VERSATILE BEAMLINE CRYOSTAT FOR THE CRYOGENIC CURRENT COMPARATOR (CCC) FOR FAIR*

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Abstract

The Cryogenic Current Comparator (CCC) extends the measurement range of traditional non-destructive current monitors used in accelerator beamlines down to a few nano-amperes of direct beam current. This is achieved by a cryogenic environment of liquid helium around the beamline, in which the beam's magnetic field is measured with a Superconducting Quantum Interference Device (SQUID), which is itself enclosed in a superconducting shielding structure. For this purpose, a versatile UHV-beamline cryostat was designed for the CCCs at FAIR and is currently in production. It is built for long-term autonomous operation with a closed helium re-liquefaction cycle and with good access to all inner components. The design is supported by simulations of the cryostat's mechanical eigenmodes to minimize the excitation by vibrations in an accelerator environment. A prototype at GSI has demonstrated the self-contained cryogenic operation in combination with a 15 l/day re-liquefier. The cryostat will be used in CRYRING to compare the FAIR-CCC-XD with newly developed CCC-types for 150 mm beamlines. Both will supply a nA current reading during commissioning and for the experiments.

INTRODUCTION

The non-destructive measurement of DC beam currents of a few nano-ampere with a Cryogenic Current Comparator (CCC) has been a goal at GSI since the 1990s [1]. Among many other advantages that come with the precision of nano-ampere, this low detection threshold brings an immense benefit during the commissioning of accelerators and allows the monitoring of weak (slowly-extracted) ion beams. Therefore, up to five CCCs will be installed in the FAIR accelerator complex in Darmstadt, Germany. The first of them will become part of the low energy storage ring CRYRING in summer 2020 in order to supply several experiments with precise current readings. The extremely high sensitivity is achieved by moving the principle of 'classic' current transformers into a cryogenic environment, using superconductors to detect the magnetic field of the passing ion beam. A SQUID measures the azimuthal magnetic field down to fractions of a flux quantum (2.07 E 15 Wb) while being surrounded by a complex superconducting shield that attenuates (>130 dB) all other field components. Similar to a current transformer the CCC encloses the beamline in order to detect the azimuthal field. However, it is a significant challenge to provide a stable cryogenic environment that can house the CCC as close to the beamline as possible during a beamtime of several months without any direct access to the system. Furthermore, it was shown that the CCC is very sensitive to changes of temperature and pressure. In fact, there is a drift of the current signal of 73.7 nA/mbar or an average of 33.5 nA/mK [2]. The cryogenic infrastructure of the FAIR facility is not built to ensure the stability required. Therefore, a beamline cryostat with an independent cooling cycle based on a local helium re-liquefier has been designed together with the company ILK Dresden. The closed cooling concept has been tested in a prototype at GSI. A lot has been learnt from the cryostat built for the CCC at the Antiproton Decelerator at CERN [3].

The high sensitivity to magnetic fields coincides with a susceptibility to mechanical vibrations. At the moment, the current resolution is limited by the background noise of ~30 pA/√Hz at frequencies between 5 Hz and 100 Hz [4], while the white noise is at 3 pA/√Hz up to 100 kHz. A significant part of the background at low frequencies can be linked to mechanic oscillations of the environment. Therefore, a study of the mechanical resonances needs to be part of the design process of the cryostat in order to minimize their impact on the quality of the signal.

In the following, an overview of the thermal design followed by the results of a FEM study to determine the resonant behaviour is given. An additional approach to minimize the current noise and to increase the sensitivity by modifying the CCC itself is presented in [5]. For a more detailed explanation of the measurement principle and a summary of previous installations please refer to [2, 6].

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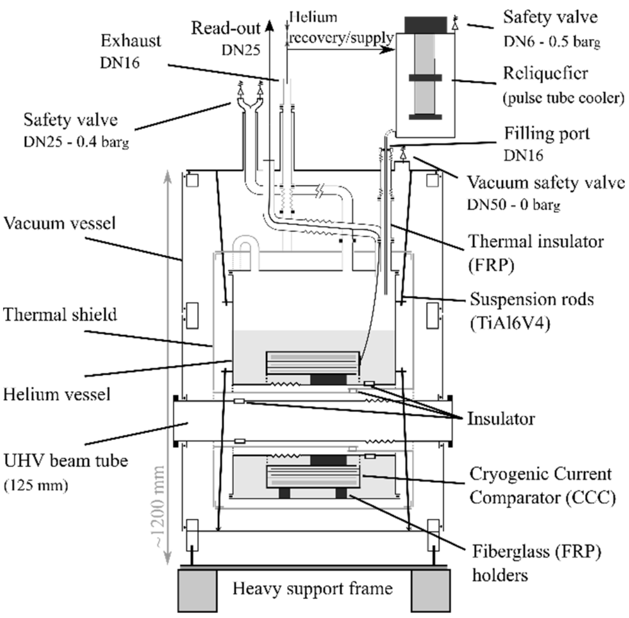

Figure 1: Schematic of the CCC cryostat for CRYRING.

CRYOSTAT DESIGN

The CCC beamline cryostat (850 x 850 x 1200 mm) [7] is built up by three layers depicted in Fig. 1 and Fig. 2: an insulation vacuum vessel (VV), a thermal shield (TS) made from OF-copper and a helium vessel (HV) made from 316Ti that houses the CCC. The vacuum vessel consists of a stainless steel frame (304) with two fully demountable windows on each side made from aluminium that allow access to the inside. There is an enthalpy cooling line made from OF-copper soldered to the surface of the thermal shield with a length close to 15 m and an inner diameter of 10 mm. Two service ports in the shield and the helium vessel give access to the interior from two sides. The helium chamber is connected to the vacuum vessel with eight suspension rods made of TiAl6V4 (4 towards the top and the bottom respectively), each with a diameter of 3 mm. All the vessels have concentric beam tubes with a diameter of 125 mm or bigger to link to the UHV-beamline of CRYRING. The CCC with an inner diameter of 250 mm [4] is mounted inside the helium chamber and is centred on the beam tube by a ring made from fibre-reinforced plastic (FRP) while its weight is carried by two FRP half-shells below (see Fig. 2). Each beam tube is split by an insulator to redirect the mirror currents and to allow the magnetic field of the travelling ions to reach the CCC. The beam line of the vacuum chamber and the helium vessel use a ceramic gap while the thermal shield is split by an electrical insulator made from PEEK.

Thermal Design

The total cooling power of 0.85 W at 4.2 K is supplied by a pulse tube cooler PT415 helium re-liquefier from Cryomech® [8]. All evaporating helium gas is guided through the cooling lines along the thermal shield to the re-liquefier keeping the shield close to an estimated average equilibrium temperature of 88 K. At this temperature the heat input to the helium vessel leads – according to our estimates – to an evaporation rate of around 15.1 l/day which is the gas flow that is needed to maintain the temperature of the shield. If more helium evaporates, the temperature of the shield declines, reducing the heat input to the helium vessel and thus the gas flow is lowered. During commissioning a major task is to minimize these oscillations and to operate the system at a state of equilibrium.

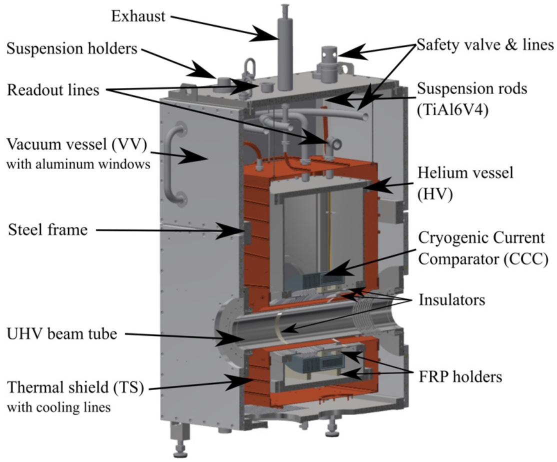

Figure 2: Rendering of the CCC cryostat for CRYRING.

Table 1 shows a summary of the contributions that lead to the total heat input of 0.39 W to the HV and 6.61 W to the TS. In order to reduce the heat transfer by thermal radiation, the outer surface of the thermal shield and the surface along the beam tube of the helium vessel is insulated with 20 layers of multi-layer insulation (MLI), the remaining surface of the helium chamber is covered with 30 layers of MLI. In this way a heat load via thermal radiation of 1.125 W/m² (TS, 30 layers) and of 0.04 W/m² (HV, 20 layers) can be assumed.

Table 1: Estimated Heat Load on Helium Vessel (HV) and Thermal Shield (TS)

	TS [W]	**HV [W]**
Thermal radiation	3.74	0.08
Suspensions rods	1.42	0.04
All ports	1.30	0.07
Instrumentation & liquid helium line	0.15	0.20
Total	6.61	0.39

In tests with the existing CCC cryostat at GSI, re-liquefaction rates as high as 19.4 l/day were measured which is sufficient to compensate the evaporation of 15.1 l/day in equilibrium. The evaporation rate of the test cryostat was only 6.2 l/day, consequently, during the testing period of two weeks rising helium levels were observed when additional helium gas was supplied. The system was operated at a constant overpressure at values between 50 and 200 mbarg in order to prevent contamination of the helium gas. The pressure was controlled by a heater mounted to the

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cold head of the re-liquefier that reduces the active cooling power to a level at which the rate of liquefaction is identical to the evaporation rate. Once the system is close to an equilibrium, the temperature of the helium bath is stable within variations of a few milli-kelvin or even below during ten or more hours of operation. Therefore, the effect on the current measurement during an acceleration cycle of several seconds is negligible. Moreover, with knowledge of the temperature drift, the current value can be corrected if necessary.

In contrast to the new cryostat for CRYRING, the cryostat used for this test measurements was not designed to rely solely on the evaporating gas to cool the thermal shield but rather has a second cryocooler that keeps the temperature of the shield constant. Without this additional thermal stabilization a thorough design of the exhaust gas line is crucial to reach thermal equilibrium. Nevertheless, by removing the cryocooler at the TS we eliminate a significant source of mechanical vibrations, which – at earlier tests – had to be removed by switching off the cold head in order to obtain a stable signal. In this case the resulting deviation from the thermal equilibrium and the effect of the thermal drift on the signal had to be accepted. Several modifications to stabilize the new system by using buffer volumes, fans and additional regulators like pressure controllers to control thermal oscillations are in preparation.

Vibration Analysis

In addition to providing a constant cryogenic environment, the second purpose of the cryostat is to shield the CCC from mechanical vibrations of the surrounding. Therefore, the cryostat will be stabilized by a heavy support frame and will be isolated from the environment and the re-liquefier with welded bellows and rubber feet. Furthermore, numerical simulations have been carried out to predict the eigenmodes of the helium vessel and to investigate different configurations to shift all eigenmodes off critical frequencies. In this way, we keep the excitation of the resonances and the resulting current noise as small as possible.

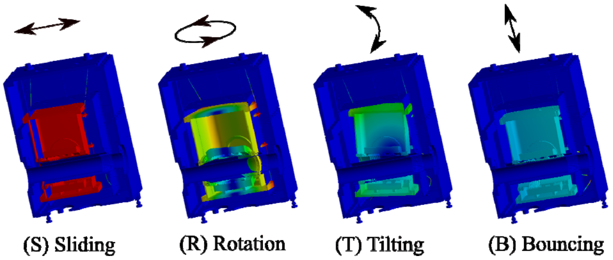

Figure 3: Mode patterns of helium vessel inside the vacuum chamber simulated within the ANSYS® framework.

To obtain the mechanical resonances, a finite element model has been set up based on a CAD model of the cryostat and was solved numerically within the ANSYS® framework. Figure 3 shows the simplified CAD model that was used including the pattern of motion linked to the excitations. At frequencies below 50 Hz there are four different patterns of movement: sliding, rotating, tilting and bouncing. It is likely that each pattern couples to the CCC with a different efficiency, the degree of which is still under investigation. Each pattern is connected to one or more resonance frequencies that are listed in the bottom right of Fig. 4.

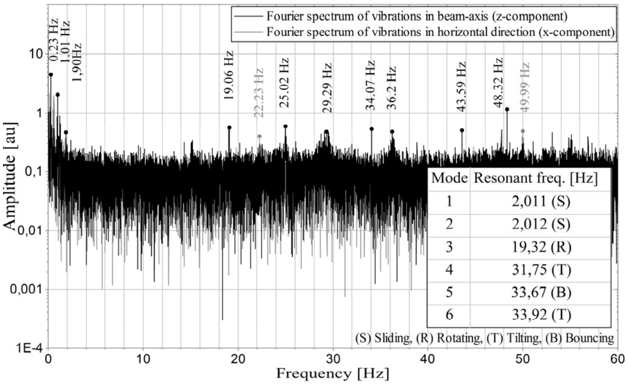

Figure 4: Fourier spectrum of mechanical vibrations measured directly at the beamline at CRYRING. At the bottom right there is a list of the resonance frequencies predicted by the ANSYS simulation.

The graph in Fig. 4 shows the Fourier spectrum of the vibrations at CRYRING where the cryostat will be installed and which illustrates the vibrations of the environment. The data were taken with all relevant sources of vibrations at the accelerator including vacuum pumps and cooling water lines in operation. As additional noise sources we expect the pulse tube cooler inside the re-liquefier (that was measured to oscillate close to 1.4 Hz) and miscellaneous other devices driven by the 50 Hz of the power supply. The black line shows the signal from the vibrations along the beam axis (z) while the horizontal motion perpendicular to the beam axis is depicted in grey (x). The spectrum is mainly composed of very sharp frequencies. Unfortunately, in this configuration two of the predicted resonances (at 19.32 Hz and at 33.92 Hz) are close to the measured excitation frequencies (19.06 Hz and 34.07 Hz) and – as a consequence – will be shifted to different levels. However, it is difficult to predict the quality factor and the width of the resonances of the helium vessel and thus the final amplitude of its movement. Therefore, additional support structures – as long as the extra heat input can be handled – will only be added once the frequencies and their effect on the current signal have been measured in the assembled cryostat. Using this approach, it is possible to tailor any additional measures to the individual frequencies and the higher order modes that are shown to cause excess noise. With the simulation model we have an excellent tool to calculate the effect of mechanical modifications on the eigenmodes and are prepared to make modifications should the need arise. As a next step, the oscillations of the cryostat will be investigated in more detail once the simulations can be compared to measurements on the cryostat.

CONCLUSION

The mechanical and thermal design of the cryostat for the CCC at CRYRING was presented. It provides stable operating conditions for the measurement of low beam currents and can be adapted for other applications in which a temperature stability of a few milli-kelvin during ten or more hours of operation and in which very small levels of mechanical vibrations are required. The closed helium cycle was tested with a prototype and re-liquefaction rates as high as 19.4 l/day were measured. The results of a FEM study of the eigenmodes of the helium vessel were compared to a vibration spectrum at CRYRING. While in the current model there are two background vibrations with a frequency close to the resonances of the helium vessel, we are prepared to shift the frequencies in case they become a problem. Following a verification of the performance of the assembled cryostat the CCC is ready for the installation in CRYRING.

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