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Low-noise magnetoencephalography system cooled by a continuously operating reliquefier

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Abstract

We fabricated a low-noise magnetoencephalography (MEG) system based on a continuously operating reliquefier for cooling of low-temperature superconducting quantum interference device gradiometers. In order to reduce the vibration transmission, the gradiometers are mounted in the vacuum space of the helmet dewar with direct thermal contact with the liquid helium helmet. The reliquefier uses a 1.4 W pulse tube cryocooler with a remote motor, and a horizontal transfer tube with a downslope angle of 1°. The white noise of the system is 3.5 $fT_{rms}/\sqrt{Hz}$ (at 100 Hz). The vibration-induced peak at 1.4 Hz is 18 $fT_{rms}/\sqrt{Hz}$ averaged over the whole helmet array of 150 channels, which is the lowest among the reported values using reliquefier cooling and comparable to the noise peak cooled by conventional direct liquid helium cooling with axial gradiometers of the same baseline. The spontaneous brain activity signal showed nearly identical signal quality with the reliquefier turned on and off, and the reliquefier-based MEG system noise is well below the brain noise level.

Keywords: SQUID, biomagnetism, magnetoencephalography, closed-cycle cooling

(Some figures may appear in colour only in the online journal)

1. Introduction

Magnetoencephalography (MEG), the measurement of magnetic fields generated by ionic currents of human brain activity, provides useful information for diagnosis and functional study of the working brain [1, 2]. Presently, MEG systems are based on low-temperature superconducting quantum interference devices (SQUIDs) and require regular refill of liquid helium (LHe), which is cumbersome and a major factor in the operation cost. Furthermore, the availability of helium gas is limited and the cost of LHe is gradually increasing [3].

Therefore, an MEG system not using LHe at all or not requiring periodic LHe refills is desirable. There have been several attempts to cool the SQUID array using a cryocooler of either Gifford–McMahon (GM), GM with Joule–Thompson, or pulse-tube (PT) type, where the SQUID arrays are cooled by thermal conduction from the cold head of the cryocooler [4–6]. The thermal conductor material can be copper rods or flexible braids of copper. To ensure better thermal conduction, the cross-sectional area of the conductor should be as large as possible or the distance between the cold head and SQUID array should be as short as possible, which inevitably increases the vibration transmission from the cold head proportionally. Eventually, SQUID systems based on cryocooler cooling produced too-high noise peaks to be used for low-noise MEG measurements.

Another approach is to use reliquefaction of the evaporating helium gas from the MEG dewar, where the helium gas is liquefied by the cold head and returned to the dewar in closed cycle. The concept of reliquefaction-based cooling has been widely used in magnetic resonance imaging and SQUID susceptometers, etc. For MEG application, Takeda *et al* developed a special transfer tube of multiple pipes for efficient collection and transfer of helium [7]. However, this helium-circulation system is quite complex in the design of both the transfer tube and the system configuration, and it requires two 1.5 W GM cryocoolers. More recently, Adachi *et al* reported a reliquefaction system using a 1 W pulse tube cryocooler for a MEG with partial SQUID coverage (16 channels on the right-hemispherical area) [8] and a magnetospinogram with 44 vector gradiometers [9]. The noise-measurement results show that the reliquefier introduces a vibration peak with a magnitude of about 20 $fT/\sqrt{Hz}$ at 3.4 Hz, and peaks of smaller amplitudes at higher frequencies. Using a noise-reduction algorithm based on time-shifted principal component analysis, the average noise level of the 16 channels at the dominant 3.4 Hz peak was decreased to about 10 $fT/\sqrt{Hz}$. The MEG measurements were successful with partial sensor coverage, but the reliquefier circulation system needs buffer tanks for storage of helium gas and a circulation pump. Laine *et al* reported a reliquefaction system for a commercial whole-head MEG system (Elekta Neuromag Triux) with the cold head mounted directly on top of the MEG dewar [10]. Since the vibration and magnetic noise from the cold head are too strong, the reliquefier system has to be turned off during MEG measurements, and large storage tanks and a separate control system are needed to collect the helium gas and control the recycling. In addition, due to contamination from the storage tanks and circulation system, the reliquefier system has to be stopped for regeneration of the cold head about every eight months.

For a simpler configuration of the reliquefier system, Wang *et al* reported direct liquefaction of the evaporating gas using a short recycling path without a buffer tank, where they used a 1.5 W pulse tube cryocooler of remote motor type for cooling a baby MEG having 375 magnetometers in a coil-in-vacuum assembly [11]. Thanks to the high ceiling height of the main building, the rotary valve unit (remote motor) and reliquefier chamber could be installed above the magnetically shielded room (MSR), and the transfer tube is downward and thus transfer loss can be minimized. Though the thermal gap between the pickup coils and room temperature is short, about 8.5 mm on the average, the operation of this compact reliquefier system was reported to be successful for more than 18 months [12]. However, the vibration-induced 1.4 Hz noise peak seems rather high, about 300–2000 $fT/\sqrt{Hz}$, measured by magnetometers. After using external active shielding with fluxgate magnetometers and compensation coils, and applying the signal space projection and synthetic gradiometer, the low-frequency vibration noise peaks could be reduced to near the white noise level of the MEG system, about 10 $fT/\sqrt{Hz}$.

For a compact and low-noise MEG system without refill of LHe, in this work we introduce a continuously operating reliquefier-based MEG system having a gradiometer-in-vacuum configuration, for reduced sensitivity to vibration, and horizontal flexible transfer tube. We also analyze magnetic noise and its relation to vibration noise.

2. Configuration of reliquefier MEG system

2.1. Configuration of the reliquefier system

The reliquefier system consists of a reliquefier chamber with a pulse-tube cryocooler inside, rotary valve, compressor, and chiller. The layout of the reliquefier system is shown in figure 1. Due to space limitation around the MSR, the compressor is located 5.5 m from the MSR, with a chiller next to it. The rotary valve unit and the reliquefier chamber are installed 30–40 cm from the MSR wall. The rotary valve unit is a remote motor type in order to reduce vibration transmission to the pulse tube, and is 63 cm from the pulse tube. The cryocooler system (Cryomech model PT415RM) has a cooling capacity of 1.4 W at 4.2 K, with a remote rotary valve unit [11]. Typical power consumption of the cryocooler system is about 10 kW. The guaranteed liquefaction rate is 15 l/day from a room-temperature gas and 27 l/day from a cold gas, with a cool-down time of 4 h.

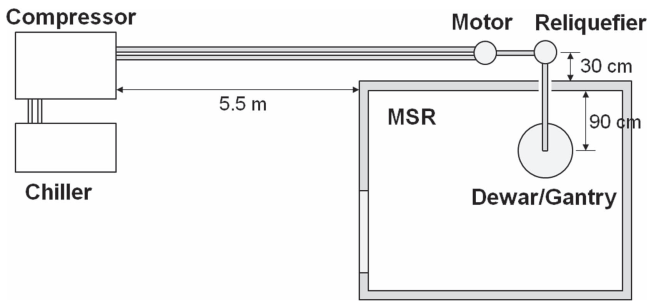

Figure 1. Top-down schematic diagram of the reliquefier system. The distance between the reliquefier chamber center and MSR outer wall is 30 cm.

The rotary valve unit is mounted onto an aluminum frame, which is fixed on the floor using anchor bolts. To reduce the vibration transmission from the pulse tube to the MEG dewar, a flexible bellows is used between the reliquefier chamber and the pulse tube head. Both the pulse tube head and reliquefier chamber are supported by separate aluminum frames for vibration isolation. The transfer tube has a flange mounted on the side wall of the MSR, and is supported by a wooden frame inside the MSR and inserted into the MEG dewar.

The transfer tube is made of low-magnetic stainless steel, but showed a big magnetic field signal when measured with a fluxgate magnetometer due to compositional change on welding. To reduce the magnetic moment of the tail part of the transfer tube, demagnetization of the tail part was done using a small solenoid coil. After demagnetization, the magnetic field amplitude from the tail part was decreased by about 10 times.

Total length of the transfer tube from the side wall of the reliquefier chamber to MEG dewar top is 130 cm, with 90 cm inside the MSR as shown in figure 1. The recommended slope angle of the transfer tube is 10°, but due to height limitation of the laboratory (2.8 m height), the slope angle of the transfer tube inside the MSR is about 1°.

Again, due to the height limitation of the laboratory, the reliquefier chamber and transfer tube could not be positioned high, resulting in low positioning of the MEG dewar. The space between the bottom of MEG dewar and MSR floor is only 37 cm, meaning that measuring MEG signals under the

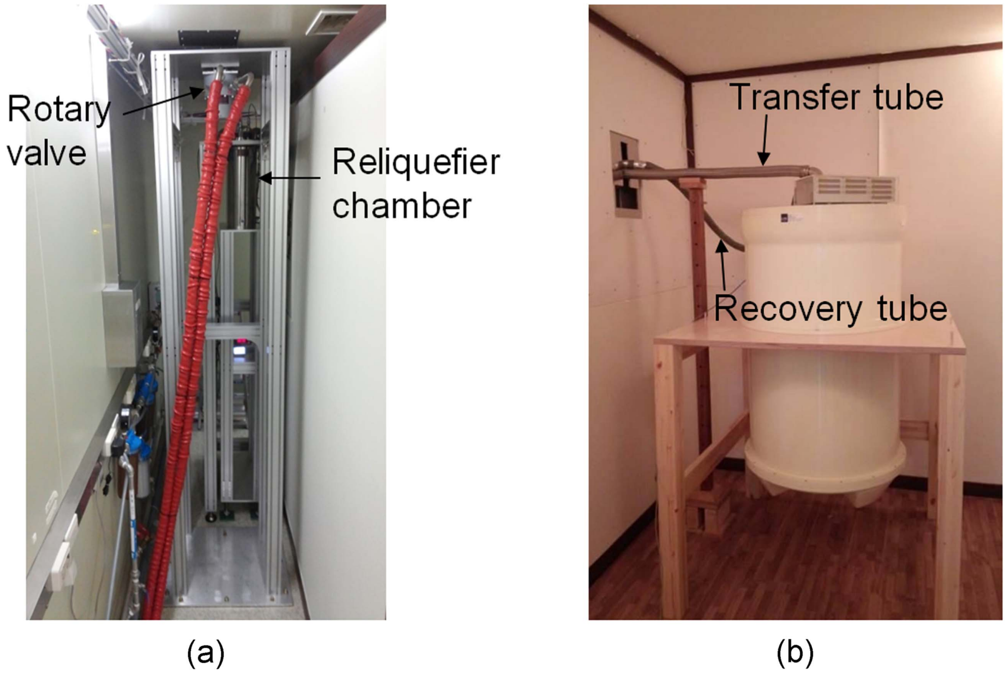

Figure 2. Photos of the installation. (a) Rotary valve and reliquefier chamber installed next to the left wall of the MSR. (b) Helmet dewar inside the MSR. Length of the transfer tube between MSR inner wall and dewar top is 90 cm, with a downslope angle of 1°.

helmet dewar is inconvenient. Figure 2 shows the laboratory pictures after installation of (a) the rotary valve and reliquefier chamber and (b) transfer tube and helmet dewar inside the MSR. The helmet dewar is supported by a wooden gantry.

The MSR consists of two layers of Mumetal (1.4 and 1.75 mm for the inner and outer layer, respectively) and one layer of aluminum (12 mm thick) with a wall thickness of 10 cm. The shielding factor (average of three axes) is 36, 52, and 72 dB at 0.1, 1, and 10 Hz, respectively. This MSR was originally built for a magnetocardiography measurement study. Therefore, its shielding performance seems a little insufficient for MEG measurement, resulting in greater internal field gradient and field noise from the reliquefier system, if any. Since the MSR is located in the basement of the building, the building vibration is minimal and it is more suitable to study the vibration of the reliquefier system.

2.2. Gradiometer-in-vacuum MEG

The test MEG system used in the present reliquefier cooling is a gradiometer-in-vacuum configuration, where the SQUID gradiometers are mounted in the vacuum space of the LHe helmet. The concept of coil-in-vacuum has already been adopted in other MEG systems [12]. However, in the previous approach, the pickup coil is near the helmet and the SQUIDs are installed in a separate space in the LHe reservoir. This causes large stray inductance between the pickup coil and the SQUID, as well as a complex superconductive connection using mechanical screws. In this paper, the SQUID gradiometer has a single-body bobbin structure, with the SQUID chip at the end part of the bobbin rod. In order to achieve a compact and low-stray-inductance superconductive connection between input and pickup coils, direct ultrasonic bonding of Nb wire was used [13, 14]. To soften the Nb wire suitable for bonding, vacuum annealing was done [15]. Figure 3(a) shows a SQUID gradiometer having a total length of 67 mm, with a 50 mm baseline and 20 mm coil diameter. The pickup coil is made of 0.125 mm diameter NbTi wires. In addition to reduced stray inductance, this short gradiometer structure is especially advantageous in a gradiometer-in-vacuum configuration for reducing the thermal mass, resulting in more effective cooling of the whole gradiometer body.

To provide good thermal conduction for the gradiometer, an alumina inset with printed circuit board and female connectors was fixed on the helmet surface of the LHe reservoir. Thus, the gradiometer bobbin can be assembled into the mounting inset simply by pressing connector pins and fastening with a plastic screw. Three types of bobbin material were tried: sintered alumina, fiberglass reinforced plastic (FRP), and FRP with stycast painting after pickup coil winding to improve thermal conduction. Alumina and FRP with stycast painting showed good cooling performance, but some of the base FRP showed non-superconducting behavior of the pickup coil. In terms of magnetic field noise, the alumina bobbin showed slightly increased white noise, possibly due to magnetic impurity in the alumina powder.

Since the gradiometer-in-vacuum configuration does not have the mechanical insert structure, where a heavy helmet sensor array is hung at the bottom, it is less sensitive to the vibration caused by the boiling LHe and the vibration of the transfer tube. The schematic cross-sectional view of the dewar is shown in figure 3(b). Inside the LHe reservoir of the dewar, only a level sensor is installed. To ensure sufficient cooling of the gradiometer bobbins, an insulated helmet-shaped copper mesh was used to cover the bobbin array, and then superinsulation layers and a thermal shield layer were installed. A

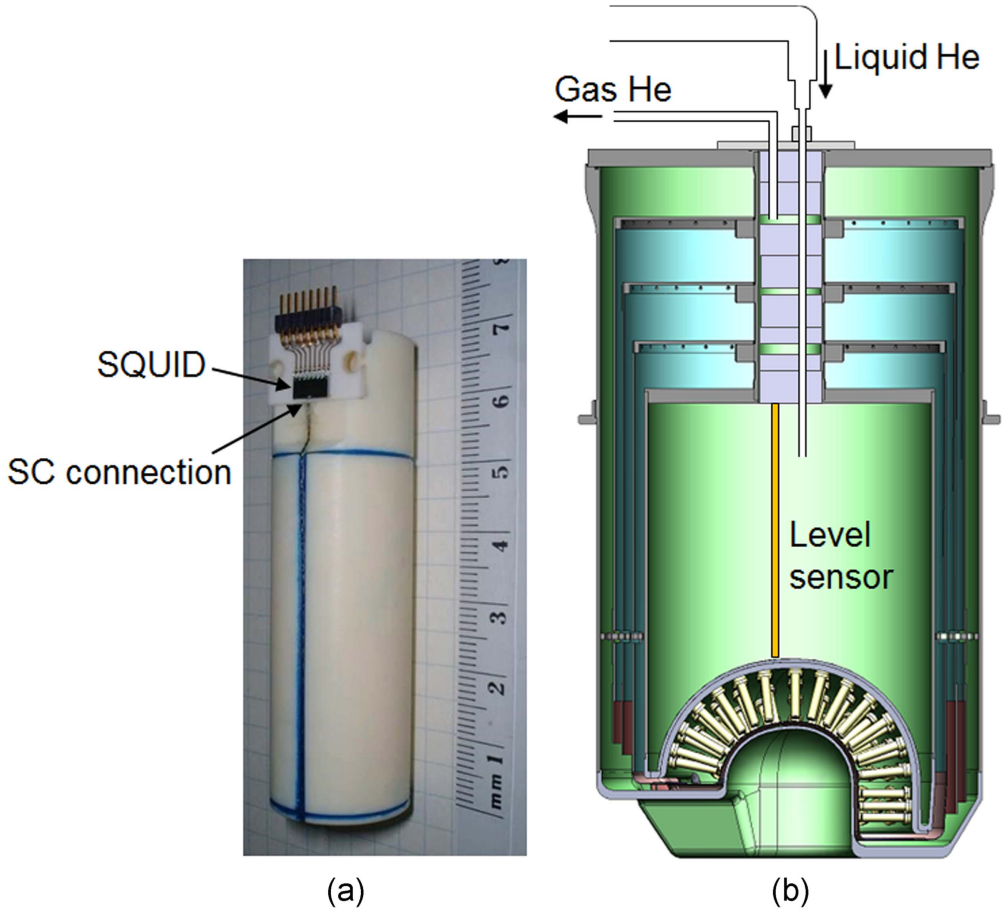

Figure 3. Gradiometer-in-vacuum MEG system. (a) Photo of a SQUID gradiometer having alumina bobbin for the pickup coil support and SQUID chip at the end of the bobbin. Superconductive (SC) connection was done by direct bonding of Nb wire between the pickup coil wires and input coil pads. (b) Schematic drawing of the dewar cross-section.

total of 150 bobbins are installed in our gradiometer-in-vacuum MEG system.

The SQUID sensor is a double-relaxation-oscillation SQUID having a large flux-to-voltage transfer of typically about 1 mV/Φ_0, with Φ_0 being the flux quantum [16, 17]. Thus, the contribution of the preamplifier input noise can be negligible in direct voltage readout mode. The flux-locked loop (FLL) circuit has DC bias current and direct voltage readout using two pairs of SSM2210 transistors as the preamplifier. For simplifying the SQUID electronics system, the FLL output was directly digitized and converted into optical signal and transmitted through optical fibers. The digitization is carried out at 2 kHz sampling rate per channel with 24-bit resolution [18].

3. Operation of the reliquefier MEG system

3.1. Reliquefaction characteristics

The test MEG dewar has reservoir capacity of 90 l and the boil-off rate was 13–14 l/day when it was in direct LHe cooling with weekly refill mode. First, the dewar was filled with LHe using the standard LHe transfer process. About 2 h after the LHe transfer, the vent line of the MEG dewar was connected to the reliquefier gas inlet port and then the transfer tube of the reliquefier was inserted into the MEG dewar. Care should be taken to purge the reliquefier chamber, gas inlet line, and transfer tube carefully with helium gas before connecting to the MEG dewar. Otherwise, icing of air can happen on the cold head surface of the cryocooler, resulting in deteriorated reliquefaction performance.

Figure 4 shows reliquefaction characteristics of the reliquefier-MEG system. For the safety of the dewar, a 5 psi relief valve is installed at the inlet port of the reliquefier so that the pressure of the chamber is at most 5 psi relative to atmospheric pressure. Based on the phase diagram of the helium, liquefaction can occur at 4.5 K when the pressure is 5.0 psi, resulting in rapid decrease of the pressure. From the start time of reliquefier operation, it took about 5 h for the cold head to cool down to 4.2 K. In about 12 h, the pressure becomes stabilized at around 1 psi. When the pressure decreased to below 0.9 psi, a heater at the cold head (second stage) is activated to heat some helium (liquid and/or gas), resulting in slight increase of pressure to 1.0–1.1 psi. In this way, the pressure is maintained near constant. The cooling power of the cryocooler (1.4 W with remote motor) is more than sufficient to liquefy the helium gas evaporated from the MEG dewar. Finally, the temperature is maintained at 4.06 K, with an average heating power of about 0.3 W.

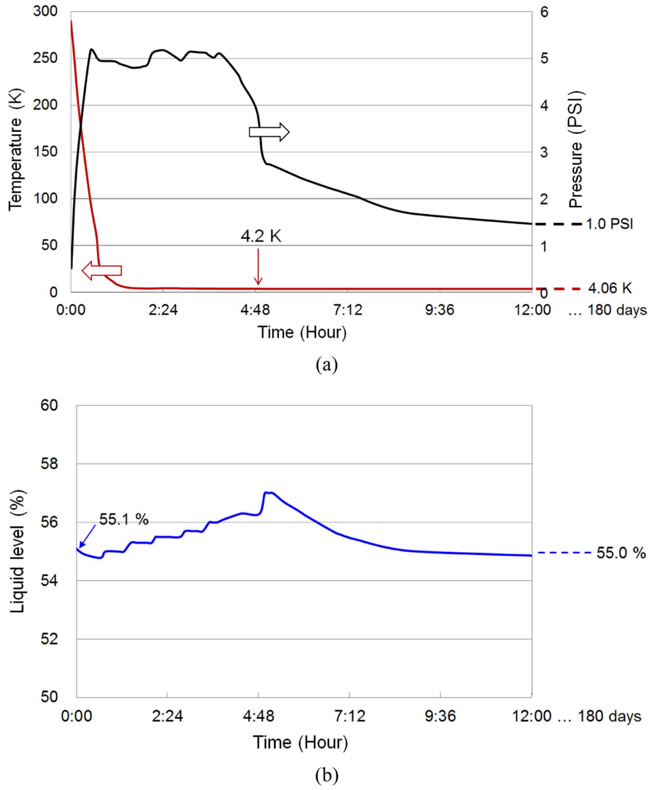

Figure 4. Reliquefaction characteristics of the reliquefier system. (a) Temperature and pressure change with cryocooler operating time. Temperature is measured at the second stage of the cold head and pressure is measured at the gas inlet port of the reliquefier chamber. Pressure is the relative pressure against the atmospheric pressure. (b) Change of LHe level with cryocooler operating time. For 180 days, the temperature, pressure, and liquid level are maintained at the steady-state values.

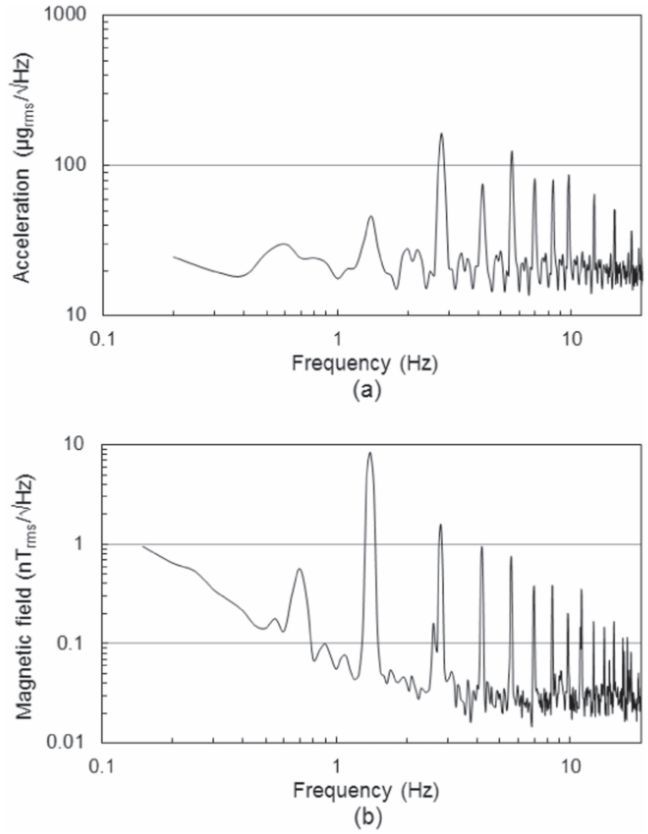

Figure 5. Vibration and magnetic noise on top of the pulse tube head. (a) Acceleration and (b) magnetic field noise.

3.2. Analysis of vibration and magnetic noise

Sources of magnetic noises measured by SQUID gradiometers inside the MSR can be divided into three major parts: (i) external environmental noises remaining inside the MSR due to insufficient shielding performance, (ii) magnetic field noise from the reliquefier system (compressor, rotary valve unit, and pulse tube), and (iii) vibration-induced noise with vibration energy coming from the reliquefier system. When the MEG system was operated with direct LHe cooling, there was no appreciable noise peaks below 10 Hz except for a weak vibration noise peak around 8 Hz. We measured and compared magnetic noise and vibration noise at several points: compressor, rotary valve unit, pulse tube top, and reliquefier bottom plate.

3.2.1. Compressor. When the accelerometer (homemade, having a sensitivity of 5 and 3 $\mu g_{\mathrm{rms}}/\sqrt{\mathrm{Hz}}$ at 1 and 10 Hz, respectively, with g being the acceleration (9.8 m s^{-2})) was fixed on top of the compressor, the main acceleration peaks were observed at 1.4, 5.2, and 7 Hz with amplitudes of 1.7, 3.6, and 1.8 $\mathrm{m}g_{\mathrm{rms}}/\sqrt{\mathrm{Hz}}$, respectively. Magnetic field noise was also measured using a three-axis fluxgate magnetometer at a 30 cm distance from the compressor front panel. The vertical component of the field is about 0.1 $\mathrm{nT}_{\mathrm{rms}}/\sqrt{\mathrm{Hz}}$ in the frequency range of 1–10 Hz. Considering this field noise and distance between the compressor and MSR wall (5.5 m), the compressor does not seem to be the source of noise measured inside the MSR.

3.2.2. Rotary valve unit. The rotary valve unit opens and closes periodically to flow the compressed high-pressure helium gas to the pulse tube. During this 1.4 Hz cycle, it generates vibration and transmits it to the pulse tube. When the accelerometer was fixed on the bottom of the rotary valve unit, periodic vibration peaks were observed at 1.4 Hz and its harmonics with peak amplitudes in the range of 2.7–4.6 $\mathrm{m}g_{\mathrm{rms}}/\sqrt{\mathrm{Hz}}$. The magnetic field noise was measured in between the rotary valve and the MSR wall, 20 cm from the rotary valve. It shows a high 0.7 Hz peak with amplitude of 13 $\mathrm{nT}_{\mathrm{rms}}/\sqrt{\mathrm{Hz}}$, as well as 1.4 Hz and its harmonics peaks with amplitudes in the range of 0.2–0.6 $\mathrm{nT}_{\mathrm{rms}}/\sqrt{\mathrm{Hz}}$.

3.2.3. Pulse tube head. The vibration measured on top of the pulse tube head, as shown in figure 5(a), is 20–30 times smaller than that measured at the bottom of the rotary valve. The magnetic field noise measured at the same point on top of the pulse tube shows noise peaks at nearly the same frequencies as the vibration peaks, as shown in figure 5(b). We can see that the vibration-induced magnetic field noise

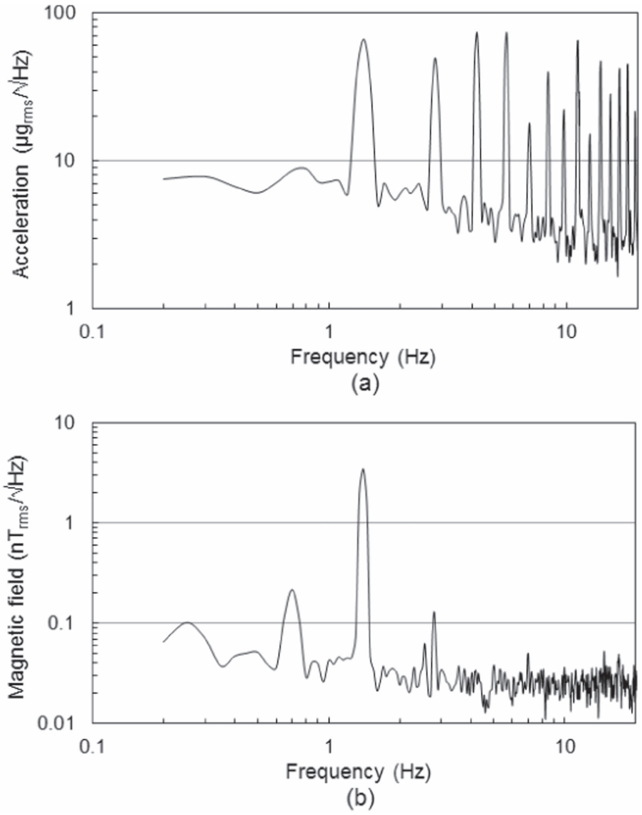

Figure 6. Vibration and magnetic noise on the bottom of the reliquefier chamber. (a) Acceleration and (b) magnetic field noise.

has a highest peak at 1.4 Hz, with decreased amplitudes at higher frequencies.

3.2.4. Reliquefier bottom plate. The vibration measured on the bottom plate of the reliquefier chamber shows two to three times smaller amplitudes than on top of the pulse tube head, and its magnitudes are in the 50–70 $\mu g_{rms}/\sqrt{\text{Hz}}$ range. As shown in figure 6(a), the vibration peaks are quite periodic at 1.4 Hz and its harmonics. Magnetic field noise measurements at the same point shows one main peak at 1.4 Hz and smaller peaks at 0.7 and 2.8 Hz, as shown in figure 6(b).

Vibration measured on the top of the dewar and on the floor of the MSR did not show any peaks, and the vibration level is under the noise level of the accelerometer.

4. Noise analysis of reliquefier MEG system

4.1. MEG system noise

For comparison, the average white noise level (at 100 Hz) of the system was 3 $\text{fT}_{rms}/\sqrt{\text{Hz}}$ when the MEG dewar was directly cooled by LHe three years ago, measured inside a moderately shielded room having a wall thickness of 20 cm and higher shielding factors. Figure 7 compares the MEG system noise in the present study depending on the operation status of the reliquefier system. The noise data are average of all the channels. Except for the vibration-induced peaks, the noise levels are nearly the same, with a white noise level of

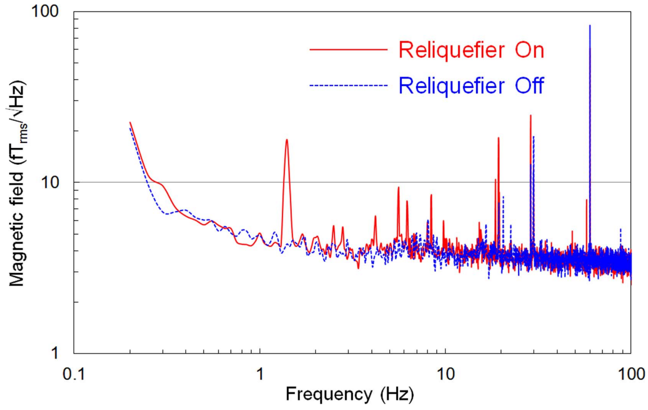

Figure 7. Comparison of magnetic field noise of the MEG system with the reliquefier turned on and off. The noise spectra were averaged over all the channels.

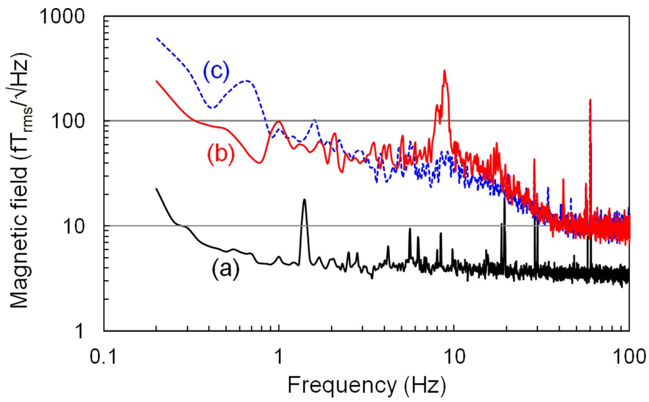

Figure 8. Comparison of magnetic field noise of the reliquefier MEG system with brain activity noises. (a) Without subject, (b) with subject and eyes closed, and (c) with subject and eyes open. All the noise spectra were averaged over all the channels.

3.5 $\text{fT}_{rms}/\sqrt{\text{Hz}}$, slightly higher than the directly cooled data measured in a better shielding condition. The average amplitude of the 1.4 Hz peak is 18 $\text{fT}_{rms}/\sqrt{\text{Hz}}$. The amplitude of the 1.4 Hz peak varies depending on the channels. Some channels show 1.4 Hz peak amplitude well below 10 $\text{fT}_{rms}/\sqrt{\text{Hz}}$. Though the 1.4 Hz peak amplitude is clearly greater than the white noise level, similar peaks can be observed even in MEG systems directly cooled with LHe. Vrba *et al* reported an MEG system noise data of first-order axial gradiometers with a baseline of 5 cm inside a moderately shielded room. The peak amplitude at 1.5 Hz is about 20 $\text{fT}/\sqrt{\text{Hz}}$ [19], similar to our peak value. Thus, the noise level of the present reliquefier MEG system is quite comparable to that of the directly cooled system. In another low-noise MEG system using the reliquefier-based cooling, about 20 $\text{fT}/\sqrt{\text{Hz}}$ of the average peak value was observed at 3.4 Hz, with first-order axial gradiometers of 5 cm baseline [8].

4.2. Comparison with brain noise

The empty room noise of the reliquefier MEG system is compared with the brain noise. Figure 8 shows reliquefier-MEG noise and whole-head brain noise with eyes closed and

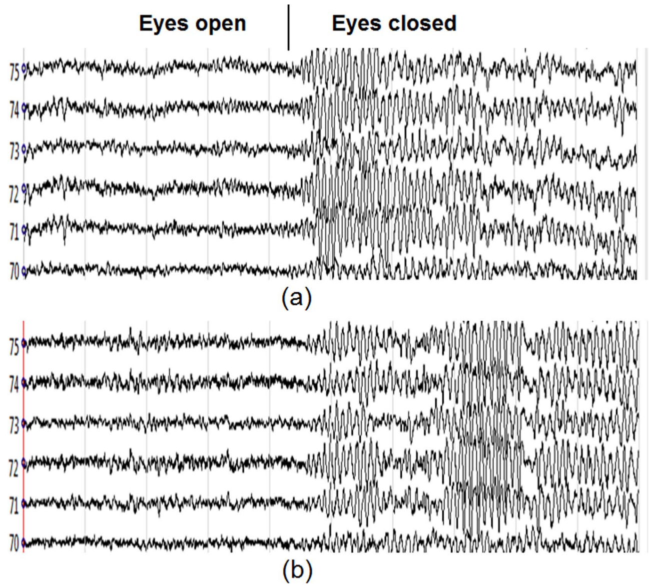

Figure 9. Comparison of brain activity with reliquefier on and off. (a) Reliquefier turned off, and (b) reliquefier turned on. Analog low-pass filtering (cut-off frequency 234 Hz) and digital baseline correction were used.

open. Compared with the spontaneous brain signal, which is considered to be brain noise, the noise level of the reliquefier MEG system is about 10 times lower. That is, the spontaneous brain signal has signal-to-noise ratio of about 10 at each frequency up to about 20 Hz, which corresponds to the main frequency range of spontaneous brain activity. For 1.4 Hz, however, the brain noise level is about three times greater than the MEG system noise.

4.3. MEG measurement

To test the feasibility of the system in measuring MEG signals, spontaneous brain activities were measured and compared for different reliquefier operation status. The subject was lying on the floor of the MSR, with the head straight up under the MEG helmet, and opened and closed his eyes alternatively every 10 s.

Figure 9 shows time series of some MEG channels in the occipital area of the head during the period when the eye condition was switched from open to closed. Analog low-pass filtering was applied with a cut-off frequency of 234 Hz, but no digital filtering was applied except a baseline correction for removing DC drift due to a breathing artifact. We can clearly see the alpha rhythm signal in the reliquefier-on state, with signal quality nearly the same as the reliquefier-off state.

5. Discussion and conclusion

The reliquefier-based MEG system was shown to keep the initial LHe level for six months without any drop in the liquid level. Considering the pressure and temperature change, the cooling power of the present cryocooler seems more than sufficient. Even with a very small downslope angle of 1° or nearly horizontal transfer line, transfer of LHe was done efficiently. Since the closed-loop lines are short and all made of stainless steel tubes, the possibility of contamination from the lines is extremely low, meaning that long-term operation of the LHe recycling is possible. Comparing the noise spectra with reliquefier on and off, dominant noise peak in the reliquefier-on state occurrs at 1.4 Hz. Though this peak is clearly visible, peaks of similar magnitude were also reported in MEG systems using conventional direct LHe cooling, meaning that the reliquefier-induced 1.4 Hz peak is acceptable. The low amplitude of the 1.4 Hz peak seems to be attributable to tight mounting structure of the gradiometer-in-vacuum configuration, so that vibrations from the transfer tube and gas turbulence are minimized.

The MSR used in this experiment is thinner than the standard MSR thickness for MEG measurements. Therefore, the internal DC or AC field and its gradient can be greater than usual. If the operation of the present MEG system was done inside a thicker MSR, the vibration-induced noise could be smaller.

In the present installation configuration, the space around the MSR is not sufficient in that the reliquefier and rotary valve unit has to be installed parallel and in close proximity to the MSR wall. Therefore, the penetration of both the vibration and reliquefier-induced external magnetic noise into the MSR is thought to be greater. In addition, the total length of the transfer tube is only 1.3 m. For further reduction of the noise, the rotary valve unit can be extended out perpendicular to the MSR wall from the penetration to increase the distance, and the transfer tube length can be increased. Cylindrical magnetic shields around the rotary valve unit and the pulse tube head, and additional local suppression of vibrations, will reduce the vibration-induced noise peaks. Furthermore, installation of reference channels and signal processing using software gradiometers or adaptive filtering can be applied to reduce the 1.4 Hz peak.

Though further reduction of the vibration peaks can be done using these realistic approaches, the present system by itself shows overall noise performance good enough for low-noise MEG measurements.

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