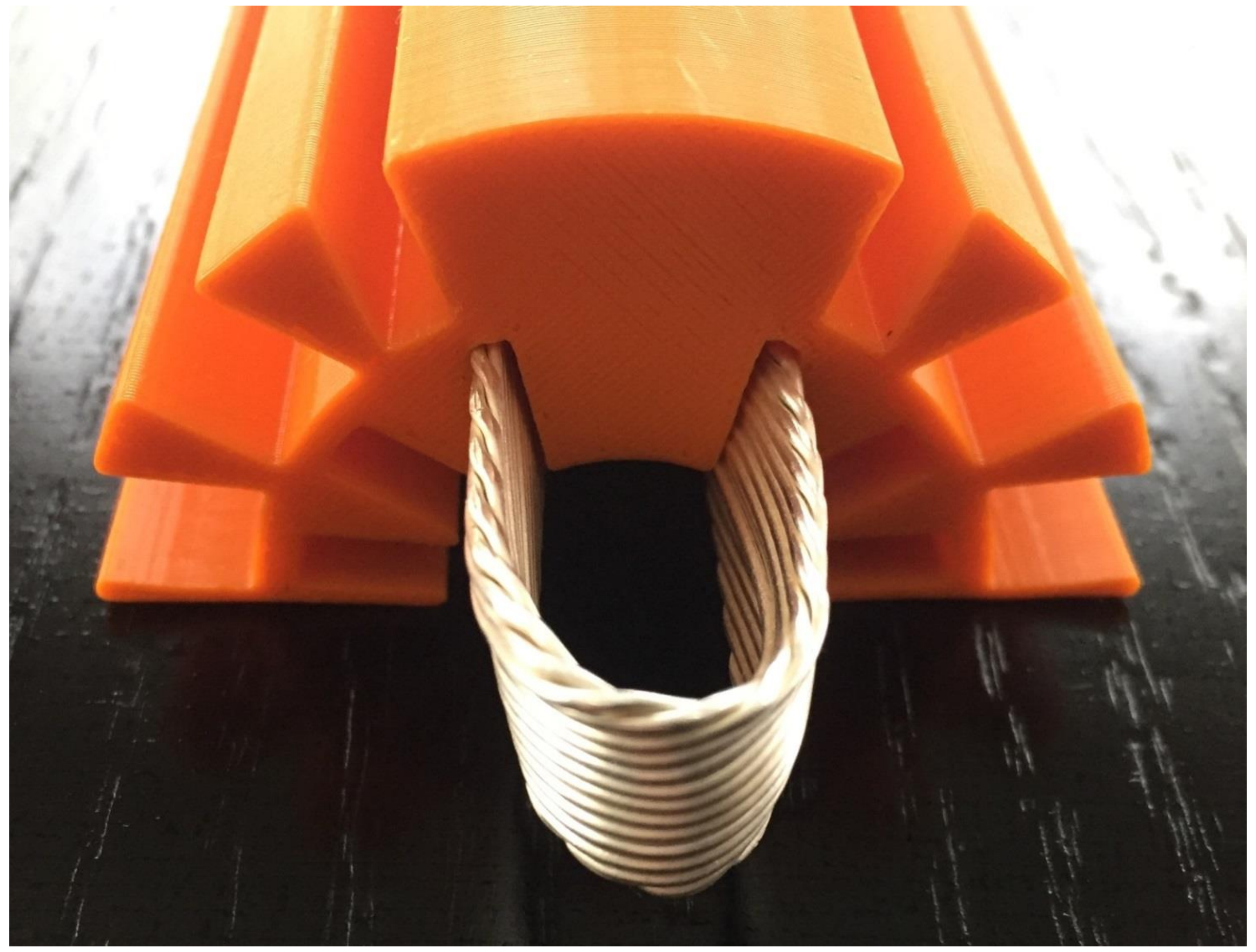
Calculated stress in Bi2212 and Nb_3Sn coils at 0 and 8 kA.

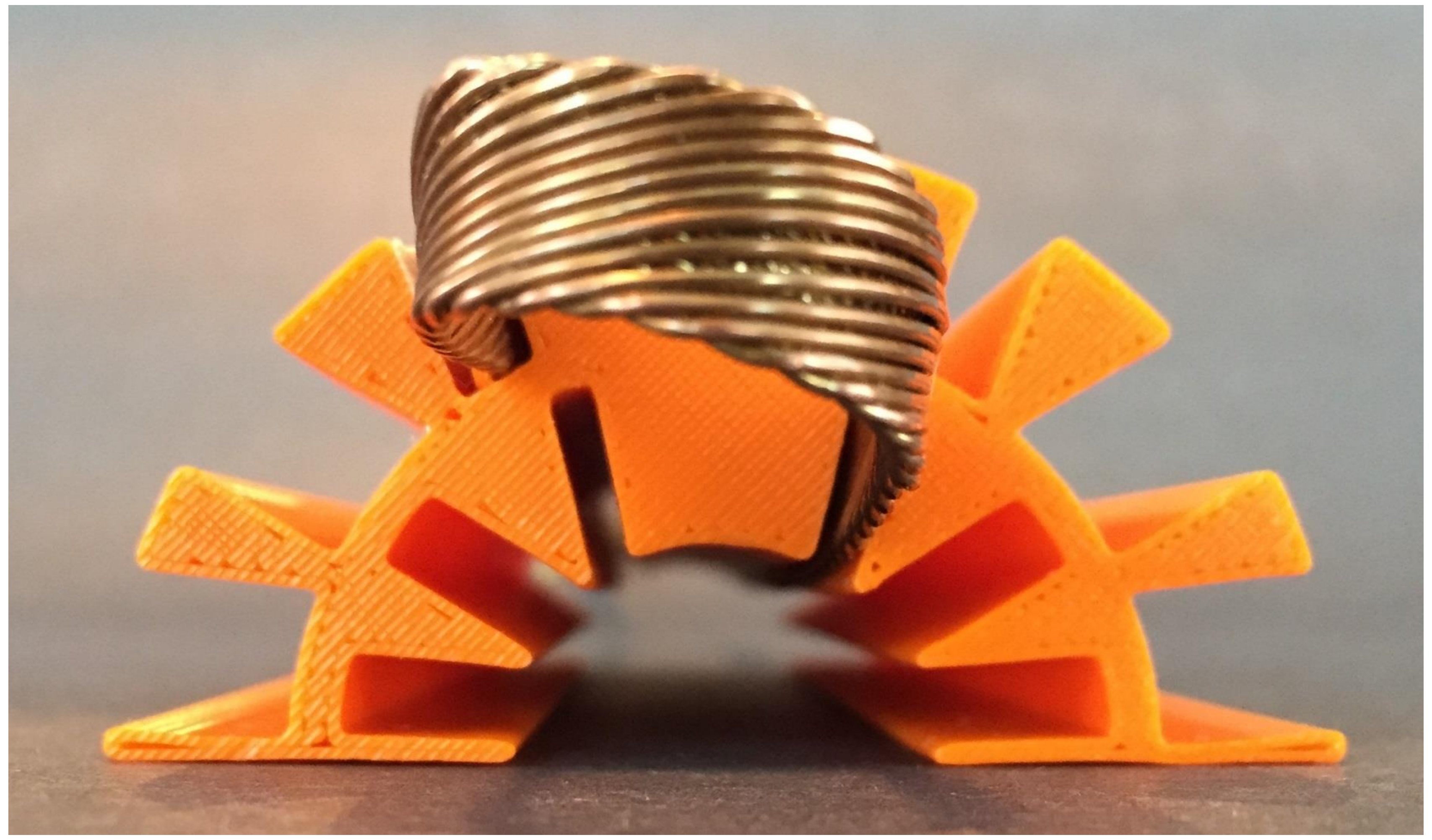


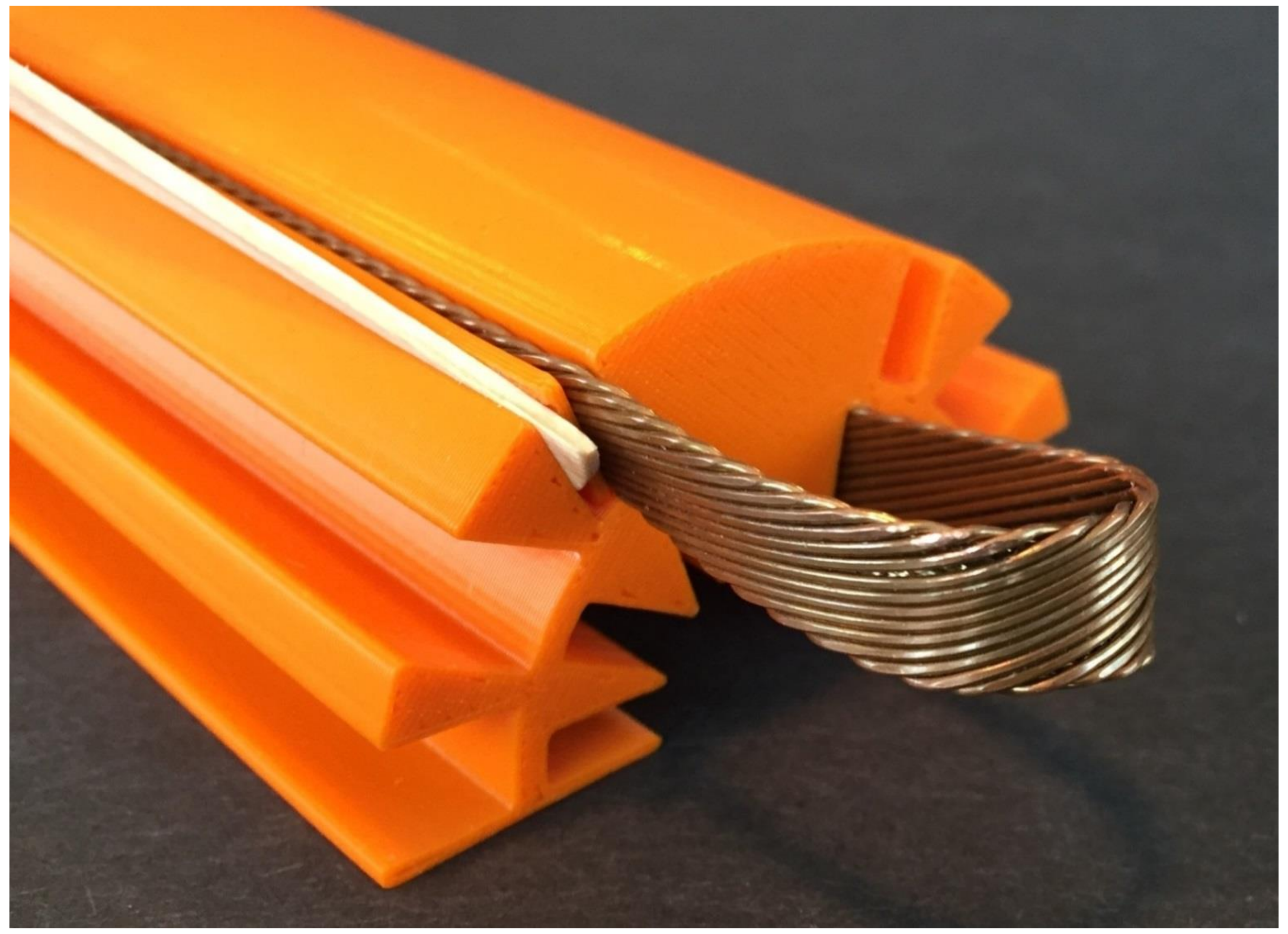
The maximum stress in Bi2212 coil with Inconel 718 structure is achieved at 8 kA and is less than 105 MPa.

Plastic model of Bi2212 coil structure



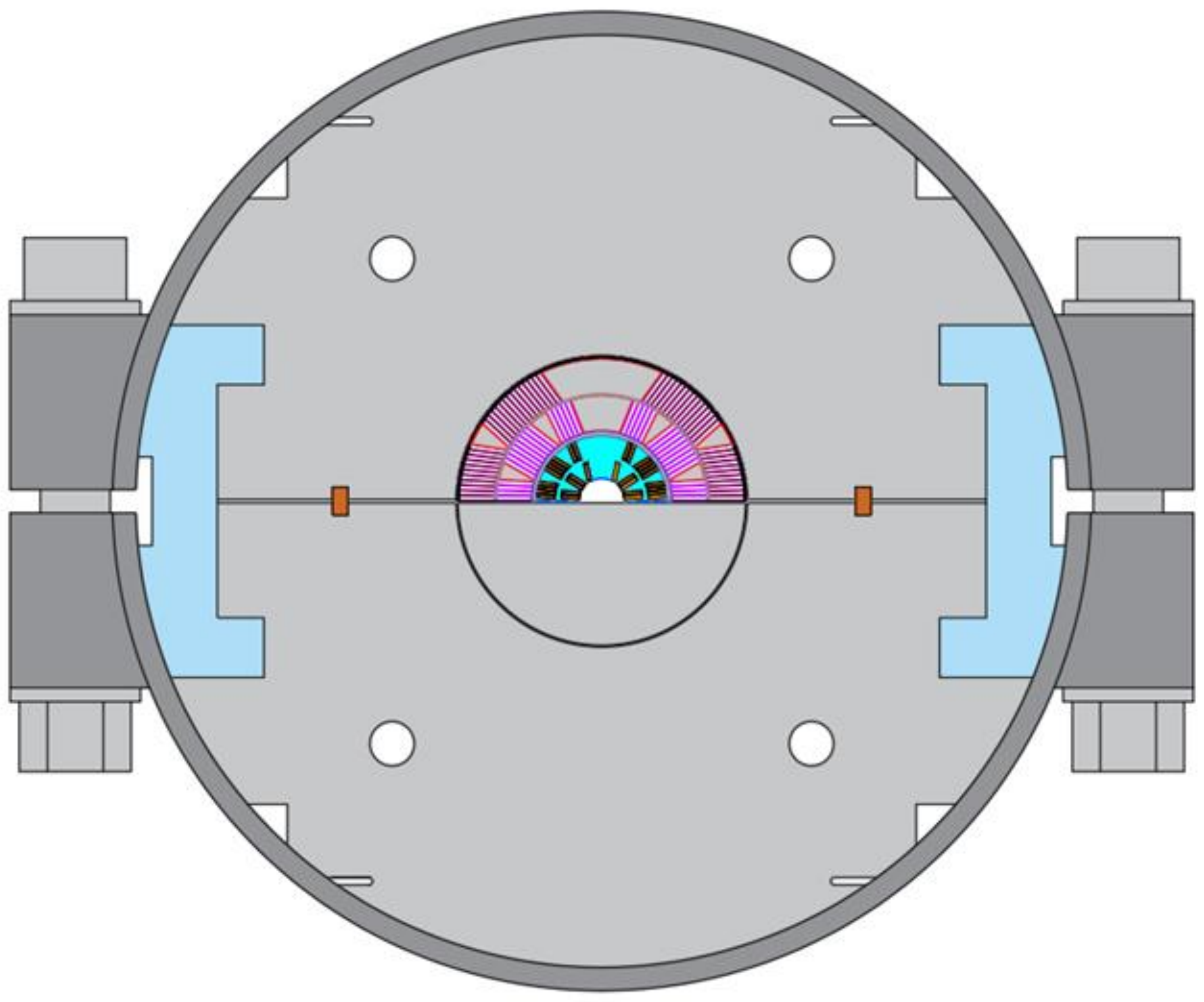




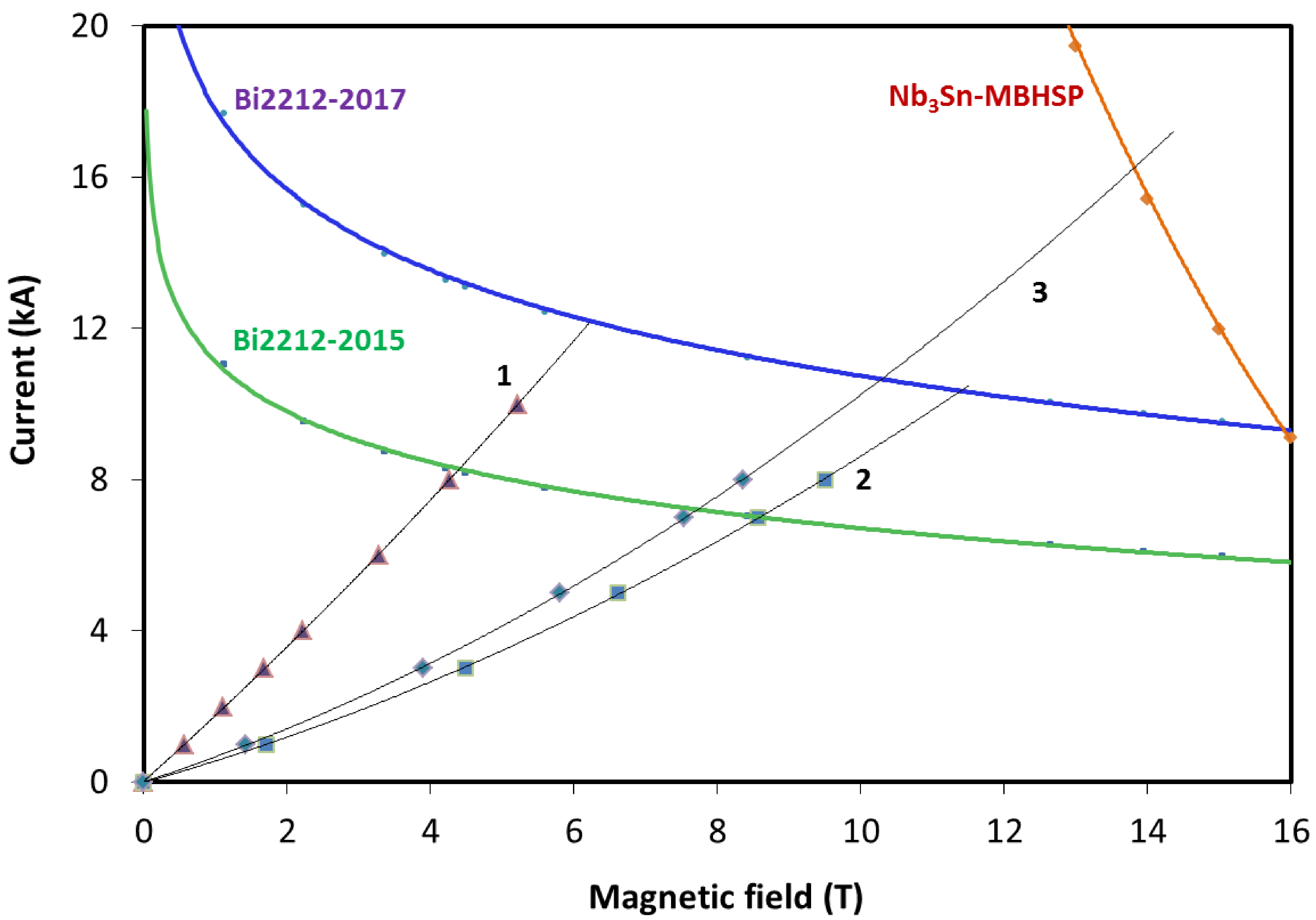


- 3D printed plastic parts
- Practice winding of key turns using Nb_3Sn cable with the same width and slightly smaller thickness
- Objectives:
  - cable bending around small poles
  - layer jump

Bi2212 coil test plan and target parameters



Bi2212 coil in the dipole mirror configuration with 11 T dipole coil
- 1st test single Bi2212 coil
- 2nd test Bi2212 coil in series with Nb_3Sn coil



$I_c(B)$ curves and load lines of Bi2212 (1, 2) and Nb_3Sn (3) coils in various test configurations: 1 – single Bi2212 coil in dipole mirror; 2 – Bi2212 coil in 4-layer hybrid mirror; 3 – Nb_3Sn coil in the 4-layer dipole mirror.

Dipole mirror structure developed at Fermilab and used to test superconducting dipole coils
- no modifications are needed

Conclusions and next steps

- The design of the Bi2212 insert coil and coil support structure were developed and optimized to improve their performance parameters and simplify coil winding and instrumentation.
- For 19 mm aperture it was possible to achieve small values of low-order geometrical field harmonics.
- FEA shows that the maximum stresses in the Bi2212 coil and coil support structure are within the acceptable level for Bi2212 cable and for a support structure made of Inconel 718.
- A plastic model of the coil support structure was printed. Practice winding of the most challenging turns shows that their mechanical stability during winding can be preserved.
- The presented insert design concept, as well as the basic technological solutions, will be studied experimentally on a series of short coils.
- The development of the Bi2212 coil engineering design is in progress. Tests of the first Bi2212 coil in dipole mirror configuration are planned for end of 2022.

Acknowledgment

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