Workshop on Advanced Superconducting Materials and Magnets

AdvSCMws 2019 / Workshop on Advanced Superconducting Materials and Magnets

Design and testing of a metal-insulated ReBCO dipole magnet prototype

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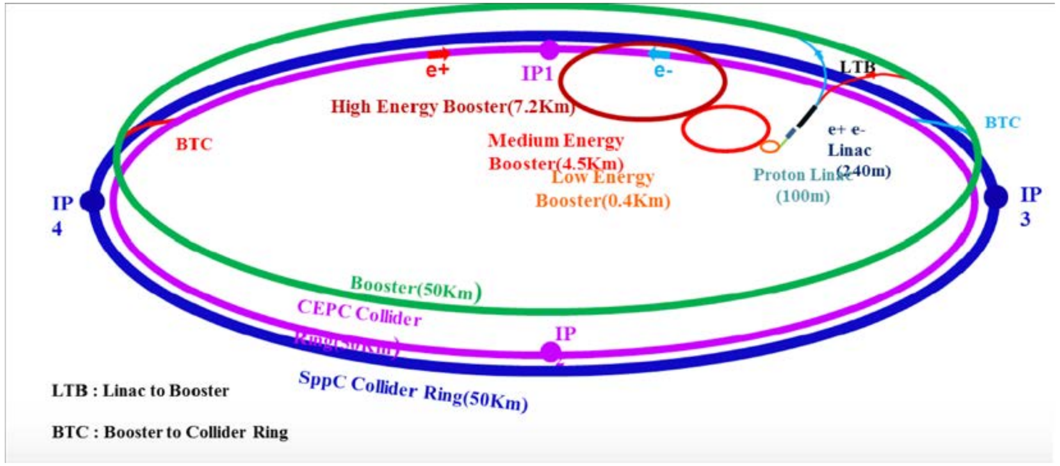
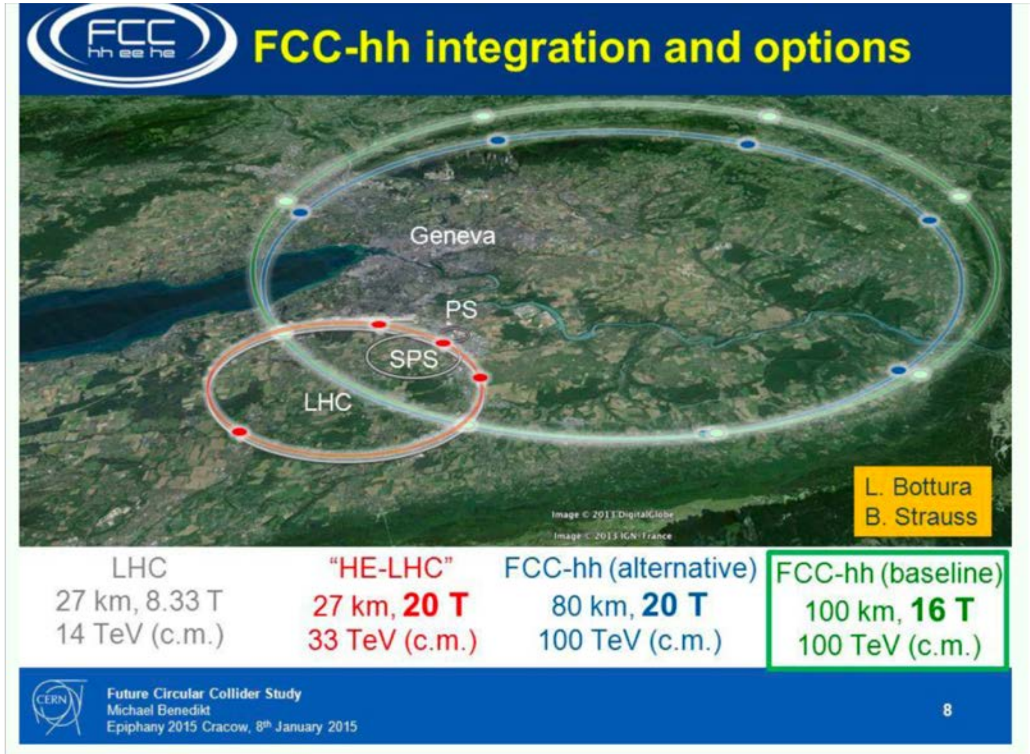
Outline

1. Background
2. Metal-insulated ReBCO dipole magnet
   a) Design
   b) Manufacturing
   c) Test at 77 K
3. MgB_2 testing coils
4. Summary

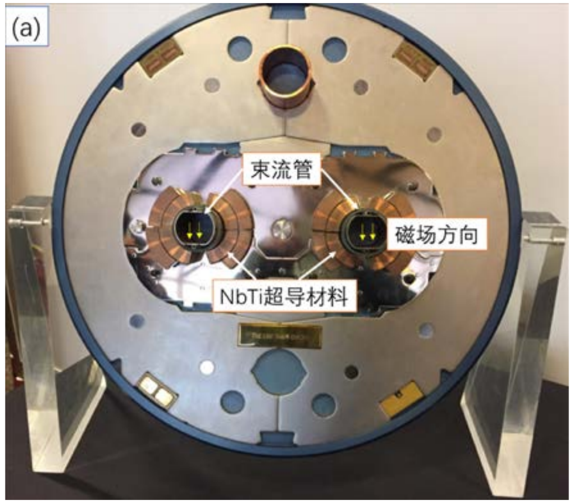
Accelerators in the future





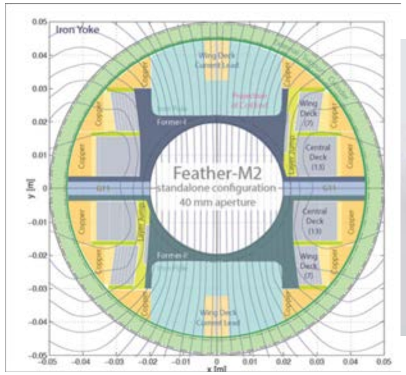
- ✓ We need SC magnets up to 16 T - 20 T
- ✓ Candidate SC materials: **Nb_3Sn**
  ReBCO, BSCCO
  IBS

Superconducting Dipole Magnets

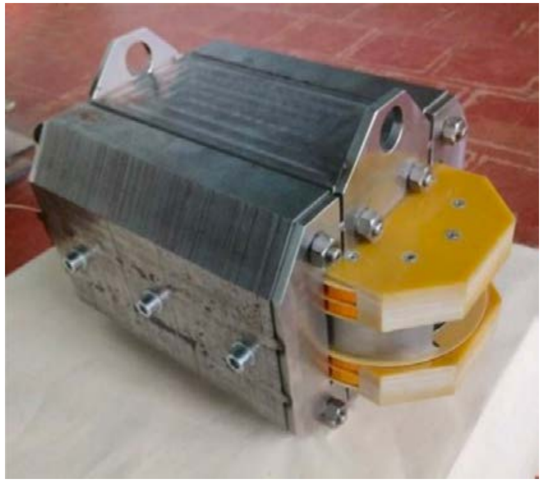


LTS Dipole Magnet, CERN

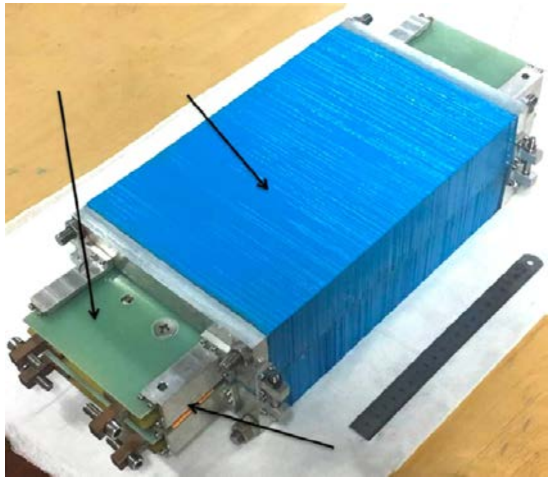
Superferric Dipole Magnet, CAS



5 T HTS dipole, Roebel Cable, CERN



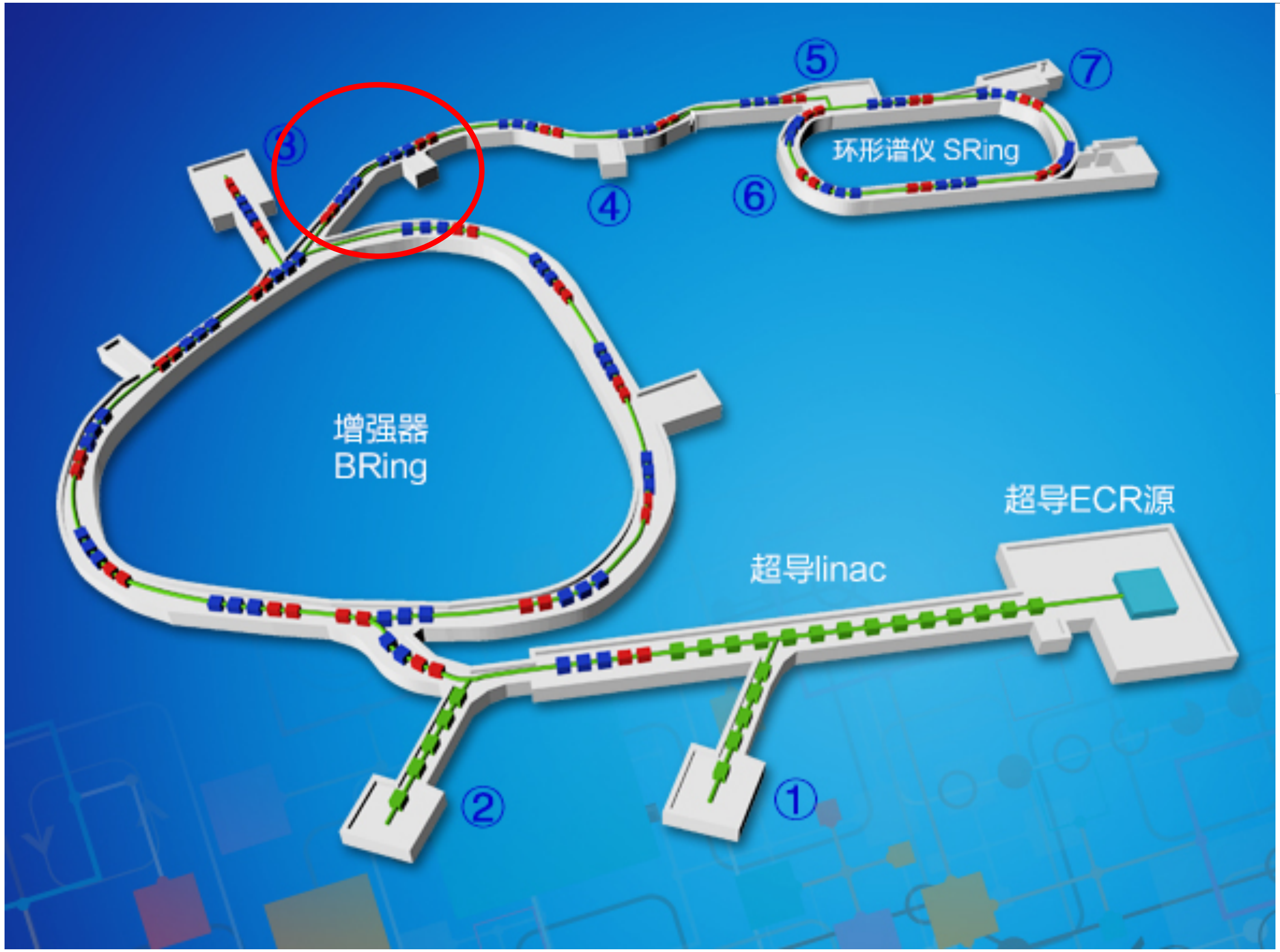
ReBCO Dipole Magnet, Russia

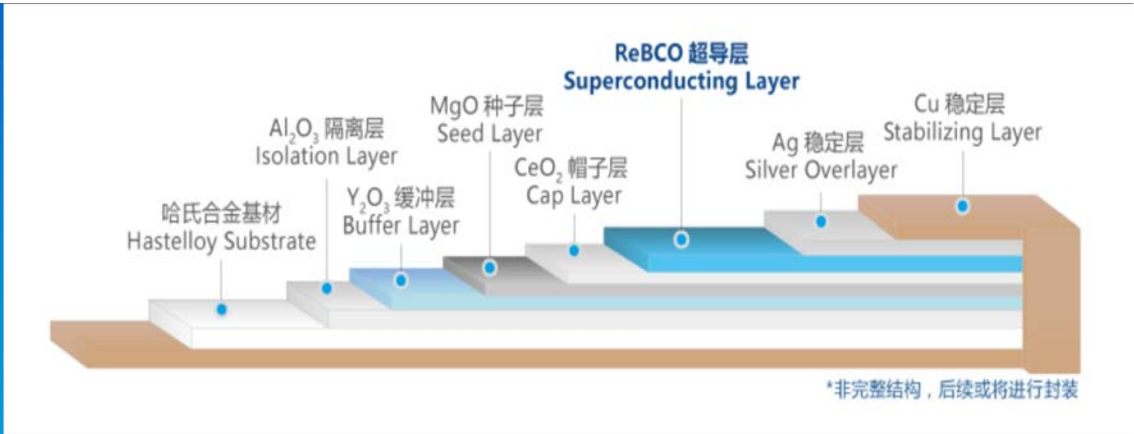


Bi-2223 Dipole Magnet, THU&CAS

- ✓ LTS accelerator magnets as the baseline
- ✓ HTS prototypes under investigation, using ReBCO, Bi-2223, Bi-2212.
- ✓ HTS is not necessary to be always connected with high temperature and high field.

Overview of HIAF

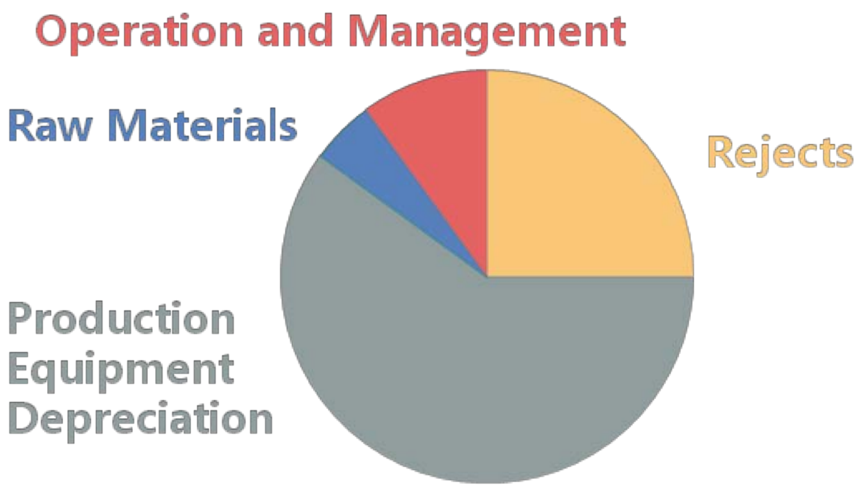




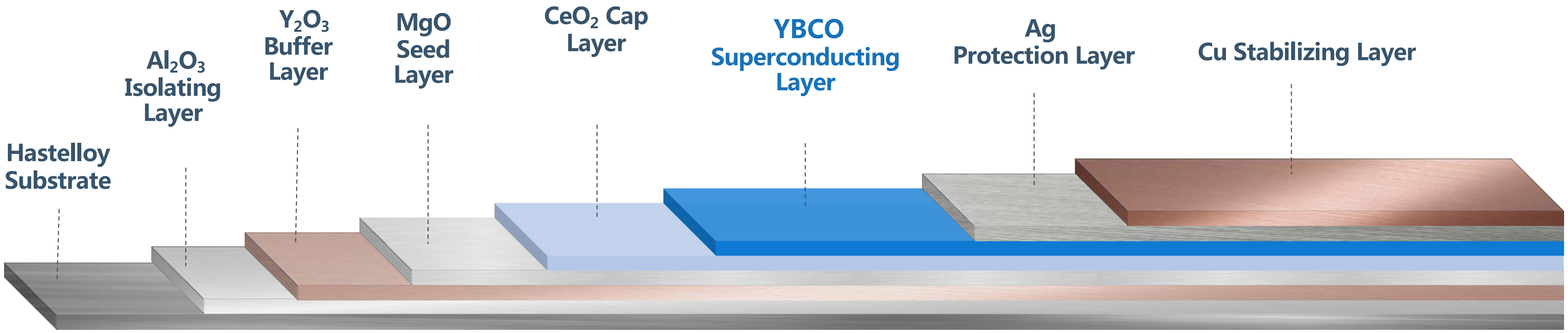
HTS radiation resistant accelerator magnet

- ✓ DC field, @ Beam Separator Line
- ✓ ReBCO tapes with SS insulation - Partial no insulation
- ✓ No ceramic insulation required

About ReBCO tapes

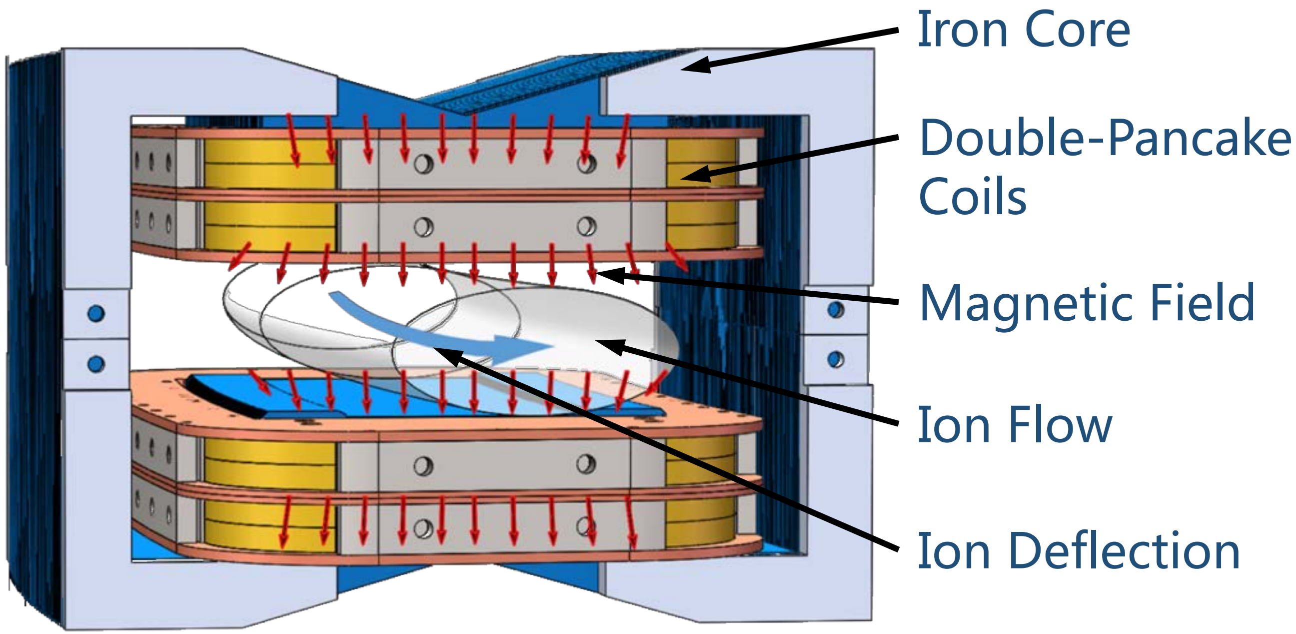


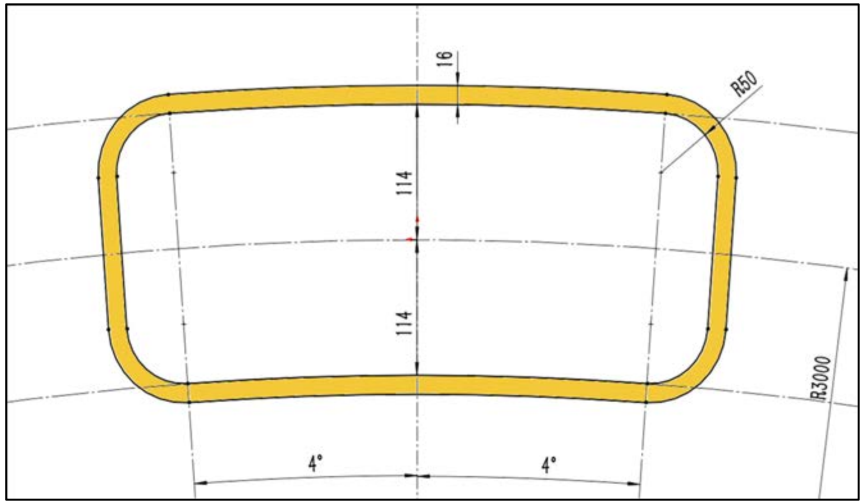
- ✓ ReBCO should not be expensive in the future. We need to find applications,
- ✓ The anisotropy in geometry and EJ characteristics is **a challenge** for magnet people, but **not obstacles**.
- ✓ Mechanically: Delamination
  EM: Influence of SCF for field qualities and strain distribution.



Courtesy of Shanghai Superconductor

Parameters of Prototype Magnet

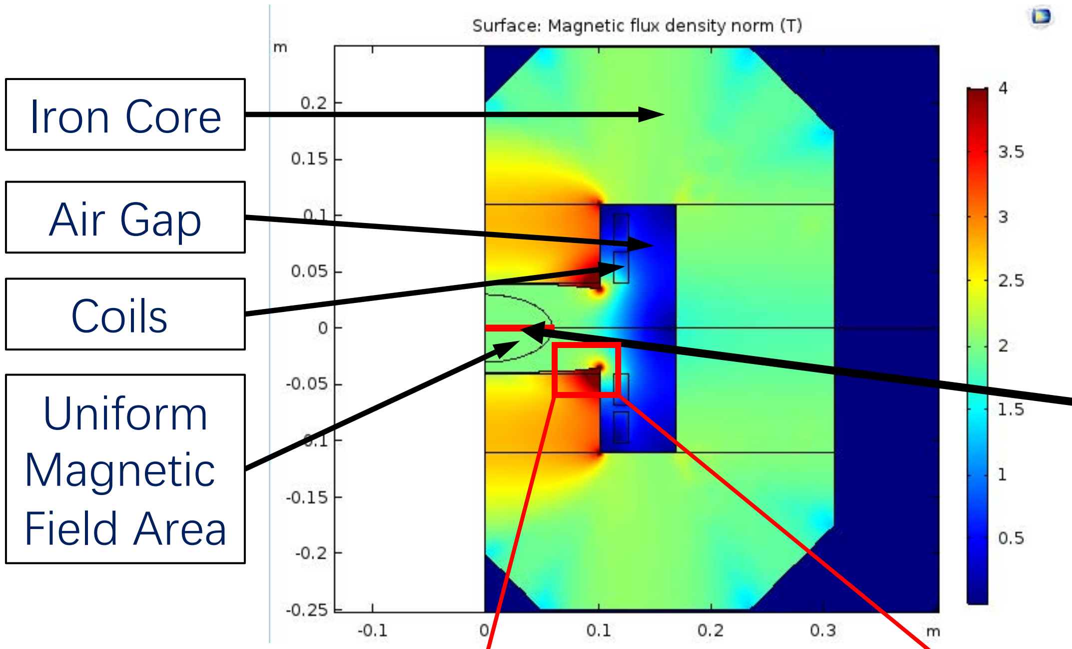


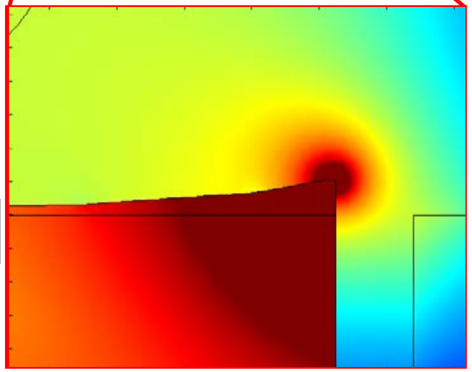


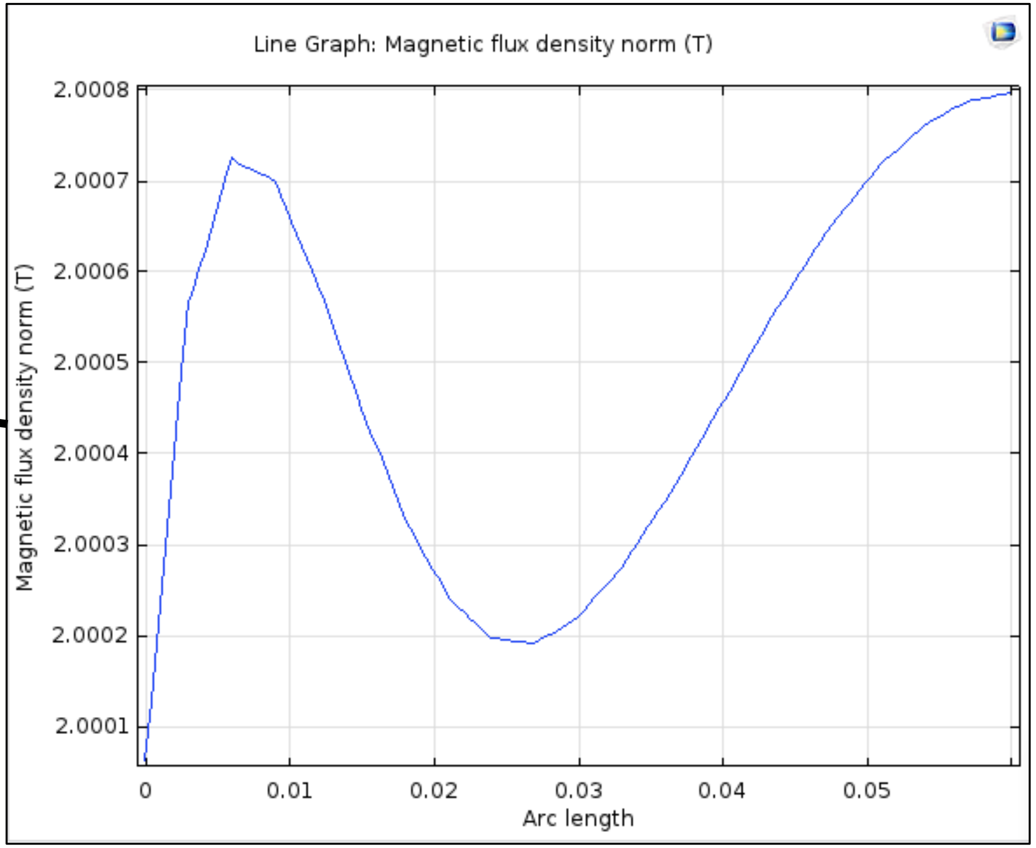
Arched racetrack Coil

Parameters	Value
Thickness of tapes /mm	0.39
Turns of each pancake	35
Width of tapes /mm	12
Air Gap /mm	6
Min radius of chamfer /mm	50
Angle of deflection / °	8
Radius of deflection /m	3
Operating direct-current /A	450
Operating temperature /K	20
Insulation material	Stainless Steel

Electromagnetic Design







Operating Current: 450 A

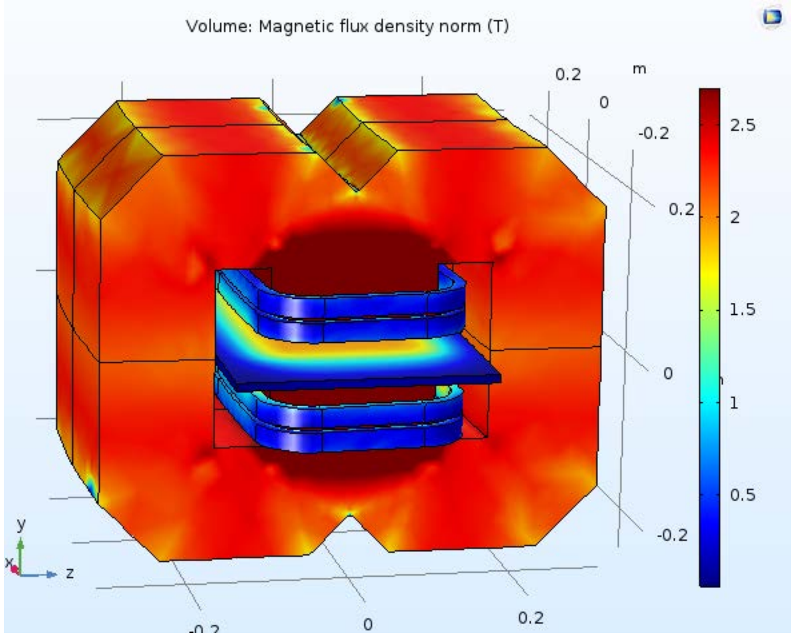
Operating Temperature: 20 K

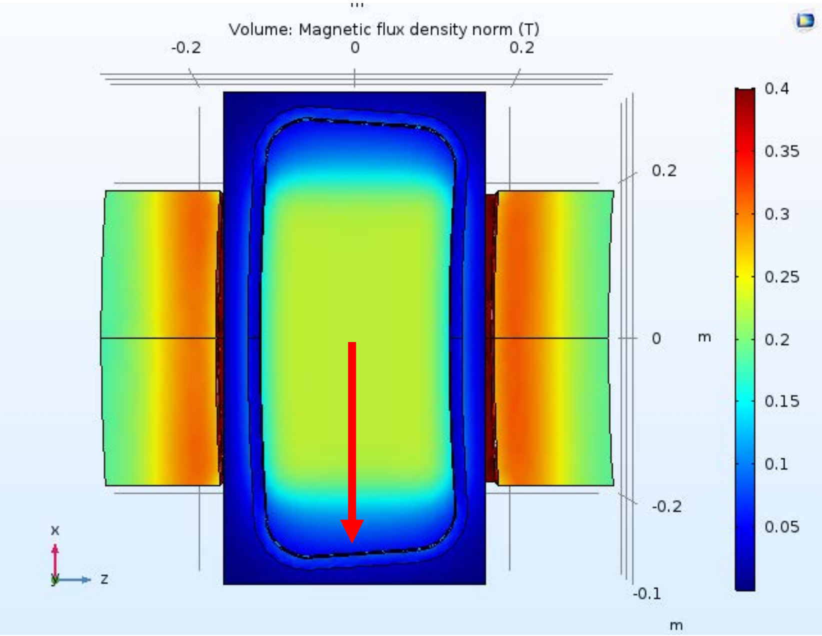
Magnetic field intensity: 2 T

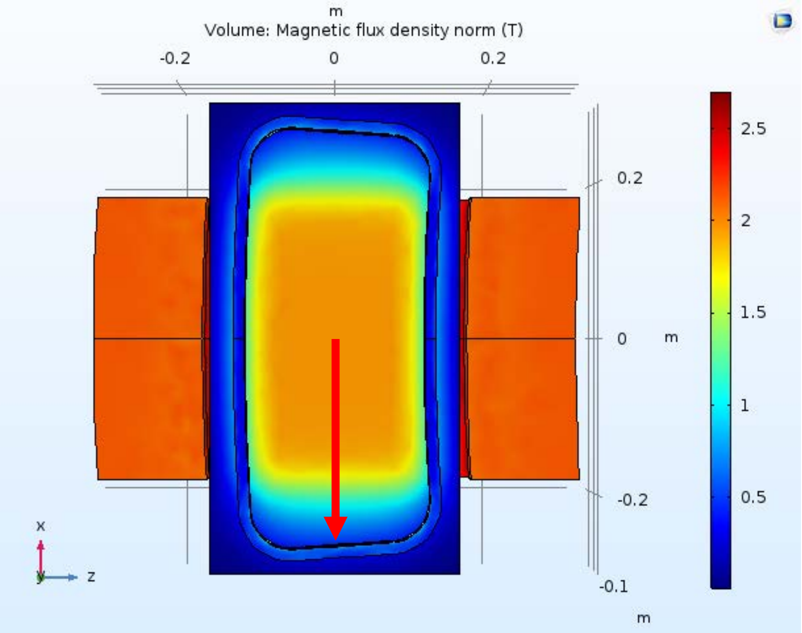
Operating Current / A	Central Magnetic Field / T	Uniformity of Magnetic Field / ‰
50	0.229	±6.10
80	0.366	±6.00
450	2.000	±0.19

Uniformity: $\delta = \pm \frac{2.0008-2.00005}{4} = \pm 0.19‰$

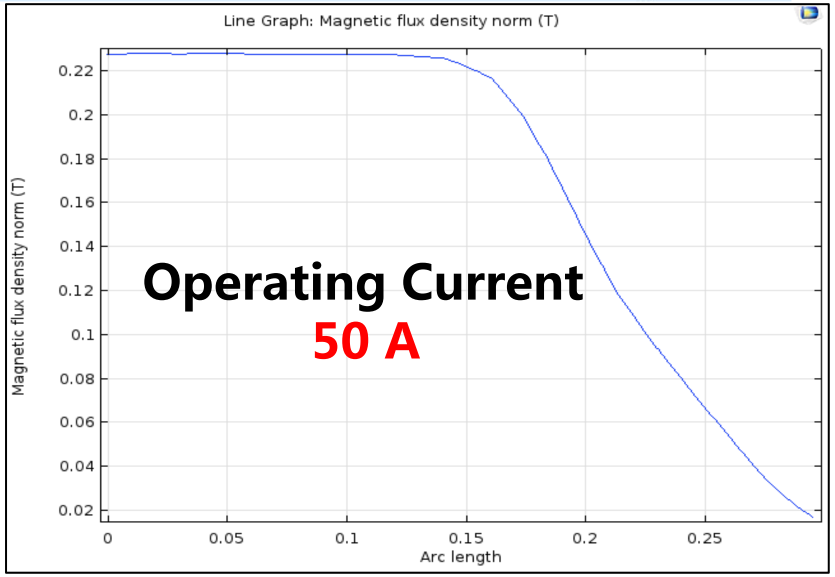
3D Field Simulation

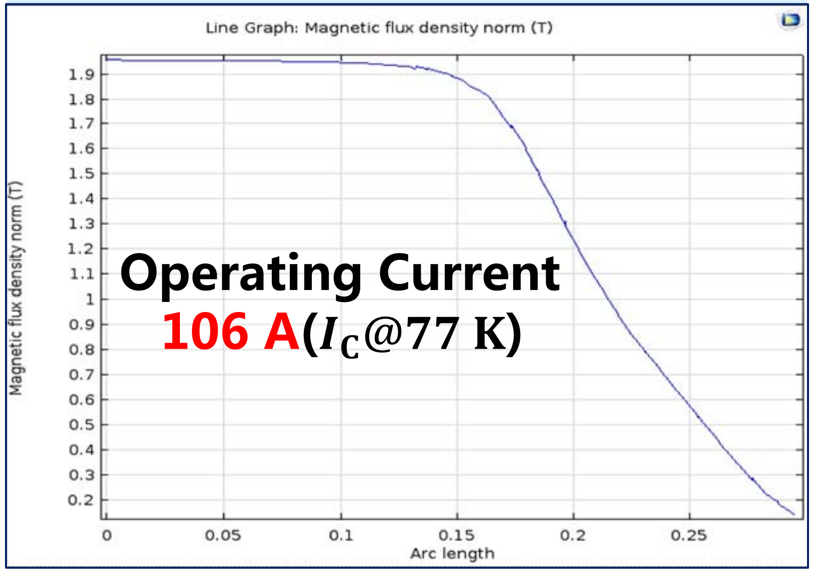




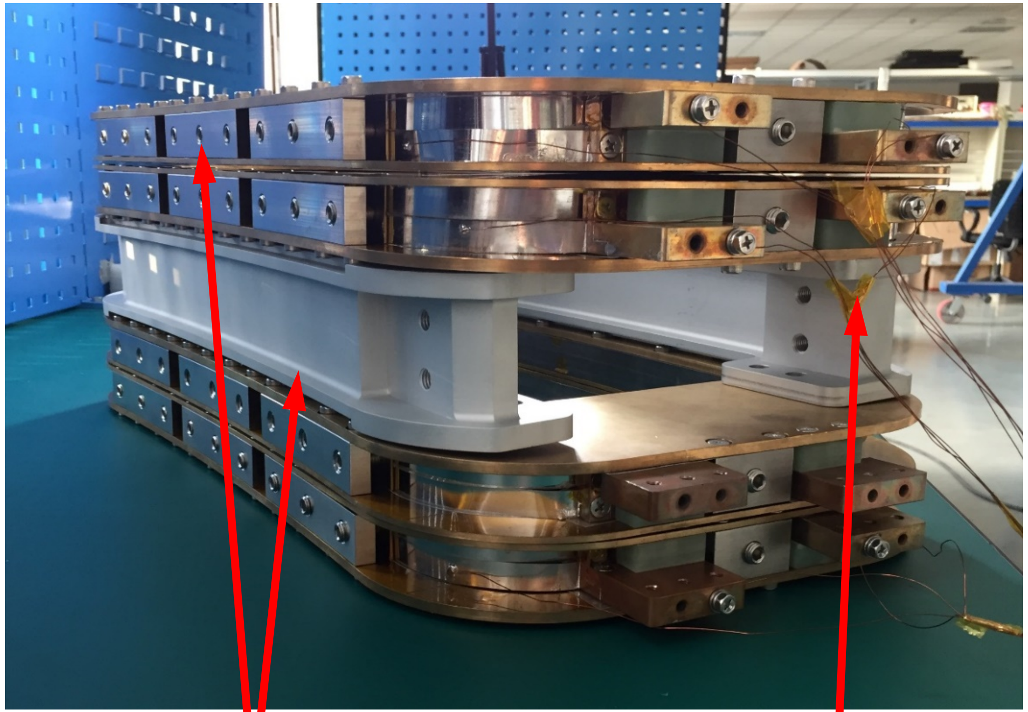


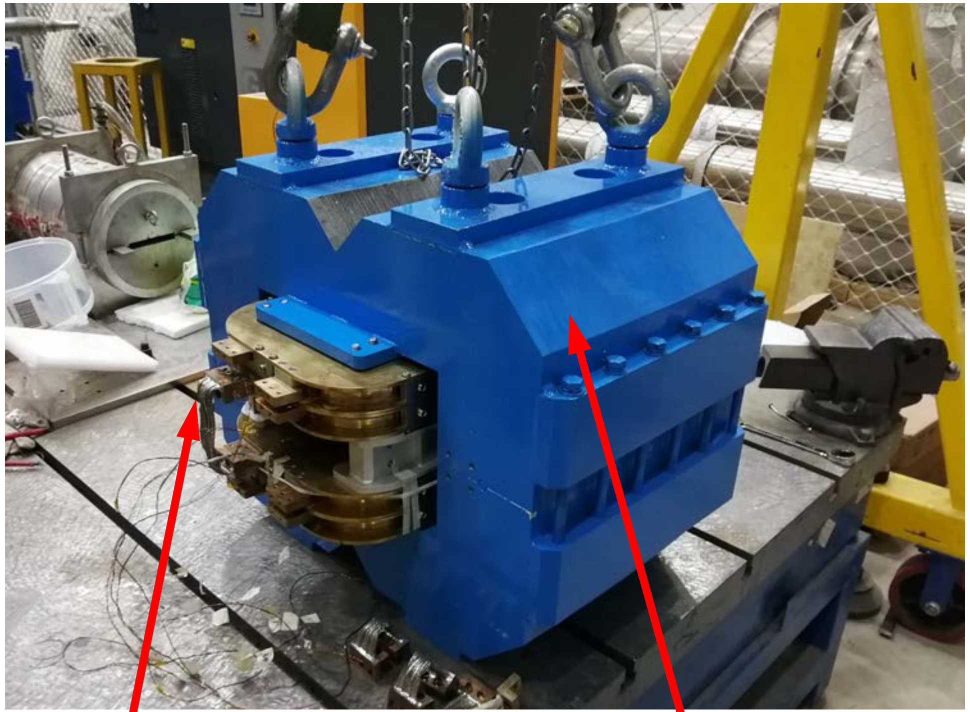
Operating Current / A	Central Magnetic Field / T	Temperature / K
50	0.228	77
80	0.365	77
106	0.483	77
450	1.957	20





Structural Design





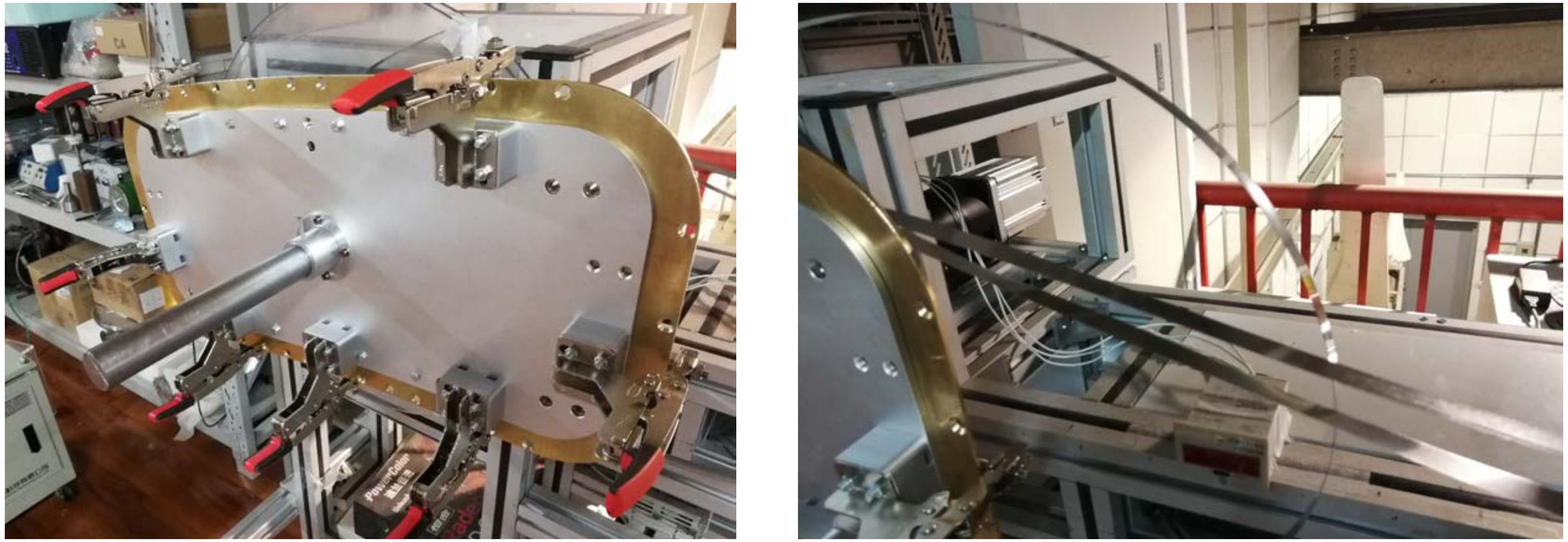
Support Structures
(support & force adjustment)

Sensors
(voltage, magnetic field & temperature)

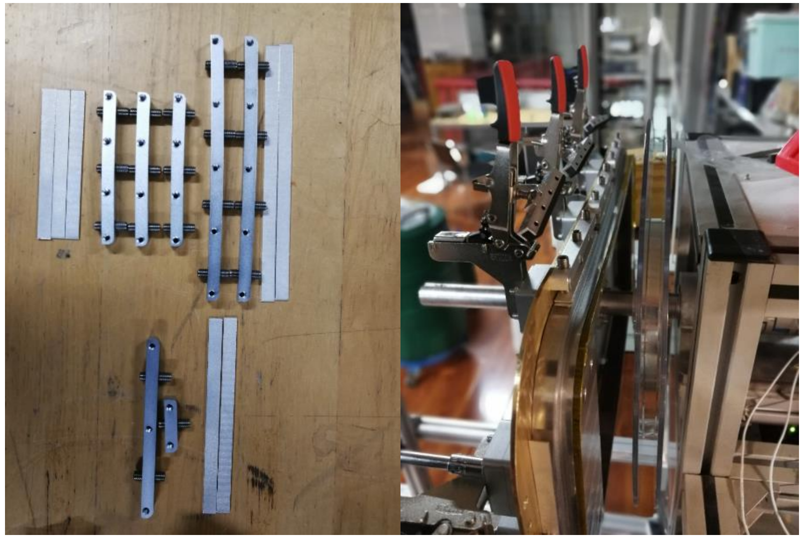
HTS coils
(four coils in series circuit)

Iron Core modular

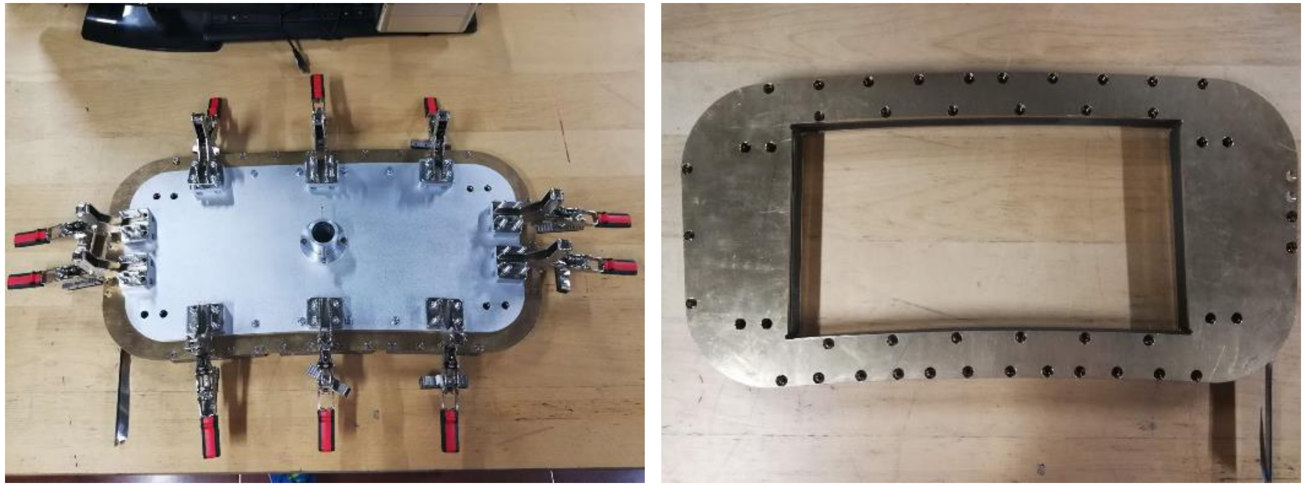
Coil manufacturing



SS tape co-wind



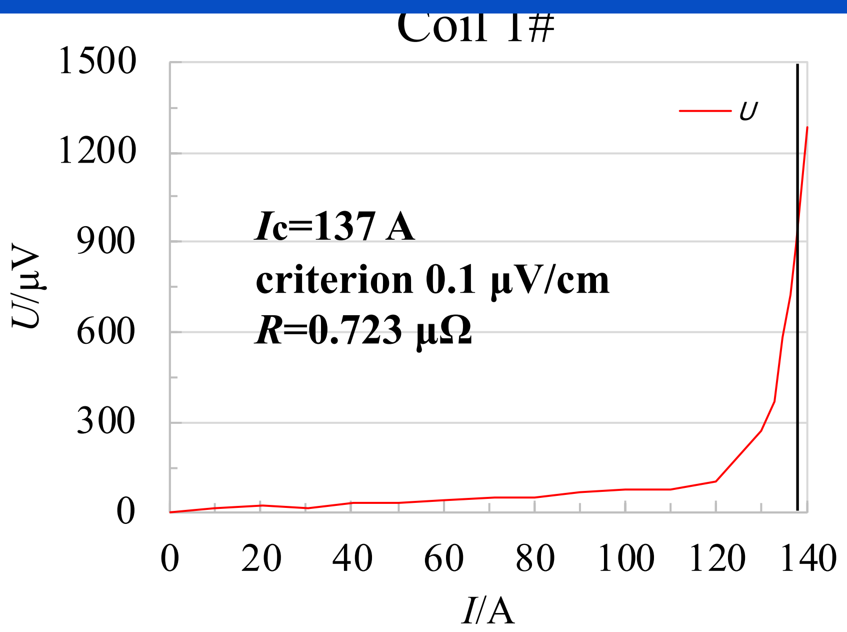
Mechanical support at long sides

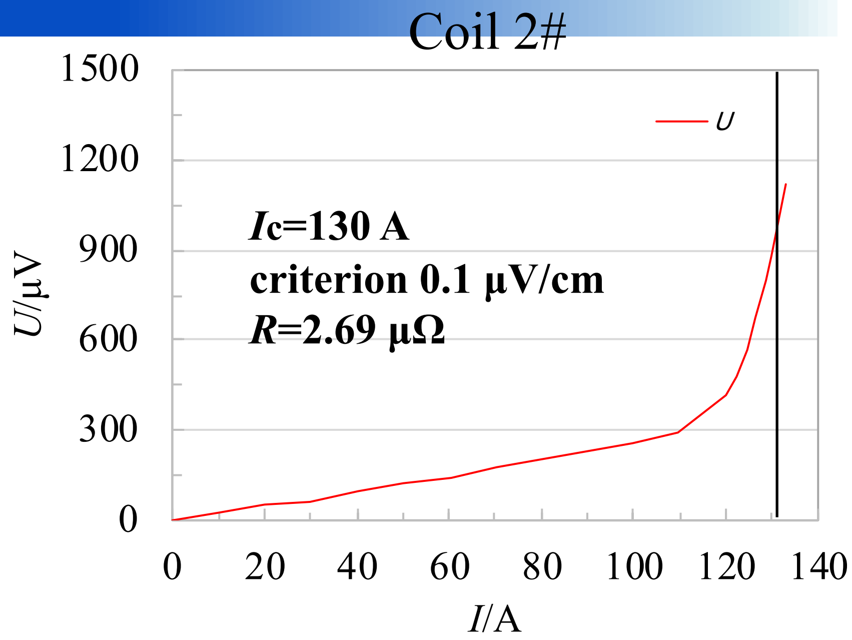


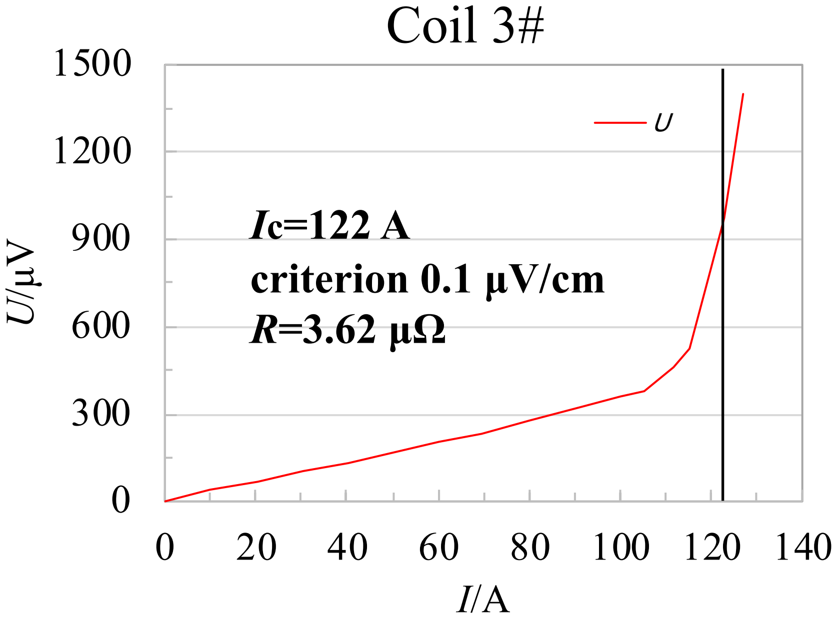
Final assemblage

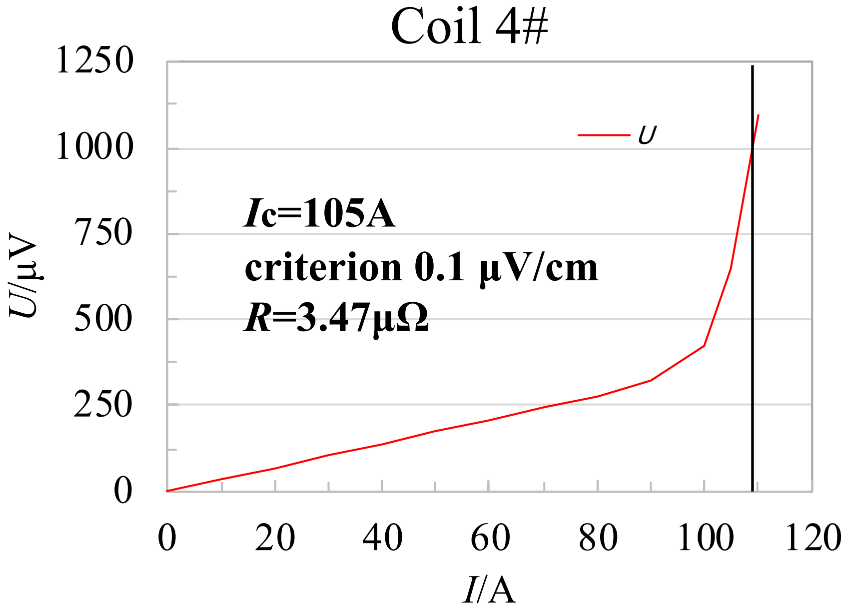
- ✓ SS tape co-wind for the radiation resistant requirement
- ✓ Special design for current terminals
- ✓ Two types of ReBCO tapes were used: Stainless Steel, Copper

I_c measurement of coils at 77 K

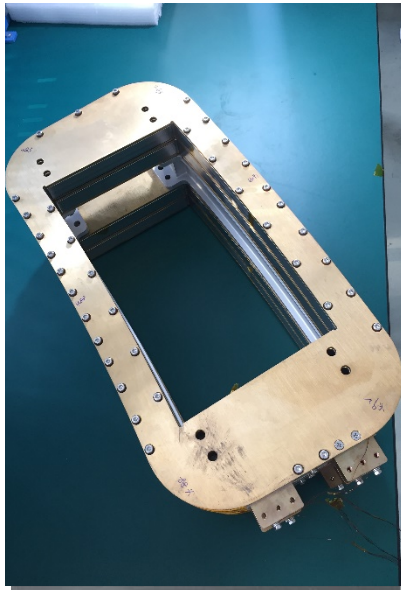


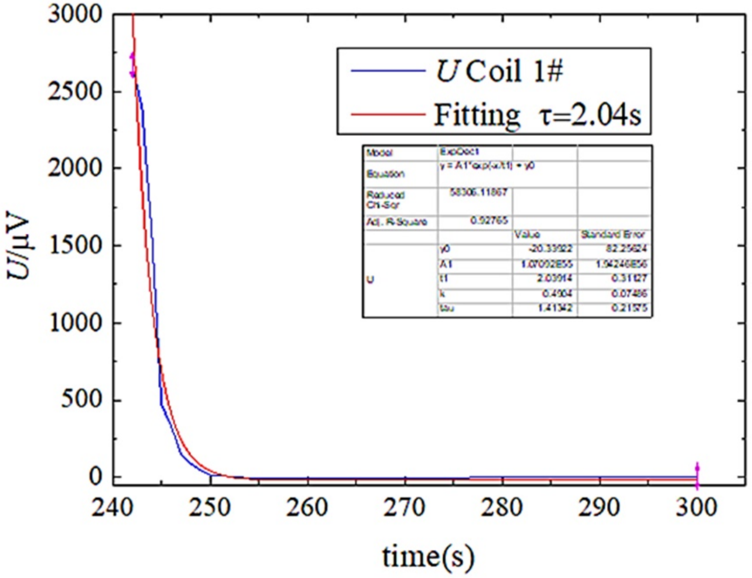


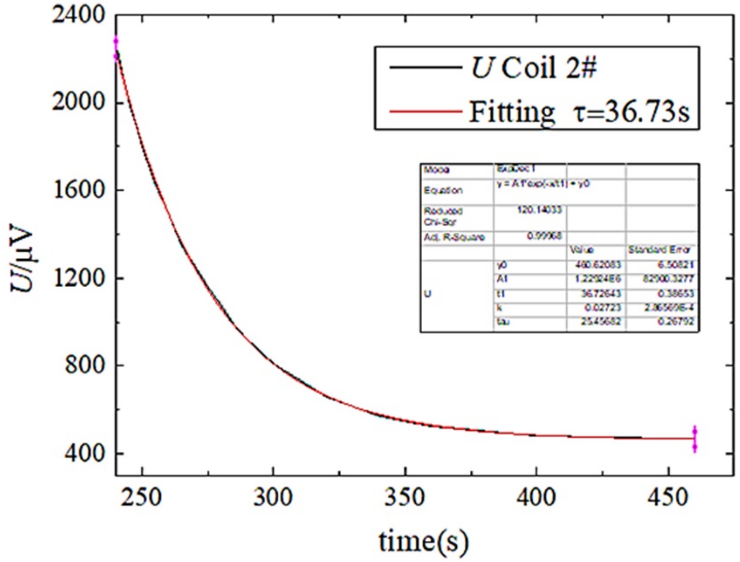


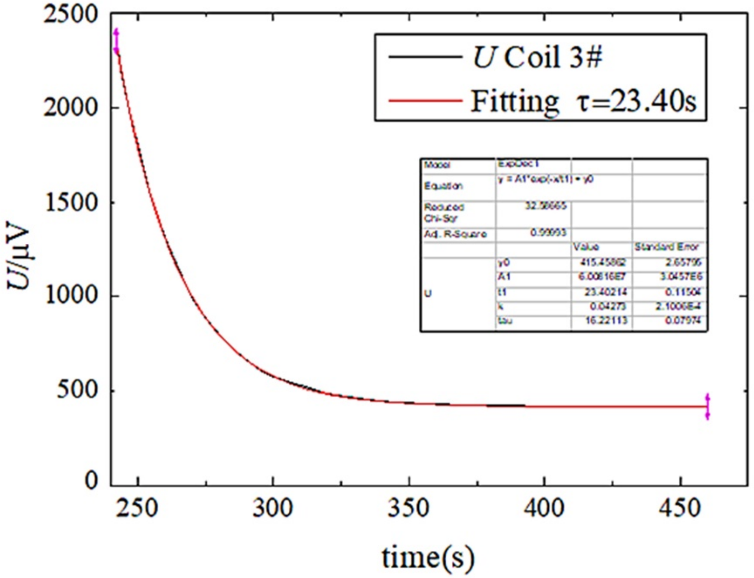


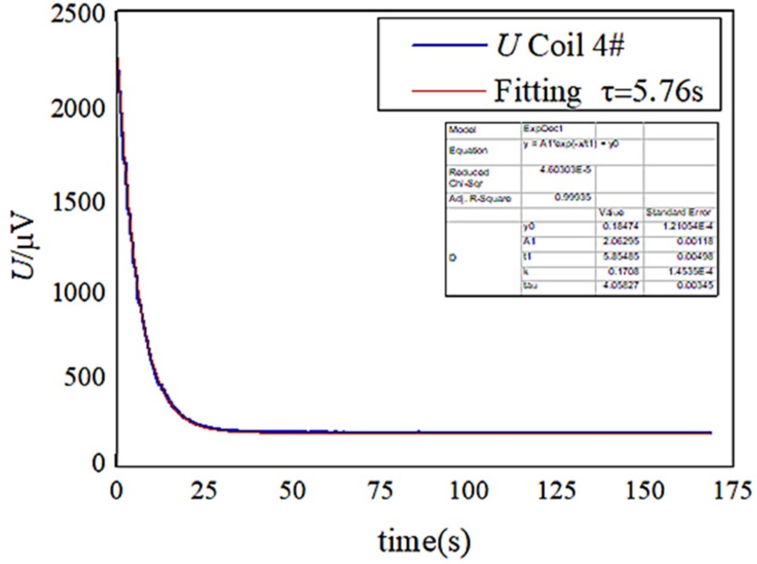
Decay analysis of coils at 77 K



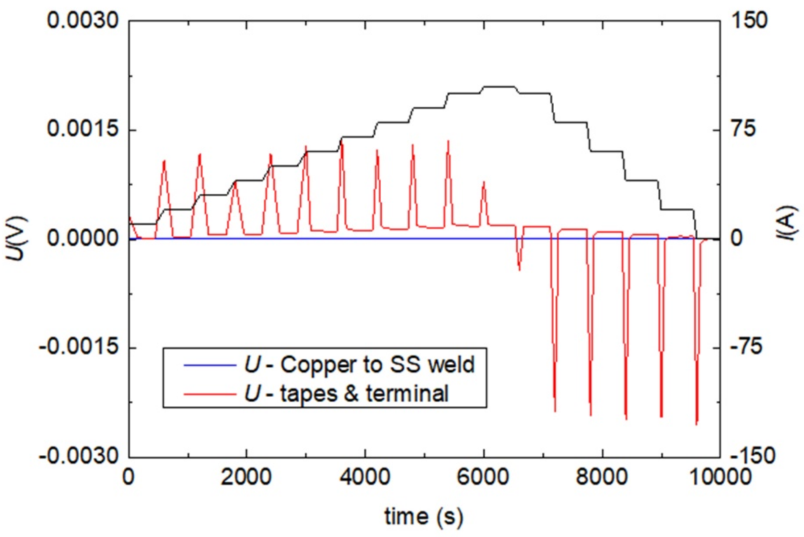


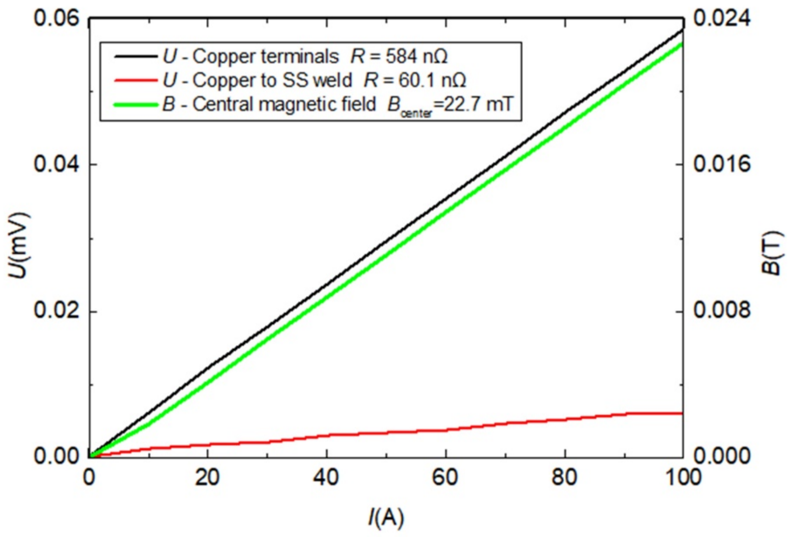


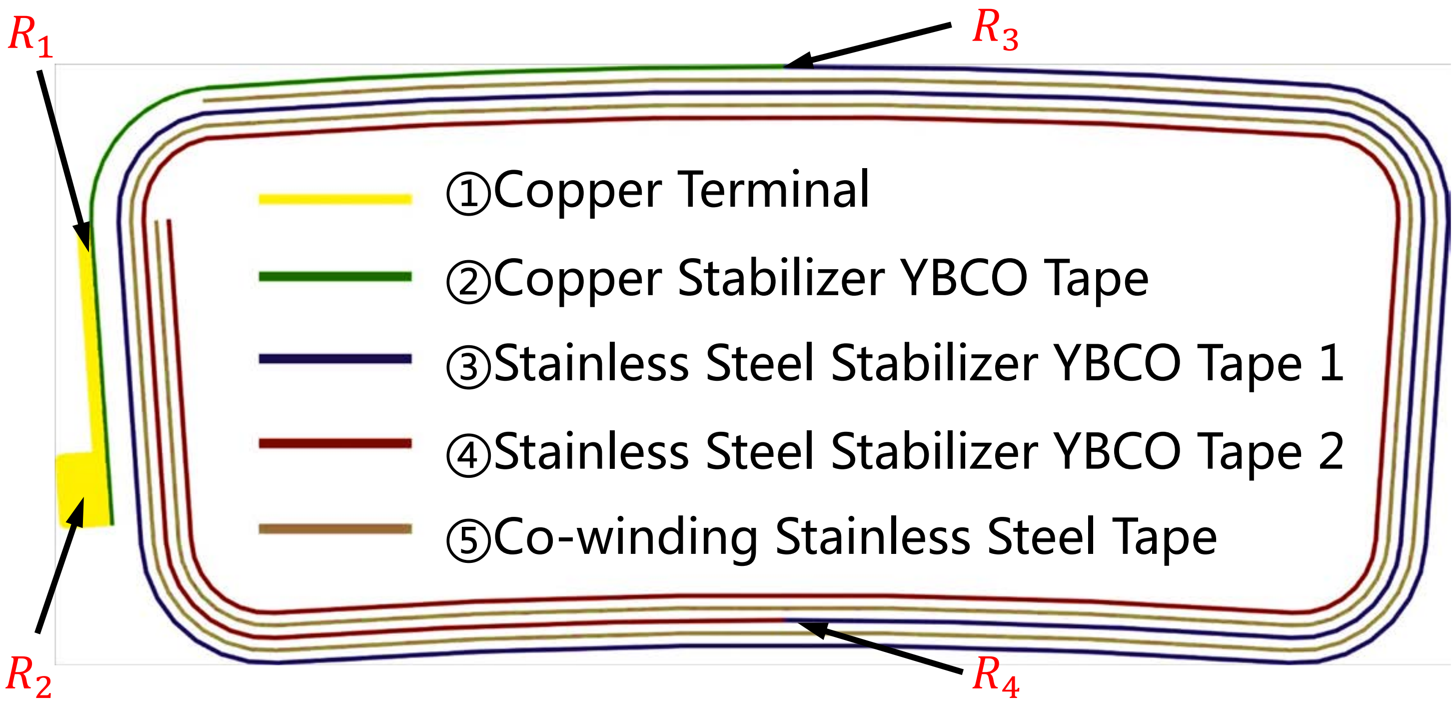




Resistance Analysis of Coil 4#



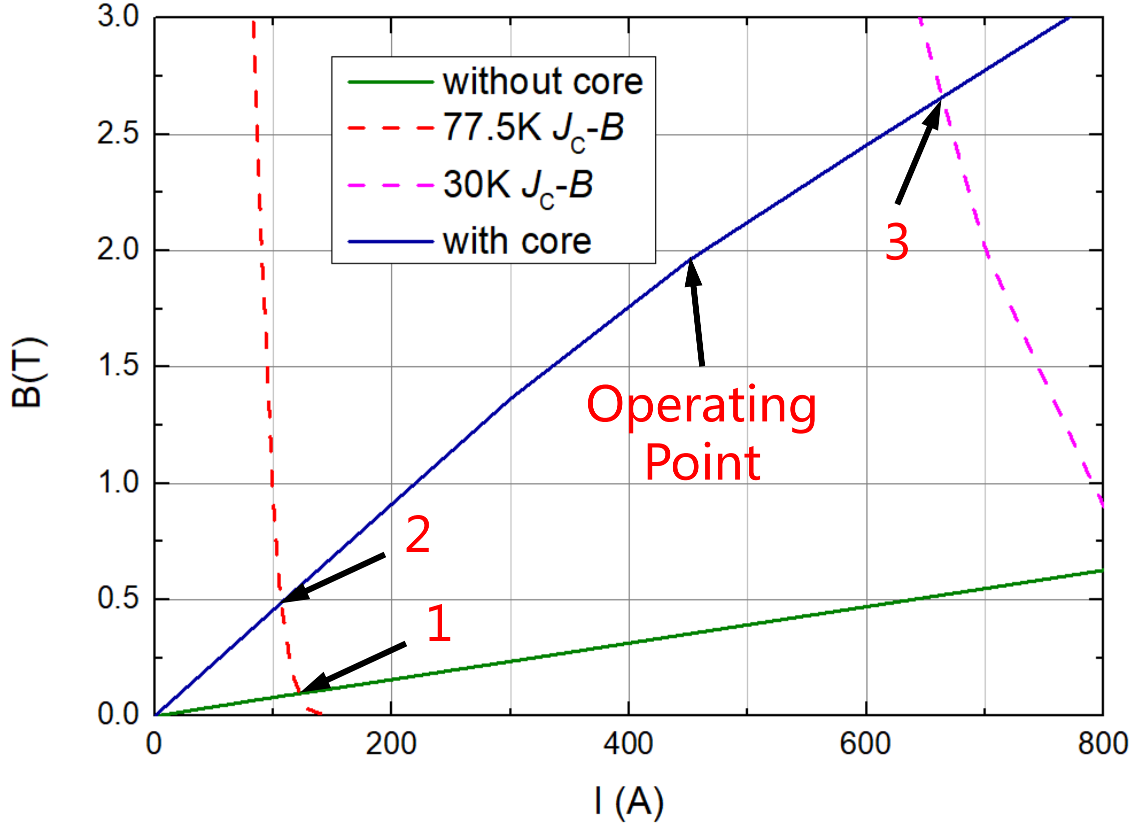




No.	Connections	Type	Resistance / μΩ
R_1	① to ②	Tin Soldering	0.15
R_2	① to ②	Distributed Resistance	0.43
R_3	② to ③	Tin Soldering	0.06
R_4	③ to ④	Tin Soldering	1.3

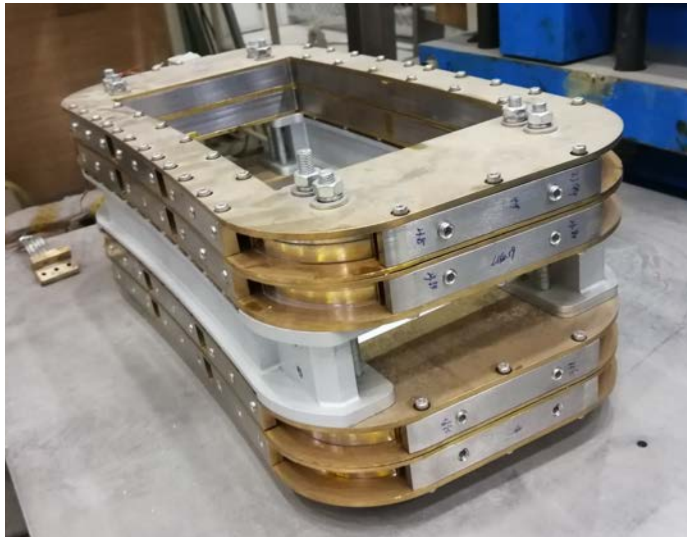
- There are two large resistors in the coil, R_2 is generated by the distributed current, R_4 is due to a large soldering resistance.

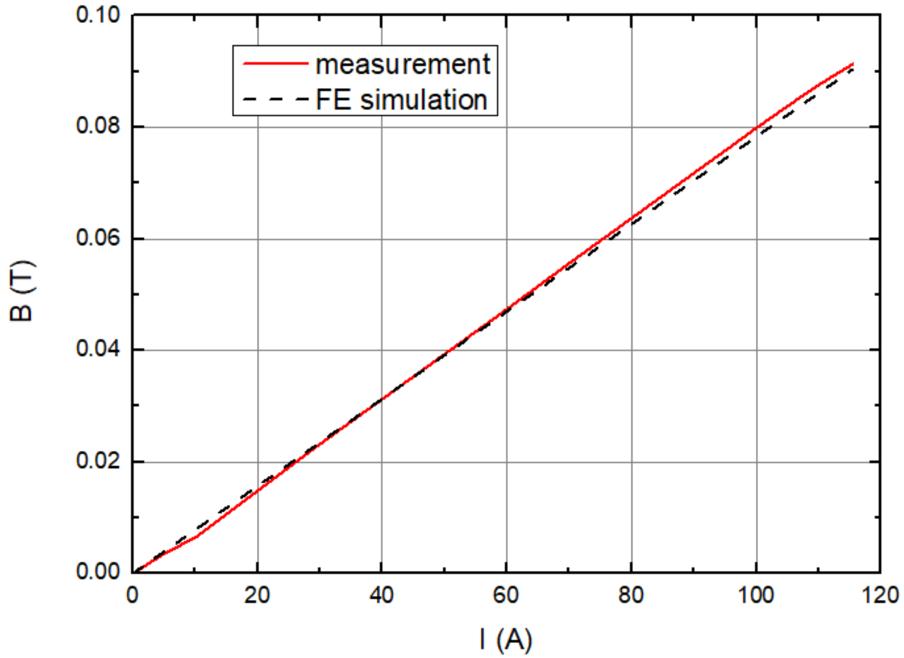
Load line at 77K

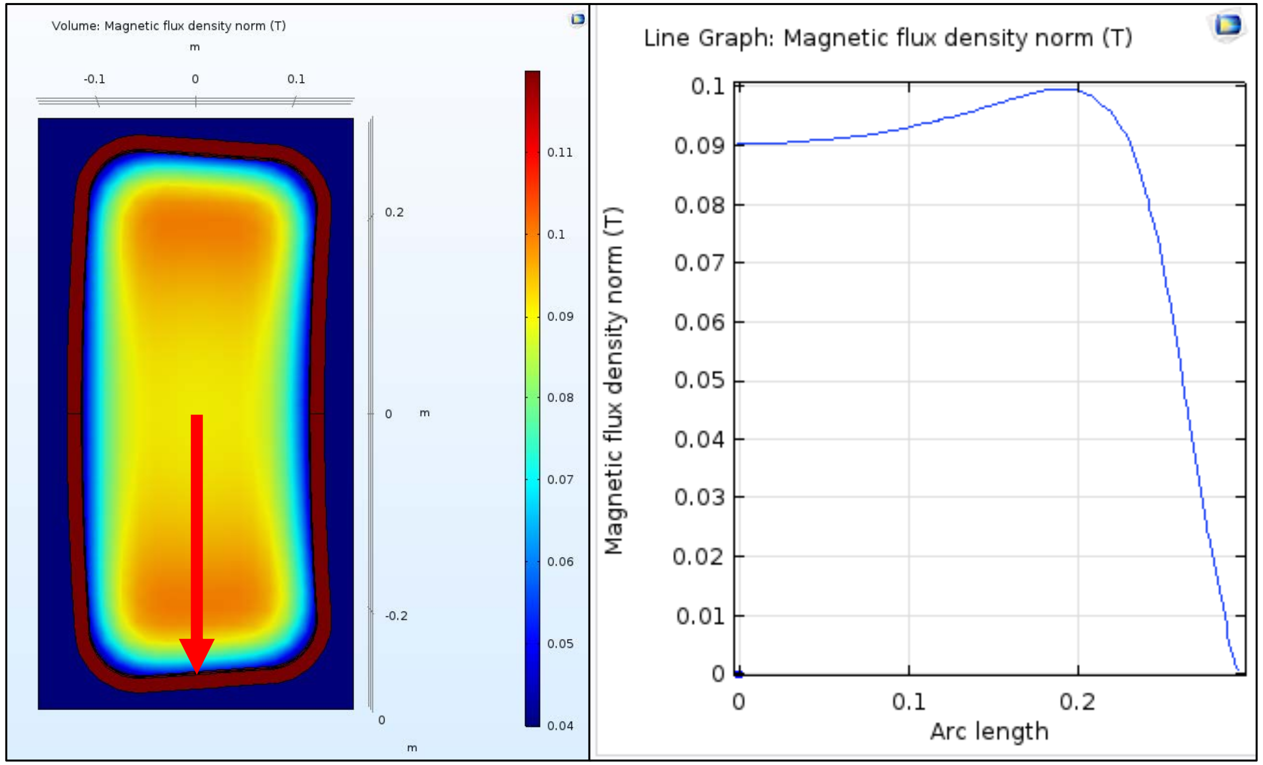


No.	Current / A	Magnetic Field / T	Temperature / K
1	115.5	0.092	77
2	106	0.494	77
3	660	2.691	30
Operating Point	450	2	20

Test without Ion Core at 77K

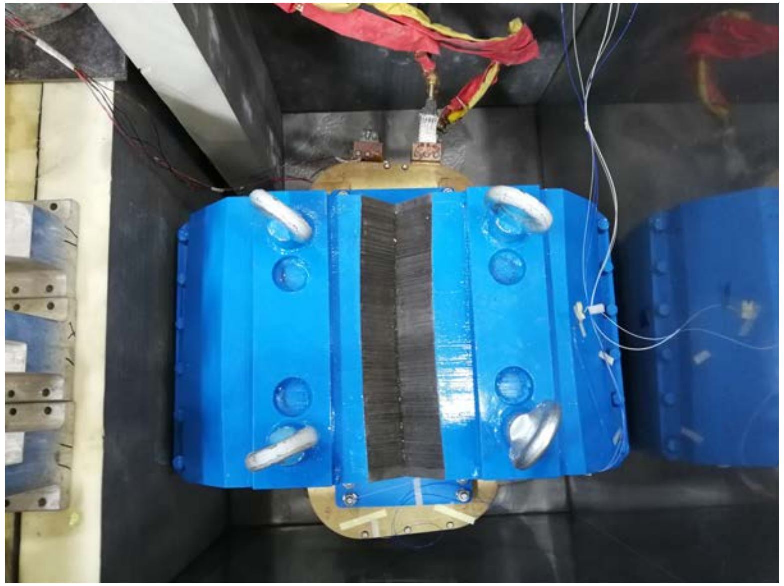


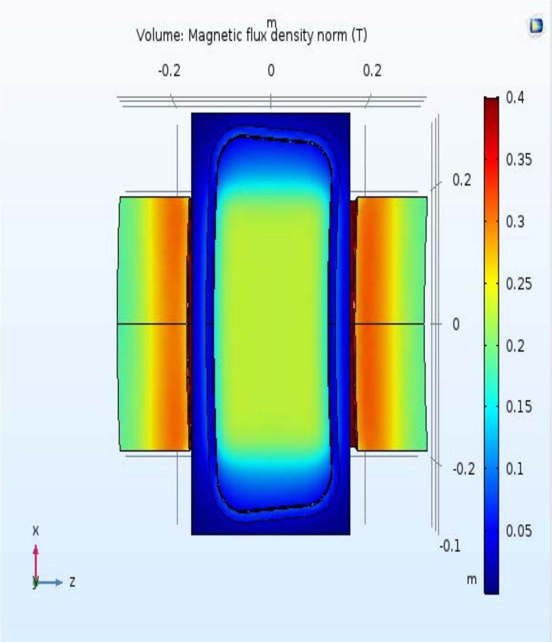


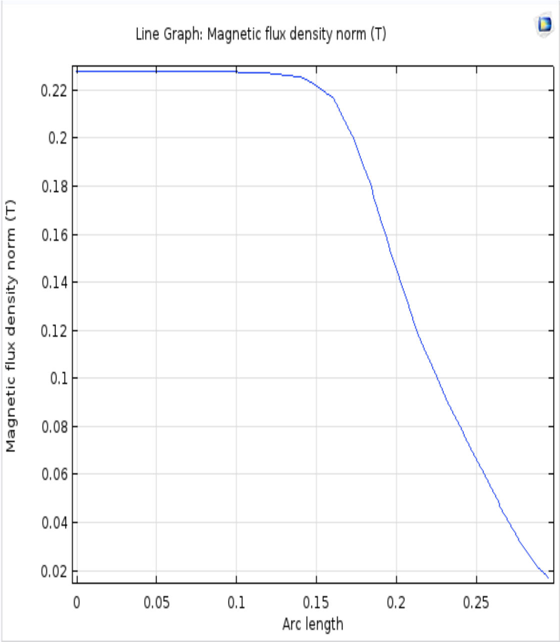


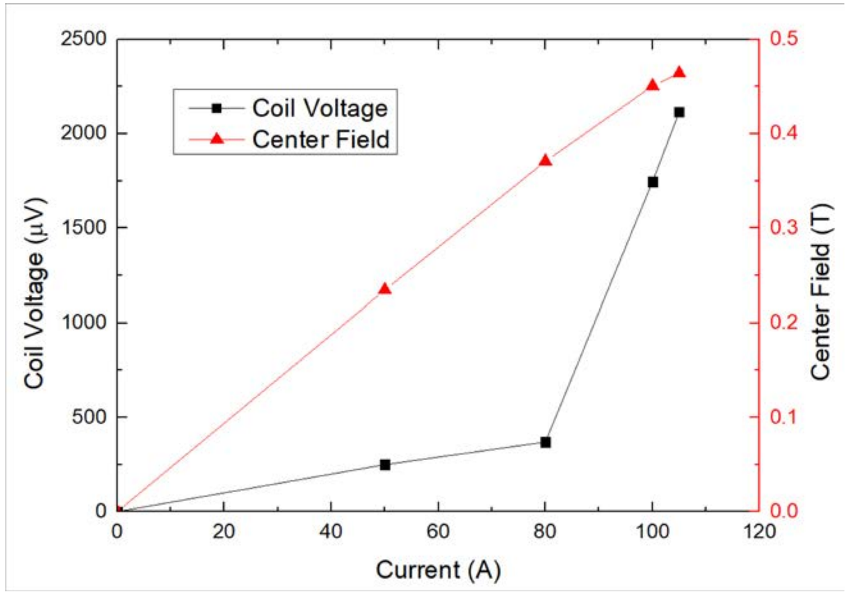
- The dipole magnet was tested without ion core at 77 K.
- Charge to the simulated critical current I_c = 115.5 A while cooling with liquid nitrogen.
- The measured and simulated field at 115.5 A are 89.0 mT and 90.1 mT, respectively. The difference might be due to the SCF effect.

Test with Ion Core at 77K



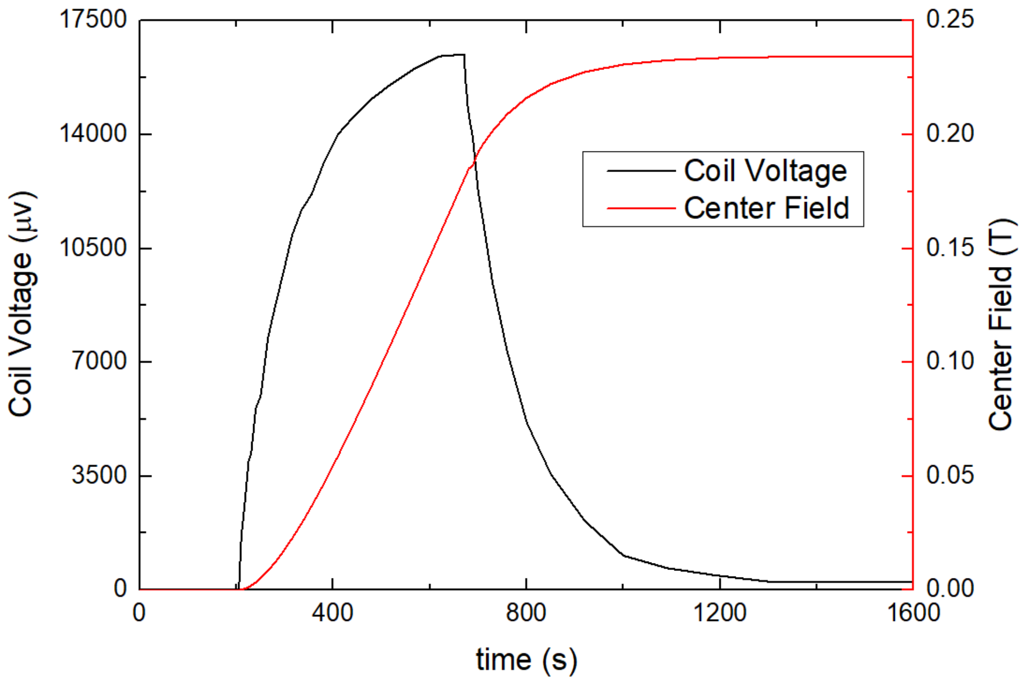






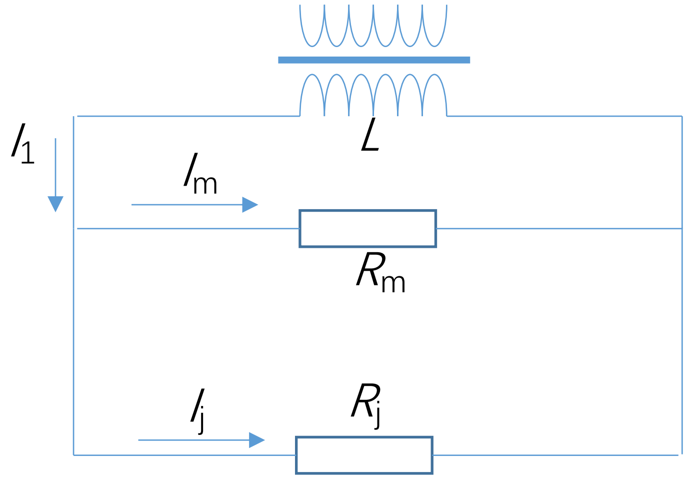
- The dipole magnet was tested with ion core at 77 K.
- Charged to the simulated critical current I_c = 105 A, while cooling with liquid nitrogen.
- The central field reached **0.464** T, at 105 A.

Metal insulation-Decay behavior of the whole dipole



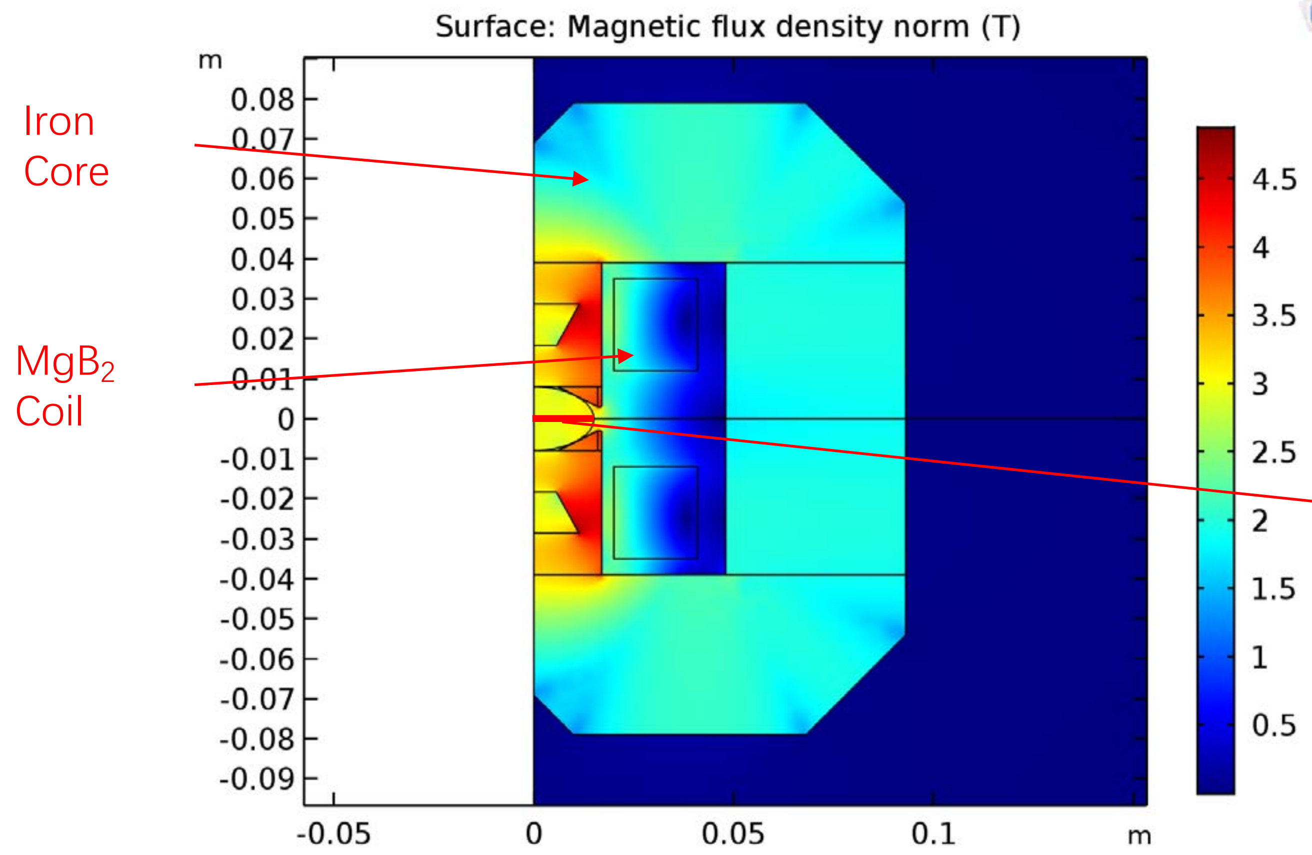
Voltage and field vs. time when charged from 0 A to 50 A

$$V_c(t) = \alpha L_m (1 - e^{-t/\tau})$$



Parameters	Value
Operating Current / A	50
L_m / H	0.966
τ / s	108.4
R_m / mΩ	9.19

Electromagnet Design of MgB_2 Dipole Magnet

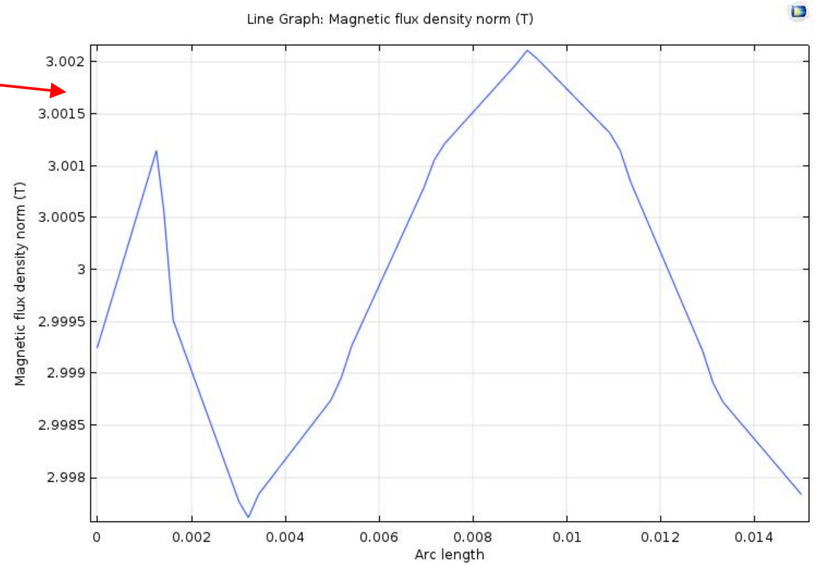


Magnetic Field of the MgB_2 Magnet

Parameters of the MgB_2 Magnet

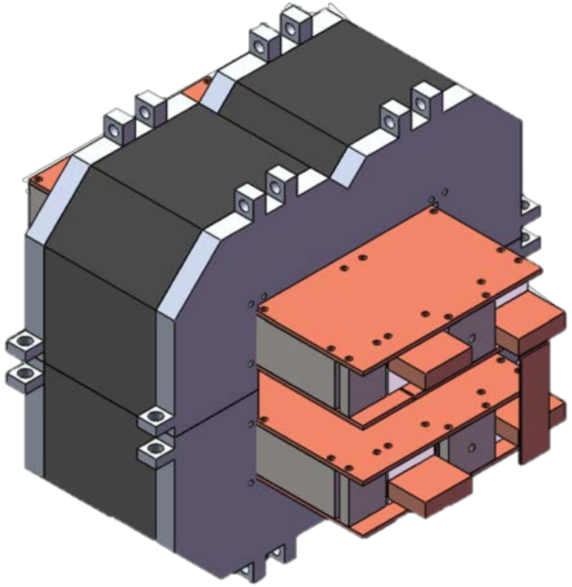
Parameters	Value
Operating Current [A]	125
Central Magnetic Field [T]	3
Magnetic Field Uniformity	0.08%
Number of Turns*	23x24
Wire Length [m]*	331

*Each Coil.



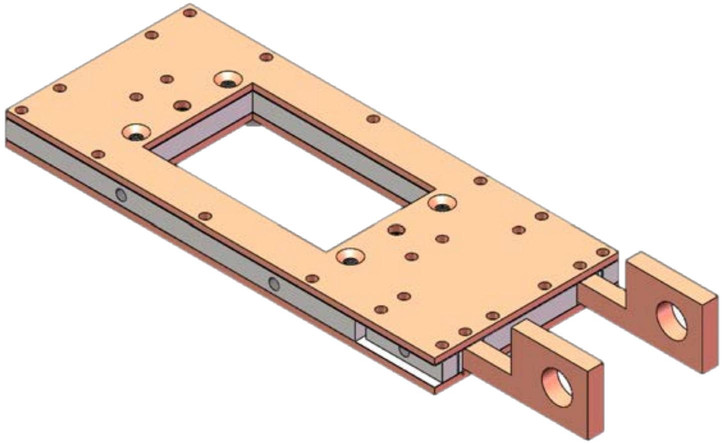
Central Magnetic Field

Structural Design and Manufacture



MgB_2 Magnet with Iron Core

MgB_2 Sample Coils

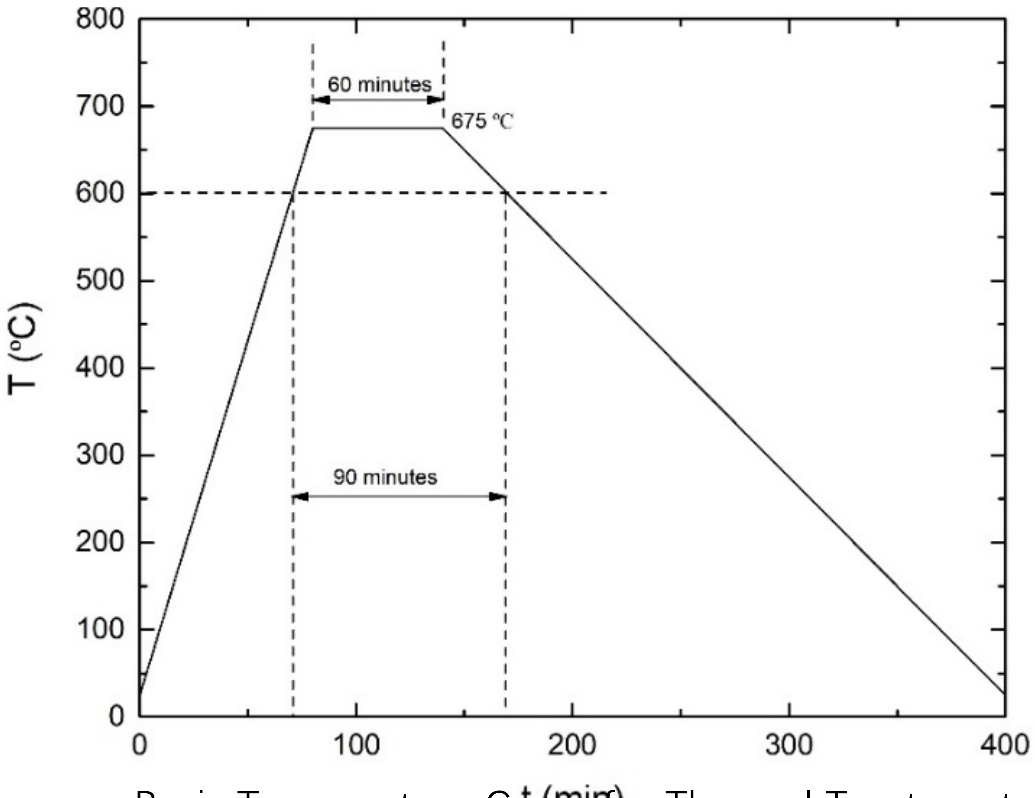


MgB_2 Sample Coil

Parameters of the MgB_2 Sample Coil

Parameters	Value
Operating Current	280 A
Central Magnetic Field	0.33 T
Number of Turns	6x3
Wire Length	5.1 m

Heat Treatment of MgB_2 Sample Coils



Basic Temperature Curve for Thermal Treatment

Coil Wound → Heat Treatment → Copper Terminals Welded

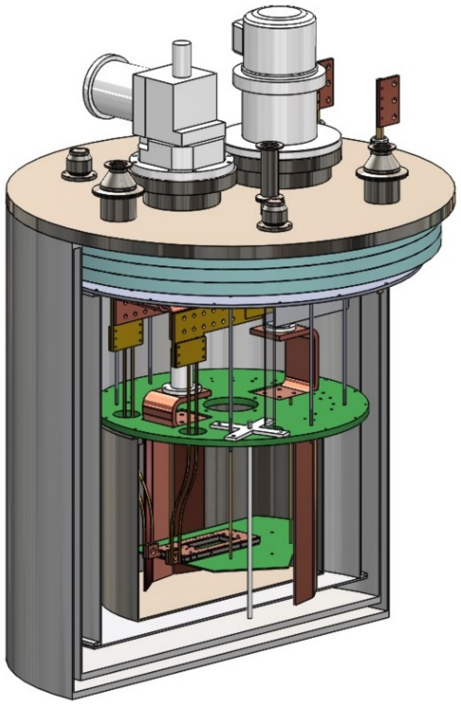
Heat Treatment Temperatures for MgB_2 Sample Coils

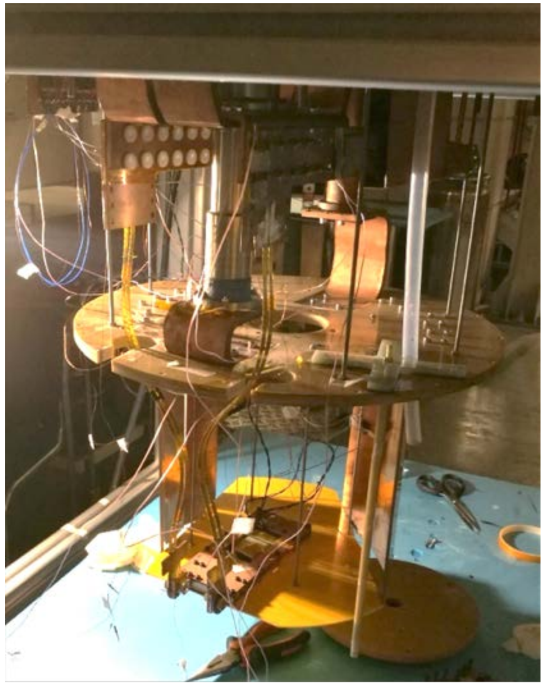
Coil	Temperature
Coil #1	650 C°
Coil #2	675 C°
Coil #3	700 C°

Different heat treatments on 3 sample coils

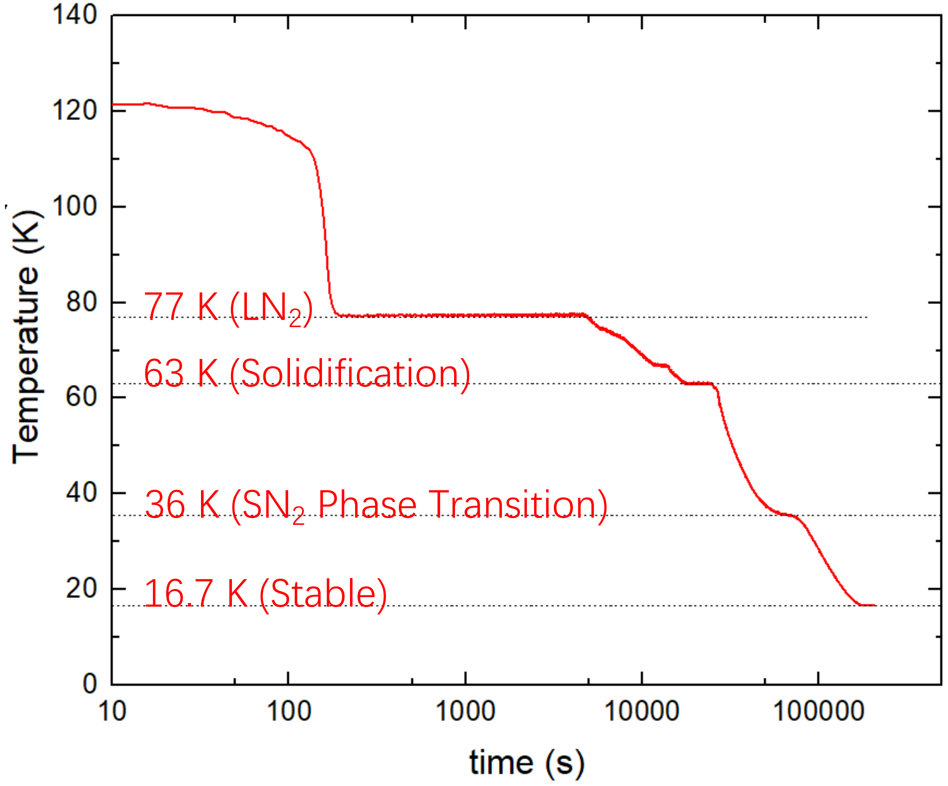
- Basic temperature curve at left.
- Different maximum temperatures for 3 coils.
- Same heating and cooling rates.

Test System for MgB_2 Sample Coils





Cryogenic System with Solid Nitrogen

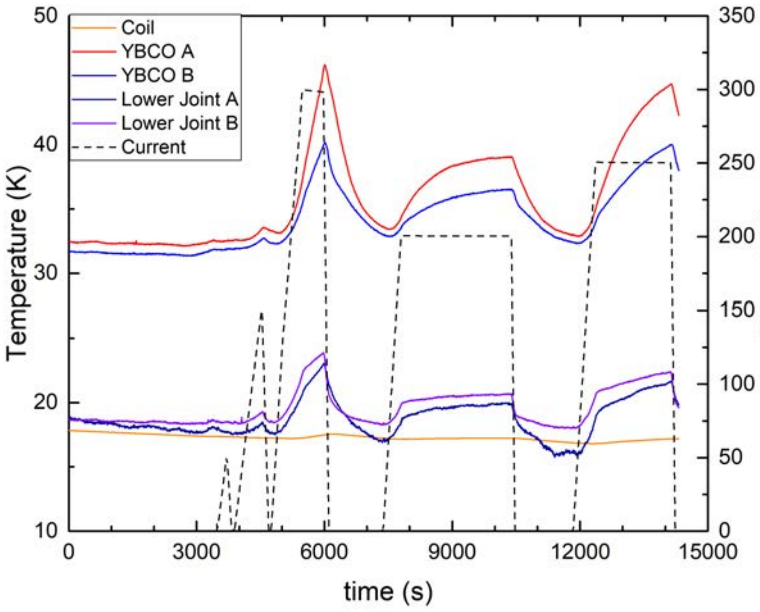


Temperature of the Coil during Cooling

- Solid nitrogen is used as thermal stabilizer
- YBCO tapes are used for the low-temperature section of current leads
- Stable coil temperature is ~16.7 K after 48.6 h cooling

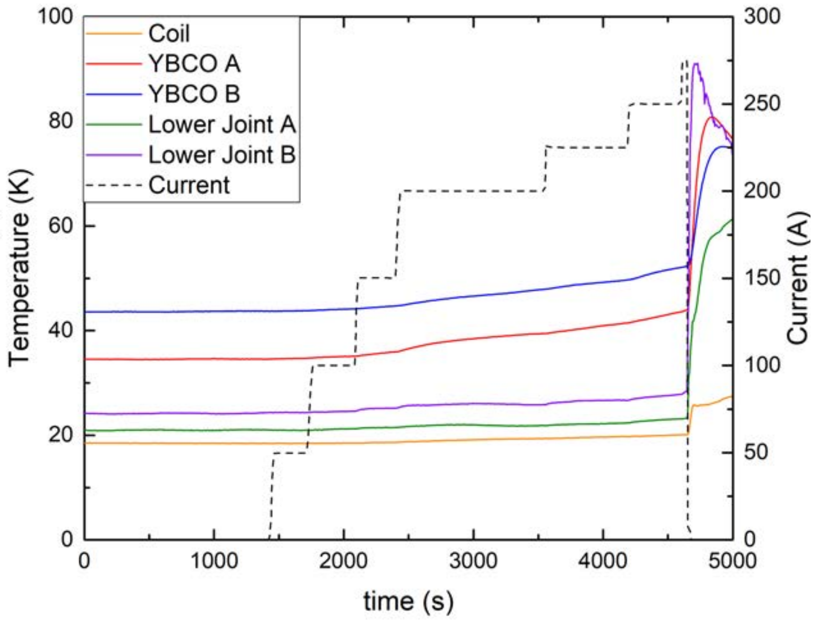
Test Results for MgB_2 Sample Coils

Coils have been tested at the temperature under 20 K.
Temperatures of the coils, YBCO current leads and joints have been tested.



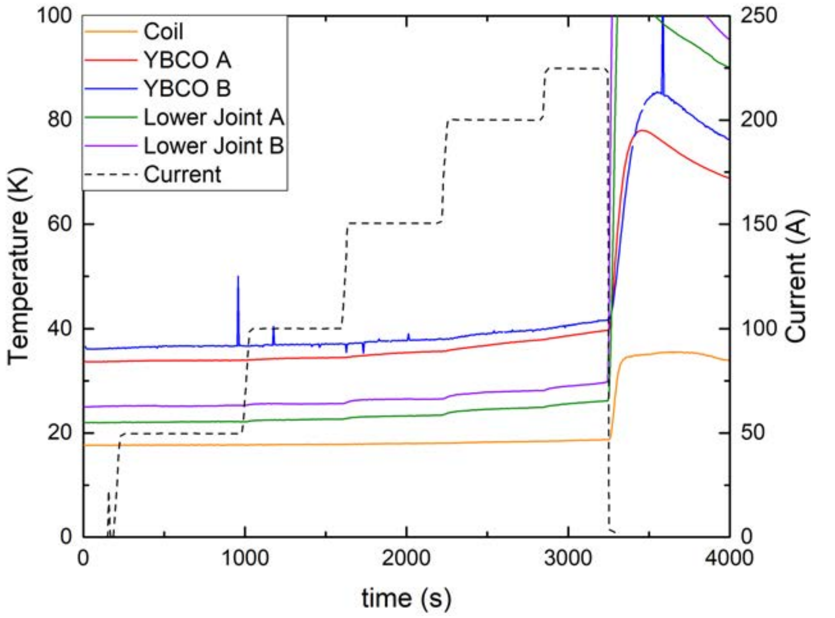
Test of Coil #1

- Charged with current at different values
- Stable at 250 A for more than half an hour
- Charged at 300 A for ~5 minutes



Test of Coil #2

- Current was loaded step by step
- Quenched at 275 A



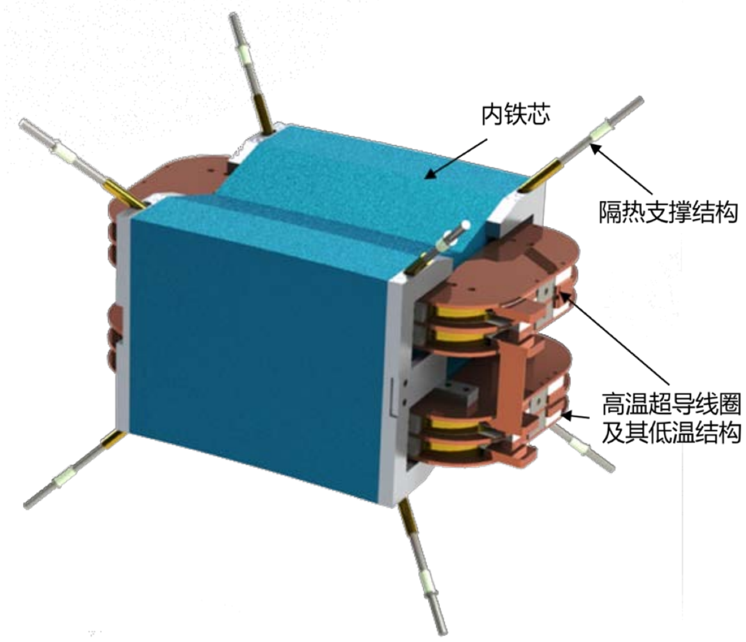
Test of Coil #3

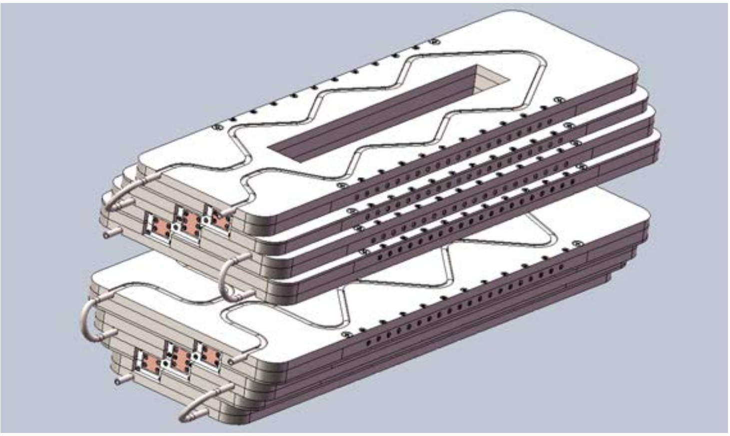
- Current was loaded step by step
- Quenched at 225 A

Caused by performance degradation of YBCO current leads.
Further test will be performed recently.

Summary and future work

1. A superferric type dipole magnet was developed by using metal-insulated ReBCO tapes.
2. Tested at 77 K. τ=108.4 s, B=0.464 T at 105 A. The 4 K test will be done in March.
3. MgB_2 testing coils were produced and tested at 20 K.





Gas-He cooled structure

Thank you for your attention!