Development of zero boil-off cooling systems for superconducting self-shielded MEG

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Abstract. A mobile Magneto encephalography (MEG) of Sumitomo Heavy Industries, Ltd. (SHI) uses a high temperature superconducting magnetic shield (HTSMS), Superconductor-Normal-metal-Superconductor (SNS) type Superconducting Quantum Interface Device (SQUID) sensors, and they are cooled by a zero boil-off cooling system. The zero boil-off cooling system consists of a circulating cooled helium gas system for cooling the HTSMS below temperature 90 K and a helium recovery system for cooling the SNS type SQUID sensors to liquid helium temperature. The zero boil-off cooling system are designed to allow measurement in an operating state, allowing arbitrarily long usage. We succeeded first measurement of neuron current in brain by using SHI’s MEG with Helium zero-boil-off cooling system at April, 2018. This paper describes overview of SHI’s MEG, the thermal design of the zero boil-off cooling system for our MEG and the results of cooling tests.

1. Introduction
Sumitomo Heavy Industries, Ltd. (SHI) began development on a mobile Magneto encephalography (MEG) composed of a high temperature superconducting magnetic shield (HTSMS), Superconductor-Normal-metal-Superconductor (SNS) type Superconducting Quantum Interface Device (SQUID) sensors, and a zero boil-off cooling system in 2007.

Historically, the system began as a collaboration between SHI, Shimadzu, and Japan’s National Institute of Information and Communications Technology [1]. For a period the project progressed steadily and showed promise of commercial applications, but was terminated following the untimely passing of the primary investigator and the onset of global economic downturn. In 2014, SHI acquired the rights to the project and resurrected it internally.

SHI’s MEG system is designed to allow measurement with the zero boil-off cooling system in an operating state, allowing arbitrarily long usage. These results show that our system is capable of operating in a nearly worst case scenario. We believe these results show promise for our vision of a more mobile MEG – one not only free from a shielded room, but perhaps even capable of traveling to where it is needed.

Integration tests have been performed with all major components, and we have shown that the MEG system is capable of measuring brain activity. These results are particularly noteworthy because they demonstrate the ability of the superconducting magnetic shield to reject noise even in hostile environments, as no shielding measures were taken apart from the aforementioned superconducting self-shielding. Furthermore, this data was captured while the zero boil-off system was running. Zero boil-
off systems are becoming more common, but some impose an upper limit on both the length of a single recording session and the number of hours in a given week that the system can be used.

Design and fabrication of all subsystems has been completed, and integration testing of the system as whole has begun. This paper describes an overview of SHI’s MEG, the thermal design of the zero boil-off cooling system for our MEG and the results of cooling tests.

2. System overview
Sumitomo Heavy Industries is currently developing an MEG system with an emphasis on mobility and usability. SHI-MEG shown in Figure 1 consists of a high temperature superconducting magnetic shield (HTSMS), SNS type SQUID sensors, and a zero boil-off cooling system. Key features of the system include a HTSMS that makes the device self-shielding and eliminates the need for a magnetically shielded room, an array of proprietary SNS type SQUID sensors that provide both sensitivity and robustness, a state of the art zero boil-off cooling system build on decades of experience in making MRI coolers and space cryogenics, and an open source software environment that can keep pace with rapidly changing research trends. Figure 2 shows a photograph of the test configuration of the SHI-MEG in the SHI Niihama Factory.

2.1. High temperature superconducting magnetic shield
SHI’s MEG features a high temperature superconducting magnetic shield (HTSMS) around the Dewar and sensor array in place of a conventional magnetically shielded room. The HTSMS functions on the principal of perfect diamagnetism.

Figure 2 shows photographs of the outside view and supporting system of the HTSMS. The HTSMS’s inner diameter is 650 mm, thickness is 3mm and height is 1600 mm. The superconducting material used is (Bi,Pb)2Sr2Ca2Cu3Ox (Bi2223), a high temperature superconductor with a favorable critical temperature. The critical temperature of the Bi2223 film was measured to be 103 K. Bi2223 is spray-coated on the inner surface of a nickel cylinder by high-temperature plasma in the atmosphere. A cooling pipe is welded at 90 degree pitch in longitude direction on the outer surface of nickel cylinder. The HTSMS is supported by eight glass fiber reinforced plastic (GFRP) flat bars at the both ends of the cylinder from the outer vacuum chamber shell. In order to reduce radiation heat transfer to the HTSMS, multilayer insulation (MLI) of 30 layers is covered up the HTSMS. The cylinder of superconductor is free from mechanical vibrations during neuro-magnetic measurement because it is cooled down to cryogenic temperature below 90 K by circulating helium gas sent from a closed-cycle helium cooling system which is several meters far from the SQUID system.

The critical current density of the shield material is at least 100 A/cm². The shielding factor is defined as the ratio of the outside magnetic field to the inside magnetic field.
The shielding factor is more than 5000 at center of the HTSMS cylinder and it is almost constant below 10 Hz while those of conventional Permalloy shield decrease below 10 Hz [1]. This is important because major ambient magnetic noise due to traffic is largest below 1 Hz. It should be noticed that the good shielding factor of the superconducting magnetic shield in low frequencies consistently yields the high sensitivities of the SQUID system in low frequencies. The HTSMS allows installation in settings without a dedicated magnetically shielded room, which makes SHI’s MEG relatively easy to transport, and is a key factor in our vision of a more mobile MEG.

2.2. SNS type SQUID sensor
The sensors employed in SHI’s MEG system are internally developed SNS-junction SQUIDs with intrinsic flux noise of less than $5fT/\sqrt{Hz}$ at 10Hz and less than $20fT/\sqrt{Hz}$ at 1Hz. The array is composed of 64 radial gradiometers, upgradable to 128. Each gradiometer has a diameter of 30mm and baseline of 45mm. The increased size of the pickup coil improves their sensitivity and resilience to noise [2]. In addition to low noise and good sensitivity, SHI’s SNS junction SQUIDs are also robust to temperature cycling and electrical current. After 40 thermal cycles between room temperature and liquid helium temperature, they show no deterioration in performance. Similarly, no degradation is observed following applications of currents as high as 90 mA.

2.3. Electronics, control systems and open source software
The measurement system consists of a 64 channels Frequency Lock Loop (FLL) unit, a 64 channels Filter and Amp (F&A) unit, a 65 channels AD conversion unit, and a measurement control PC. In combination with SHI’s SNS type SQUID sensors, the FLL unit outputs a signal with a sensitivity of 0.84 nT/V. The F&A unit can arbitrarily select a high pass filter and signal amplification factor, and outputs the signal to the AD conversion unit through the chosen circuit. The AD conversion unit allows selection of sampling frequencies between 250 Hz and 10 kHz. The AD converted signal is then transmitted to the MNE plug-in module by the TCP server installed in the measurement control PC.

SHI’s acquisition software is built as a plugin to MNE Scan [2], and allows real time processing and visualization of recorded data. Parallel and series pipelines can be assembled using graphical function blocks to perform preprocessing, averaging, noise reduction, and source space estimation.

3. Thermal design of zero boil-off cooling system
Figure 3 shows a diagram of the zero boil-off cooling system. The zero boil-off cooling system is responsible for cooling both the SQUID sensors, Dewar radiation shield and the high temperature superconducting magnetic shield (HTSMS). It is comprised of two closed-cycle cooling systems. One is a helium recovery system for cooling the SQUID sensors to liquid helium temperature, and the other is a circulating cooled helium gas system for cooling the HTSMS below temperature 90 K. GM coolers have moving parts that could be sources of noise, and so are located remotely. A flexible pipe with triple structure is used for connecting a vacuum chamber for GM coolers and a vacuum chamber for the Dewar and HTSMS. The flexible connecting pipe is approximately 8 m of length and 100 mm of outside diameter. Figure 3 also shows the cross section view of flexible connecting pipe. The supply (high pressure) gas and return (low pressure) gas pipes between second heat exchanger (HEX2) and third heat exchanger (HEX3) in the JT cooler, and a supply gas pipe of the circulating cooled helium gas system are located at the most inside of the flexible connecting pipe. A return gas pipe is a double tube with a large diameter and acts as a radiation shield for the inner three pipes. The return gas after cooling the HTSMS of the circulating cooled helium gas system flows inside of the return gas pipe. Multi-layer insulation (MLI) is used outside of the return gas pipe for reducing the radiation heat leak. The inner shell for containing liquid helium and outer shell for keeping vacuum of the Dewar are made of a kind of fiber reinforced plastic (FRP). Two-stage radiation shields of copper meshed type are installed between the inner shell and outer shell. Both radiation shields are attached to the inner shell (FRP) by bonding for mechanical and thermal functions. Multilayer insulation (MLI) of 10 layers is covered on the outside of the outer radiation shield. The supply gas line of the circulating cooled helium gas system is attached to the outer radiation shield before cooling the HTSMS. The evaporation helium rate of the Dewar is 12 L/day without the re-condensing system.
3.1. Helium recovery system for cooling the SQUID

The helium recovery system for cooling the SQUID is a 4K Joule-Thomson (JT) cooler (SHI Model: GC310SCR) paired with a two-stage GM cooler (SHI Model: RDK415D) for cooling the SQUID sensors below 4.5 K. The original GC310SCR used a two-stage Solvay cooler, and the specification of cooling powers is 5.0 W at the final stage temperature of 4.3 K, 12.5 W at the second stage temperature of 12.5 K and 29.5 W at the first stage temperature of 49.5 K. The power consumption is 6.4 kW at the operating frequency of 60 Hz. We replaced the two-stage Solvay cooler with a two-stage GM cooler to reduce the self-vibration level and to increase the cooling capacity.

We select the location of the HEX3 and JT valve as inside the Dewar for the SQUID, because the influence of the heat leak by radiation through the flexible pipe is less than in the case of liquid helium transportation. The cooling system for the SQUID precools helium gas by a two-stage GM cooler and two heat exchangers (HEX1 and HEX2), before sending it to HEX3 and the JT valve inside the Dewar. A re-condenser located after the JT valve is used for re-liquefying the evaporated helium gas to liquid helium. The JT valve, which has no moving parts, re-liquefies the evaporated helium gas. The JT valve does not directly produce noise, but the movement of liquefied helium within the Dewar is a source of noise, and separate measures had to be developed to relegate those effects. We changed the materials of the JT piping, HEX3 and re-condenser inside the Dewar to non-ferrous metals such as copper, titanium and aluminum etc.

Under the steady state condition, the high-pressure gas is cooled through the three heat exchangers and by the two stages of the GM cooler before expansion through the JT valve. The HEX1 cools the high-pressure gas from room temperature down to around 40 K by exchanging heat with the returning low-pressure gas. This is followed by a heat exchange at the first stage of the GM cooler, which absorbs heat from the high-pressure gases. The HEX 2 cools the high-pressure gas from around 40 K down to 10 K. This is further followed by a heat exchange at the second stage of the GM cooler. Finally, the high-pressure gas passes through the HEX3, and is cooled to a low enough temperature for the JT effect. Through the JT valve, the high-pressure gas will be converted into saturated helium by the JT effect. The saturated helium absorbs the heat from the evaporated gas helium through the re-condenser as a re-liquefying action, then returns to the inlet of the low pressure line of HEX3. This zero boil-off cooling system is capable of reducing the Dewar’s 12 L/day boil-off to zero, and is low noise enough to run during measurement.

3.2. Optimization of 4K-JT cooler for the helium recovery system

Optimization of the cooling capacity and the high pressure (supply pressure) for the 4K JT cooler was attempted on the basis of the thermal analysis [3]. We consider a system composed of the flexible connecting pipe, the third heat exchanger, the JT valve and the 4 K stage as in Figure 4. The cooling capacity at the 4 K stage (Q3) is estimated from the equation.

\[ Q_3/m = h_7 - h_5 - \eta_3 \Delta h_{HEX3} \]

Here we have;

- \( h_n \): \(^4\)He-gas enthalpy at temperature \( T_n \)
- \( \eta_3 \): efficiency of third heat exchanger
- \( \Delta h_{HEX3} \): heat exchanged in third heat exchanger when efficiency of 100%
- \( m \): mass flow rate of \(^4\)He-gas

Also, a heat leak (\( Q_a \)) into the supply pressure line and a heat leak (\( Q_b \)) into the return pressure line in the flexible connecting pipe are expressed by the equation (\( Q_a/m = h_a - h_5 \)) and (\( Q_b/m = h_b - h_7 \)).

For example, Figure 5 present analysis results of the cooling capacity (\( Q_3 \)) in the 4 K stage shown respectively against the supply pressure (\( P_H \)) with the inlet temperature (\( T_5 \)) at the supply pressure side of the third heat exchanger as a parameter. The \( \eta_3, m, \) return pressure (\( P_L \)), and 4K stage temperature (\( T_7 \)) are fixed, respectively, as 0.97, 1 Nm\(^3\)/hr, 1.3 Mpa, and 4.5 K.
3.3. Circulating cooled helium gas system for HTSMS
The second cooling system is a circulation loop, a heat exchanger (HEX) and a two-stage GM cooler (SHI Model: RDK-408R) for cooling the radiation shield of the Dewar and the HTSMS below 90 K. The cooling powers of the RDK-408R is 35 W at the first stage temperature of 35K and 6.3 W at the second stage temperature of 10 K. The power consumption is 9.5 kW at the operating frequency of 60 Hz. The HEX is same as HEX1 of the JT cooler in the helium recovery system. The circulating cooled helium gas system precools helium gas by a two-stage GM cooler and a HEX, and send it to the Dewar for cooling the two kinds of radiation shields inside the Dewar and the HTSMS. A series-connected pipe for the cold supply helium gas is thermally connected to the radiation shields inside the Dewar and welded on the outer surface of the HTSMS. Under the steady state condition, the supply gas is cooled through the HEX and by the second stage of the GM cooler before cooling the radiation shields of the Dewar and the HTSMS. The HEX cools the supply gas from room temperature down to around 70 K by exchanging heat with the returning gas. This is followed by two heat exchanges at the first stage and second stage of the GM cooler, which absorbs heat from the supply gas. The supply gas after flowing the flexible pipe cools the outer radiation shield of the Dewar first, and cools the HTSMS next, finally, the supply gas cools the radiation shield located at upper part of HEX3 in the Dewar. Then return gas cools the outer radiation shield inside the flexible pipe and returns to the inlet of the return line of the HEX.

4. Cooling performance test results

4.1. Cooldown performance
Figure 6 shows the cooldown of the zero boil-off cooling system. The temperature of the HTSMS decreases to below 90 K after about 22 hours from when the cooler operation started. The cooler for the SQUID cooling started after 17 hours, then the liquid helium started to transfer into the Dewar after 42 hours. A total liquid helium volume of 100 L was used in this operation. Finally, a zero boil-off state reached with a liquid helium volume of 43 L after 53 hours from the start of the operation.

4.2. Cooling performance of zero boil-off cooling system
Figure 7 shows a steady state operation status under zero boil-off conditions. Table 1 shows an estimation of heat loads at the main parts from the temperature, pressure and mass flow in Figure 7. As the first stage of the GM cooler in the circulating cooled helium gas system cools a radiation shield of
the cooler unit chamber and circulating helium gas, the heat loads becomes 63.84 W. The heat load of
the return line in the flexible connecting pipe is 53.59 W, because it is a radiation shield for the three
pipes located at the most inside of the flexible connecting pipe which are a supply gas line and a return
gas line of the 4K JT cooler, and a supply gas line of the circulating cooled helium gas system. As the
pressure drop in the supply line of the 4K JT cooler is estimated from about 0.2 Mpa to 0.3 Mpa, the
cooling power at the 4K stage for recovery of the evaporated helium is estimated at 3.31 W from Figure
5, when the supply pressure (PH) is 1.7 MPa in the case of the temperature (T5) of 11.67 K.

![Cooler for HTSMS](image1)

**Figure 6.** Cool down profile of the zero boil-off cooling system

![Dewar Cooler Units of Zero boil-off system](image2)

**Figure 7.** A steady state operation status under zero boil-off condition
Table 1. Estimation of heat loads from test results in Figure 7

| Cooling system                  | Main parts                                      | Heat Loads (W) |
|--------------------------------|-------------------------------------------------|----------------|
| Circulating cooled helium gas system | First stage of GM cooler                        | 63.84          |
|                                 | Second stage of GM cooler                       | 24.89          |
|                                 | Supply line in flexible connecting pipe         | 13.64          |
|                                 | Outer radiation shield of Dewar                 | 1.48           |
|                                 | HTSMS                                           | 7.42           |
|                                 | Radiation shield at upper part of HEX3          | 9.41           |
|                                 | Return line in flexible connecting pipe         | 53.59          |
| Helium recovery system          | First stage of GM cooler                        | 10.78          |
|                                 | Second stage of GM cooler                       | 7.50           |
|                                 | JT Supply line in flexible connecting pipe      | 1.96           |
|                                 | JT Return line in flexible connecting pipe      | 2.30           |
|                                 | Cooling power at 4K stage                       | 3.31           |

4.3. Noise level and brain activity measurement

Measurements of the noise-level have been performed under zero boil-off operation. The noise level is realized less than 10 fT/√Hz at 10 Hz. The noise level at several frequency regions was low enough for a MEG measurement compared to the noise level of the conventional magnetic shield room (MSR). What makes these results noteworthy is that they were performed outside of a magnetically shielded room, with the zero boil-off cooling system continuously running. In addition, the shielding efficiency of our HTSMS shows no degradation during over 20 years after production, this is a worthy of mention. We also succeeded in measurements of neuron current in the brain in response to tactile stimulation and auditory stimulation with the helium zero boil-off cooling system [4]. Despite this, the MEG’s robust SNS sensors, low noise cooling system, and superconducting magnetic shield worked in tandem to produce reasonable results.

5. Conclusions

We have designed, fabricated and tested the zero boil-off cooling system for cooling SHI-MEG. The verification test results showed the zero boil-off cooling system has a satisfactory performance with respect to the specifications required for SHI-MEG. We believe these results show promise for the future of our system and support the feasibility of measuring biomagnetic signals outside of a magnetic shield room (MSR). An agreement has been reached for lending out the first unit to an institution in Japan. The next steps will be to implement feedback received from our development partners and to place the second and third units.

6. References

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