Closed-Loop Cryogenic Cooling for a 21 T FT-ICR Magnet System

Yeon S. Choi, Dong L. Kim, Thomas A. Painter, William D. Markiewicz, Byoung S. Lee, Hyung S. Yang, and Jong S. Yoo

***Abstract*—A closed-loop cooling concept for 21 T Fourier transform ion cyclotron resonance (FT-ICR) superconducting magnets is presented. In the magnet system, low temperature superconducting coils are immersed in a subcooled 1.8 K bath, which is connected to the saturated helium reservoir through the weight load relief valve. Saturated liquid helium is refrigerated by a Joule-Thomson (JT) heat exchanger and flows through the JT valve, isenthalpically dropping its pressure to approximately 1.6 kPa, corresponding to a saturation temperature of 1.8 K. Helium gas exhausted from JT pump is liquefied by a two-stage cryocooler located after the vapor purify system. In the present paper, the amount of heat budget is determined and the structural design of cryostat is carried out by the relevant analyses. The position of a cryocooler in the magnet system is investigated, taking into account the requirement of magnetic field for normal performance. Helium liquefaction system, a key component of the closed-loop cooling system, is fabricated and tested in order to demonstrate the feasibility of our new cryogenic cooling for high field magnets.**

***Index Terms*—Cryogenic cooling, heat loads, radiation shield, superconducting magnets.**

I. Introduction

THE research program involving the development of Fourier transform ion cyclotron resonance (FT-ICR) mass spectrometer is underway at the Korea Basic Science Institute (KBSI) [1]. A conceptual design of the 21 T magnet set based on that in the National High Magnetic Field Laboratory (NHMFL) ultra-wide bore 900 MHz NMR system [2] has been completed. The fundamental materials and technologies to build a magnet for a 21 T FT-ICR mass spectrometer are similar to those demonstrated in the 900 MHz system [3]–[8]. Table I presents the main design parameters for a 21 T FT-ICR superconducting magnet system.

The NHMFL 900 MHz system used the standard batch-fill operation of the liquid nitrogen and helium reservoirs. An attractive performance and availability of cryocooler, however, enables to update the standard batch operation with cryocooling technology that allows theoretically infinite refill periods. It provides a more user-friendly and cost-effective system by minimizing the use of cryogens, maximizing the refill interval. The Joule-Thomson (JT) refrigerator will still be used to achieve the required 1.8 K operation temperature in the magnet bath.

The paper presents the closed-loop cooling by a cryocooler that will be applied to a 21 T FT-ICR magnet system. The amount of heat in the magnet system is determined and the structure of cryostat including the radiation shield is investigated by relevant analyses. The position of a cryocooler in the magnet system is discussed, taking into account the requirement of the magnetic field for normal performance. The helium liquefaction system, a key component of the closed-loop cooling system, is designed, fabricated, and tested in order to demonstrate the feasibility of our new cryogenic cooling for high field magnets.

TABLE I
Design Parameter of a 21 T FT-ICR Magnet System

Parameter		Unit	Description
Central field		T	21
Warm bore diameter		mm	110
Operating current		A	290
Conductor		-	Nb_3Sn / NbTi
Magnet axis orientation		-	Horizontal
Storage energy		MJ	29
Main field coil	Inner diameter	mm	150
	Outer diameter	mm	800
	Length	mm	1450
Shield coil	Inner diameter	mm	1510
	Outer diameter	mm	1550
Cooling system		-	Cryocooler / JT refrigerator
Outer vacuum vessel	Height	mm	2500
	Length	mm	3150
Operating temperature		K	1.8

II. Superconducting Magnet

Fig. 1 shows the cross-sectional view of the superconducting coils for a 21 T FT-ICR design and the coil dimensions are summarized in Table II. Detailed superconducting magnet conceptual design is available [9]. The current fraction of the superconductor is nominally 70% of the critical current at the maximum field on each coil. The maximum allowed strain in the Nb_3Sn is 0.25%. The operating current of the magnet is 290 A and it is designed to operate at 1.8 K. The stored energy is 29 MJ and the total inductance is 690 H. The field inhomogeneity is maintained to less than 10^{-5} over an 80 mm long cylinder whose center is coincident with the field center. The fringe field is maintained to less than 50 G at 1.5 m on axis from field center by three pairs plus one single shield coil and the detail magnetic field will be

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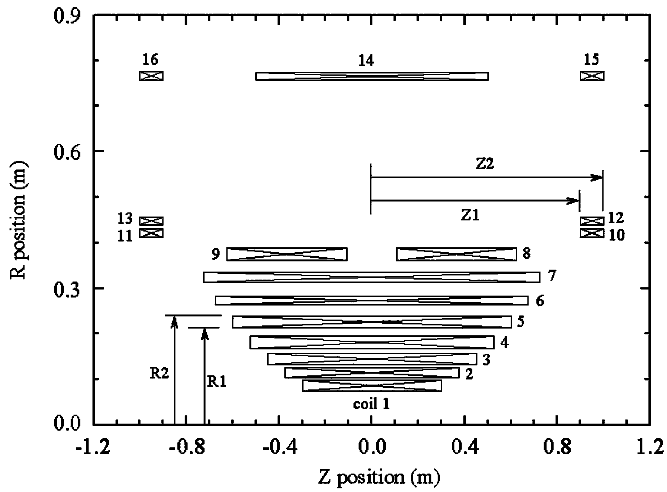

Fig. 1. Cross-sectional view of superconducting coils.

TABLE II
COIL DIMENSION FOR 21 T FT-ICR DESIGN

Coil No.	Z1 (mm)	Z2 (mm)	R1 (mm)	R2 (mm)
1	0.0	300.0	75.0	98.5
2	0.0	375.0	104.3	126.4
3	0.0	450.0	132.4	157.5
4	0.0	525.0	168.7	194.7
5	0.0	600.0	213.5	239.4
6	0.0	675.0	263.8	283.0
7	0.0	725.0	314.5	335.9
8, 9	107.0	625.0	360.7	388.7
10, 11	900.0	1000.0	411.6	430.0
12, 13	900.0	1000.0	440.0	456.7
14	0.0	500.0	756.7	774.3
15,16	900.0	1000.0	756.7	775.8

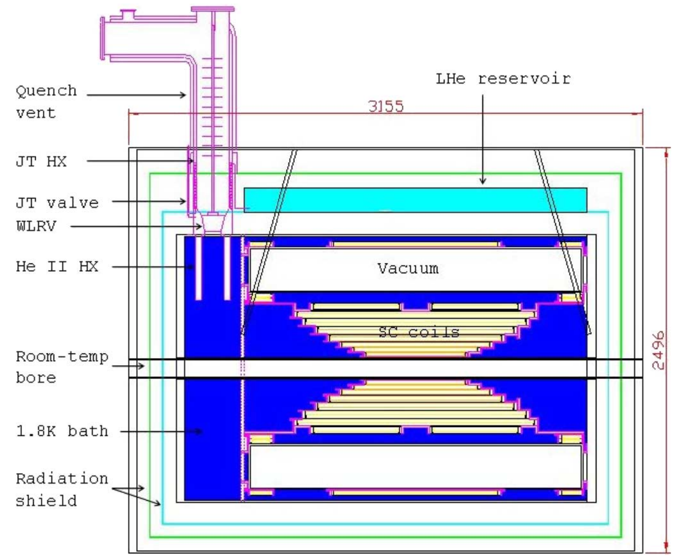

Fig. 2. Cryogenic cooling system for 21 T FT-ICR magnets.

TABLE III
CRYOGENIC HEAT BUDGET

Cooling stage	1 stage	4.2 K	1.8 K
Conduction	7.67	0.74	1.82 E-2
Radiation	32.69	0.21	1.37 E-6
Current Lead	24.4	~ 0	~ 0
Superfluid Leak	n/a	n/a	0.217
Instrumentation	1.09	0.06	0.01
Total	65.85	1.01	0.245
Cryocooler capacity (PT415)	80W @ 65K	1.5	n/a

described in the next section. The overall mass of the magnet system including coil forms, reinforcement, structural hardware and helium was calculated to be around 9500 kg.

III. Cryogenic Cooling for Magnet

A. *Closed-Loop Cooling System*

The cryogenic cooling system for the 21 T FT-ICR superconducting magnets considered here is shown in Fig. 2. The low temperature superconducting coils are immersed in a subcooled 1.8 K bath, which is connected to the saturated helium reservoir through the weight load relief valve (WLRV). Saturated liquid helium is refrigerated via a Joule-Thomson (JT) heat exchanger and flows through the JT valve, isenthalpically dropping its pressure to approximately 1.6 kPa, corresponding to a saturation temperature of 1.8 K as it enters the helium II heat exchanger (or evaporator). Helium leaves the He II heat exchanger as vapor, passing through the JT heat exchanger. Then helium gas exhausted from JT pump is liquefied by a two-stage cryocooler located after the vapor purify system, and stored in a 4.2 K reservoir maintained at a certain liquid level. The cryogenic cooling system, therefore, is a closed-loop system.

In the system the cryogenic cooling requirements are continuously generated by four different physical mechanism; thermal conduction, thermal radiation, heat through current lead, and superfluid heat leak through the weight load relief valve. Table III shows the estimated heat budget in the 21 T FT-ICR magnet system. Heat leak through the weight load relief valve between the helium reservoir and the superfluid helium bath is a dominant load on the superconducting magnet bath [10]. The amount of superfluid heat leak was calculated by Bon Mardion's model [11] depending upon the gap of the valve. Total heat budget at first stage and 4.2 K stage are matched with the refrigeration capacity of cryocooler PT415 [12] measured by our own test [13].

The operation of cryocooler is limited by the magnetic field. The performance of a two-stage pulse tube cryocooler (PT415) is slightly degraded when the magnetic field is over 1 T around the second-stage regenerator, and magnetic field should be lower than 600 G for a stepper motor in the warm end [14]. In order to verify the performance we carried out the analysis of the magnetic field around the superconducting coils and the results are plotted in Fig. 3. We did consider several possible positions of a two-stage cryocooler for this application. One of the conservative designs is that a cryocooler directly mounted on the top of the outer vacuum vessel provides cooling to the first-stage radiation shield and 4.2 K reservoir, as shown in Fig. 3. The magnetic field at the second-stage regenerator and stepper motor are around 200 G and below 100 G, respectively to allow the normal performance of a cryocooler in the magnet system.

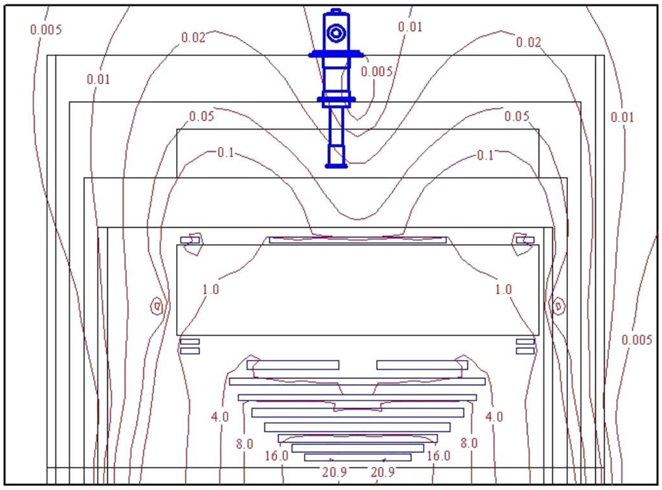

Fig. 3. Magnetic field around superconducting coils in the system. Unit: T.

B. Cryostat and Radiation Shield

The design of cryostat was performed, taking into account the self weight, thermal contraction, off-normal condition, heat leakage, system integrity, and position correction with respect to the field. The magnet vessel was designed to be suspended from the outer vacuum vessel with a transverse and axial suspension system. The suspension angle of rod/strap is 16° from the vertical, taking into account the thermal contraction and the shortest load path for structure integrity.

The radiation shield between the outer vacuum vessel and the 4.2 K helium reservoir is thermally connected to the first-stage cold head of a cryocooler. The copper rings will be assembled to the support structure with an interference fit such that they do not detach during cooldown. The major source of distributed load to affect the temperature of radiation shield is thermal radiation which is imposed from the room temperature surface to the shield. In order to maintain the temperature of radiation shield at the designed level, the cold head temperature of a cryocooler must be lower such that the load might be removed from the radiation shield. Therefore, small value of the thermal gradient of shield contributes to promote cooling efficiency. The temperature distributions of the shield obtained by commercial code, ANSYS, are shown in Fig. 4. In the analysis the refrigeration capacity of the PT415 was entered as the curve-fitted functions and the effective emissivity of layered surface by MLI was used. The warmest temperature is 73.4 K when the cold head (or heat sink) temperature, material and thickness of shield are 70 K, aluminum (Al 6061) and 2 mm, respectively.

A parametric structure analysis was carried out in the ANSYS environment, using the linear static analysis option with three dimensional brick element. Fig. 5 presents the result of the structure analysis considering the differential thermal contraction caused by the cooldown to the magnet operating temperature and the electromagnetic forces on the coils when the magnet is energized at the designed current level. The maximum equivalent stress of 55.8 MPa is occurred near the position of cryocooler and the maximum strain is 0.372E-3. It is noted that the above value is far below the yield stress of aluminum at 70 K (150 MPa).

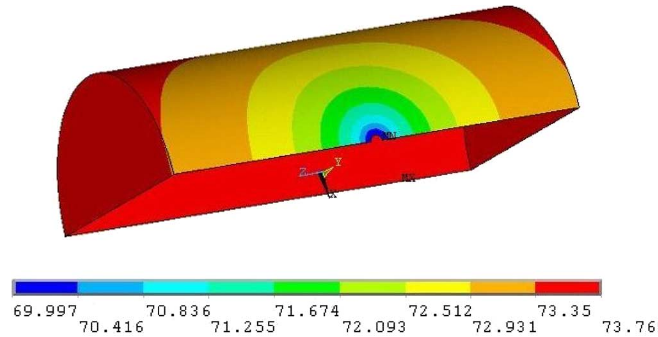

Fig. 4. Temperature distributions of radiation shield. $\mathrm{MLI} = 30$ layers.

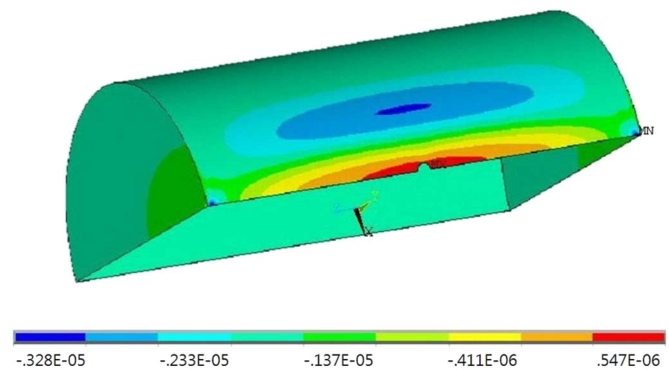

Fig. 5. Structural analysis of radiation shield under self-weight.

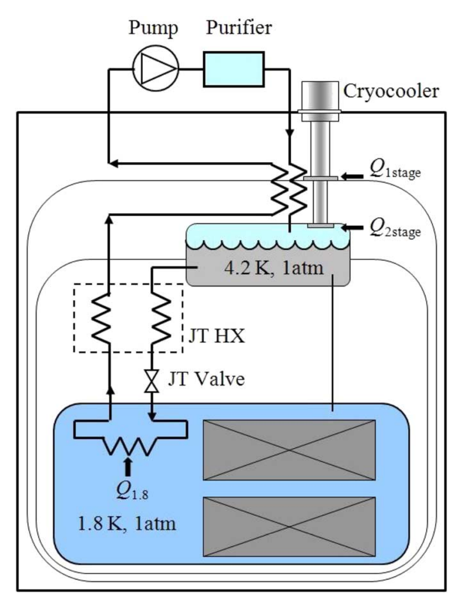

Fig. 6. Schematic of the closed-loop cooling for high field magnets.

IV. Helium Liquefaction System

One of the key technologies of the closed-loop cooling is helium liquefaction by a cryocooler. In order to demonstrate the feasibility of our cryogenic cooling for high field magnets the helium liquefaction system was designed and fabricated. Fig. 6 shows the schematic flow of the closed-loop cooling system for high field magnets. In the present study, instead of the purify system the research grade helium gas is supplied and regulated by a mass flow meter (OMEGA). Also, a dummy winding with

Fig. 7. Helium liquefaction system for the closed-loop cooling.

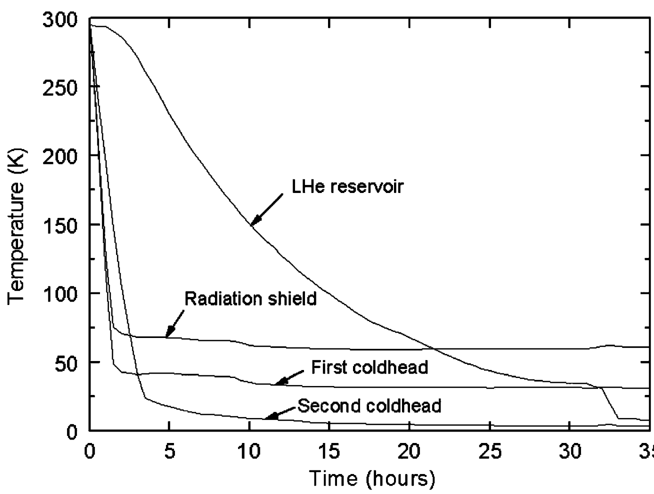

Fig. 8. Representative cooldown curves of the helium liquefaction system.

electrical heater is employed. The cold head of a cryocooler PT415 has a very limited surface area, so a cylindrical copper piece was thermally anchored to the cold head of the cryocooler and a copper tube of 3.2 mm diameter was soldered onto the outer surface of the copper cylinder. The cryocooler integrated helium liquefaction system was installed in the vacuum vessel, as shown in Fig. 7.

Fig. 8 shows the cooling down process of the helium liquefaction system after turning on the cryocooler PT415. At the initial cool-down process the temperature decreased almost at a constant rate; it took approximately 1.5 hours for the first cold head to reach 43 K and 3.5 hours for the second cold head to reach 24 K. Then temperatures decreased slowly until they reached the lowest temperature. Cooling down the helium reservoir below 30 K took around 30 hours due to its large heat capacity. After 35 hours operation, the final temperatures of first and second stage cold heads reached 31.2 K and 3.3 K, respectively. In the cooling system for 21 T FT-ICR magnets, 25 mg/s of the mass flow rate through helium II heat exchanger is required for normal operation.

V. Summary

The concept of the closed-loop cooling by a cryocooler for a 21 T FT-ICR magnet system was presented. A two-stage pulse tube cryocooler was employed to provide cooling to the first-stage radiation shield and 4.2 K reservoir, and the cooling capacity of a cryocooler met well the total heat load estimated from the relevant analyses. The position of a cryocooler was determined, taking into account the requirement of the magnetic field for a normal performance. The helium liquefaction system using a cryocooler was designed, fabricated, and an initial cool-down process was successfully performed. The helium liquefaction system will be integrated into the proto-type 21 T magnet system in the near future.

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