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COMMISSIONING OF THE CRYOGENIC CURRENT COMPARATOR (CCC) AT CRYRING*

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Abstract

Accurate non-destructive measurement of the absolute intensity of weak ion beams (< 1 μA) in storage rings is often restricted to special beam conditions and, even then, is associated with large uncertainties and tedious calibration procedures. However, experiments with rare ions in particular depend on excellent current resolution. In order to make these beams accessible, the Cryogenic Current Comparator (CCC) monitors deviations of the DC beam current on a scale of nA and compares the signal to a calibrated reference current. At the heavy-ion storage ring CRYRING at GSI a CCC prototype for FAIR was installed and first results of the commissioning are reported here. Preceding the operation with beam, a careful design of the beamline helium cryostat was required to provide the stable cryogenic environment needed for CCC operation. Mechanical and electro-magnetic perturbations that interfere with measurement of the beam's faint magnetic field are suppressed by the internal structure of the system and a superconducting magnetic shield, while the remaining interference can be filtered with adequate signal processing. In this way, a current resolution in the nA range was demonstrated.

INTRODUCTION

In the second half of 2020, a Cryogenic Current Comparator (CCC) was installed at the heavy-ion storage ring CRYRING at GSI to serve as the prototype for a total of up to five CCC installations at FAIR. A CCC monitor consists of a cryogenic system supporting the stable operation of the sensing unit and a CCC detector as developed within the CCC collaboration at the FSU Jena [1] and the Leibniz IPHT [2]. The FAIR prototype consists of a newly manufactured beamline cryostat that has been developed with ILK Dresden§ at GSI specifically for the needs at FAIR [3]. The particular CCC detector (FAIR-Nb-CCC-XD [1]) that is installed is part of the same design family (CCC-XD) as the one developed for the use at the Antiproton Decelerator at CERN [4] with extended dimensions to accommodate the FAIR beamlines with a diameter of 150 mm. Both, the cryostat and the CCC detector, were tested separately in a laboratory environment.

Herein, we will introduce the first results of the commissioning of the assembled setup in an accelerator setting. In the following, the configuration of the detector setup at the CRYRING is presented and the effect of the environment on the performance of the CCC is discussed.

BEAMLINE SETUP

The CCC beamline setup (see Fig. 1) is based on a helium bath cryostat with a volume of 80 l, a gas-cooled heat shield with a nominal throughput of 15 l/day and a local cryocooler-based liquefier from Cryomech¶ with a performance of up to 19.4 l/day. At the moment, the cold operating time is limited to 7 days due to an excessive heat load and an oscillating gas flow to the liquefier. The additional heat input that leads to an increased evaporation rate of 22 l/day is most likely due to the installation of heating foils for the bake-out of the UHV beamline which is surrounded by the cryostat (c.f. Fig. 2). In this area, the cryogenic CCC detector and the heat shield is placed as close to the beamline as possible and the additional material from

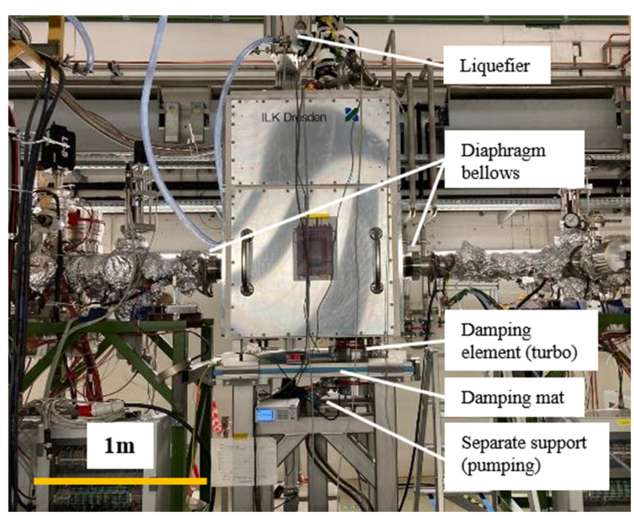

Figure 1: CCC beamline setup at the CRYRING.

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¶Model PT415 from Cryomech Inc, Syracuse, NY, USA
‡Datasheet, Sylomer SR28, Getzner Spring Solutions GmbH, Germany

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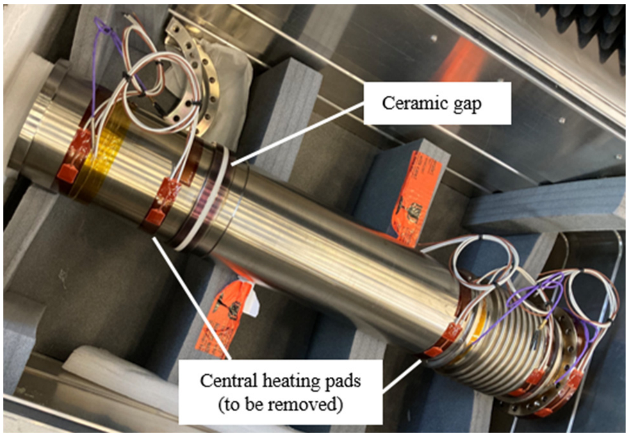

Figure 2: UHV beamline with Kapton heating foil for bake-out and a ceramic gap. In the final assembly it is closely surrounded by the cryogenic helium vessel of the cryostat.

the heating pads increase the heat transfer to the helium vessel. However, the bake-out at CRYRING has shown that it is sufficient to passively heat the section of the beamline that is surrounded by the helium vessel by heating pads right before and after the section to reach a beamline vacuum of better than $1 \cdot 10^{-10}$ mbar. Therefore, at the next opportunity the heating foils will be removed to restore the nominal evaporation rate of 15 l/day. Unfortunately, no reliable solution to stabilize the helium flow was found so far. However, a detailed investigation of the flow resistances is ongoing and has already resulted in several modifications to promote the gas flow along the cooling line and suppress the gas intake through the liquid helium return nozzle of the liquefier.

The UHV beam line, the heat shield and the helium tube as part of the helium vessel each need to incorporate an electrical insulator along the beam tube at the position of the CCC detector such that mirror currents do not shield magnetic field components of the ion beam. In general, ceramic gaps are used for this purpose. However, no ceramic gap could be produced in time which can withstand the mechanical stress on the helium vessel during the cooldown. Therefore, the helium tube features a gap made from polyimide that was glued to the stainless steel tube and is currently in use with a leakage rate smaller than $1 \cdot 10^{8}$ mbar·l/s.

Mitigation of External Perturbations

An accelerator environment is far from an ideal operating condition for the CCC which, in fact, is also a highly sensitive magnetometer. External magnetic field disturbances, mechanical vibrations and small temperature/pressure fluctuations all affect the measurement significantly. Therefore, an effective electromagnetic and mechanical decoupling of the CCC from the environment is important (see Fig. 1). The setup at the beamline is supported by a massive sand-filled stainless steel stand. The two are isolated by a Sylomer SR28 damping mat that attenuates mechanical vibrations above a cut-off frequency of 26.8 Hz[‡]. The beamline and the liquefier are mechanically decoupled from the cryostat by diaphragm bellows while the turbo pump is connected via a dedicated damping element. Due to these measures, the signal quality was not noticeably deteriorated by mechanical perturbations during this measurement campaign.

All external magnetic fields are attenuated by the superconducting shield of the CCC detector with a damping factor of 85 dB [5]. To minimize local magnetic perturbations as few permeable materials as possible are used in the construction of the cryostat. Finally, the cryostat provides a very stable operating temperature and pressure. Any such changes are gradual and their effect on the measurement is small and can often be neglected.

COMMISSIONING

After the installation at the beamline the CCC was calibrated using an electric reference current that simulates the ion beam. This calibration current is sent through the detector via a wire that runs parallel to the beamline. During the subsequent commissioning all major components of the storage ring (dipoles, HF cavity, vacuum pumps, etc.) were active in order to establish realistic operating conditions. Apart from the dipoles no other accelerator component had a significant effect on the signal of the CCC. Figure 3 shows the response of the CCC to an electric calibration signal in the shape of a square wave with an amplitude of 21.2 nA and a frequency of 1 kHz. One can see that currents in the tens of nA can be resolved very well, but also that there are fluctuations of the baseline on the scale of individual nA that produce a small error on the absolute measurement at these bandwidths. At frequencies from ~1 kHz up to the maximum bandwidth of 200 kHz deviations of the current by individual nA can be resolved. At lower frequencies down to DC and in order to convert the

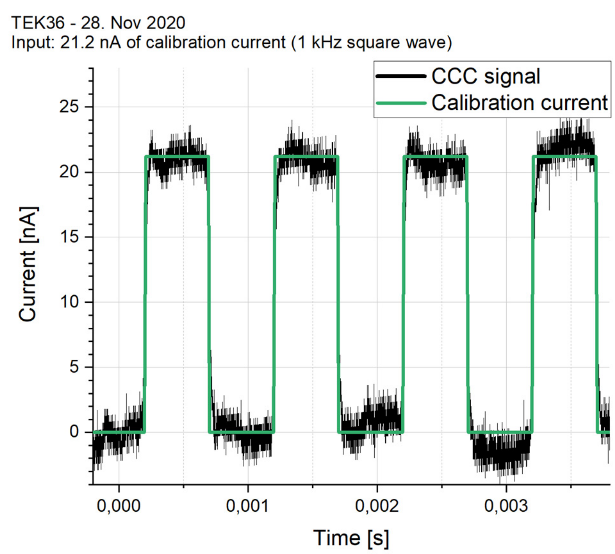

Figure 3: CCC signal (black) of an electric calibration current with amplitude of 21.2 nA and a frequency of 1 kHz (green). The measurement is performed with the CCC installed at the CRYRING and with all major accelerator component running.

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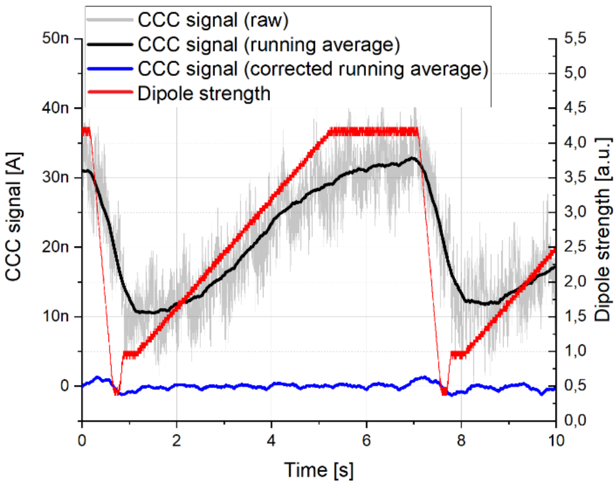

Figure 4: Magnetic field strength of the dipole (red) during one accelerator cycle. The resulting signal of the CCC before the dipole correction (black & grey) and the corrected CCC signal in which the effect of the dipole is subtracted by using the recorded CCC response for this ramp (blue).

signal from a relative measurement to an absolute current reading, additional signal-processing is necessary to determine the signal baseline and to remove the two main sources of perturbations, the dipole ramp and the helium liquefier. Finally, also the much smaller error caused by slow temperature or pressure drifts of the helium vessel (generally < 0.7 nA/s) can be corrected by using the temperature data from the cryostat.

Despite the field attenuation of the superconducting shield a small magnetic stray field from the neighbouring dipoles reaches the CCC and produces a signal with a maximum amplitude of ~23 nA that follows the dipole ramp (see Fig. 4). Since the ramp of the dipole is strongly deterministic, the response of the CCC to the dipole ramp can be measured in a dry run before there is any beam current in the storage ring. This data can then be used to subtract the effect of the dipole on the CCC in order to get the true current data. The blue line in Fig. 4 shows the CCC signal during a background measurement after the elimination of the dipole using the recorded response of the CCC. After this correction the remaining current noise due to the dipole is generally below 2 nA and is concentrated at the fast ramp down of the magnets at the end of the accelerator cycle. An attempt to determine a single response function that predicts the reaction of the CCC to the dipole strength for arbitrary dipole ramps was not yet successful. Therefore, a dedicated measurement of the dipole response function is necessary whenever a new dipole ramp is implemented.

The perturbation originating from the liquefier is created by the periodic pumping of the pulse-tube cryo-cooler at a fixed frequency of 1.4 Hz. Measurements with an accelerometer have shown that mechanical vibrations of the liquefier are strongly attenuated before they reach the cryostat. However, there is evidence that the coupling is based on the pressure fluctuations created by the periodic refrigeration at the cryo-cooler. While the operating frequency is stable, the phase of the cryo-cooler is fluctuating and the

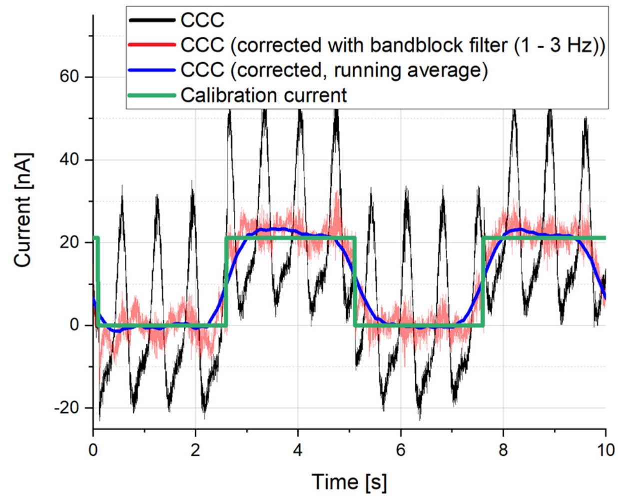

Figure 5: Signal perturbation induced by the helium liquefier (1.4 Hz) visible in the CCC signal (black), resulting signal after band-block filter (red), running average (blue) and the applied calibration current of 21.2 nA (green).

exact shape of the resulting signal at the CCC depends on the system state (e.g. remaining liquid helium level). This makes it difficult to use background measurements to directly subtract this noise source. Therefore, a digital FFT-based band-block filter is used to eliminate signals with a frequency between 1 and 3 Hz. The effect of this filtering can be seen in Fig. 5. The graph shows the response of the CCC to a calibration signal in the form of a square wave, again with an amplitude of 21.2 nA but with a much slower frequency of 200 mHz. At this timescales the perturbation by the liquefier at 1.4 Hz is visible and makes it difficult to extract the beam current. Figure 5 shows that after the application of the band-block filter the perturbation by the liquefier is strongly attenuated and the applied calibration current can be observed. Alternative means to suppress the pressure fluctuations before they can reach the CCC detector are in preparation. The resulting current resolution of the CCC system depends strongly on the successful elimination of noise signals, the errors of the initial calibration and on the desired measurement range. The first results of the commissioning have shown that at measurement ranges below 1 μA, current resolutions better than 10 nA are feasible.

While the results of the commissioning are very promising and not too far from the optimal current resolution achieved in the laboratory [1], a significant reduction of the SQUID performance parameter was observed when moving the setup to the accelerator environment. More specifically, the modulation swing of the SQUID voltage in the flux to voltage characteristics was reduced. This is most likely due to a substantial increase of rf interference that reaches the detector through the enclosed beam tube. Such a phenomenon which could be reproduced in a lab experiment. Moreover, the critical current of the SQUID was reduced by up to 70 % which implies that the superconductor experiences additional strain imposed by the environment. At the moment, there is no conclusive explanation to this

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phenomenon but the presence of static or dynamic magnetic fields during the transition to the superconducting state might lead to such an effect. It is planned to incorporate a small local soft-iron shield to protect the SQUID and its housing from external fields during the cooldown.

CONCLUSION

A Cryogenic Current Comparator was installed and commissioned at CRYRING and shows excellent absolute current resolution better than 10 nA in a noisy accelerator environment. The dominant sources of perturbation are the dipole magnets and the helium liquefier which both can be filtered with adequate signal-processing. The beamline setup successfully decouples the CCC from mechanical vibrations of the surrounding and reduces the influence of temperature fluctuations to a minimum. However, the limited cryogenic operating time of up to 7 days due to an oscillation of the helium gas flow is still to be improved. Further investigations are planned to stabilize the SQUID performance under the influence of the high level of electromagnetic interference in the accelerator environment. The demonstrated accuracy makes the CCC an excellent tool for diagnostics of low ion beam intensities when an absolute non-destructive current monitor with a current resolution of nA is required.

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