A 4 T Superconducting Magnet for Gyrotron With Homogenous Regions of150 and 250 mm

Q. Wang, Y. Dai, B. Zhao, Y. Lei, H. Li, Y. Luo, K. Kim, and S. Oh

***Abstract*—The development of a high frequency, high harmonic gyrotron based on a superconducting magnet is described. A conduction-cooled superconducting magnet with the warm room of Φ 80 mm and the center field of 4 T was designed and fabricated. The superconducting magnet has two homogenous regions with length of 150 mm and 250 mm. The homogeneity of magnetic field is about ±0.25%. All the homogeneous regions are with the same starting point and the field is decayed to 1/6–1/7 from the front point of the homogeneous region to 195 mm. This paper describes the design and fabrication of the superconducting magnet for Gyrotron.**

***Index Terms*—Conduction-cooled superconducting magnet, fusion, gyrotron, multi-homogeneous regions.**

I. INTRODUCTION

HIGH power microwave sources have to meet stringent requirements in the different research areas, such as thermonuclear plasma heating, materials processing, plasma chemistry, radar applications and particle accelerators. The gyrotron consists of an electron gun, an acceleration chamber, a resonance chamber immersed in a strong magnetic field, and finally a collector. An electron beam is accelerated and introduced in a high magnetic field generated by superconducting magnets. To generate microwaves, a precise magnetic field profile and series of superconducting magnet around the gyrotron tube are necessary. The development of a conduction-cooled magnet technology allows high field superconducting magnets to be operated without use of liquid helium and nitrogen [1]–[3]. The superconducting magnet can be employed in situations where the liquid helium and cost are prohibitive, such as in fusion, radar and industrial microwave heating. The reliable 4 K 1.5 Watt GM refrigerator and the Bi_{2223} high temperature superconducting current leads have been used. The magnet has characteristics, such as low operating costs, no expensive liquid helium or nitrogen required. Only mains electric power is required to operate the system so that measurements can be made at any time at the convenience of the user. Since this kind of superconducting magnet can generate a high magnetic field for a long time operation [4], it is very suitable for the gyrotron applications. It is expected that the superconducting magnet used for the gyrotron magnet-cooled by the liquid helium will be replaced by the easy-operating conduction-cooled superconducting magnet. For the goal of superconducting magnet applications in the high power microwave, a superconducting magnet has been designed, fabricated and tested with available warm bore of Φ 80 mm and center field of 4 T. The system is automated by using the LabVIEW software, which includes all the necessary operational fail-safe features. This allows measurements to be performed in a repeatable and reliable fashion. In this paper the detailed design of the magnet system is summarized.

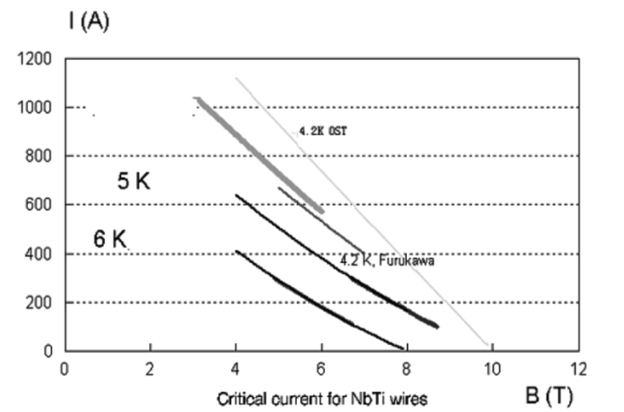

Fig. 1. Short sample characteristic for φ 0.85 mm NbTi wire in various temperatures.

II. MAGNETIC FIELD AND STRESS ANALYSIS FOR CONDUCTION-COOLED SUPERCONDUCTING MAGNET

Based on the requirements of the gyrotron, the superconducting magnet should have the following specifications: the warm bore is over than Φ 80 mm, there are two homogenous regions with lengths of 150 and 250 mm, the homogeneity of magnetic field is ±0.25% and the magnetic field will be decayed 1/6–1/7 of its center field from the original point to 195 mm, the center field is about 4 T. In order to design the superconducting magnet for the application of gyrotron, we take the trial-to-test method for the optimal design. The short sample characteristics for the superconducting wire are shown in Fig. 1 at various operating temperatures. In the design, it is necessary to select the safety factor for the magnet operated by the GM refrigerator. The operating current safety factor in 0.7 and the maximum operating temperature of 5.5 K are selected for the magnet. Fig. 2 shows the arrangement of superconducting coils. There are four coils employed for the magnet with two homogenous regions, each region consists of three coils. The specifications for the superconducting magnet are listed in Table I. The coils can be divided into two layers. The internal coil referred as the main

Manuscript received September 9, 2005. This work was supported in part by the High Technology program 863 and NSFC.

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Digital Object Identifier 10.1109/TASC.2006.869999

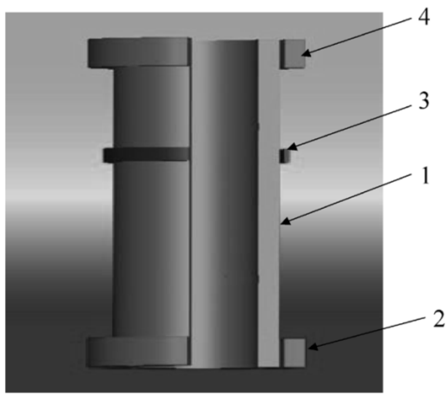

Fig. 2. Arrangement of coils for conduction-cooled magnet in gyrotron.

TABLE I
SPECIFICATIONS OF SUPERCONDUCTING MAGNET

R1 (cm)	R2 (cm)	H (cm)	turn	I A	Safety factor	coil
150 mm homogeneous region						
6.4	8.62	45	15458	94.324	69.72	1
9.12	11.26	3.9	1296	94.324	47.12	2
9.12	9.67	2	161	94.324	24.15	3
250 mm homogeneous region						
6.4	8.62	45	15458	94.158	69.73	1
9.12	11.26	3.9	1296	94.158	47.09	2
9.12	11.26	3.9	1296	94.158	47.09	4

coil which is utilized to yield background magnetic field, can supply magnetic field of about 4 T along the axis of the magnet. The external layer is employed to compensate for homogeneity in magnetic field. The external layer includes two sections that are located at the top and bottom of the main coils, respectively, so that they are used in the compensation for the 250 mm homogeneity region. The second part consists of a pair of compensation coils, one located in the middle and the other one located at the bottom of the main coil, which is employed for compensating the 150 mm homogeneity region. The same size superconducting wire is employed to wind the superconducting coils. The magnetic field distribution and homogeneity for the regions of 150 mm and 250 mm are plotted in Figs. 3 and 4. For the superconducting magnet, the training effect is related to a plastic hardening process. The superconducting magnet is a composite structure. 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 many difficulties in stress-strain characteristics. However, to solve the stress problem in composite structures, an analysis has to be carried out by using average properties based on mechanical characteristics of individual materials in the composite. In some cases, the material properties are averaged according to the volume occupied by the materials. 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. Such a prediction is possible by detailed finite element analysis. The distribution of hoop stress for the superconducting magnet is plotted in Fig. 5. The maximum hoop stress is about 4.2 MPa. A stainless steel wire with diameter of 1.0 mm is employed on the out-

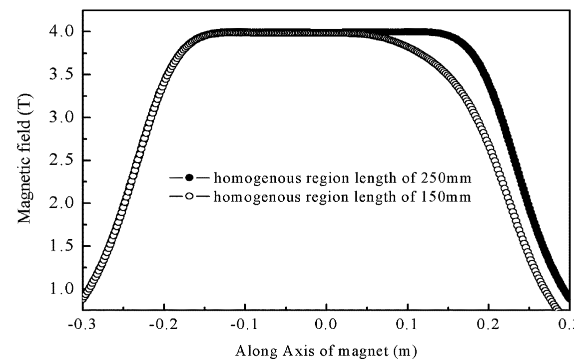

Fig. 3. Field distribution along the axis for two homogenous regions.

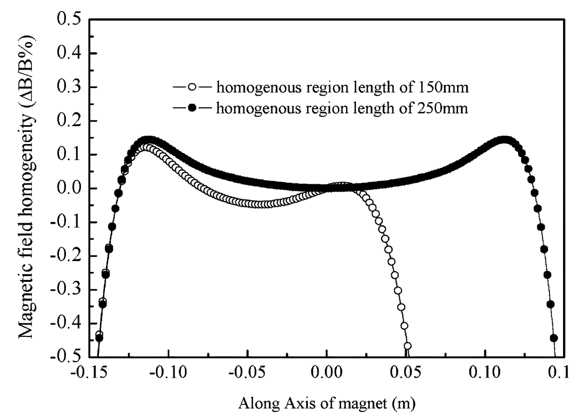

Fig. 4. Field homogeneity along the axis for two homogenous regions.

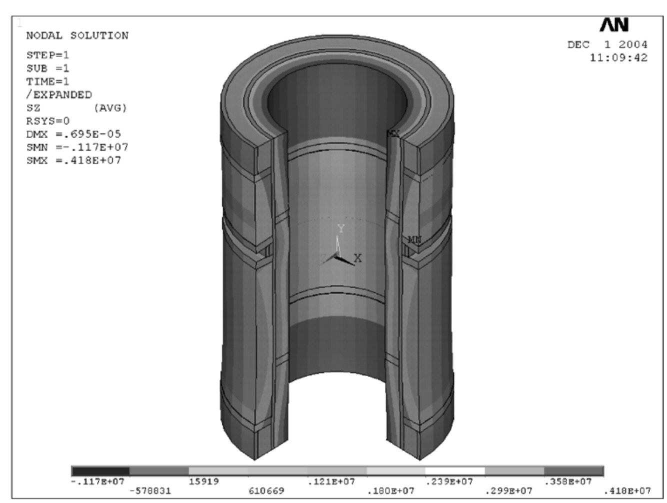

Fig. 5. Hoop stress distribution in superconducting magnet (Unite: Pa).

side surface of the coils to support against the electromagnetic forces.

III. QUENCH ANALYSIS AND PROTECTION SCHEME

When the magnet system is designed, we should ensure that the requirements for magnetic field distribution and center magnetic field are satisfied. Under the condition of some unexpected quench in magnet, the protect devices should be used to protect the magnet. The total inductances for 250 mm and 150 mm homogeneous regions are about 11.5 H and 10.2 H, respectively.

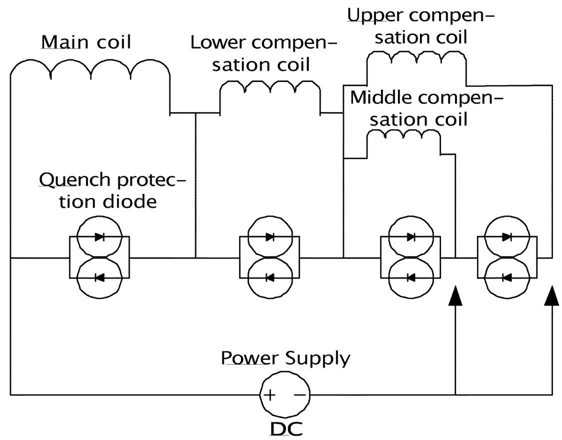

Fig. 6. Quench protection circuit of the superconducting magnet and current leads for two homogenous regions with length of 150 mm and 250 mm.

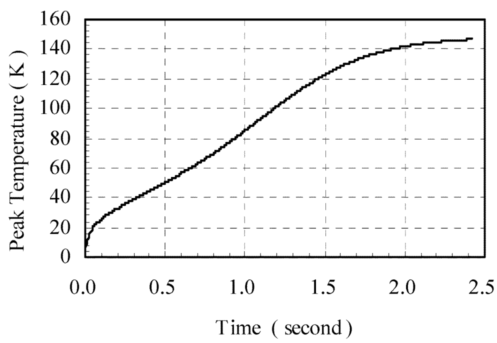

Fig. 7. Hot spot temperature rise in superconducting magnet.

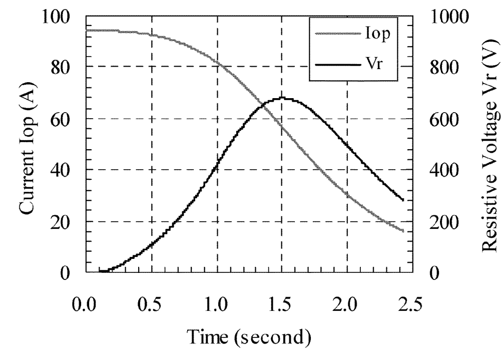

Fig. 8. Current and voltage versus time after quench.

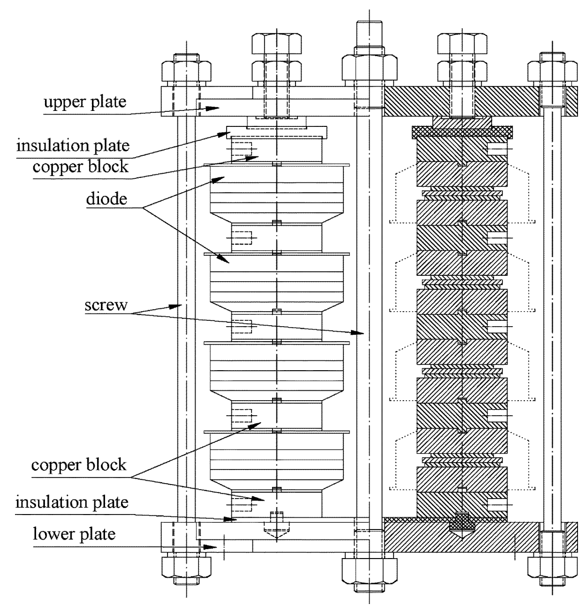

Fig. 9. Configuration of protection diodes and resistors in the magnet system.

The total storage energies of 250 mm and 150 mm homogeneous regions are about 51 kJ and 45 kJ for the center magnetic field of 4 Tesla, respectively. The energy will change into the heat energy that is released through a diode in the external circuit during the quench of the magnet. An open loop circuit is strictly prohibited due to high voltage in coils. Based on the numerical analysis code [5], the process of quench occurred in the 250 mm homogeneity region is simulated. The protection circuit using a diode can convert about 51 kJ energy stored into the heat energy, which is dissipated in the normal zone resistance. Consequently, it induces the hot-spot temperature rise in the magnet and current decay, as well as magnet voltage peak.

We assume the quench started at the center point of the inner layer of the main coil and spread to other regions. The protect circuit of the magnet is shown in Fig. 6 and the simulation results are shown in Fig. 7 and Fig. 8. As shown in Fig. 7, when the quench occurs in the magnet, the hot-spot temperature is increased. The numerical results show the hot spot temperature rise is lower than 150 K. However, after 1.85 s, the temperature rise tendency becomes slow and tends to be stable after 2.4 s. Fig. 8 shows the current variation versus time in the magnet. After 2.4 s, the current decays to 19% of its original value, which means that there is about 96% stored energy changed into the heat energy. The peak voltage is about 680 V at 1.5 s. On the basis of results, the superconducting magnet should survive the operating conditions.

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 protect circuit would be cut off. The magnet discharges through the protect circuit. Therefore, the temperature rise in superconducting magnet is restricted. The protect diodes installed in the cryostat are shown in Fig. 9.

IV. Fabrication Technology of Superconducting Magnet

The superconducting magnet is conduction-cooled by the GM refrigerator. The magnet keeps a good performance in thermal connection. The thermal linking construction should have high thermal conduction. Due to the electrical linking, high insulation breakdown voltage between cooling system and coils is necessary. The configuration by both main and auxiliary formers is employed in the magnet coil. The internal main coil is directly wound on the main former and an insulation layer of 5 mm in thickness is wound at the outside interface of the main former. The auxiliary former is used to constraint the axis length of the external compensating coils. The main former is available after a series processing including cutting, milling, grinding and polishing of the alloy material. In order to meet the

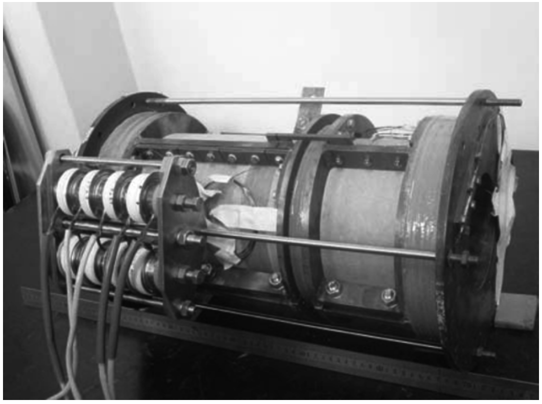

Fig. 10. Configuration of completed coil fabrication.

requirements for magnetic field homogeneity, the geometrical precision of the former must be strictly controlled. Some slots for the position are fabricated. The residual resistivity RRR must be greater than 100. The magnet structure is shown in Fig. 10.

The NbTi coils are fabricated by wet-winding technology and impregnated with epoxy resin DW-3 from Shanghai China. The heat treatment time for the epoxy-resin is 8 hours at temperature of 60°C. The thermal conductivity of epoxy-resin is improved by adding AlN powder with weight ratio of 1:2.5. The fiber-glass cloth with thickness of 0.04 mm is located between the layers to increase the electrical insulation. About 20 thin high pure copper slices with area of 0.5 mm $\times$ 10 mm are layered in the lateral surface of the winding to increase the thermal conductivity. A stainless steel wire with diameter of ϕ 1.0 mm is employed to support the electromagnetic force in the coils. All the coils are thermally connected with high pure copper bulk. All the copper bulk will be connected with the 4 K GM cryo-cooler through copper tapes with purity of 99.999% and thickness of 0.5 mm. The thermal conductivity coefficient of the high pure copper tape is about 70 Watt/cm.K at 4.2 K [5].

V. Design of Cryostat

According to the requirements of the gyrotron, the conduction-cooled superconducting magnet system has to supply two uniform magnetic field regions. We need to consider the change in size of the warm bore in the cryostat along the axial direction. Fig. 11 shows the 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 with 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 4.0 K. The GM refrigerator used in the superconducting magnet system is conventional and commercially available 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 source and

Fig. 11. Configuration of cryostat and thermal conduction structure.

measuring system. There should be a part of refrigeration power to overcome the heat caused by the AC losses in current wires and coils. When we design the cryostat, the heat leak should be reduced as much as we can, otherwise it will lead to larger refrigeration power allowance. The dimensions of the cryostat, which can meet the practical requirements are the following: external diameter 640 mm, the height 770 mm. There is an extensive warm bore at the bottom, which the diameter of extensive warm bore is about 290 mm, and the depth is 75 mm. The heat leak load of the first-class cold heat is about 18.6 W, while the heat leak load of the second cold head is about 0.32 W. Therefore, the superconducting magnet can stably operate.

VI. Conclusion

A conduction-cooled superconducting magnet for the gyrotron has designed and fabricated. The magnet system can provide a 4 Tesla center magnetic field with two homogenous regions and warm bore of Φ 80 mm. The superconducting magnet system is cooled by a two-stage 1.5 Watt 4 K GM refrigerator, with a nominal operating temperature of 4.2 K. The detailed finite element model of the magnetic field, stress and quench analysis has been performed to verify the safe operation for the magnet system. The superconducting magnet is charged to the operating current of 94.3 A.

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