Operation of a High-T_c DC-SQUID-Gradiometer on a Non-Metallic Pulse Tube Refrigerator

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***Abstract* - A planar high-T_c DC-SQUID gradiometer has been operated with a specially developed low-noise pulse tube refrigerator. The cold finger of the refrigerator consists only of non-metallic and non-magnetic materials. During the operation of both the sensor and the refrigerator, the noise generated by the cryocooler is below the noise level of the SQUID-gradiometer. We demonstrate the potential of this non-metallic pulse tube refrigerator by measuring the magnetic field originating from a human heart (magnetocardiogram), without additional suppression of the intrinsic refrigerator noise.**

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I. INTRODUCTION

Sensors based on high transition temperature (T_c) superconductivity have advanced considerably and many possible applications have been demonstrated, particularly in the field of superconducting quantum interference devices (SQUIDs) [1-6]. However, superconductivity requires cooling and for high-T_c SQUID sensors additional requirements like low vibration, low temperature fluctuations, and extremely low magnetic disturbances arise for the source of refrigeration. Commercially available cryocoolers generate significant interferences which affect directly the operation of the SQUID sensor [7]. These disturbances are vibrations in a residual (earth and laboratory) magnetic field, temperature fluctuations and magnetic interferences from the cryocooler [8].

The pulse tube cryocooler (PTC) [9, 10] is one type of possible refrigerators that has the potential to avoid some of those disturbances because it has no moving part in the cold head, in contrast to conventional cryocoolers like the Stirling cooler. Without these moving parts pulse tube cryocoolers have a relatively simple design and low level of vibrations. The general advantages of a pulse tube cryocooler for high-T_c superconducting devices were discussed in [11-14].

II. EXPERIMENTAL SET-UP

A low-noise refrigerator for cooling highly sensitive SQUID sensors achieves low temperatures with the SQUID mounted directly on the cold heat exchanger (cold finger) of the cooler. However, it is necessary that the cold finger consists only of non-metallic and non-magnetic materials in order to avoid magnetic interferences from motion in enviromental fields, as well as induction of eddy currents or existence of any remnant magnetization [15].

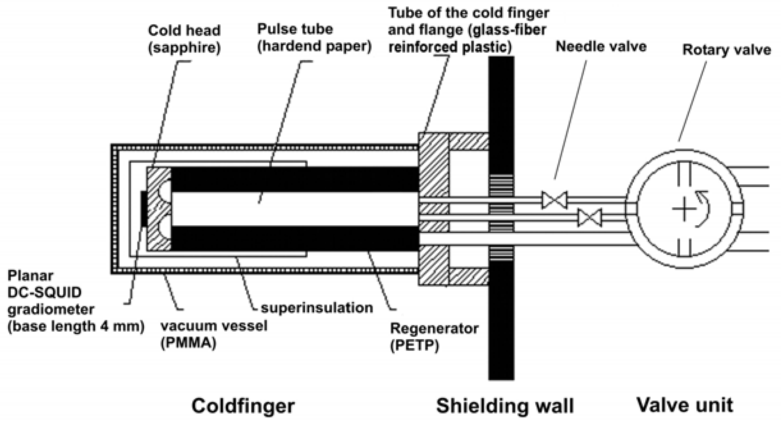

Fig 1. Scheme of the developed split configuration of a single stage pulse refrigerator using a non-magnetic and electrical insulating coldfinger.

We started the design with our four-valve version of a PTC [16]. First, we spatially separated the electrically driven rotary valve from the cold finger in order to reduce the interferences from that valve unit [17]. The main problem was to find an adequate regenerator material, which does not reduce the efficiency of the refrigerator [18]. Gap regeneration is not possible because PTC have an extremely high mass flow rate of the working fluid in contrast to Stirling coolers with a solid piston. Zimmermann *et al*. built a plastic Stirling cooler with gap regeneration for low-T_c SQUIDs [19]. Their operating parameter led to a 125 times lower mass flow rate than in our PTC. Considering only non-metallic materials that have a sufficient heat capacity, we developed a new regenerator with polyamide 6.6 and polyethylene terephtalate mesh screens [18].

We built a new split pulse tube refrigerator with a totally non-metallic cold finger. The cold finger has a coaxial configuration with the regenerator around the pulse tube to obtain a very low level of vibrations. The tubes and flanges of the cold finger are made of fiber-reinforced plastics. Sapphire was used for the cold heat exchanger due to its high thermal conductivity at temperatures around 50 K. Further details on materials, construction and properties of this cryocooler are given in [18].

Figure 2 shows the cooling power versus temperature of the developed pulse tube cryocooler with the non-metallic cold finger. This measurement was done with an optimized low pressure difference (0.3 MPa) using one layer of super insulation foil to avoid radiation losses. A copper instead of a sapphire heat exchanger was used for technical reasons (integrated heater to determine the cooling power). The cooler is able to reach temperatures down to 40 K. The SQUID-sensor and its lines require a cooling power below 100 mW. Thus it is possible to cool the SQUID in the temperature region around 50 K where no liquid cryogen is present, and where the SQUID parameters are more favorable than at the boiling point of liquid nitrogen.

The spectra of temperature fluctuations and the vibrations exhibit narrow peaks at the working frequency of the cooler (4 Hz) and decreasing peaks at their harmonics. The peak value of the temperature fluctuation is 1 mK. The measured mechanical vibrations in transversal direction are in the range of 0.25 μm, which corresponds to an angle of $6*10^{-5}$ degrees between the base and the top of the pulse tube [18].

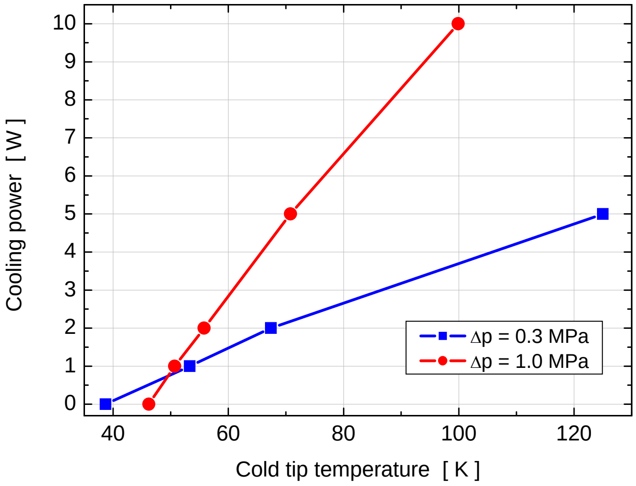

Fig 2. Cooling power of the non-metallic pulse tube refrigerator versus the temperature at two pressure differences of the working fluid.

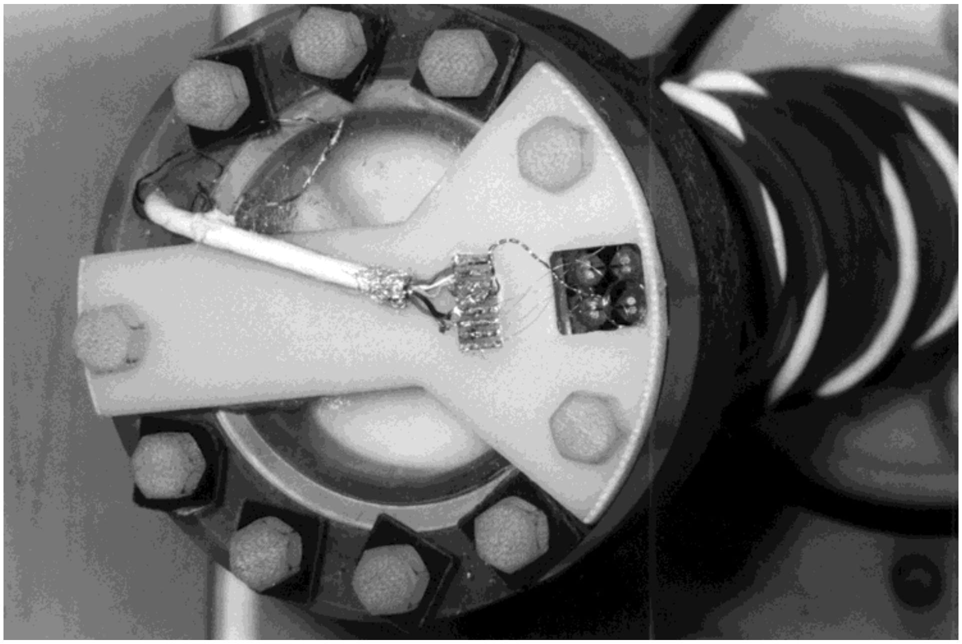

Fig 3. Non-metallic cold finger of a pulse tube cryocooler with two planar SQUID-gradiometers mounted on the cold heat exchanger. The white polymeric regenerator material can also be seen behind the sapphire cold heat exchanger (diameter: 68 mm).

Figure 3 shows two mounted planar SQUID gradiometers on the cold heat exchanger of the non-metallic cold finger. Our planar first-order direct current SQUID gradiometers, which are made from a single $YBa_2Cu_3O_{7-x}$ thin film on $SrTiO_3$ bicrystal substrates with a baseline of 4 mm and an effective area of 0.2 mm^2, are described in references [20-22]. For the preliminary tests, the cold finger was fixed on a wall inside a magnetically shielded room, so that it was orientated horizontally. The rotary valve and the compressor were placed outside the room. The lowest temperature we achieved with this set-up was around 70 K with the SQUID-gradiometer mounted in the cold heat exchanger. This temperature limit is due to the connection loss [23] in the pulse tube when the inclination angle is not zero.

III. EXPERIMENTAL RESULTS

Figure 4 shows the noise spectrum of the gradiometer during operation of the pulse tube cryocooler. The working frequency of the cryocooler is 4 Hz, so we expected the main interferences to be at 4 Hz and higher harmonics, but the results of the measurements show no additional interferences caused by the cryocooler.

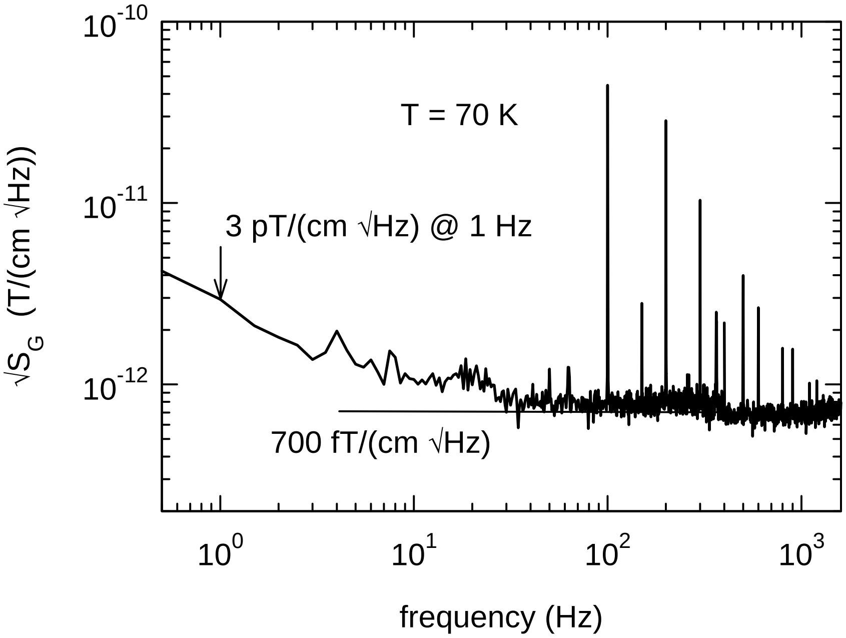

Fig 4. Noise of the SQUID-gradiometer which is mounted on the cold heat exchanger of the non-metallic pulse tube cryocooler during operation of the refrigerator.

The white noise level is below that at 77K, because of the reduced working temperature. When the pressure difference was increased, a peak at 4 Hz appeared in the noise spectrum, because the vibrations and the temperature fluctuations increased with increasing pressure differences [12]. The low pressure differences have an additional advantage of providing lower cooling temperatures. The refrigerator-cooled gradiometer has a white noise level of 0.7 pT/(cm $Hz^{1/2}$), and noise of 3 pT/(cm $Hz^{1/2}$) at 1 Hz. It is thus able to detect the magnetic flux density B originating from a human heart, without the necessity to separate the signal from the heart from the disturbed signal of the cooler.

For heart signal detection, a test person was sitting close to the cold finger. Despite this not optimized arrangement a magnetocardiogram (MCG) could be recorded in real-time without any signal processing to separate disturbances due to the cryocooler, see Figure 5.

The cardiac signal was averaged using the electrocardiogram as a trigger in order to improve the signal-to-noise ratio. An example is shown in Figure 6.

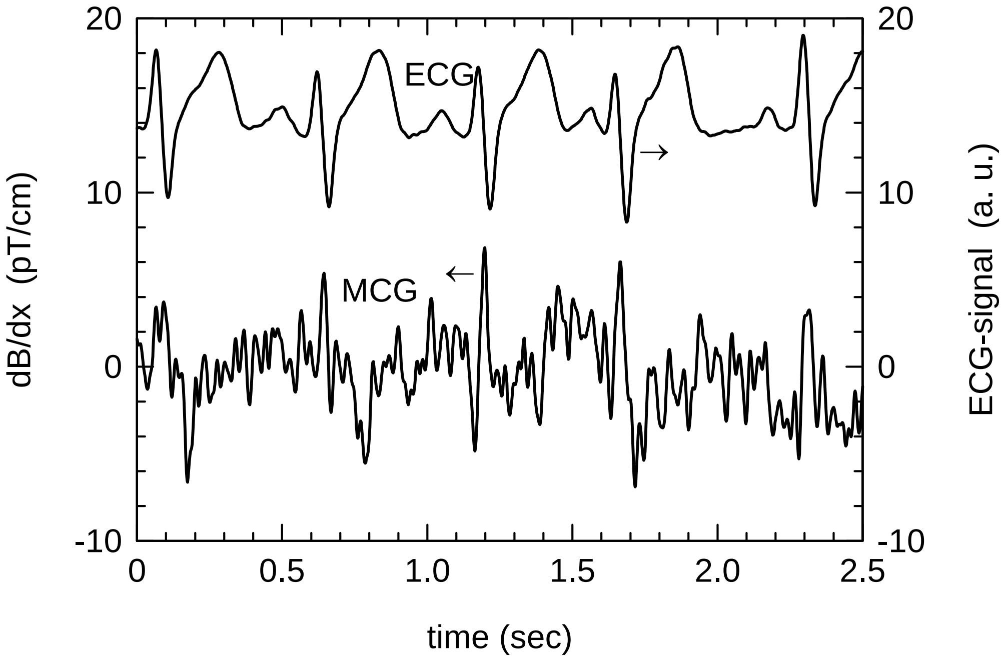

Fig 5. Magnetocardiogram recorded by a refrigerator-cooled SQUID gradiometer without filtering out signals from the cooler; an electrocardiogram was recorded simultaneously.

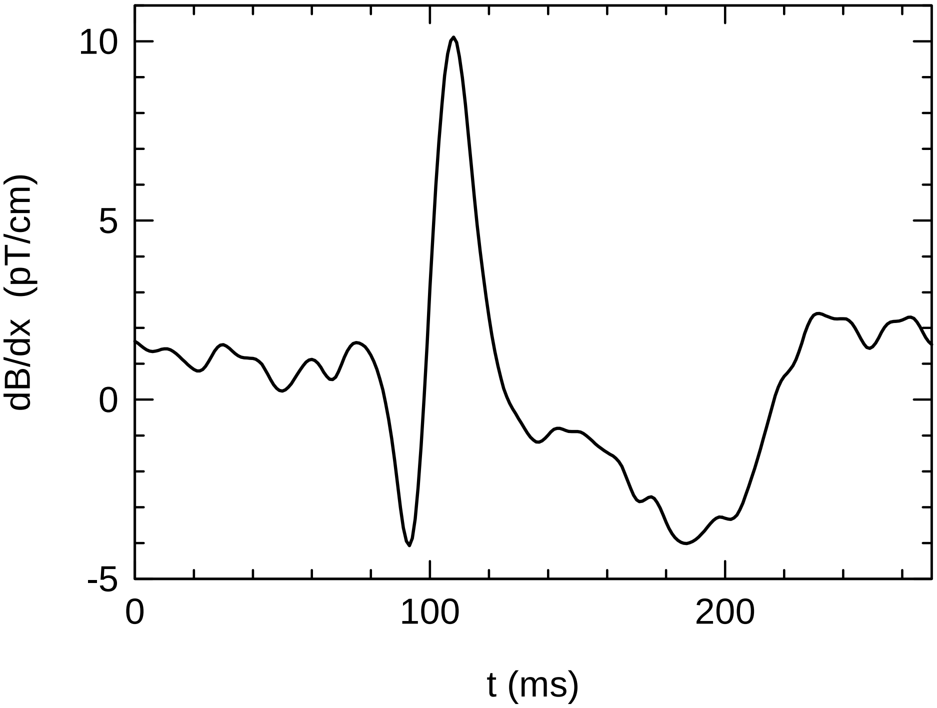

Fig 6. Magnetocardiogram obtained by a refrigerator-cooled SQUID gradiometer without filtering out signals from the cooler, is more than adequate but averaged 231 times.

IV. CONCLUSIONS

The cooling power of approximately 2.5 W at liquid nitrogen temperatures is more than adequate for high-T_c SQUID applications. These investigations demonstrate the applicability of our non-metallic pulse tube cryocooler for direct cooling of high-T_c SQUID gradiometers. The measured noise characteristics of the sensor demonstrate that the operating pulse tube refrigerator does not increase the noise level of the used SQUID sensor if the pressure difference is sufficiently low. As an example, we detected a human magnetocardiogram while the refrigerator was running. We could show that this new type of pulse tube cooler can be successfully used for low-noise sensors applications.

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