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DEVELOPMENT OF PROTOTYPE MgB_2 SUPERCONDUCTING SOLENOID MAGNET FOR HIGH-EFFICIENCY KLYSTRON APPLICATIONS

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Abstract

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***Index Terms*— MgB_2, conduction cooling, klystron, quench propagation velocity, passive protection**

I. INTRODUCTION

According to a CLIC (Compact Linear Collider)-380GeV staging scenario at CERN, about 5,000 sets of X-band (12 GHz) klystrons will be used in the CLIC project [1]. The klystrons need electron-beam-focusing solenoid magnets, and the energy consumption of a current Cu magnet is 20 kW for cooling the Joule heat of the magnet [2]. In the case of NbTi superconducting magnets for klystrons, the energy consumption was 6 kW in previous studies [3]. The MgB_2 superconducting solenoid magnet is planned to reduce this energy consumption, 20 kW, to about one tenth. In addition, the number of magnets for the CLIC project is so large that the stored energy should be consumed in itself without a special quench protection system (passive quench protection) so that the system is as simple as possible. Fig. 1 shows the current klystron with Cu-conductor magnet.

MgB_2 conductors have also been developed worldwide. H. Tanaka et al. developed a MgB_2 conductor with 10 filaments that was 1.5 mm in diameter, and they confirmed that the conductor performed well by using a wind-and-react coil with 300 m of MgB_2 conductor; the coil had an outer diameter of 190 mm, and it was operated with a B_{max} of 2.3 T at 24 K and 286 A [4]. However, to save energy as mentioned above, decreasing the current is effective, so the MgB_2 conductor for the magnet has been developed [5].

As for MgB_2 coils, D. Zhang et al. successfully made a coil by using a react-and-wind method with 1.7 km of conductor, that was 900 mm in diameter; the operation point of the coil was 200 A at 13 K and 1.93 T [6]. A magnet using this coil will be protected by active quench protection with heaters [7]. This paper describes a coil and magnet design fulfilling the above requirements for energy saving and passive quench protection and the test results of a preliminary experimental coil, a pair of prototype coils (before assembling), and a prototype magnet after assembling with the cryostat also functioning the magnetic flux return yoke. The performance tests of the prototype magnet were successful.

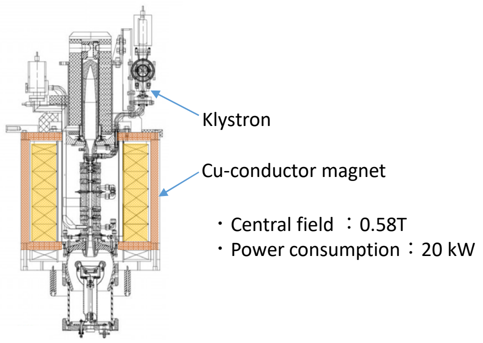

Fig. 1. Current Cu-conductor magnet for klystron

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II. DESIGN AND EXPERIMENTAL APPROACH

A. *Energy-saving design concept and conductor parameters*

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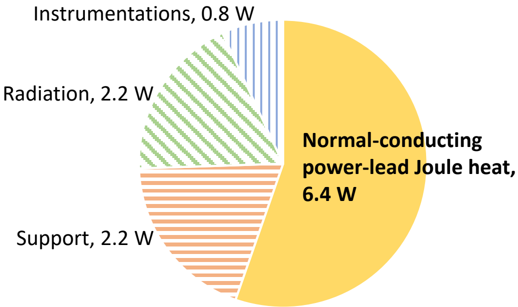

Fig. 2. Heat load distribution of MgB_2 magnet

It is effective to reduce the current in order to reduce the energy consumption of the MgB_2 magnet because the heat generation of a normal-conducting, Cu power lead from 300 K to about 70 K accounts for about 60% of the MgB_2 magnet as shown in Fig. 2. Factors except for the power-lead Joule heat are determined by the concept of the magnet, but the lead heat is proportional to the current [8], so reducing the current is effective for decreasing heat load. However, decreasing the current increases the number of coil turns and the coil production cost. In consideration of the current, the number of coil turns, and coil productivity, a rated current of 57.1 A was chosen, while the loadline ratio of the conductor was 46%, and the diameter of the conductor was 0.67 mm before insulation. Fig. 3 shows a cross-section of the MgB_2 conductor, and Table I shows the conductor parameters. Fig. 4 shows the I_c-B-T properties from a short sample wire and a coil load line of the MgB_2 magnet for klystrons [4].

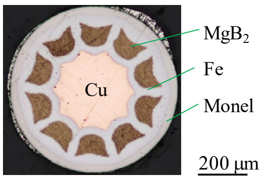

Fig. 3. Cross section of MgB_2 conductor

TABLE I
PARAMETERS OF MgB_2 CONDUCTOR

Filament number	Mono Sheath	Multi Sheath	Stabilizer	Mg:B	OD (mm)
10	Fe	Monel	Cu	1:2	0.67

The conductor OD is about 0.83 mm with insulation by using T-glass cloth. Monel is a registered trademark or trademark of HUNTINGTON ALLOYS CORPORATION in the United States and other countries.

B. Coil structure

This coil is aimed at being able to consume stored energy by itself without a special quench protection system. Therefore,

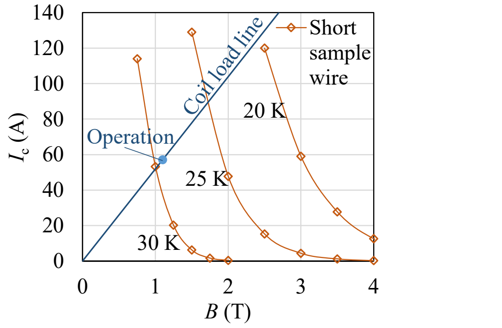

Fig. 4. I_c-B-T properties measured from short sample wire and coil load line of the MgB_2 klystron magnet. Operational current is 57.1 A, and maximum magnetic field in the coil is 1.06 T.

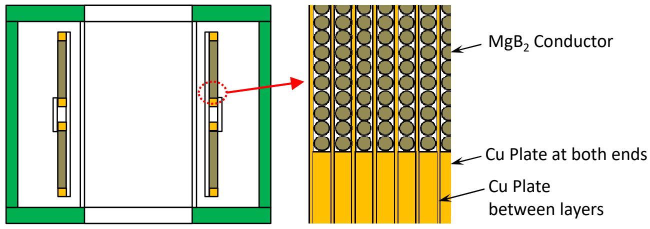

Fig. 5. Coil structure of magnet for klystron

a coil structure that has conductors between Cu plates was adopted in the expectation of restraining the local temperature rise at quench.

Fig. 5 shows this coil structure. A simulation of thermal conduction was conducted to understand how the coil temperature rise changes depending on the thickness of Cu plates, and thicknesses of 0.1, 0.2, and 0.3 mm were used. The symmetric condition was set at the longitudinal center of the coil, and a two-dimensional cylindrical model was adopted. The center conductor of the coil quenches, and the heat generation of the Cu stabilizer of the conductor starts. When the temperature of other conductors rises to a current-sharing temperature of 29 K, the heat generation of the conductor's stabilizer starts, and the quenching propagates one after another. On the assumption that the quench propagation velocity was 200 mm/s, the voltage of the conductor considering Cu resistivity due to temperature was estimated. When the voltage between the coil leads became 5 V, the power supply was turned off, and the stored energy was consumed in the quenched coil through the power supply circuit. Fig. 6 shows the coil temperature distribution at a coil voltage of 5 V in the case that the thickness of the Cu plate was 0.2 mm. After this time, the power supply was turned off, and the stored energy was consumed in the components of the normal-conducting area.

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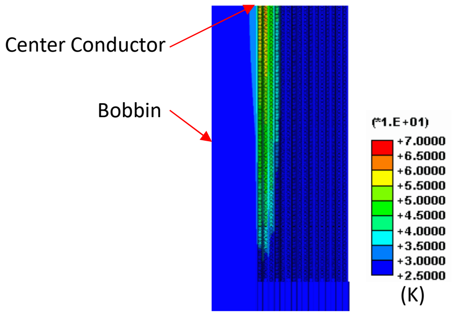

Fig. 6. Coil temperature distribution when coil voltage was 5 V for 0.2-mm Cu plate

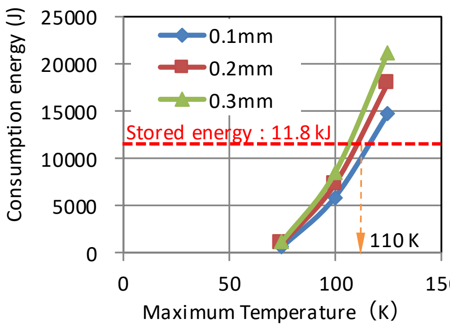

Fig. 7. Consumption energy as a function of maximum temperature at different Cu-plate thicknesses

As shown in Fig. 6, the normal-conducting area is wide enough for the coil temperature not to rise too high. Fig. 7 shows the consumption energy as a function of the coil maximum temperature for different Cu-plate thicknesses. It shows the contribution of the Cu-plate thickness was almost similar, so the 0.2-mm Cu plate was adopted in view of coil productivity.

C. Magnet design

The magnet was designed to be attached to a klystron as well as the current Cu-conducting magnet. Therefore, the magnetic return yoke is almost similar in external dimensions to the current Cu magnet, and it also fulfills the function of vacuum vessel.

The coils were produced by using the "wind and react" method so that the performance of the MgB_2 conductor could be fully demonstrated. The two coils have terminal leads at the middle of the coils and are connected in series. The coil leads are set on a cooling plate and conduction-cooled by a cold head, which is a CH-204 made by Sumitomo Heavy Industries, Ltd. The coils are supported by a CFRP support system, which consists of six horizontal supports and three vertical ones. As for the power lead, a BSCCO (Type G made by Sumitomo Electric Industries, Ltd.) lead is used between the 1st stage and 2nd stage, and a phosphorous-dioxide Cu lead is used between the terminal at 300 K and the 1st stage at 70 K. Fig. 8 shows a transparent view of the magnet, and Fig. 9 shows the structure of the magnet. Table II shows the specifications of the magnet.

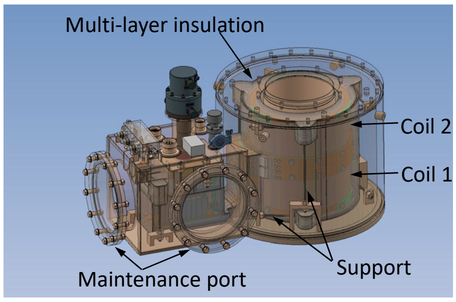

Fig. 8. Transparent view of magnet

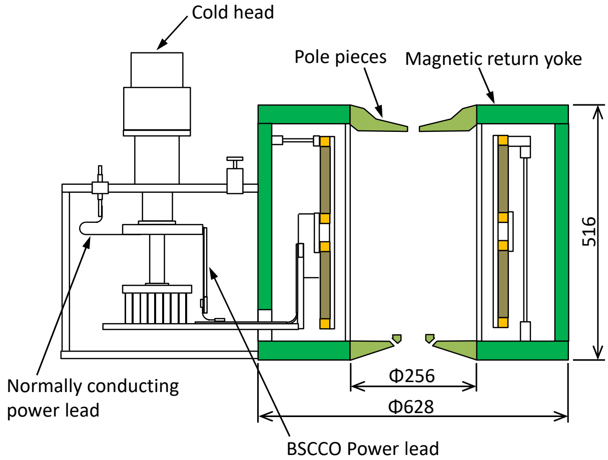

Fig. 9. Structure of magnet

TABLE II
SPECIFICATIONS OF MAGNET

PARAMETER		SPECIFICATION
Current (A)		57.1
Coil	Inner diameter (mm)	337
	Outer diameter (mm)	379
	Length (mm)	136.6 × 2 coils
	Turn number (turns)	4946 (16 × 152 × 2 coils)
	Weight of 1/2 coil (kg)	7.1 (only conductor)
	Weight of 1/2 coil (kg)	19.5 (including Cu plates)
	Heat treatment	600 ℃ × 6 h
	Molding	Epoxy-resin impregnation
Central field (T)		0.8
Inductance (H)		7.23
Stored energy (kJ)		11.8
Maximum field in winding (T)		1.06
Load factor (%)		46 (at 20 K)
Conductor length (m)		5450 (2 coils)
Magnetic return yoke material		Carbon steel (SM400)
Cold head (CH-204 by SHI)		
	20 K (W)	6.7 (at 50 Hz)
	80 K (W)	13.5 (at 50 Hz)
Compressor (Zephyr by SHI)		
	Power consumption (kW)	3
Total weight (kg)		600

Zephyr is a registered trademark or trademark of SUMITOMO (SHI) CRYOGENICS OF AMERICA, INC. in the United States and other countries.

D. Series of various tests

1) Preliminary experimental coil test

To verify the basic concept of the coil structure, a preliminary experimental coil test was carried out. The main objective was to measure the quench propagation velocity, which greatly influences the quench propagation as shown in Fig. 6.

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The MgB_2 conductor has a Monel sheath, which needs a strong acid flux to be soldered because of oxidization after heat treatment in order to set voltage taps. Therefore, the measurement of quench propagation velocity should be executed with this coil, not prototype coils due to the corrosiveness of the residual acid. Table III shows the specifications of this coil. Fig. 10 shows the test situation.

2) Prototype-coil test

To check the coil performance before magnet assembly with the cryostat functioning also magnetic flux return yoke, individual coil test was carried out. The main objective was to measure the coil temperature rise after quench because the quenching point of a coil in an assembled magnet is at the inner section of the coil near the cooling plate, and it is difficult to measure the temperature of it. Fig. 11 shows the test situation. Though the assembled magnet has a magnetic return yoke, the coils of this test do not have one, whose stored energy is less than that of the assembled magnet. Therefore, the test result should be evaluated considering this.

TABLE III
SPECIFICATIONS OF PRELIMINARY EXPERIMENTAL TEST COIL

PARAMETER	VALUE
Current (A)	57.1
Coil Inner diameter (mm)	165.7
Outer diameter (mm)	175.7
Length (mm)	53.6
Turn number (turns)	236
Inductance (H)	0.05
Stored energy (kJ)	0.08
Load factor (%)	21

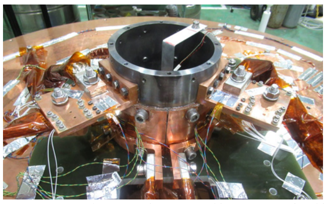

Fig. 10. Preliminary experimental test coil on test facility

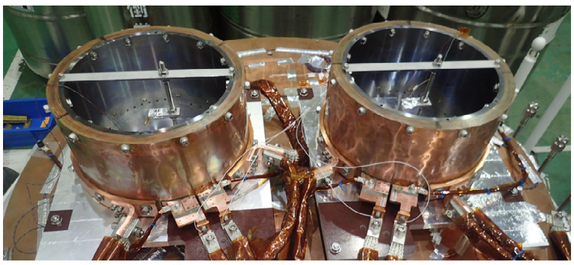

Fig. 11. Prototype coils on test facility

Fig. 12. Finished magnet

3) Prototype magnet test after assembly with return yoke

To verify the performance of the assembled magnet, a magnet test was carried out as follows.

- Quench tests
- 10-hour excitation test
- Power outage test
- Magnetic field distribution measurement

Fig. 12 shows the magnet configuration after assembly into a cryostat also functioning the magnetic flux return yoke.

III. RESULTS AND DISCUSSION

A. *Quench propagation velocity in the test coil*

Using the preliminary experimental test coil, the

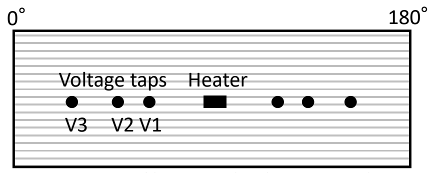

Fig. 13. Arrangement of heater and voltage taps. The quench propagation velocity is gotten with the time lag between V1-V2 and V1-V3, and the distance between V2 and V3.

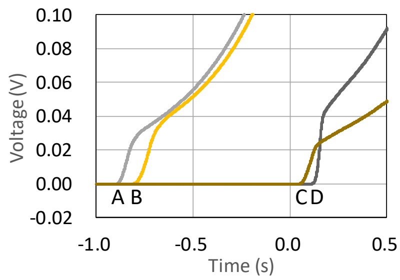

Fig. 14. Examples of voltage change at quench of preliminary

TABLE IV
QUENCH PROPAGATION VELOCITY OF PRELIMINARY EXPERIMENTAL TEST COIL

Points	Time lag (s)	Length between two points (mm)	Quench velocity (mm/s)
A-B	0.090	21	233
C-D	0.060	15	250

quench propagation velocity was evaluated. Fig. 13 shows the arrangement of heater and voltage taps set in the holes of the outermost Cu plate. Fig. 14 shows an example of voltage change and the quench propagation velocity is shown in Table IV. A velocity of 200~400 mm/s was observed.

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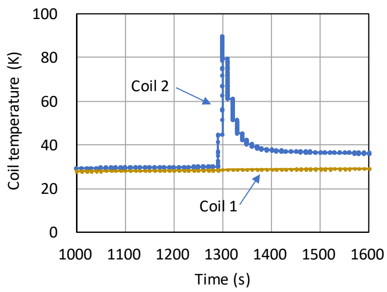

Fig. 15. Coil temperature rise at prototype coil quench test

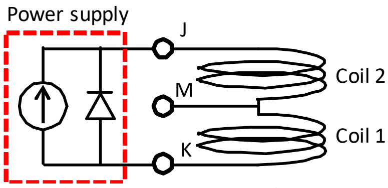

Fig. 16. Test Circuit of Magnet. Power supply was 2260B-30-72, made by Keithley Instruments, Inc. When voltage between coil leads was over 5 V, power supply was turned off. Stored energy was consumed in quenched coil through the diode circuit of power supply.

B. Peak temperature after a quench at the prototype coil

Using the prototype coils, the highest temperature of the coils at quench could be measured because a cryogenic thermometer was put on the coil surface near the heater.

Fig. 15 provides the test results. It shows that the maximum temperature was 93 K. The stored energy of two coils without the magnetic return yoke was 67% of the finished magnet. Therefore, considering the ratio of the stored energies, the highest temperature at quench of the magnet was estimated to be 139 K, which is not gotten by considering thermal dependence of specific heat of the coil. It is reasonable compared with the result of the simulation shown in Fig. 7.

C. Critical temperature in operation of the magnet

Using the magnet, several quench tests were carried out by raising the coil temperature with the heater on the second stage of the cold head.

Fig. 16 shows the test circuit. When the voltage between the J and K terminals was over 5 V, the power supply was turned off, the current flowed through the diode of power supply, and the stored energy of the coils was consumed in the quenched coil. Fig. 17 shows the result of a 57.1-A quench test. The quench occurred at a coil temperature of 29 K at 1.06 T, which meets the current sharing temperature, T_{cs} of the short sample shown at Fig. 18 [4].

D. Power consumption

As the stage temperatures of the cold head were measured, the cooling performance could be estimated. Table V shows the performance of the refrigerator which became steady in the

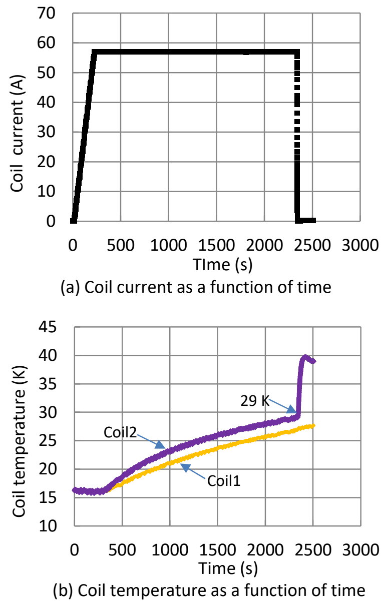

Fig. 17. Result of 57.1 A quench by coil temperature rise

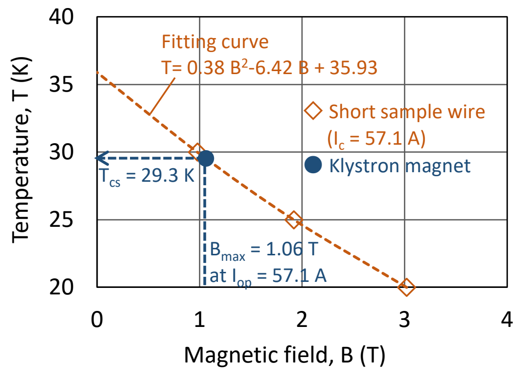

Fig. 18. B vs. T at I_c = 57.1 A obtained from I_c-B-T properties of short sample wire written in a dashed line shows fitting quadratic function. [4]

10-hour excitation test. The heat load to the 1st stage was roughly the same as that for phosphorous-dioxide Cu lead heat generation. As for the 2nd stage, though the heat load was 5.3 W at 14.7 K, as the T_{cs} of this coil was 29 K, operation at 25 K was possible.

The cooling performance of the 2nd stage at 22 K was 12 W, so if two magnets were connected in series, the power consumption per magnet would be 1.5 kW.

E. Power outage test

A power outage test was carried out assuming the case where the power supplies of the refrigerator and magnet are stopped during excitation. Fig. 19 shows that the current decreased at the time constant determined by the coil inductance and the effective resistance of the power-supply circuit. The temperature rise of the 1st stage was 10 K and the one of the 2nd stage was about 7 K. The result has confirmed that this system is robustly sustainable in power outages.

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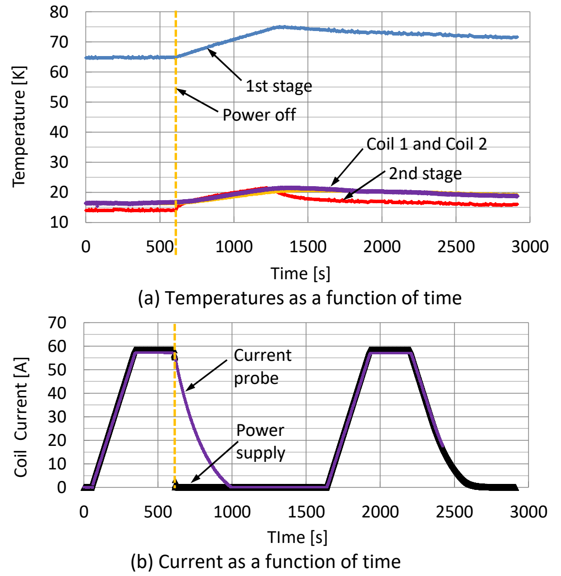
TABLE V
EXPERIMENTAL DATA OF COOLING PERFORMANCE

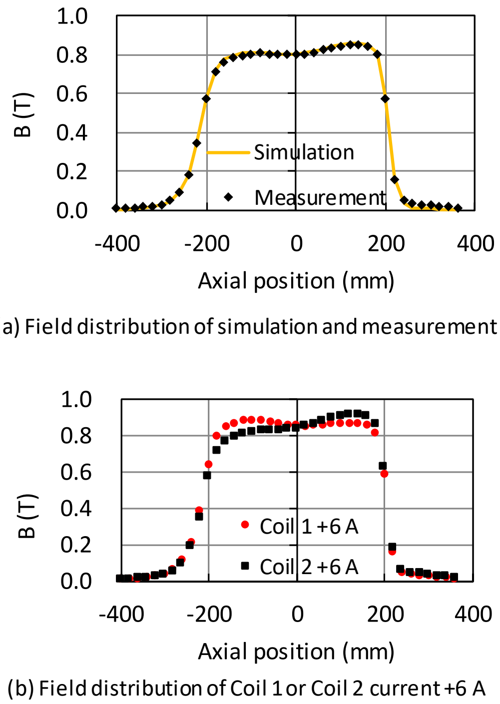
	Temperature (K)	Cooling Performance (W)
1st Stage	71.3	13.2
2nd Stage	14.7	5.3



(a) Temperatures as a function of time

(b) Current as a function of time

Fig. 19. Temperature and current as function of time at power outage test.



(a) Field distribution of simulation and measurement

(b) Field distribution of Coil 1 or Coil 2 current +6 A

Fig. 20. Field distribution as function of axial position

When about 17 minutes passed after the power off, the magnet could be normally excited again.

F. Magnetic field distribution

Fig. 20 (a) shows the magnet field distribution at the rated current, 57.1 A, along the coil axis direction compared with the expected profile in simulation in good agreement. As this magnet has an intermediate current terminal, enabling either half coil current to be adjusted at ±6 A, the field profiles to be tuned are shown in Fig. 20 (b).

IV. CONCLUSION

A performance test of a prototype MgB_2 magnet for klystrons was successfully demonstrated. The energy consumption per magnet was less than 3 kW. In the case of two magnets in a series, as the heat load of the power lead was the same, it is possible that the energy consumption per magnet could be less than 1.5 kW.

Putting conductors between Cu plates enables the coils to consume the stored energy in itself through a power supply by-pass diode circuit without a special protection system.

Wind-and-react was adopted for these coils, but react-and-wind is expected to be adopted in the future. MgB_2 superconducting magnets have huge potential for further development and in various areas including MRI applications.

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