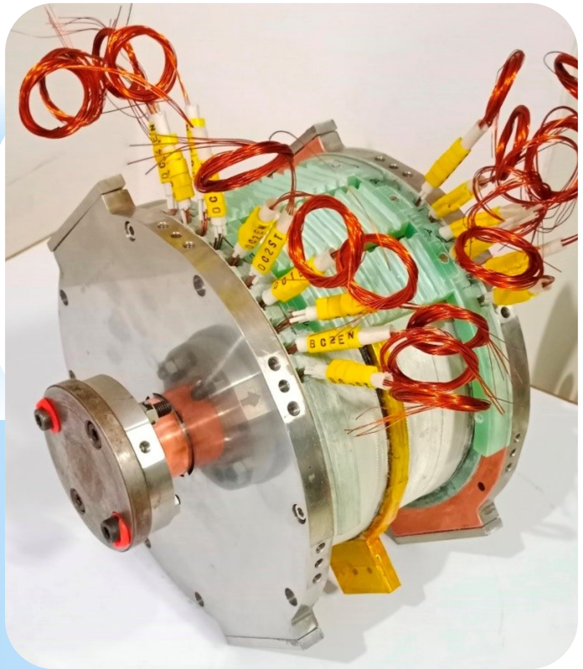
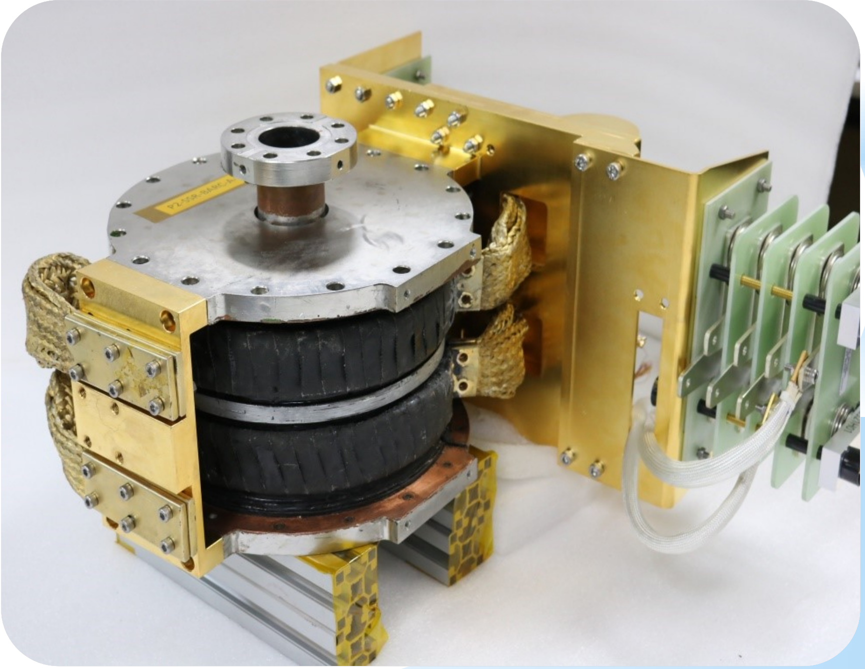
Test stand integration and cryogenic qualification of pre-series 6T conduction cooled magnet assemblies



Electromagnetic Application & Instrumentation Division

Bhabha Atomic Research Centre



Tests carried out on Magnet assemblies

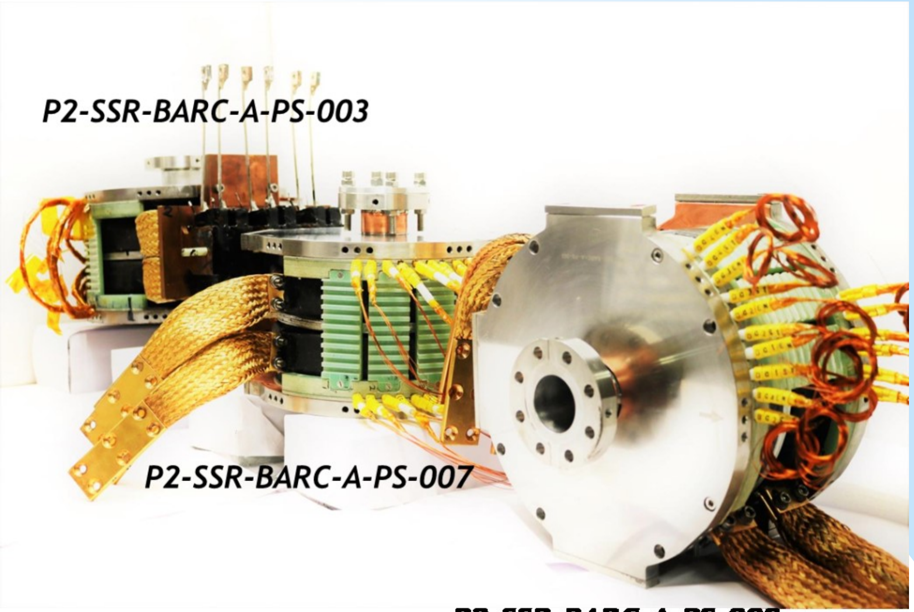
Warm Electrical Qualification – R,L and Q, Impulse test and Hipot test

Warm magnetic field measurement (Transfer function, coil polarity measurement)

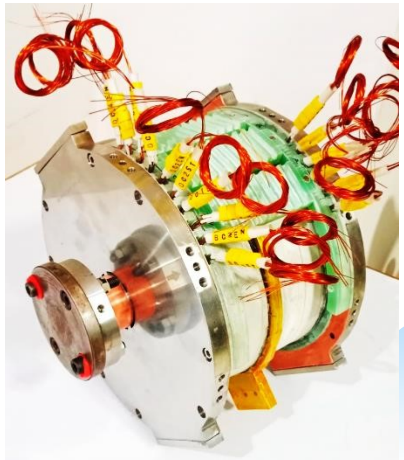
Cold transfer function measurement for main solenoid, dipole corrector coils

Axial field mapping of main solenoid, dipole correctors and combined field mapping

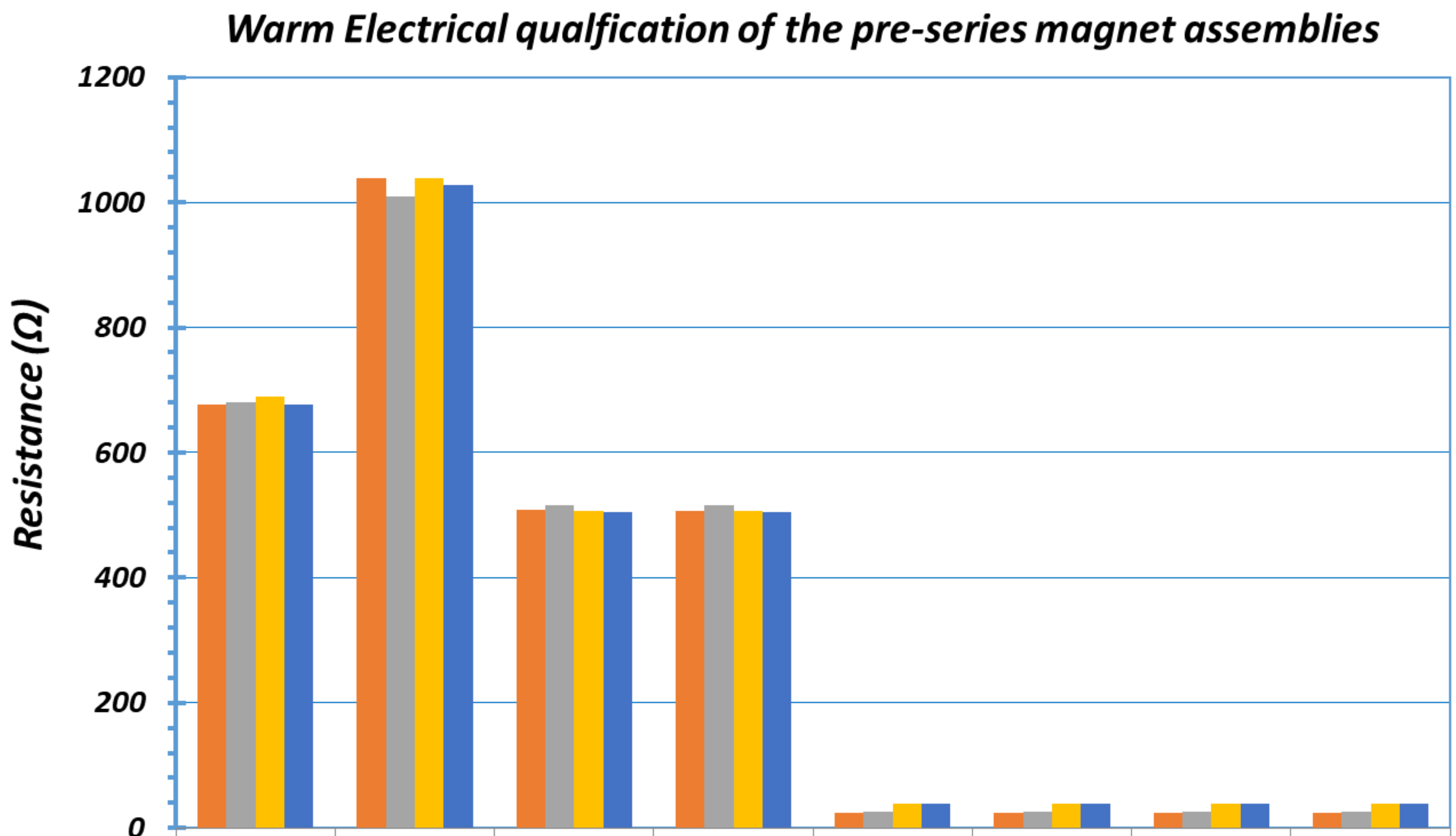
Fringe field measurements, temperatures logging, ramp rate tests, Quench monitoring



P2-SSR-BARC-A-PS-008

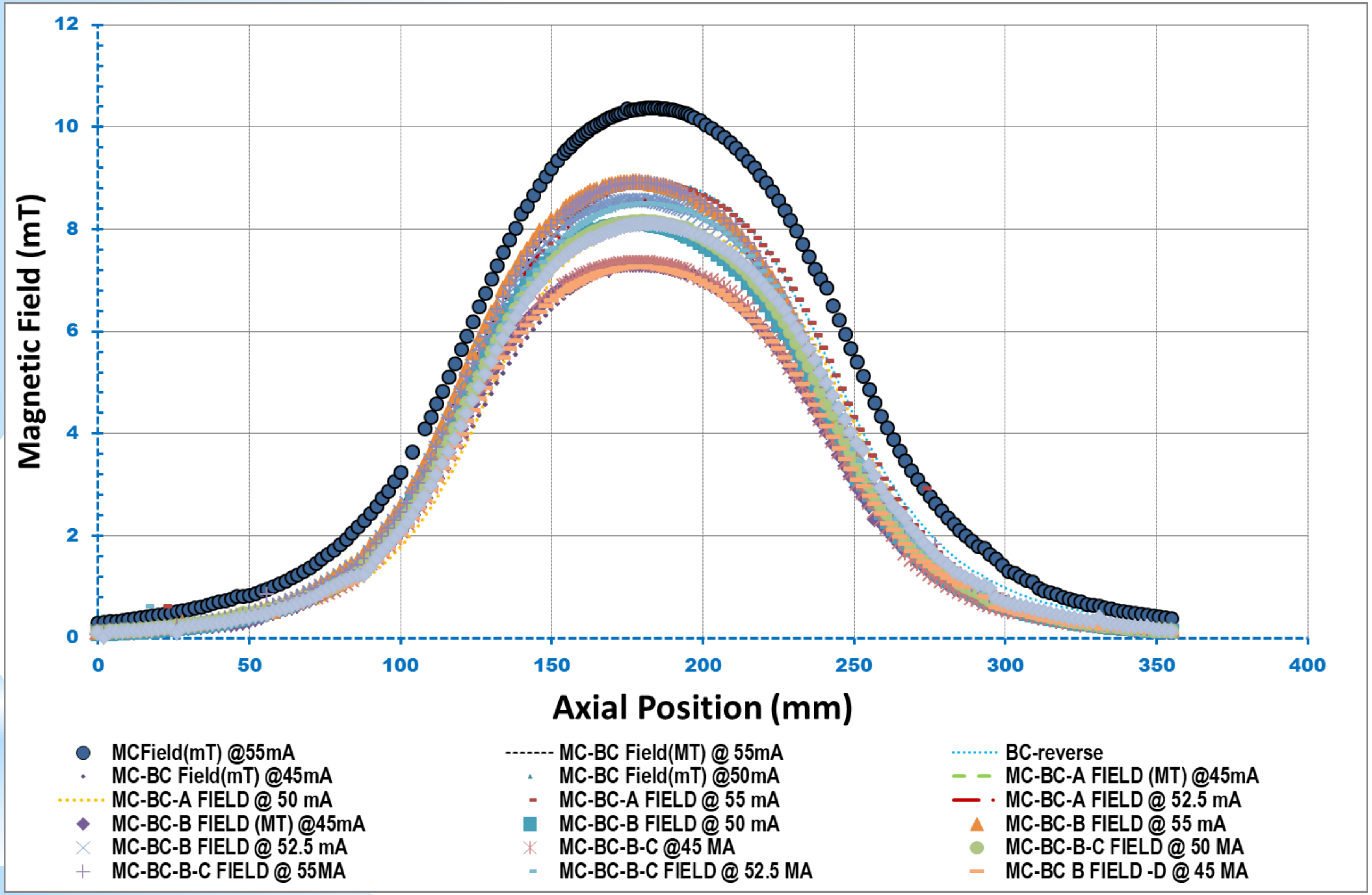

P2-SSR-BARC-A-PS-009

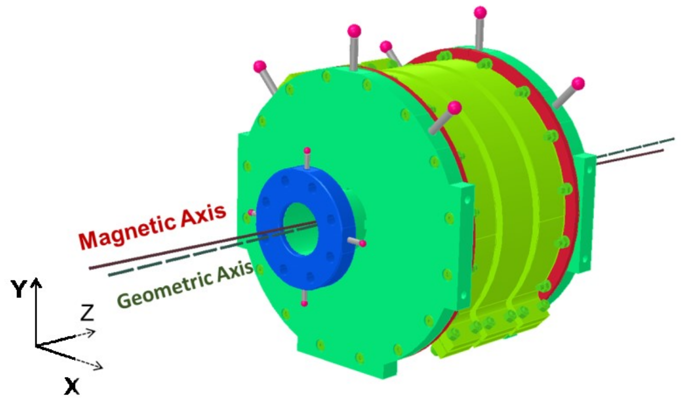
Electrical Measurement



	Main coil 1 nresistance (Ω)	Main Coil 2 resistance (Ω)	Bucking Coil 1 resistance (Ω)	Bucking Coil 2 resistance (Ω)	Dipole Corrector 0deg Coil resistance (Ω)	Dipole Corrector 90deg Coil resistance (Ω)	Dipole Corrector 180deg Coil resistance (Ω)	Dipole Corrector 270deg Coil resistance (Ω)
Magnet No.:- P2-SSR-2PS-A-BARC-004	676.96	1038.9	508.9	506.8	24.627	24.635	24.765	24.336
Magnet No.:- P2-SSR-2PS-A-BARC-007	680.74	1009.75	516.51	516.65	25.31	25.35	25.32	25.39
Magnet No.:- P2-SSR-2PS-A-BARC-008	690	1038	507.1	507.1	38.2	38.2	38.2	38.2
Magnet No.:- P2-SSR-2PS-A-BARC-009	677	1027	505.4	505.2	39	38.74	38.56	38.73

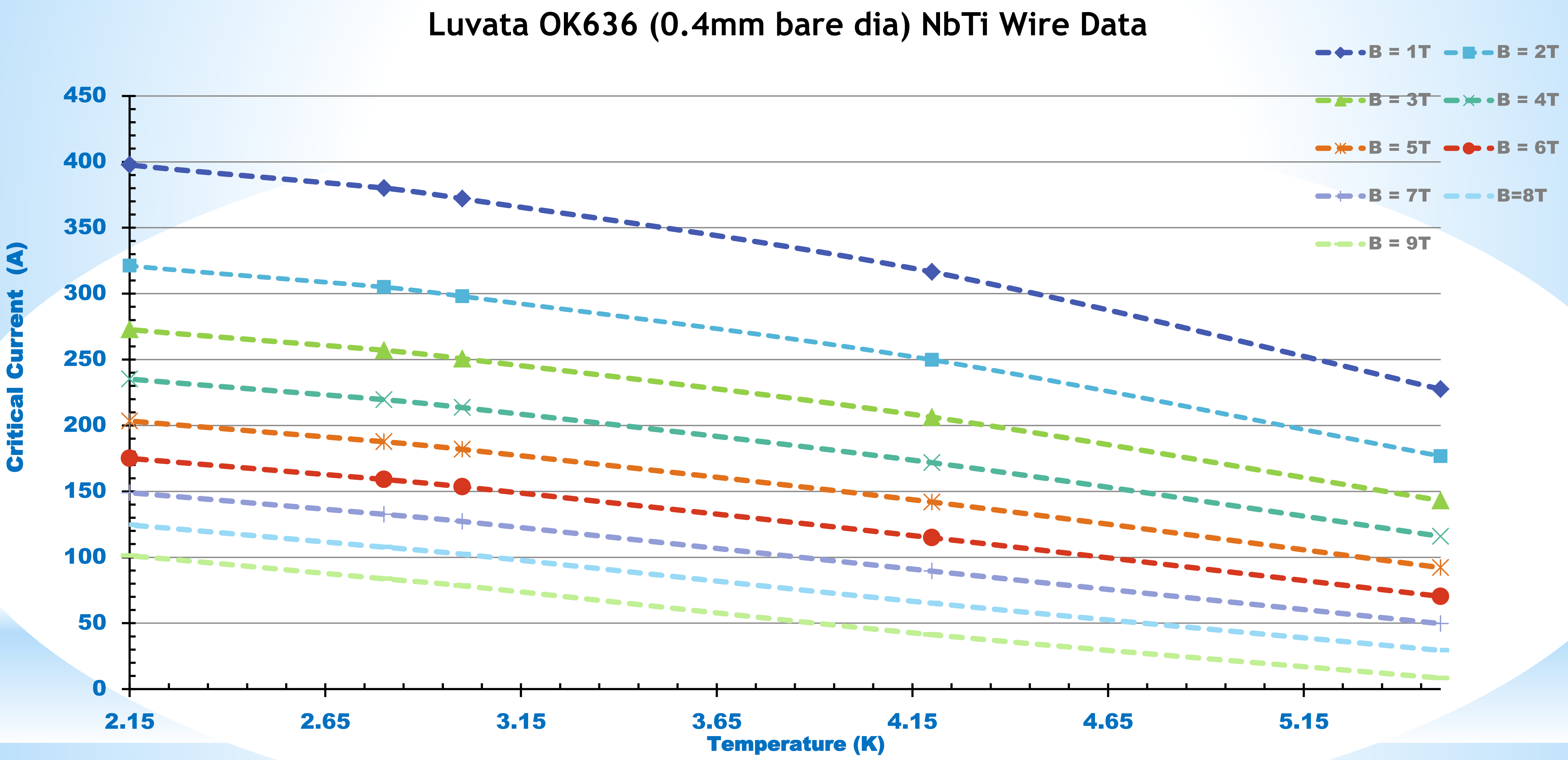
Warm magnetic field mapping





- To diagnose transfer function, coil polarity, Bucking coil position errors during manufacturing

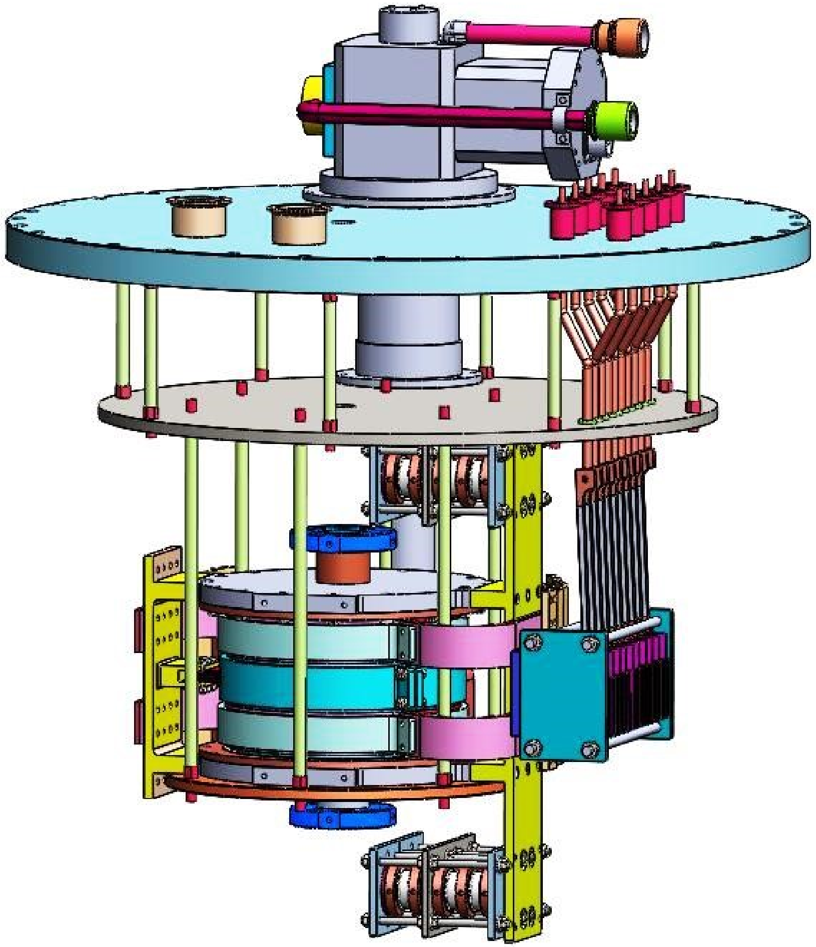
Superconducting Wire strand properties (A vs T) {mail query response}



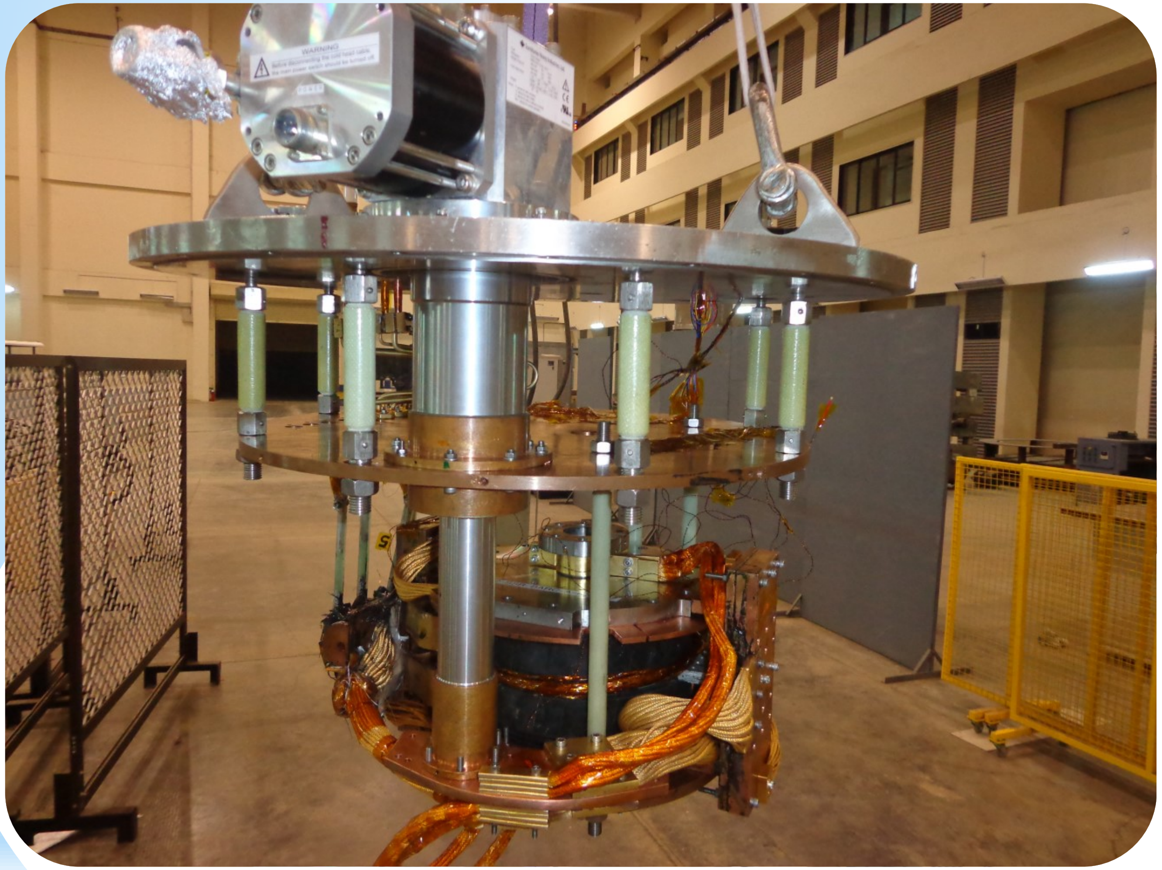
Superconducting Wire strand material properties

t(K)/ B (T)	1	2	3	4	5	6	7	8	9	10
2	408.24	329.38	279.50	240.75	207.86	178.55	151.60	126.27	102.04	78.51
2.15	403.46	325.23	275.68	237.16	204.43	175.24	148.38	123.12	98.93	75.42
2.5	391.40	314.77	266.06	228.09	195.77	166.88	140.25	115.15	91.07	67.59
2.8	380.09	304.96	257.04	219.59	187.64	159.04	132.62	107.67	83.68	60.19
3	372.07	298.00	250.65	213.57	181.88	153.48	127.21	102.36	78.42	54.92
3.5	350.41	279.23	233.38	197.30	166.33	138.45	112.56	87.97	64.12	40.48
4	326.58	258.56	214.38	179.39	149.19	121.88	96.39	72.01	48.16	24.07
4.2	316.46	249.79	206.32	171.78	141.92	114.84	89.50	65.19	41.28	16.80
4.5	300.69	236.11	193.75	159.93	130.56	103.84	78.72	54.48	30.38	4.59
5	272.86	211.99	171.57	139.00	110.51	84.36	59.55	35.23	10.02	0.00

Cryogenic test stand for magnet testing



Magnet testing – Temperature & voltage tap monitoring

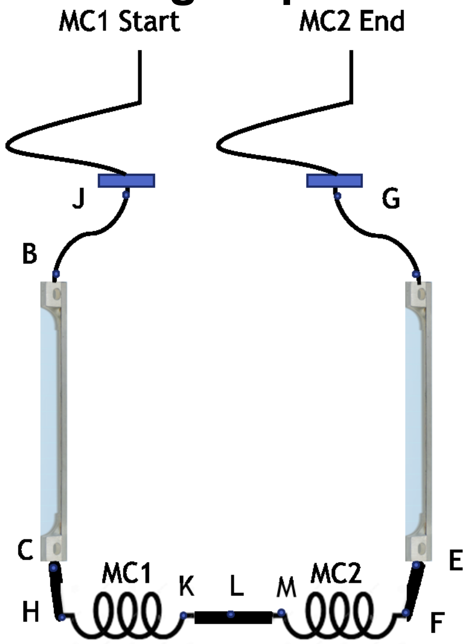


Magnet assembly integrated with test stand

Temperature sensors

Sensor 1	Sensor 2	Sensor 3	Sensor 4
Magnet strap 1	Magnet strap 2	2nd stage Cold head plate	LH heat sink
Sensor 5	Sensor 6	Sensor 7	Sensor 1
RH heat sink	CL heat sink	Bobbin	Thermal shield bottom

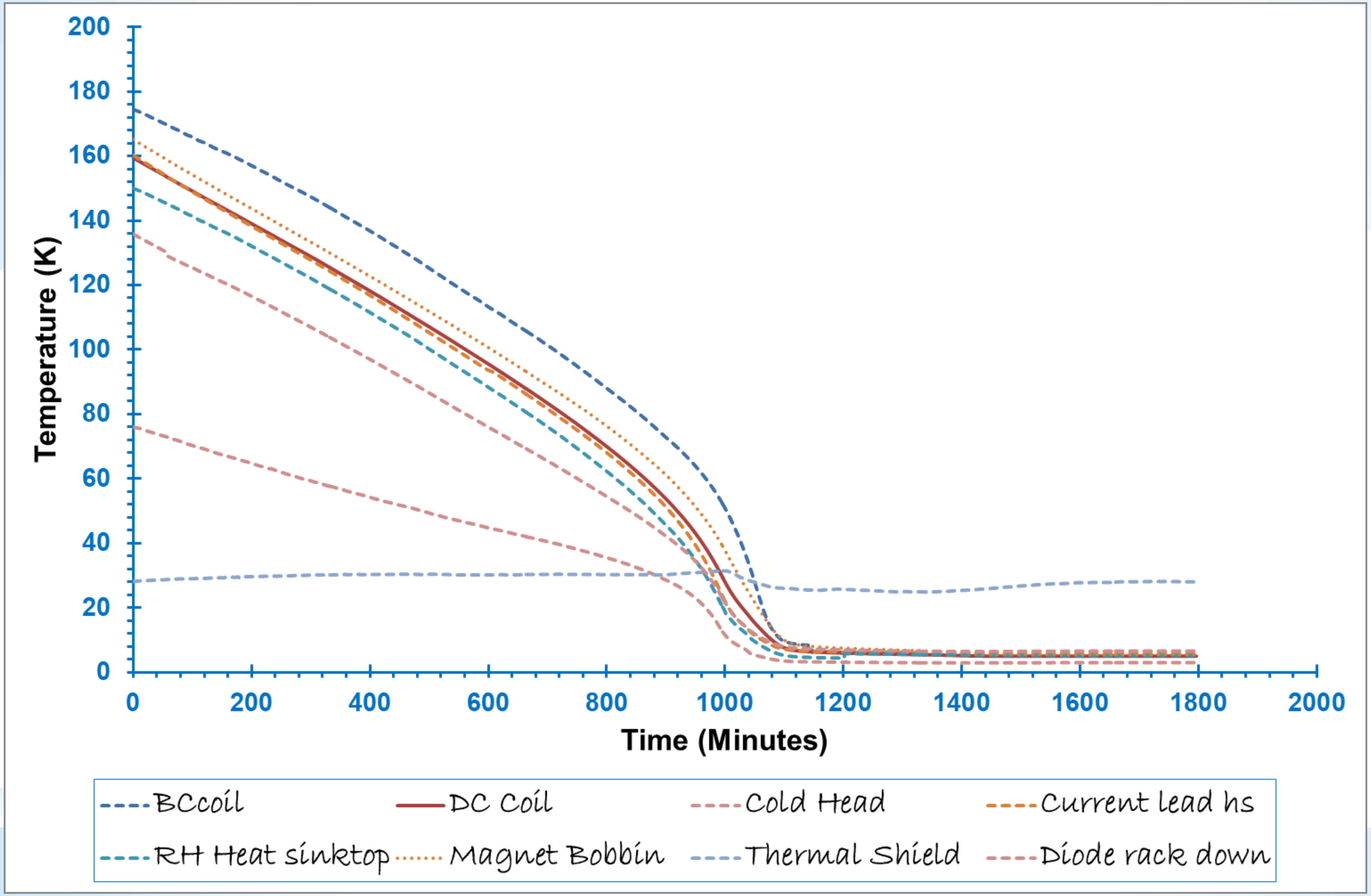
Voltage taps



Voltage tap Locations
MC1 Start HTS lead Top “B” & Bottom “C”
MC1 END HTS lead Top “D” & Bottom “E”
MC2 Start HTS lead Top “F” & Bottom “G”
MC2 End HTS lead Top “H” & Bottom “J”

BJ -drop gives ***warm lead drop***
HF -drop monitoring for ***Ldi/dt***
BC-drop gives information for ***HTS drop***
KM -check whether joint is ***superconducting***

Magnet cool down



Electrical Measurement P2-SSR-BARC-A-007

Magnet Sr. No.	P2-SSR-BARC-A-PS-007

WINDING DETAILS OF MAIN COILS

MC-1	
Total Turns	11700
Total Layrs	45
Supercouctor Dia.	0.44
Superconductor Grade	OK636
Resistance	667 Ω
Diameter	97.0 mm

MC-2	
Total Turns	11817
Total Layrs	45
Supercouctor Dia.	0.44
Superconductor Grade	OK636
Resistance	989 Ω
Diameter	137.0 mm

WINDING DETAILS OF BUCKING COILS

BC-1	
Total Turns	3600
Total Layrs	30
Supercouctor Dia.	0.44
Superconductor Grade	OK 636
Resistance	507 Ω
Diameter	203.0 mm

BC-2	
Total Turns	3600
Total Layrs	30
Supercouctor Dia.	0.44
Superconductor Grade	OK 636
Resistance	507 Ω
Diameter	203.0 mm

WINDING DETAILS OF DIPOLE CORRECTOR COILS

DC-1	
Total Turns	300
Supercouctor Dia.	0.44
Superconductor Grade	OK 636
Resistance	24.5 Ω

DC-2	
Total Turns	300
Supercouctor Dia.	0.44
Superconductor Grade	OK 636
Resistance	25.0 Ω

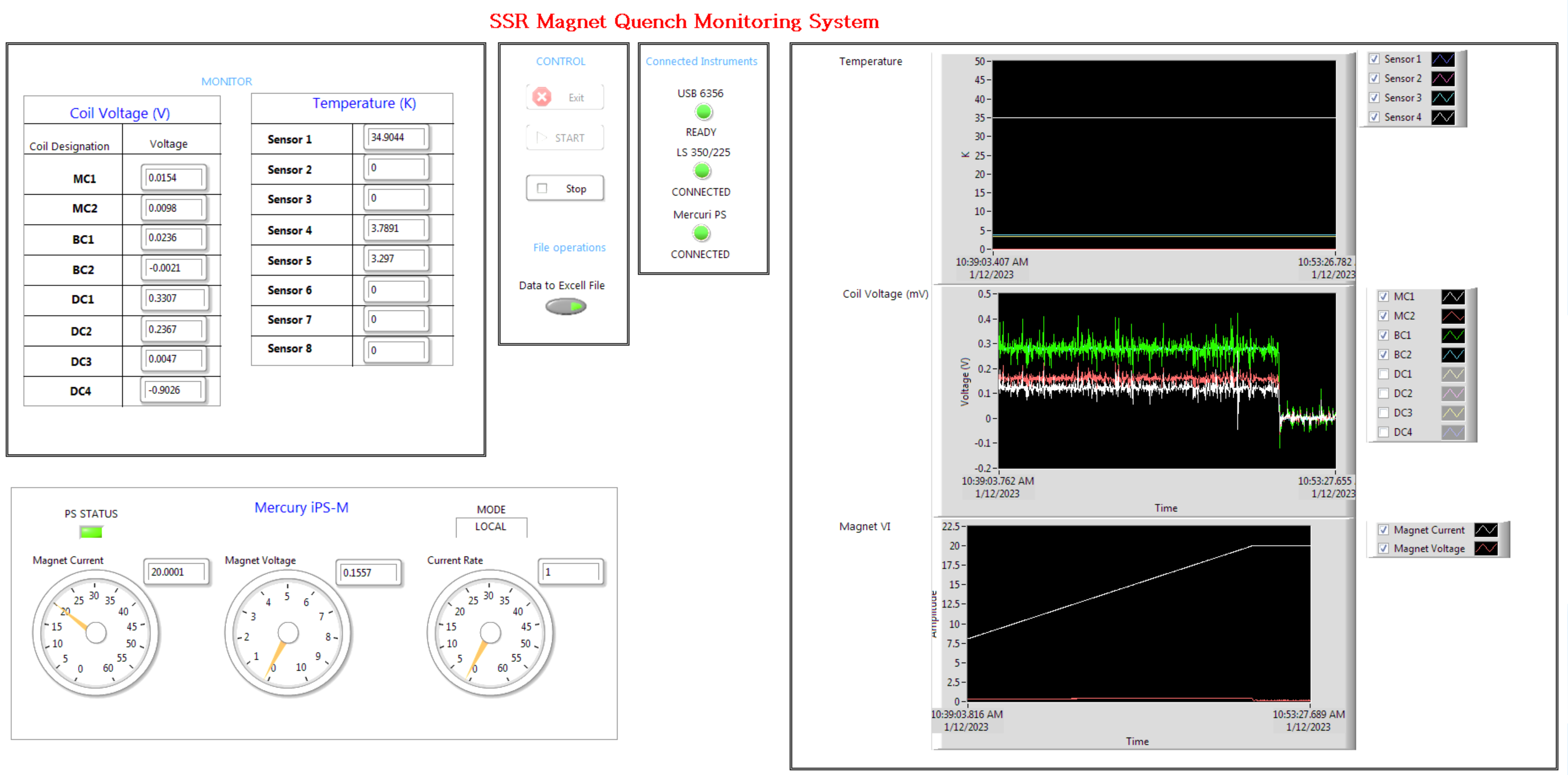
DC-3	
Total Turns	300
Supercouctor Dia.	0.44
Superconductor Grade	OK 636
Resistance	24.7 Ω

DC-4	
Total Turns	300
Supercouctor Dia.	0.44
Superconductor Grade	OK 636
Resistance	25.2 Ω

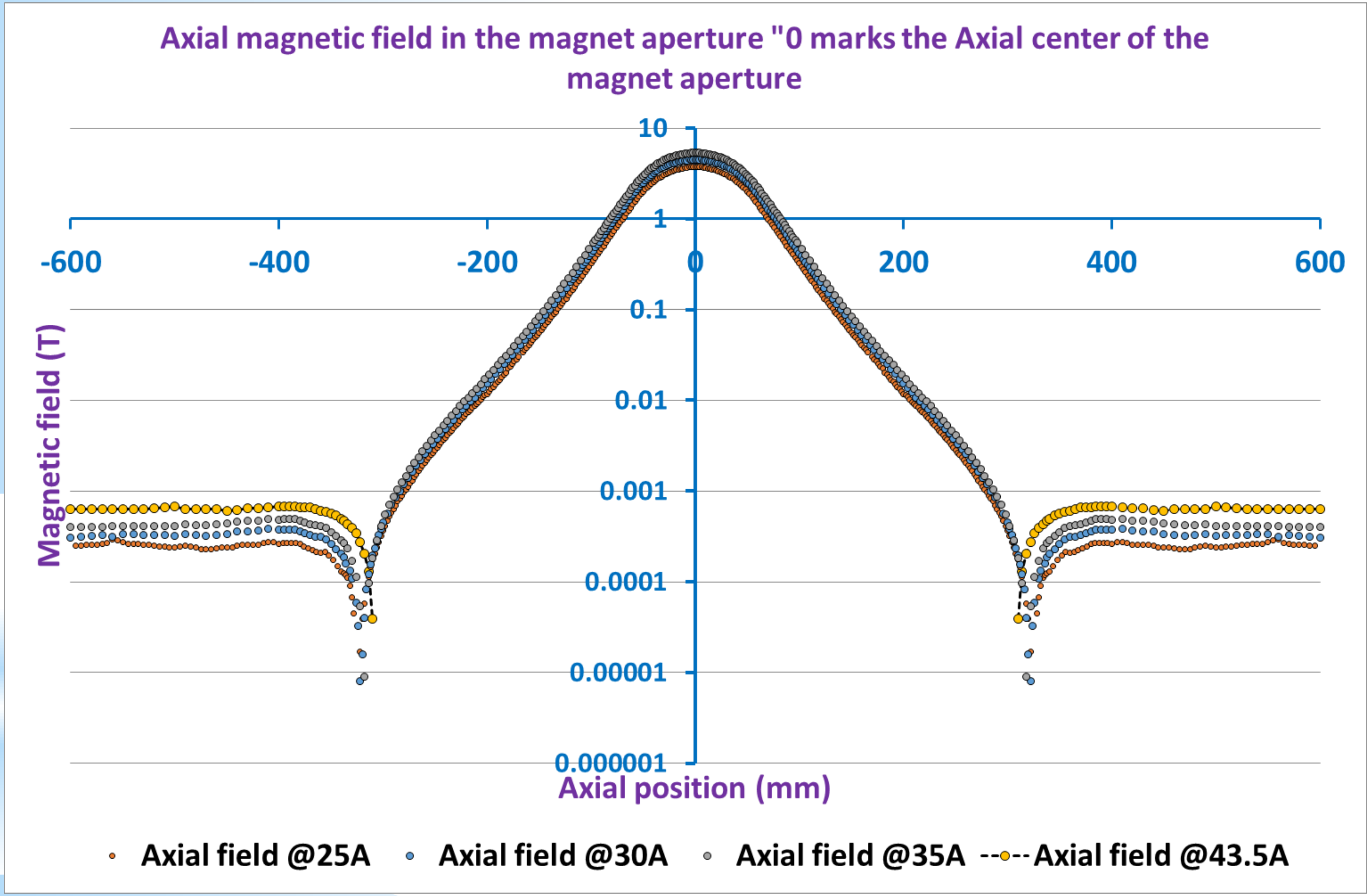
Measured Resistance, Inductance and Q

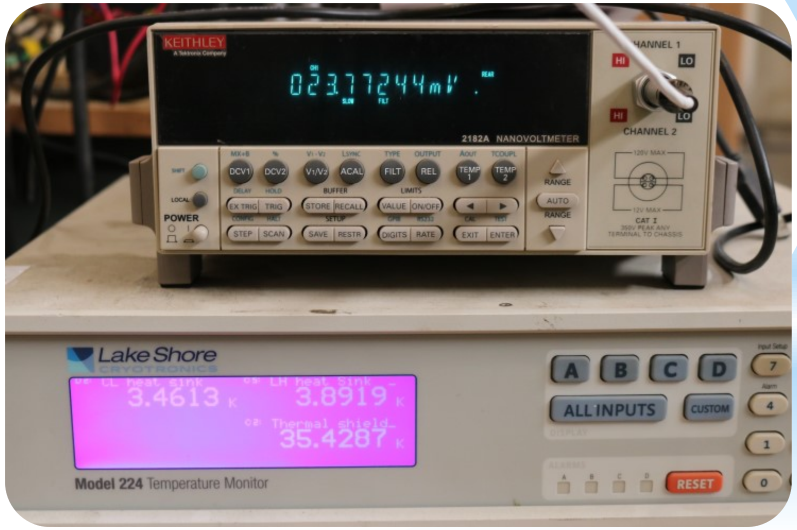
Coil	Resistance (Ω)	L@100Hz (mH)	Q@100Hz	L@1KHz (mH)
MC1	680.74	3793.3	2.11	2002.4
MC2	1009.75	6284.7	1.50	650.75
BC1	516.51	1467.5	0.81	775.51
BC2	516.65	1580.6	0.88	846.85
DC1	25.31	15.88	0.40	14.9
DC2	25.35	15.93	0.40	14.99
DC3	25.32	15.99	0.40	15.03
DC4	25.39	15.92	0.40	14.98

Ramping up of main coil

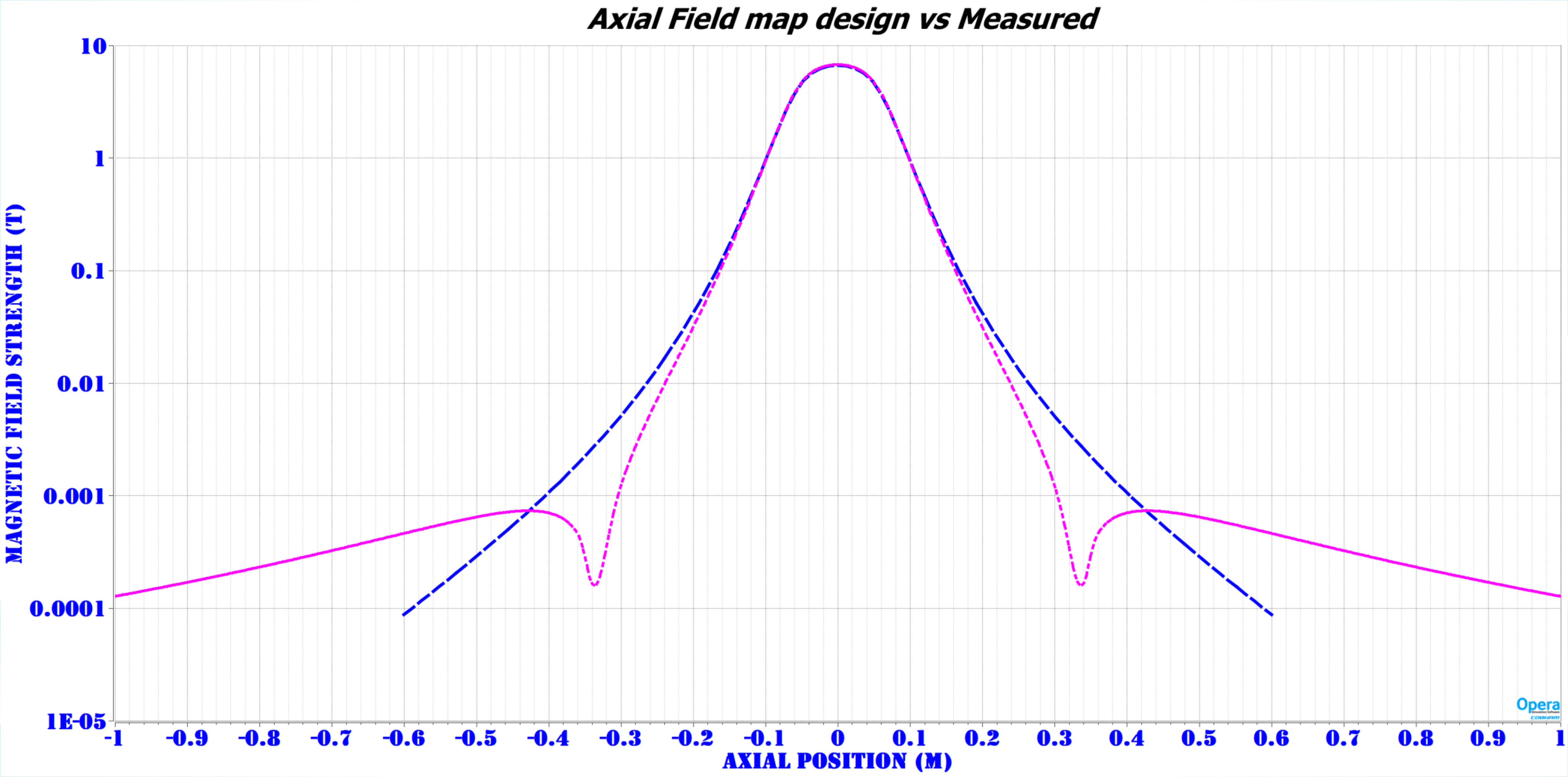


SSR magnet assembly – Axial field mapping

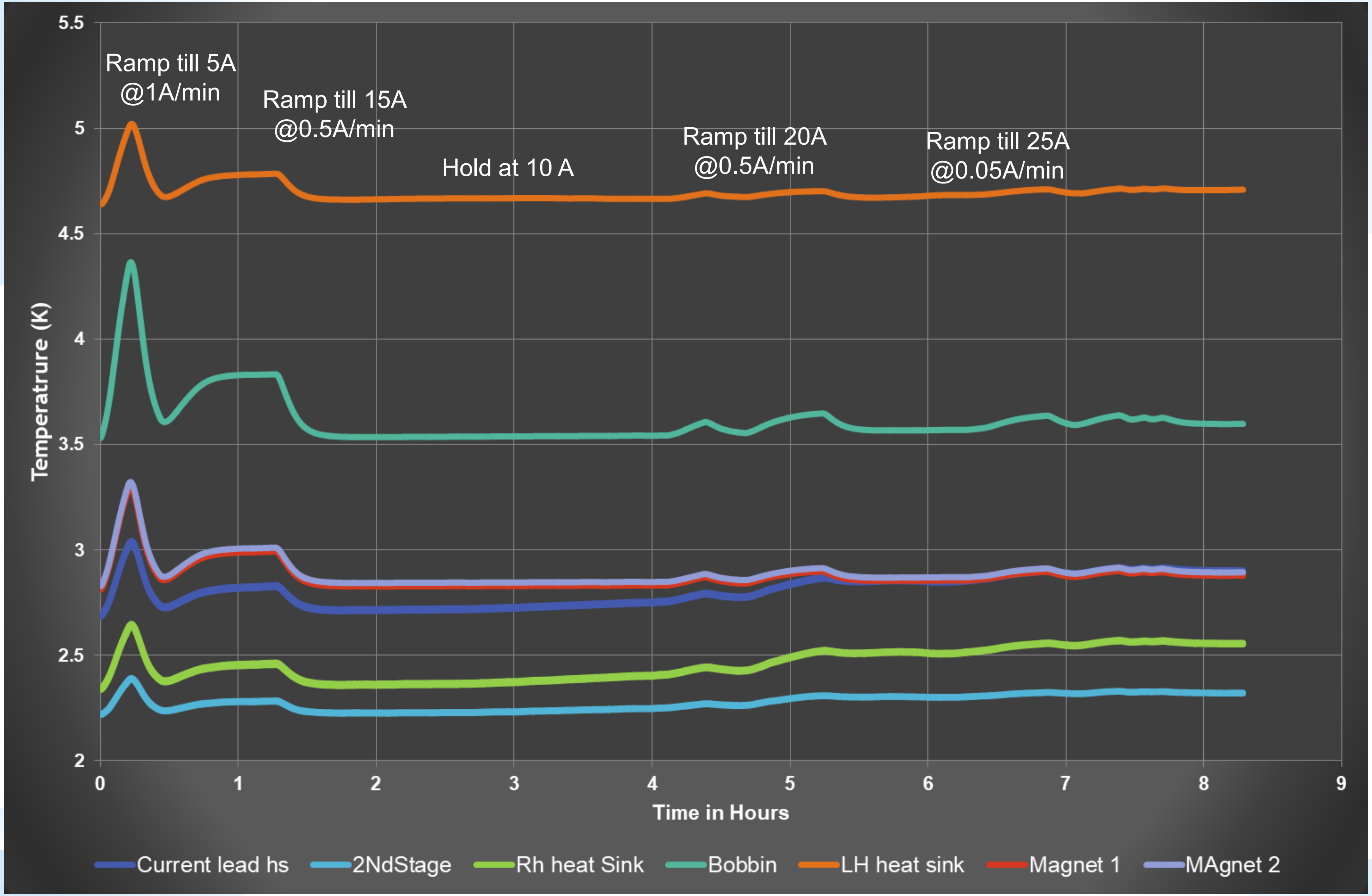




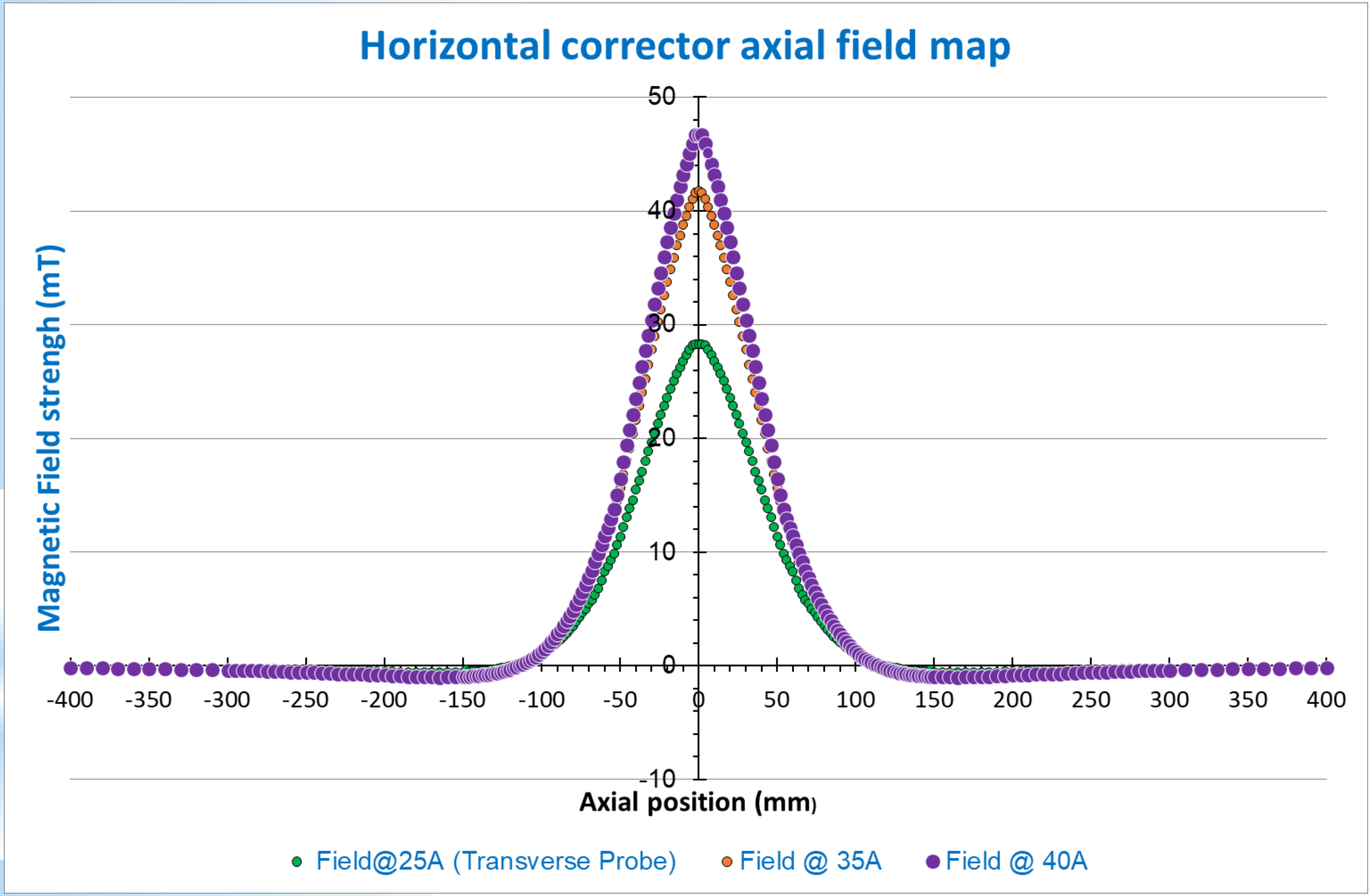
As constructed magnet vs design



MC Ramp tests



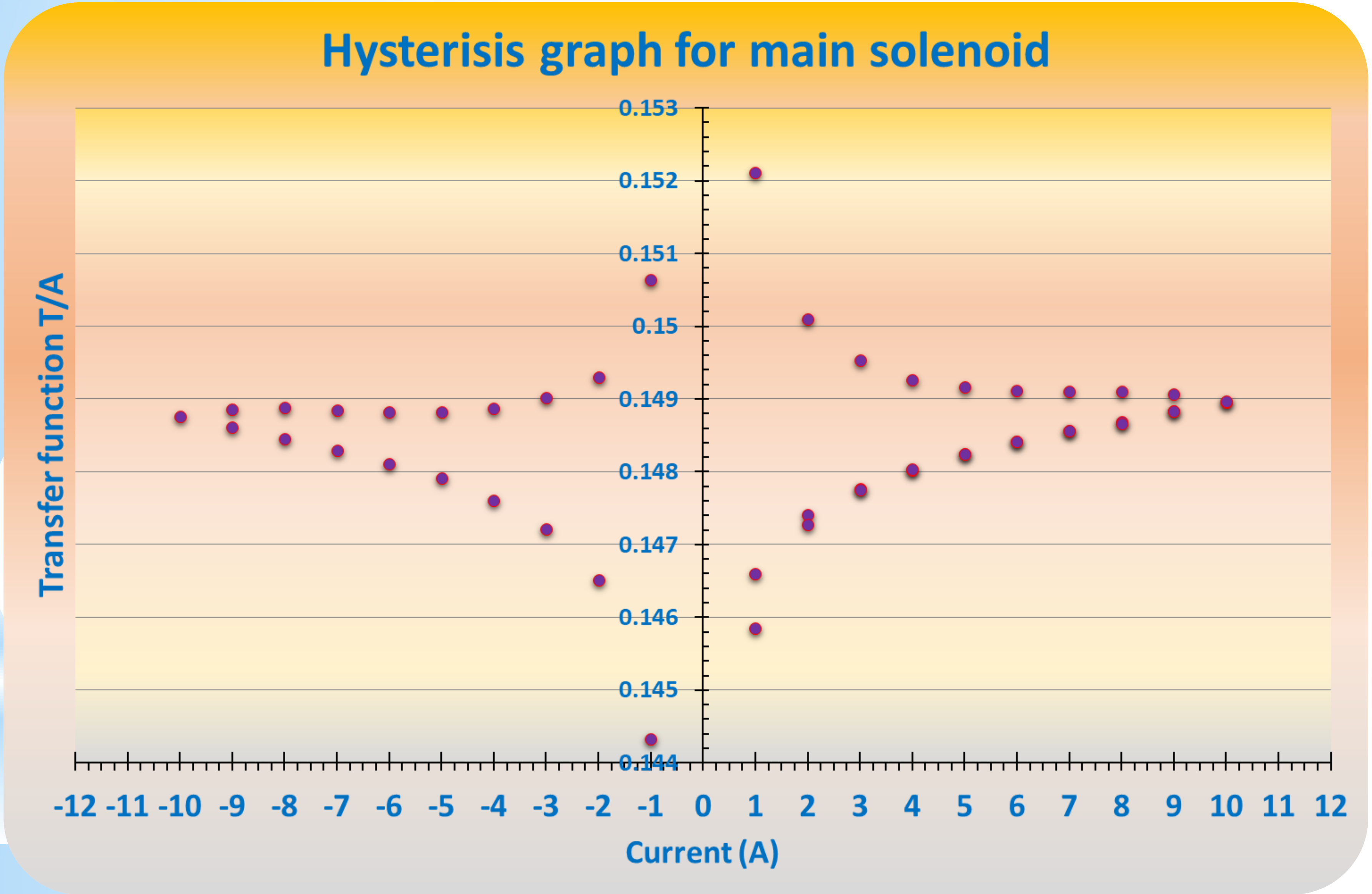
Dipole corrector Axial field map

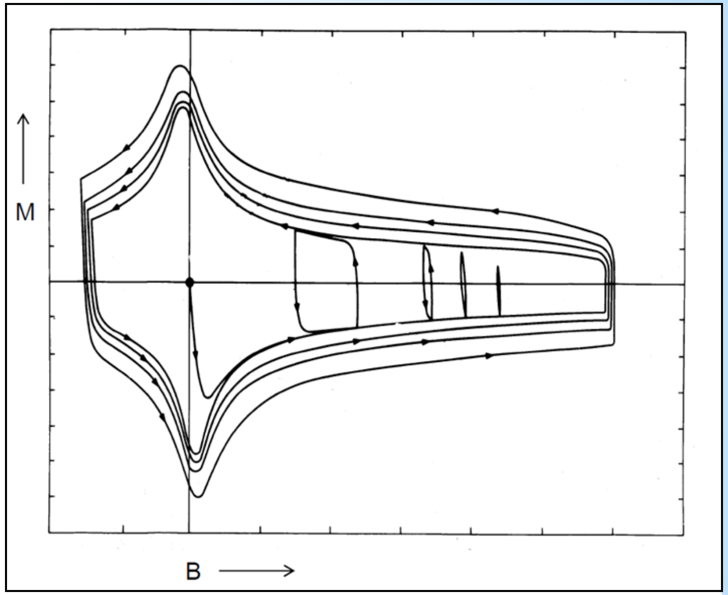


Horizontal corrector transfer function – 1.19mT/A

Vertical corrector transfer function – 1.1 mT/A

Magnetization of the superconductor





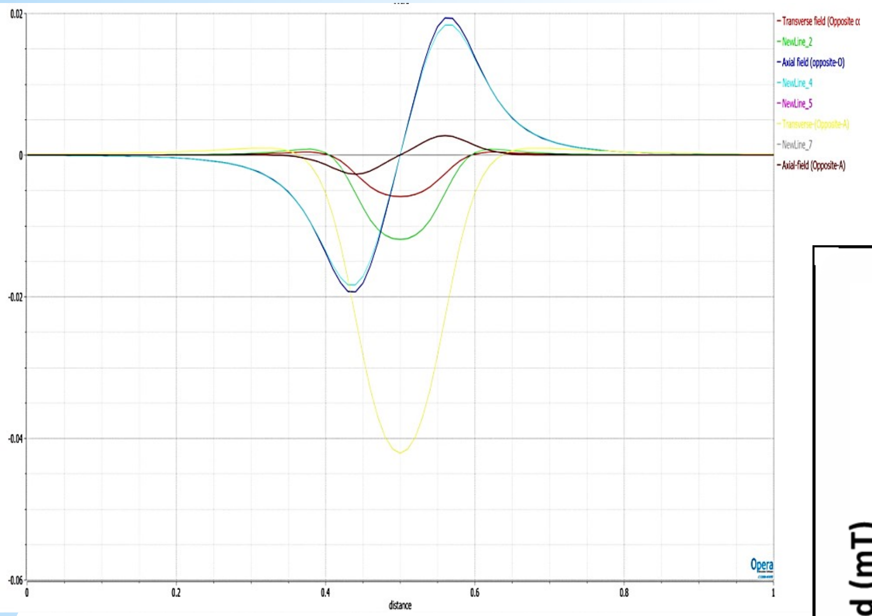
Magnetization has two components :Persistent current in the filaments

$M_f = \frac{2}{3\pi} J_c d_f$ depends on B

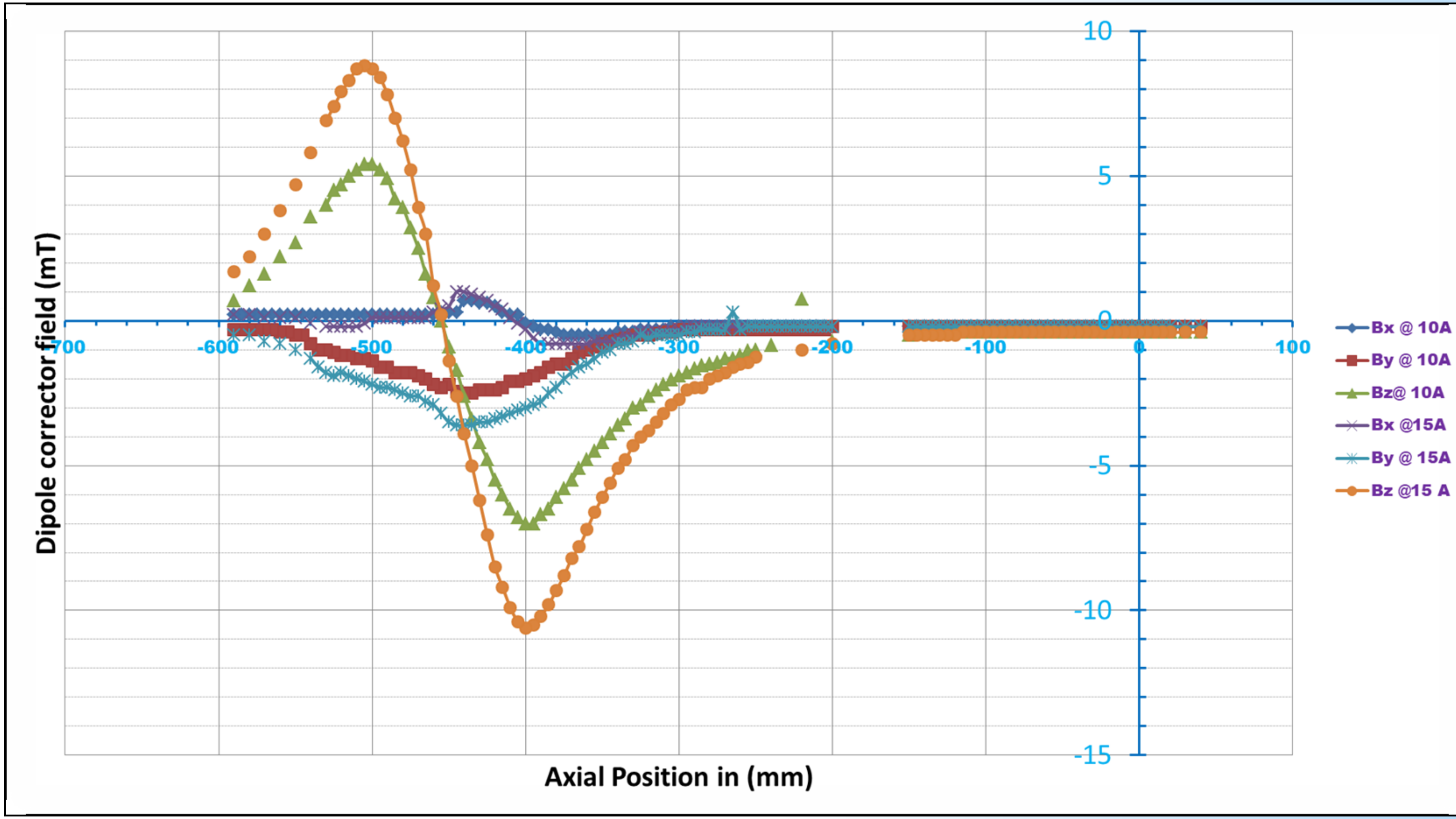
Eddy current coupling between filaments

$M_e = \frac{dB}{dt} \frac{1}{\rho_t} \left[\frac{p_w}{2\pi}\right]^2$ depends on dB/dt

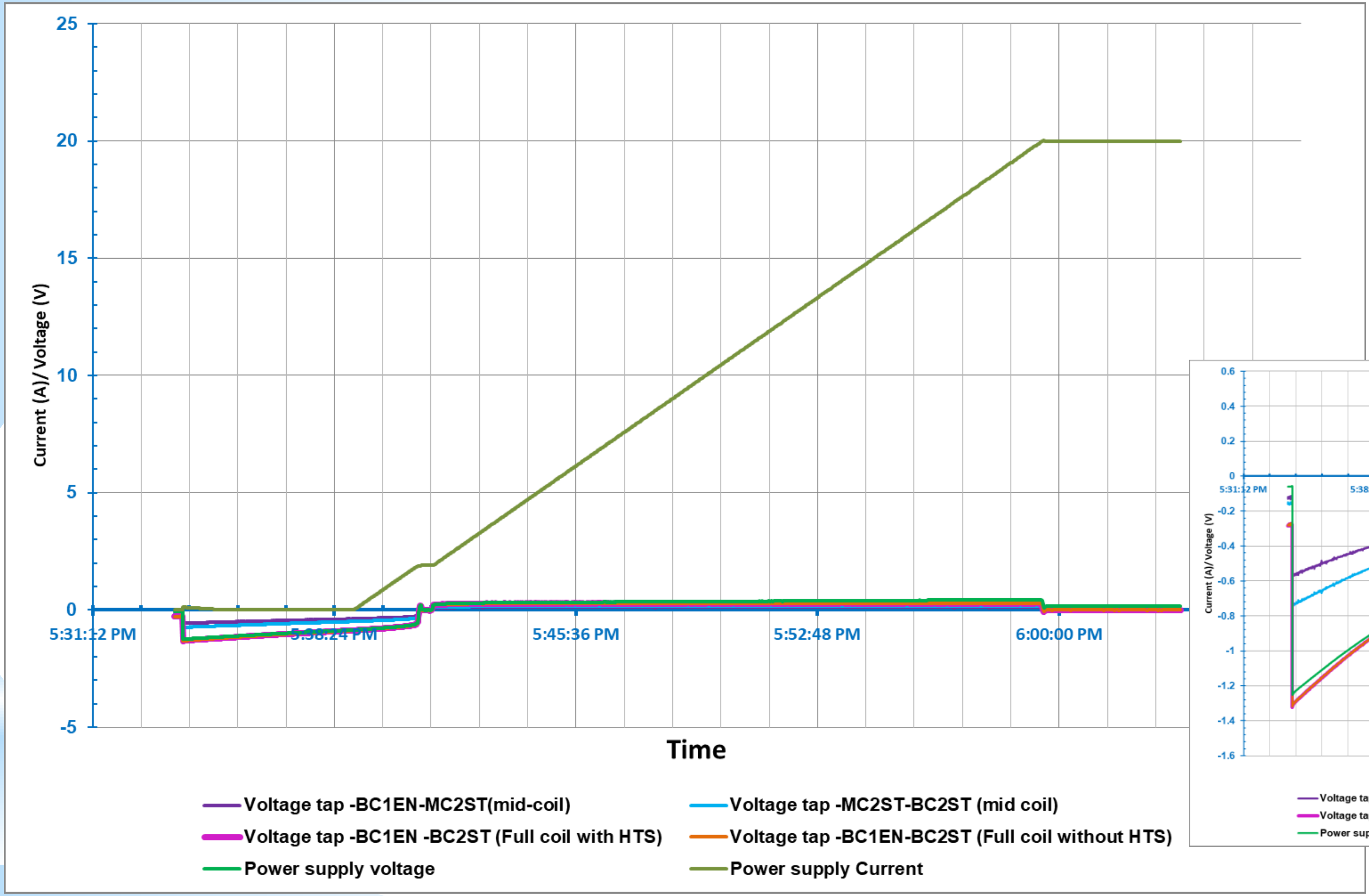
Dipole corrector measurements in Quad mode



Simulated field Profile



Voltage tap measured data on 007 Magnet assembly



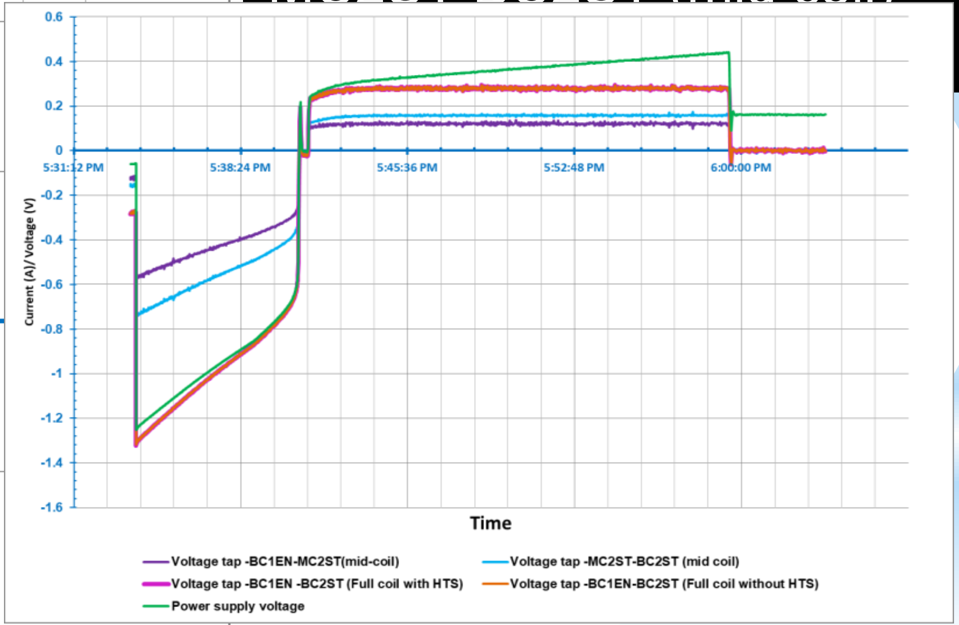
Voltage taps:

BC1EN -BC2ST (Full coil with HTS)

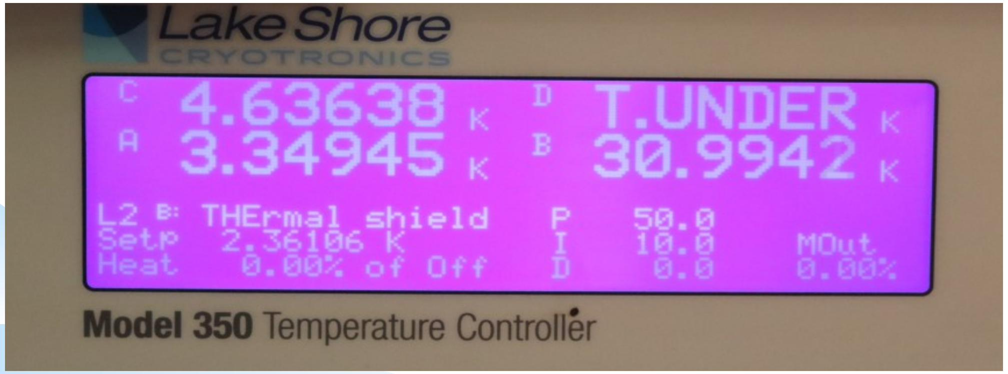
BC1EN-BC2ST (Full coil without HTS)

BC1EN-MC2ST(mid-coil)

MC2ST-BC2ST (mid coil)



003 & 008 Testing progress



Previous limitations for magnet ramping

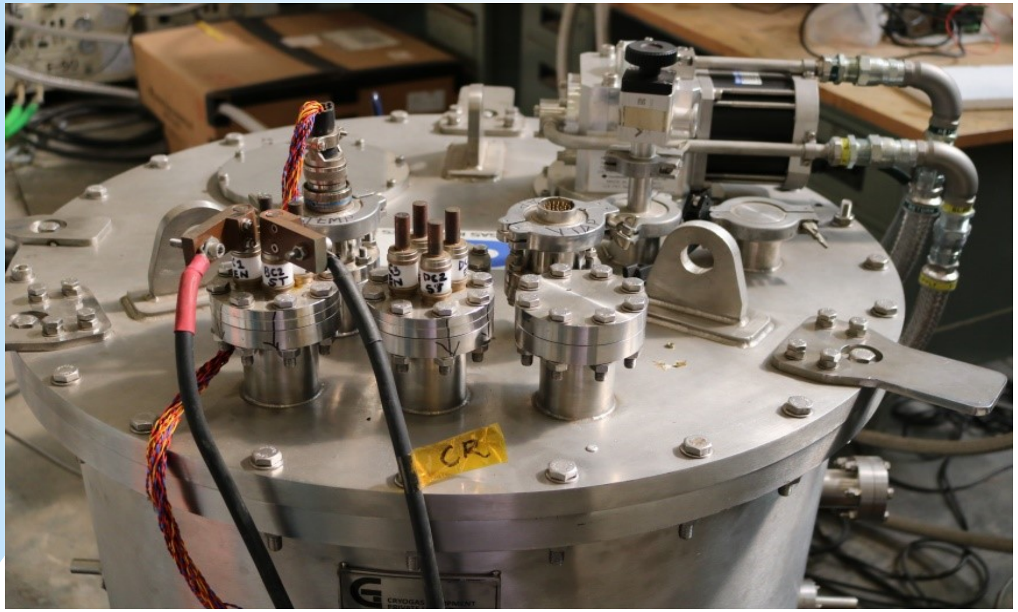
- Issue of heating beyond 30A observed ; Drop across coil increases indicating heat load due to coil splices and interconnections was suspected
- However there is an issue with flag solder degradation (probably during warm up)
- Heating (temperature rise observed) even after shorted connections at the flag

Changes incorporated

- Flag directly bolted to the heat sink fin with kapton tape (two layers-760 μm) insulation
- Improvement observed, however heating is still significant for higher currents
- Solder interconnections will need to be changed after this testing
- Magnet 003 ramped upto 5T aperture field @ 33A

Temperature Reading
(C :LHS Heat sink; A : Flag ; B Thermal shield)

003 Testing progress

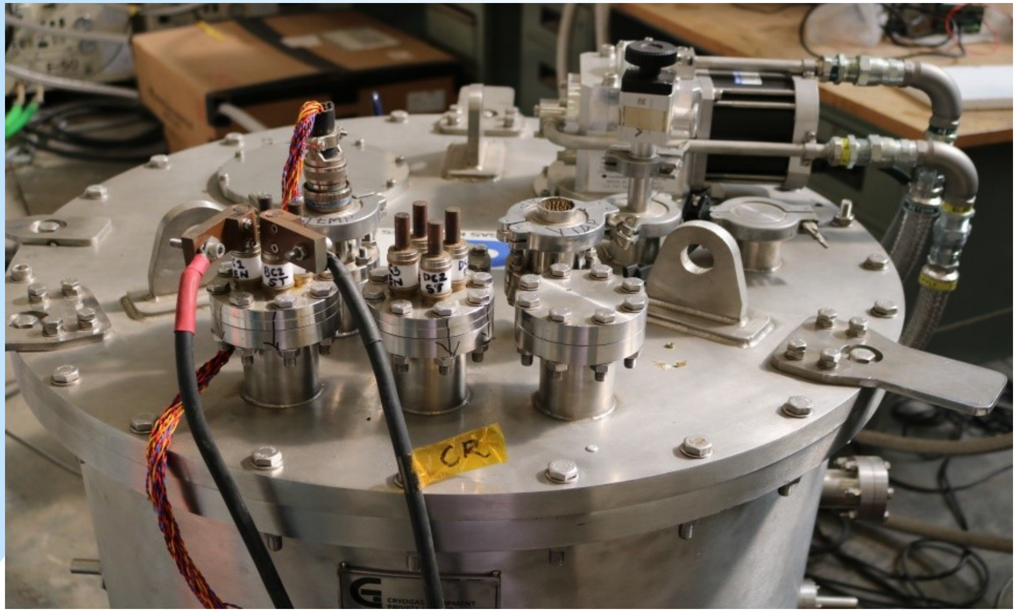


Changes incorporated - 003 Magnet

- Flag directly bolted to the heat sink fin with kapton tape (two layers-760 μm) insulation
- Improvement observed, however heating is still significant for higher currents
- Magnet 003 ramped upto 5.55T aperture field @ 36.5 A. Axial field mapping carried out.
- Fringe field levels within 10G

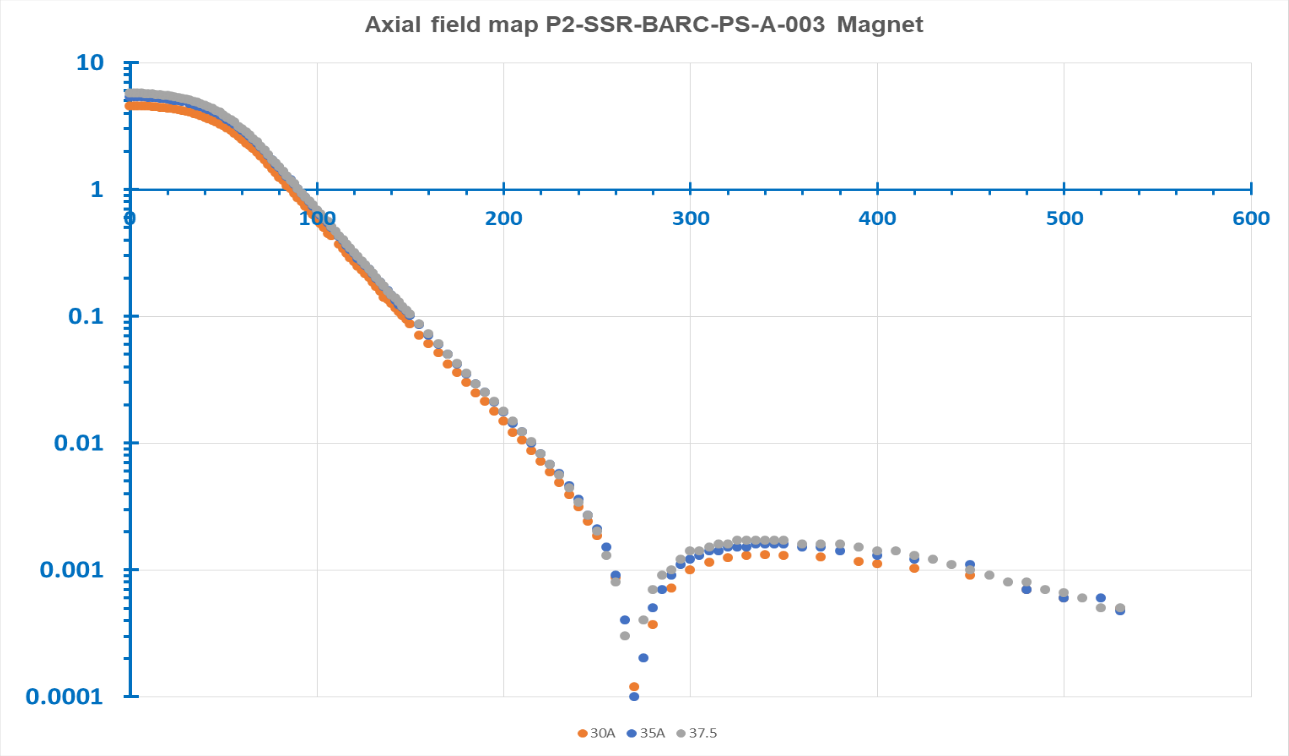
Temperature Reading
(C :Bolted Flag Surface ; A : LHS Heat sink ; B Thermal shield)

003 Testing progress



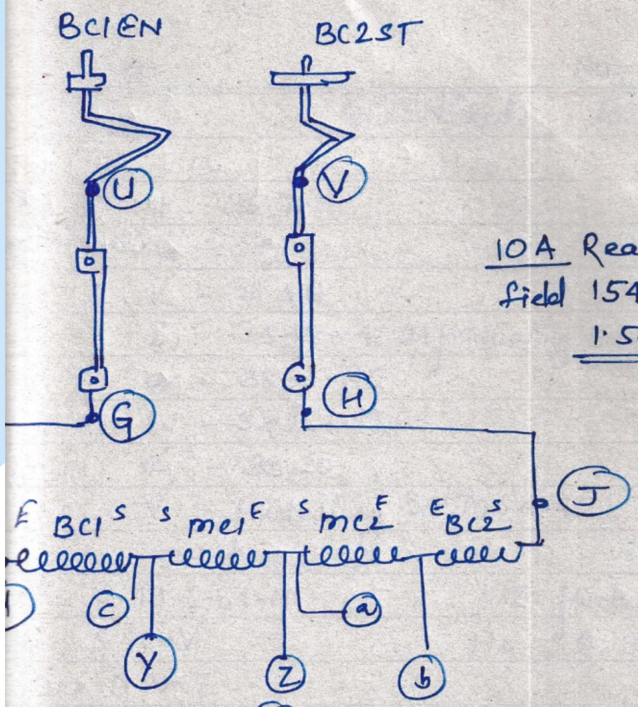
Changes incorporated - 003 Magnet

- Magnet 003 ramped upto 5.8T aperture field @ 37.5 A. Axial field mapping carried out.
- Fringe field levels within 10G



Temperature Reading (C :Bolted Flag Surface ; A : LHS Heat sink ; B Thermal shield)

Heat sink assemblies for pre-series magnets



042

10A Reading
field 1545 mT
1.545 T

BC1EN (Red-PS Red-mm)
- U 23.64mV
- G 24.46mV
- d OL
- c 25.03mV
- Y 24.92mV
- Z 24.89mV
- a 24.94mV
- b 25.76mV
- J 28.32mV (fluctuating)

BC1EN - H 25.70
- V 26.72

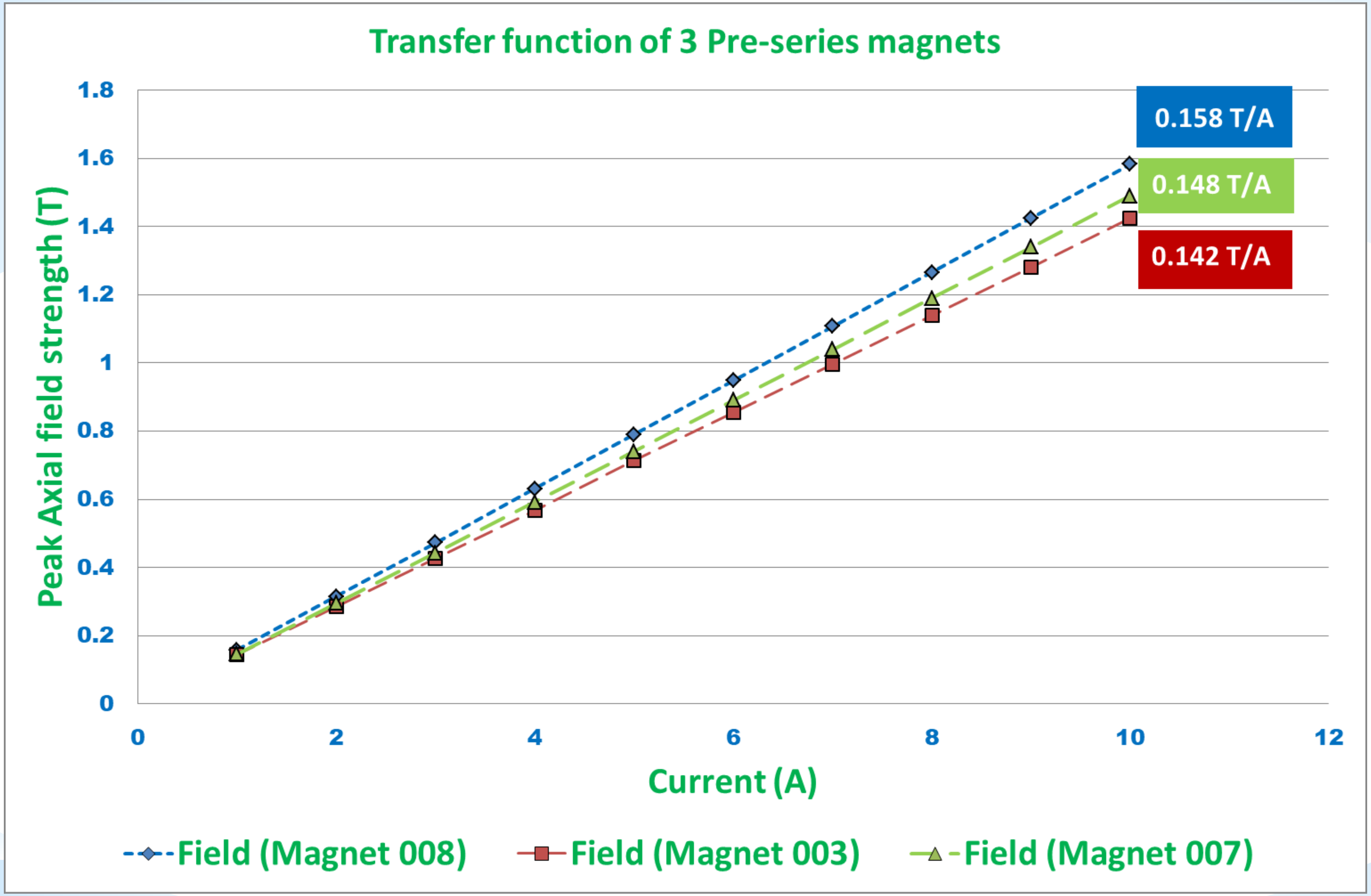
20A $B_z = 3.078T$ $B_{tot} = 3.130T$

BC2ST - V - 51.51mV
U - 52-59mV fluctuating
H - 52.07
J - 52.07
b - 51.98-52.17mV
z - 49-52 fluctuating
c - 52-55 "
Y - 48-54

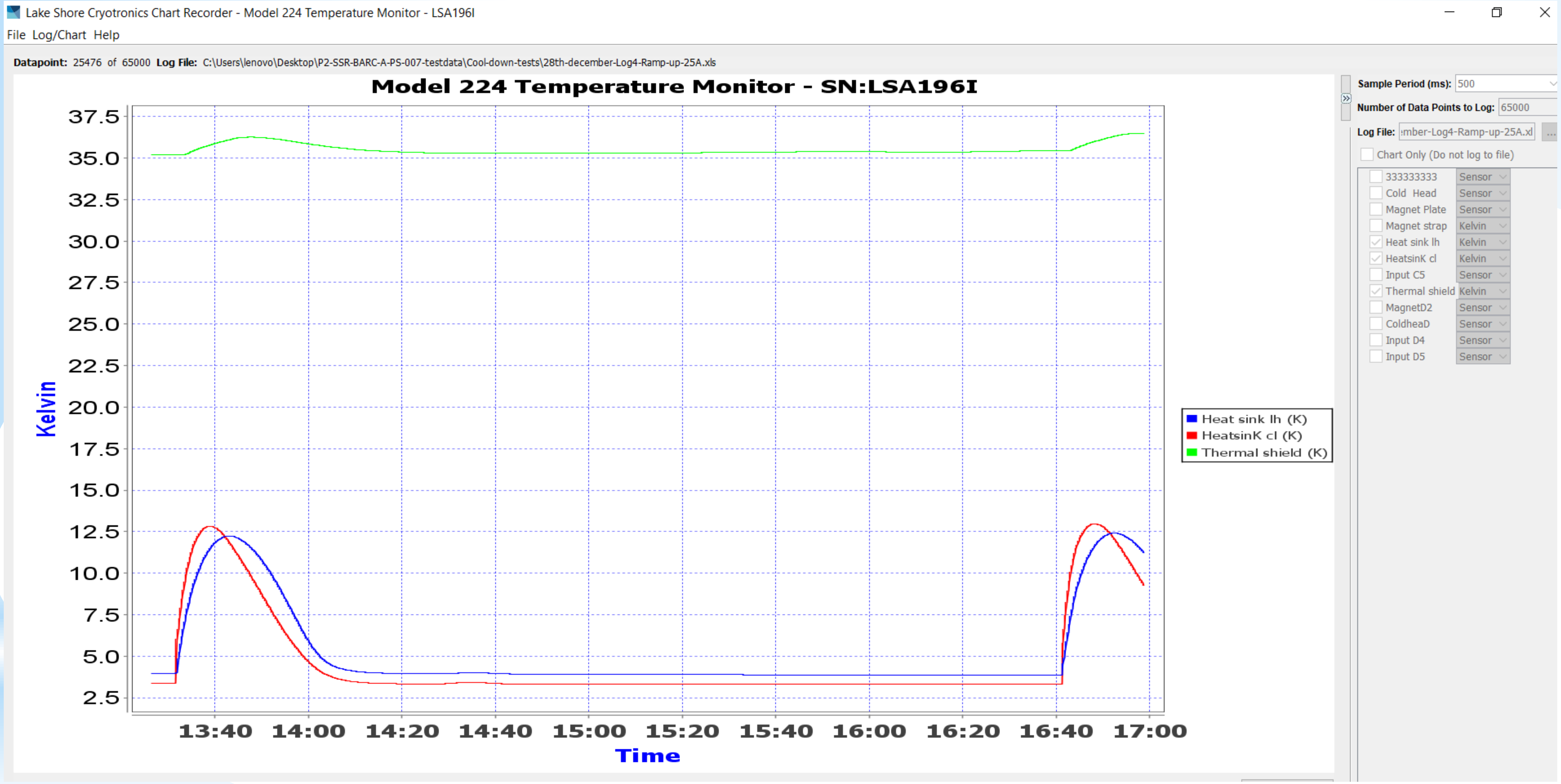
UV - 4.35mV average
VH = 0.56mV
UG = -2.06mV
UY = -4.22mV
UZ - fluctuating -3.8 - 5.58mV
Uc = -4.12-4.47mV.

D2 - 3.1629 D3 3.2097
D4. 4.8373 C2 ·
C3. 3.0511 C4 . 63.5021
C5. 3.4929 PS - 53.1750

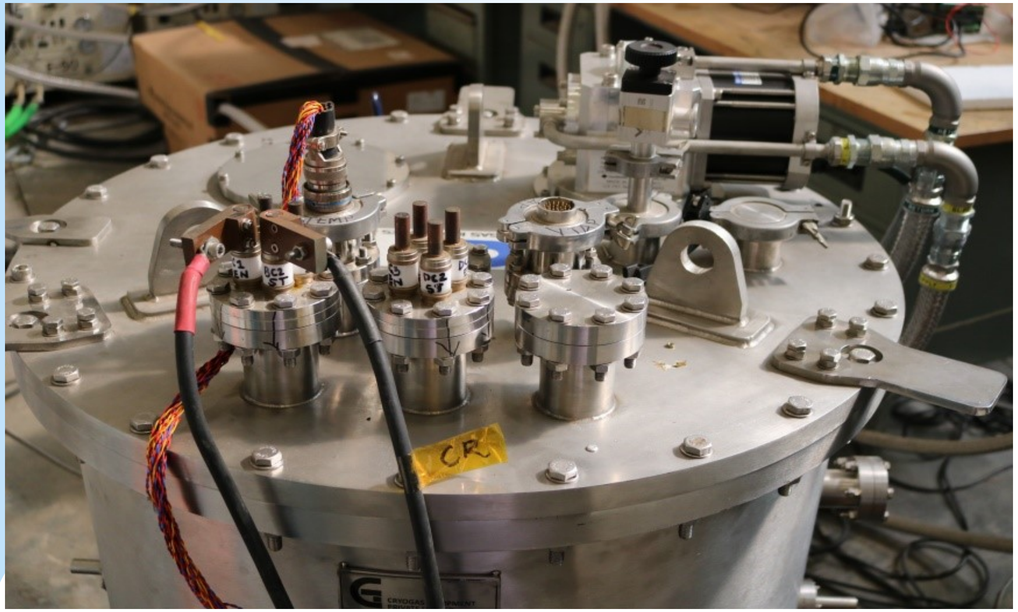
Transfer function

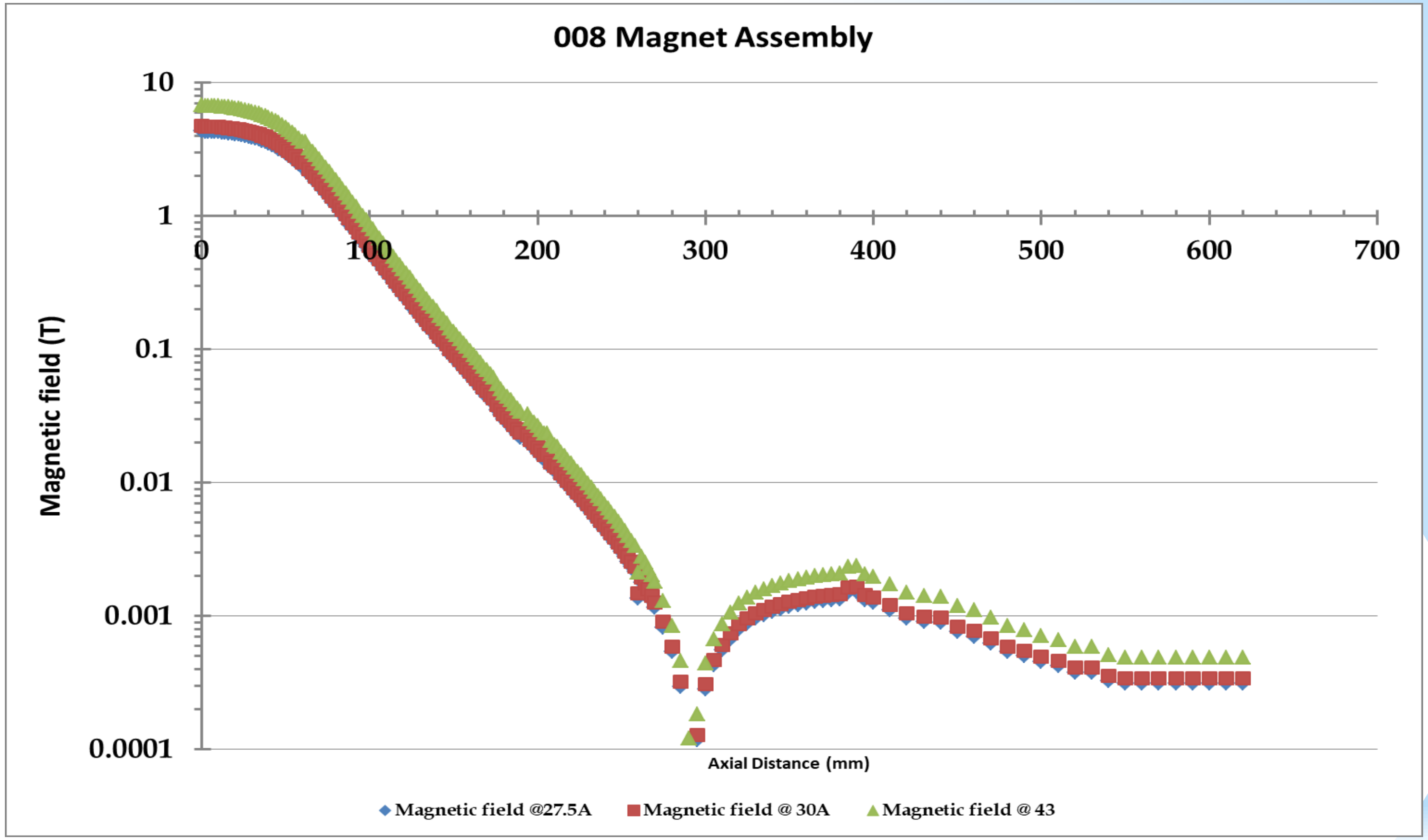


Quench Temperature rise



008 Testing progress

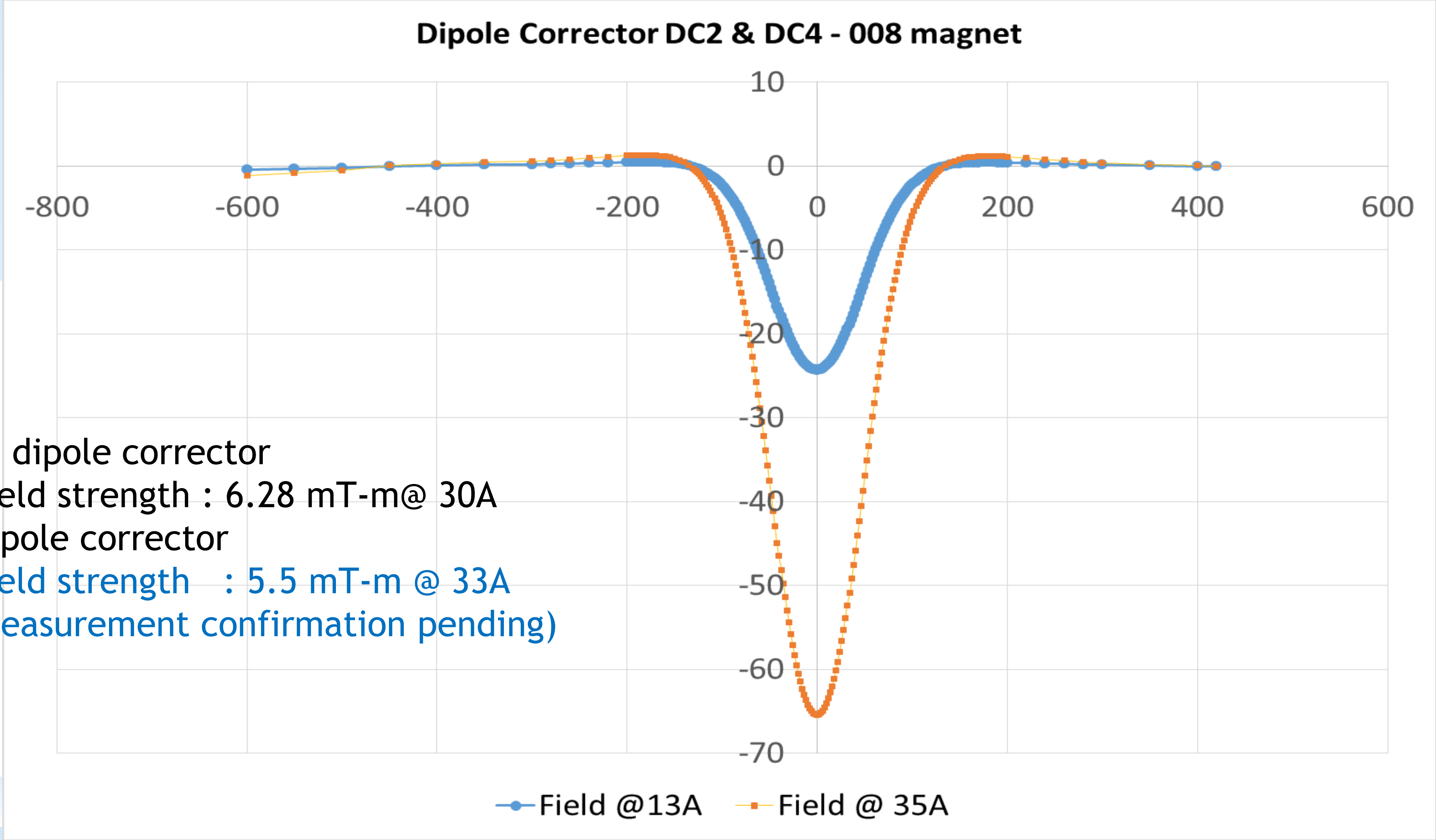




Field Integral @ 4.5T^2m @ 43A

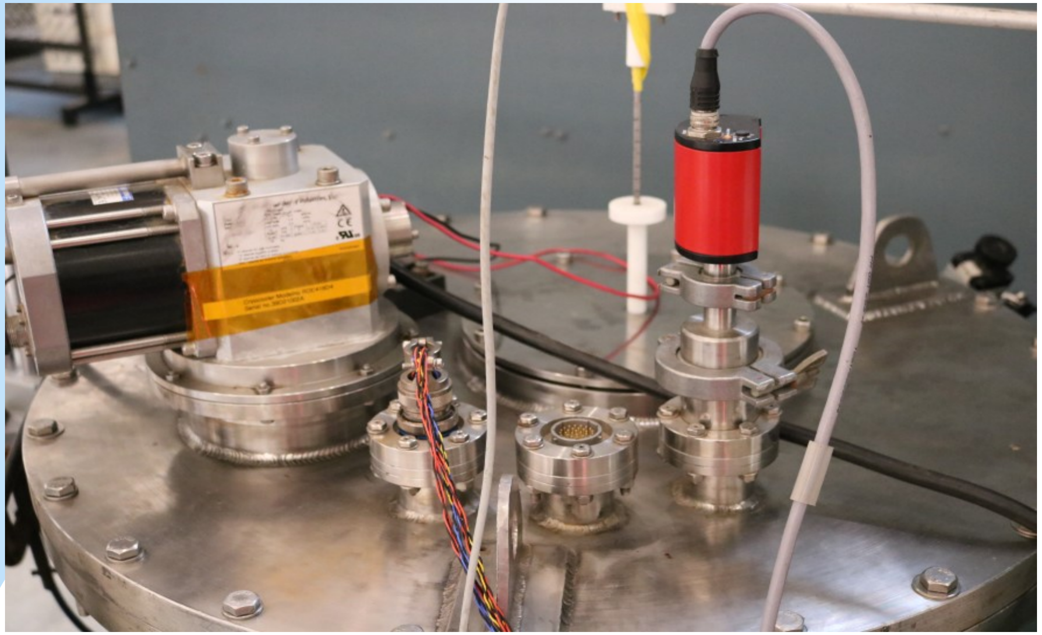
Fringe field levels ~ 10G Within measurement uncertainties

008 Dipole corrector Map

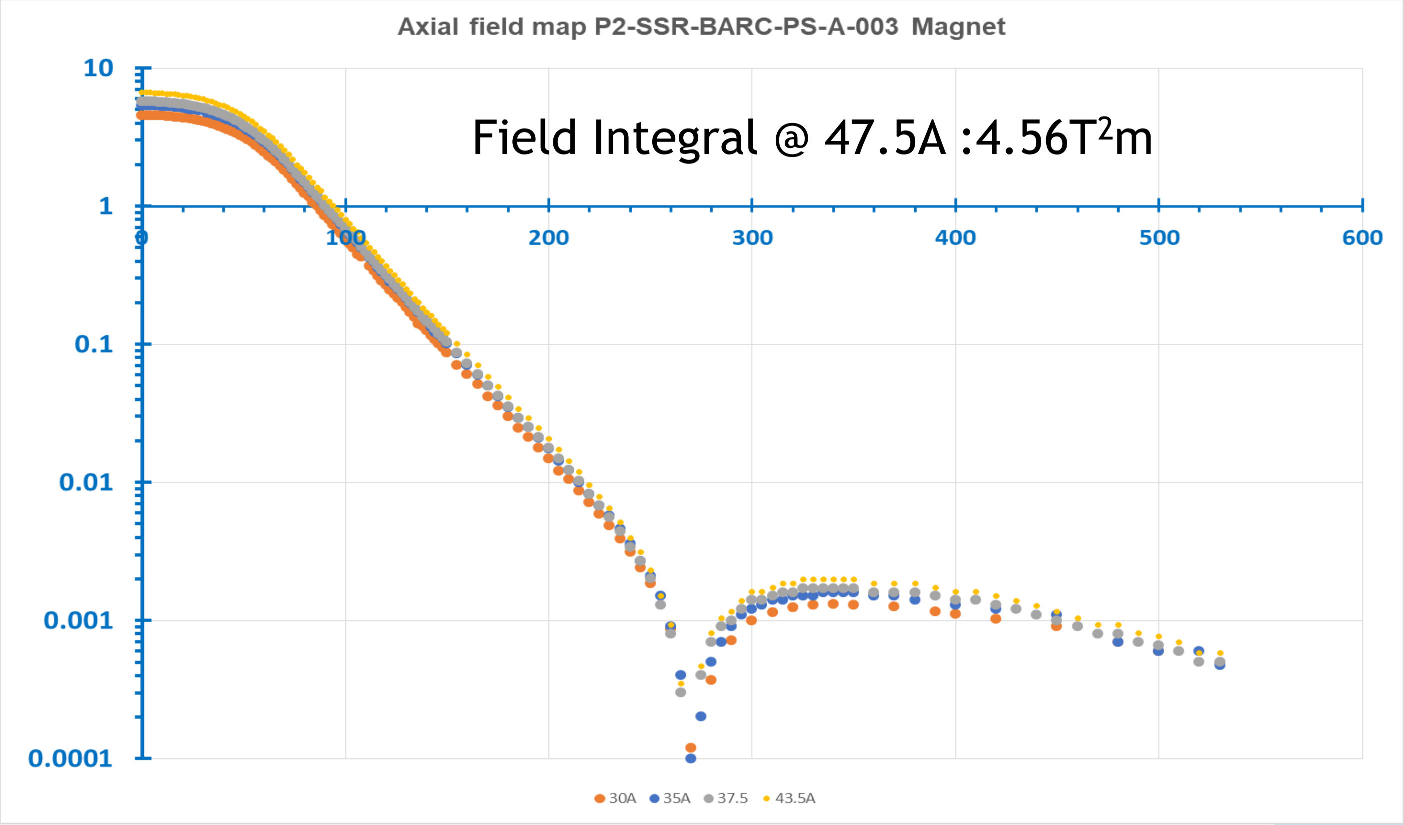


Horizontal dipole corrector
Bending field strength : 6.28 mT-m@ 30A
Vertical dipole corrector
Bending field strength : 5.5 mT-m @ 33A
(Repeat measurement confirmation pending)

003 Testing progress



- Fringe field levels within 10G

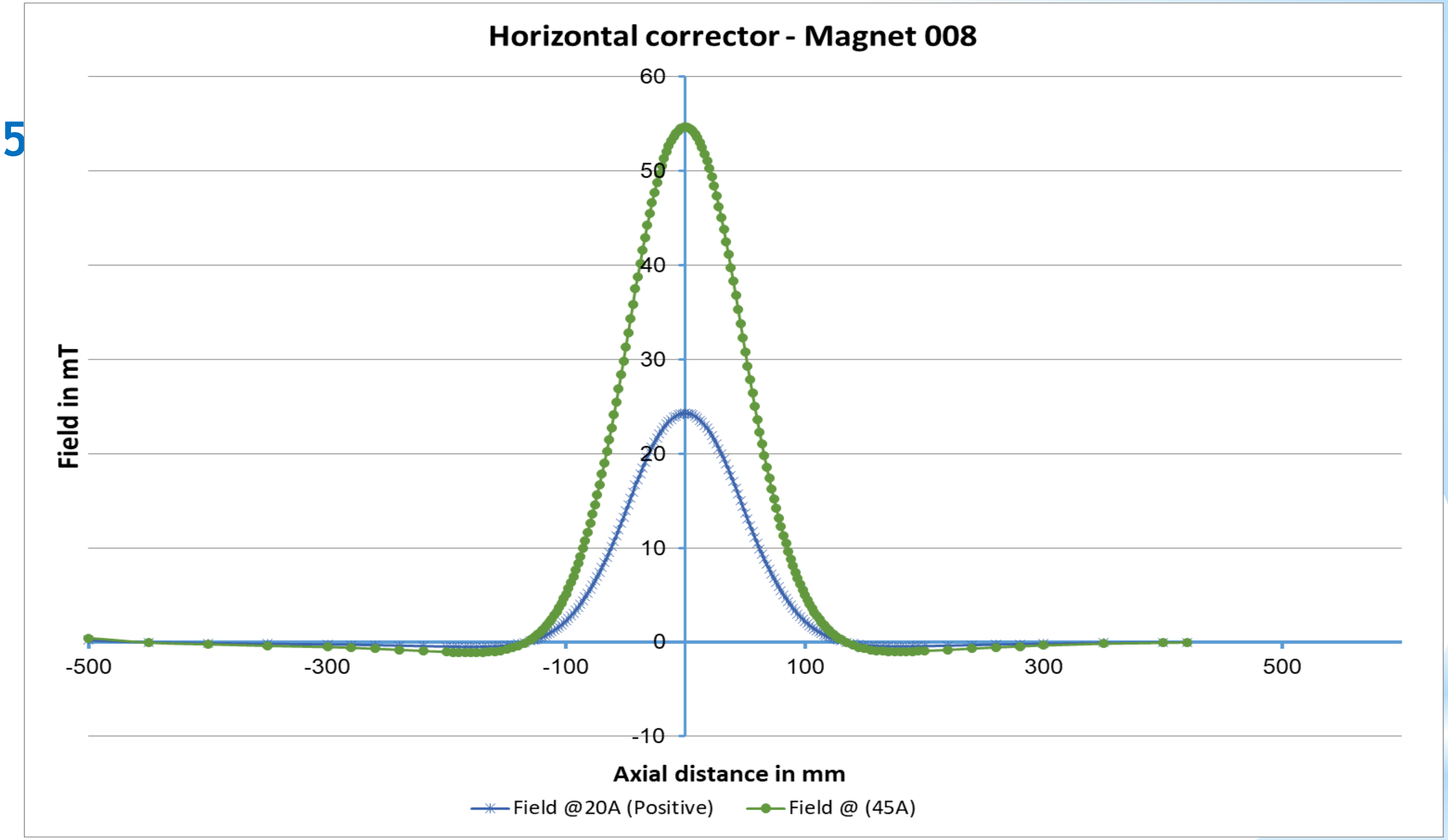


Temperature Reading (C :Bolted Flag Surface ; A : LHS Heat sink ; B Thermal shield)

003 and 008 Magnet dipole corrector measurement

Transfer function : 1.21mT/A

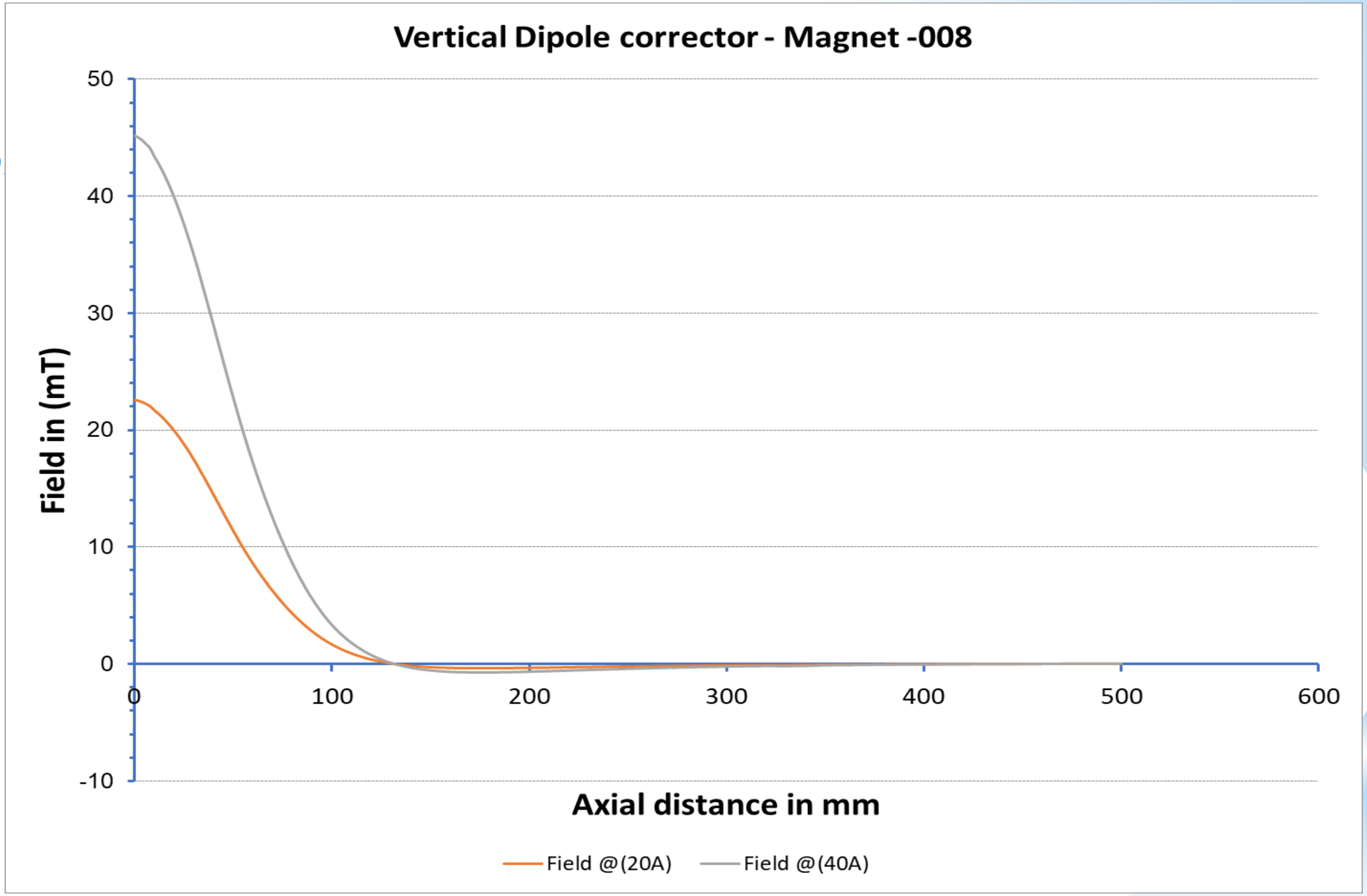
Bending Strength : 6 mT-m @ 45



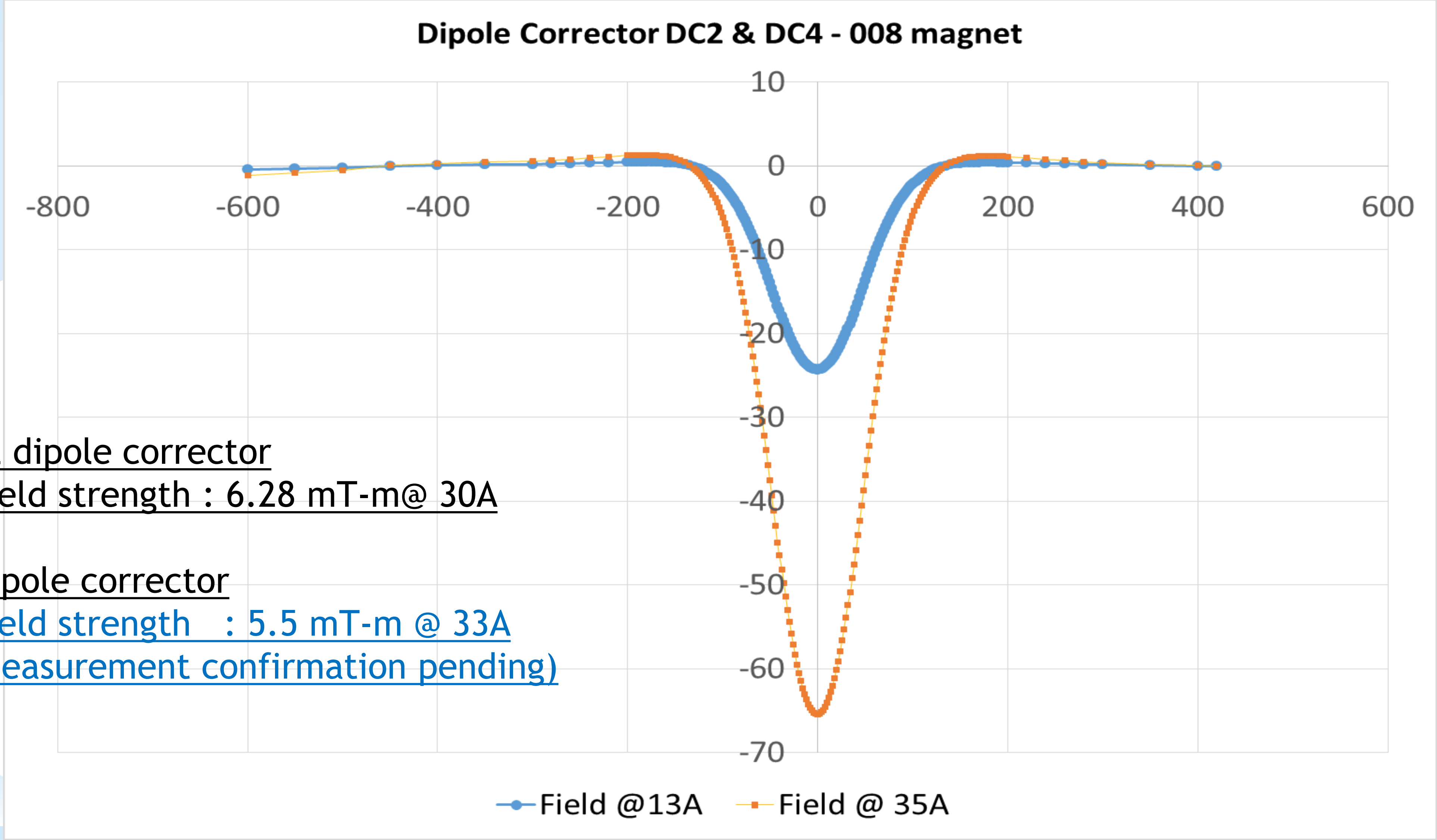
003 and 008 Magnet dipole corrector measurement

Transfer function : 1.12mT/A

Bending Strength : 5.2mT-m @ 45



008 Dipole corrector Map (Earlier data – corrected in first slide)



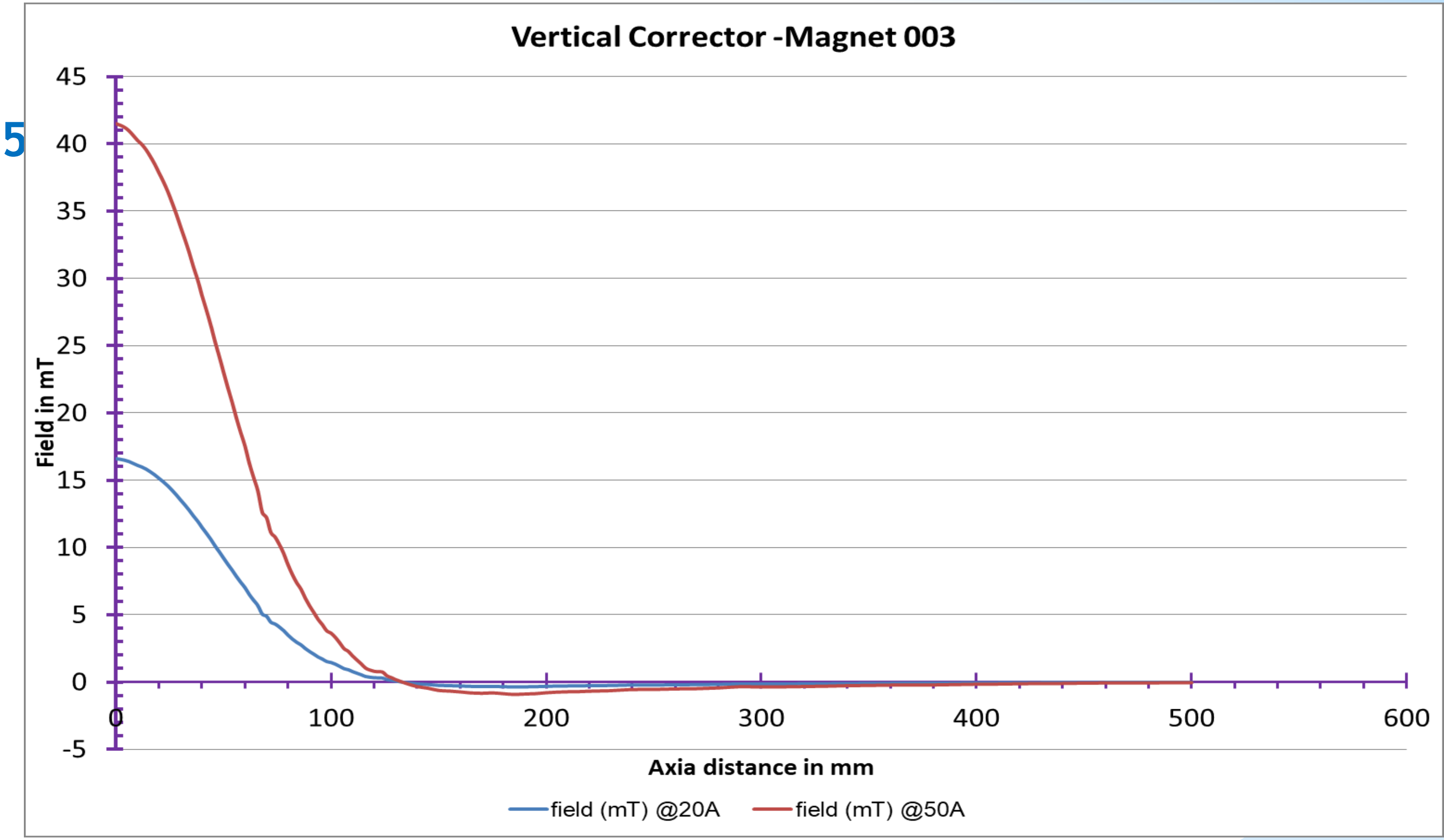
Horizontal dipole corrector
Bending field strength : 6.28 mT-m@ 30A

Vertical dipole corrector
Bending field strength : 5.5 mT-m @ 33A
(Repeat measurement confirmation pending)

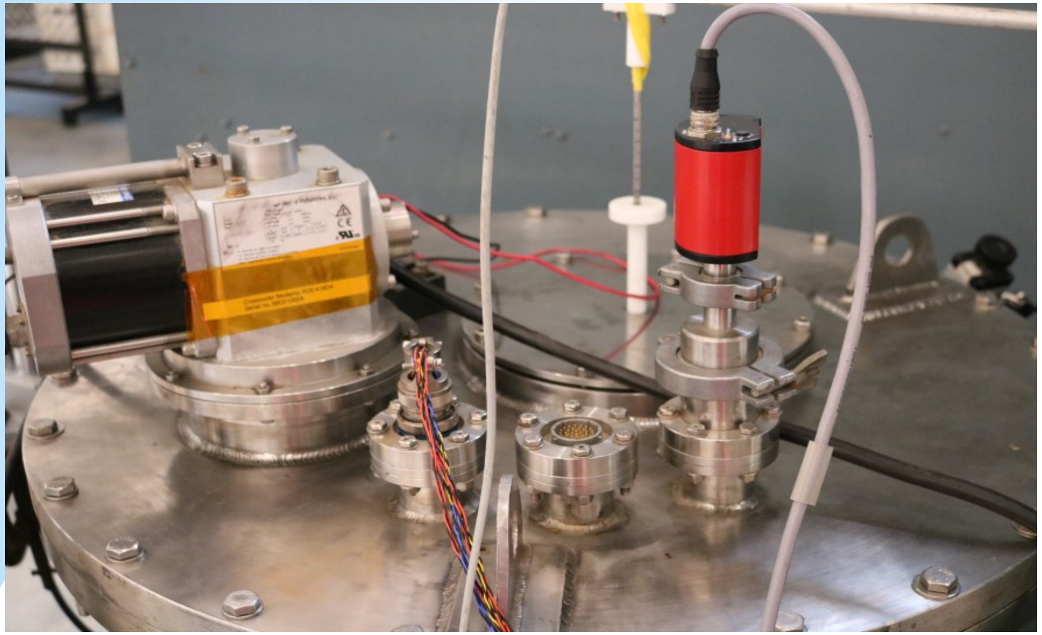
003 and 008 Magnet dipole corrector measurement

Transfer function : 0.83mT/A

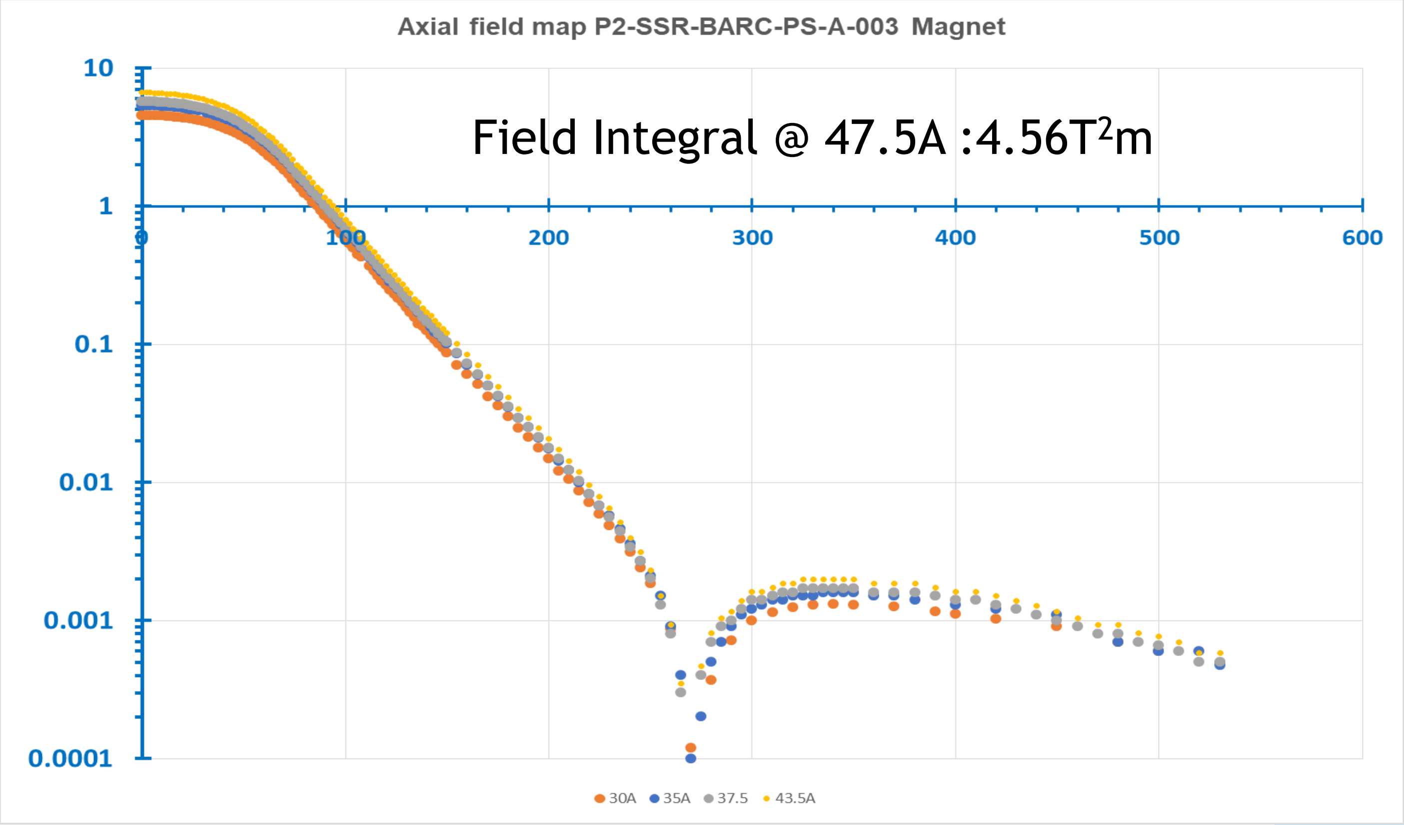
Bending Strength : 4.5 mT-m @ 5



003 Testing progress

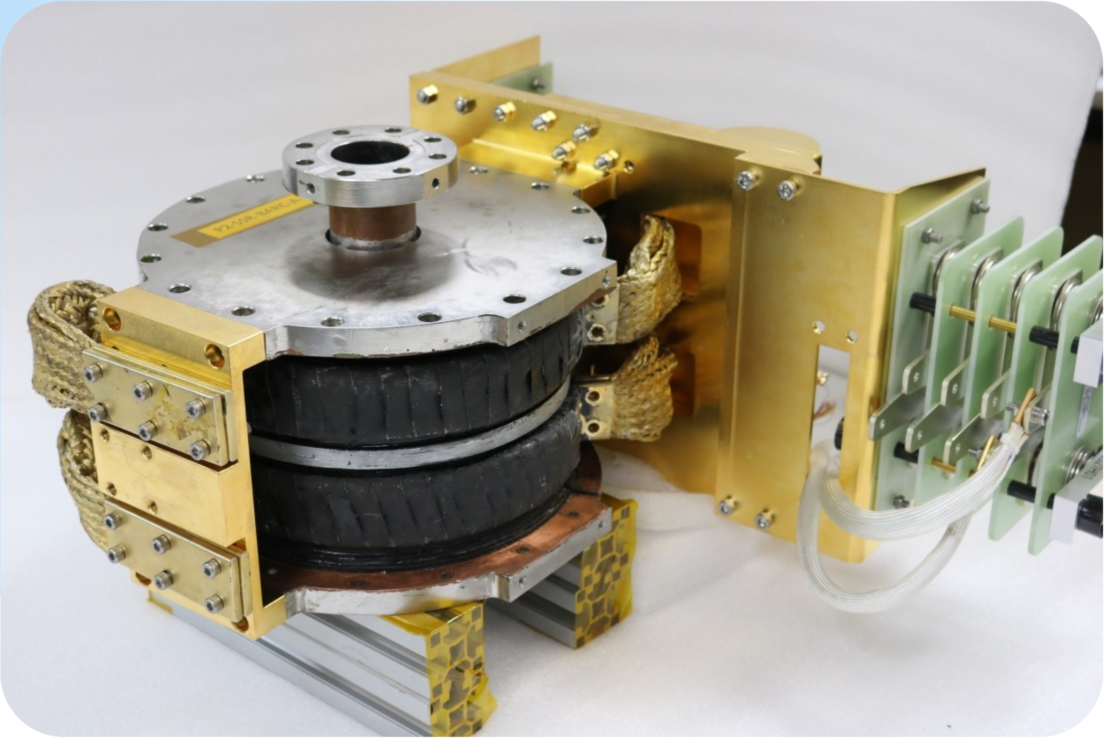


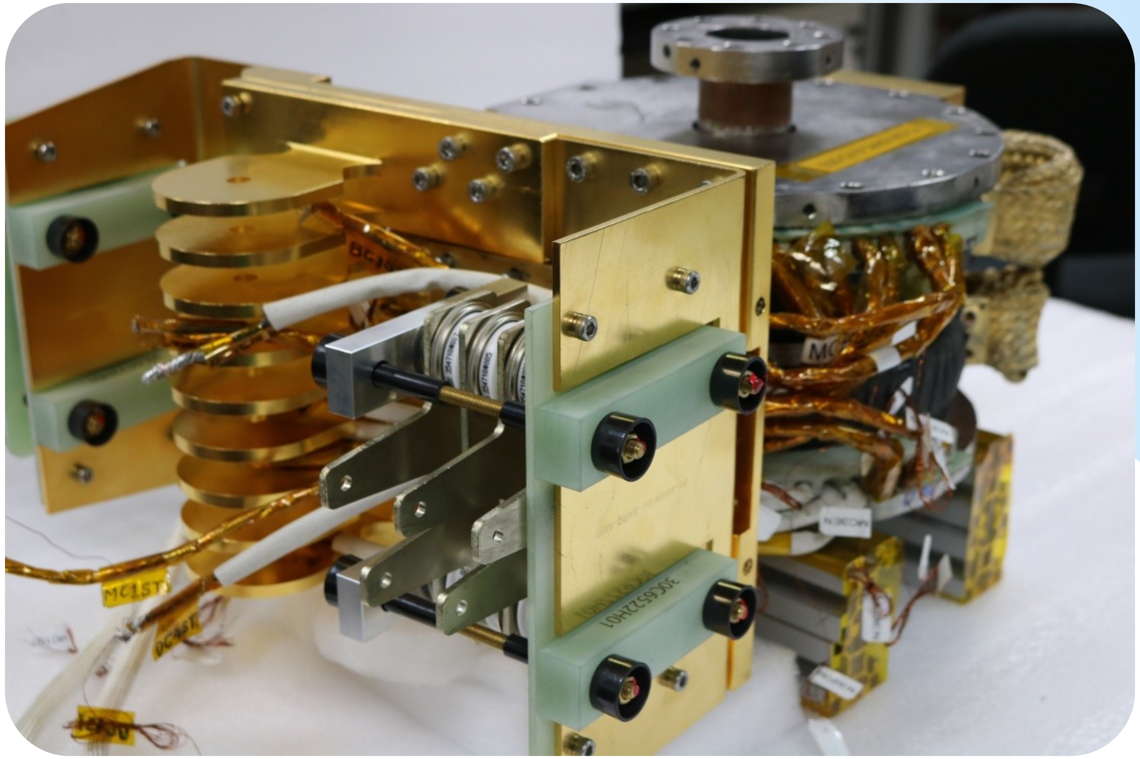
- Fringe field levels within 10G



Temperature Reading (C :Bolted Flag Surface ; A : LHS Heat sink ; B Thermal shield)

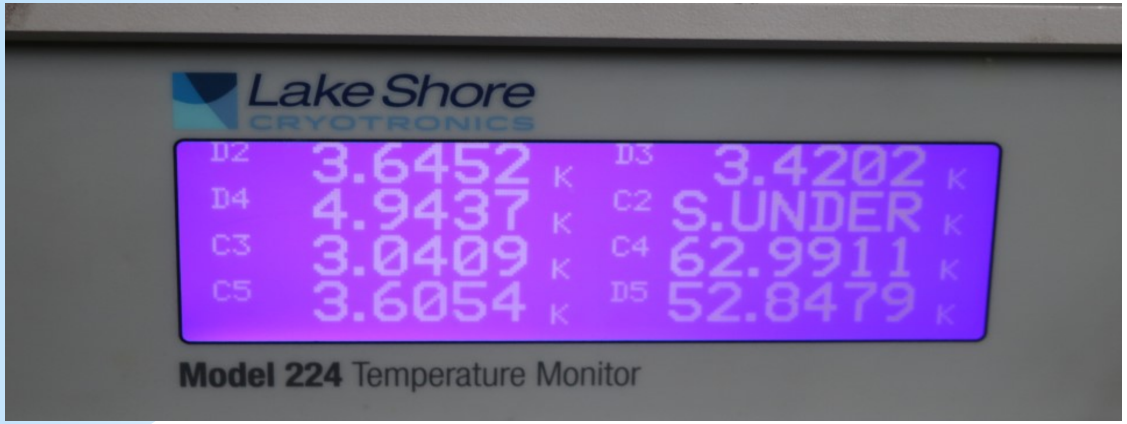
Prototype magnet and pre-series magnet assembly sent to FNAL





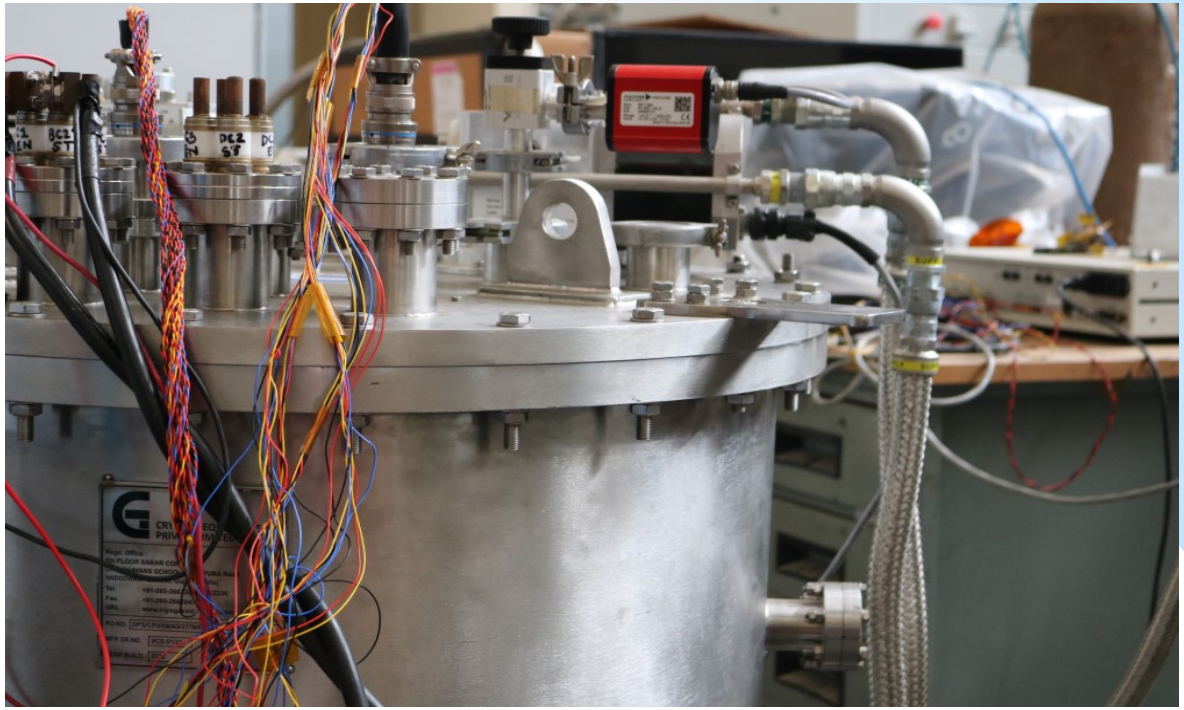
- One number of magnet assembly has been shipped to FNAL for integration with test stand

008 Testing



Temperature Reading
(C3 cryocooler:D3 magnet strap; D5 Thermal shield; C4 feedthrough intercept

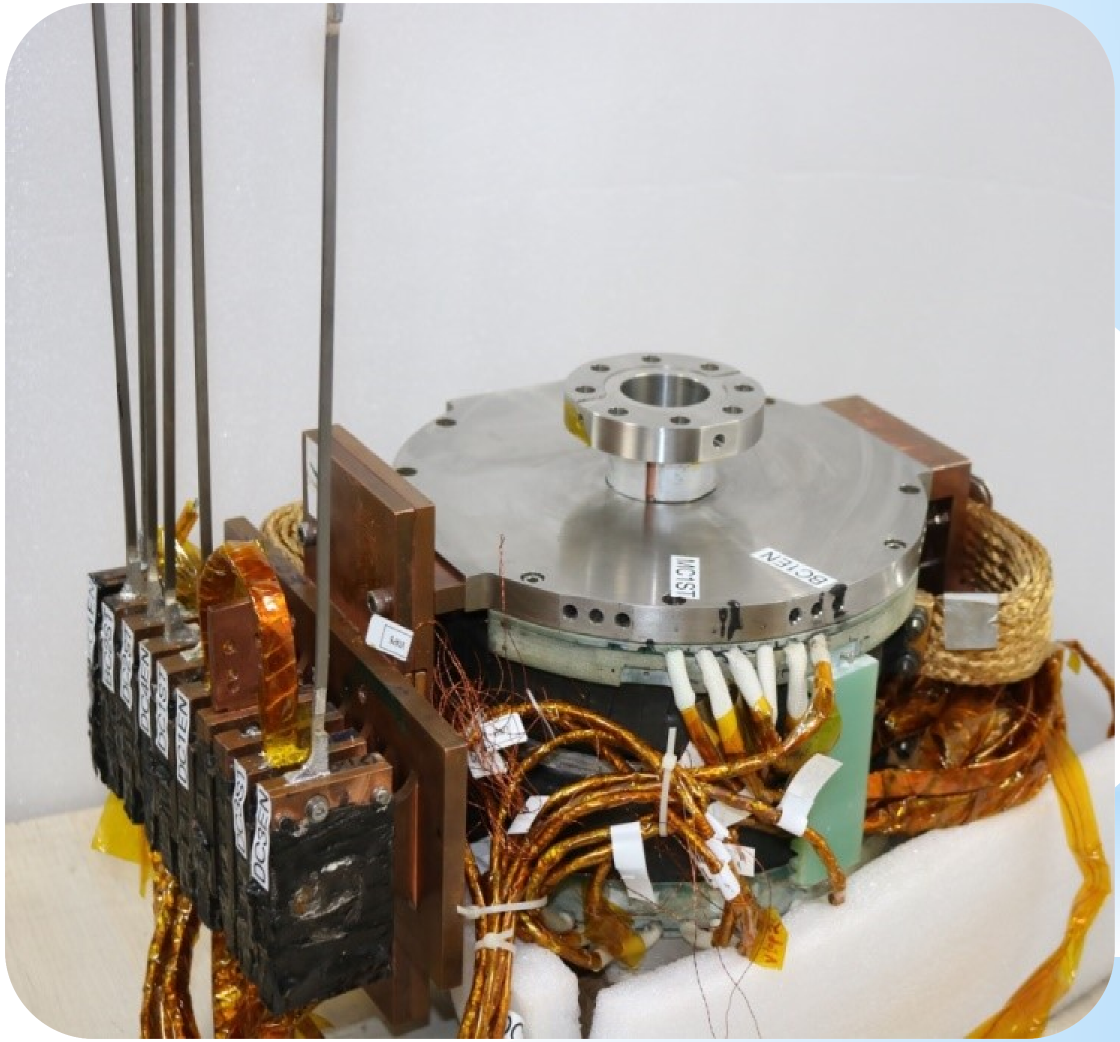
Joint resistance (Coil drop) Voltage drop



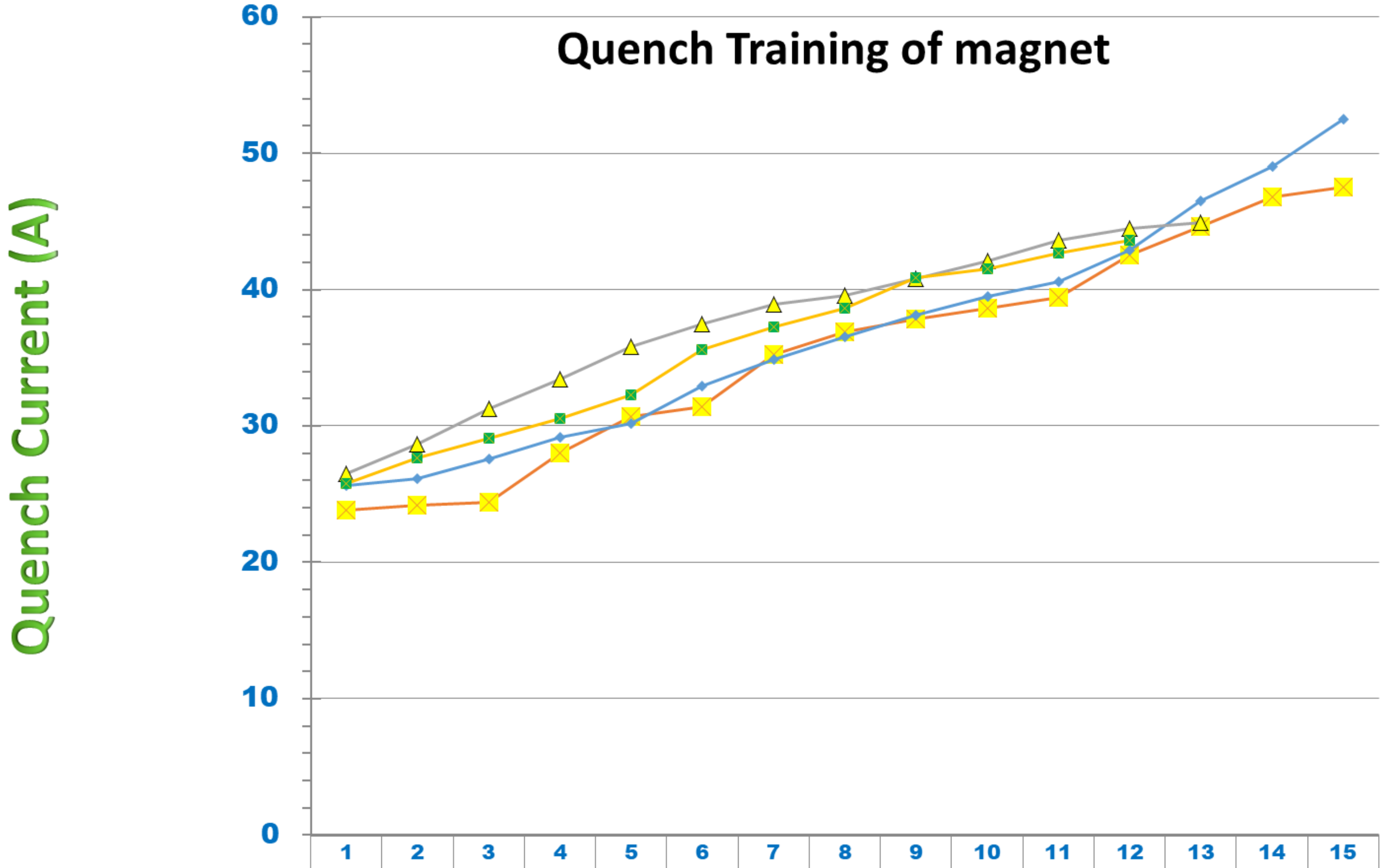
Test stand with voltage taps and temperature sensors

- Issue of heating beyond 30A observed
- Drop across coil increases indicating heat load due to coil splices and interconnections
- Solder Make has been changed (However material composition analysis has been verified)
- Cryocooler recharging done post 007 testing

Magnet 008 tested in horizontal test stand



Quench Currents at BARC during magnet testing



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Quench Current (007)	23.804	24.19	24.4	27.99	30.7	31.4	35.2	36.9	37.8	38.6	39.4	42.5	44.6	46.8	47.5
Prototype magnet	25.6	26.1	27.6	29.2	30.2	32.9	34.9	36.5	38.1	39.5	40.6	42.9	46.5	49	52.5
Quench (003)	26.5	28.69	31.27	33.419	35.8	37.5	38.9	39.6	40.8	42.1	43.6	44.5	44.9		
Quench (008)	25.747	27.62	29.1	30.56	32.3	35.6	37.25	38.63	40.9	41.5	42.7	43.6			

Summary of test results

Sr. No	P2-SSR-BARC-A-007	P2-SSR-BARC-A-003	P2-SSR-BARC-A-008
Maximum field	6.76T	6.87T	6.82T
Maximum Current	45A	47.5A	43.5A
Integral field	4.5 T^2m	4.56T^2m	4.5 T^2m
Dipole corrector Transfer function	HC– 1.19mT/A VC– 1.1 mT/A	HC– 0.8302mT/A VC– 0.8945 mT/A	HC– 1.12mT/A VC– 1.215 mT/A
Dipole corrector Integral field	5mT-m @50A	5.4mT-m@55A	5mT-m@50A

Summary

- ✓ Design, development and qualification of conduction cooled magnet assemblies for Superconducting Proton Accelerator is completely an indigenous effort.
- ✓ 4 No.s of pre-series magnet assemblies developed.
- ✓ Design change from bath cooled to conduction cooled technology was quickly adapted in terms of EM, thermal design, test stand development, prototype development and qualification.
- ✓ R&D phase magnet delivery & integration with the cryomodule will pave way for development and characterization of series magnets for Indian programmes as well as under collaboration.

Thank you for your kind attention