Development of 7-tesla superconducting wiggler at NIRS

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Abstract

A wiggler with three-pole is under development. Each coil was wound with superconducting wires. The assembly was finished and various tests such as cooling test, quench test and a magnetic filed measurement were carried out. The field of the main pole achieved 7 T. The refrigeration system works well as it is almost expected according to the design specifications.

1. INTRODUCTION

We have been designing a compact synchrotron light source for medical applications [1]. Especially in clinical uses of synchrotron radiation, high intensity and high energy X-rays are required. In order to satisfy the requirements, not only a high current storage ring but also a multipole wiggler with a high field is indispensable. In our design of a 2 GeV class storage ring, a 7-tesla wiggler with eleven poles is required for performing energy subtraction coronary angiography by using the synchrotron radiation [1]. We have been developing a seven-tesla superconducting wiggler with three poles as a prototype of the 7T11P wiggler. The main purpose of the development is to study feasibility of a compact superconducting wiggler. Since our proposed synchrotron light source is assumed to be used by mainly medical staffs, the machine should be operated without any special knowledge or technique for accelerators. This concept has also been applied on the design of the wiggler. In the development of the 7T3P wiggler, a refrigerator is being used to cool down the superconducting coils to about 5 K instead of directly cooling by immersing in liquid helium. This concept is the same as that for a medical apparatus for magnetic-resonance-imaging (MRI) and so forth. The assembly of the 7T3P wiggler was completed. Various tests were carried out. In this paper, the design specifications and the test results are described.

2. STRUCTURE OF 7T3P WIGGLER

Outline of the wiggler

The cryostat is made of stainless-steel with a dimension of 840 mm wide, 1184 mm long and 1150 mm high. The inner structure is thermally insulated from the outer wall by a 50 K thermal shield. The cryostat has a refrigerator on the top. The refrigerator cools a thermal buffer tank with a volume of 3.4 liters through a flexible thermal connector. The wiggler coils are thermally anchored at the thermal buffer tank temperature. In normal operation, the thermal buffer tank contains liquid helium to stabilize a heat load for the refrigerator.

Coils are confined in stainless-steel cases to keep the positions. A beam pipe has a tapered shape to keep clearance for emitted radiation from electrons running along the wiggling beam path. Its horizontal aperture is 300 mm at the exit. The aperture for an electron beam has an elliptical shape of 20 mm (vertical) by 50 mm (horizontal). Since the inner surface of the beam pipe is at room temperature, the beam pipe is surrounded by a superinsulation to shield heat radiation. The gap distance between the upper coil and lower coil is 66 mm. HTS (High Temperature Superconductor) current lead of Bi-2223 are used. The design parameters are summarized in Table 1. Figure 1 shows the view of the cryostat.

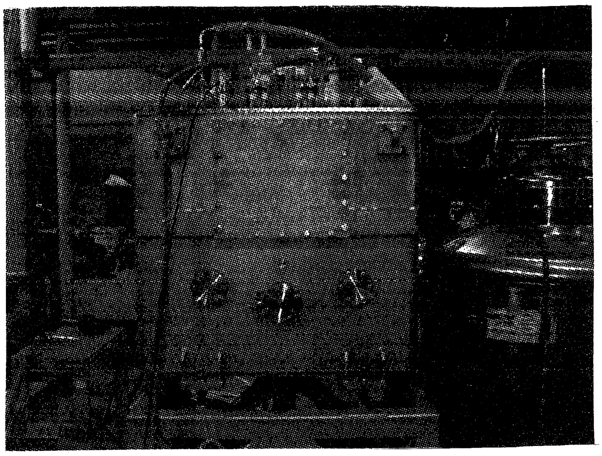
Table 1. Design parameters of 7T3P wiggler

Cryostat dimension(mm)		840W×1184L×1150H
Number of pole	Main	1
	Auxiliary	2
Field of pole	Main	7 T
	Auxiliary	4 T
Coil of main pole		Nb_3Sn, Racetrack
Coil of auxiliary pole		NbTi, Racetrack
Coil Gap		66 mm
Period length		420 mm
Operating current for 7T		208 A
Ramp speed		10 A/min
Refrigerator	4K-GM type	1.3W @4.2K, 40W @45K
Heat leakage		0.9W @4K
Average AC loss		0.53W

Magnetic design

The peak magnetic field at the central pole is 7 T and return field at the auxiliary poles is about –4.1 T. Then the magnetic field of 9.5 T is produced in the coils of central pole. Nb_3Sn is the best choice for the central coil to operate at a suitable ratio of the operating current to the critical current. The coils of the auxiliary poles were wound with wires of NbTi. All coils have the shape of racetrack to give a compact wiggler design. However, the racetrack coil has a problem of receiving electromagnetic stress in imbalance. Especially the central coils receive a stress of 175 MPa at the corner and 40 MPa at the straight

Figure 1. A view of the 7T3P wiggler in a test



sections. In order to stand for the stress, a Nb_3Sn wire reinforced by aluminum-copper has been developed [2]. The wire's tensile stress is as twice as that of the conventional Nb_3Sn wire. Each coil has an iron core in the center to increase the magnetic field with aid of magnetization of iron. It increases the magnetic field by about 10 %.

All the coils are connected in series to a main power supply and a current is fed into the coils commonly. The coils of the auxiliary poles are additionally connected with the auxiliary power supplies. Each coil connects with diodes in parallel. The diodes protect the coil by bypassing a current when a quench occurs in the coil. Figure 2 shows the circuits. The coil voltages and the current lead voltages are monitored. The coil voltage more than 3V or the current lead voltage more than 2 mV, which could indicate a quench in the coil or in the current lead, causes the main power supply to turn off automatically.

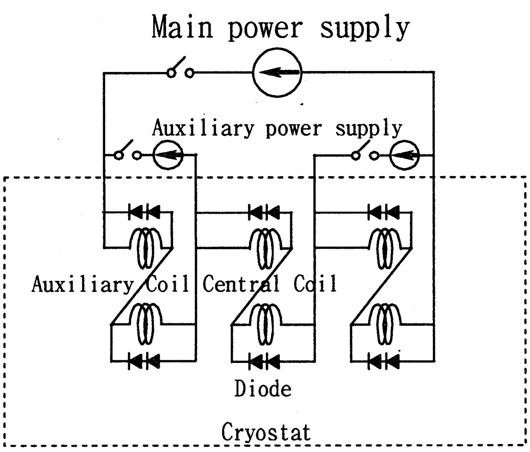


Figure 2. Circuits of coils

Refrigeration system

In this refrigeration system, a 4K-GM type refrigerator cools directly a thermal buffer tank made of OFHC. The tank can contain a coolant such as helium to absorb a temporally high heat load. In the test mentioned later, 0.5 liter LHe was contained in the tank. The coils are anchored to the tank with flexible thermal connectors made of aluminum. In normal operation, the coils will be repeatedly charged or discharged in a rate of 10 A/min after beam injection into the storage ring. During the period of ramping the current, a maximum quantity of heat of 2 W is produced in the coils for a short time due to AC loss. The refrigerator needs a high power, if the refrigerator compensates directly the quantity of heat. However, using latent heat of helium contained in the thermal buffer tank, the quantity of heat is temporally compensated independently of the refrigerator's power. Besides, since the thermal buffer tank itself has a heat capacitor, it can absorb a heat load to a certain extent without LHe. It has been ensured that the coils are normally charged to 208 A in 20 min without LHe. The thermal buffer tank causes the refrigerator power to be less and also to realize the stable operation. The refrigerator has the power of 1.3 W at 4.2 K and 40 W at 45 K. Since the static heat leakage is estimated in 0.9 W at 4 K and 30 W at 50 K, only the refrigerator can compensate the heat leakage.

3. TESTS AND RESULTS

Various tests have been carried out to study the characteristics of the wiggler. The results were briefly mentioned as follows.

Cooling test

It takes a long time to cool down the whole system from room temperature. Before assembly, a test for cooling a single coil by using only the refrigerator of 0.7 W power without any coolant was carried out. It took about 500 hours until the temperature achieved 5 K. If the time is scaled for cooling six coils of the wiggler with a refrigerator of 1.3 W power, it takes about 1000 hours. After assembly, the cooling test was carried out using the 1.3 W refrigerator with aid of coolants of liquid nitrogen and LHe. It took about 250 hours to cool all the coils down to 5 K. The coils were finally cooled down to 4.2 K in the both cases. At the early stage of cooling in the latter test, the temperature difference between the refrigerator's head and each component was ensured to be less than 40 K. It indicates the refrigeration system cools the whole system homogenously.

Excitation and de-excitation test

The coils were repeatedly charged to 208 A and discharged to 0 A in a rate of 10 A/min to simulate the actual operation after electron beams would be stored in the storage ring and accelerated. The coil voltages behaved in a non-linear manner at the charged current lower than 10 A. However, the voltage became a constant value of 1.2V at the current more than 10 A in which the magnetization of iron-core was saturated. The voltage is larger than the value anticipated by calculation of –HdI/dt with a coil inductance of 5.4 H because of a mutual inductance. No flux-jump was observed while the magnetic field was being ramped. It tells that the coil works stably even in the high magnetic field. The magnetic field measured by a Hall probe at the center of the beam pipe was 6.96 T at 208 A. This is very close to the design field. The temperature of coils did not rise over the designed value of 5 K while the coils were being charged or discharged.

Quench test

In order to study a transitional characteristic of a coil when a quench occurs, a quench test was carried out with a model coil. Applying current from 120 A to 208 A to the coil, the coil was heated up by a heater. Measuring the voltages between an inner, a middle and an outer points on the coil, it was observed that the radial propagation of quench from the inner part of the coil to the middle part took about one second. The measurement of the voltage between the two points resulted that 19 V was induced between adjacent two layers of the coil due to a quench. This is much lower than the accepted maximum internal voltage between layers of 200 V. Although the matrix's resistance of the final coil is slightly higher than that of the model coil used in this test, the specifications of both the coils are closed. Therefore, the transitional characteristics of the model coil approximately simulated those of the final coils of the main pole. The temperature of the coil rose up to 30 K when a quench occurred. This value is lower than the designed value. It is probable that energy relieved in a quench is partly dissipated by the thermal buffer tank due to an eddy current induced on it.

Magnetic field measurement

The space distribution of magnetic field was measured using a Hall probe along the centre line of the beam pipe in a interval of 5 mm. The result is shown in Figure 3. The current of 204.5 A was applied on all the coils commonly, besides the currents of 9.17 A and 8.93 A were additionally applied on the coil pairs of auxiliary poles of the entrance side and the exit side, respectively. These test currents were determined by calculation for producing a peak field of 7 T in the 7T11P wiggler. The dipole field integral was not adjusted to be zero, but the dipole field integral was 0.03 T·m. The calculated values indicated by a solid line in the figure well agree with the measured values.

4. SUMMARY

According to these test results, the design specifications have been ensured to be almost satisfied. Some characteristic, such as an internal voltage between layers of a coil, gives tolerance for the wiggler operation. The refrigeration system stably works to cool all the coils and keep them at 5 K even lower. Magnetic field measurements are still preliminary. We are planning measurements of the field distribution on the condition that the dipole field integral is zero.

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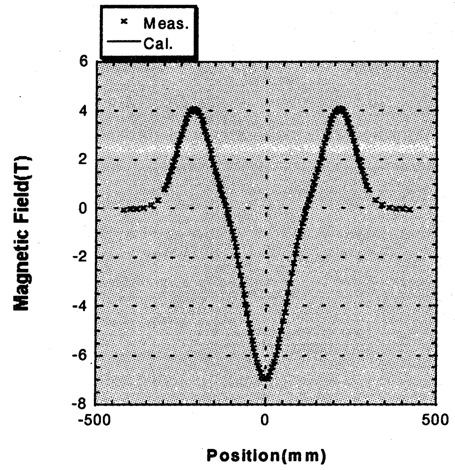

Figure 3. Field distribution along the centre line of beam pipe. The main coils are excited 208A. Crossed marks indicate measured values, and a solid line indicates a calculation.