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CRYOSTAT FOR THE CRYOGENIC CURRENT COMPARATOR

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ABSTRACT

For the non-destructive measurement of electric particle beam currents below the detection threshold of standard beam diagnostics in the beamlines and storage rings of FAIR, the so-called Cryogenic Current Comparator (CCC) will be used. In a joint effort between ILK Dresden and GSI Darmstadt a beamline cryostat for the CCC has been developed.

The CCC monitor uses a highly sensitive SQUID magnetometer to detect the magnetic field of the ion beam in order to obtain DC beam currents. SQUIDs demand a very stable operating environment to achieve good measurements. Therefore, the custom cryostat uses an exhaust-cooled copper shield to avoid vibrations that would come from an additional cold-head for shield cooling. Moreover, it was designed for minimum heat load to avoid temperature and pressure fluctuations due to boil-off effects. The temperature distribution is monitored on all major components of the cryostat. The operating time is prolonged by a helium liquefier with a capacity of 15 l/day. This value corresponds to the measured evaporation rate without liquefier. The final goal is to run cryostat and liquefier as a closed standalone system. Concerning the mechanical design, the new cryostat was built for efficient access to the detector and for the use of detectors of different sizes. It is installed at the UHV-beamline of the low-energy storage ring CRYRING at GSI for test operation and for support of the experimental program.

This publication shows several steps of the development of the LHe cryostat, the thermal shield, the vacuum chamber and the interaction of the cryostat with the external re-liquefaction in a closed circuit. Finally, details about the cryogenic setup at CRYRING and first measurement results of the CCC monitor are presented.

Keywords: CCC, Beam Instrumentation, Storage Rings, Cryostat, Liquid Helium, SQUID, Liquefaction, Gas Cooling.

1. INTRODUCTION

Sensitive magnetic measurements require equipment of extremely low magnetic noise. Especially the accuracy of SQUIDs, used to characterize and measure magnetic fields, is limited by the magnetic noise of the surrounding materials. In particular, the superconductive state emerges after cooling below the critical temperature (Tc), which depends on the strength of the exterior magnetic field. Therefore, the cryostat surrounding the SQUID is the first line of defence against not only temperature and pressure effects or mechanical vibrations but also against electromagnetic interference. Thus, the materials and cooling methods have to be selected specifically for their potential noise contribution (e.g. magnetic properties). Although, the CCC uses a magnetic field selector that surrounds the SQUID and strongly attenuates stray fields, local magnetic materials will have a significant effect.

Refrigeration can either be achieved by cryocoolers or by using cryogenic liquids. In this application both, a sufficient cooling power and a good thermal stability are important factors. This is supported by measurements at GSI that have shown that small variations in temperature have a significant effect on the detector signal (33.5 nA/mK compared to a desired resolution below nA) [1]. In addition, the installation as part of a storage ring poses additional requirements to the cryostat. The rather large UHV beamline with a diameter of 150 mm needs to be incorporated and, because of limited access, the cold operating time has to be maximized. A very similar effort was made for the CCC at CERN but with several different design decisions [2]. Overall, every application has different requirements that all need to be met for successful operation.

2. MAIN SECTION

2.1. Development of CCC-Cryostat

2.1.1. Vacuum vessel

To save weight, the outside of the cryostat was made of aluminium plates. The plates are arranged so that the cryostat is accessible from all sides, see Figure 1.

The footprint of the cryostat is 848 × 848 mm², the height is 1744 mm. The bottom plate of the isolation vacuum chamber is fixed and welded to the frame. The top plate can be lifted upwards while the complete inner structure is attached to it by titanium rods.

For the integration in the GSI beamline the cryostat is equipped with two special DN150 CF flanges. For the bake out procedure of the UHV beamline these two flanges have channels for water cooling, see Figure 2.

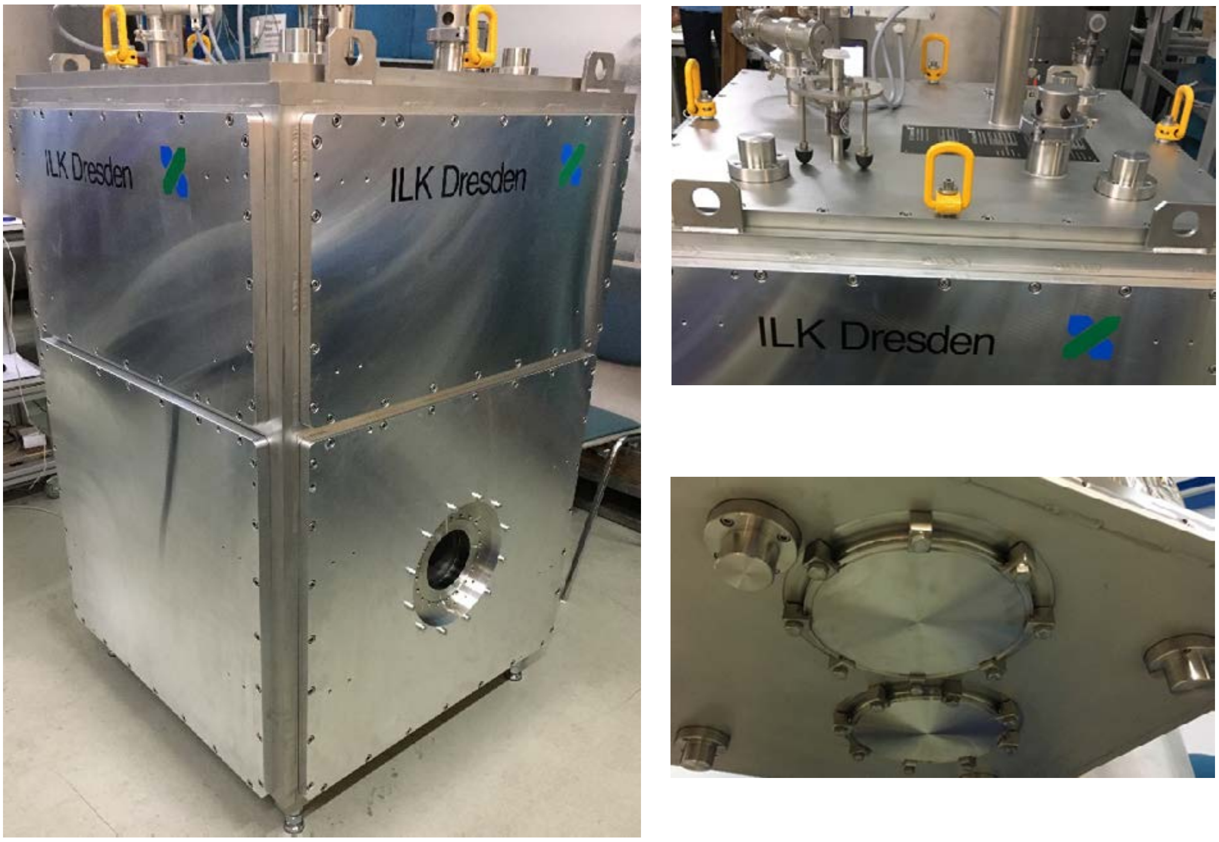

Figure 1: (left) CCC cryostat, (right) Top of the cryostat and the bottom with two DN200 ISO-K flanges.

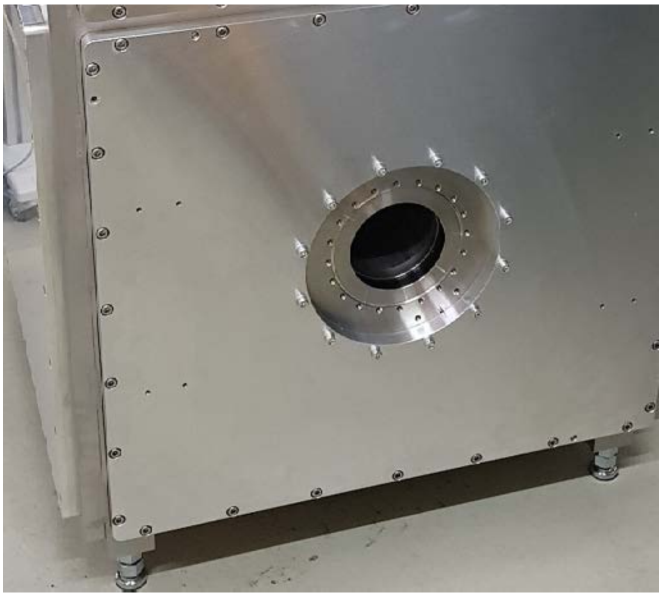

Figure 2: Aluminium plate of the beamline axis with adapter flange DN130 to DN150 and integrated cooling.

On the top cover there is a vibration-damped lifter connection KF16 for a 12 mm lifter, the safety line 25 mm for two safety valves, 2x KF40 for measuring equipment and / or vacuum generation, 1x KF25 He out and one KF50 overpressure protection for the vacuum chamber. On the bottom are two flanges DN200 ISO-K for a turbo pump and the possibility to additionally couple a cold head to the thermal shield, see figure 1 (right). The total mass of the whole cryostat is 1200 kg.

2.1.2. Thermal shield

Pipes and connections add heat load to the inner thermal shield, however, the temperature of the thermal shield is critical for the holding time of cryogenic media. In general, to keep the shield cold two options are possible: either cooling by a LN_2 reservoir or, which is the case for this cryostat, by a vapour-cooled radiation shield (see Figure 3).

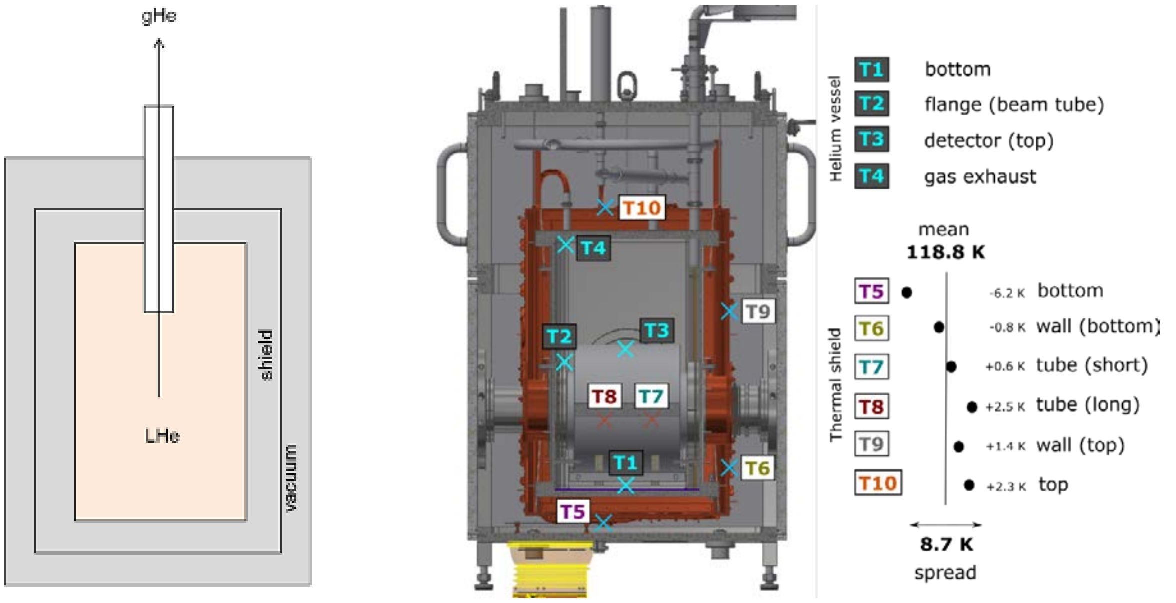

Figure 3: (left) Scheme of a ^{4}He cryostat with vapour-shield cooling. (right) Scheme of the cryostat with the ten temperature sensors to monitor the temperature distribution in the system.

To increase the efficiency of the coolant, the evaporated gas blown off through the neck pipe removes heat from the shield, caused dominantly by radiation, if a good thermal contact between shield and gas is provided.

Due to the large dimensions of the CCC cryostat we decided to use copper tube windings, soldered on the shield, see Figure 4. To avoid both large pressure losses and thermoacoustic oscillations and to ensure a good thermal transport a tube with 15 m length and 10 mm inner diameter was installed. Using this design, an average temperature of the shield of 118.8 K is achieved close to the thermal equilibrium during the operation in the configuration at the storage ring. At this point, the maximum temperature spread across the shield is 8.7 K measured by six PT1000 sensors distributed across the shield (see Figure 3 & 4b). Twenty layers of MLI insulation are installed on the outer surface of the shield as well as between the UHV beam tube and the shield.

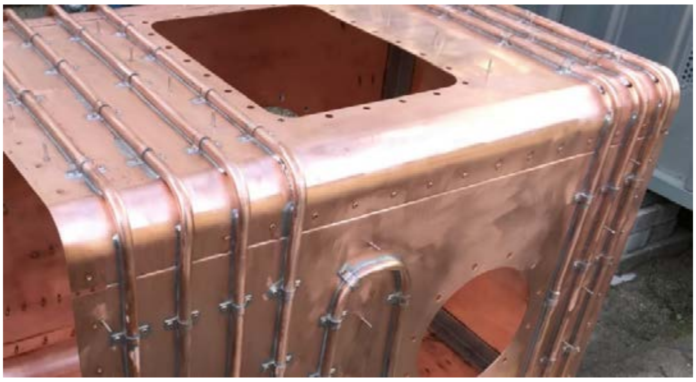

Figure 4a: Thermal shield of the CCC cryostat. During the assembly, two copper tubes surrounding the room-temperature UHV-beamline are inserted in the holes (bottom right) on either side of the shield.

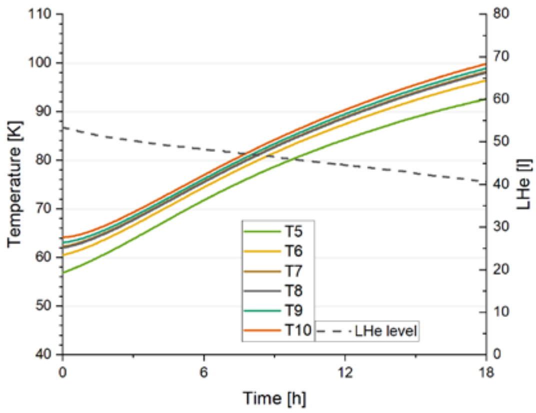

Figure 4b: Temperatures and helium level without the operation of the liquefier.

2.1.3. Helium vessel

The helium vessel, is made of stainless steel and has a total weight of 270 kg (see Figure 5). The geometrical volume is 88 l. On both sides the inner vessel as well as the thermal shield have maintenance windows of the size of roughly DN200CF, which are needed to access the SQUID for maintenance and repair work. The vessel is fixed via four titanium rods, which are attached to the lid of the vacuum vessel, and four titanium rods, connected to the bottom of the vacuum container. With this arrangement a four-fold security against static load and a double security against dynamic load (at 2 bar(g)) is ensured. The helium vessel is protected against a maximum overpressure of 0.4 bar(g) and has been tested with 2.0 bar(g). The helium leakage rate of the vessel is smaller than 1×10^{-9} mbar × l/s. Thirty layers of MLI thermal insulation on its outer surface shield the cryostat from thermal radiation.

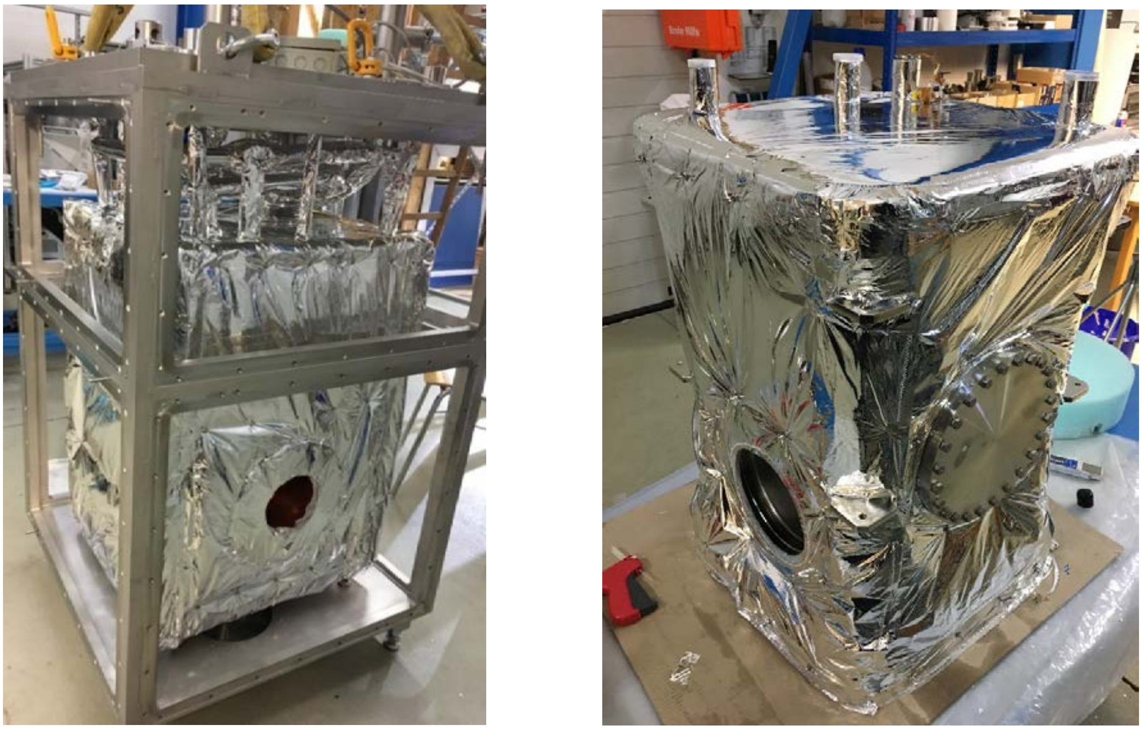

Figure 5: (left) Thermal shield surrounding the LHe vessel covered with twenty layers of multilayer insulation inside the frame of the vacuum vessel. (right) LHe vessel covered with thirty layers of insulation.

2.1.4. Cryogenic electric insulator (detector beam tube)

In order to allow the magnetic signal from a charged beam to propagate to the detector without being shielded by mirror currents along the beamline, an electrically insulating gap that separates the metal beam tube is required. Therefore, for the installation of the SQUID sensor (around the ion beam channel) a special pipe was installed inside the helium vessel, see figure 6. However, the design of a cryogenic ceramic insulator with a large diameter of 200 mm is a novelty and it is challenging to mitigate the mechanical stress that can break the ceramic during the temperature cycles. As an alternative, several different plastic insulators glued in the metal beam tube were tested in liquid nitrogen. Currently, a cryogenic plastic insulator (polyimide) is part of the CCC detector beam tube and shows excellent helium leak rates below 1×10^{-8} mbar × l/s. In the final version, a stainless steel tube with a ceramic gap should replace the plastic insulator.

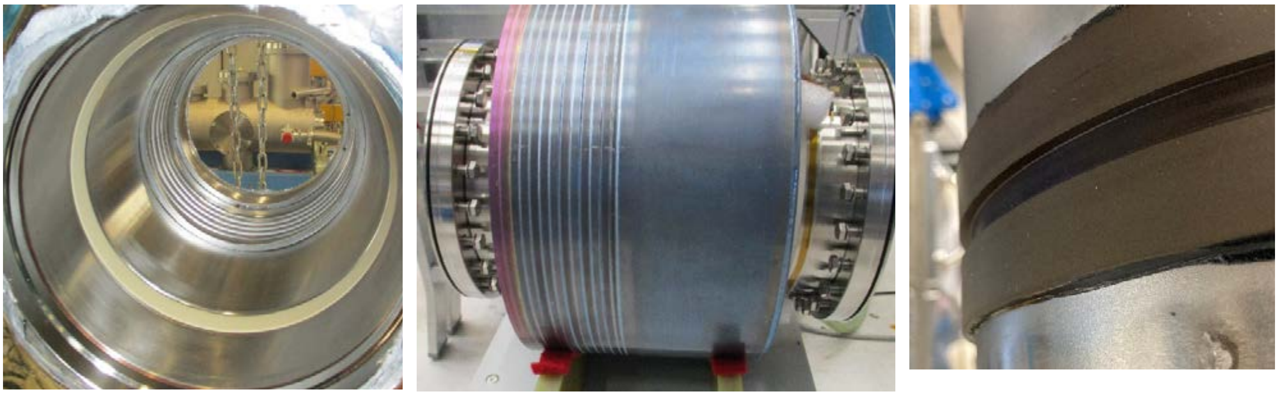

Figure 6: (left) Prototype of the ceramic gap inside the helium tube; (middle) CCC detector mounted on the helium tube.(right) The plastic insulator used in the current system.

2.2. Cryogenic performance & closed-loop setup

Final measurements result in an average evaporation rate of 15 litre/day without a helium liquefier and before the installation into the beamline. To mitigate the boil-off, the exhaust of the cryostat is connected to the gas input of a dedicated helium liquefier that feeds the liquid helium back through the lifter port into the helium vessel. The liquefier is based on a pulse tube cooler and is specified for a liquefaction rate of more than 15 l/day while rates of up to 19.4 l/days were measured in a test setup at GSI. However, in combination with the CCC cryostat the liquefier only leads to a reduction of the evaporation rate from originally 15 to 1.5 l/day or even higher rates. Additionally, when it is operated, in most cases the temperatures and the pressure in the helium vessel start to oscillate with a period of several minutes. At the moment, the mechanism for the bad liquefaction performance and for these oscillations is still being investigated. With the installation of the heating pads for the bake-out of the UHV beamline and of the bulky insulating plastic gap of the helium beam tube, unfortunately, the thermal insulation between the shielding layers along the beam tube deteriorated. As a result, large evaporation rates of 10.3 l/day or higher were observed, despite the operation of the liquefier. However, when the plastic insulator is replaced by the slim ceramic gap the situation will be improved.

2.3. Application

At the low energy storage ring CRYRING at GSI the cryostat is mounted on a heavy stainless steel frame to be connected to the beamline at a height of two metre, see Figure 8. The frame is filled with sand to damp any mechanical perturbations from the environment while two diaphragm bellows isolate the cryostat from the beam tube. Figure 8 (right) shows first calibration measurements of the CCC in preparation for the initial beam time. An electric wire that is mounted in parallel to the beamline carries an electric current of 10 nA that is detected by the CCC and is used as a reference signal. Despite the efforts to isolate the perturbations from the liquefier with a diaphragm bellow at the interface of the lifter, the cycle of the cryocooler is clearly visible in the CCC signal. This suggests a different way of coupling that is not purely mechanical. However, the frequency of the liquefier is very constant at 1.4 Hz which makes it possible to build an efficient filter. The CCC was operated successfully in a number of beam times. More detailed results on the measurements with beam will be published soon.

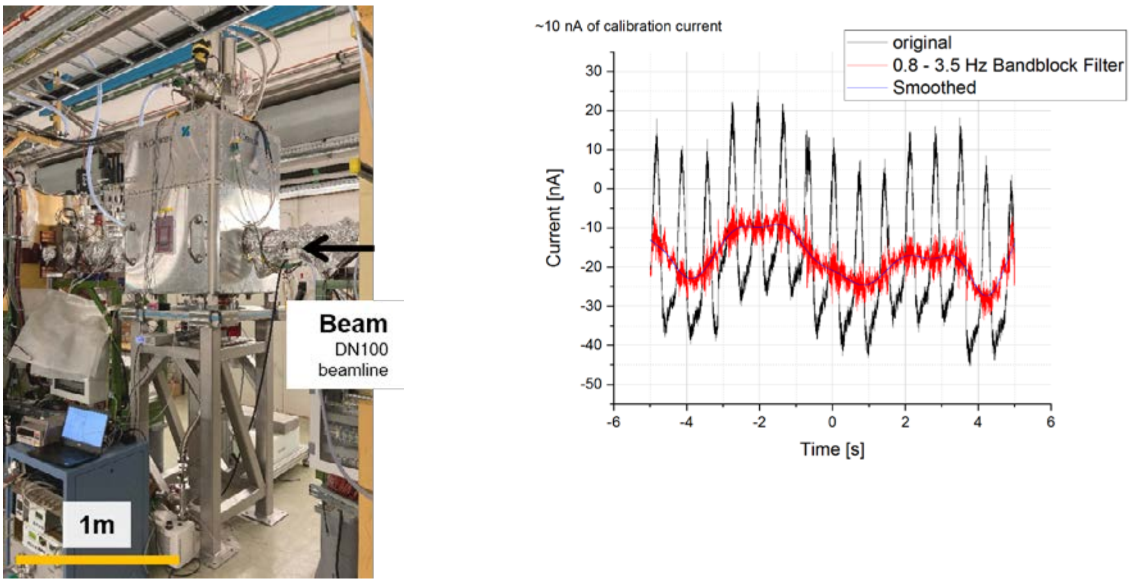

Figure 8: (left) The complete CCC system installed at the storage ring CRYRING at GSI. (right) A calibration signal of 10 nA detected by the CCC inside the beamline cryostat. The perturbation by the liquefier with a frequency of 1.4 Hz is strongly visible but can mostly be filtered out.

3. CONCLUSIONS

The development of a special CCC cryostats shows that, depending on the intended application, multiple criterions have to be kept in mind. Because of the diligent selection of non-magnetic materials and good mechanical decoupling, these factors currently do not significantly limit the sensitivity of the detector. Periodic perturbations from the liquefier have to be filtered out. The limited operating time at the storage ring of roughly 7 days before the detector warms up has to be improved. Potential problems connected to the poor thermal insulation around the beam tube are identified and will be solved in the next service. Furthermore, the temperature oscillations that are induced by the liquefier are currently being investigated. Many access possibilities through the aluminium windows allow for easy maintenance of the detector. In addition, the quality of the vacuum meets all expectations. Because of challenges in the production of the cryogenic ceramic insulator with the large diameter of the helium tube a cryo- and vacuum-compatible plastic insulator was developed and is now routinely used. Overall, after an extensive development a versatile platform for the installation of CCC monitors in beamlines and storage rings has been tested at CRYRING and, after some additional optimization of the cooling system, will be available for use throughout GSI and FAIR.

ACKNOWLEDGEMENTS

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NOMENCLATURE

SQUID Superconducting Quantum Interference Device

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