Design of Adjustable Homogeneous Region Cryofree Conduction-Cooled Superconducting Magnet for Gyrotron

Qiuliang Wang, *Member, IEEE*, Yinming Dai, Baozhi Zhao, Shousen Song, Zhiqiang Cao, Shunzhong Chen, Quan Zhang, Housheng Wang, Junsheng Cheng, Yuanzhong Lei, Bai Ye, Xian Li, Jianhua Liu, Shangwu Zhao, Hongjie Zhang, Xinning Hu, Pukun Liu, Yunlong Su, Chunzhong Wang, Luguang Yan, and Keeman Kim

***Abstract*—A conduction cooled superconducting magnet with the center field from 1.3 to 4 T and the warm bore of 100 mm in diameter has designed, fabricated and tested. The magnet was designed on the basis of the hybrid genetic optimal method. The superconducting magnet has the adjustable homogenous regions with the lengths from 200 mm to 320 mm. The magnet generated the multi-homogeneous regions with the constant lengths of 200, 250 and 320 mm. The homogeneity of magnetic field is about $\pm 0.5\%$ with the constant homogenous region lengths and $\pm 1.0\%$ for adjusting homogenous lengths. The magnetic field is decayed to 1/15–1/20 from the front point of homogeneous region to 200 mm. The magnet is cooled by one 1.5 Watt 4 K GM refrigerator. In the paper, the results on the design, fabrication and test of the superconducting magnet are presented.**

***Index Terms*—Adjust homogeneous region, cryofree conduction-cooled magnet, fusion, gyrotron.**

I. Introduction

A CRYOFREE conduction-cooled superconducting magnet has the advanced characteristics of no liquid helium and nitrogen, easy operation and used in the motion system. The superconducting magnet can be used in the industrial system and scientific instruments. The reliable 4 K 1.5 Watt GM refrigerator and the Bi2223 high temperature superconducting current leads have been employed [1]. The superconducting magnet can be operated at the convenience for the user. Since this kind of superconducting magnet can generate a high magnetic field for a long time operation [2], it is very suitable for the gyrotron applications, such as industrial microwave heating system. It is expected that the superconducting magnet cooled by liquid helium for the gyrotron can be replaced by the easy-operating cryofree conduction cooled superconducting magnet. For the goal of magnet applications in the high power microwave heating system, the superconducting magnet with the complex field distribution has been designed and fabricated with available warm bore of 100 mm in diameter and center field for 1.3 to 4 T. The magnet system can be automated by the Labview software which includes all the necessary operational fail-safe features. Due to the requirements of accuracy magnetic field distribution for the gyrotron, a new testing method has been developed. The detailed magnetic field distribution has been measured in the z and θ axial directions [3], [4]. In this paper the detailed design of the magnet system is summarized.

Manuscript received August 18, 2008. First published June 05, 2009; current version published July 15, 2009. This work was supported in part by the High Technology Program 863 and NSFC.

Q. Wang, Y. Dai, B. Zhao, S. Song, Z. Cao, S. Chen, Q. Cheng, H. Wang, J. Chen, Y. Lei, B. Ye, X. Li, J. Liu, S. Zhao, H. Zhang, X. Hu, C. Wang, and L. Yan are with the Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China (e-mail: qiuliang@mail.iee.ac.cn; lgyan@mail.iee.ac.cn).

P. Liu and Y. Su are with the Institute of Electronics, Chinese Academy of Sciences, Beijing, China (e-mail: pkliu@mail.ie.ac.cn).

K. Kim is with the National Fusion Research Institute, Yuseong-gu, Daejeon 305-806, Korea (e-mail: kkeeman@nfri.re.kr).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASC.2009.2017834

II. Design of the Superconducting Magnet

A. Electromagnetic Design for Superconducting Coil

The requirements for the superconducting magnet from our client are

- a warm bore of 100 mm in diameter;
- a homogeneity of $\pm 0.5\%$ for the constant homogenous regions lengths with 200, 250 and 320 mm;
- a homogeneity of $\pm 1\%$ for the adjust homogeneous region with lengths from 200 mm to 250 mm;
- a field decay to 1/15–1/20 from the front point in the homogeneous region to 200 mm;
- a center magnetic field of the magnet from 1.3 to 4 T.

The configuration of the magnet with superconducting coils and conventional copper coils is illustrated Fig. 1. The series of solenoid-shaped coils were connected to be satisfied to the above mentioned requirements. For the diameter of 100 mm warm bore, the diameter of coils should be 148 mm considering the cryostat structure. Basic design method is with hybrid genetic optimal method [5]. The center magnetic field is generated with the main coils. The corrected magnetic distribution is through the compensating coils. The superconducting magnet system has five high temperature superconducting current leads to supply power.

The specifications for the superconducting magnet are listed in Table I. The superconducting magnet consists of two sections. The internal section is the main coil which is utilized to yield background magnetic field. The main coil can generate a maximum magnetic field of about 4 T along the axis of the magnet.

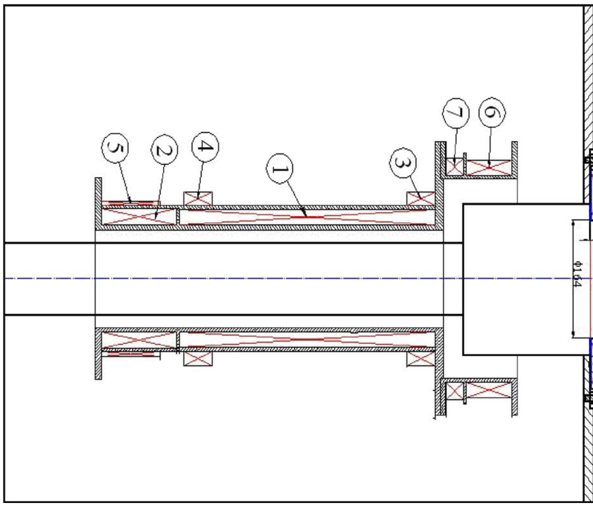

Fig. 1. 10 coils in the magnet have the same axis, the coils are installed in the cryostat, the conventional copper coils are located outside of cryostat and fixed on the flange of the cryostat, they are cooled by air convection. The superconducting coils are cooled by GM cryocooler.

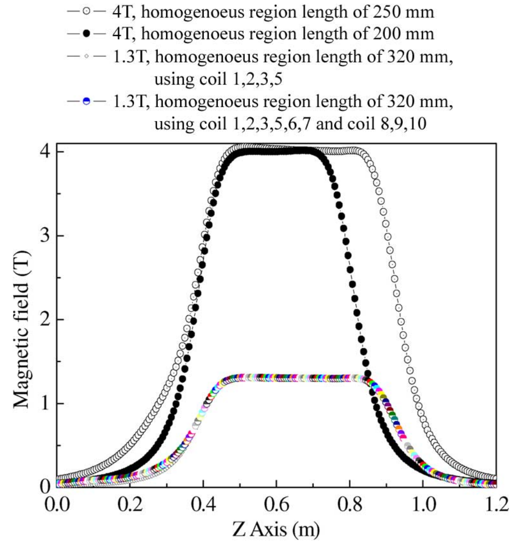

Fig. 2. Magnetic field distribution for various homogeneous region lengths.

TABLE I
SPECIFICATION FOR SUPERCONDUCTING MAGNET

	Inner radius	Inner radius	Coil height	Turn	layer	Iopt/A	
	cm	cm	cm	-	-	4T	1.3T
1	7.4	9.525	39.9	13907	28	93.6	30.366
2	7.4	9.675	11.616	4327	30	93.6	30.366
3	10.1	12.073	4.448	1417	26	93.6	30.366
4	10.1	12.035	4.448	1360	25	93.6	
5	10.1	10.775	9.14	1017	9	93.6	30.366
6	14.35	16.475	7.151	2457	28	75	10.23
7	14.35	16.779	2.774	1080	32	75	-10.23
8	8.2	15.2	2.4	505			-3.6
9	8.2	15.2	2.4	505			7.5
10	8.2	15.2	2.4	505			9.5

*Coils 1,2,3,4,5,6, and 7 are the superconducting coils.
*Coils 8, 9, and 10 are the conventional copper coils.

The external section is employed to compensate for the magnetic field homogeneity.

The main coils 1, 2 and the compensation coils 3 and 5 can generate the homogeneous region length of 320 mm with the maximum center field of 1.3 T. In order to reduce the magnetic field decay from 200 mm to 300 mm, the conventional copper coils 8, 9 and 10 are used. The coils 1, 2, 3, 5, 6 and 7 fabricated by superconducting wire and 8, 9 and 10 fabricated by conventional copper wire are used to obtain the requirement of magnetic field distribution as shown in Fig. 2.

The homogeneous region length of 250 mm with field of 4 T generated by the main coils 1, 2 and magnetic field decay to be adjustable are through compensating coils 3 and 5. The magnetic field decay can be controlled through the adding cathode compensation coils 6 and 7. The coils 6 and 7 are connected to an assisting power supply to adjust the operating current. The adjusting copper coils with 8, 9 and 10 are used through changing the operating current to correct the magnetic field distribution.

The superconducting coils were fabricated with NbTi/Cu multifilamentary wires from the Luvata Company in Italy. The critical current of ϕ0.75 mm is 495 A at 4.2 K and 5 T. The copper to NbTi ratio for the bare wire is about 2.0. In order to reduce AC losses, the diameter of NbTi filamentary is smaller than 12 μm. The pure copper wire is used to fabricate the coils 8, 9 and 10.

B. Stress Analysis for Superconducting Magnet

The superconducting magnet with multi-coils has very complex magnetic field and stress distribution. The composite structure consists of superconducting wire, supporting material and epoxy-resin. In general, composite materials contain more than one bonded material, each with very different structural properties, such as superconducting wire and epoxy-resin in magnets which make difference stress-strain characteristics. The averaged model is employed to calculate the stress distribution in the superconducting magnet. The averaged properties are based on the mechanical characteristics of individual materials in the composite. In some cases, the material properties are averaged according to the volume occupied by the materials [6]–[8]. For the magnet design and manufacturing process, it is vital for us to be able to predict the maximum hoop strain in a coil and therefore to define an appropriate reinforcement. The distribution of hoop stress for the superconducting magnet is plotted in Fig. 3. The maximum hoop stress is about 75 MPa. Over-bonding the electromagnetic forces can be controlled by winding a layer stainless steel wire with diameter of 1 mm on the outside surface of the coils.

C. Quench Protection for Coil

When the normal zone in the coils appears and is propagating, the terminal voltage of the magnet will increase, and a voltage signal will be detected by the detection system, then the protection circuit is employed to remove energy. Therefore, the hot-spot temperature rise in the magnet can be restricted to lower 150 K. The protection circuit used the series of diodes. The protection circuit for the various coil groups in the superconducting system is shown in Fig. 4.

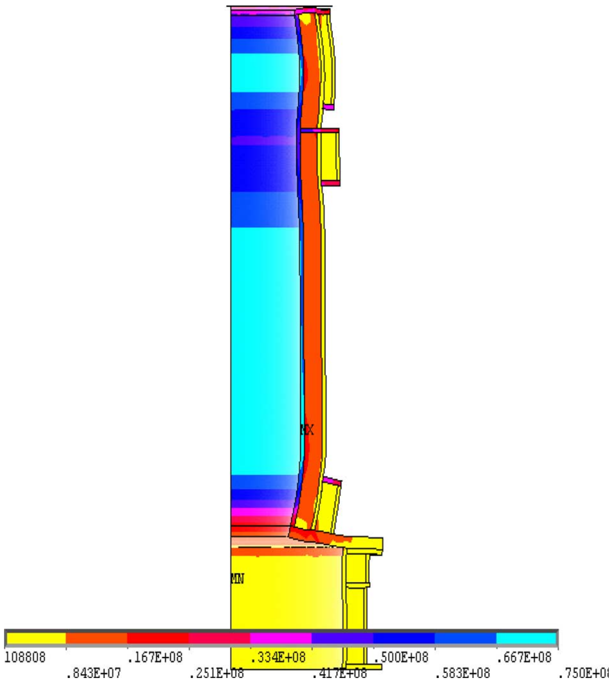

Fig. 3. Stress for superconducting magnet operated at 4 T (Unit:Pa).

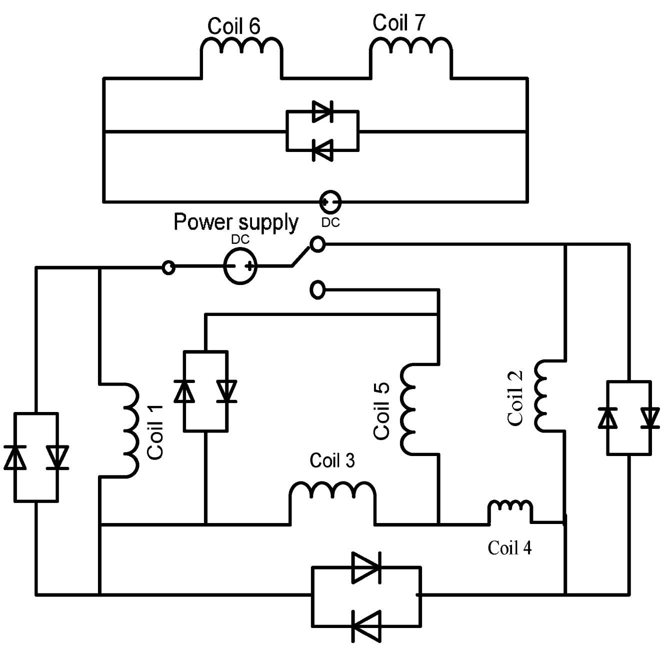

Fig. 4. Quench protection circuit of the superconducting magnet.

D. *Cryostat for Superconducting Magnet*

The conduction-cooled superconducting magnet system has to supply multi-uniform magnetic field regions. We need to consider the change in size of the warm bore in the cryostat along the axial direction. Fig. 5 shows the detailed configuration of the cryostat. The cryostat consists of the thermal radiation shield, super-insulation, pull rods, thermal connection and inner Dewar pipes. The cryostat is constructed through using stainless steel. It has an outer vacuum vessel on which is mounted the refrigerator which cools the 40 K thermal radiation shield and the magnet to 4.2 K. The GM cryocooler used in the magnet system

Fig. 5. Configuration for cryostat for the superconducting magnet.

is from Sumitomo RDK-415D. The cooling capacity of the refrigerator is 38 W at 40 K at the first stage and 1.5 W at 4.2 K at the second stage, respectively. There is the vacuum in the cryostat while the superconducting magnet is electrically connected with the external power supply and measuring system. There should be a part of refrigeration power to overcome the heat caused by the AC losses in current leads and coils. When we design the cryostat, the heat leak should be reduced due to the limitation of cooling power of GM cryocooler. The dimensions of the cryostat which can meet the practical requirements are the external diameter of 750 mm, the height of 920 mm. There is an extensive warm bore at the bottom, which the diameter of extensive warm bore is about 210 mm, and the depth is 182 mm. The heat load of the first-class cold heat is about 18.6 W, and the heat leak load of the second cold head is about 0.32 W. Therefore, the superconducting magnet can stably operate by one GM cryocooler.

III. System Cooling and Magnetic Field Measurement

During operating the superconducting magnet system, the cryostat system obtains the vacuum pressure of 1×10^{-3} Pa. After that, the GM cryocooler is operating. It takes about 80 hours to cool down the magnet to its operating temperature. The temperature of superconducting magnet is cooled to about 4 K. The maximum ramping rate is about 0.05 A/s. The charging time is about 30 min. During charging the superconducting magnet, the maximum temperature rise is lower than 1 K. The quench characteristics are tested according to the protection system. During the quench of the magnet in the operating current of 93.6 A, the maximum temperature rise is lower than 30 K. The test results show that the superconducting magnet

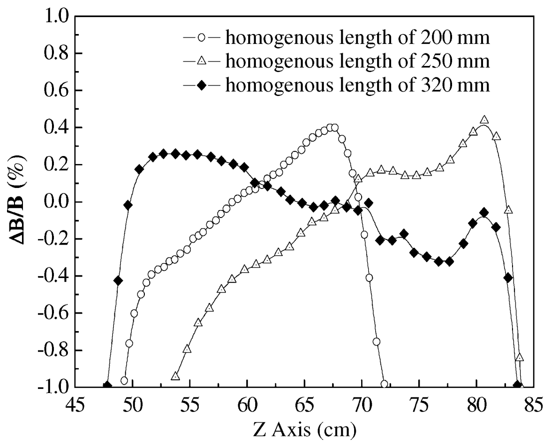

Fig. 6. Measuring results for the magnetic field along z axis.

is reliably protected during quench. The maximum hot-spot temperature can be pressed. The superconducting magnet can be recovered to superconducting state after 3 h. To check the magnetic field distribution for 200 mm, 250 mm and 300 mm, the axial direction magnetic fields were tested during operating current listed in Table I. Fig. 6 shows the $\Delta B/B$ homogeneity of magnetic field versus z coordinate. The test results show that the magnetic field distributions for homogenous lengths of 200 mm, 250 mm and 320 mm are satisfied to requirements.

For the requirements for magnetic field distribution used in the gyrotron, it is not only the magnetic field distribution in z axis, but also the magnetic field in the azimuth should be very homogeneity. The axis of magnet should be the same as the axis of the warm bore pipe in cryostat. A new method was developed to find the difference between the axial position of superconducting coils and warm bore of cryostat [9]. Based on the principle, the testing device was fabricated and used to test magnetic field distribution.

Fig. 7 shows one of testing results. We use the geometrical center of the warm bore as the rotational center. The rotational radius is 20 mm. The test probe is rotated as the azimuth from 0 to 360 to test the magnetic field distribution for various z coordinates. The test results for various z coordinates show that the maximum error for magnetic field from 0 to 360 is lower than 30 G for the center field of 4.0 T. The error of magnetic field is satisfied to the requirement of the gyrotron.

IV. Conclusion

A superconducting magnet with multi-homogenous region has been designed and fabricated. The test results show that the magnetic field distribution can be used to high power gyrotron. The axis for superconducting magnet and warm bore pipe of cryostat is almost the same in order to keep the homogeneity of magnetic field in the azimuth direction.

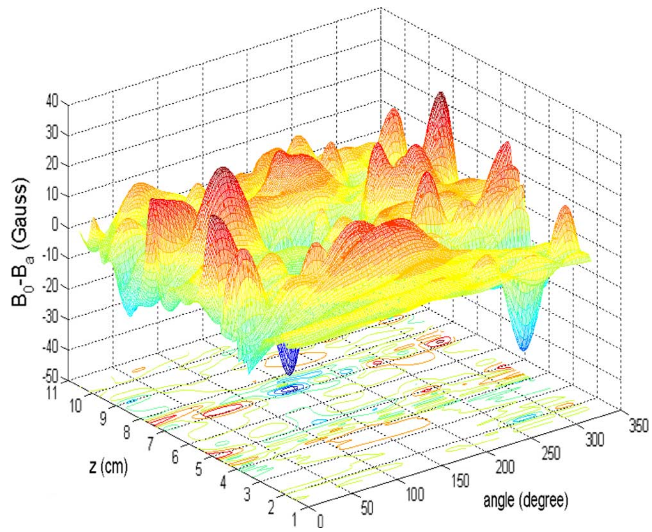

Fig. 7. Measurement results for the magnetic field error along in azimuth direction and z axis.

References

[1] K. Watanabe and K. Takahashi *et al.*, "Cryogen-free hybrid magnet for magnetic levitation," *Physica C*, vol. 386, pp. 485–489, 2003.

[2] Q. Wang, L. Yan, B. Zhao, S. Song, and Y. Lei, "Development of wide-bore conduction-cooled superconducting magnet system for material processing applications," *IEEE Trans. Applied Supercond.*, vol. 14, pp. 372–375, 2004.

[3] Q. Wang, Y. Dai, B. Zhao, S. Song, Y. Lei, H. Wang, B. Ye, X. Hu, T. Huang, H. Wang, C. He, M. Shang, C. Wang, C. Cui, S. Zhao, Q. Zhang, Y. Diao, Y. Peng, G. Xu, F. Deng, P. Weng, G. Kuang, B. Gao, L. Lin, and L. Yan, "Development of high magnetic field superconducting magnet technology and applications in China," *Cryogenics*, vol. 47, pp. 364–379, 2007.

[4] Q. Wang, Y. Dai, B. Zhao, X. Hu, H. Wang, Y. Lei, and L. Yan, "Design and test of conduction-cooled high homogenous magnetic field superconducting magnet for gyrotron," *IEEE Trans. Applied Superconductivity*, vol. 17, pp. 2319–2322, 2007.

[5] C. Wang, Q. Wang, H. Huang, S. Song, Y. Dai, and F. Deng, "Electromagnetic optimization design of a HTS magnet using the improved hybrid genetic algorithm," *Cryogenics*, vol. 46, no. 5, pp. 349–353, 2006.

[6] A. F. Clark, R. P. Reed, and G. Hartwig, *Nonmetallic Materials and Composites at Low Temperature*. New York and London: Plenum Press, 1978.

[7] S. Foner and B. B. Schwartz, *Superconductor Materials Science Metallurgy, Fabrication, and Applications*. New and London: Plenum Press, 1980.

[8] S. Yan and G. Lu, *Experimental Methods for Low Temperature Physics*. : Science Press, 1985.

[9] C. Wang, Q. Wang, and Y. Dai, "Magnetic Field Measurement for Superconducting Magnet," China Patent, 200820124544.9.