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Development of A Cryogen-free Superconducting Dipole Magnet

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Abstract -- A cryogen-free superconducting dipole magnet has been developed to search for solar Axion in cosmic ray particle, which is necessary to explain the standard model in elementary particle physics. The magnet provides a magnetic field integral of 5 T x 2 m in an aperture of 2 cm x 9 cm between a pair of race track coils in persistent mode. The magnet has been successfully developed and the first test operation has been completed. This paper describes the magnet design, fabrication and results of the performance test.

I. INTRODUCTION

A cryogen-free superconducting dipole magnet has been developed. It is planned to be operated in persistent mode continuously for more than a year to search for Solar Axion, which is expected to be observed to explain preservation of the CP (charge & parity) symmetries in strong interactions under the present standard model in elementary particle physics. In the intended experiment [1], Axion will be converted to X-ray in its interaction with a strong magnetic field in low temperature helium gas, and the X-ray will be detected by pin photo diodes at the down stream end of the detector. The sensitivity of detection is proportional to the fourth power of magnetic field and its integrated length.

To satisfy above condition, the magnet was designed as follows;

(1) to be a cryogen free superconducting magnet,
(2) to use a pair of racetrack coils to make dipole magnetic field extended a long distance,
(3) to be operated with persistent current mode for a long term operation.
(4) to be possible to incline between -30 degree to +30 degree to chase the sun direction during science observation.

II. GENERAL DESIGN

Table I gives main parameters of this magnet. Fig.1 shows cross sections of the magnet. Two racetrack coils provides an integrated dipole field of 5 T x 2 m in aperture of 2 cm x 9 cm between a pair of coils. Helium gas tube is inserted in this space. X-ray detector is installed at down stream end of the coil. The upstream end directs the Sun. When the sun is out of +/-30 degrees from the horizon, background data are taken.

TABLE I
MAIN PARAMETERS OF THE MAGNET

Coil		
Shape		racetrack
Number		2
Winding thickness and width		50 / 64 mm
Winding cross section area		3.2×10^3 mm^2
Inner/outer radius of both ends of coil		50 / 100 mm
Linear length of racetrack		2100 mm
Distance between coils		20 mm
Volume		14.95×10^6 mm^3/1coil
Weight		133.5 kg/1coil
Coil winding		
Layer x Turn		54 x 33.5/1coil
Number of turns		1809/1coil
Electric parameters		
Operation current		336A
Central magnetic field		5.0T
Maximum magnetic field		7.18T
Inductance		15.5H
Stored energy		875kJ
GM-refrigerator		
Number		2
Capacity (at 50Hz)	1st stage	20 W @ 40 K
	2nd stage	0.5 W @ 4.2 K
(Cold mass at 4 K)		(670 kg)

The magnet is cooled by a set of two staged GM-refrigerator directly. There are two thermal conductive plates at upper and bottom of coils. A thermal conductive rod (dia.100mm) is linked to the 2nd stage of refrigerator at the middle of this plate. A persistent current switch (PCS) and Bi2223 current leads are also placed on the top of the rod. These plates and rod are made of copper.

The refrigerator capacity is 20W for the 1st stage and 0.5W for the 2nd stage. By using the 1st stage, 40K radiation shield and copper current leads are cooled. By using the 2nd stage, the coil and persistent current switch are cooled through the thermal conductive rod and plate.

The coils with thermal conductive plates are mechanically supported by a coil case made of stainless steel. This case is surrounded by 40K radiation shield and is installed in a

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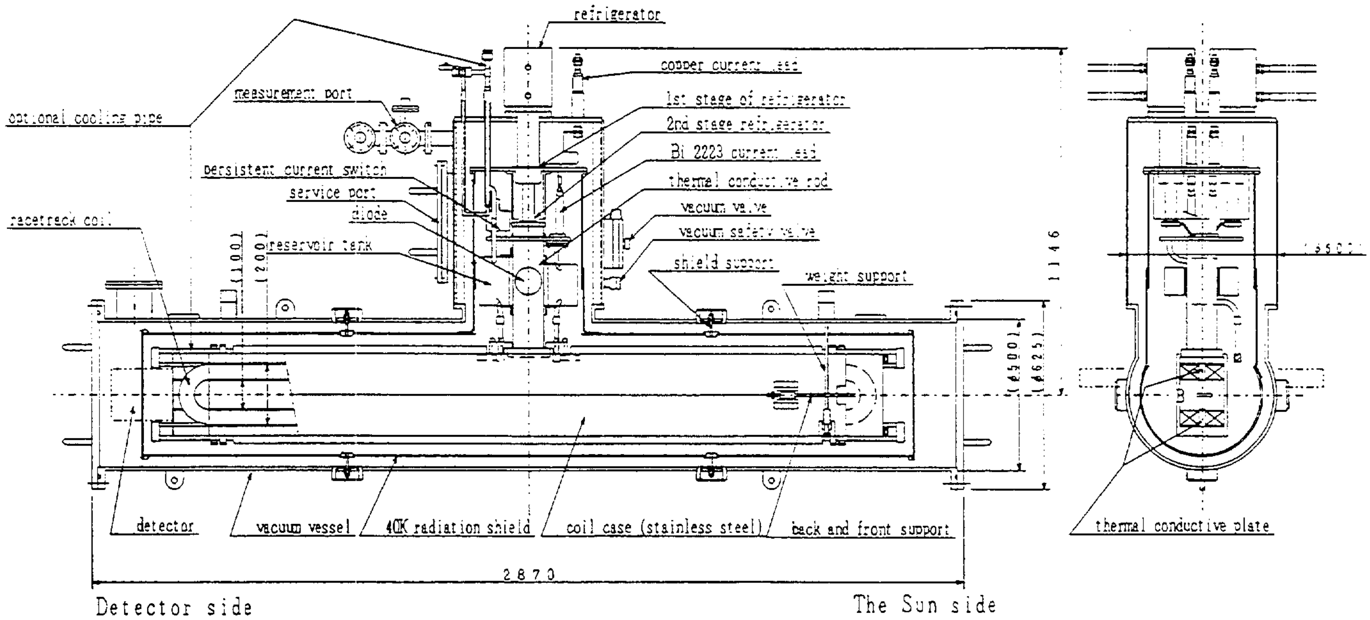

Fig.1 Cross sections of the magnet

vacuum vessel. GFRP and titanium support rods are used for supporting the coil case and radiation shield.

Fig. 2 shows the electrical circuit of this magnet system. To suppress the heat load to the refrigerator, Bi2223 current leads combined with ordinal copper current leads are used. For protection of the coils and current leads, diodes are excited and the power supply current can be cut off by the circuit breaker in case of Bi2223 leads failure and the refrigerator stop.

III. Fabrication

A. Magnet

The racetrack coil was wound by using NbTi superconductor. It designed to be operated below 5.5 K of normal transition temperature under the operating conditions of Bo = 5 T, I = 336 A. To cool the long coils and to decrease heat loss, several devices has been used. Fig.3 shows that two coils were set up.

The racetrack coil was formed by using epoxy resin coated on each layer. The resin was cured at room temperature and it may shrink with the same level of superconductor at low temperature. By winding the coils with resin coating, the insulation between turns was very thin, so that thermal conductivity in coils could be kept high. Winding mandrels were removed off from coil to save the cold mass at 4 K.

The thermal conductive plates were installed between the coils and were bonded to the coils directly. The resin was used to bond the plate, in order to eliminate peeling off after cooling.

A cooling pipe is optionally used to cool the coils by liquid or gas like helium or nitrogen. The aim of using this pipe are to shorten cooling time and the way of cooling coils while the refrigerator is maintained and so on.

Otherwise, to reduce joule heating during excitation, Bi2223 current leads are used, because of the following features; (1) becoming superconductor below 70 K and, (2) low thermal conductivity. The length of Cu conductor between Cu and Bi2223 leads were decided as sum of heat load conducted from Cu to Bi2223 leads and its joule heating was minimum. As a result, designed total heat load at the 2nd stage and the 1st stage of refrigerator was 0.35 W and 34 W, respectively, in steady state (I = 0 A) and persistent mode. In process of excitation to 5 T on 120 min, designed total heat load at the 2nd stage and the 1st stage became 0.79 W and 53 W, respectively. Therefore two set of refrigerators were installed in.

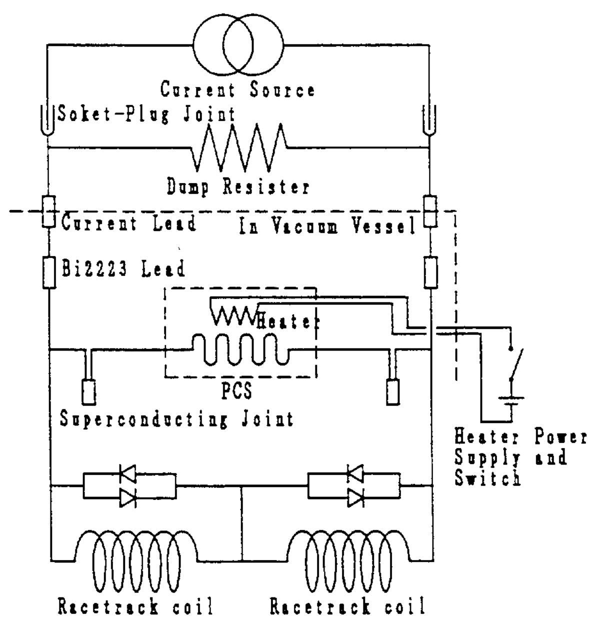

Fig.2 The electrical circuit of magnet system.

B. Electrical circuit

Since the science observation will be continued for a long time, the magnet will be operated in persistent current mode. To keep magnetic field in persistent mode for a long time, it is required that total resistance of closed circuit is minimized. The total resistance in the closed circuit is determined by joint resistance of conductors.

At the joint between main coils, we lowered resistance by soldering conductors with PbSn for about 500 mm. The joint at both ends of persistent current switch was made by diffusion bonding technique. This technique enables to make the joint resistance less than 10^{-11} Ω with a joint size of 40 mm length. Finally, the total resistance in the closed circuit was measured 5×10^{-9} Ω at 4.2 K corresponding to time constant of 3.1×10^{9} sec.

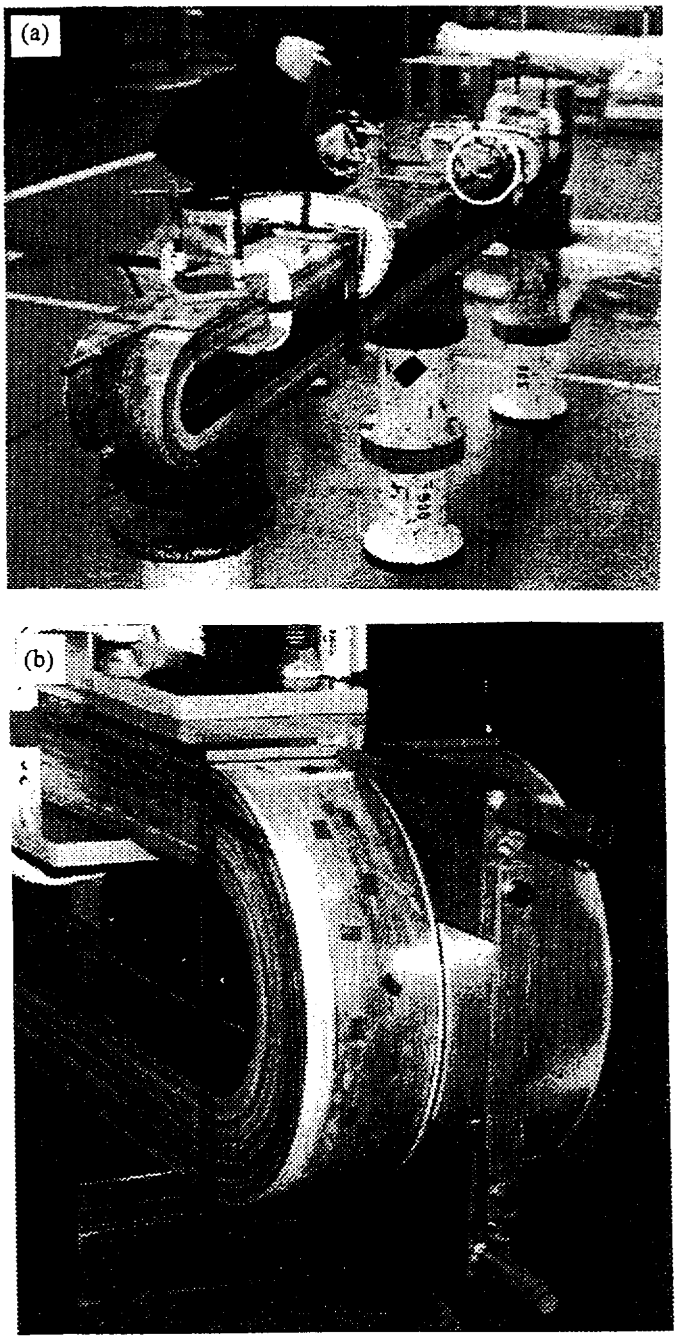

Fig. 3 (a) Photograph of a pair of racetrack coils after curing resin and assembling, (b) end of coils, there are thermal conductive plates with a cooling pipe between coils.

C. Persistent current switch

Fig.4 shows a photograph around the 2nd stage of refrigerator. The persistent current switch was installed on the top of thermal conductive rod. Table II gives its major parameters. The coil winding consists of a single layer of biphiral solenoid. The surface of solenoid was covered with copper cylinder for cooling PCS conductor uniformly. A heater was attached on the cylinder outer surface. The cylinder was connected to the top of the thermal conductive rod through a thermal conductor for cooling PCS.

Table II

MAJOR PARAMETERS OF PERSISTENT CURRENT SWITCH

Item	
Winding	non inductive winding
Resistance at switch off	~5 Ω
Winding inner Diameter	70.0 mm
outer Diameter	72.2 mm
length	57.6 mm
OFF/ON time	5 min (11.7 to 7.4K, in vac.)
Winding mandrel material	GFRP (G-10)

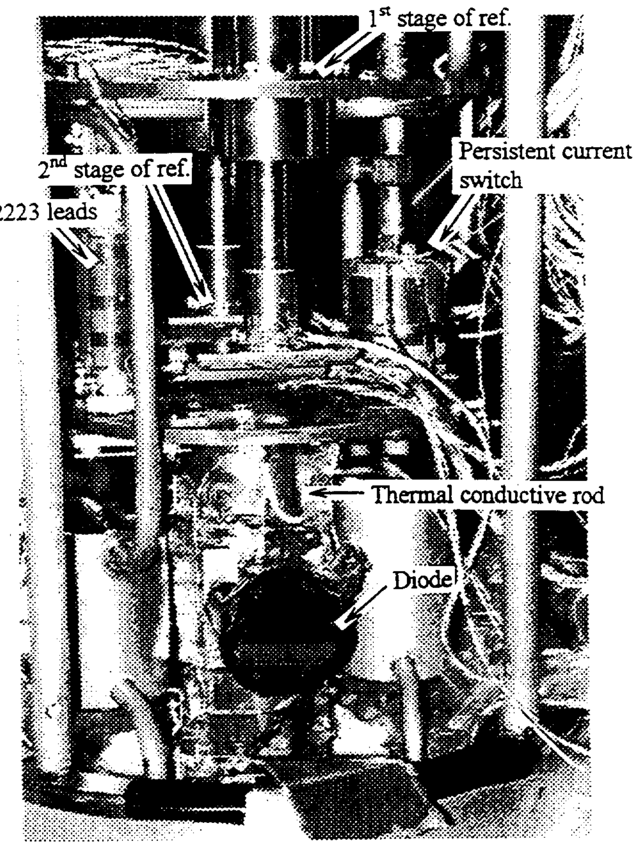

Fig. 4 Photograph around the 2nd stage of refrigerators.

IV. Cooling Test

Fig.5 shows a cooling curve by using the refrigerators starting from room temperature. It takes about 300 hours to cool down the magnet. Finally, temperature of coil became stable at 5.1 K in steady state. The temperature of the 2nd stage of refrigerator became 3.8-3.9 K and the persistent current switch was cooled down to 6.9K.

V. Excitation Test

The magnet was excited up to Bo = 4 T in the first test. Then the magnet was operated persistent mode over five days. Fig.6 shows current and temperatures in the test excitation.

It was confirmed that the persistent current switch kept off by self-heating, after once it was turned off by using the heater in the switch, on the way to reach current 268 A. When excitation was completed, the persistent current switch turned on naturally. The coil temperature was increased 0.7 K by AC loss. It was confirmed that the magnetic field was kept after the power supply was swept down.

A persistent mode operation was continued for over 5 days. During the period, the magnet was tilted within +/-30 degrees without problems. The increase of temperature of coil in tilting was 0.2K.

VI. Conclusion

A cryogen-free superconducting dipole magnet was developed to search for solar Axion. The first performance test was successfully made to realize an integral field of 8T·m and the magnet is to be used for the Axion search experiment continuously at 8-10T·m for more than a year.

An extended application is to be considered for various scientific experiments and or accelerator magnets.

Acknowledgment

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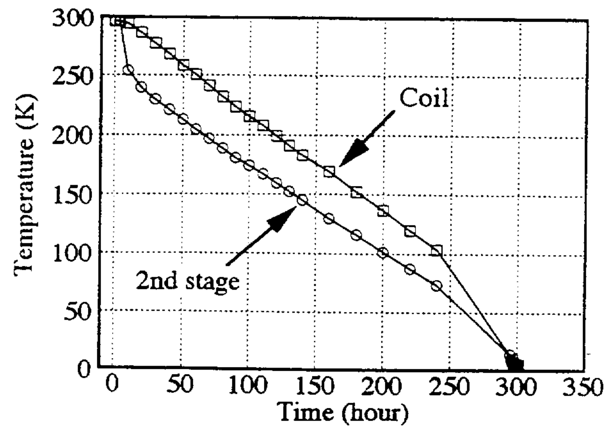

Fig.5 Cooling curve by using the refrigerators starting from room temperature.

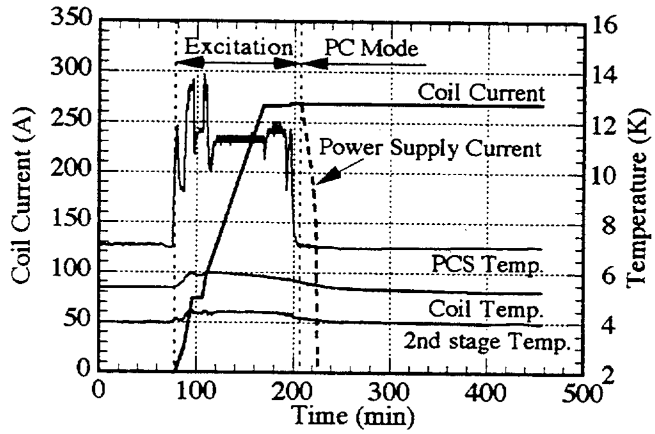

Fig. 6 Operation current and temperature during excitation and in the beginning of persistent mode.

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