MT 26
International Conference
on Magnet Technology
Vancouver, Canada | 2019

Manufacture and performance test of 3.5T High Temperature Superconducting Coil for the Magnetic Separation

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Poster ID : Wed-Af-Po3.24-05[99] **Poster Date & Time:** 25,Sep, 2019 from 14:00 to 16:00

ASIPP

INTRODUCTION

At Nowadays, the applied high temperature superconducting (HTS) technology is introduced to magnetic separation in beneficiation. It cannot make facilities obtain high magnetic intensity and gradient to improve the efficiency of the material purification and separation, but also solve effectively the problem that some weak magnetic materials are difficult to separate.

The HTS magnet, as the core of magnetic separation facilities, has the advantages of high operation temperature, simple cryogenic system, large temperature margin, strong anti-interference ability, good stability and low energy consumption. More importantly, the HTS magnet can be cooled by a cryocooler instead of the expensive liquid helium. Although all of these provide much convenience for the HTS magnet in the application, there are still some problems to be solved in magnet manufacturing. For example, it is necessary to reduce the stresses influence on the HTS tape caused by the mechanical bending and magnetic field.

A 3.5T HTS magnetic separation facility was manufactured for beneficiation in China. According to application requirements, the HTS magnet of which length is 400mm is placed horizontally into the vacuum vessel and cooled by a cryocooler[]. There is a 100mm application channel along the axis at room temperature. The magnet operation temperature is about 20K, the value of maximum central magnetic field is 3.5 T and the center axis uniformity of the magnetic field is more than 95% within the ±100mm distance from the mid- plane. Then the related work were taken place, such as magnet design, magnet manufacturing process, cryogenic system fabrication and magnet performance test.

HTS MAGNET STRUCTURE OPTIMAL CONFIGURATION

The multilayer solenoid structure is adopted in the magnet design. In order to reduce the system cooling consumption, the double pancake structure is used for decreasing the number of coils connection joints during the coil wound. The coil consists of the brass framework and the YBa$_2$Cu$_3$O$_{7-x}$ (YBCO) tape that the length is more than 100m with width of 4.8mm and mechanical and electrical properties are mentioned in Ref. Especially, it is worth noting that the critical current (I_c) of the applied tape is about 120A with self-field at 77K.

Considered that the value of the magnet operated current is about half of the value of the critical current(Ic)with maximum radius magnetic field at 20K, the magnet electromagnetic analysis results shown in Fig.1The HTS magnet structure optimal configuration is obtained and listed in the table I.

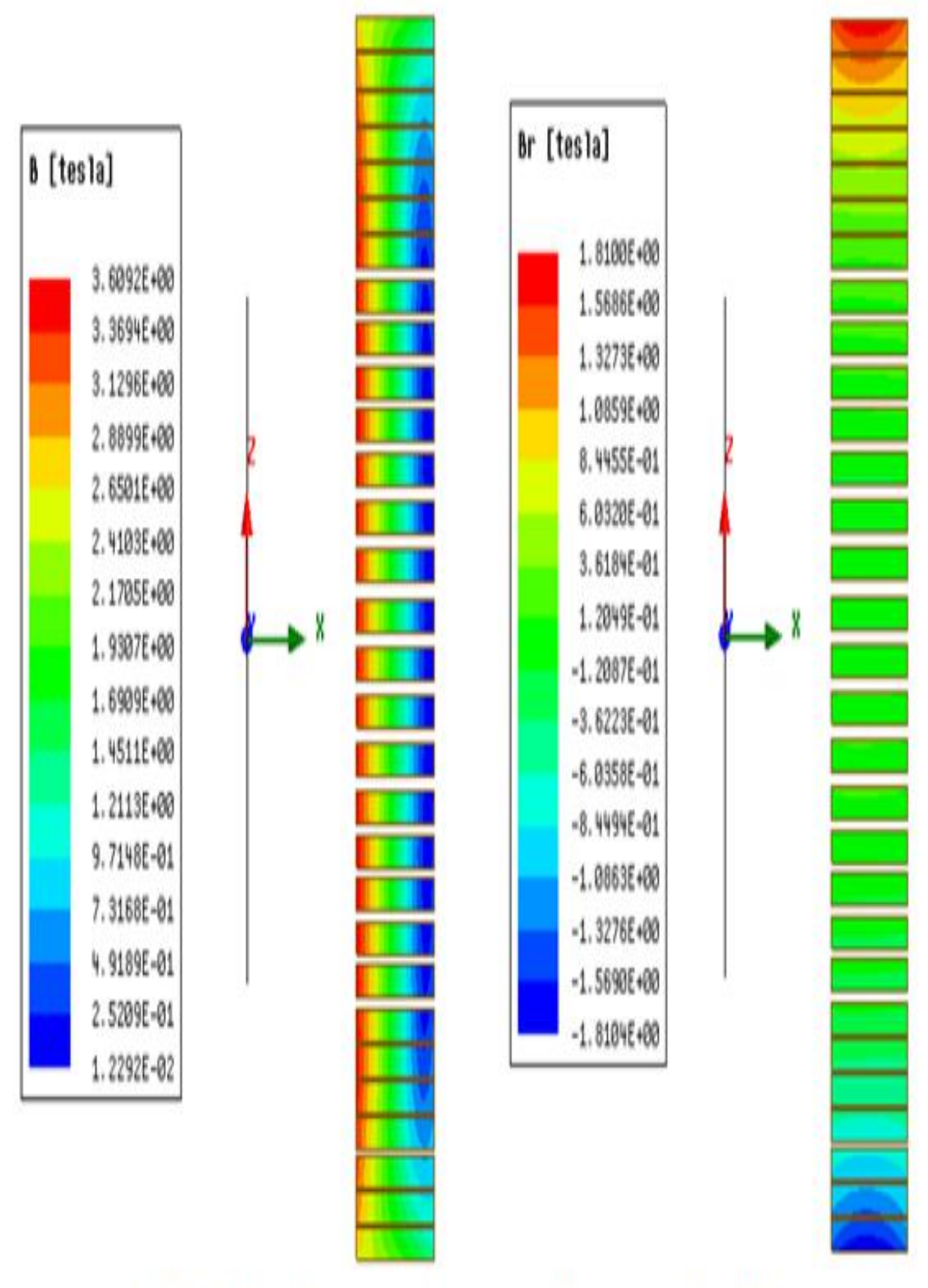


Fig.1. Distribution of entire/radius magnetic field

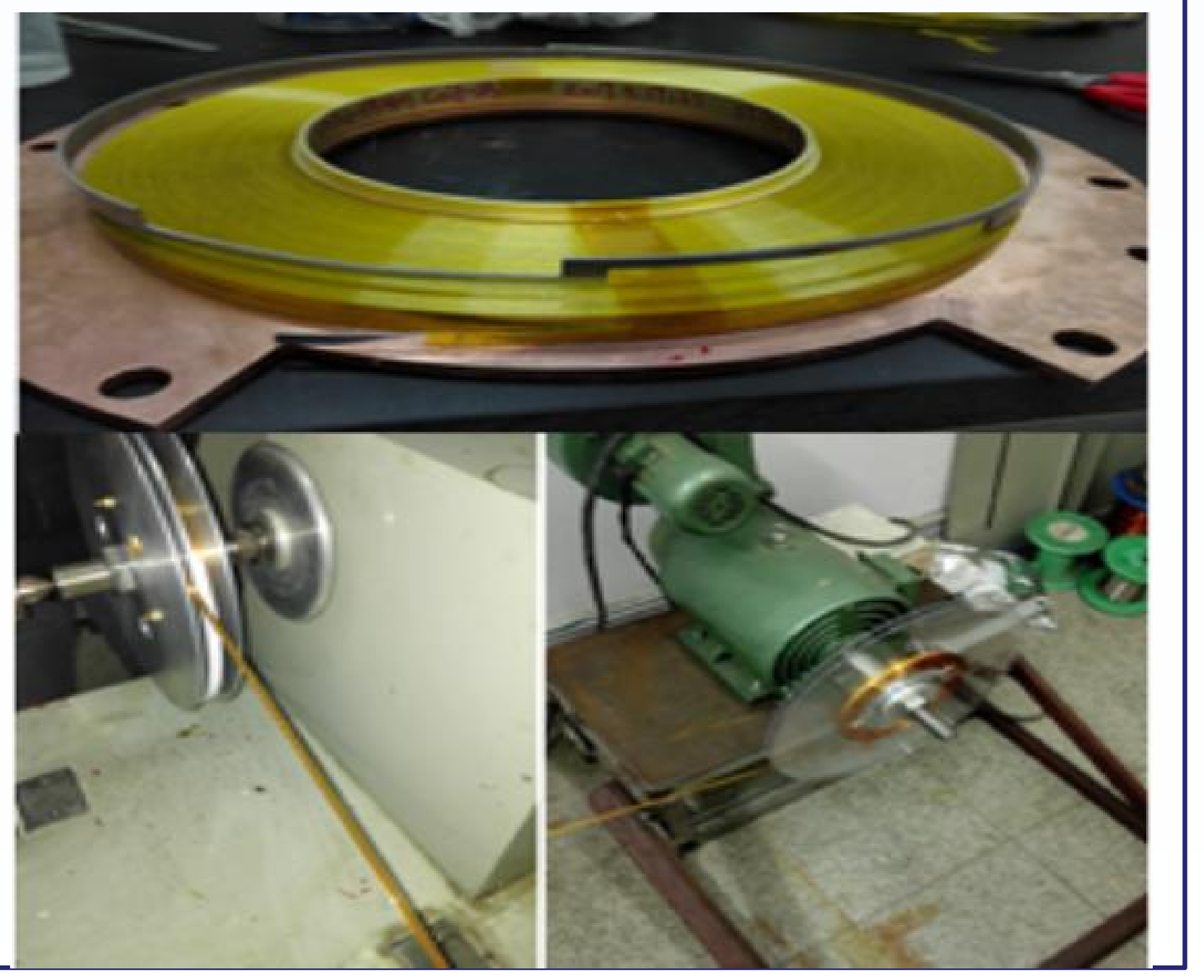
TABLE I
HTS MAGNET OPTIMAL CONFIGURATION

	Coil unit (Left)		Coil unit (Middle)	Coil unit (Right)	
Inner radius (mm)			80		
Outer radius (mm)			138.15		
Thickness of the heat conduction plate (mm)	1.0	3.0	4.5	3.0	1.0
Coil unit height(mm)	71.5	69.5	123.5	69.5	71.5
Magnet height(mm)			405.5		
Coil radial turn			127		
Coil amount	6	5	8	5	6
YBCO tape length(m)			175		
Maximum radius magnetic field (T)	1.81	0.30	0.14	0.30	1.81
I_c at 20K&2T (A)			393		
Operated current (A)			165		
Magnetic field uniform (%)			97.4 (-100mm—100mm) 94.7 (-120mm—120mm)		

HTS MAGNET MANUFACTURE

A. Double pancake coil winding

Because the THS tape will bend and suffer some mechanical deformation damage led to the degeneration of the tape current-carrying capability during the double pancake coil wound, the tape is treated by the means of axial moving some distance to solve the problem. Additionally, there is some tension acting on the tape to decrease the gap between the adjacent radius turns for enhancing the coil entire mechanical property in the period of winding the coil. The coil wound pictures are displayed in the Fig.



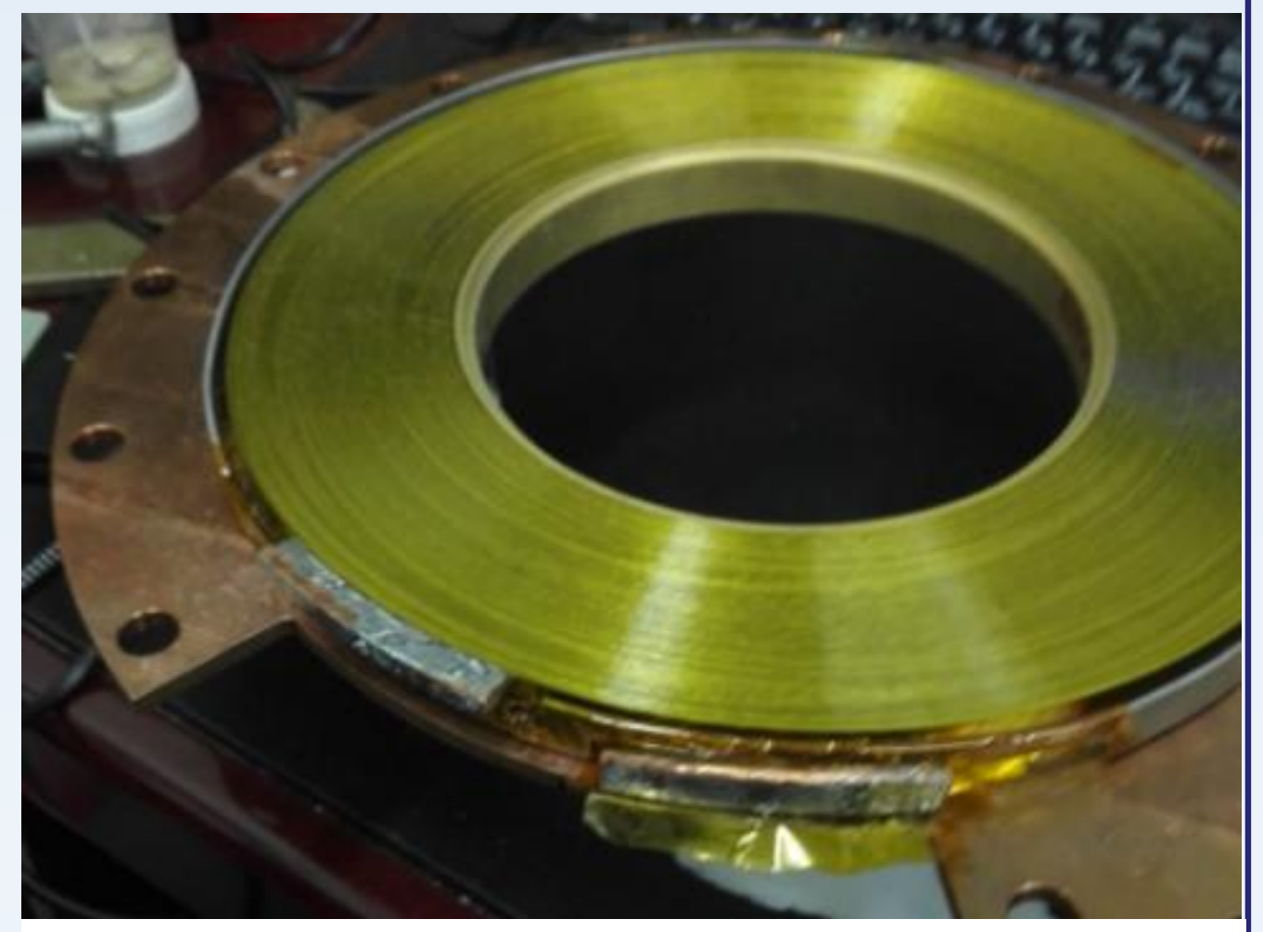
B. Coil connected joints manufacture

There are two high RRR copper blocks. The locations are the coil outside where the insulation film is got rid and connected the double pancake coil up layer left and the down layer right respectively by soldering. Then adjacent coils are connected by a Bi2223/Ag HTS tape from the up layer to the down layer.

The joints samples are carried out the resistance test at 77K by the potentiometry. tested data are measured and listed in the table II. Test results indicate that the joints resistance value is 10-7 Ω order of magnitude at 20K.

TABLE II
JOINTS RESISTANCE MEASURED AND CALCULATED RESULTS ($10^{-6}\Omega$)

NO.	77K		20K
	MEASURED VALUE	CALCULATED VALUE	CALCULATED VALUE
1	0.368	0.325	0.0237
2	0.339	0.333	0.0243
3	0.283	0.320	0.0234



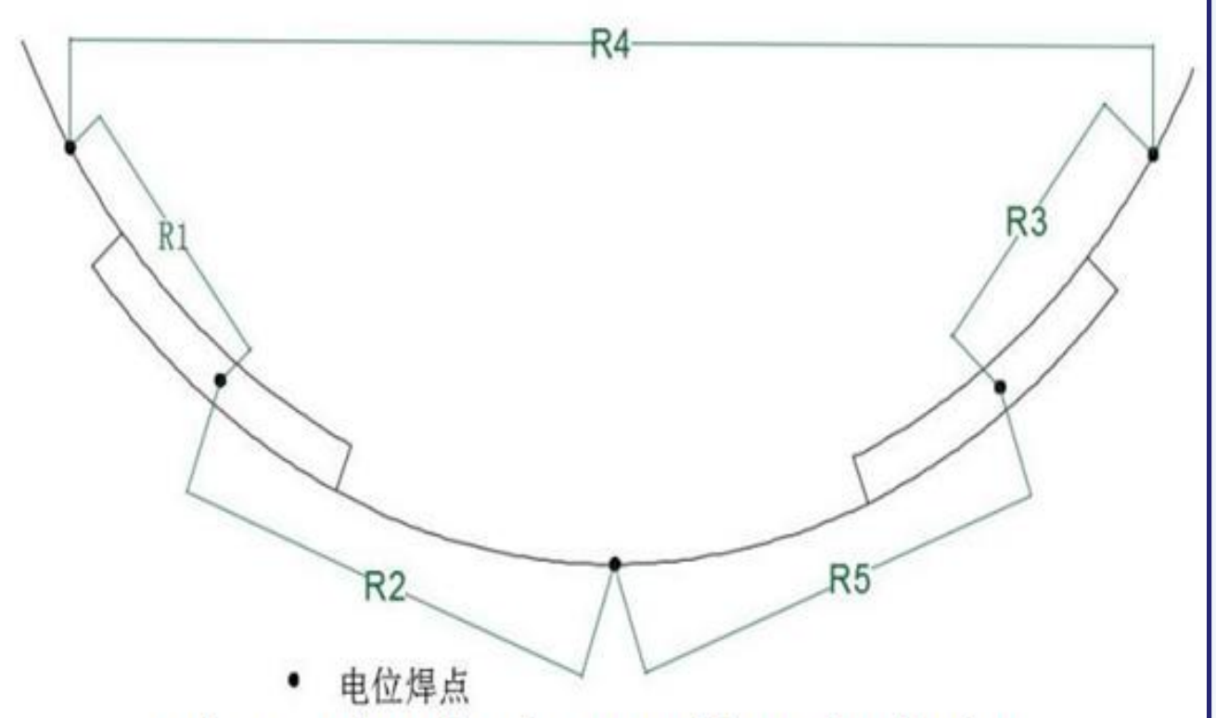


Fig.4. Joints electric potential pot distribution

C. Coil solidification

A mockup coil is put into use to carry out the performance test at 77K before and after solidification repeatedly for verifying coils treatment technology . Fig.5 is the picture of the coil performance test process before and after solidification.

The 12 times cryogenic performance tests are carried out on the mockup coil with 10A/min current before and after solidification. It turns out that the performance degeneration of the test coil almost does not occur from Fig. 6 which is the graph of *I*-*V* test curves.

As it turns out, the coil I_c is a little changed after solidification; the coil minimum I_c is about 60A with the critical current criterion of 1μV/cm that reaches 50% of the HTS tape short sample I_c. The I_c test results are consistent with the calculated values. Moreover, HTS coils n values are between 20 and 30.

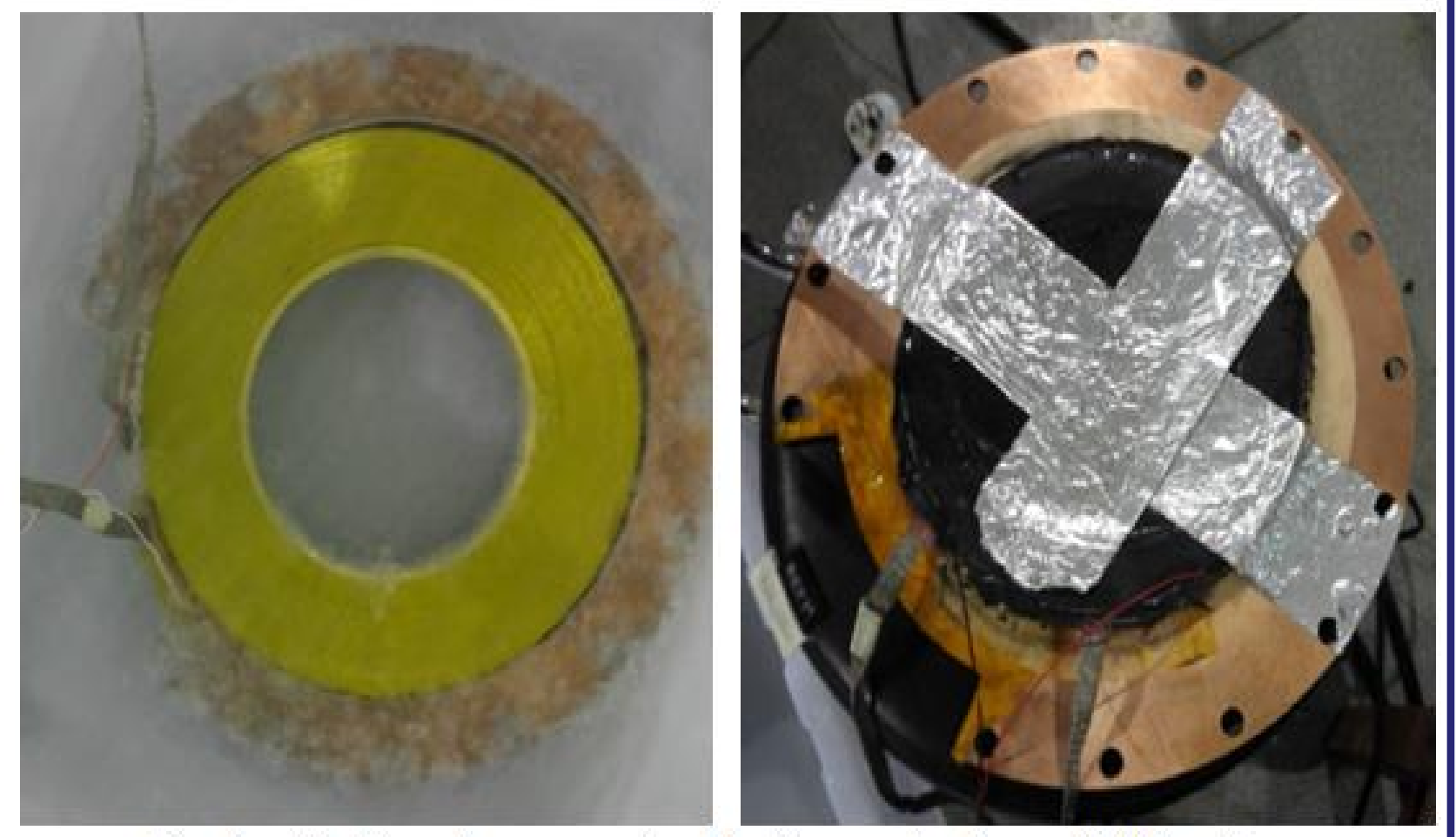
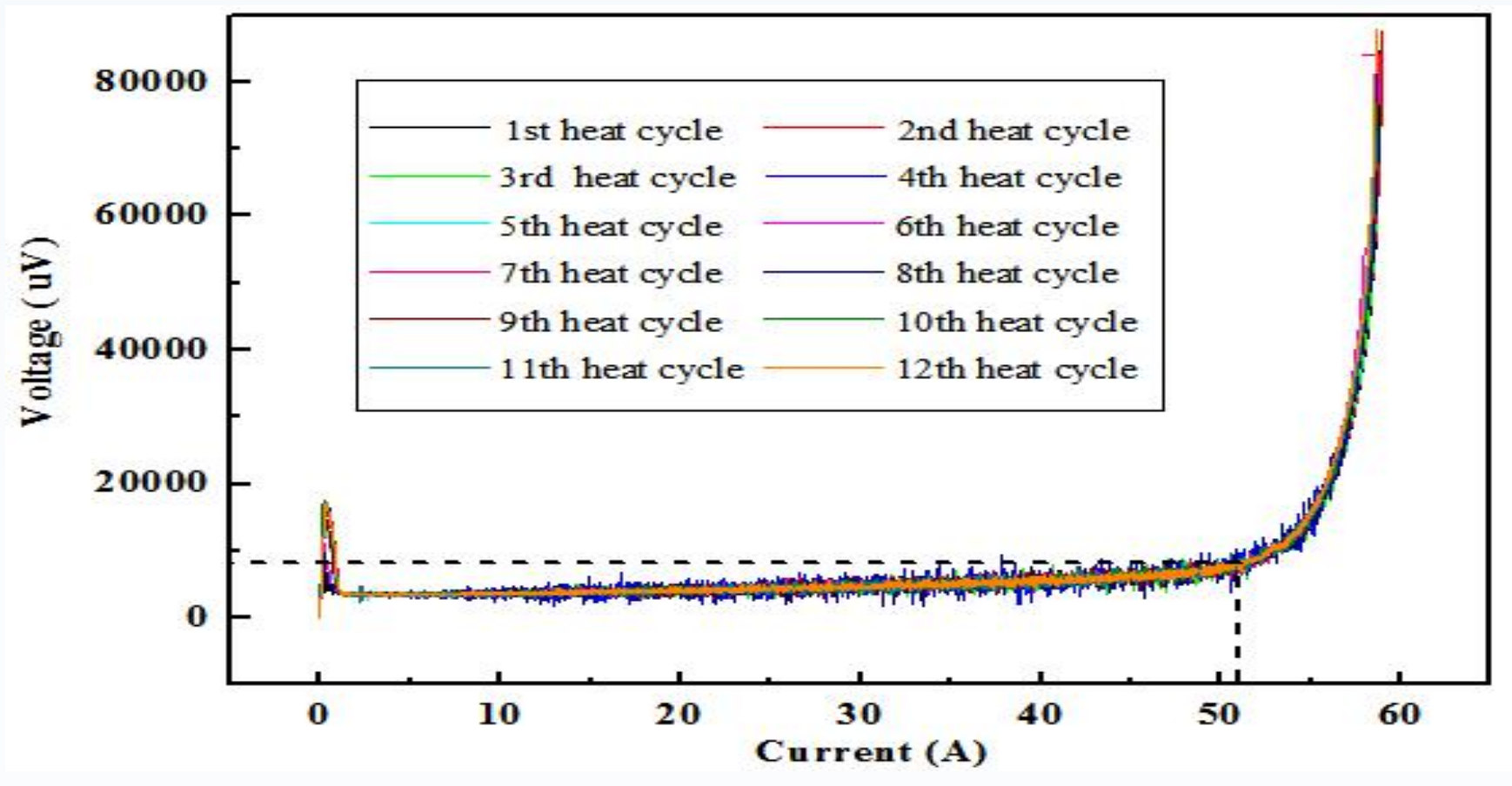


Fig.5. Coil performance test before and after solidification



D. Magnet assembly and performance test at 77K

The quench protected system and data collected system are connected to the magnet, and the magnet is placed into the liquid nitrogen（LN$_2$）tank to carry out the cryogenic performance test with 6A/min. The voltage values of each coil and the magnet two terminals are measured; *I*-*V* curves are recorded and listed in the Fig.9. It indicates that the quench happens on the magnet at the test current rising to 29.7A.


Fig.8 Magnet in the LN$_2$ tank

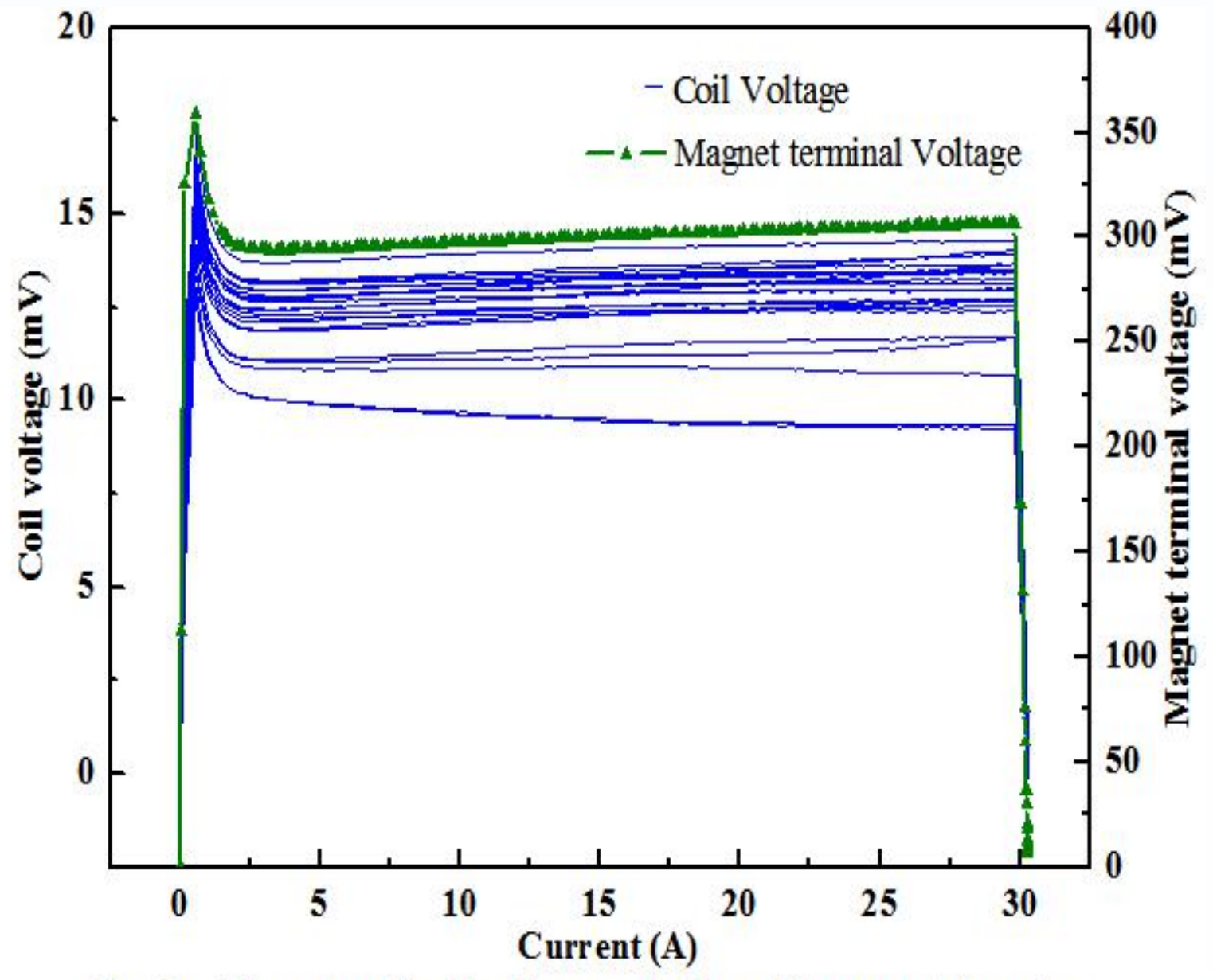


Fig. 9. Magnet and coil voltage variation with current changing

E. Magnet performance test at 20 K

The main components of the magnetic separation facility are shown in the Fig.11. There is a 500L/s molecular pump unit used for evacuating, the system pressure is decreased to 10^{-2}Pa order of magnitude within 24 hours and the helium leakage is less than 1×10^{-7}Pa.m^3/s. Then the cryocooler begins to work and it costs about 95 hours on cooling down the thermal shield, current leads and the magnet. Consequently, the thermal shield is cooled down to 46.6K whose location is on the end of neck tube and the magnet temperature could decline to 8.9K. Seven thermal sensors are located different places and monitored as shown in Fig. 11.

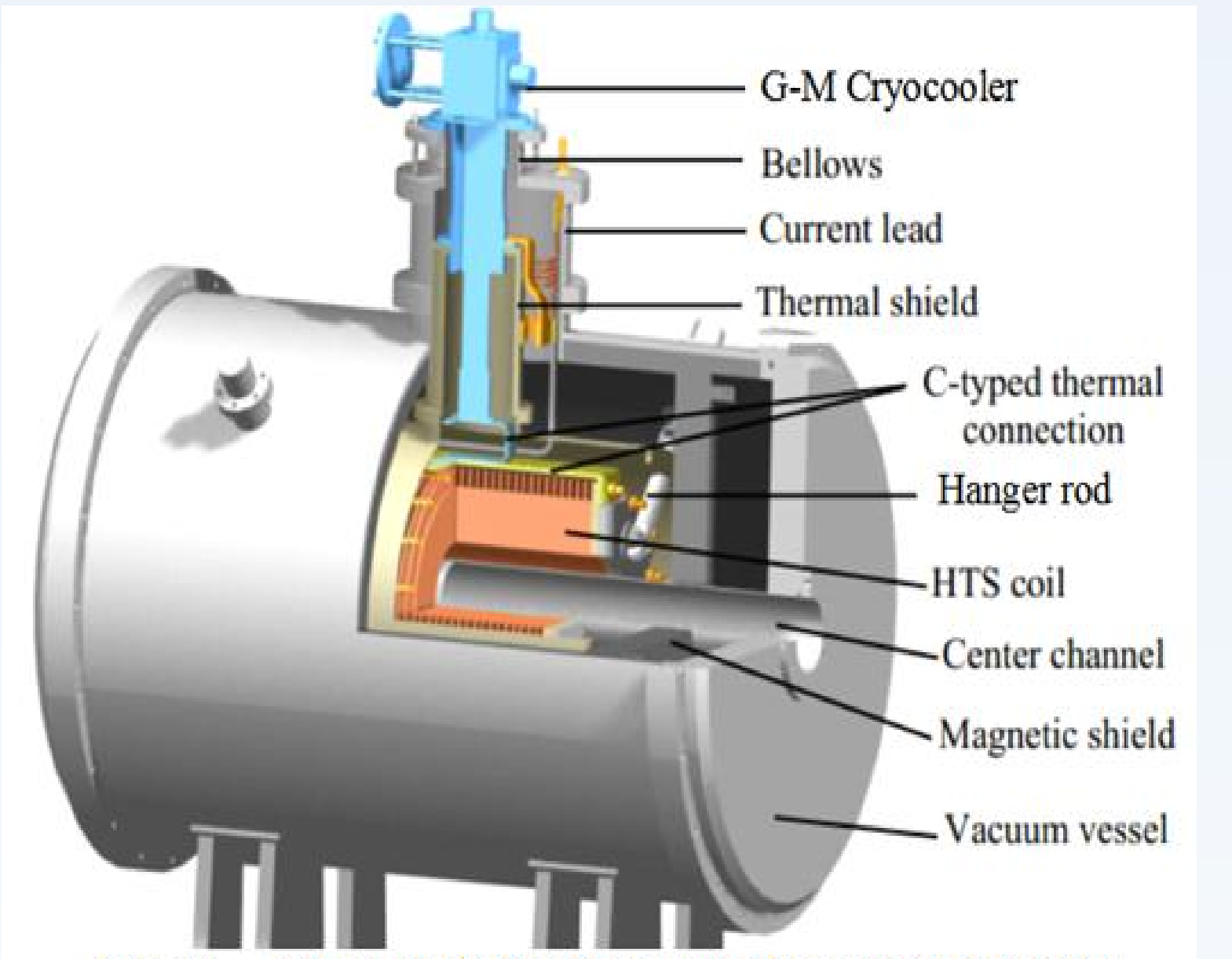


Fig. 10. Structure of the HTS magnetic separation facility

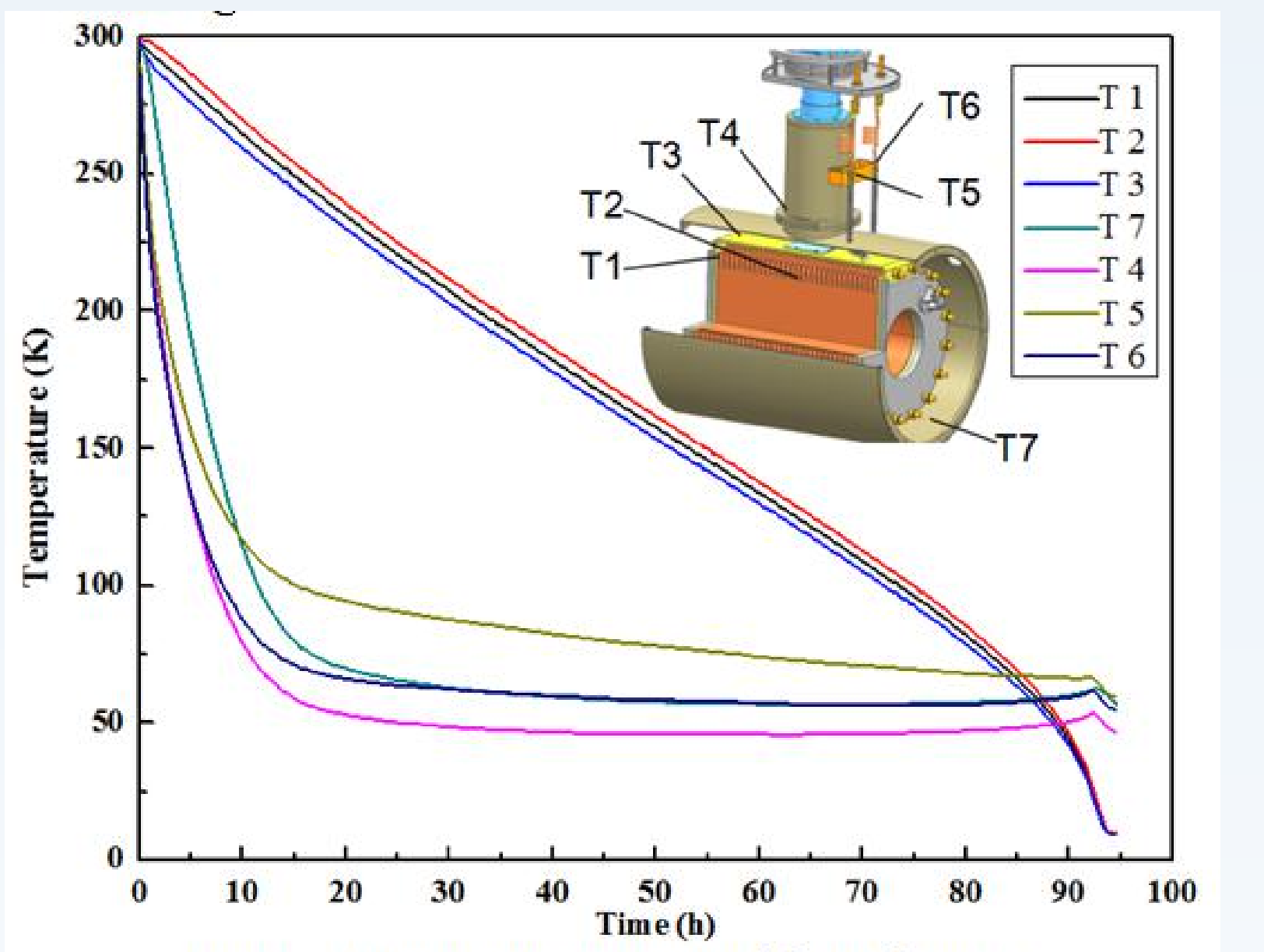


Fig.11. Temperature variation of thermal sensors

The magnet is excited with 20A/min current in the condition of normal operation several times, the test current could rise to 200A and the value of center magnetic field is about 3.57 T measured by the hall sensors; the current excited curve and the temperature variation of the magnet are shown in the Fig.13. In addition, the center axis of the magnetic field is measured and listed in the Fig.14 to verify the center axis uniformity of the magnetic field within the ±100mm from the mid- plane. The value of the uniformity is about 95.6% met the design requirements.

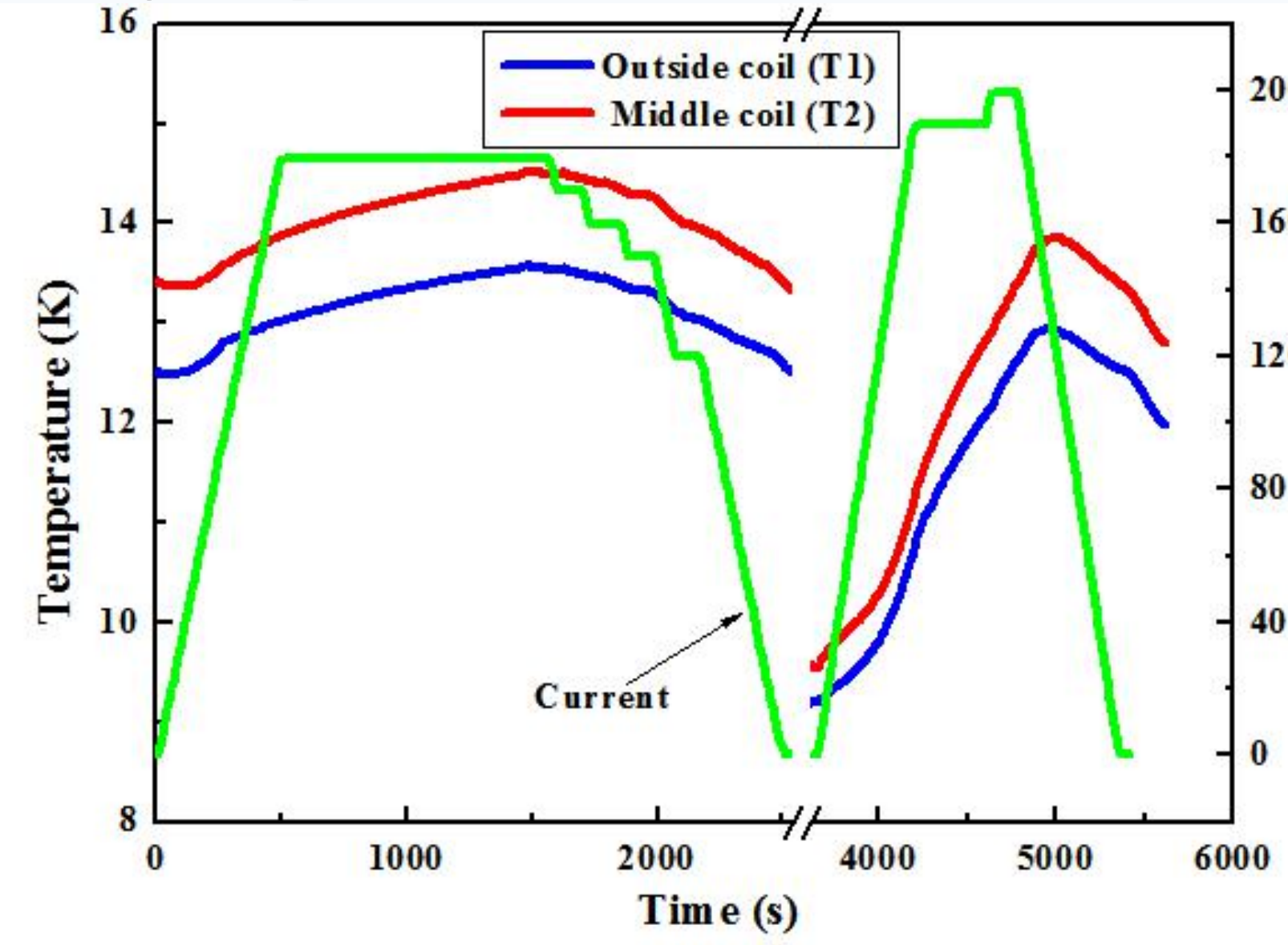


Fig.12. Magnet Temperature variation during the test

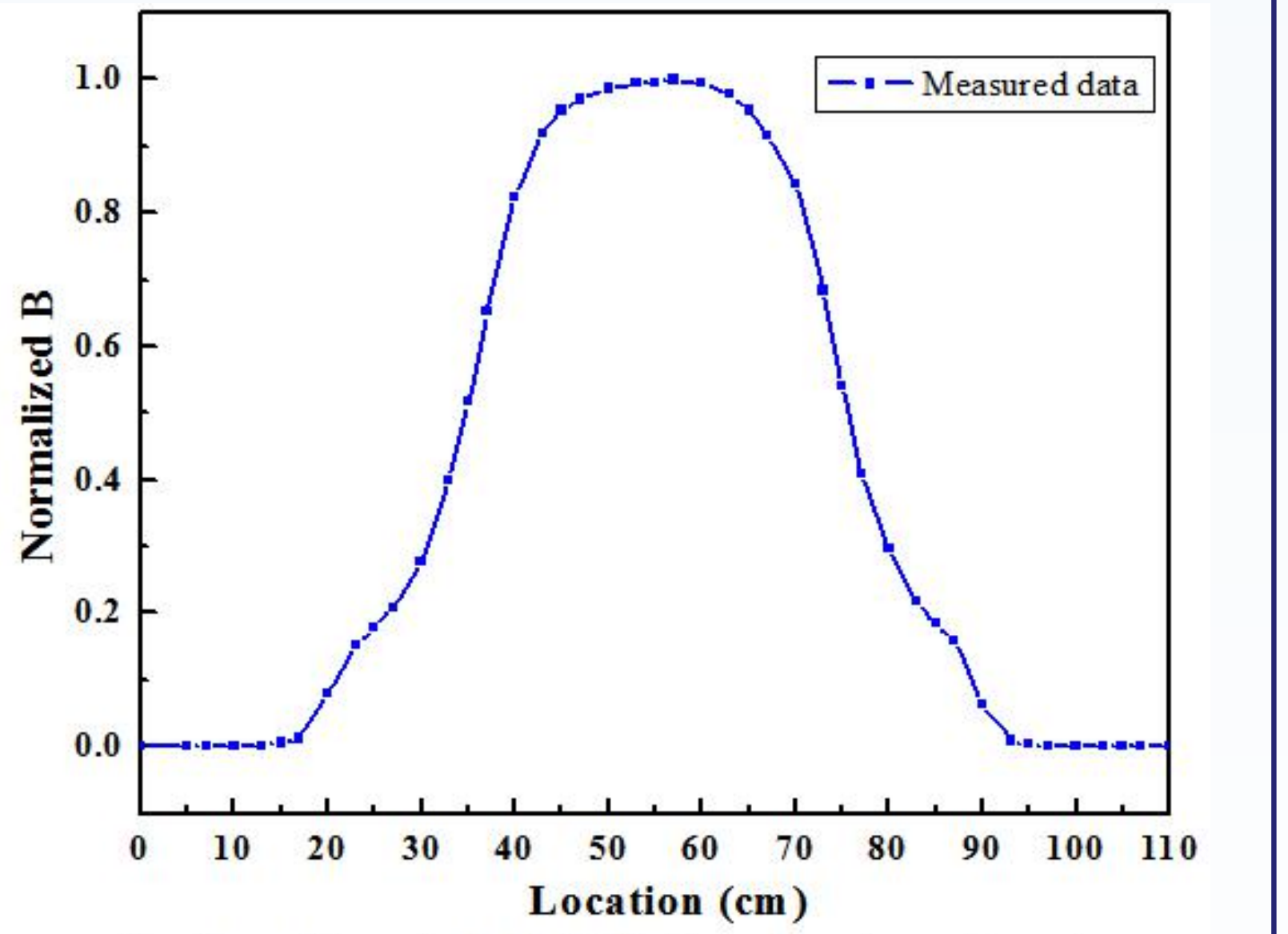


Fig.13. Magnetic field distribution along the center axis

CONCLUSIONS

The manufacture and performance test of 3.5T HTS magnetic separation facility were completed successfully. The new coil connected joints structure was used in coils fabrication and it made the magnet assembly work convenient, reliable and efficient; the Special cryogenic adhesives was applied to the solidified treatment and there was almost non-degeneration occurred on coils before and after solidification at 77K cryogenic test, it means that our solidification technology is appropriate for HTS coils.

At last, test results indicate that the magnet could be cooled below 20 K in the manner of the direct heat conduction, the center magnetic field can reach 3.57T with the capability of carrying the current 200A and the center axis uniformity of the magnetic field is more than 95% in the range of ±100mm from the mid-plane.

Author: Liu Huajun, E-mail:liuhj@ipp.ac.cn. Title: “**Manufacture and performance test of 3.5T High Temperature Superconducting Coil for the Magnetic Separation**”.