DEVELOPMENT OF ZERO BOIL-OFF COOLING SYSTEMS FOR SUPERCONDUCTING SELF-SHIELDED MEG

ABSTRACT
A mobile Magntic anechoic chamber (MEG) of Sumitomo Heavy Industries, Ltd. (SHI) uses a high temperature superconducting magnetic shield (HTSMS). Superconducting-Normal metalSUPERCONDUCTING (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 cold helium gas system for cooling the HTSMS below temperature 90K and a helium recovery system for cooling the SQUID type SQUID sensors to liquid helium temperature. The circulating cold helium gas system is designed to allow measurement in an operating state, allowing arbitrary long usage. We succeeded first measurement of human current and electric field in our MEG with helium zero boil-off cooling system in 2010. This paper describes overview of SHI-MEG, the thermal design of the zero boil-off cooling system for our MEG and the results of cooling test.

1. Introduction
Sumitomo Heavy Industries, Ltd. (SHI) began development on a mobile Magnetic anechoic chamber (MEG) composed of a high temperature superconducting magnetic shield (HTSMS), Superconducting Normal metal-Superconducting (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 (NICT). SHI’s MEG system is designed to allow measurement in an operating state, allowing arbitrary long usage. Those results show that our system is capable of operating in a nearly noise-free environment. We believe those 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 housing 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.

2. System Overview
SHI-MEG shown in Figure 1 consists of a Dewar within a high temperature superconducting magnetic shield (HTSMS), SNS type SQUID sensors, a zero boil-off cooling system, Measurement system, and a control GUC PC. [Key Features]
1) High Temperature Superconducting Magnetic Self-Shielding
2) Zero-Ball Off Helium Recovery System
3) Robust SNS Type SQUID Sensors
4) Open Source Software Environment [2]

FIGURE 1. System Configuration of SHI-MEG

2.1 High temperature superconducting magnetic shield (HTSMS) [2]
(1) The superconductor material used in HTSMS is Nb3Sn (BA2723).
(2) BA2723 is sprayed on the external surface of a tube of non-ferromagnetic material.
(3) Our HTSMS is cooled by circulating cold helium gas below temperature 90K.
(4) In its critical current density range of 10000 G, its size is 950mm×1100mm and the shielding factor is more than 10000 at center.
(5) The shielding performance is maintained even in the low-frequency region below 1Hz.

FIGURE 2. High Temperature Superconducting Magnetic Shield (HTSMS)

2.2 SNS type SQUID sensor [1]
(1) The sensors employed in SHI’s MEG system are internally developed SNS junctions SQUIDs with intrinsic flux noise of less than 5.3 nT/√Hz at 10 Hz and less than 20 fT/√Hz at 100 kHz.
(2) The array is composed of 64 radial gradiometers, upgradable to 128.
(3) Each gradiometer has a diameter of 39mm and baseline of 45mm.
(4) SHI’s SNS junctions SQUID sensors are cooled to temperatures below 90K.

3. Thermal design of Zero boil-off cooling system
Figure 3 shows diagram of the zero boil-off cooling system that is comprised of a helium recovery system for cooling the SQUID sensors to liquid helium temperature and a circulating cold helium gas system for cooling the HTSMS below temperature 90K.

FIGURE 3. Diagram of the zero boil-off cooling system

4. Cooling performance test results

4.1 Helium recovery system for cooling SQUID
The helium recovery system for cooling SQUID is a 4K JT cooler (NIK) connected to the HTSMS. We select the location of HX and JT valve as inside Dewar for SQUID, because of influence of heat load and radiation through flexible pipe is less due to case of liquid helium transportation.

FIGURE 4. Analysis result: Qf in the 4 K stage plotted against PTH with JT

4.2 Cooling performance of Zero boil-off cooling system
Figure 6 shows a steady state operation status under zero boil-off condition.

FIGURE 6. Cool down profile of the zero-biolf-off cooling system

6. References

Acknowledgments
Author wish to thank all staff of SHI-MEG project team, and the cryogenic group at SHI Nihama for their support and advice. We would like to express special thanks to associate professor Tanaka and professor Uchikawa of Tokyo Denki University, who contributed to the measurement of brain activity for our MEG.

4.3 Noise level and brain activity measurement
Measurement of the noise level has 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 range was low enough to 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 is no degradation during over 20 years after production, this is a worthy of mention. We also successfully in measurement of magnetic current to brain to stimulate stimuli with helium zero boil-off cooling system [4]. Despite this, the MEG’s robust SNS sensors, low noise cooling system, and superconducting magnetic shield worked to enable us 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 cooler has a satisfactory performance with respect to the design specification.

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. TABLE 1. Estimation of heat loads from test results in Figure 7

Table 1 shows heat loads on main parts from temperature, pressure and mass flow in Figure 7. Cooling power is measured for cooling of evaporated helium is estimated about 3.31 W from Figure 7. The supply pressure (PTH) is 1.7 MPa at temperature of the case (T5) of 15.67K.

6.2 Cooling power of Zero boil-off cooling system
Figure 7 shows a steady state operation status under zero boil-off condition.

FIGURE 7. A steady state operation status under zero boil-off condition

<table>
<thead>
<tr>
<th>Component</th>
<th>Heat Load (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor Unit</td>
<td>2.92</td>
</tr>
<tr>
<td>Pre cooler</td>
<td>2.33</td>
</tr>
<tr>
<td>Compressor Unit</td>
<td>2.58</td>
</tr>
<tr>
<td>Re-liquefies</td>
<td>1.76</td>
</tr>
<tr>
<td>Vacuum Chamber</td>
<td>0.63</td>
</tr>
<tr>
<td>Liquid He</td>
<td>0.38</td>
</tr>
<tr>
<td>Flexible pipe</td>
<td>0.13</td>
</tr>
<tr>
<td>Flexible pipe</td>
<td>0.09</td>
</tr>
<tr>
<td>MAX</td>
<td>7.31</td>
</tr>
</tbody>
</table>

6.3 Noise level of brain activity measurement
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