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NEW TYPE OF MAGNETIC LOW-NOISE GLASS FIBER REINFORCED PLASTIC CRYOSTATS FOR MAGNETOCARDIOGRAPHY OF THE HUMAN HEART

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ABSTRACT

Magnetocardiography (MCG) is an innovative method of non-invasive diagnosis that can record the magnetic activity of the human body without contact. The magnetic fields of the body are caused by the muscle tissues activity inside the body. The extremely weak magnetic field generated by the human heart, in the range of 10^{-9} Tesla is detected by highly sensitive SQUID sensors. To reduce the external disturbing magnetic noise (e.g. the influence of the earth's magnetic field), the examination must be performed in a shielding chamber. The sensors are cooled down to a temperature of 4.2 Kelvin (-269°C) using liquid helium, which puts them into the superconducting state.

In the publication, we present a new type of magnetic low-noise glass fiber reinforced plastic (GFRP) cryostat with a closed cooling circuit, which is able to re-liquefy evaporating helium directly in the cryostat via an integrated cold head of a cryocooler. In addition, the heat input to the cryostat has been minimized to such an extent that the power of the cryocooler is sufficient to reliquefy evaporating helium from a collection bladder after a short case of cryocooler downtime. In order to be able to perform the examination in a position that is comfortable for the patient, the MCG can be set and operated at an angle range between 0 and 45 degrees. The development aims to provide a much more accurate examination of the human heart, replacing the current state of the art in cardiac examination (the echocardiogram ECG) for clinical use.

Keywords: Magnetocardiography, Human heart, Cryostat, SQUID, Magnetic low noise, Glass fiber reinforced plastic

1. INTRODUCTION

Medical facilities with a cardiological focus (hospitals, medical centres), medical facilities without a cardiological focus (emergency departments, general practitioners) as well as non-medical facilities (competitive sports centers, recreational sports centers) address basic and specific questions about cardiac function and heart disease in humans. Consequentially, the state of the art in cardiac diagnostics has to be improved to making it accessible to a wider general public. For this, novel measurement and examination methods are needed.

Magnetocardiography (MCG) as a young and very promising method in non-invasive cardiac diagnostics records the magnetic activity of the human body without contact. The magnetic field of the heart muscle changes during the heartbeat. The change can be visualized by measuring the magnetic activity. The MCG allows visualization of the magnetic field distribution at different times of the heartbeat. The main difference to other diagnostic imaging techniques is that magnetocardiography visualizes the function of the heart activity and does not represent its shape change during beating.

This publication presents the state of development achieved so far of an adjustable and magnetic low noise cryostat for magnetocardiography made of GFRP with closed cooling circuit. Statements on the arrangement and mounting of the highly sensitive SQUID sensor technology in the cryostat are made and initial results on the cold and tilt tests are shown.

2. MAIN SECTION

The origin of the development idea was the combination of a purely evaporating bath cryostat with a cryocooler cold head in order to be able to build up a closed cooling circuit within the cryostat. Figure 1 shows a purely evaporative bath cryostat which can become a closed-loop cryostat by using a cryocooler cold head directly in the neck tube of the cryostat.

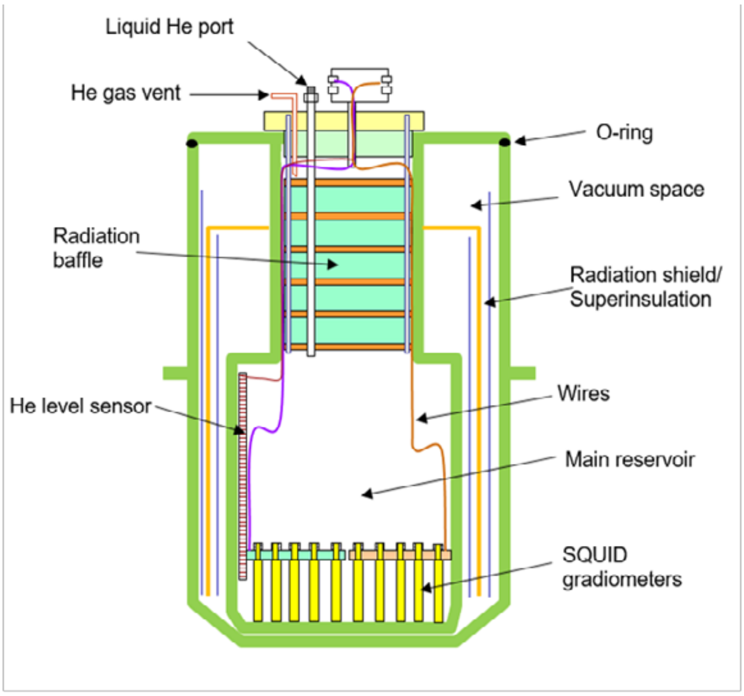

Figure 1: Schematic of a purely evaporative bath cryostat for magnetocardiography

A closed cooling circuit would significantly increase the practical handling of the cryostat, because regular refilling of the cryostat with liquid helium would no longer be necessary. A key difference between a purely evaporative bath cryostat and a closed-loop cryostat is the way in which the introduced heat load on the cryostat can be dissipated. The heat radiation load applied to the cryostat must be dissipated mostly through the radiation shield. This radiation load absorbed by the radiation shield must be dissipated via the cryocooler in a cryostat with a closed cooling circuit. After the initial rough design definition based on a determination of the number of SQUID sensors and the thermal balancing of the cryostat, the solution to the question "What specification must the cryocooler satisfy in terms of the performance parameters and the adaptation possibilities of the cryostat neck tube?" has significantly influenced the development work.

2.1. GFRP cryostat design

The dimensions of the cryostat were basically determined by the number and size of the SQUID sensors to be included (Kade et al., 2018). According to a first estimation, the arrangement of the SQUID sensors is to be provided in a round cylinder of 290 mm inside diameter. The sensors were divided equally into quadrants. In each quadrant, four sensors were installed in the z-direction and twelve sensors in the x- and y-directions. The number of sensors specified for the cryostat (see Figure 2) is fixed to the bottom of the cryostat via four separate sensor holder plates. This allows the sensors to hold the position and orientation stable when the cryostat is tilted.

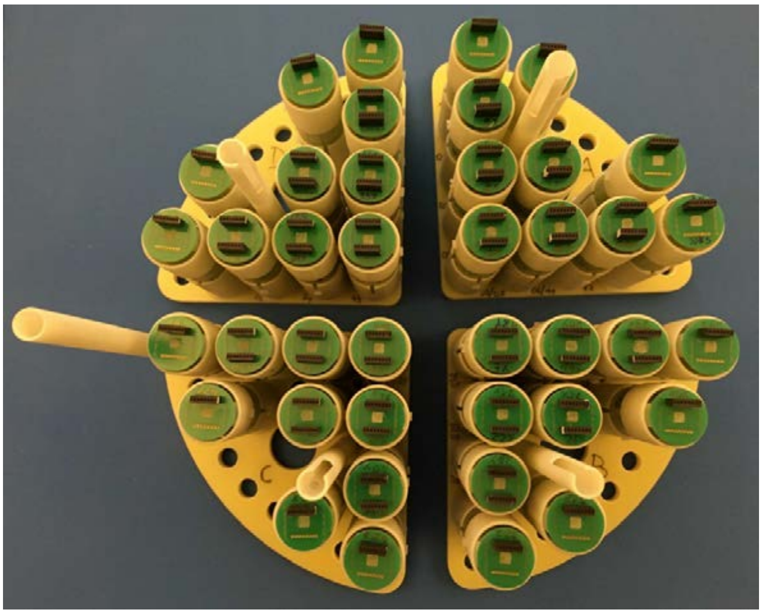

Figure 2: SQUID Sensor arrangement and mounting (© Biomagnetik Park AG)

Based on the determination of the number and arrangement of the SQUID sensors, the dimensions of the cryostat could be defined (with a vessel length of 565 mm and a neck tube length of 475 mm), calculated and heat balanced. With the calculated theoretical heat load (0.2 W), it was possible to select a cryocooler suitable for the performance and with a low vibration level. Selected was a two-stage pulse tube cryocooler with a relatively small cold head geometry (see Figure 3) and a cooling capacity of 35 W at 45 K (1st stage) and 0.9 W at 4.2 K (2nd stage) with < 90 min. cooldown time.

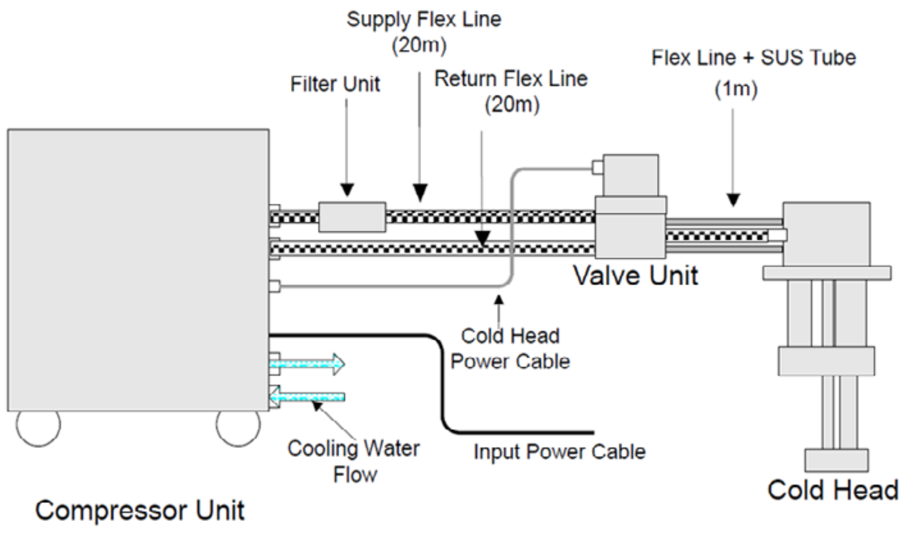

Figure 3: Schematic of a Pulse tube cryocooler from the company SHI (2013)

Further design work consisted of the helium-tight connection of the first stage of the cryocooler cold head with the radiation shield. The connection was created via a quite solid copper plate (see Figure 4 right top). The copper connection plate was sealed in the neck tube at the top and bottom with an indium round cord. In addition to contacting the first cold head stage, feedthroughs were created through the copper plate for helium lifters and cryostat measurement cables and SQUID sensor cables.

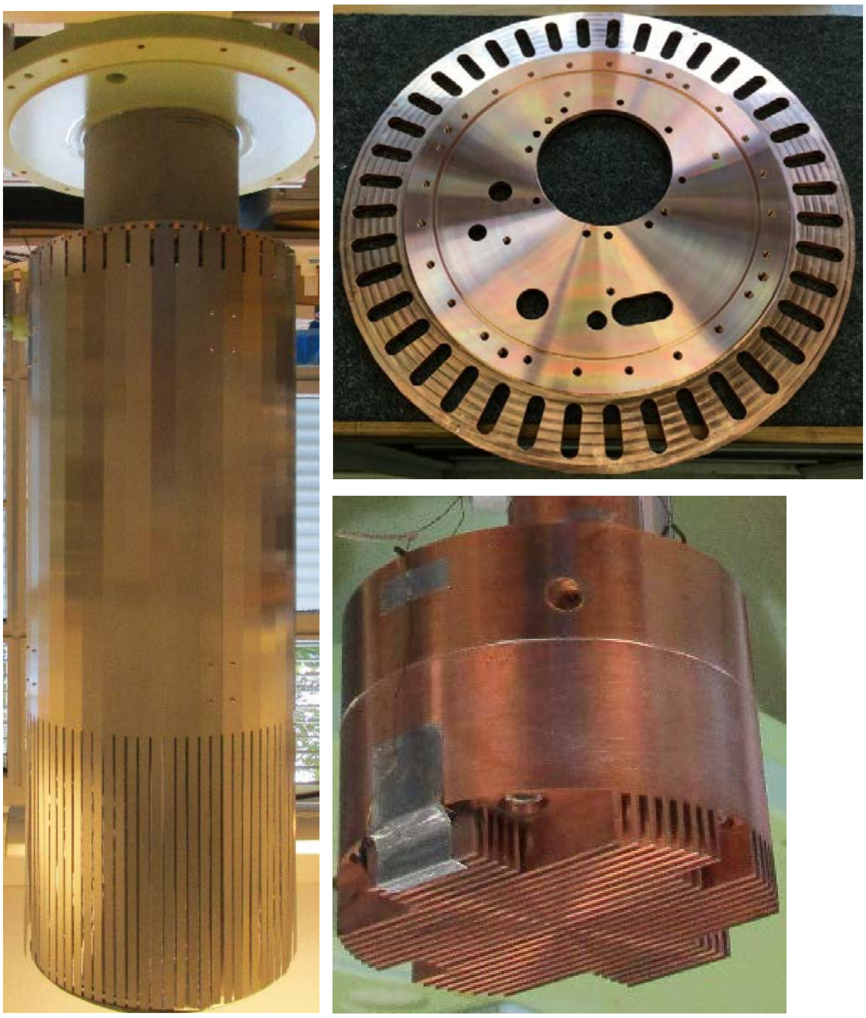

Figure 4: (left) Radiation shield without multi-layer insulation L 860 mm; (right top) copper connection plate Ø 344 mm; (right bottom) condenser Ø 92 mm mounted on the second stage of the cryocooler

The further construction of the radiation shield dealt with the solution of the question between the use of well thermally conductive and at the same time of magnetic low-noise material in the area of the SQUID sensors. The thermal shield is made mainly of aluminium, with slits in the jacket area of the SQUID sensors to prevent ring currents (see Figure 4 left). Different non-magnetic materials were tested for use in the bottom area (Kade et al., 2014). As a result, however, the shield was kept open to minimise the influence on the measurement. The resulting slightly increased evaporation rate was accepted. To optimize the helium liquefaction performance at the second cold head stage a special copper heat exchanger was designed (see Figure 4 right bottom) (Muley et al., 2017). It optimizes the gas flow and can be mounted with the same diameter (Ø 92 mm) directly on the second stage. Figure 4 right bottom shows also the fin geometry of the heat exchanger, which was realized as a result of the theoretically compared variants.

It was then of crucial importance to make optimum use of the space still available in the neck tube in order to be able to place the SQUID sensor cables, the cryostat measurement technology and the connections for the helium lifter and helium exhaust gas. For reasons of access to assembling, the SQUID sensor cables have been designed to be re-connectable at the level of the first cold head stage. The number of PINs and the PIN assignment of the SQUID were specified by its manufacturer. The PCB design was carried out in close coordination with the sensor manufacturer. The cables fed through the cryostat lid were placed on two external connector boxes (see Figure 5 left). Afterwards, only the cable harness that had been routed through the cryostat lid had to be glued helium-tight.

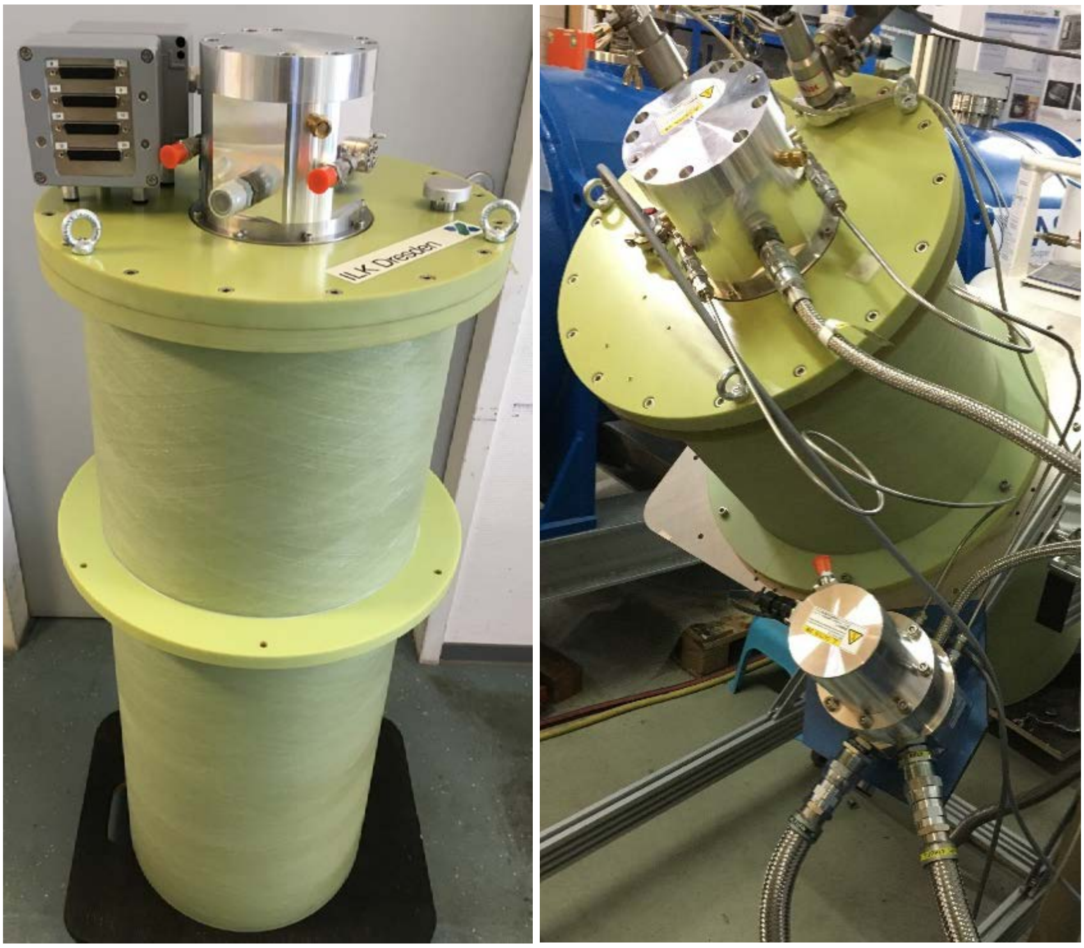

Figure 5: (Left) Side view of the LHe cryostat for magnetocardiography with the cold head mounted in the centre of the lid and the SQUID sensor connection boxes on the left side of the lid. (Right) Cryostat tilted at 45 degrees in cold condition (without SQUID's).

2.2. Cold and tilt tests

The cryocooler was switched on after the initial filling of the cryostat with liquid helium. Following the cool down time of the cryocooler a liquefaction capacity could be measured at the cryostat. Using the measured gas supply from an external bladder (see Table 1 – Gas meter [m³]), it was possible to determine a liquefaction capacity of 0.25 l/h liquid helium in the vertical state of the cryostat with a cooling capacity of 1.8 W at the second stage (latent and sensitive part). The radiation baffle design in the cryostat and the mounted condenser even improved the performance parameter specified by the manufacturer (0.9 W at the 2nd stage).

Table 1: Liquefaction capacity / cooling capacity (cryocooler switched on)

date	time	Liquefaction capacity (l/h)	Cooling capacity (W)	Gas meter [m³]
17.11.2020	08:21			0.159
17.11.2020	08:51	176 (GHe) ➔ 0,25 (LHe)	1,8 (2nd)	0.247

With the liquid helium-filled cryostat and the cryocooler in operation, the cryostat was carefully moved 45 degrees in the intended tilt plane (see Figure 5 right). When the cryostat was tilted, the internal construction supported itself on the vacuum vessel and thereby relieved the cryostat neck construction. This tilt position corresponding to the maximum possible displacement was hold for approx. 20 min. This time window corresponds to a measurement on the patient. After the 20 min, the cryostat was moved back to the vertical position. By monitoring the vacuum pressure, no leakage was observed during this tilting movement. Tilting the cryostat by 45 degrees destroyed the helium gas stratification. However, the helium level did not decrease significantly during tilting. The liquefaction performance began with the recreation of the helium gas stratification in the vertical state of the cryostat. In conclusion of the previous test phase, the rate of evaporation of the cryostat was evaluated with the cryocooler switched off. The rate of evaporation of this cryostat is not linear and depends on the temperature of the switched-off cryocooler and the amount of liquid helium in the cryostat. In the test described in Table 2, the cryocooler still had a temperature of about 4 K at the beginning of the measurement and the level in the cryostat was 28 cm. Approximately 40 hours later, a level of 10 cm could still be measured during this test. This resulted in an evaporation rate of 217 l/h helium gas and a heat load of 0.23 W. This corresponds approximately to the calculated theoretical value of 0.2 W heat load.

Table 2: Rate of evaporation / heat load (cryocooler switched off)

date	time	rate of evaporation (l/h)	Heat load (W)	level [cm] (Liter)
17.11.2020	16:20			28 (19 Liter)
19.11.2020	08:15	217 (GHe) → 0,31 (LHe)	0,23	10 (6 Liter)

3. CONCLUSIONS

A new type of magnetic low-noise glass fiber reinforced plastic (GFRP) cryostat for magnetocardiography has been developed to expand and improve the diagnostics of the human heart. The cryostat has a closed cooling circuit, which is able to re-liquefy evaporating helium directly in the cryostat via an integrated cold head of a cryocooler. A closed cooling circuit increases significantly the practical handling of the cryostat, because regular refilling of the cryostat with liquid helium would no longer be necessary. The dimensions of the cryostat were basically determined by the 64 special SQUID sensors to be included, which were placed equally on a cylindrical bottom. A suitable two stage cryocooler was selected for the performance, with a low vibration level and a small cold head geometry. The thermal shield made of aluminium was helium-tight connected with the first stage of the cryocooler via a solid copper plate. The thermal shield was kept open at the bottom to minimise the influence on the measurement. To optimize the helium liquefaction performance at the second cold head stage, a special copper heat exchanger was used.

Cold and tilt tests have been carried out with the cryostat. It was possible to determine a liquefaction capacity of 0.25 l/h liquid helium in the vertical state of the cryostat. The cryostat can moved 45 degrees in the intended tilt plane. This tilt position corresponding to the maximum possible displacement. By monitoring the vacuum pressure, no leakage was observed during the tilting movement. Further measurements on the cold and tilting behavior and the function and influence of the SQUID sensors on the cryostat behavior are still outstanding.

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NOMENCLATURE

MCG	magnetocardiography	SQUID	superconducting quantum interference device
ECG	echocardiogram	GFRP	glass fiber reinforced plastic
l/h	liters per hour		

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