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Development of a superconducting magnet for relativistic backward-wave oscillator

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Abstract: A homogeneous magnetic field superconducting magnet with a room-temperature bore of 30 mm and a central field of 5.51 T for relativistic backward-wave oscillator was designed, manufactured and tested. As a result of magnetic field homogeneity considerations, the magnet is composed of three coaxial coils. All coils are connected in series and charged with a single power supply. The magnetic field homogeneity is better than ±0.5% from −30 mm to 30 mm in axial direction. The magnet can be operated in persistent mode with a superconducting switch. In addition, a pair of HTS current leads and a two-stage GM cryocooler with cooling capacity of 1.5 W at 4.2 K were adopted to realize a zero liquid helium boil-off. Here the design, manufacture, mechanical behavior analysis, and the test results of the magnet were presented.

Word keys: magnetic field homogeneity; mechanical behavior analysis; relativistic backward-wave oscillator (RBWO); superconducting magnet

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相对论返波振荡器超导磁体的研制

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摘要:一台相对论返波振荡器匀场超导磁体现已完成设计、制造和测试,磁体室温孔径为 30 mm、中心场为 5.51 T. 为了提高磁场的均匀性,设计的磁体由 3 个同轴线圈组成. 所有的超导线圈串联运行,并由 1 台电源供电. 磁体轴向从−30 mm 至 30 mm 处磁场均匀性优于±0.5%. 磁体可以通过超导开关进行闭环运行. 此外,利用一对高温超导电流引线和两级 GM 制冷机(4.2 K@1.5 W)可以实现超导磁体的零液氦蒸发. 这里给出了该超导磁体的设计、制造、力学分析,并给出了磁体的测试结果.

关键词:磁场均匀性;力学分析;相对论返波振荡器;超导磁体

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0　Introduction

Relativistic backward-wave oscillator (RBWO) is a device that is used to generate high-power microwave radiation up to the terahertz range[1-4]. The output power of the RBWOs is strongly dependent on the magnitude of the magnetic field and the magnetic field homogeneity. Usually, the magnetic field is generated by the NbTi superconducting magnet. In order to improve the magnetic field homogeneity, a superconducting magnet, which consists of a main coil and two compensation coils, was designed and constructed. The NbTi superconducting magnet can generate a 5.51 T central magnetic field with a room-temperature bore of 30 mm and a magnetic field homogeneity better than ±0.5% from −30 mm to 30 mm in axial direction for RBWO cooled by liquid helium. However, with the rising cost of helium, the superconducting magnet system would be expected to have a lower operating cost[5]. The Bi-2223 HTS current lead was adopted to reduce the heat load[6]. The two-stage GM cryocooler was used to recondense the evaporated helium gas inside the cryostat to maintain the liquid helium during operation. So, a zero liquid helium boil-off superconducting magnet system has been constructed. This paper presents the magnet design, manufacture, mechanical behavior analysis, and the test results.

1　Magnet design and fabrication

In order to improve the magnetic field homogeneity, the superconducting magnet consists of a main coil and two compensation, as shown in Fig. 1. The magnet can generate a central magnetic field of 5.51 T at an operating current of 82 A. The maximum magnetic field of the superconducting coils is 5.872 T located at the inner surface of the main coil with a displacement of 49 mm from the midplane, as shown in Fig. 2. The total inductance of the magnet is 10.8 H and the stored magnetic energy is 36.33 kJ at the rated current of 82 A. The magnet has a magnetic homogeneous region with 60 mm in axial length. The homogeneity of magnetic field is better than ±0.5%. The multifilament NbTi superconducting wires in diameters of 0.74 mm and 0.63 mm were adopted. Tab. 1 lists the main parameters of the superconducting magnet. Fig. 3 shows the load lines of the two superconducting coils. The NbTi

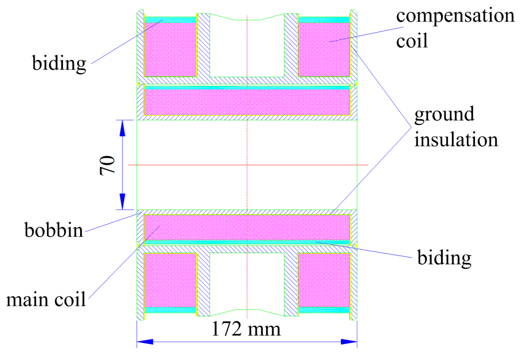

Fig. 1　Superconducting magnet structure

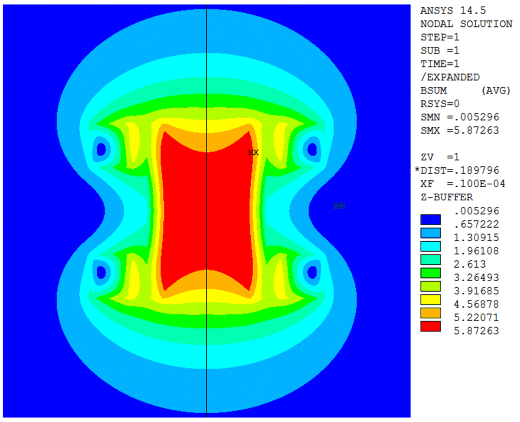

Fig. 2　Magnetic field distribution of the superconducting magnet

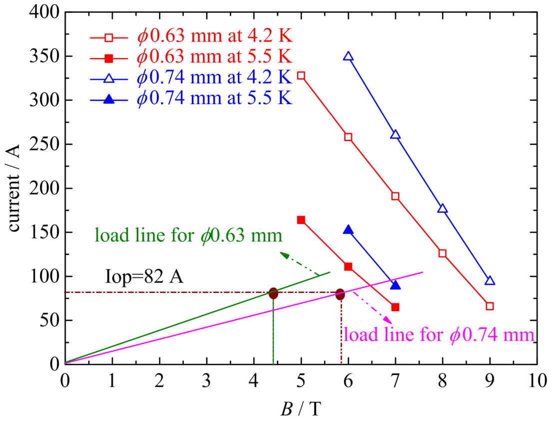

Fig. 3　Load lines of the superconducting magnet

superconducting magnet was impregnated with a filling material of paraffin wax to prevent the turns from moving during operation. Two separate bobbins for the main coil and compensation coils are welded to maintain the integrity. All coils are connected in series and charged with a single power supply for easy operation.

Tab. 1　Main parameters of the superconducting magnet

	main coil	C1 coil	C2 coil
strand	NbTi		
strand diameter/mm	0.74	0.63	
Cu/Sc ratio	1.3		
twist pitch/mm	42±10		
insulator	formvar		
inner diameter/mm	78	137	137
outer diameter/mm	111	217	217
mid-plane/mm	0	60	−60
height/mm	160	40	40
turns	5 072	4 092	4 092
operating current/A	82		
inductance/H	10.8		
stored energy/kJ	36.33		
central field/T	5.51		

A pair of binary current leads, composed of conventional copper leads and Bi-2223 HTS current leads, were employed to reduce the heat leak to the cold mass at 4.2 K from 300 K. The heat loss of the current leads is less than 0.1 W at the rated current of 82 A. The re-condensing magnet cryostat is designed to be cooled by a two-stage GM cryocooler with cooling capacity of 1.5 W at 4.2 K and 45 W at 50 K. The evaporated helium gas was cooled by the second-stage of the cryocooler and the radiation thermal shield and the relevant support structure were cooled by the first-stage of the cryocooler. In order to reduce the performance degradation of the cryocooler caused by the magnetic field, the cryocooler is located at the top of the cryostat[7,8]. The superconducting switch was used to realize a persistent mode for the superconducting magnet system[9]. The superconducting coils are protected by subdividing them into three sections with dump resistor and diode protection circuits to avoid the excessive heating or terminal voltage.

2　Mechanical behavior analysis

Quench of NbTi compact superconducting magnet was often caused by the mechanical disturbance results from the electromagnetic force[10,11]. So, it is important to evaluate the magnetic force and the mechanical behavior of the superconducting magnet during excitation. Fig. 4 shows the magnetic force distribution for the superconducting magnet. A large attraction force in axial direction of 41.2 kN exists between two compensation coils at the operating current of 82 A. To reduce the mechanical disturbance results from the Lorentz force during excitation, the pretension of the NbTi superconductor and the reinforcement structure were used.

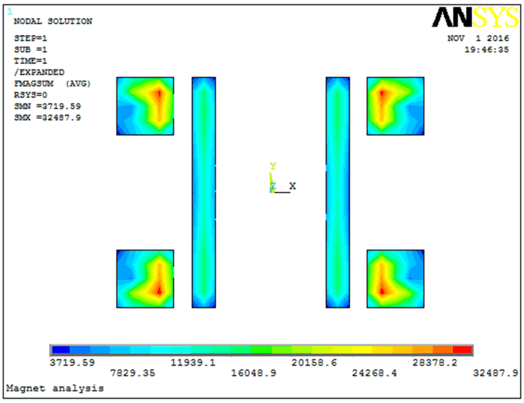

Fig. 4　Magnetic force distribution for the superconducting magnet

A 2D non-linear finite element model with ANSYS was used to analyze the mechanical behavior of the superconducting magnet[12]. Fig. 5 shows the hoop stress, deformation and strain distribution of the superconducting coils when the superconducting magnet is ramping up to the rated field. The calculated results indicated that the superconducting coil is under compression during excitation. The maximum deformation and the hoop stress of the superconducting coils are about 0.07 mm and 111 MPa, respectively. The calculated results also show that the superconducting coils are always in close contact

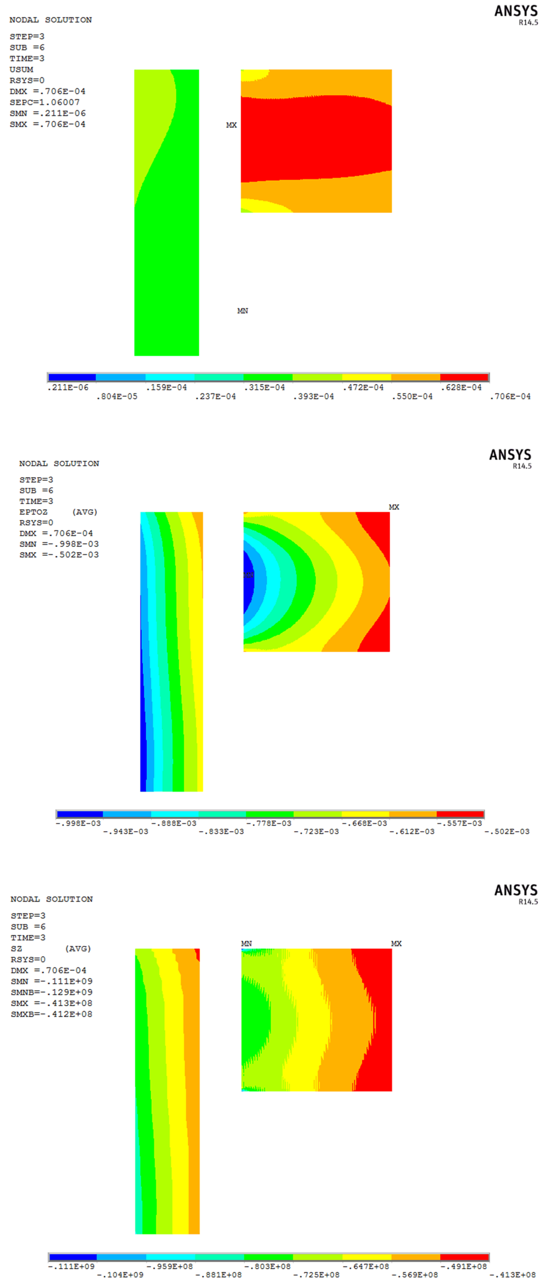

Fig. 5　Deformation, stress and strain distribution of the superconducting magnet during excitation

with the bobbin during excitation conditions.

3　Experimental results

After completing the manufacturing of the superconducting magnet system, the superconducting coils were cooled by the 1.5 W GM cryocooler, as shown in Fig. 6. The cooling process for the magnet system is shown in Fig. 7. It takes about 45 h to cool down to 4.2 K. After the magnet was cooled down to 4.2 K, the magnet was energized. A 150 A, 6 V DC power supply was employed for the magnet performance tests. The magnet reached 5.51 T in 52 min at an operating current of 82.0 A without any quench. Fig. 8 shows the dependence of the central

Fig. 6　The superconducting magnet system for RBWO

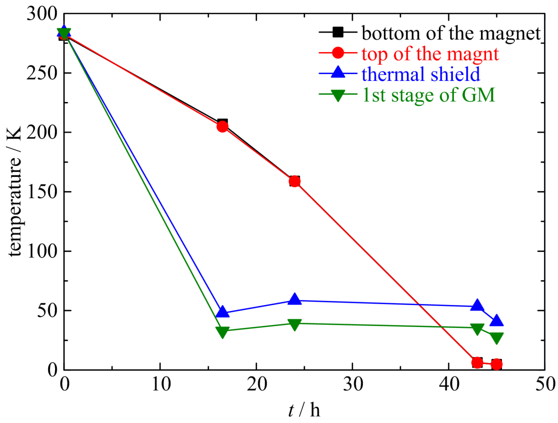

Fig. 7　The cool down curve of the magnet system using a 1.5 W GM cryocooler at 4.2 K

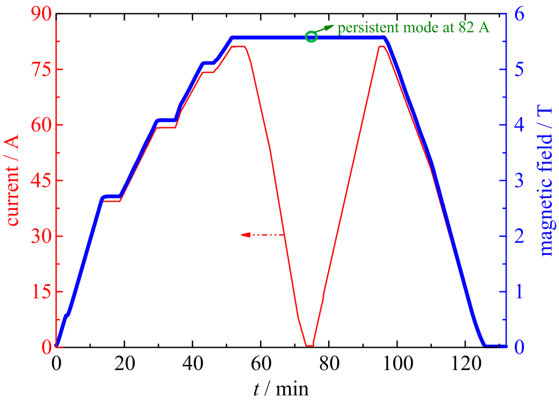

Fig. 8　The dependence of the central magnetic field as a function of time

magnetic field as a function of time. The test results also show that the magnet can realize a static operation with persistent mode at 82 A. Fig. 9 shows the magnetic field distribution along the axial direction for experimental and calculated results. The central magnetic field distribution measured agrees well with its calculated value.

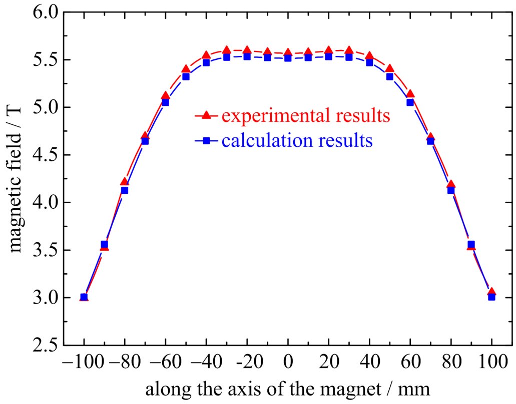

Fig. 9 Central magnetic field distribution along the axial length

The magnetic field homogeneity of the superconducting magnet can be expressed as

$$\Delta B/B=\frac{B}{(B_{\max}+B_{\min})/2}-1 \qquad (1)$$

where $B_{\max}$ and $B_{\min}$ are the maximum magnetic field and the minimum magnetic field for special region. Fig. 10 shows the magnetic field homogeneity along the axial direction for calculation and experimental results are better than ±0.5% from −30 mm to 30 mm, which satisfies the requirements for RBWO.

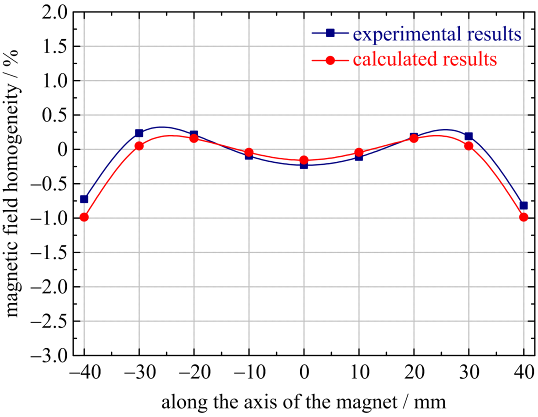

Fig. 10 Magnetic field homogeneity distribution along the axial length

After completing the magnetic field and magnetic field homogeneity performance evaluation, we shut down the cryocooler to evaluate the cryogenic performance of the superconducting magnet system. Tab. 2 gives the temperature profile of the superconducting magnet system as a function of time. Temperature in the first-stage GM cryocooler increased to about 83 K from 28 K during the shutdown interval. Temperature of the top of the magnet only increased to 4.35 K from 3.98 K.

Tab. 2 Temperature profile of the superconducting magnet system when shut down the cryocooler

time /h	bottom of the magnet/K	top of the magnet/K	thermal shield /K	1st stage GM cryocooler/K
0	3.82	3.98	36.61	28.00
1	3.92	4.18	63.69	68.41
2	4.00	4.35	79.06	83.14

4 Conclusion

A 5.51 T superconducting magnet with a homogeneous region of 60 mm in axial length was designed and constructed for RBWO application. The superconducting magnet was impregnated with a filling material of paraffin wax to prevent the turns from moving during operating. A large Lorentz force in axial direction and radial direction exist when the magnet is charged to the full operational current. The reinforcement structure of the superconducting magnet is used. The superconducting magnet can reach a 5.51 T central magnetic field without any quench. The magnetic field homogeneity of the magnet satisfies the requirements for RBWO application. A detailed finite element analysis was performed to predict the performance of the magnet. The test results also show that the magnet system can realize a zero liquid helium boil-off during static operation.

References

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