Development of a superconducting magnet system for magnetic refrigeration using a switching power supply

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***Abstract*— Magnetic refrigeration, utilizing the magnetocaloric effect, has seen various applications due to its theoretically high efficiency, including helium liquefaction at 4 K, hydrogen liquefaction at 20 K, and room temperature magnetic cooling. Generally, the magnetocaloric effect becomes more significant with stronger magnetic fields, so when a substantial cooling capacity is required, superconducting magnets are employed. Superconducting magnets are cooled by GM cryocoolers and require dedicated power supplies. Generally, the dedicated power supplies for superconducting magnets are large in size and expensive.**

In this study, a superconducting magnet system has been fabricated and operated with small switching power supplies rather than a dedicated power supply for superconducting magnet, to examine the feasibility and controllability of superconducting magnet operation.

***Index Terms*—Magnetic refrigerator, Superconducting magnet, Switching power supply**

I. INTRODUCTION

THE magnetocaloric effect was discovered by Warburg in 1881[1], followed by Weiss and Piccard in 1917 [2]. In 1933, Giauque and McDougall experimentally demonstrated the magnetocaloric effect through cooling experiments [3] in response to theoretical predictions by Debye in 1926 [4] and by Giauque in 1927 [5]. Magnetic refrigeration is composed of magnets that generate a magnetic field, magnetic materials exhibiting the magnetocaloric effect, and, if necessary, thermal switches for controlling heat flux. Magnetic refrigeration harnesses the magnetic entropy change in the spins induced by an external magnetic field, making it particularly effective at extremely low temperatures where lattice entropy is limited. Although Giauque's experiments were conducted at sub-kelvin temperatures, in 1984, Nakagome et al. and Numazawa et al. succeeded to demonstrate helium liquefaction using magnetic refrigeration at 4 K [6][7]. In 1986, Hakuraku and Ogata succeeded in producing superfluid helium with magnetic refrigeration at 1.8 K [8]. In 2000, Ohira and his team successfully liquefied hydrogen using static magnetic refrigeration system at around 4 K [9], and Kamiya et al., achieved hydrogen liquefaction with a reciprocating magnetic refrigeration system in 2007 [10]. Barkley and his team built a magnetic refrigeration system that cools from room temperature and successfully liquefied propane in 2019 [11].

Because the liquefaction of such cryogenic gases requires a significant cooling capacity, magnetic refrigeration requires typically 5 T using superconducting magnets. Superconducting magnets generally need dedicated large power supplies, but a smaller and less expensive power supply is more desirable. This study focuses on investigating the operability of superconducting magnets using a small switching power supply.

II. PRINCIPLE OF MAGNETIC REFRIGERATION

Fig. 1 shows the principle of magnetic refrigeration. The entropy S_{total} of a magnetic material consists of spin entropy S_{spin} and lattice entropy $S_{lattice}$, and the S_{total} does not change in the adiabatic state. When a magnetic material is placed in a magnetic field in the adiabatic state (magnetization), the S_{spin} decreases due to the alignment of spins, but the $S_{lattice}$ increases in order to keep the S_{total} of the magnetic material constant. Since the temperature of a magnetic material is a lattice vibration, or lattice entropy, the temperature will increase due to magnetization. Similarly, when the magnetic body is removed from the magnet (demagnetized), it cools. A list of typical magnetic materials is shown in Table I.

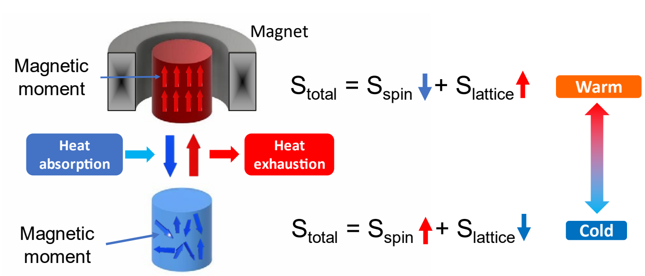

Fig. 1. Principle of magnetic refrigeration.

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TABLE I
List of magnetic materials.

Magnetic material	$T_{C,N}$ (K)	Magnetic material	$T_{C,N}$ (K)
$Gd_3Ga_5O_{12}$	0.8	$ErCo_2$	32
$GdLiF_4$	2	$DyAl_2$	63
$ErAl_2$	12	$GdNi_2$	73
$HoAl_2$	27	$HoCo_2$	77

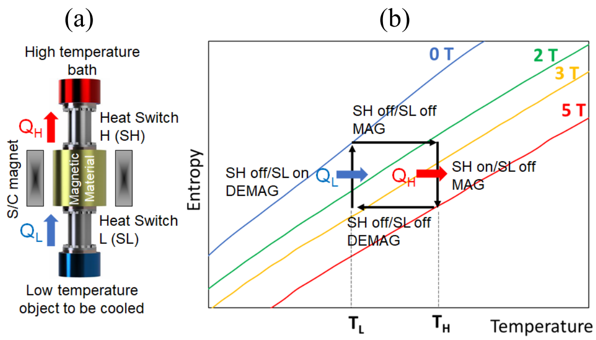


Fig. 2. (a) Illustration and (b) T-S diagram of ADR.

Fig. 2 is an illustration of an example of magnetic refrigerators and its temperature-entropy diagram. The magnetic refrigerator consists of superconducting magnets, magnetic materials, and heat switches. Magnetic refrigeration is highly efficient because it can achieve a refrigeration cycle close to that of reverse Carnot. As shown in Fig. 2, magnetic refrigeration utilizing heat switches is generally referred to as Adiabatic Demagnetization Refrigeration (ADR) [12]. The ADR was applied to liquefaction of cryogenic gasses such as hydrogen and helium. Since liquefaction takes place in gas rather than in an adiabatic process, magnetic refrigeration for liquefaction is distinguished from ADR and is called Carnot Magnetic Refrigeration (CMR) [9].

On the other hand, magnetic refrigeration at higher temperature ranges operates not through thermal switches but by blowing a heat exchange gas, allowing it to function over a broader temperature range compared to ADR, based on the principle of regenerative cooling. This type of magnetic refrigeration is known as Active Magnetic Regenerative Refrigeration (AMR) [11] and is distinct from ADR. Whether it is the ADR or the AMR, magnetic refrigerators often utilize superconducting magnets, making the cooling system and power supply for these superconducting magnets crucial challenges for the entire system.

III. Experiment of Superconducting Magnet

In this study, we manufactured small-scale superconducting magnets for experimentation and compared their operation using three different power supplies: a dedicated superconducting magnet power supply and two types of general-purpose switching power supplies. The inductance of the small-scale magnets reaches 38 H, and the primary goal of this research to control high-inductance magnets with switching power supplies.

A. Superconducting Magnet

An experimental set-up of a superconducting magnet and its electric circuit are shown in Fig. 3 and 4, respectively. The specifications of the superconducting wire and magnet are outlined in TABLE II. The superconducting magnets are cooled by conduction cooling with a GM cryocooler (ULVAC Cryogenics HE05).

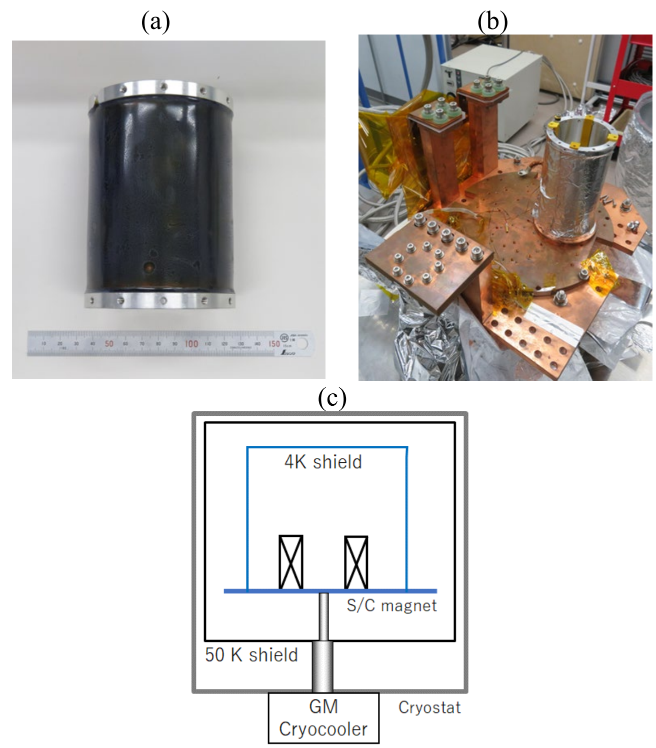


Fig. 3. Pictures of (a) the NbTi magnet, (b) a whole test apparatus, and (c) a schematic of the test apparatus.

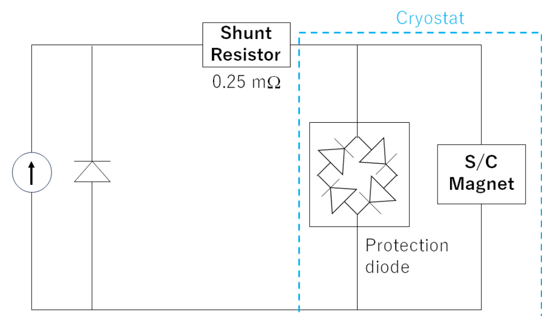


Fig. 4. An electrical circuit for the test apparatus.

TABLE II
Specification of NbTi wire and the solenoid magnet.

NbTi wire specification			
Manufacturer and model number	SuperCon 54S43	Filament diameter	18 μm
Bare diameter	0.203 mm	Number of filaments	54
Insulated diameter	0.229 mm	Winding method	Wet
Cu: NbTi ratio	1.3:1	Epoxy resin	Nito fix SK-230

Magnet design parameter			
Inner diameter	70 mm	Rated center field	4.48 T
Outer diameter	88.3 mm	Rated current	16 A (0.28T/A)
Length	130 mm	Number of turns	33463
Inductance	38 H	Total wire length	8366

Fig. 5 presents the results of the quench training for this magnet. It can be observed that the maximum current value increases with the number of quenches, reaching the rated 17 A as shown in Fig. 5.

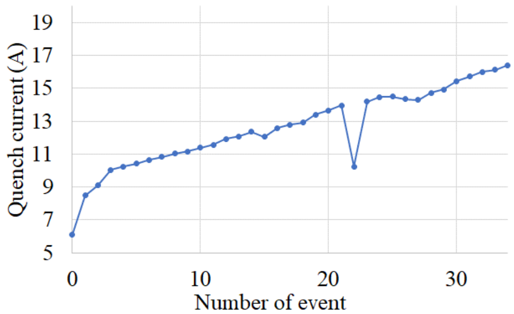


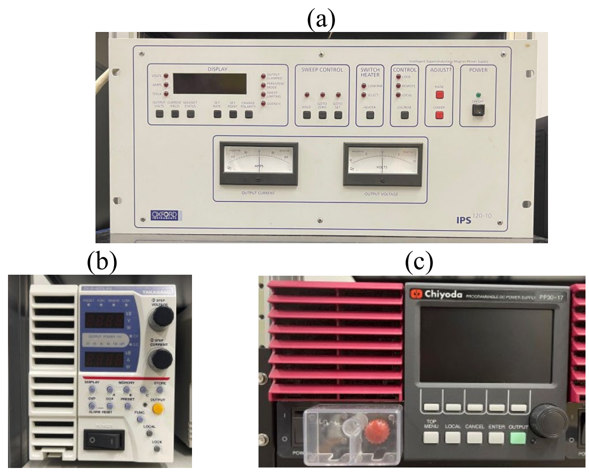
Fig. 5. Quench current vs number of event.

B. Power Supply

For comparison, three different power supplies were utilized. One is the dedicated switching superconducting magnet power supply, Oxford Instruments IPS120-10. Unlike the other two ordinary power supplies, the dedicated power supply is designed to protect itself during a quench, can be controlled to match the inductance of the magnet as a load, enabling high-precision current control. The other two are general-purpose switching power supplies from Takasago ZX-S-400, and NF Chiyoda, PP30-17. The specifications of these three power supplies are summarized in TABLE III.

TABLE III
Specification of 3 power supplies.

	(a)	(b)	(c)
	Dedicated switching power supply to S/C magnets	Switching power supply 1	Switching power supply 2
Manufacturer	Oxford Instruments	Takasago	NF Chiyoda Electronics
Product	IPS120-10	ZX-S-400LAN	PP30-17
Rated Current	±120 A	+40 A	+17 A
Maximum Voltage	±10 V	±40 V	±30 V
Feature	Bipolar	Unipolar	Unipolar
Dimension (W)×(H)×(D)	482×223×530 mm	107×130×405 mm	214×133×495 mm
Weight	35 kg	5.2 kg	9 kg
Price range	Several $10 k	Several $1 k	Several $1 k



IV. Experimental Results

The experiments were conducted ramping up at a rate of 0.01 A/s, holding for 300 seconds, and then ramping down at a rate of 0.01 A/s with the three different power supplies. Fig. 6 compares three voltages generated by the superconducting magnet when using the power supply of Oxford, Takasago, and NF Chiyoda. It can be seen that the voltage by Oxford is extremely stable and well-controlled except for discontinuities in the slope of the current.

In contrast to the Oxford power supply, the voltage exhibited significant oscillations when using Takasago and NF Chiyoda power supply. Particularly in the case of Takasago, there was a tendency for oscillations to diverge during ramp-up, making it challenging to control high-inductance magnets effectively. In the case of NF Chiyoda, oscillations were considerably better suppressed during ramp-up compared to Takasago. Of note is that during both the holding and demagnetization phases, the NF Chiyoda power supply exhibited less amplitude in oscillations.

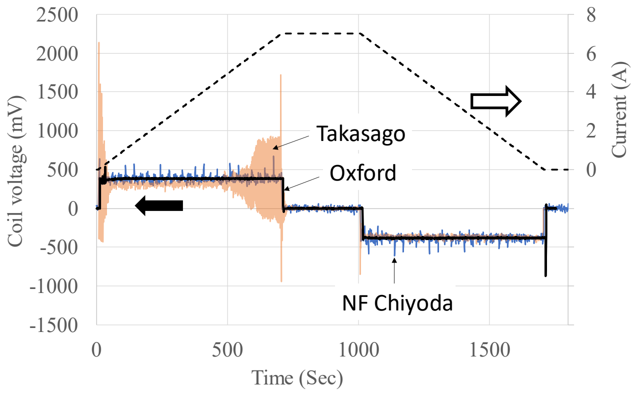


Fig. 6. Applied current and 3 resultant voltages.

V. Cooling Test

Using the NF Chiyoda power supply, cooling experiments were conducted with a magnetic material Gadolinium Lithium Fluoride (GLF) disk with 60 mm diameter and 5 mm thickness. The property and a picture of the GLF are presented in Table IV and Fig. 7, respectively. The GLF was chosen because it is relatively easy to mold and because its transition temperature is closest to the GM refrigerator temperature of 4 K, making it suitable for simple magnetic refrigeration experiments.

A one-shot adiabatic demagnetization experiment was conducted as a simple magnetic refrigeration experiment. A schematic of the experimental is shown in Fig. 8. First, a special fixing jig made of resin was created using a 3D printer to fix the GLF at the center of the superconducting magnet. The upper part of this jig was fixed at the edge of the superconducting magnet, and the GLF placed at the bottom of the jig. The thermometer (Lakeshore Cernox, CX-1010-CU-HT-0.1L) coated with Apiezon N grease was attached to the top of the GLF with aluminum tape. The experiments began with an initial temperature of 5.06 K and a magnetic field of 3.86 T (13.8 A) at a sweep rate of 0.01 A/s. Although a faster demagnetization speed is desirable for the cooling power of magnetic refrigeration, this study first selected a relatively slow sweep rate of 0.01 A/s to measure the adiabatic demagnetization temperature of the GLF and the heat loss.

TABLE IV
Specification of GLF.

J	Ordering temperature	Density (g/cm^3)	Molar mass (g/mol)
7/2	2 K	5.37	240.18

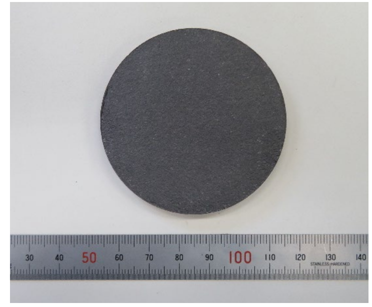


Fig. 7. A picture of Gadolinium Lithium Fluoride with 60 mm diameter and 5 mm thickness.

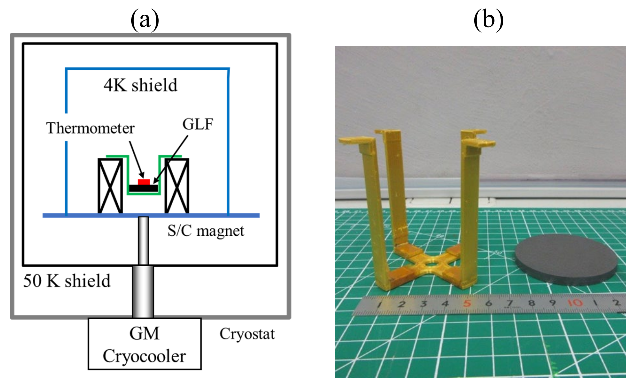


Fig. 8. (a) a schematic of the cooling test and (b) picture of GLF with 60 mm diameter and 5 mm thickness.

Fig. 9 shows the temperature change in the GLF during the demagnetization process. The temperature of the GLF consistently decreases during demagnetization, demonstrating that the current control by the NF Chiyoda power supply and the accompanying temperature decrease of the magnetic material are carried out. The GLF eventually reached a minimum temperature of 0.693 K.

To evaluate the validity of the results in Fig. 9, we consider the temperature was plotted in the entropy temperature diagram of the GLF at 0 T, 2 T, and 4 T as shown in Fig. 10. If the GLF is demagnetized from 3.86 T with pure adiabatic conditions, the GLF temperature theoretically reaches the temperature below 0.5 K. On the other hand, the experimental value is found to be 0.693 K, a difference of about 0.2 K. The cause of this difference is due to heat transfer and radiation.

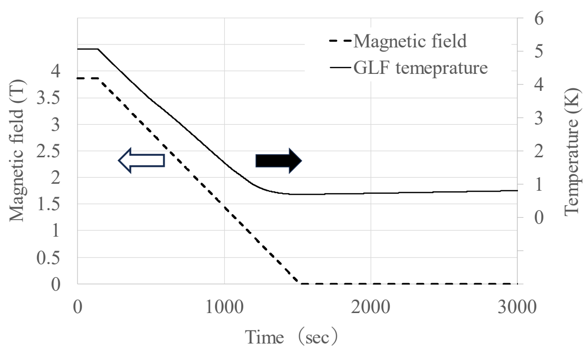


Fig. 9. The change of the magnetic field and the GLF temperature as a result of demagnetization.

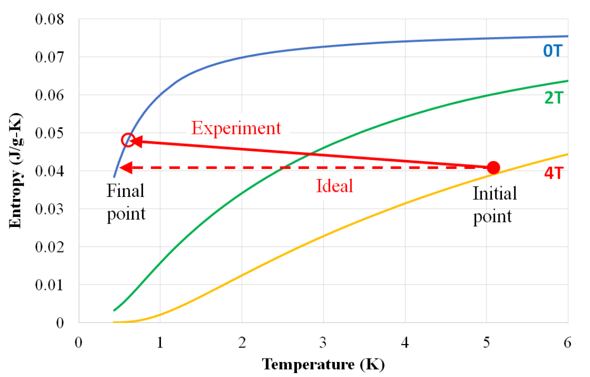


Fig. 10. The T-S diagram of the GLF and a theoretical prediction of the cooling test.

Excluding these losses, the GLFs are close to the temperature variation predicted by the entropy temperature diagram. We achieved a temperature change of 4.37 K versus about 3.6 K in our previously study [13], an improvement of more than 20%. This indicates that the ADR in this study has great potential.

VI. Summary

In this study, we manufactured a small-scale superconducting magnet with high inductance of 38 H was manufactured and controllability using three different power supplies was compared. In the comparison between the representative general-purpose switching power supplies, by Takasago and NF Chiyoda, it was confirmed that the NF Chiyoda power supply allows for more stable control.

Finally, using the magnetic refrigeration system composed of the small-scale superconducting magnet, the NF Chiyoda power supply, the magnetic material GLF was successfully cooled, achieving stable temperatures as low as 0.693 K, which is close to the prediction.

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References

[1] Warburg E. G., Magnetische Untersuchungen über einige Wirkungen der Coerzitivkraft, Ann. Phys. 13, p. 141-164, 1881.

[2] Weiss, Pierre; Piccard, "Le phénomène magnétocalorique". J. Phys. (Paris). 5th Ser. (7): pp. 103–109, 1917. https://doi.org/10.1051/jphystap:019170070010300

[3] W. F. Giauque and D. P. MacDougall, Attainment of Temperatures Below 1° Absolute by Demagnetization of $Gd_2(SO_4)_3{\cdot}8H_2O$. Phys. Rev. 43, pp. 768, May, 1933, https://doi.org/10.1103/PhysRev.43.768

[4] P. Debye, "Einige bemerkungen zur magnetisierung bei tiefer temperatur", Ann. Phys. vol. 81, pp. 1154-1160, 1926, https://doi.org/10.1002/andp.19263862517

[5] W. F. Giauque, "A thermodynamic treatment of certain magnetic effects. a proposed method of producing temperatures considerably below 1° absolute", J. Am. Chem. Soc. 49, pp. 1864-1870, August, 1927, https://doi.org/10.1021/ja01407a003

[6] H. Nakagome, N. Tanji, O. Horigami, H. Ogiwara, T. Numazawa, Y. Watanabe, and T. Hashimoto, "The helium magnetic refrigerator I: Development and experimental results", Adv. Cryog. Eng. 29, pp. 581-587, 1984, https://doi.org/10.1007/978-1-4613-9865-3_66

[7] T. Numazawa, T. Hashimoto, H. Nakagome, N. Tanji, and O. Horigome, "The helium magnetic refrigerator II: Liquefaction process and efficiency", Adv. Cryog. Eng. 29, pp. 589-596, 1984, https://doi.org/10.1007/978-1-4613-9865-3_67

[8] Y. Hakuraku and H. Ogata, "A rotary magnetic refrigerator for superfluid helium production", J. Appl. Phys. 60 pp. 3266-3268, November, 1986, https://doi.org/10.1063/1.337716

[9] K. Ohira, K. Nakamichi, and H. Furumoto, "Experimental study on magnetic refrigeration for the liquefaction of hydrogen", Adv. Cryog. Eng. 45, pp. 1747-1754, 2000, https://doi.org/10.1007/978-1-4615-4215-5_101

[10]K. Kamiya, H. Takahashi, T. Numazawa, H. Nozawa, and T. Yanagitani, "Hydrogen liquefaction by magnetic refrigeration", Cryocoolers 14, pp. 637-644, 2007, https://cryocooler.org/resources/Documents/C14/080.pdf

[11]J. A. Barclay and W. A. Steyert, "Active magnetic regenerator," U.S. Patent 4,332,135 (1982), http://globaldossier.uspto.gov/#/result/patent/US/4332135/1.

[12]P.J. Shirron, E.R. Canavan, M.J. DiPirro, J.G. Tuttle, C.J. Yeager, "Multi-Stage Continuous-Duty Adiabatic Demagnetization Refrigerator" Advances in Cryogenics Engineering 1629-1638 (2000). https://doi.org/10.1007/978-1-4615-4215-5_86

[13]Takenori Numazawa, Koji. Kamiya, Jing Li, Hideki Nakagome, and Peter Shirron, "Development of a Continuous Adiabatic Demagnetization Refrigerator, J. Cryo. Super. Soc. Jpn, Vol. 50 No. 2 pp. 96-103 (2015), http://doi.org/10.2221/jcsj.50.96