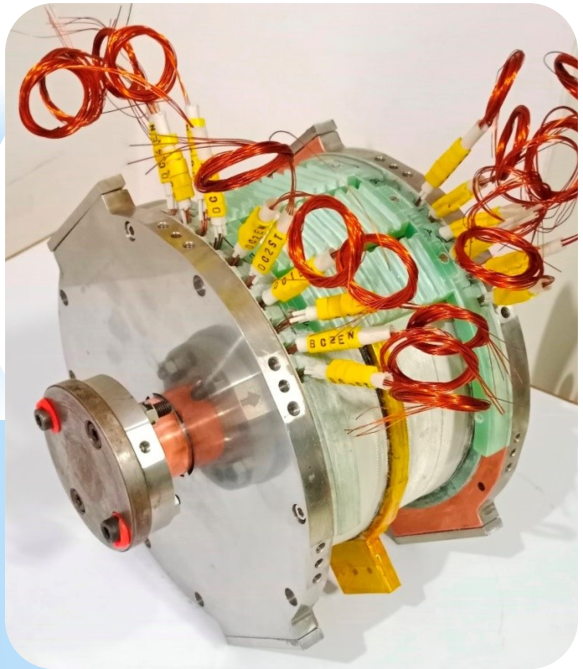
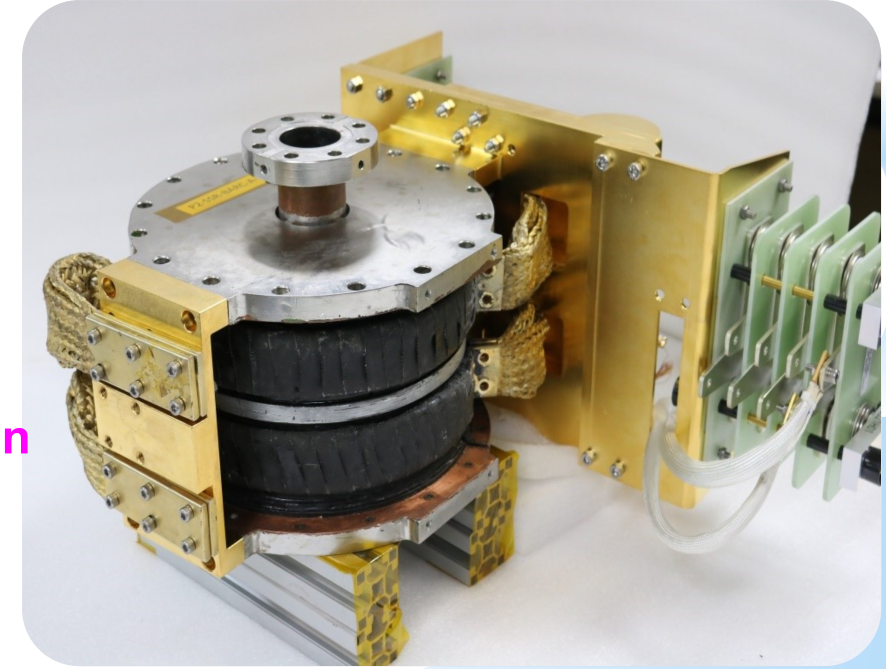
SSR Solenoid Design & Fabrication and pre-series magnet fabrication





Electromagnetic Application & Instrumentation Division

Bhabha Atomic Research Centre

Outline

- Introduction
  - *Functional requirements specifications*
  - *Arrangement of magnet assemblies inside cryomodule*

- SSR magnet design studies
  - *Electromagnetic Design*
  - *Bucking coil optimization & tolerance studies on BC dimensions*
  - *Quench studies & Thermal design*
  - *EM Forces*

- SSR magnet development
  - *Engineering design and fabrication*
  - *Coil Winding*
  - *Magnet termination and quench protection diode*
  - *Development stages*

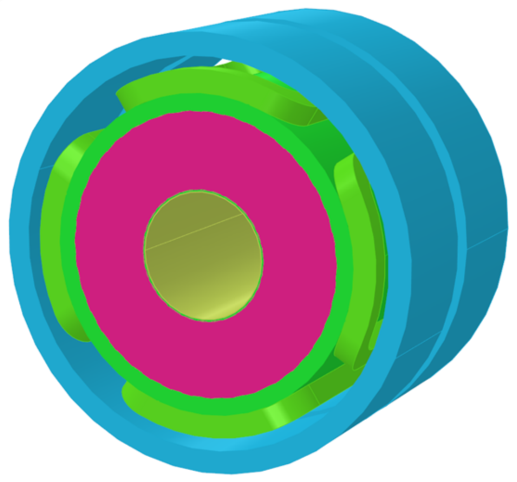
- Summary

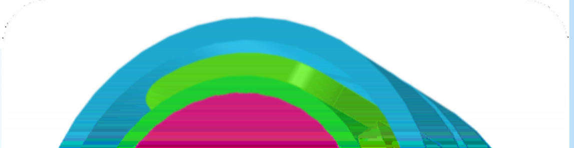
Functional Requirement Specifications (FRS)

Parameters	Specification
Focusing Strength	4.5 T^2m
Bending strength of Dipole correctors	5 mT-m
Beam pipe aperture	40 mm
Uncertainty in the location of magnetic axis w.r.t Reference points (Transverse and angular alignment)	<0.1mm RMS <0.5 mrad RMS
Effective length of solenoid (FWHM)	Insertion length of Max 180mm
Active magnetic shielding requirements (derived by expt. on spoke cavities at FNAL)	~ <10G
Maximum current in the solenoid	100A
Maximum current in the dipole correctors	50 A

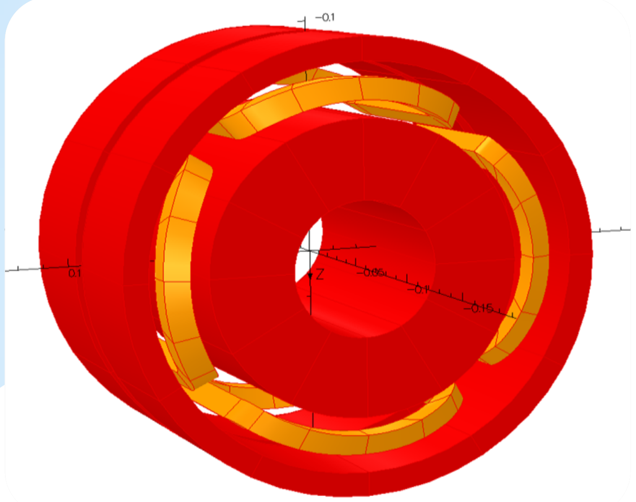
Primary Design objectives:

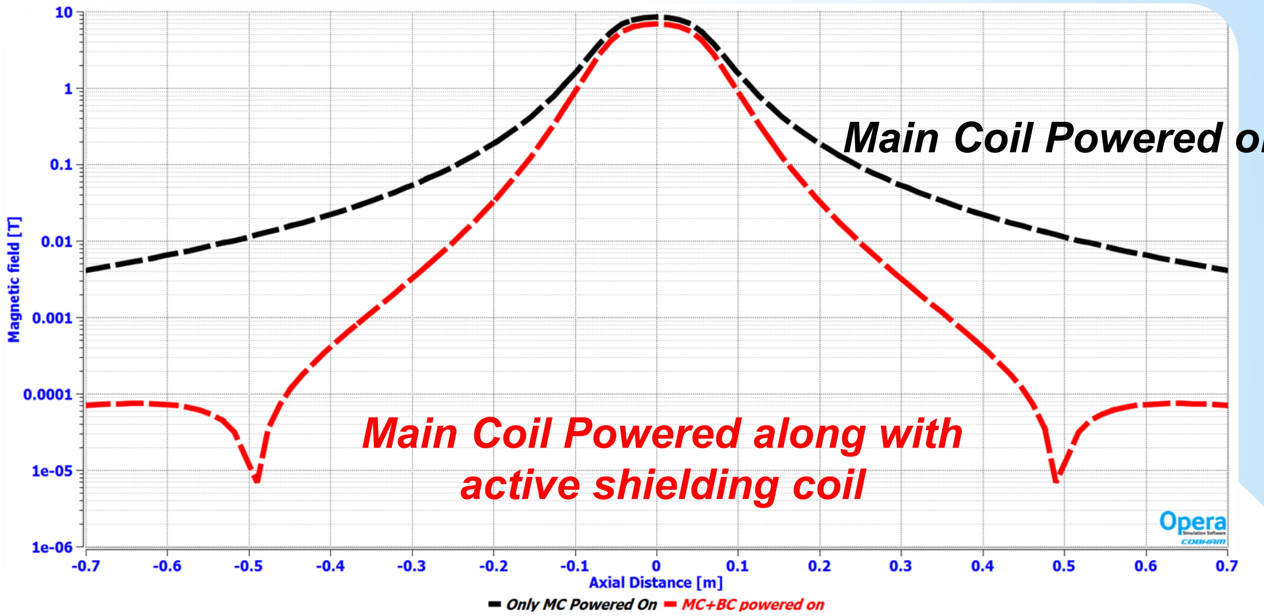
- ***High Field (focusing strength)***
- ***Low stray field as fringe field level on the adjacent spoke cavity surface is a major concern.***
- ***Dipole field and skew quadrupole field coils incorporated in the same magnet package.***





Electromagnetic Design of Main Solenoid





Bmod field vs axial distance plot

Objective function :

$\int B_z^2 . dz \geq 4.5\ T^2m$

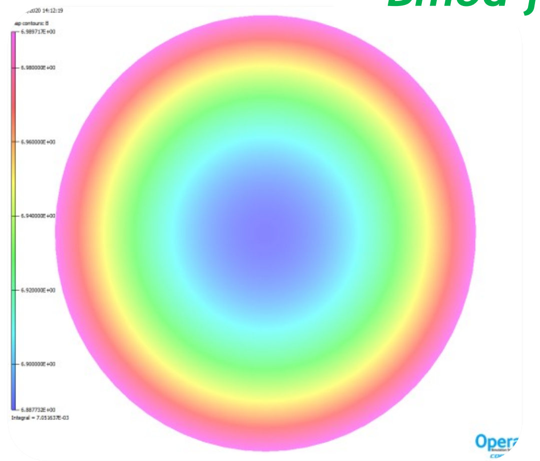
Minimize $\int^{r=0.3} B.dl$ at z= 0.5m cavity location

Constraints:

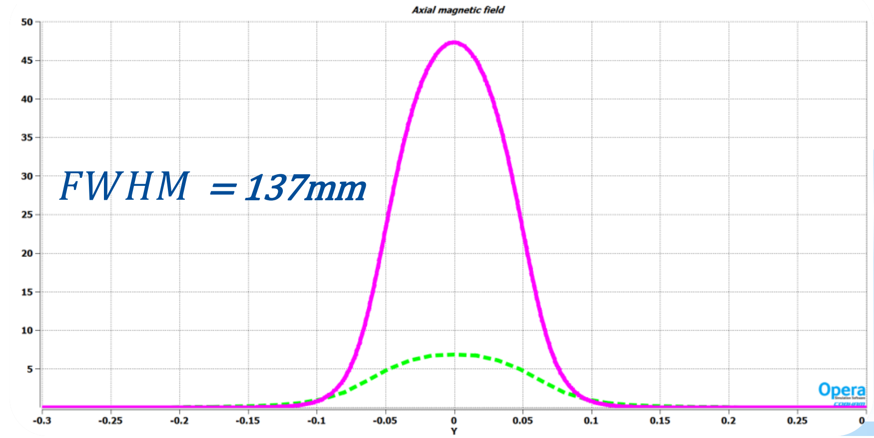
$\frac{\int (B_z * dz)}{B_0} \leq 150$ cm ; $I_{exc} < 100$A

Optimization Parameters:

N_{main}, OR_{main}, IR_{main}, IR_{BC}, OR_{BC} L_{BC}, $Z_{center-BC}$

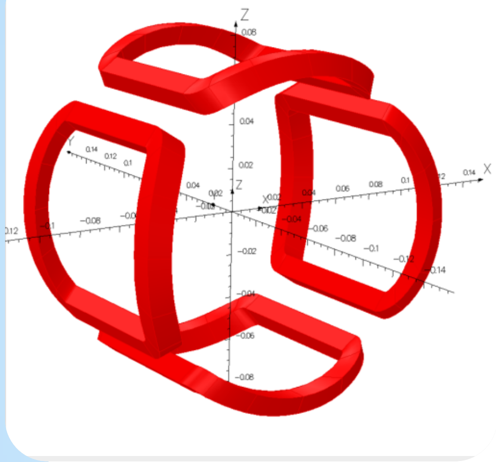


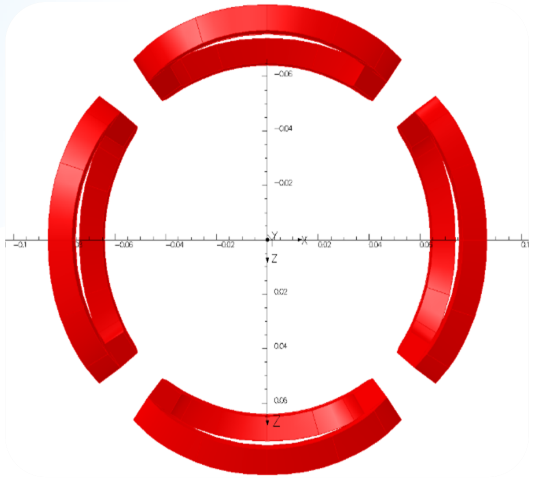
Field homogeneity 1.4% @ r=18 mm

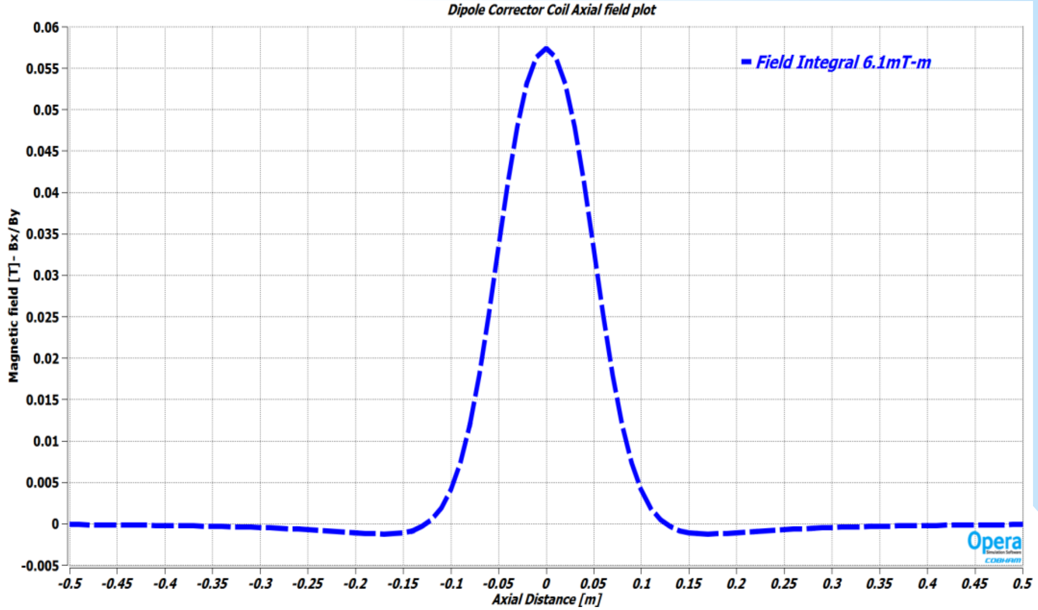


B field plot & B^2 Plot along the axial length

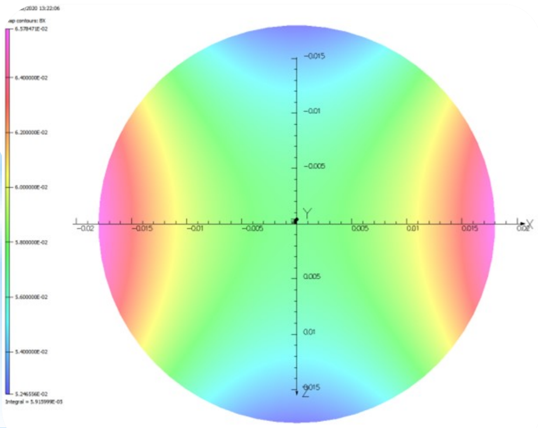
Dipole corrector design



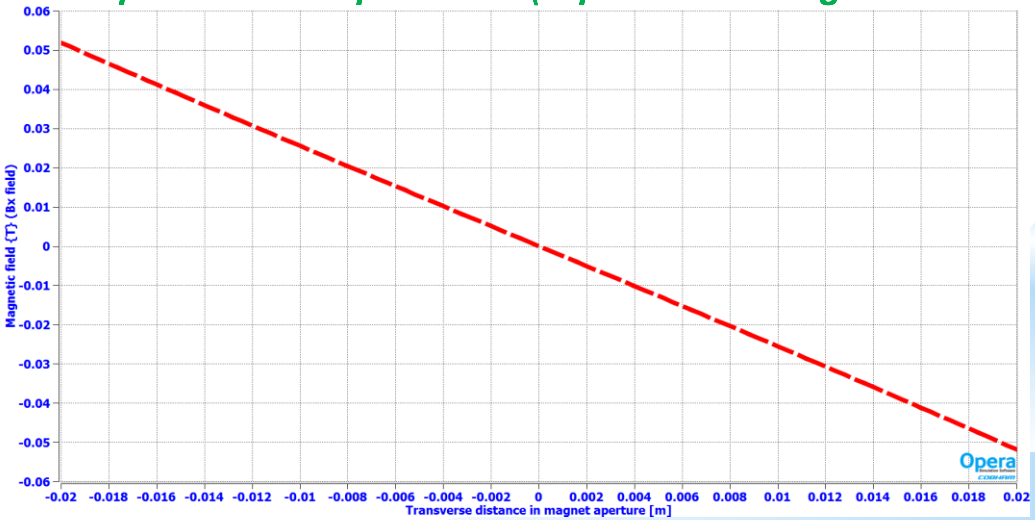




Magnetic Field plot for the dipole field (Dipole field Integral 6.1 mT-m)



Bending strength req. : 5 mT-m
Achieved : 6.1 mT-m
Gradient in Quad mode : 2.6T/m



Bx field plot vs radial distance in magnet aperture (Gradient = 2.59T/m)

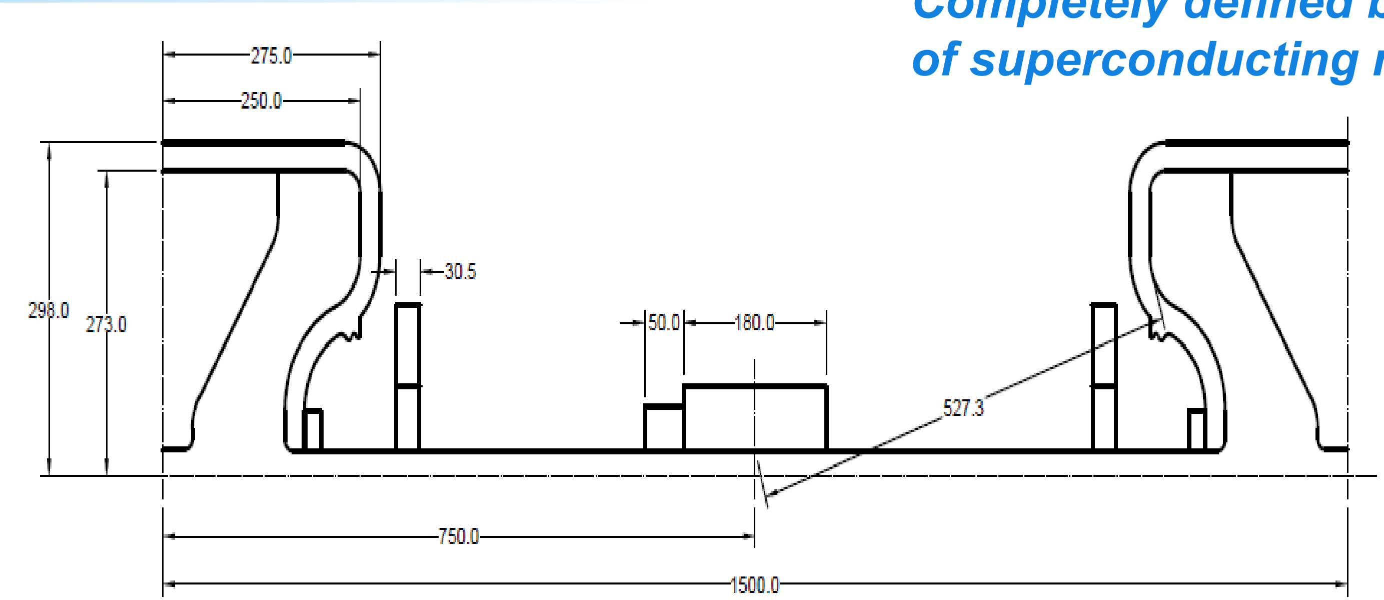
Fringe field on cavity surface

Completely defined by the properties of superconducting material

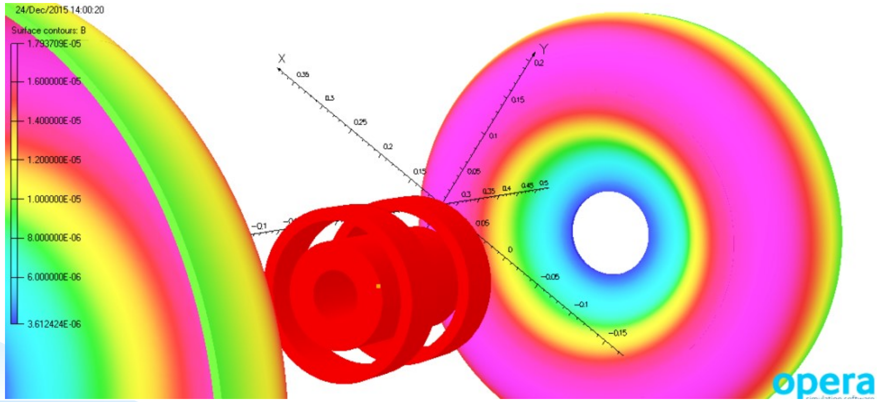
Cavity Specific

$$\Phi_{tr} = \frac{2\mu_0\Phi_0}{(Rs\cdot \xi_0^2)} * \frac{f\cdot V}{(\Lambda Q_0)} * \frac{(1-\eta)}{\eta}$$

Acceptable degree of degradation η with allowed amount of the trapped flux.



Placement of a focusing lens inside the SSR



$\mu_0=4\pi\cdot10^{-7}$H/m ; $\Phi_0=2\cdot10^{-15}$Wb

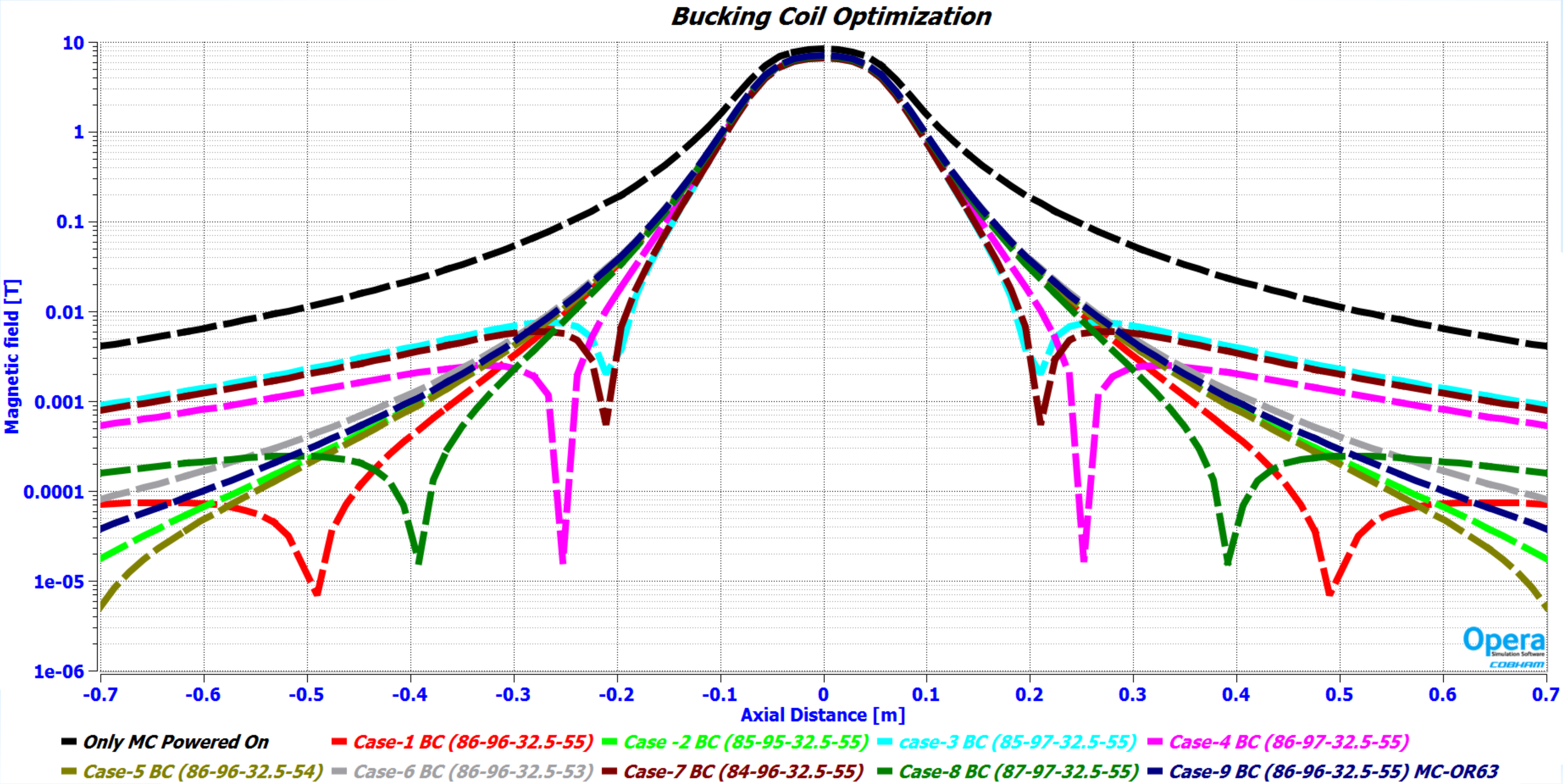
$\xi_0=3.9\cdot10^{-8}$ m is the coherent length in Nb, f is the frequency of the cavity,

Rs is the surface resistance of Nb at this frequency,

V is the volume of the cavity,

$$\Lambda = \frac{\text{Magnetic energy density at the location of the quench}}{\text{Average energy density in the cavity}}$$

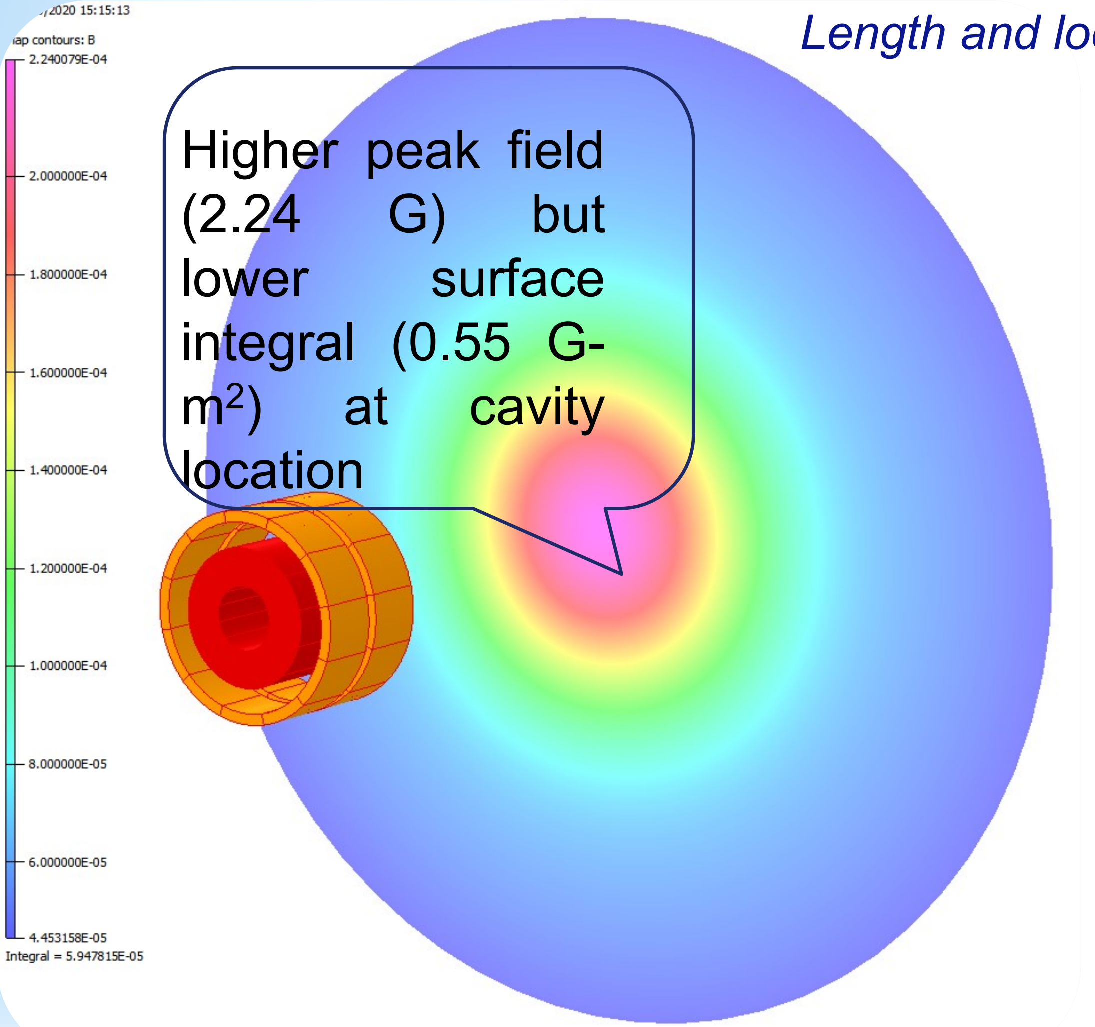
Surface integral / line integral at the maximum magnetic energy density location needs to be minimized during the design of bucking coil



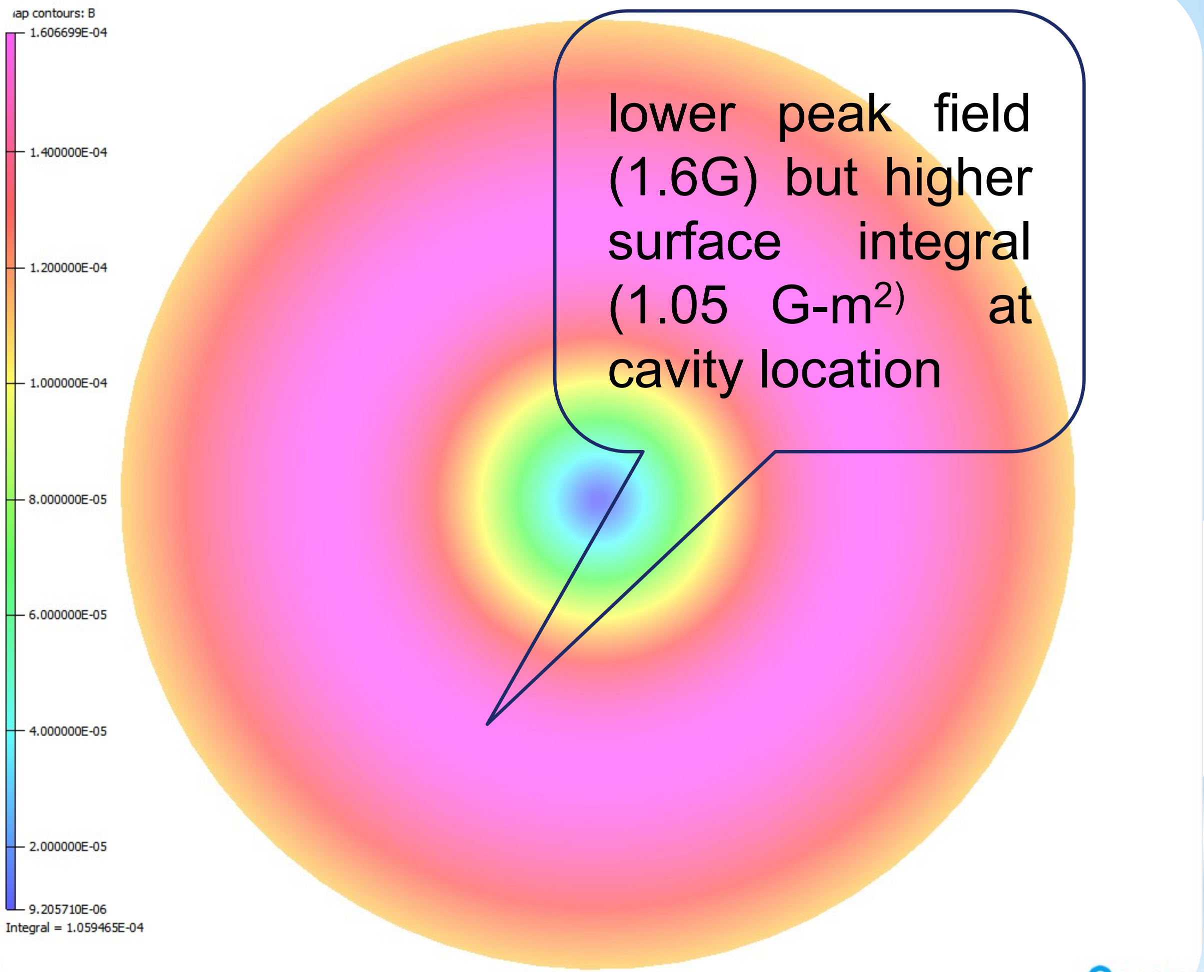
B field vs axial distance plot for different cases of Bucking coil

Fringe field on cavity surface

Length and location w.r.t main coil is same for the cases



Higher peak field (2.24 G) but lower surface integral (0.55 G-m^2) at cavity location

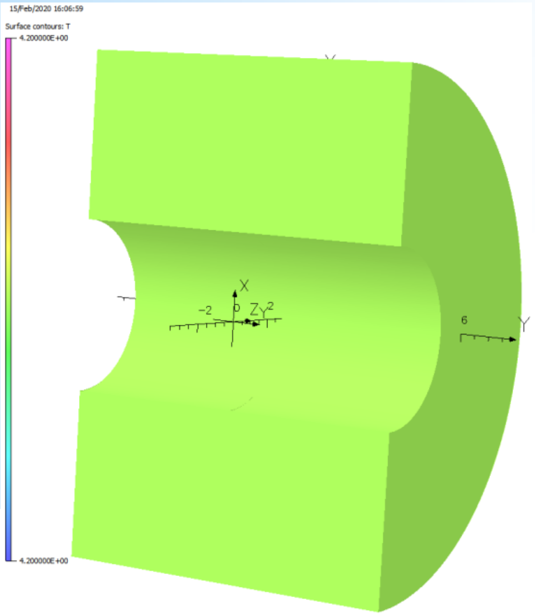


lower peak field (1.6G) but higher surface integral (1.05 G-m^2) at cavity location

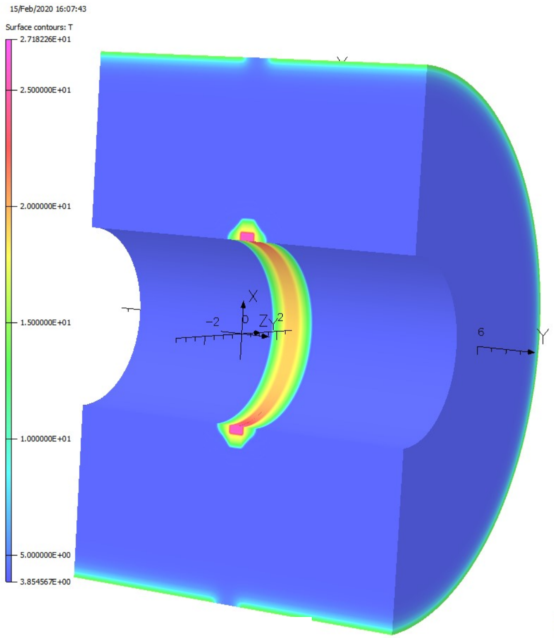
Case 1: BC IR = 85mm ; BC OR = 95 mm √

Case 2: BC IR = 86mm ; BC OR = 96 mm X

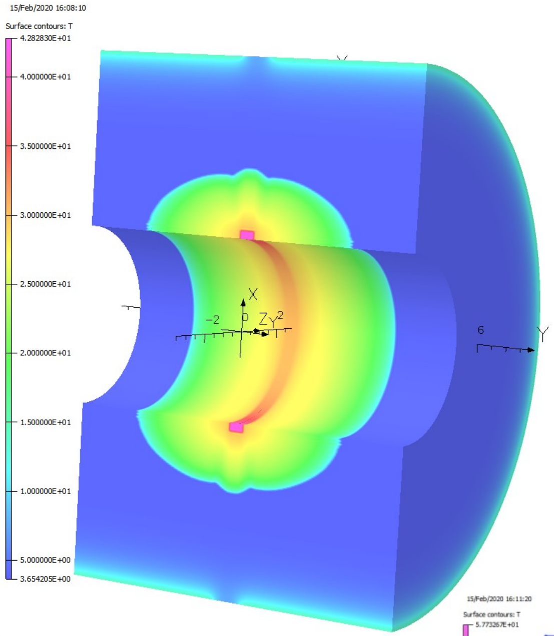
Quench Studies (Quench initiated in main coil)



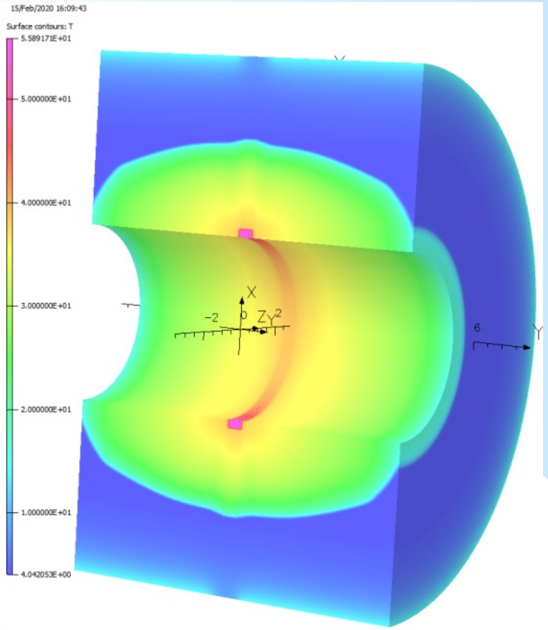
At t = 0s



At t = 0.01s



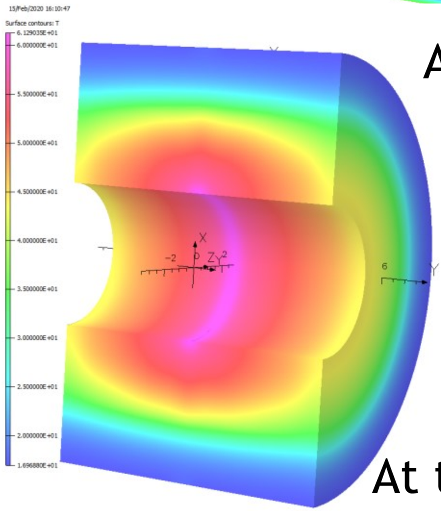
At t = 0.1s



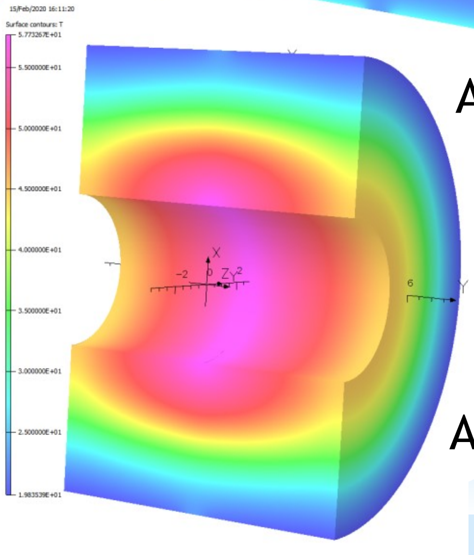
At t = 0.4s

Flux initiated by ~4W of heat deposition at peak B field location

To study peak temperature & peak coil voltages



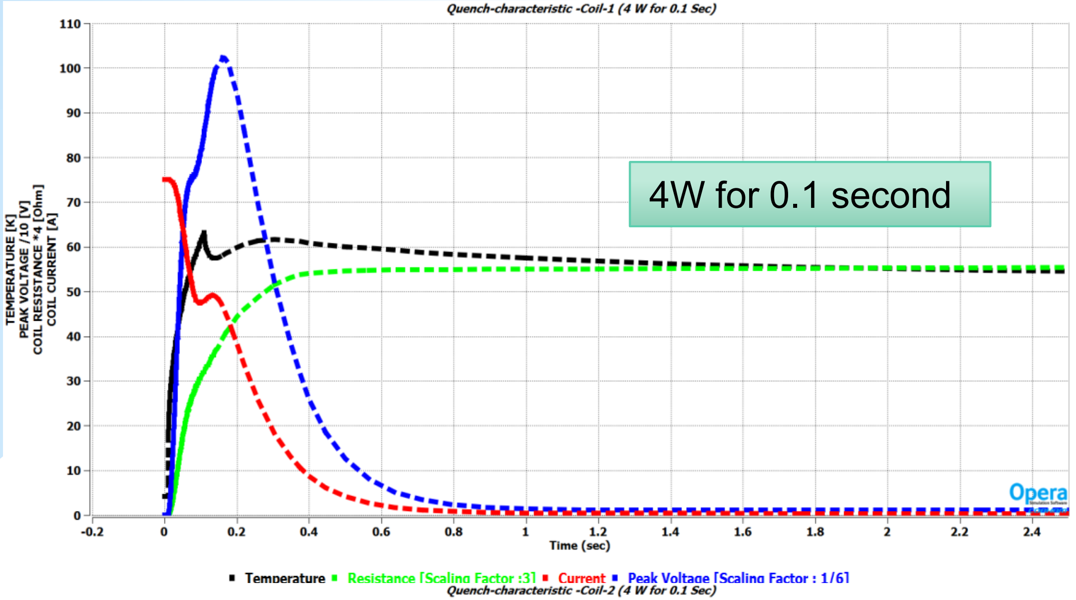
At t = 5s

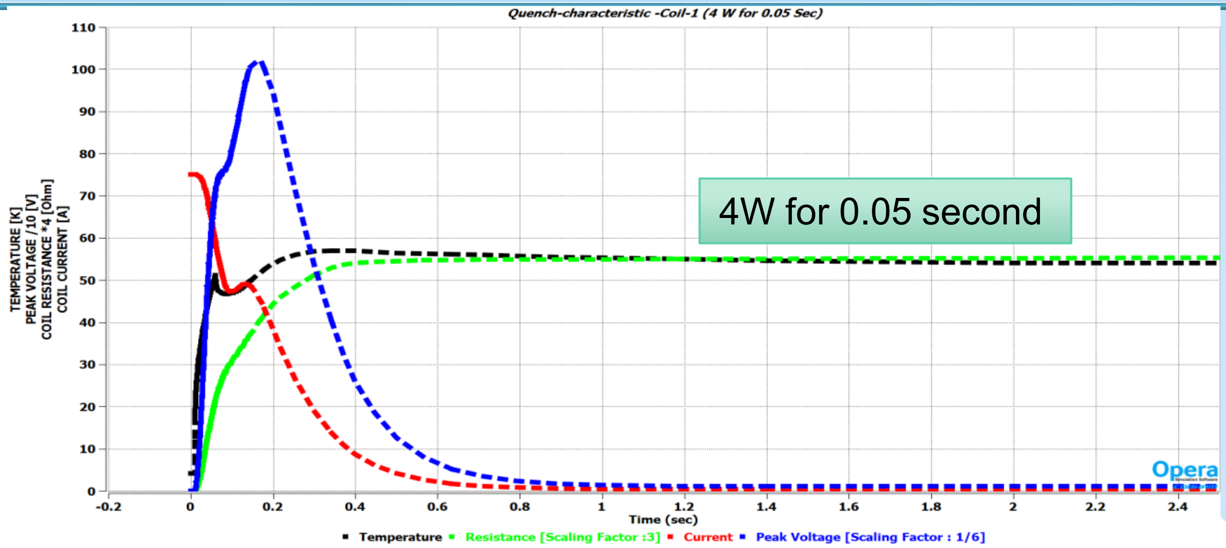


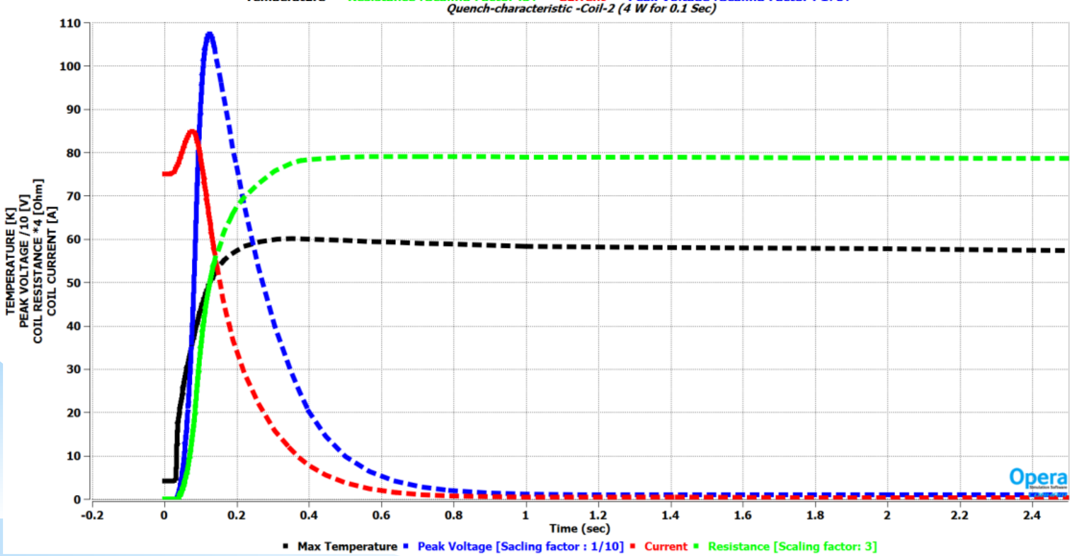
At t = 20s

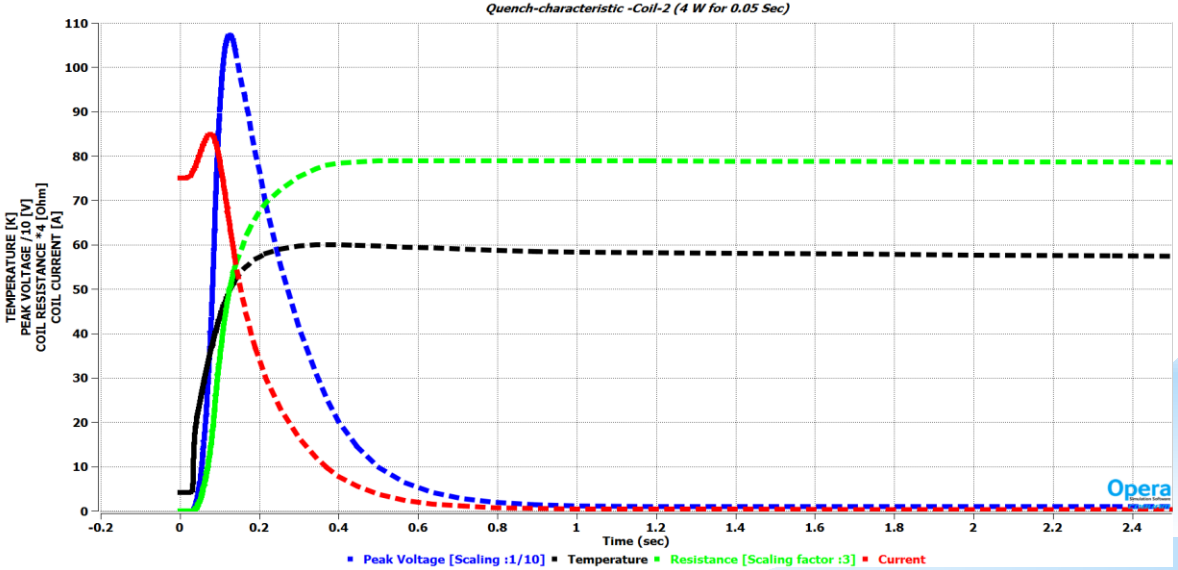
Quench Design (Variation in heat pulse)

Quench Characteristic for two coils sub-sections of main coil



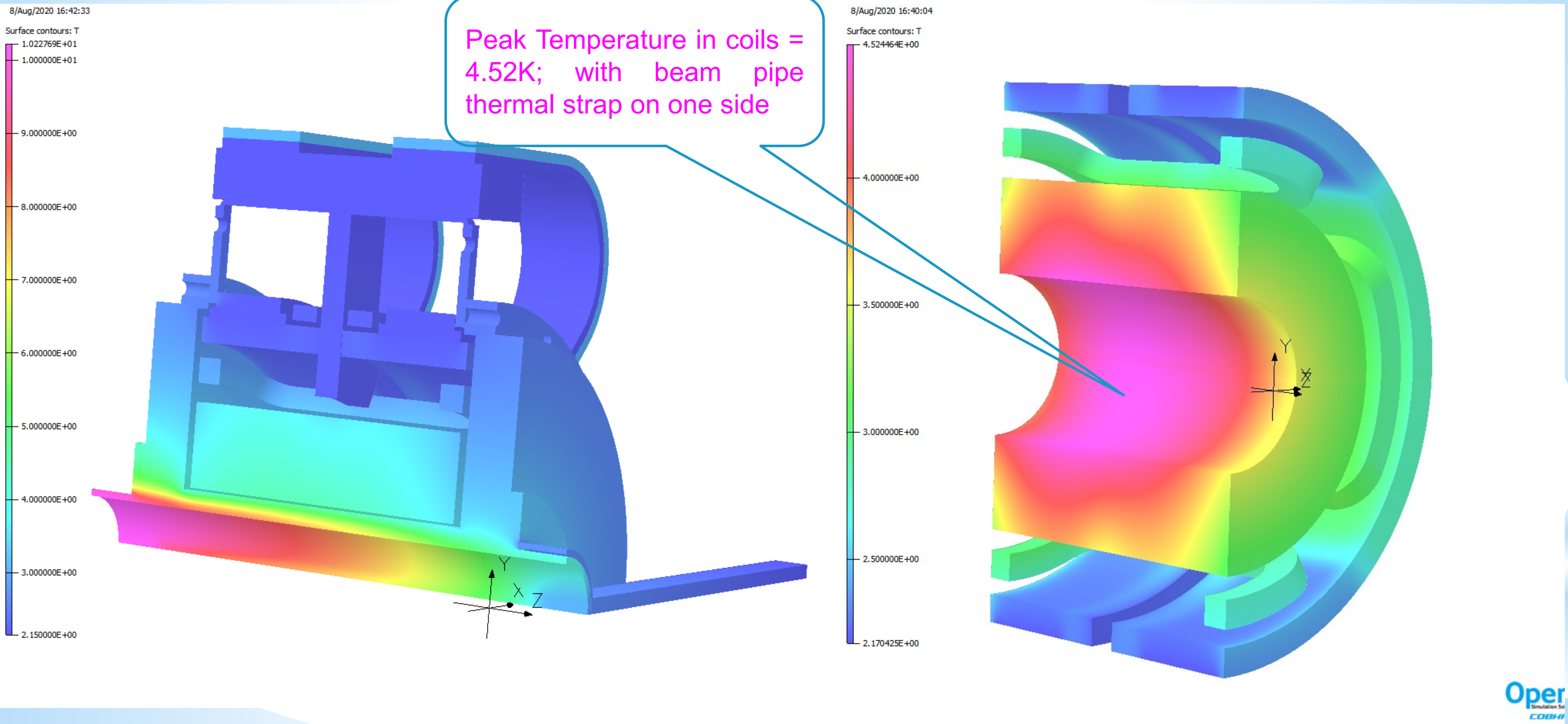




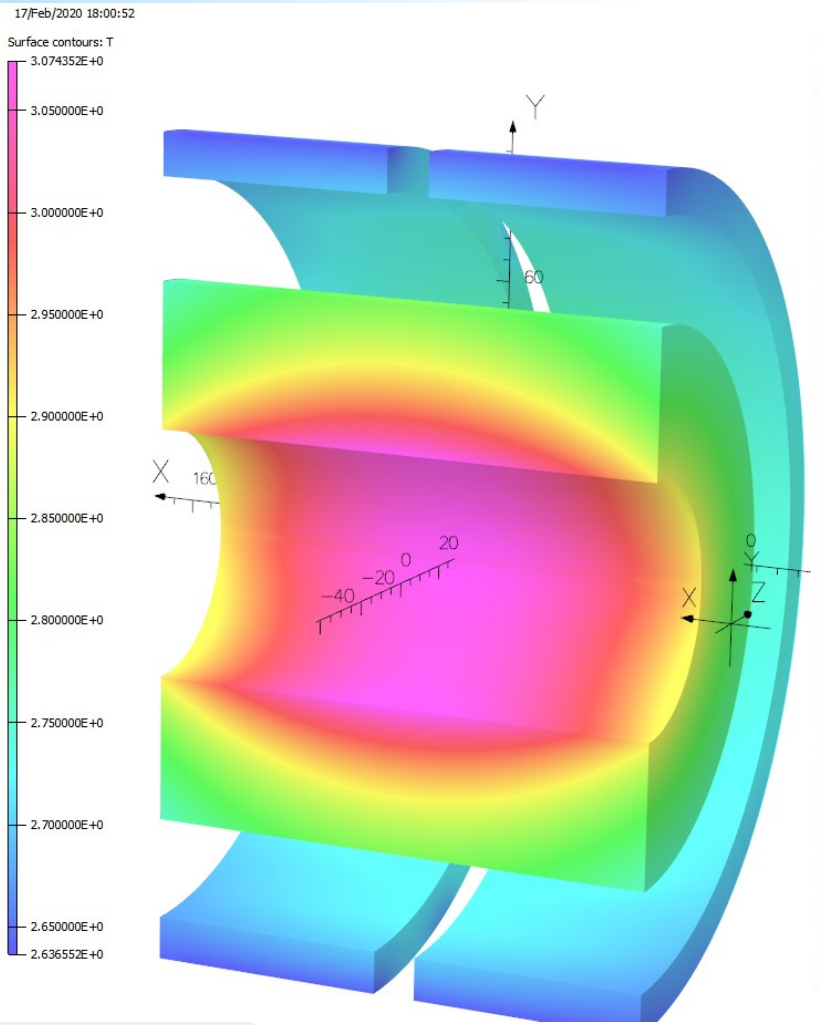


Dedicated beam pipe thermal strap for limiting peak temperatures

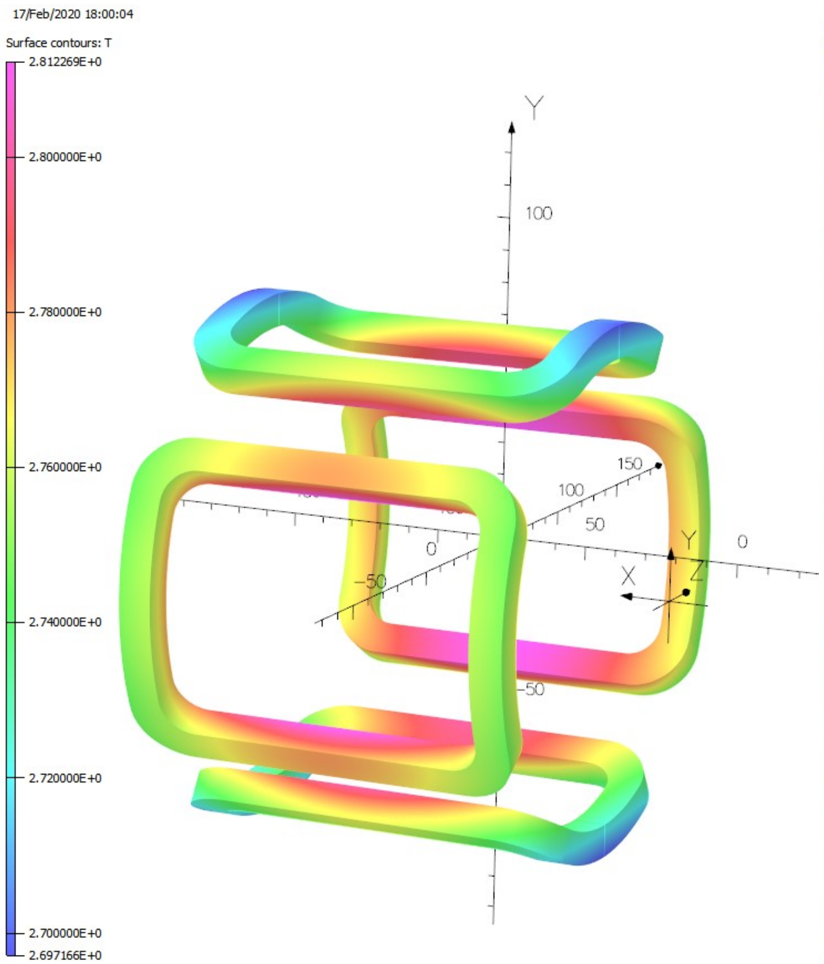
Peak Temperature in coils = 4.52K; with beam pipe thermal strap on one side



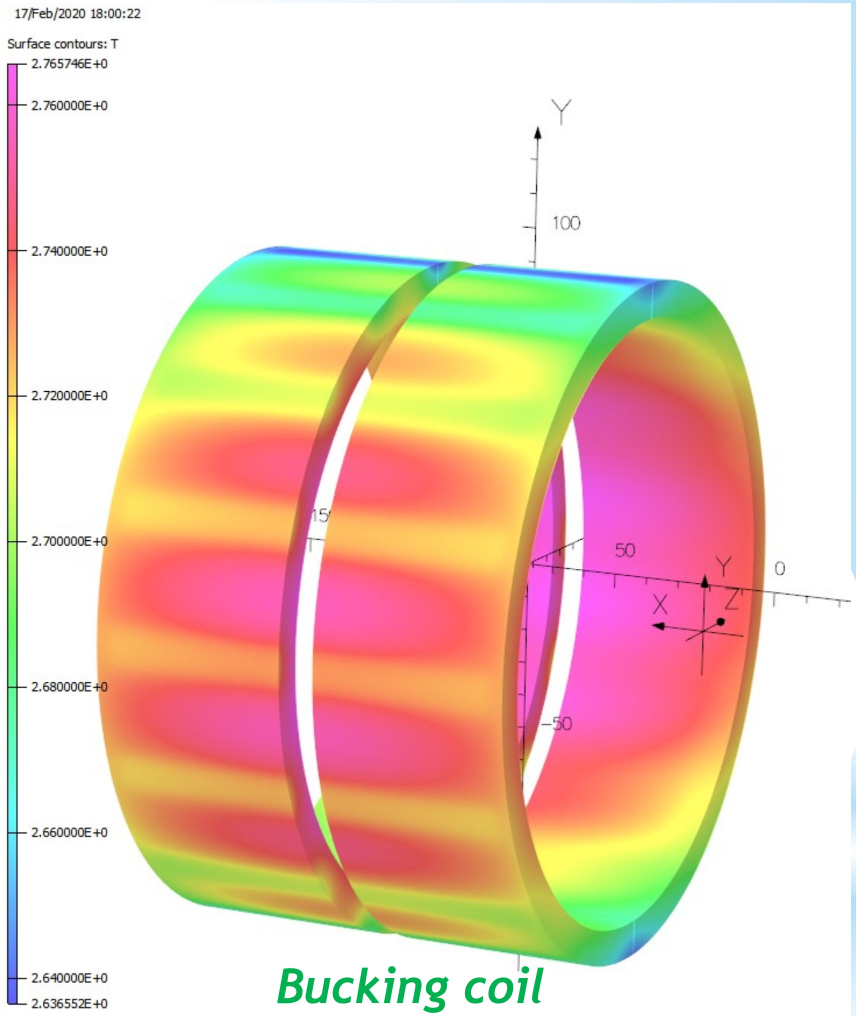
Peak temperature in coils



Main coil

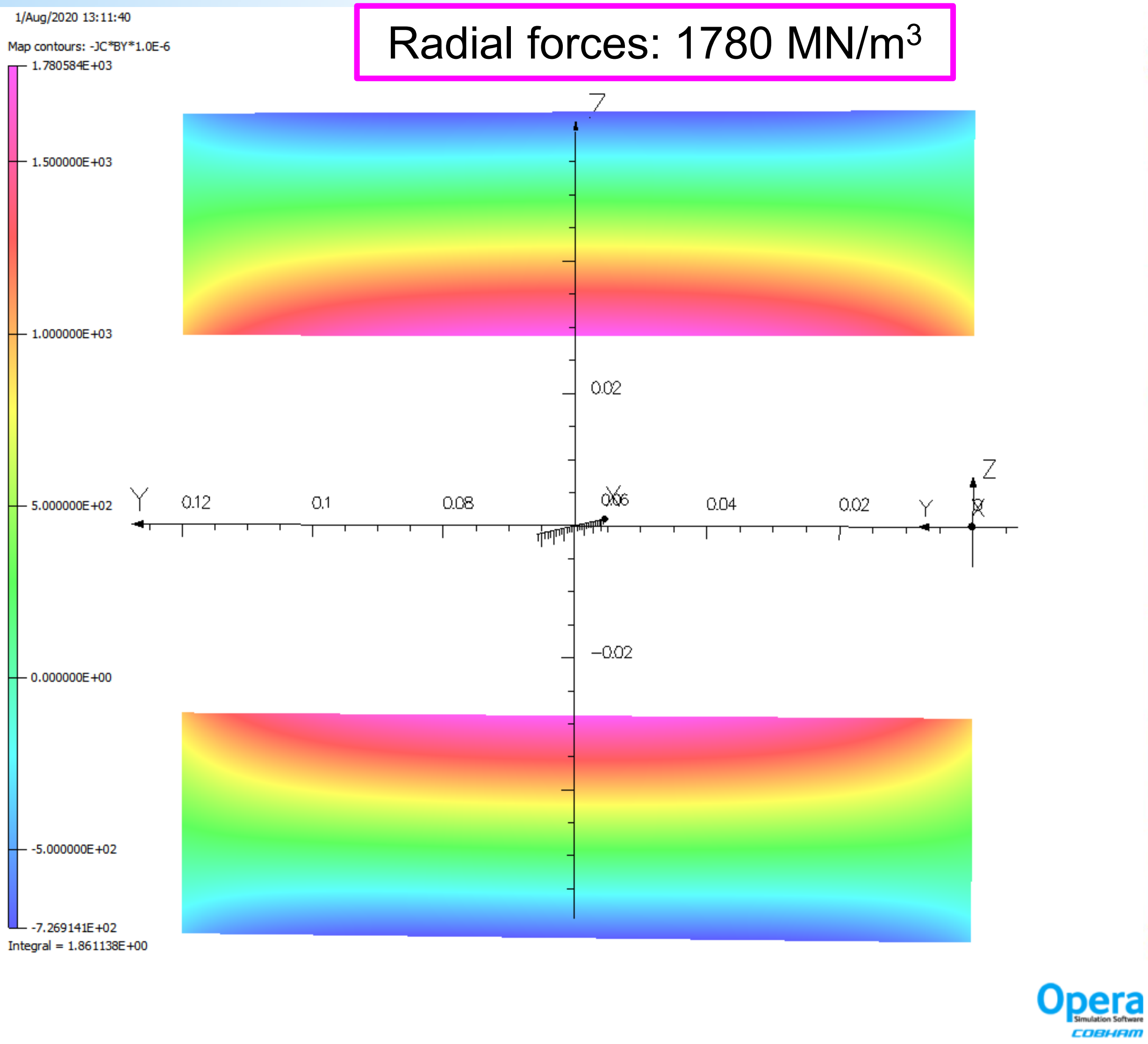


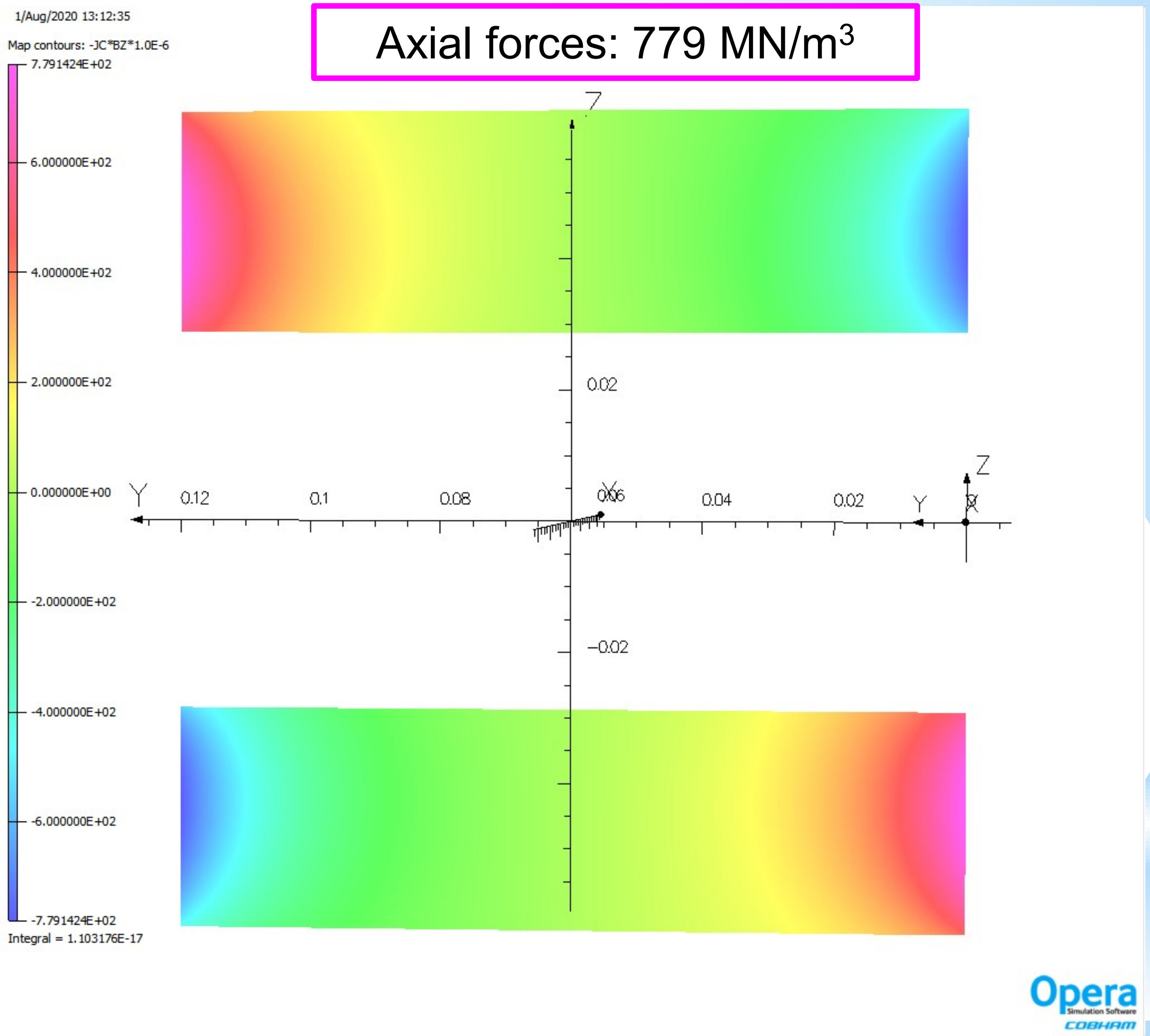
Dipole Corrector coil



Bucking coil

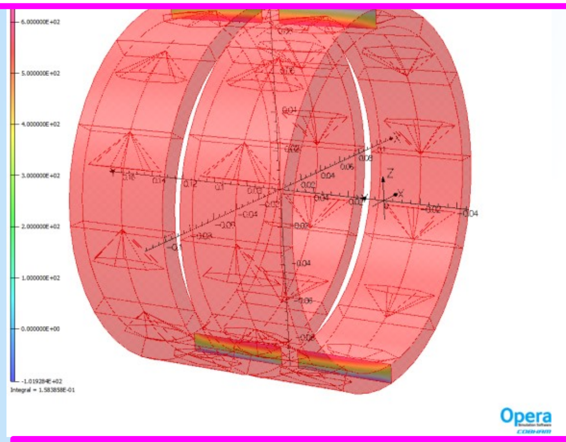
Electromagnetic Forces (Main Coil)



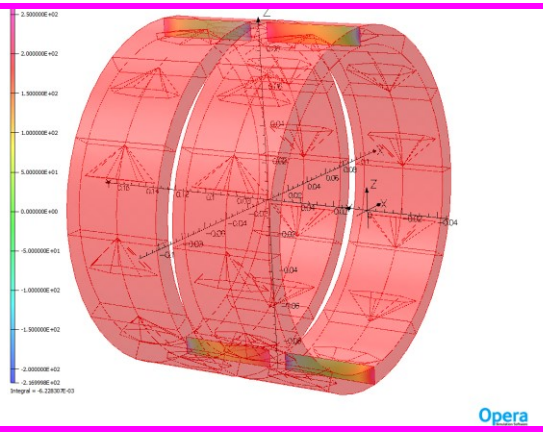


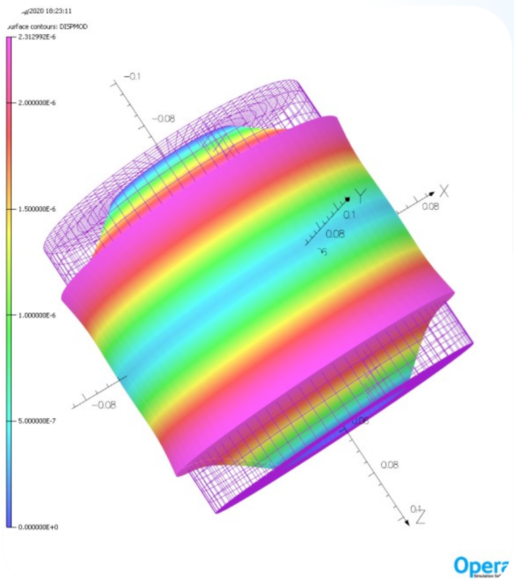
Electromagnetic Forces (Bucking & DC Coil)

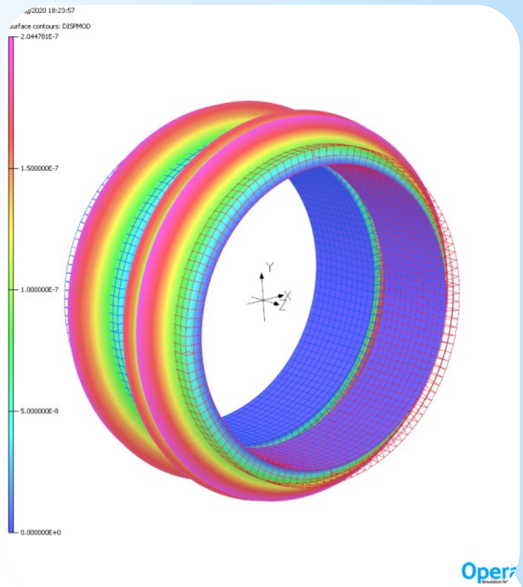
Radial forces : 702 MN/m^3



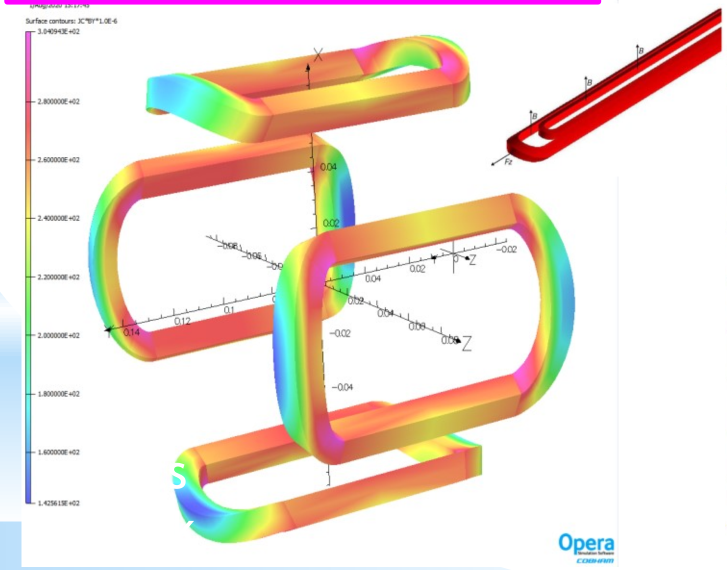
Axial forces : 281 MN/m^3



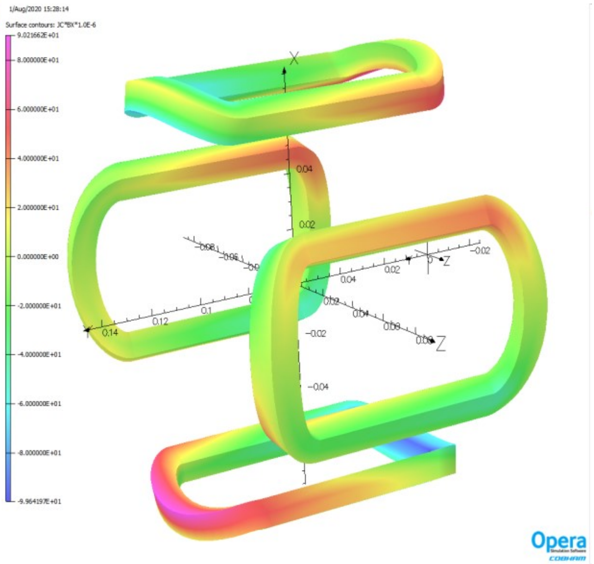




Radial forces : 304MN/m^3



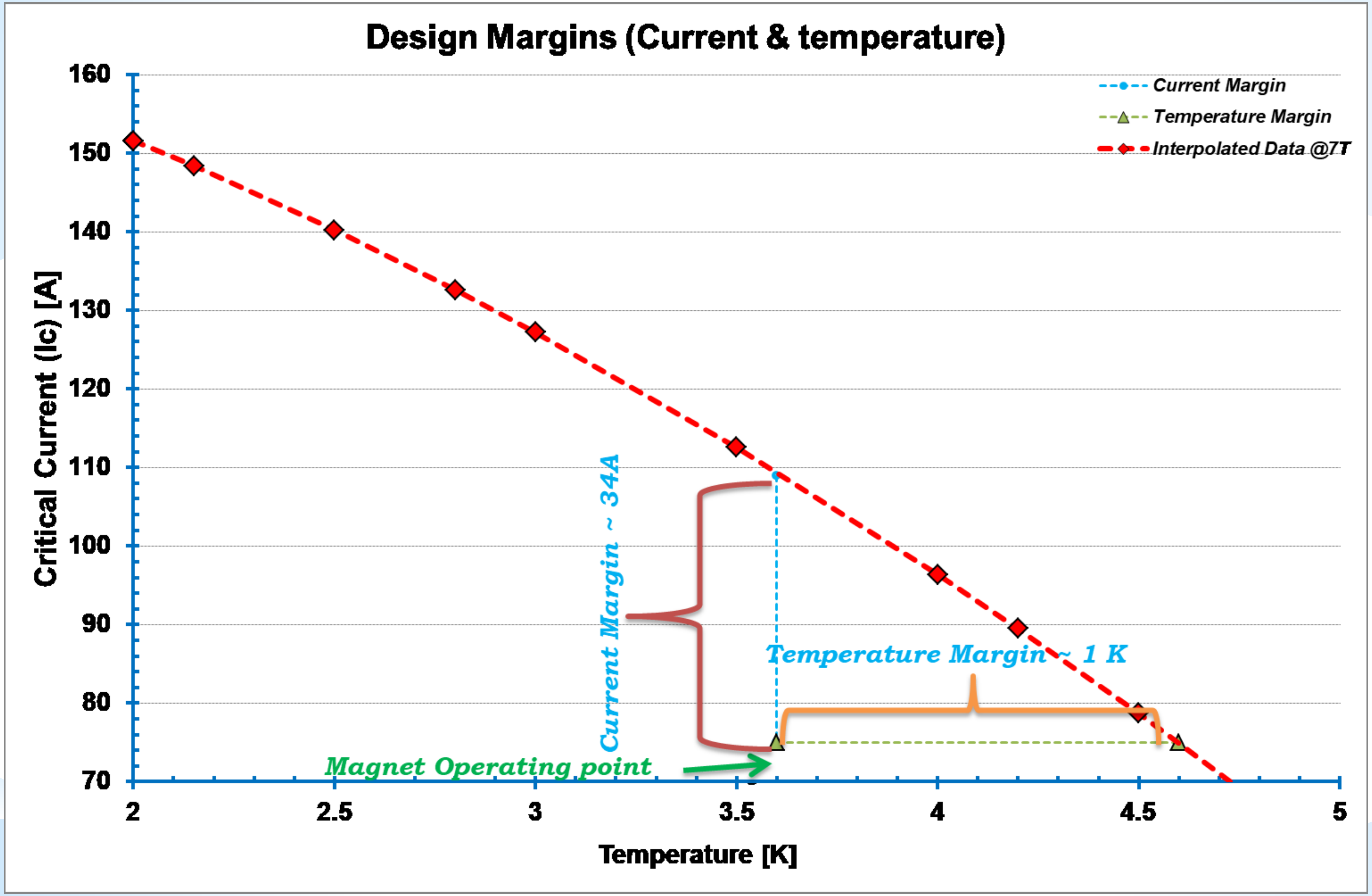
Axial Forces : 90MN/m^3



The EM Forces in a dipole magnet tend to push the coil

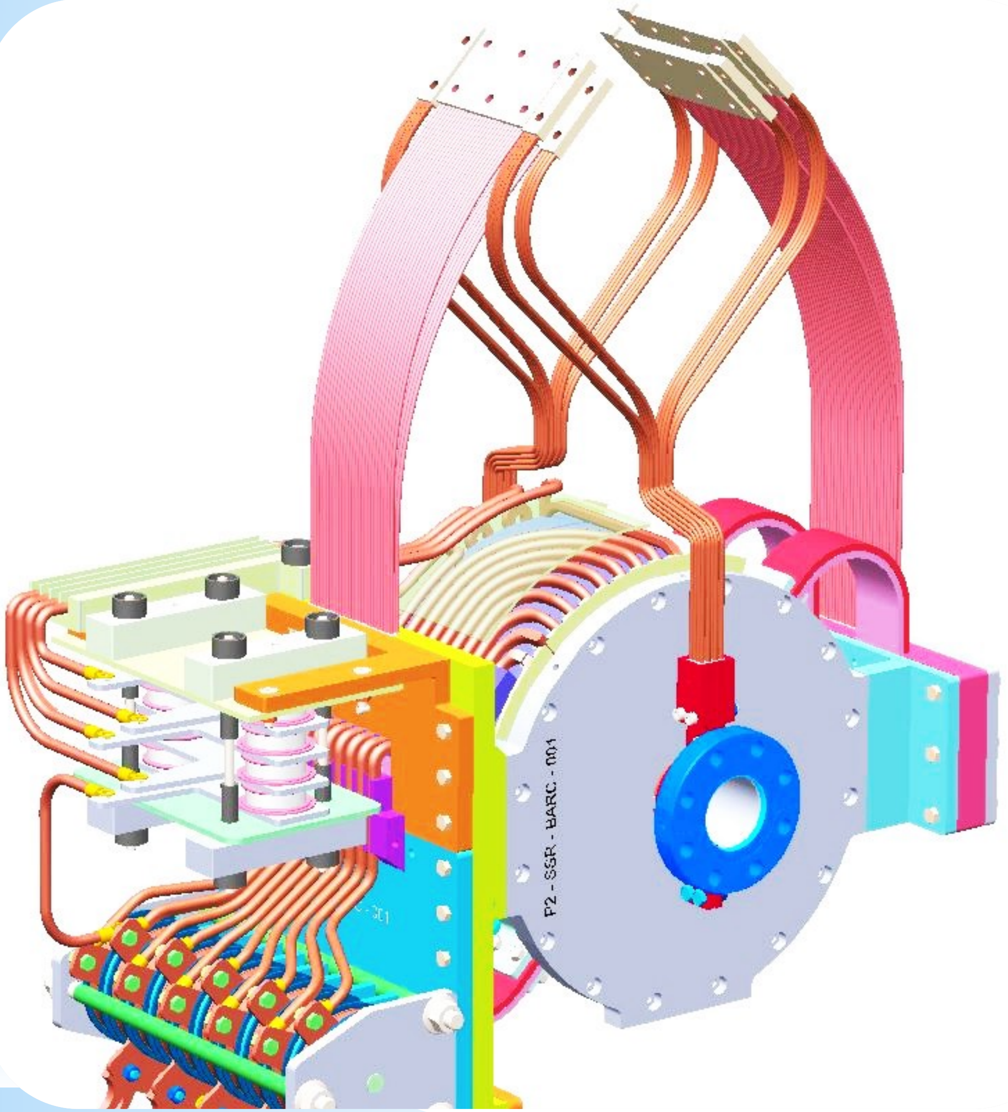
Towards the mid-plane in the vertical-azimuthal direction (Fx, $F_\theta < 0$) ; Outwards in the radial-horizontal direction (Fz, Fr > 0). In the coil ends the Lorentz forces tend to push the coil outwards in the longitudinal direction (Fy> 0)

Design Margin



Engineering Design & Development

SSR conduction cooled magnet assembly



Magnet Sub-assemblies:

- Non-magnetic SS316L bobbin
- Winding packs
- Diode racks for quench protection
- Heat sink assemblies
- HTS Current lead Interface
- Magnet, Beam pipe and 2K thermal straps

SSR conduction cooled magnet assembly

Material :

- Non-magnetic SS316L bobbin – permeability < SS316L
- Luvata OK636 wire 0.4mm (bare dia)
- Insulation material : FORMVAR (PVA)
- Cold-diodes :Powerex diodes
- Epoxy STYCAST 2850FT with LOCTITE CAT 23LV
- HTS 110 current leads

LUVATA
Partnerships beyond metals

TEST REPORT

Technical data for:

OK 636 Superconductor No: 210113-2A

Spool	29032
Length[m]	60000

Customer.. Mahbros Intertrade PVT. Ltd.
P.O. Number.. DPS/CPU/04/B3/89/PT/PO/248523

Diameter, nominal.. 0.45 ± 0.010 mm
Diameter, bare, nominal.. 0.40 mm
Insulation.. PVA
Number of filaments.. 636
Filament diameter (nominal).. 10.5 µm
Cu/Sc, nominal.. 1.3

Measured Data:

Spool	Side	Bare Diameter	Insulated Wire Diameter				Cu/Sc
			Min	Avg	Max	Stdev	
29032	Inner	0.406	0.451	0.452	0.454	0.0007	1.25
29032	Outer	0.406	0.451	0.452	0.453	0.0007	1.25

Twist pitch.. 79 mm (spec. 50 - 100 mm)
RRR.. 109 (spec. >60.0)

Critical currents, current densities and n-factors:

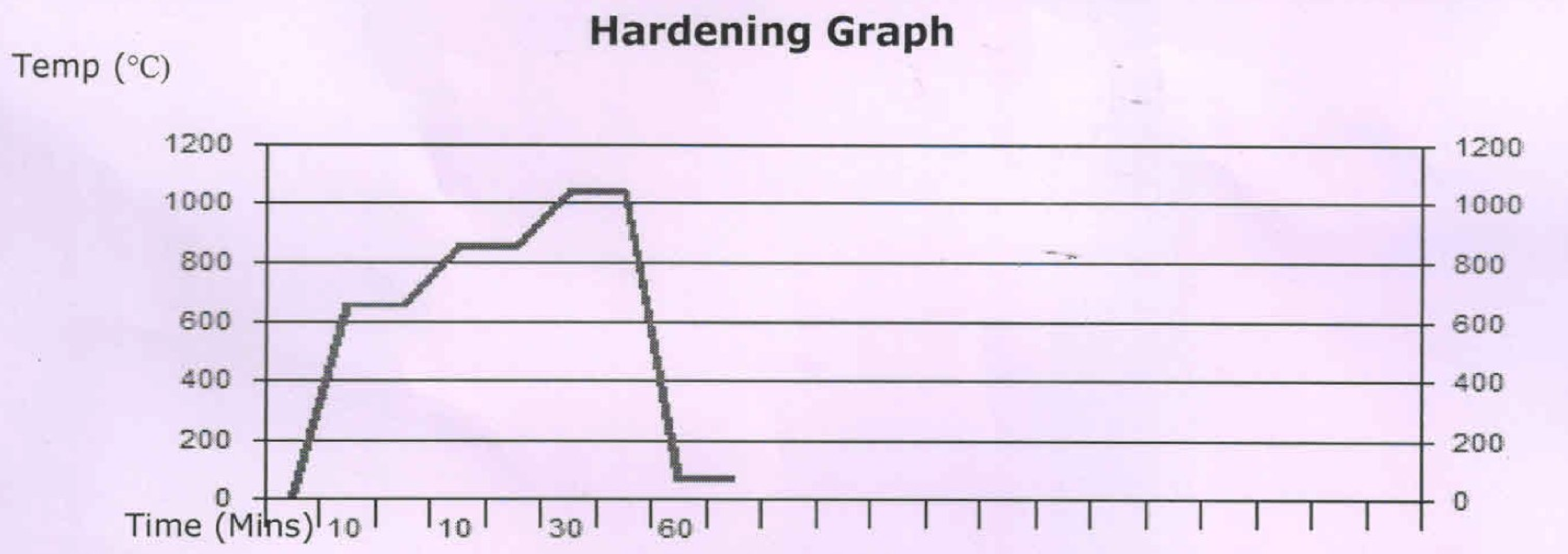
Field	I_c		J_c	n-factor	
1	403	(380)	7043	41	(30)
2	290	(290)	5057	59	(30)
3	236	(230)	4128	61	(30)
4	202	(180)	3532	67	(30)
5	172	(140)	3008	66	(30)
6	140	-	2448	54	(30)
7	107	(80)	1869	41	(30)
8	72	(55)	1255	33	(25)

Temperature 4.2 K. Criteria 0.1 µV/cm. Specified values on the brackets.

Annealing cycle for SS316L

Magnet bobbin material: SS316L (ASTM A 240M or equivalent) Material condition : Annealed

Relative magnetic permeability at room temperature < 1.02 at 200 Oersted.



Development stages

Magnet bobbin material: SS316L (ASTM A 240M or equivalent) Material condition : Annealed

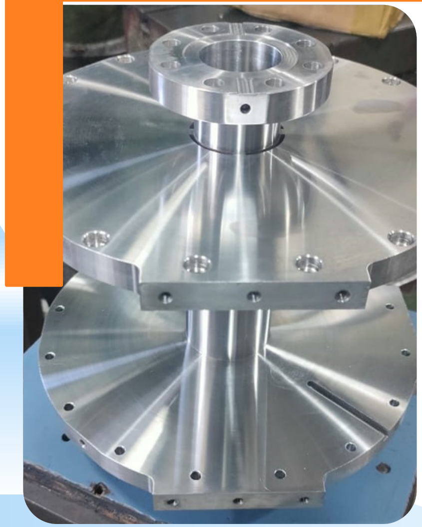
Relative magnetic permeability at room temperature < 1.02 at 200 Oersted.

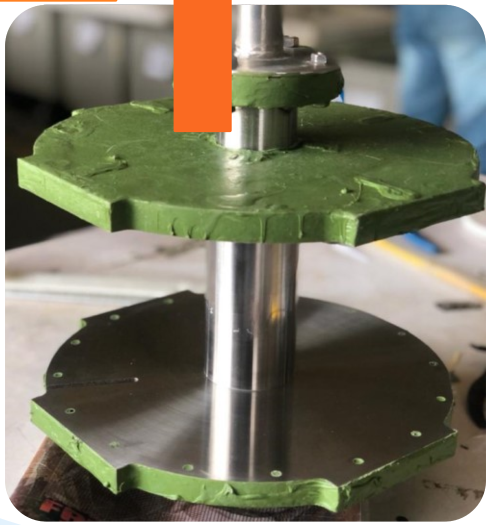
Masking Electroplating preparation

Electroplating

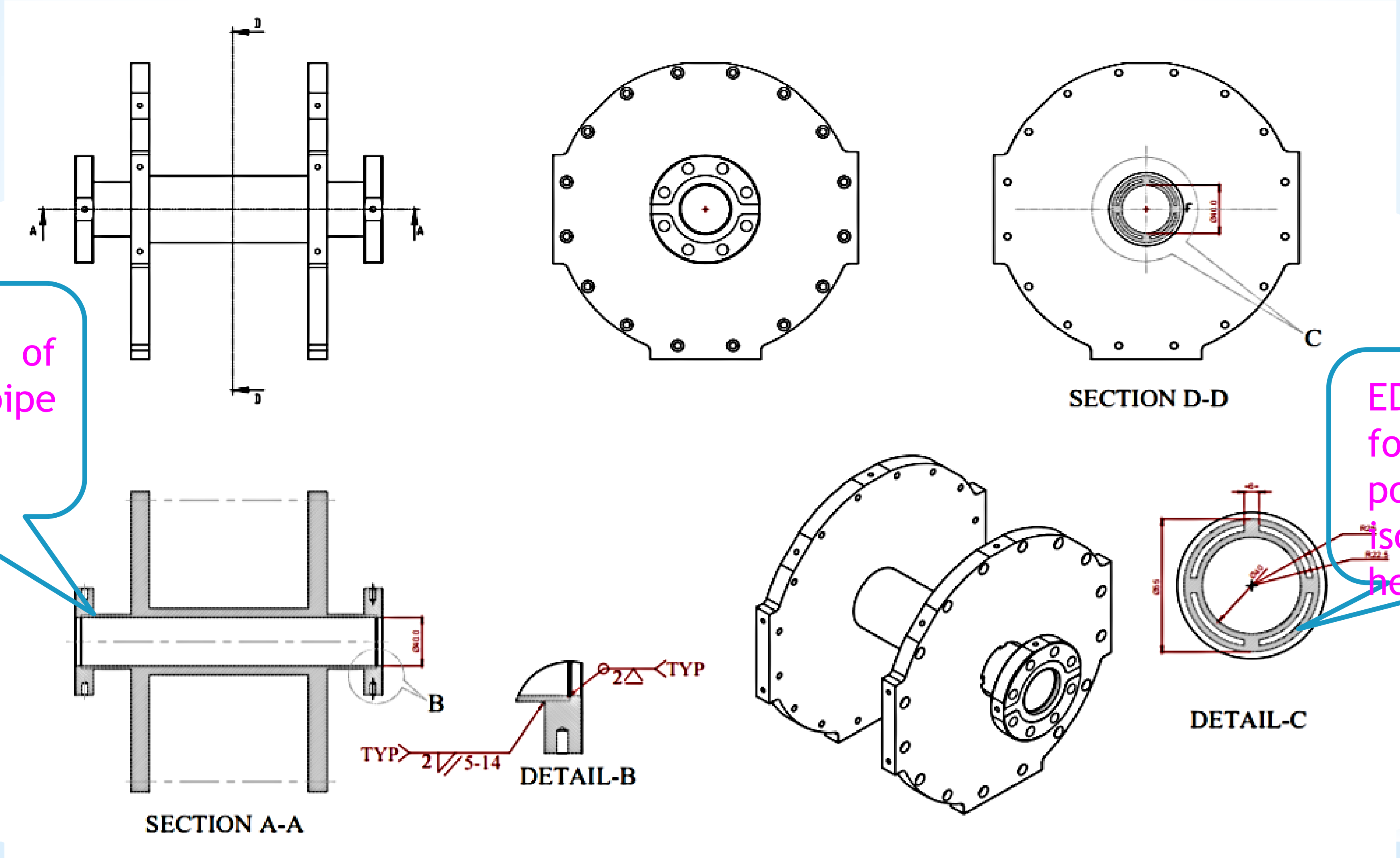
Winding

Test stand Integration





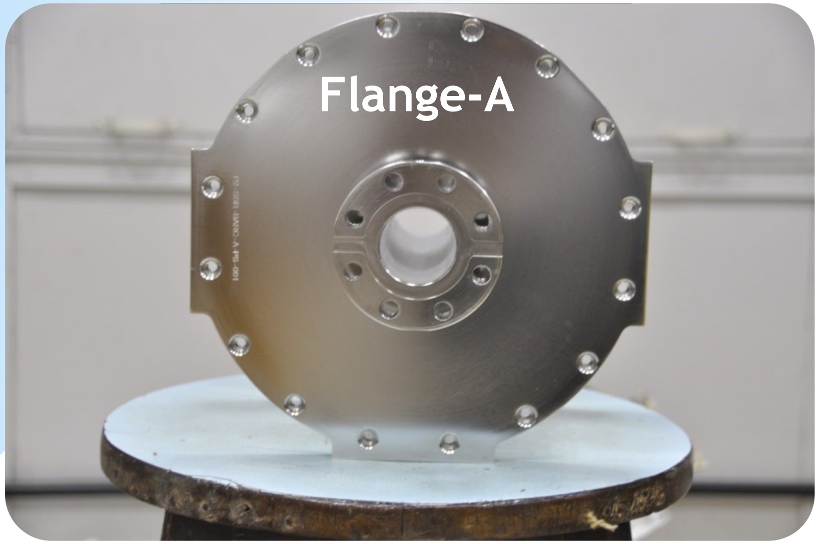
Bobbin Machining

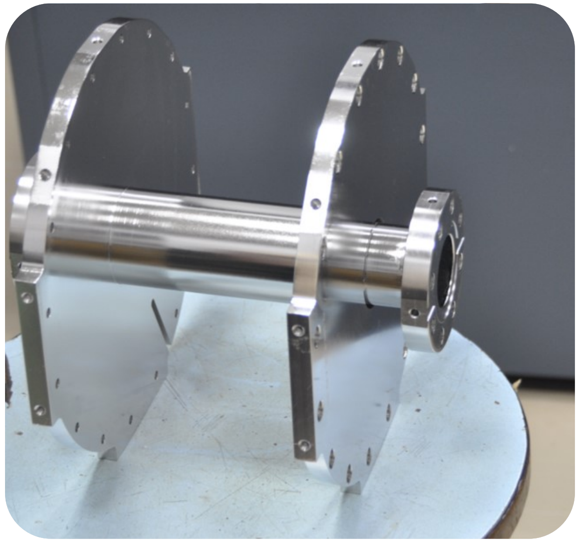


Welding of beam pipe flanges

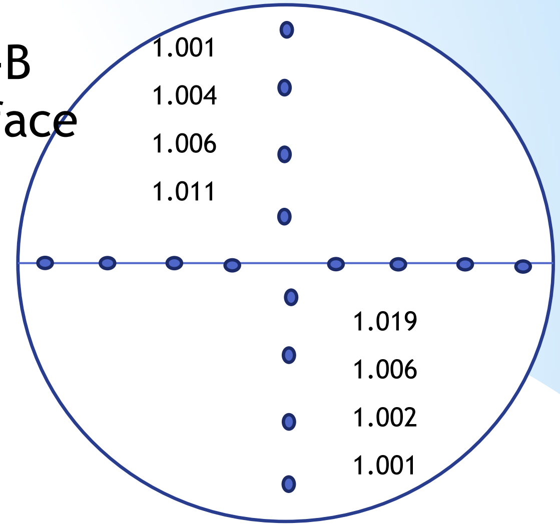
EDM machining for radial pockets to isolate beam heat load

Relative permeability measurement

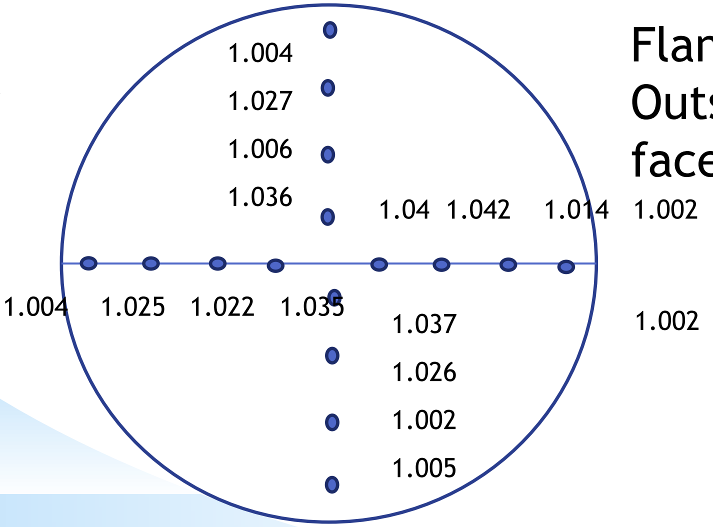




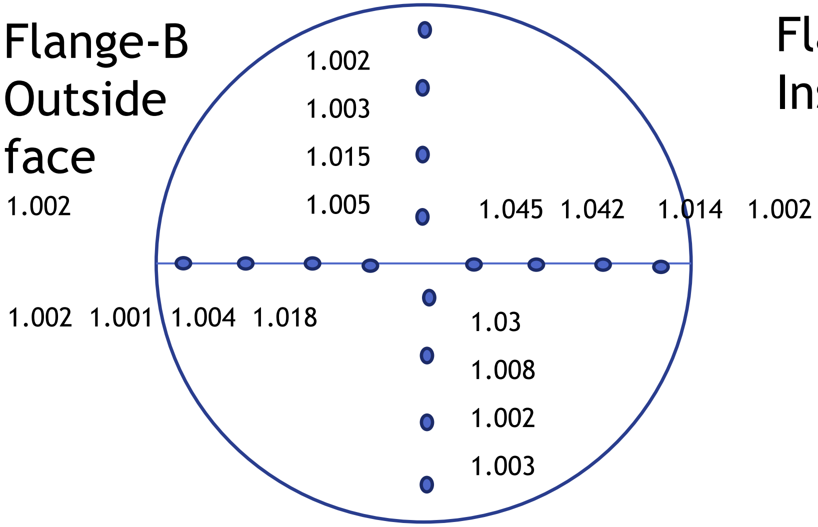
Flange-B
Inside face



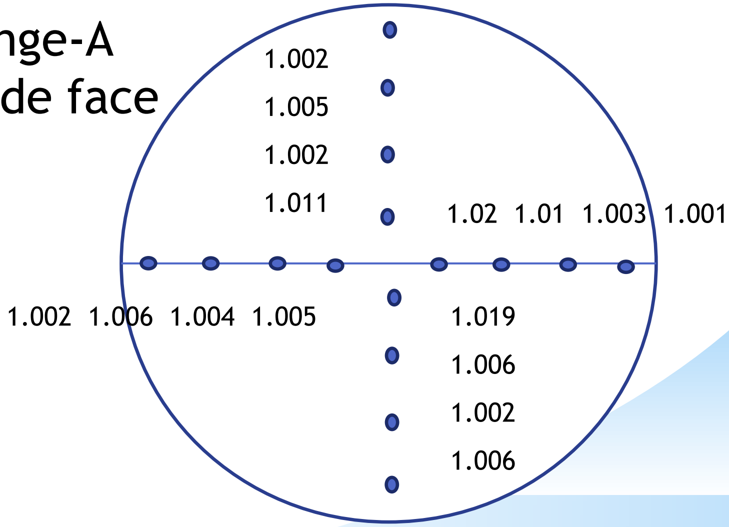
Flange-A
Outside
face



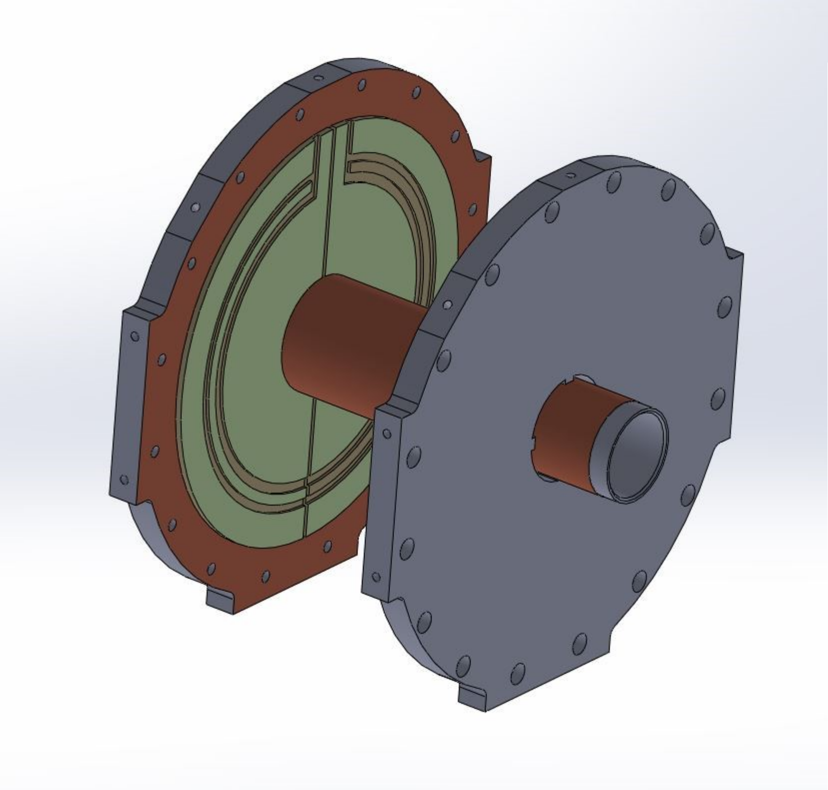
Flange-B
Outside
face

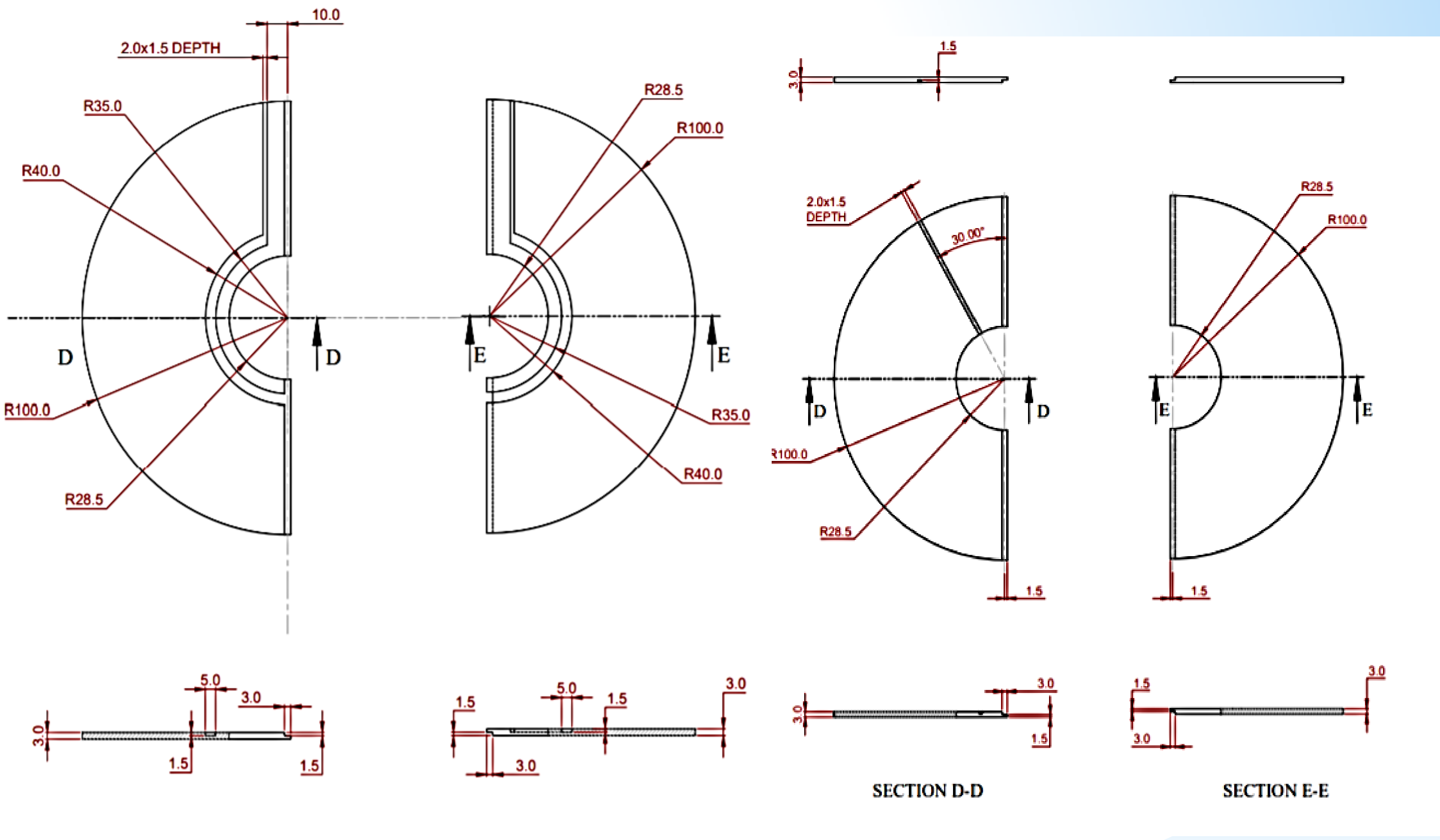


Flange-A
Inside face



Bobbin Insulation



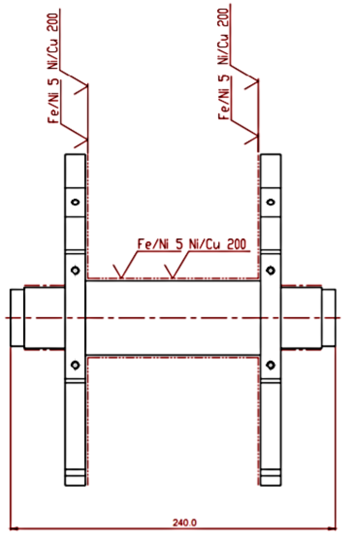


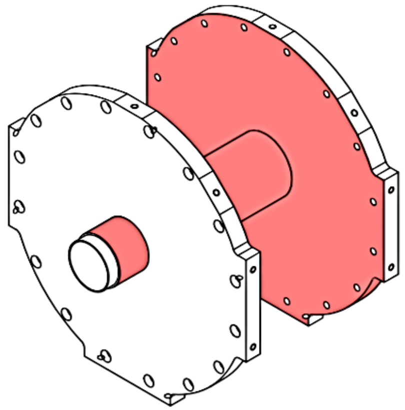
Side insulation flanges have radial slots for winding wire inlet and outlet Front flange will accommodate the solenoid and BC coil wire channels & Back Flange will accommodate dipole corrector wire channels

Electroplating

The SS316L bobbin needs to be electroplated with copper on magnet winding contact surfaces and beam pipe OD. The optimum values of the coating characteristics (e.g. thickness, purity, low hydrogen content, residual electrical resistivity ρ_R, low temperature thermal conductivity kCu(T), low temperature surface resistance R_S (T), adhesion on stainless steel substrate and surface roughness R_a are essential criteria for the above application

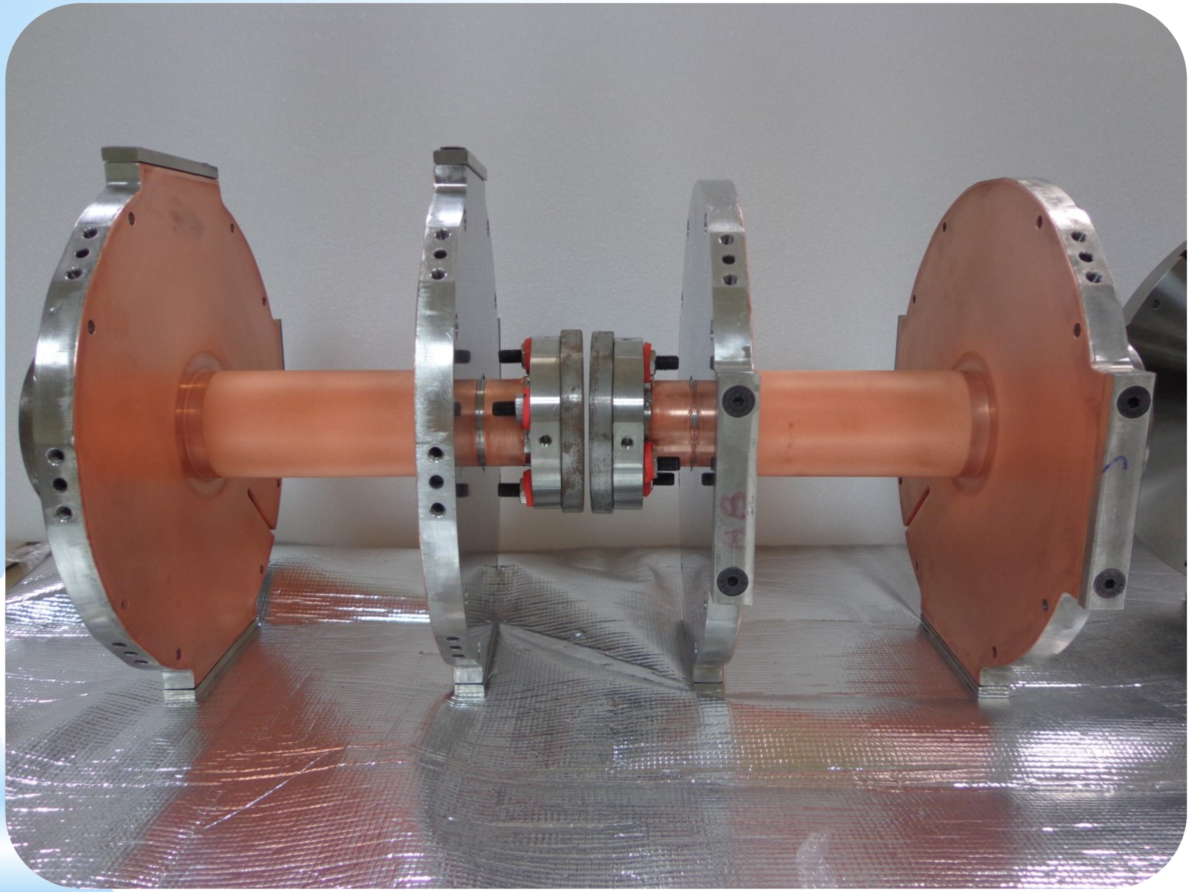
Nickel strike shall be provided for adhesion of Cu on SS surface.

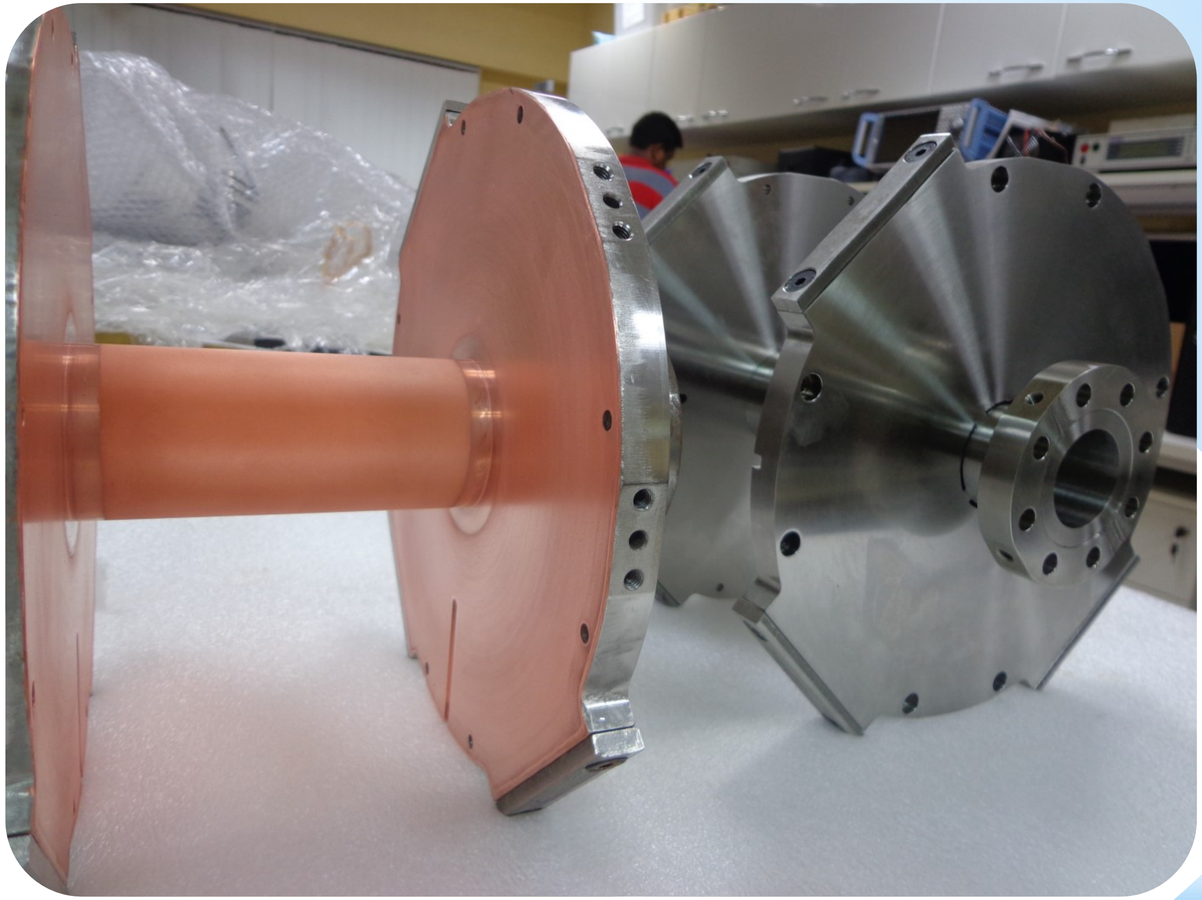




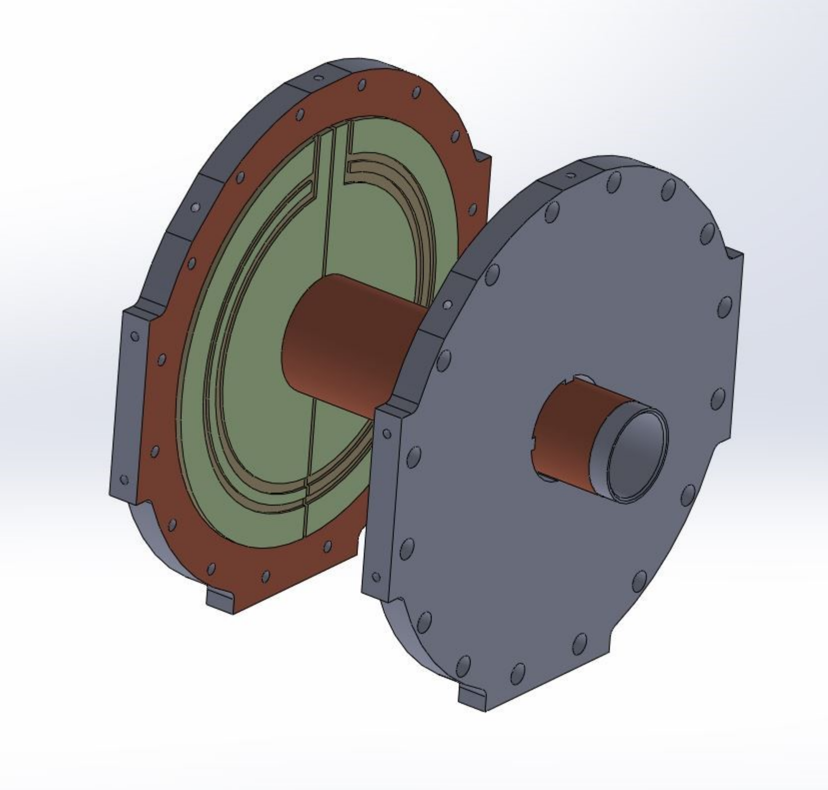
Specification	Unit	Value	Standard
Material of plating	-	Copper	Chemical composition as per ASTM B152
Conductivity of plated deposit	IACS	≥ 100%	Measured as per ASTM E1004
Surface roughness (R_a) using 17.5mm stroke	Microns (max)	~ 3.2	Measured as per ISO 16610-21
Thickness after Final polishing*	Microns (max)	200 ±10	Measured as per ASTM B499
Uniformity	% of coating thickness	±5	___
Adhesion strength (on samples)	No peeling-off flaking shall be observed on performance of tests		Heat Quench test, Scrib grid line test, Impact test ASTM B571
Porosity (on samples)	Modified Feroxyl test to be carried out on test specimen.		ASTM B 765

Electroplated bobbins

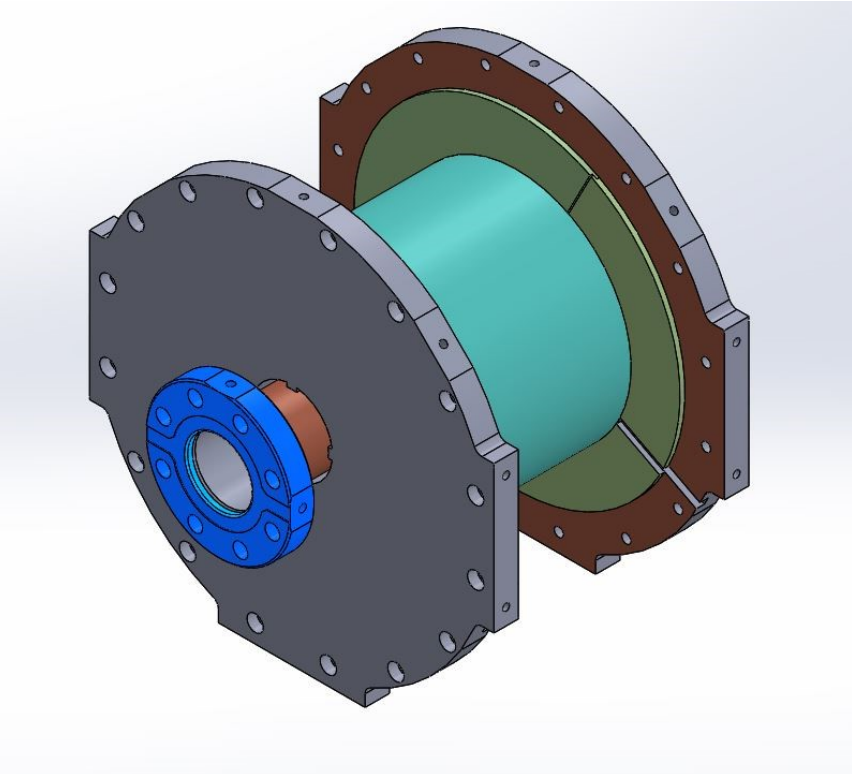




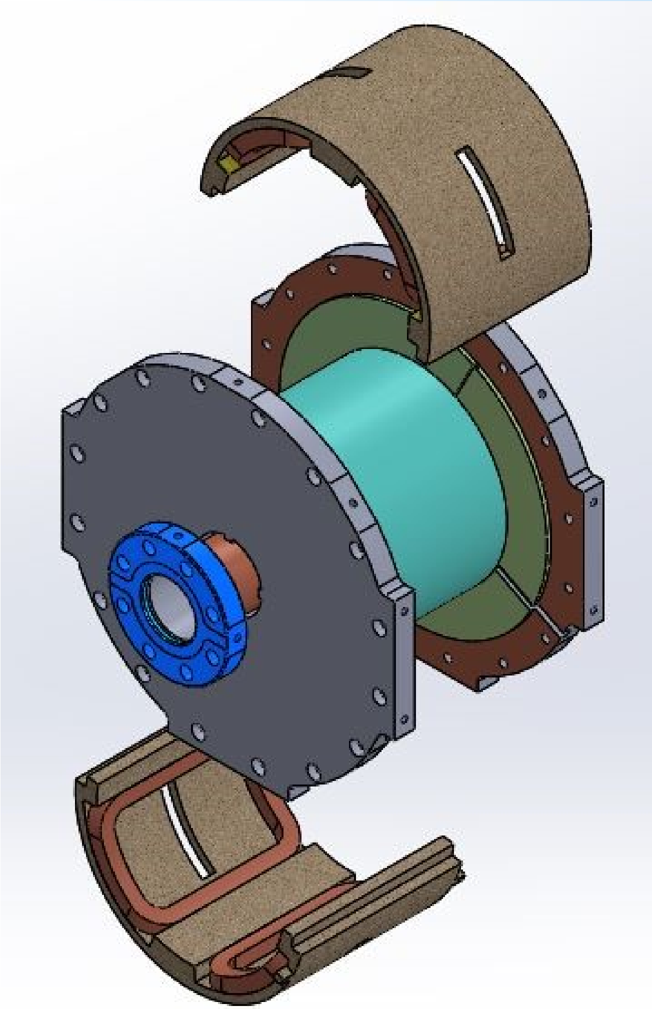
Winding steps



Ground insulation

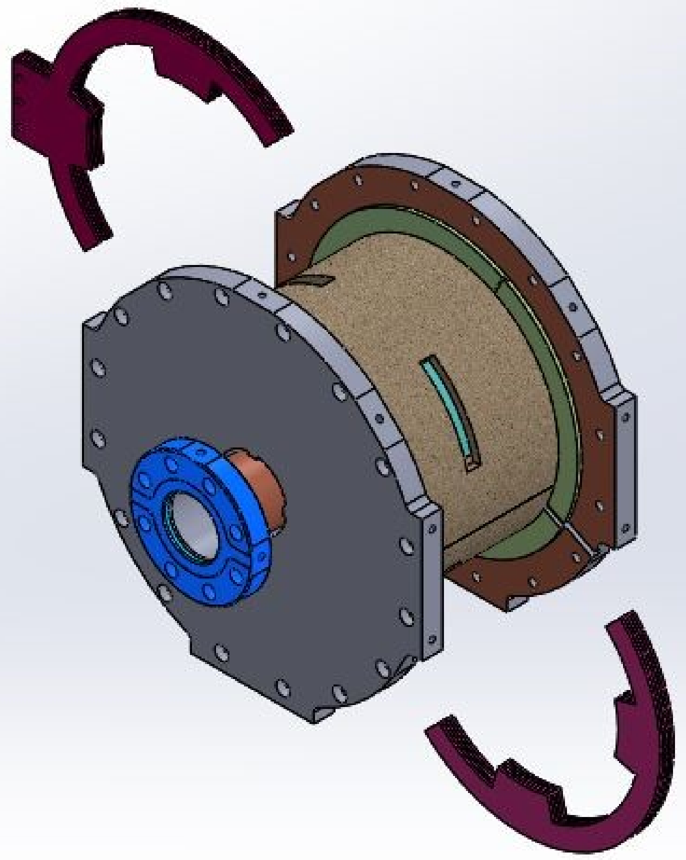


Main coil winding

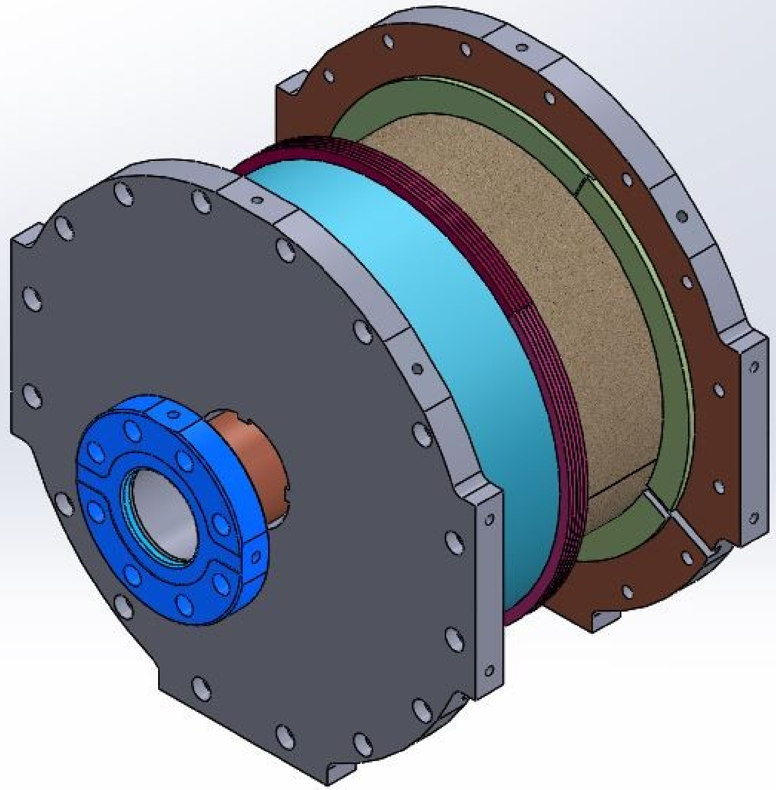


Corrector coil placement

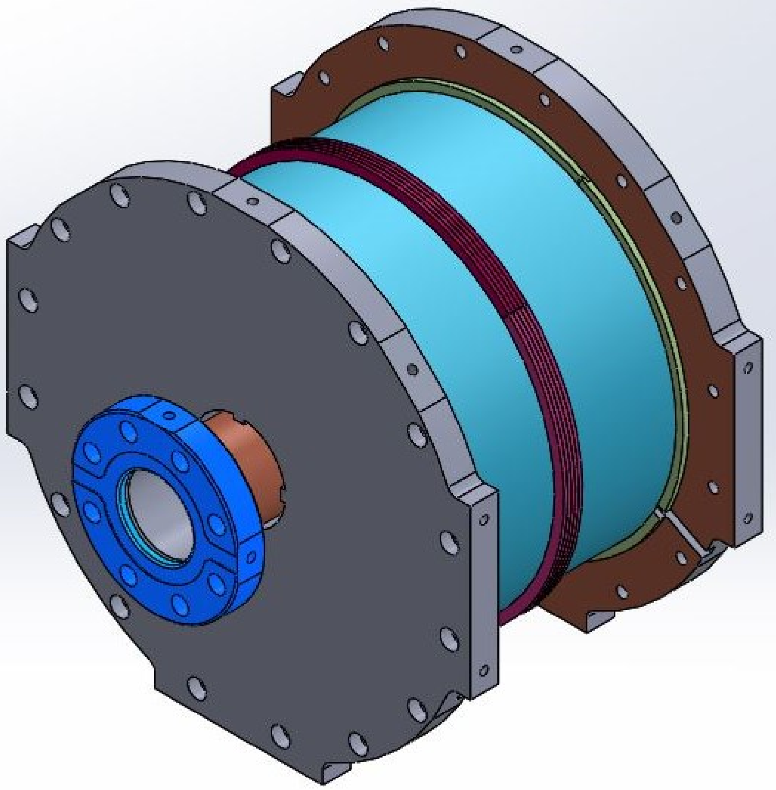
Winding steps



Aluminium Collar Placement

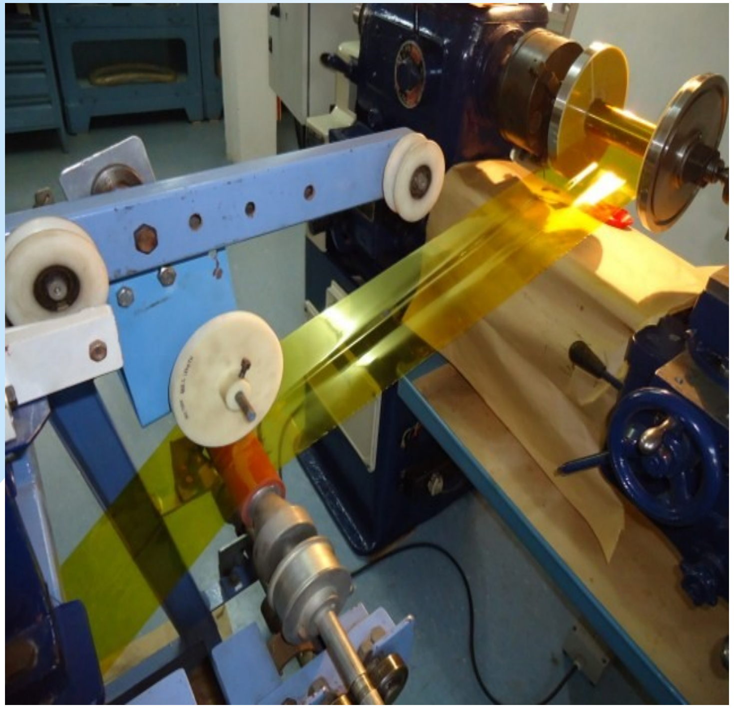


Bucking coil winding

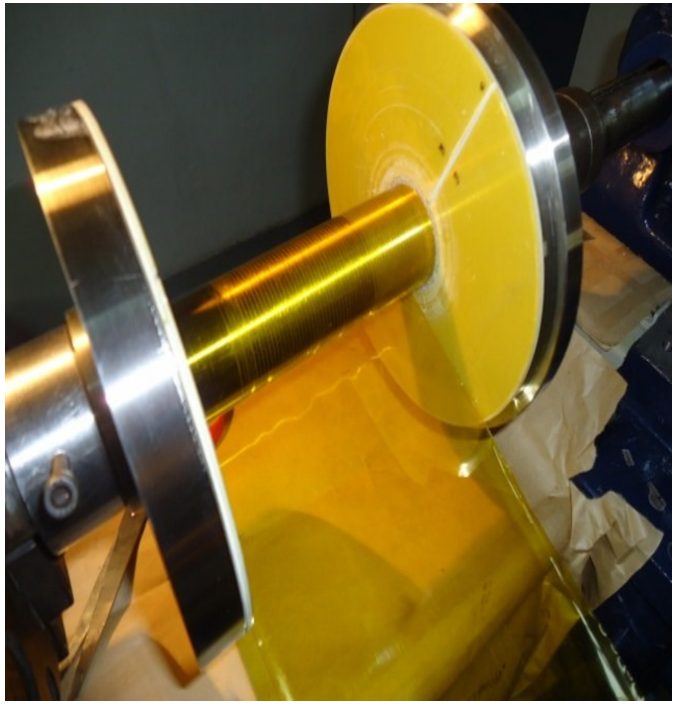


Bucking coil winding

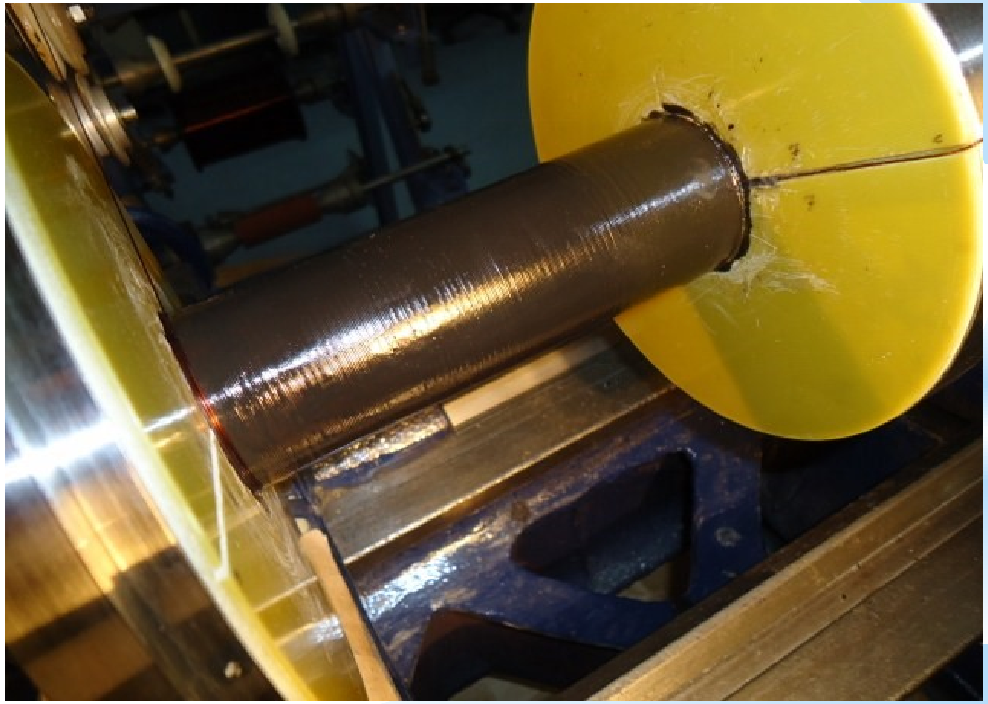
Coil winding progress



Core insulation with Kapton

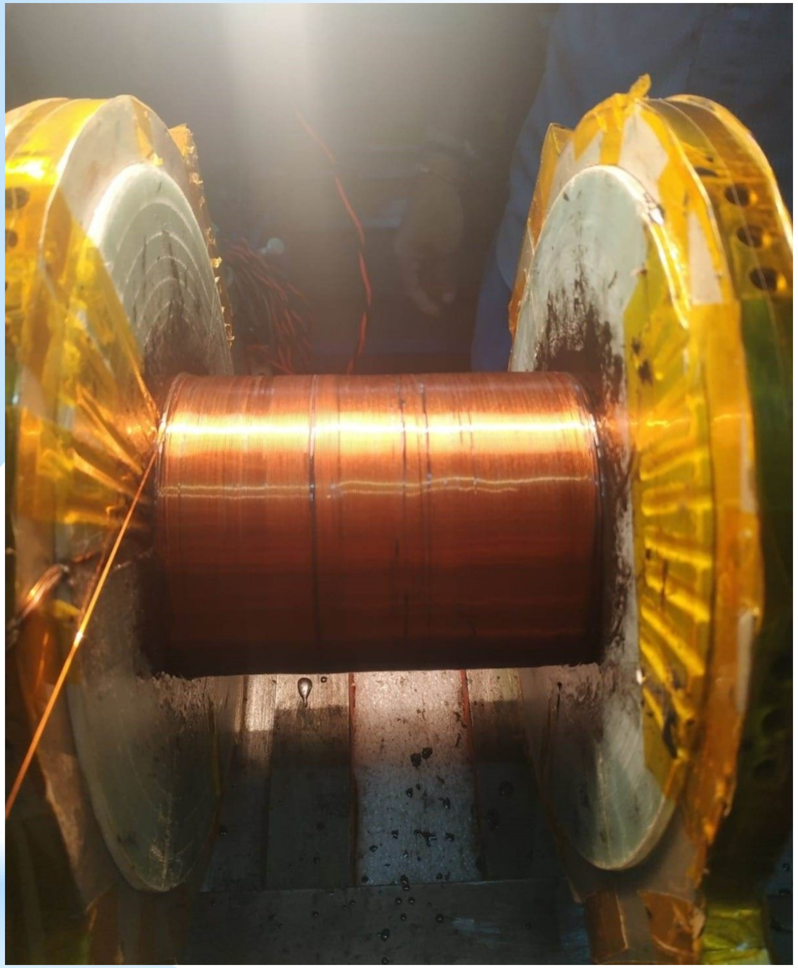


Flange insulation with G-10

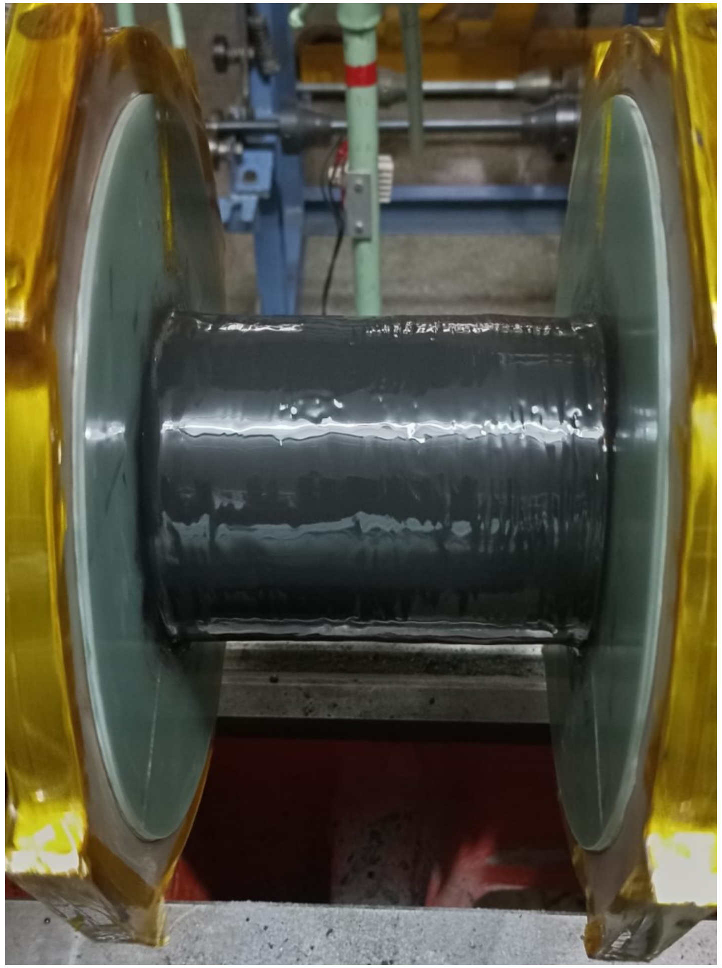


Wet winding with Stycast

Winding steps



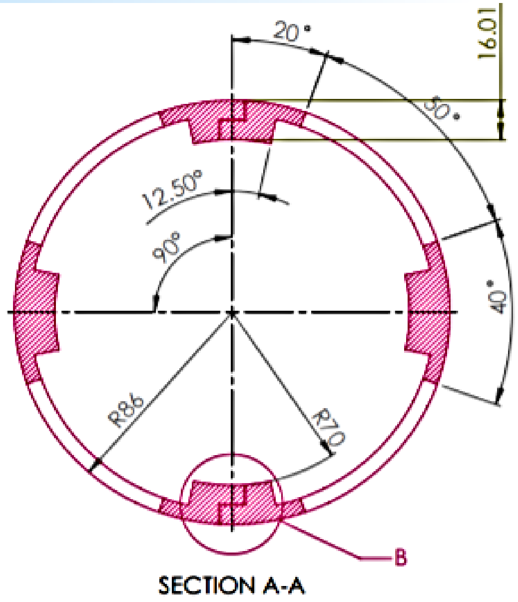
MC1 last layer



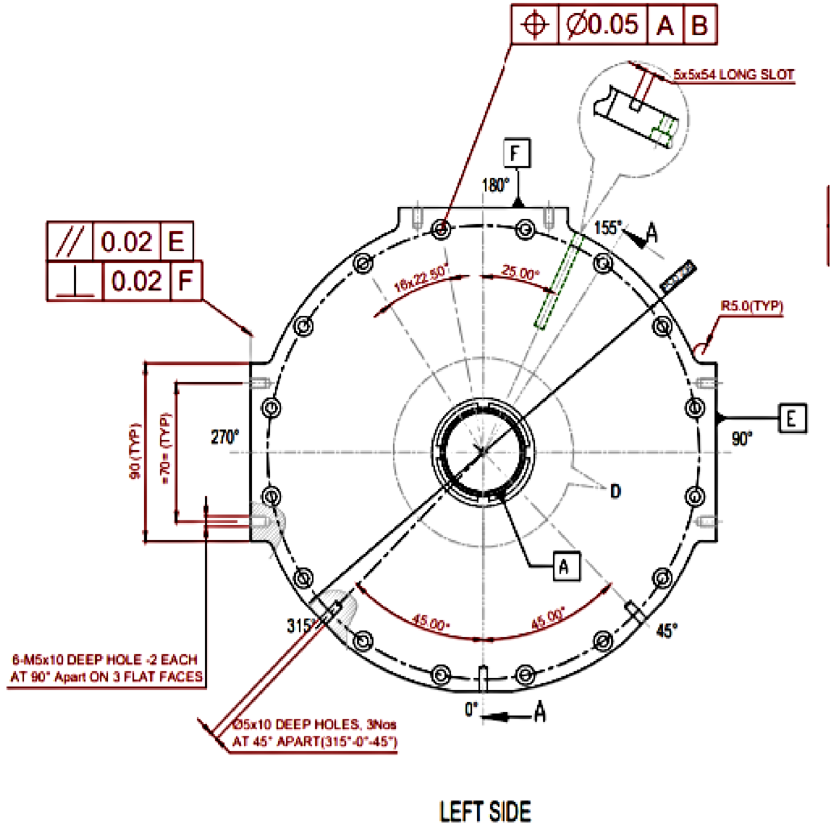
MC1 last layer with STYCAST

MC2 last layer with STYCAST

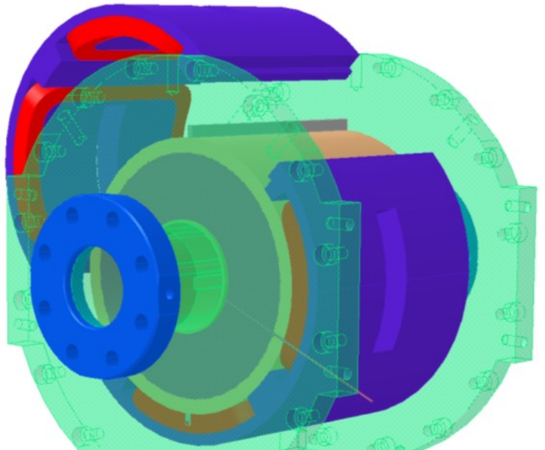
Corrector coil housing frame and its alignment



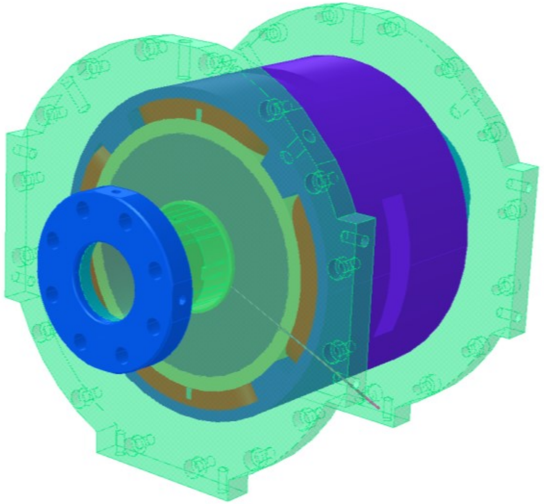
Cross-section corrector coil cage



Alignment slot for corrector coil cage in magnet bobbin flanges



Corrector coil housed inside G-10 CR cage

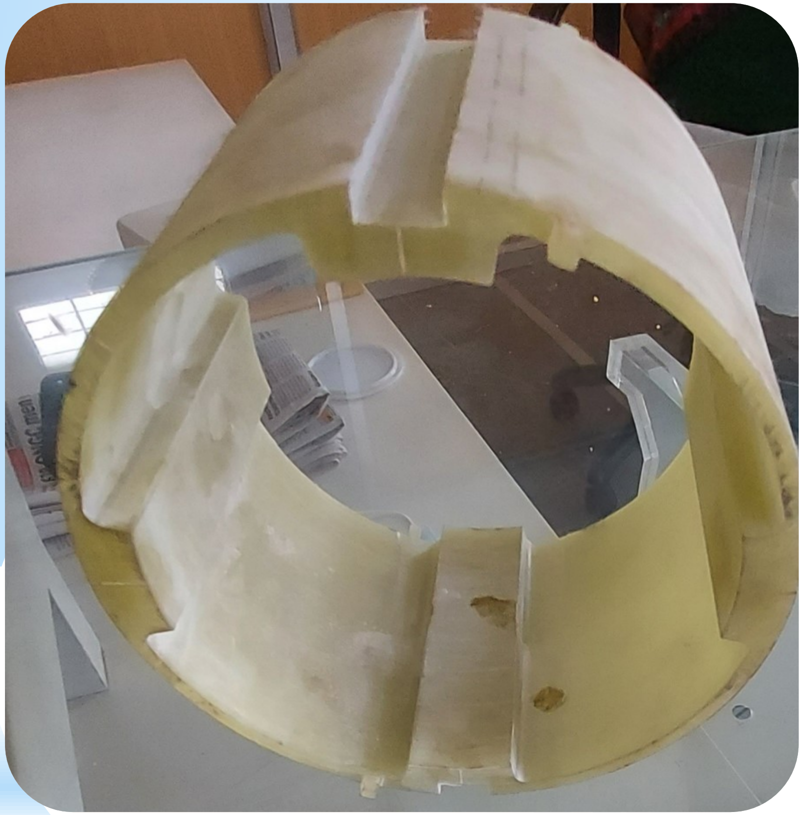


Corrector coil winding

Core insulation with Kapton

Corrector coils after winding

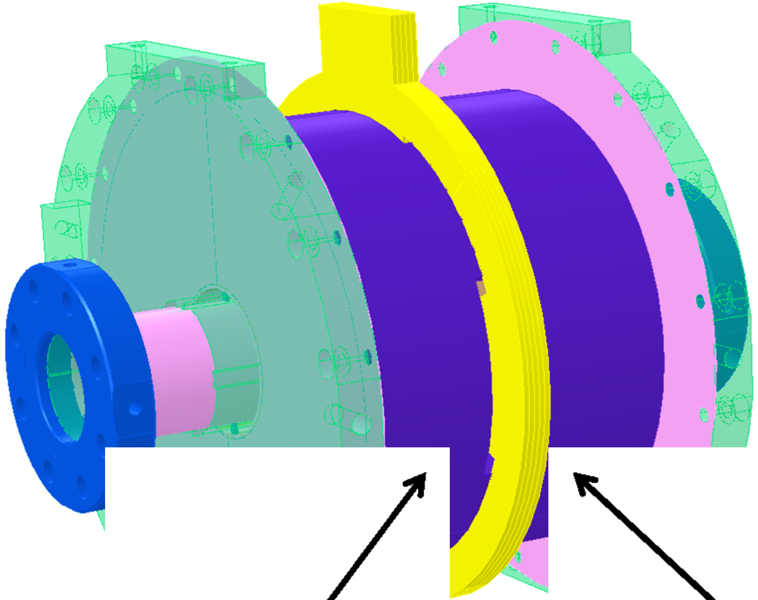
Corrector coil winding



G-10 corrector coil positioning cage

Corrector coil positioned inside cage

Bucking Coil positioning



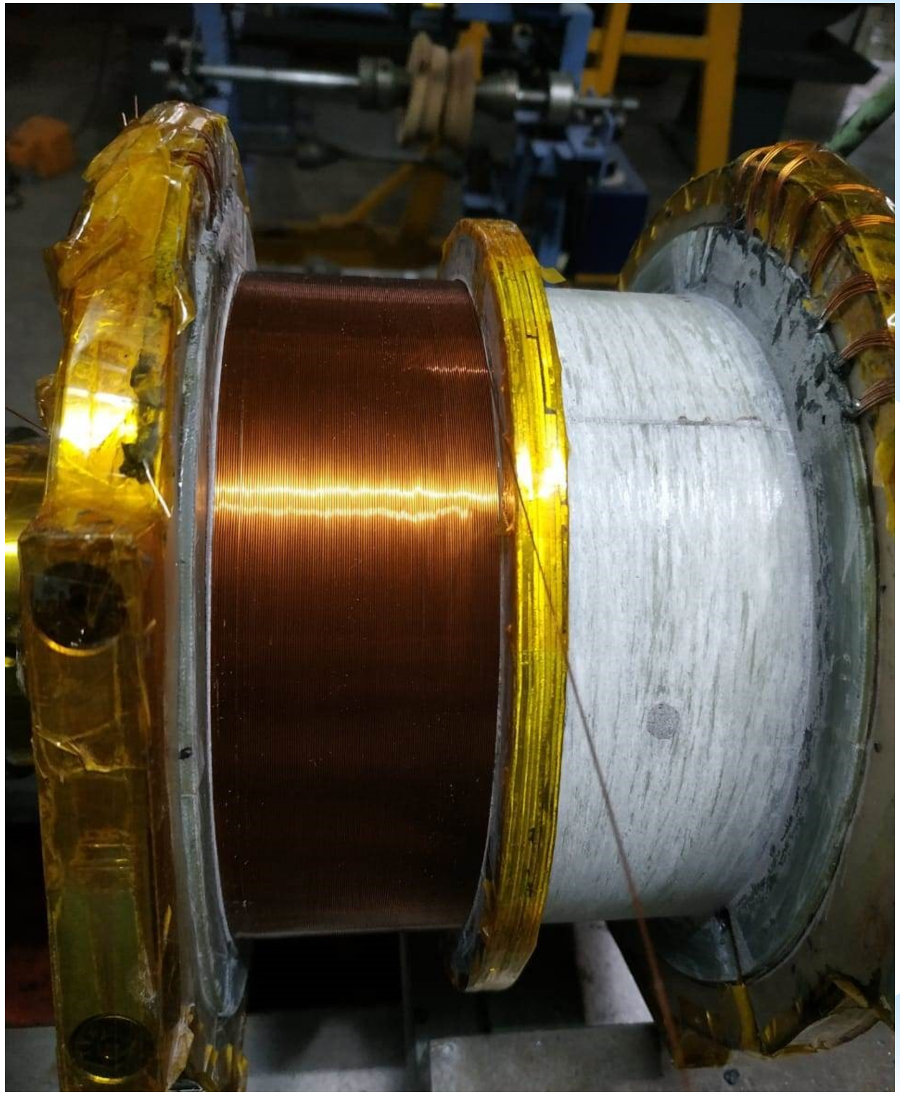
Laminated Aluminium sheets precisely stacked together are used as a accurate spacer between two bucking coils and serves the function of thermal conduction plate to conduct the heat away from center of the magnet bulk.

An accurate steel clamp shall be placed to lock the aluminium spacers in position and start winding Bucking coil1 and subsequently remove the clamp for winding bucking coil2.

uminium collars are assembled in two halves.

Bucking coil winding

Surface before bucking coil winding



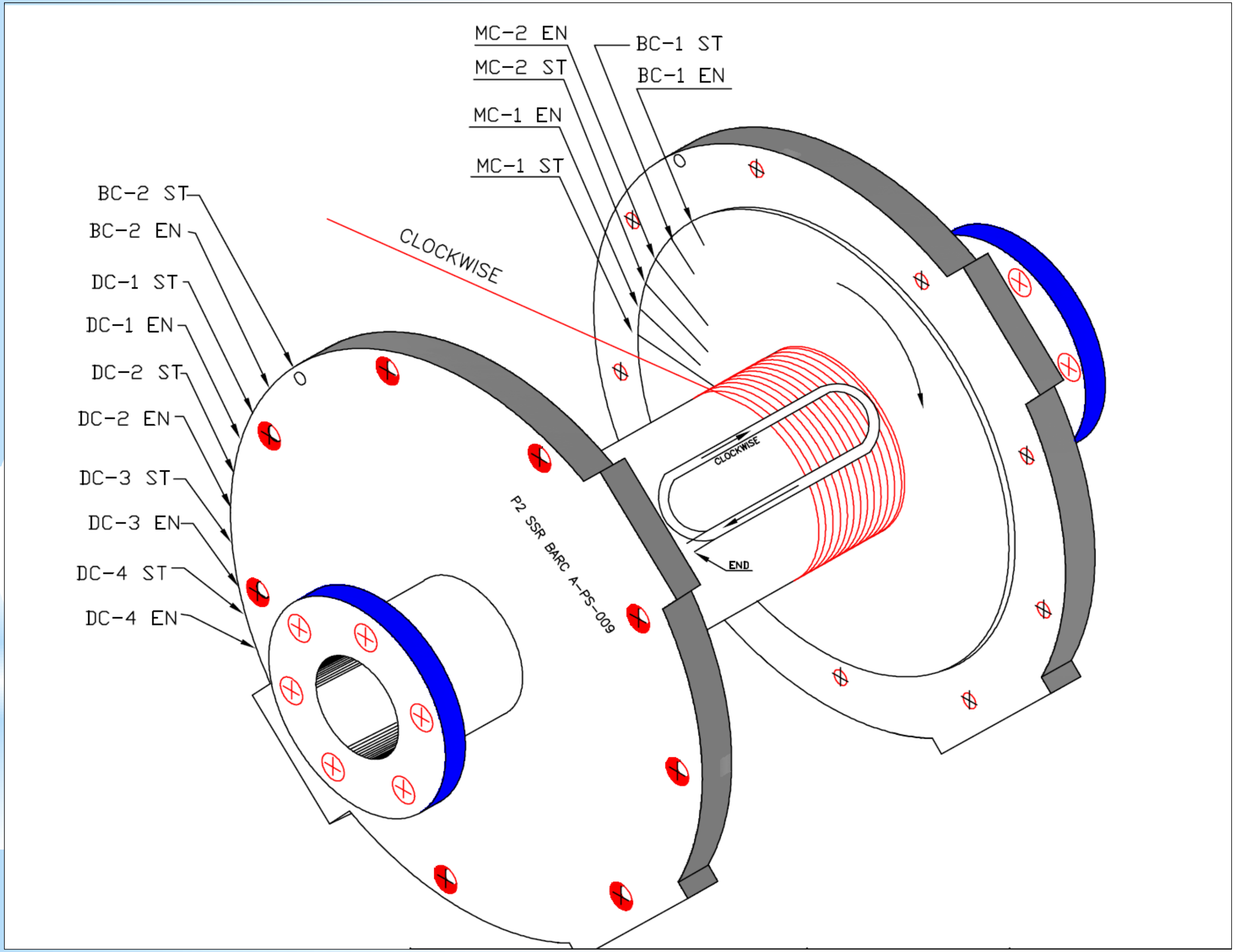
BC 1 winding first layer

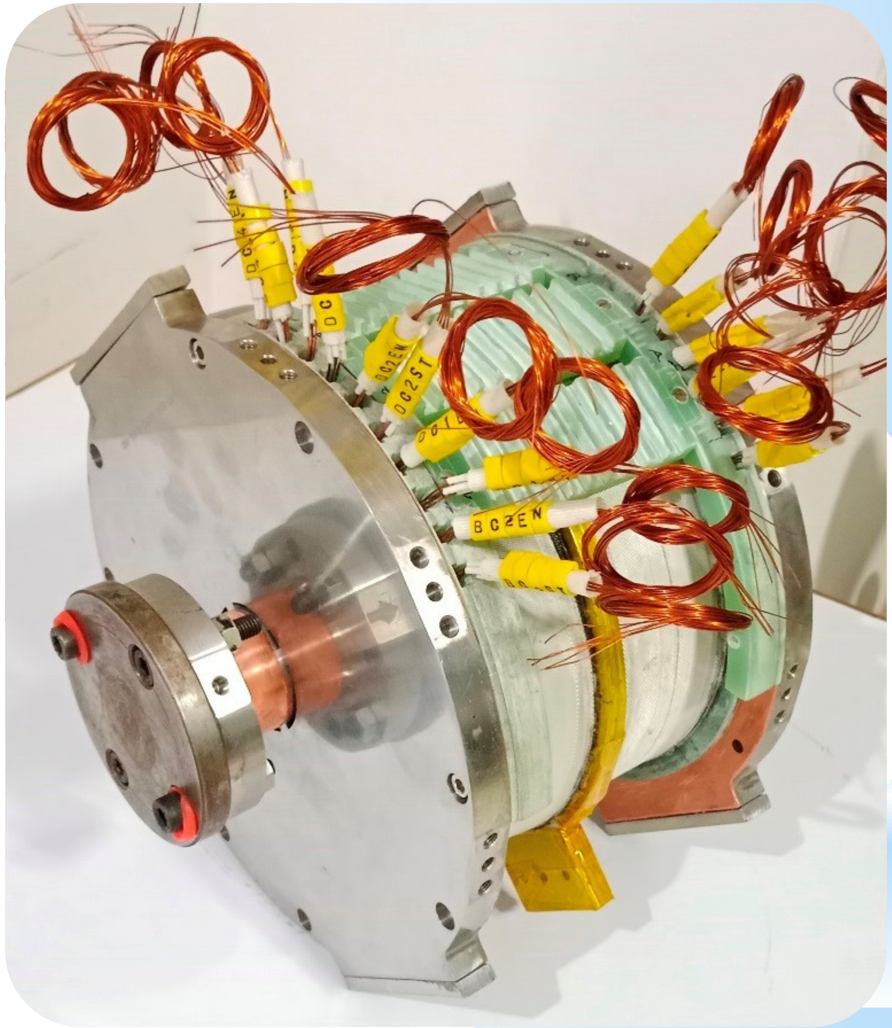
Bucking coil winding

Bucking coil 1 last layer after STYCAST

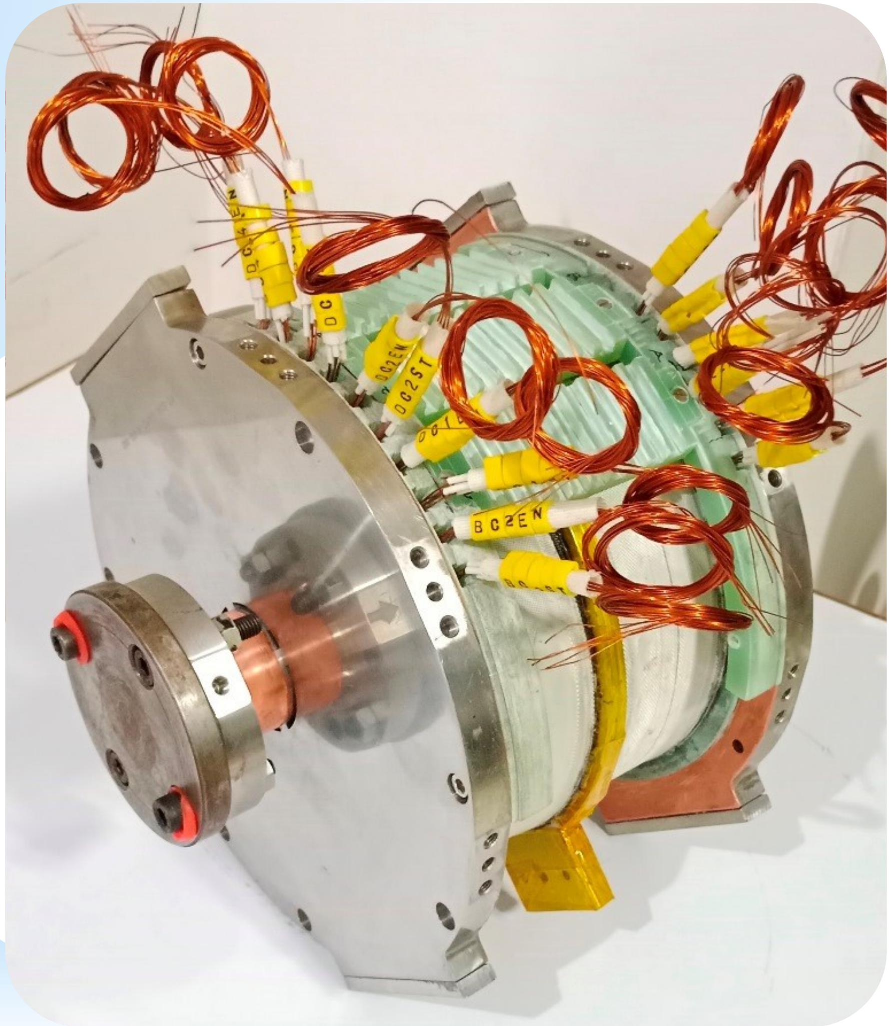
Bucking coil 2 first layer

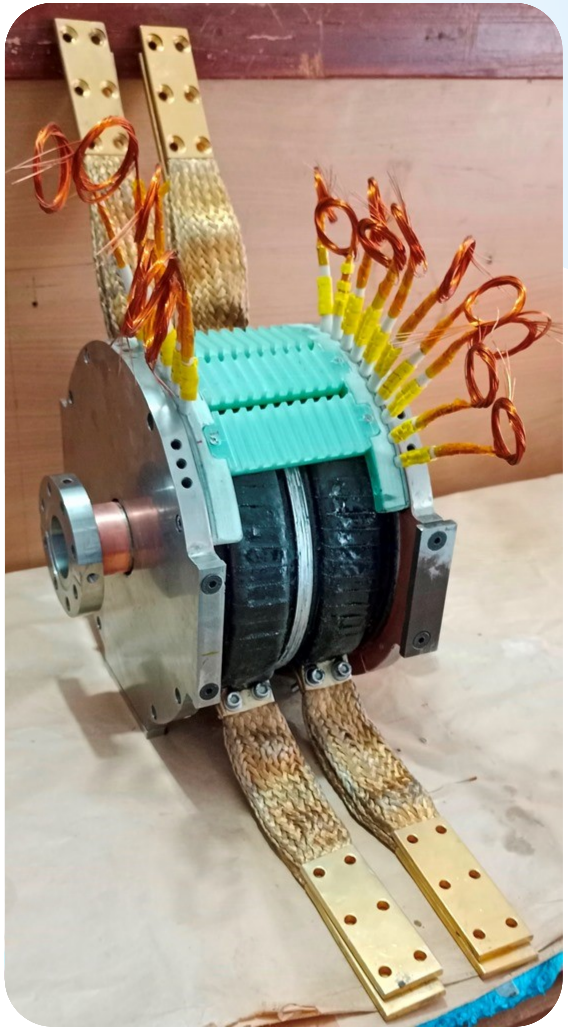
Winding terminations



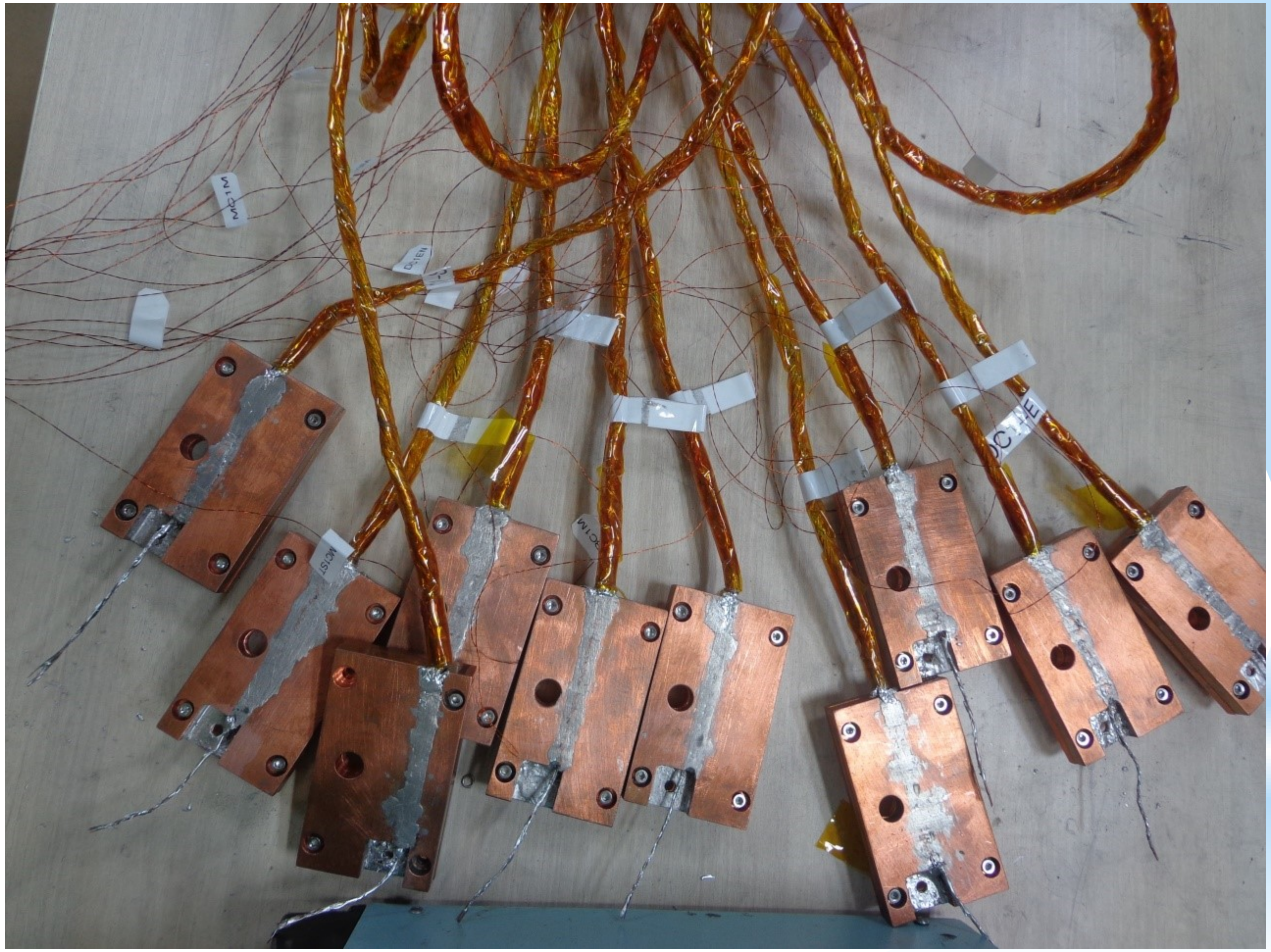


Bare SSR conduction cooled magnet assembly





Copper flags



Diode Stack

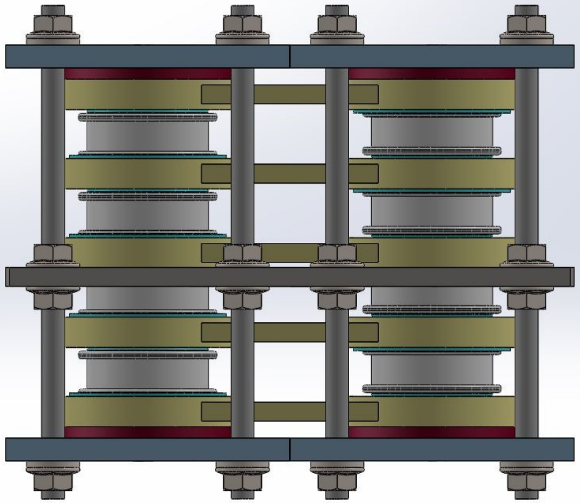
Powerex R620 Diodes (R62C1250XX50)

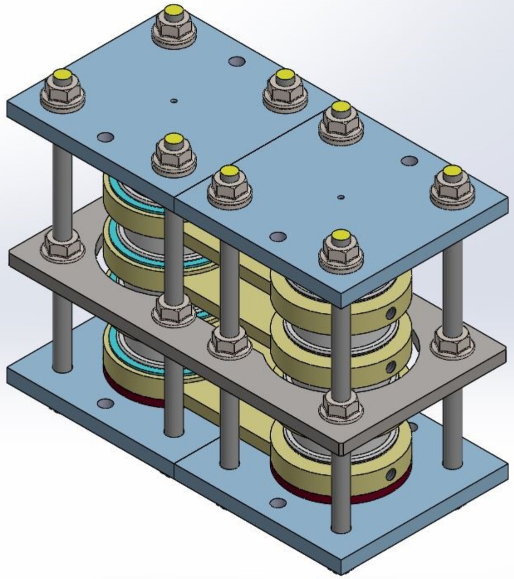
The cold diode assembly is a **protective component** of the superconducting magnets: in case of a quench, the diode bypass the magnet.

Mounting Force: 1000 to 1400 Lbs

Multiple Cu-Be washers shall be used to provide the clamping force and the spring action will ensure its reliable performance at operating temperature of the magnet assembly.

Diode stack assembly to be tested independently before integration with the magnet





Type	Voltage V_{RRM} (Volts)	Voltage Code	Current $I_{F(av)}$ (A)	Current Code	Recovery Time t_{rr} (µsec)	Recovery Time Code	Recovery Time Circuit	Recovery Time Circuit Code	Leads Case	Leads Code
R620	200	02	300	30	11	X	JEDEC	X	R62	OO
	400	04								
	600	06	400	40	9	X				
	800	08								
	1000	10	500	50	6 (Typical)	X				
	1200	12								
	1400	14								
	1600	16								
	1800	18								
	2000	20								
	2200	22								
	2400	24								

Quench protection diodes

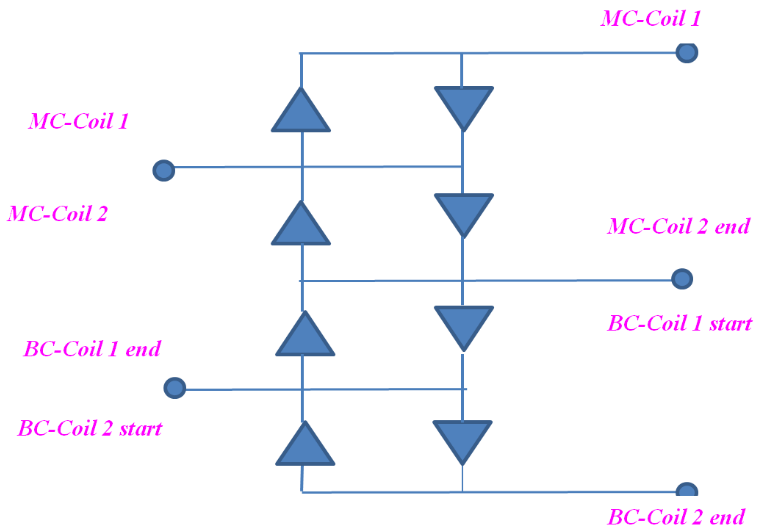


Fig-7: Electrical Schematic of Upper diode stack (routed from terminal block)

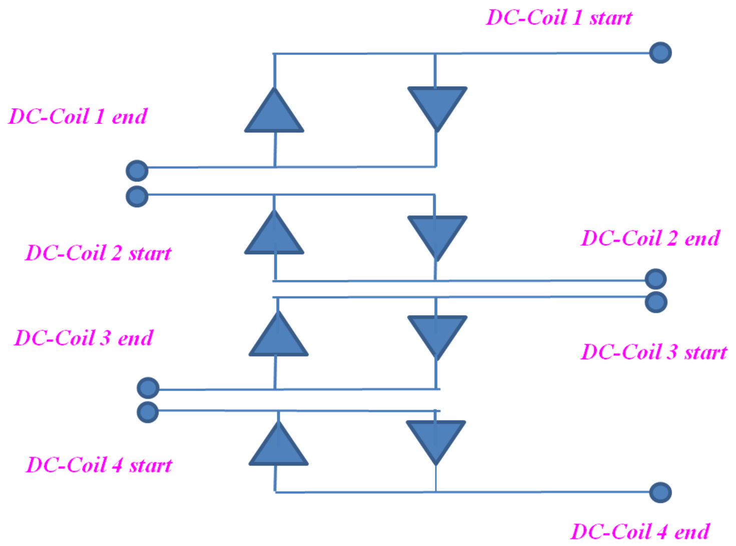
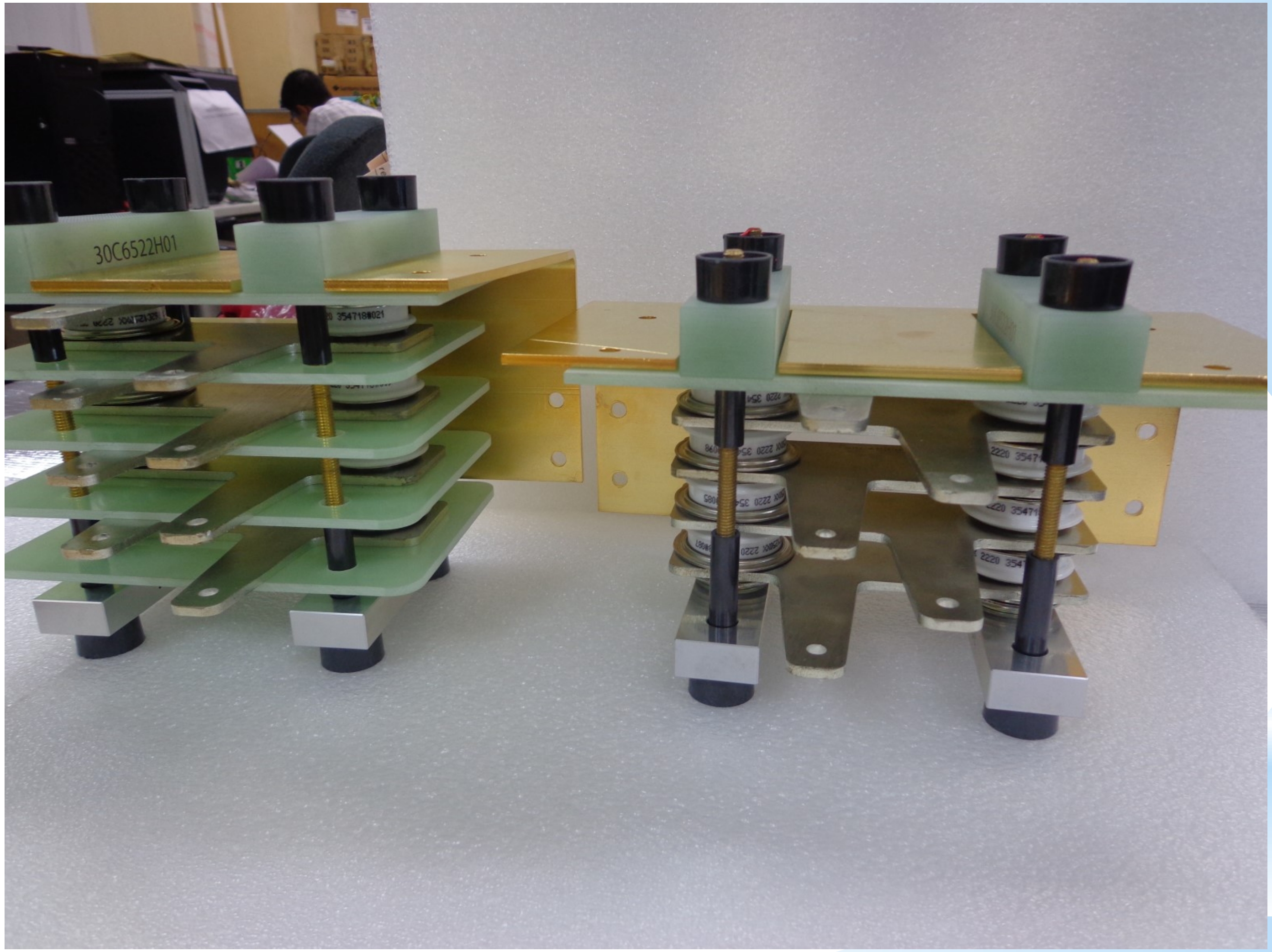


Fig-8: Electrical Schematic of Upper diode stack (routed from terminal block)



Strap material

Sample Details:Cut Piece of Ø 55 mm Round bar, Sample ID: E, Material: OFHC Copper (C101)

Submited Size: Cut Piece of Ø 55 mm Round bar — Test No. A

Discipline & Group: (Chemical) & (Metals and Alloys)

Test Method: W/OPN/01 Issue No.:06,BSEN 15079:2015 — **Date of Analysis:** 28/05/2021

Ref Standards: -- -- -- -- -- — **Machine ID:** ME/OES/191

Spectro Analysis — **Test No. A**

Parameter	Min. Value	Max. Value	Result/Observation
Oxygen %	--	--	0.0005
Copper %	--	--	99.996
Bismuth %	--	--	<0.001
Cu + Ag*	--	--	99.9961
Silver %	--	--	0.0001

Witnessed By: — **Authorized Signatory**

Checked By:

metaLAB Enterprise A'bad ORIGINAL

Ashok Shah (LM)

-- END TEST --

Annealing not carried out

Heat sink material

MATERIAL DESCRIPTION : COPPER PLATE

SIZE : 220 MM X 270 MM X 46 MM THK

GRADE : ELECTROLYTIC GRADE

	Zn%	Pb%	Sn%	S%	P%	Cr%	Mn%	Si%	Mg%
COMP	0.006	0.002	0.004	0.000	0.000	0.002	0.003	0.003	0.001
REQD	---	0.005 Max	---	---	---	---	---	---	---

	Fe%	Ti%	Al%	Ni%	Cu%				
COMP	0.002	0.000	0.002	0.005	99.970	---	---	---	---
REQD	---	---	---	---	99.900 Min	---	---	---	---

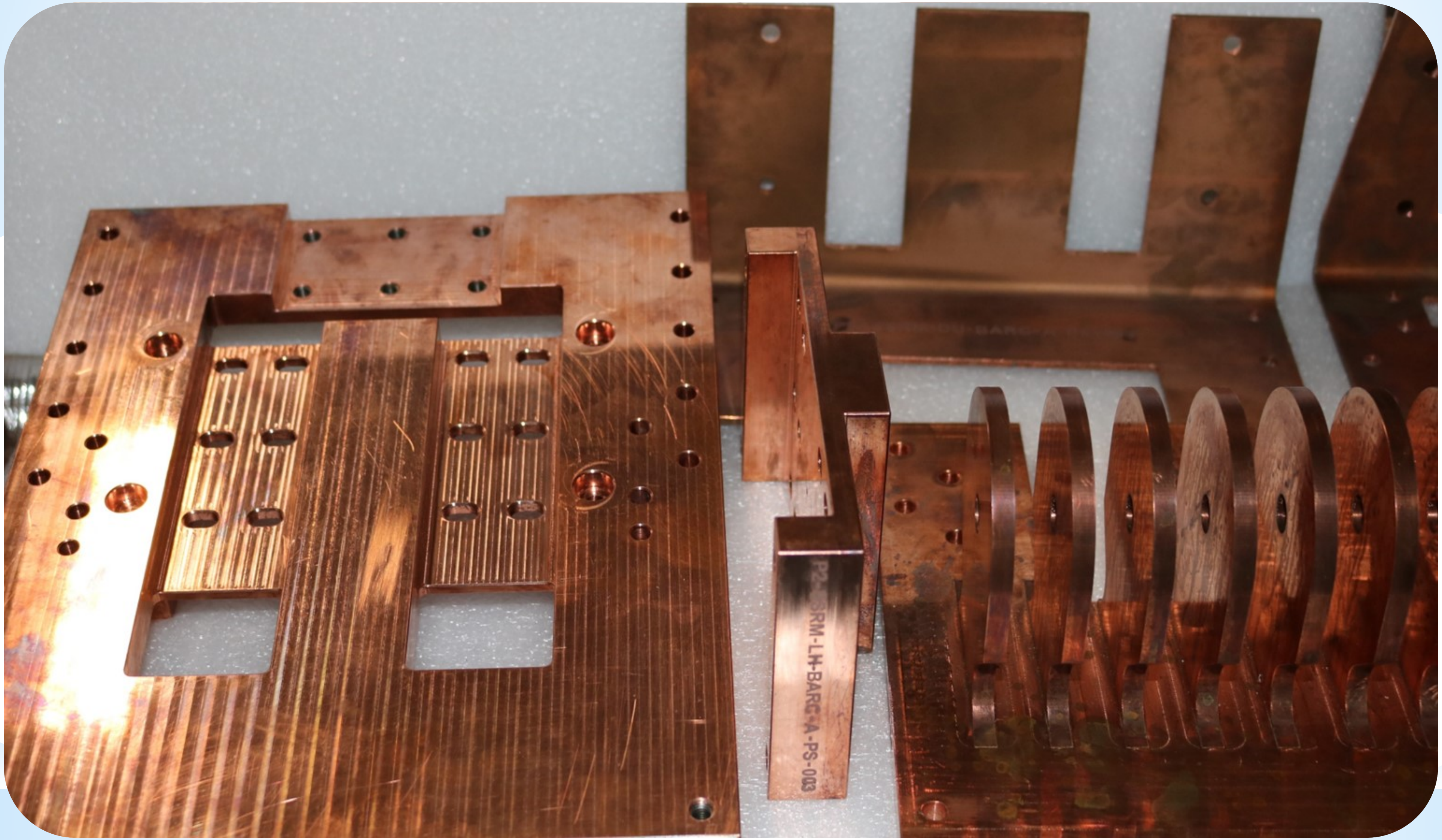
REMARK : THE ABOVE MATERIAL CONFORMS TO E.C. GRADE W.R.T. ELEMENTS SPECIFIED.

FOR MATERIAL TEST LABORATORY

AUTHORISED SIGNATORY

Annealing not carried out

Heat sink assemblies

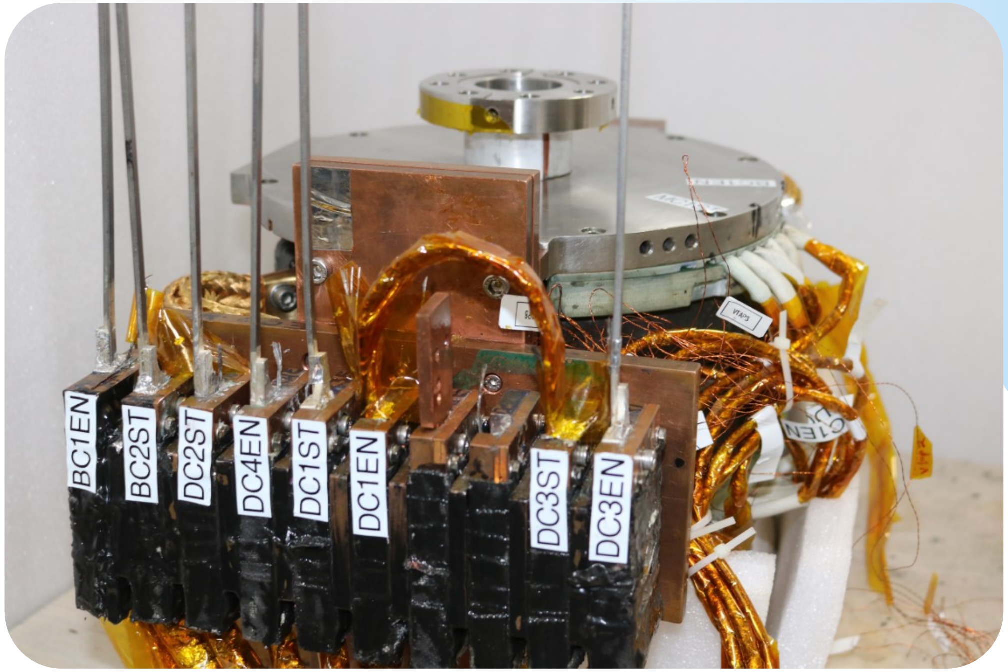


Current lead stack

BALLASTED HTS LEADS

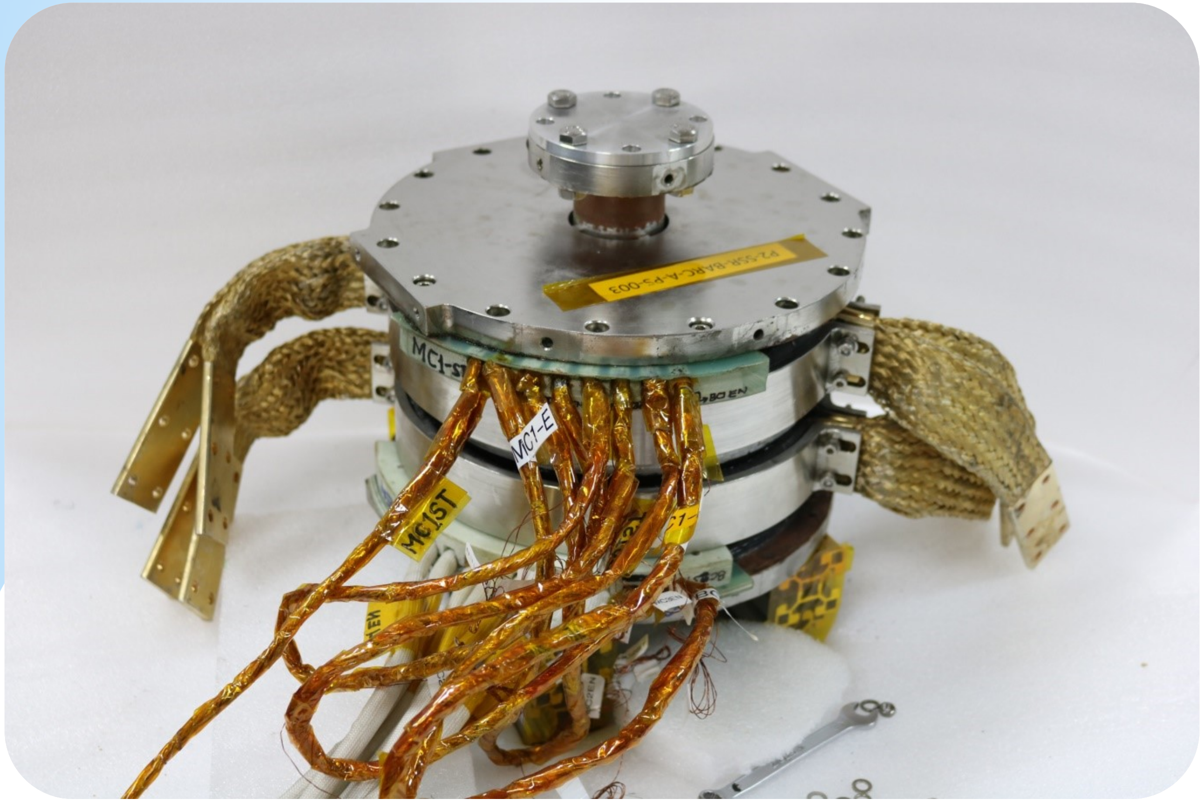
These incorporate a current shunt in the lead body to protect inductive loads in case of lead quench. These have superior mechanical properties compared with conventional leads and can tolerate minor misalignment of contact surfaces.

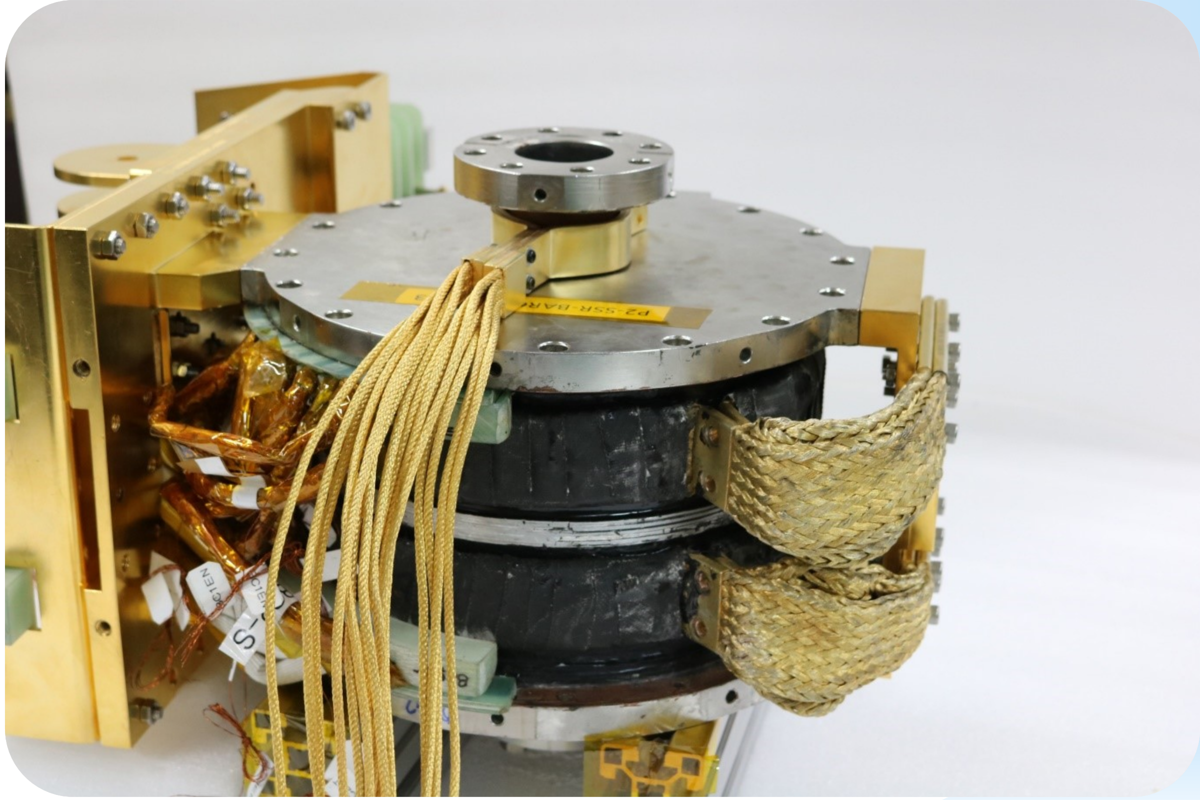
Warm end of the current leads needs slight optimization along with cryomodule Interface and connections on the top flange.



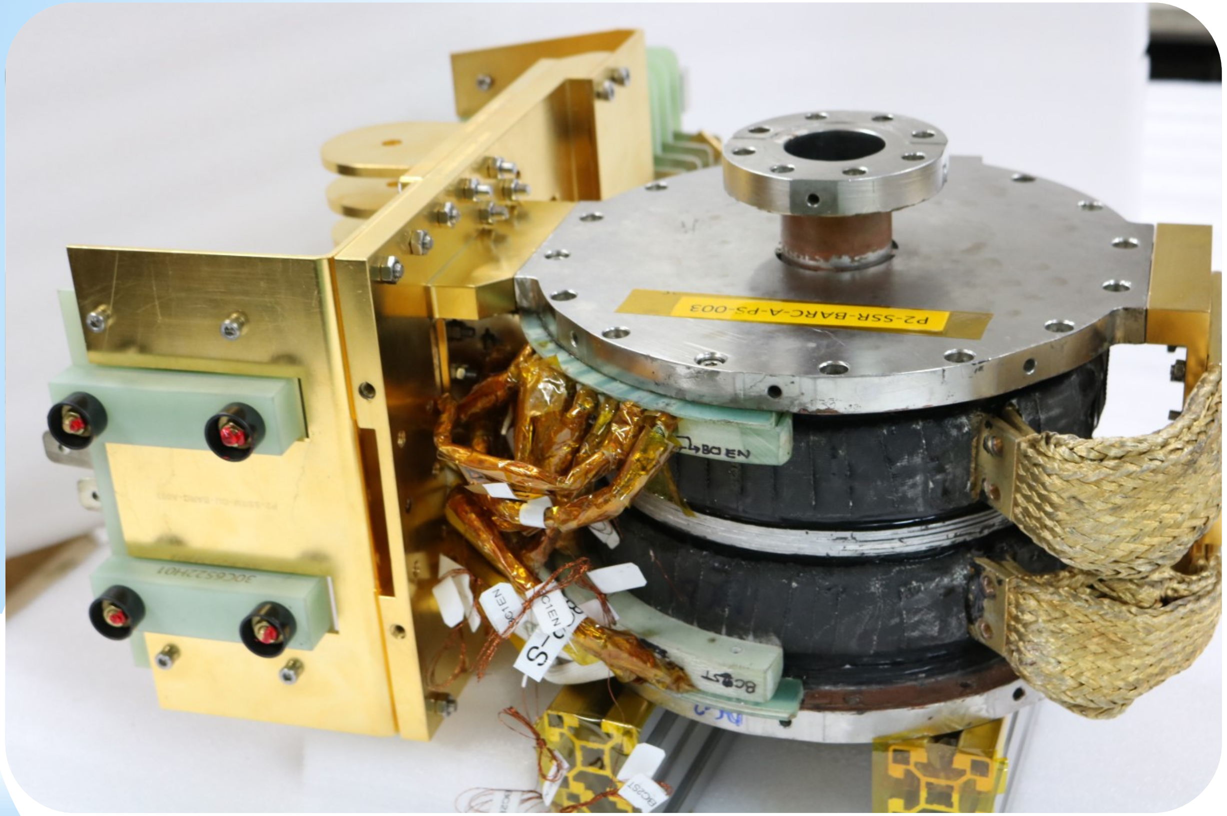
Operating Current A (@ 64K)	Width	HTS length (mm)	Terminal	Connection holes	Calculated Heat Leak 64-4.2K (pair), mW
150A	14-16	114	16x16mm	R2.6 x 2	73mW

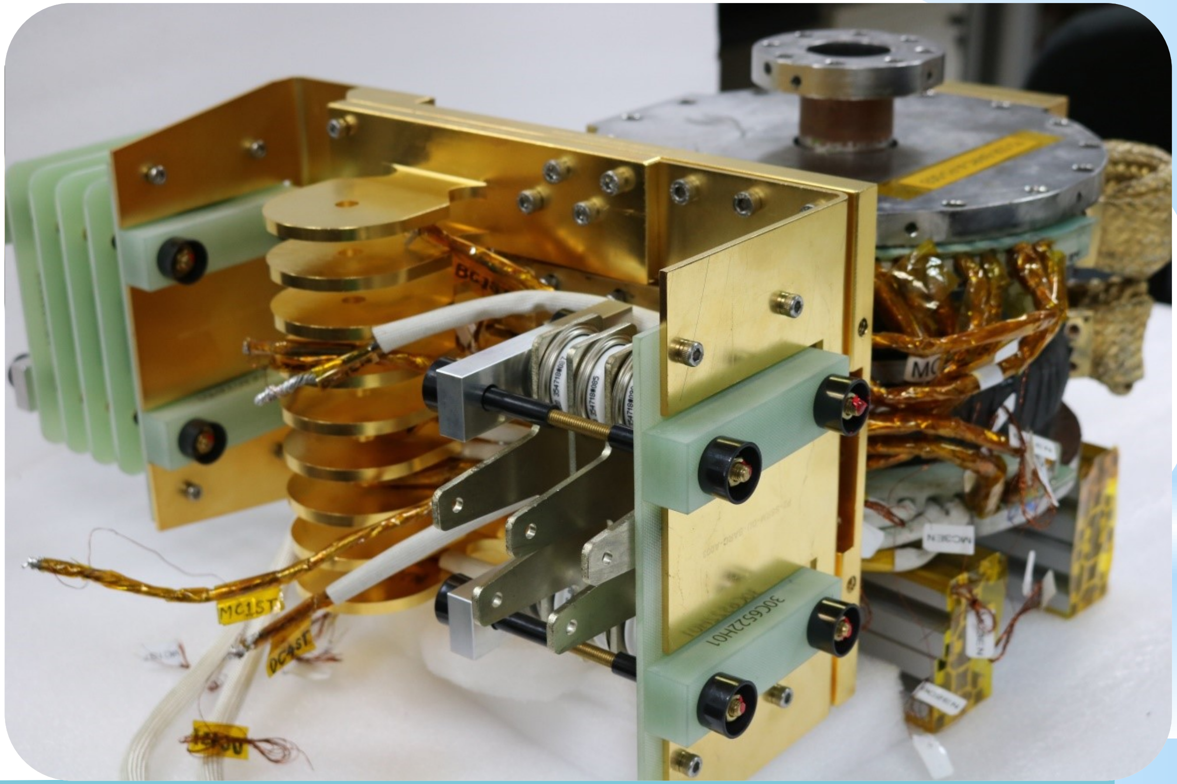
Magnet assembly





Magnet assembly





Summary

- Coil winding carried out under pre-tension (8MPA)
- Wet winding techniques used for coils
- Corrector cage is the largest cross-section without any metal and hence heat escape is challenging from the localized area
- Additional thermal straps from bulk of the magnet assembly shall help improving the Thermal performance.

Thanks