ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TUP31

THE CRYOGENIC CURRENT COMPARATOR AT CRYRING@ESR*

L. Crescimbeni†, D. M. Haider†, A. Reiter, M. Schwickert, T. Sieber
GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany
H. De Gersem, N. Marsic, W. F. O. Mueller, TU Darmstadt, Darmstadt, Germany
M. Schmelz, R. Stolz, V. Zakosarenko[3], Leibniz IPHT, Jena, Germany
F. Schmidl, Friedrich-Schiller-University Jena, Jena, Germany
T. Stoehlker[1,2], V. Tympel, Helmholtz Institute Jena, Jena, Germany
[1]also at GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany
[2]also at Institute for Optics and Quantum Electronics, Jena, Germany
[3]also at Supracon AG, Jena, Germany

Abstract

The Cryogenic Current Comparator (CCC) at the heavy-ion storage ring CRYRING@ESR at GSI provides a calibrated non-destructive measurement of beam current with a resolution of 10 nA or better. With traditional diagnostics in storage rings or transfer lines a non-interceptive absolute intensity measurement of weak ion beams (< 1 µA) is already challenging for bunched beams and virtually impossible for coasting beams. Therefore, at these currents the CCC is the only diagnostics instrumentation that gives reliable values for the beam intensity independently of the measured ion species and without the need for tedious calibration procedures. Herein, after a brief review of the diagnostic setup, an overview of the CCC operation with different stored ion beams at CRYRING is presented. The current reading of the CCC is compared to the intensity signal of various standard instrumentations including a Parametric Current Transformer (PCT), an Ionization Profile Monitor (IPM) and the Beam Position Monitors (BPMs). It could be shown that the CCC is a reliable instrument to monitor changes of the beam current in the range of nA.

INTRODUCTION

The non-destructive and absolute monitoring of ion beams with an intensity in the order of nA plays an essential role in accelerator facilities that produce slowly extracted ions for nuclear physics research or rare isotopes and antiprotons in storage rings. In general, for coasting beams standard diagnostic systems are not able to provide measurements in the range of nA without major efforts. Even then, the instruments that can provide some information in this range have problems to deliver the high precision and reliability that is required (e.g. Schottky [1]), or are destructive, at least partially, reducing severely the possibility of using them as monitoring devices in storage rings (e.g. Faraday Cups and Secondary Electron Monitors) or are limited to bunched beams (BPM, Integrating Current Transformer).

The Cryogenic Current Comparator (Fig.1) is a superconductive device that can measure currents in the order of nA detecting the magnetic field of the beam itself. The CCC uses a DC Superconducting Quantum Interference Device (SQUID) as a highly sensitive magnetometer, shielded from external magnetic fields thanks to an elaborate superconductive magnetic shielding, to provide absolute high-precision measurement of low-intensity currents while being non-destructive and easy to calibrate.

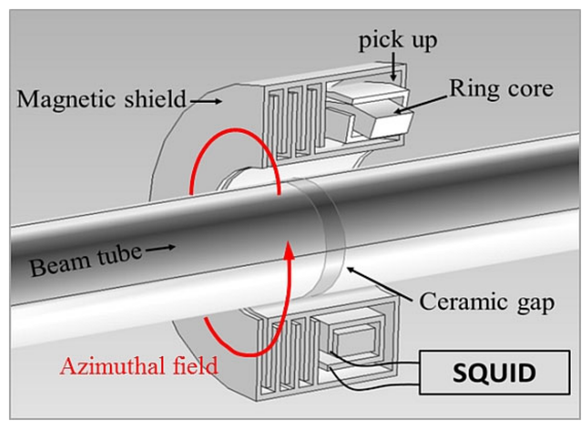

Figure 1: Schematic view of the CCC.

Five CCCs are planned to be installed in the FAIR facility and, in preparation, a prototype was installed in the heavy-ion storage ring CRYRING@ESR at GSI to be tested with beam. The prototype is based on the FAIR-Nb-CCC-XD [2] that is part of the family of CCC-XD that has been developed for the use with large beam-lines diameters (e.g. at Antiproton Decelerator at CERN [3]) and that was adapted to the beamline dimensions at FAIR (Ø 150 mm). At CRYRING, the CCC was operated with several different ion species (D^{+}, O^{6+}, Nb^{2+}, Pb^{78+}, U^{91+}) and various beam conditions (e.g. coasting/bunched) with beam intensities between 5 nA and 20 µA to demonstrate the detector performance that can be expected for FAIR.

COMMISSIONING IN CRYRING

The CCC detector is allocated in a newly manufactured beamline cryostat developed in collaboration with ILK Dresden§ to fulfil the needs of the installation at FAIR [4]. The SQUID sensor of the CCC is a highly sensitive magnetometer and is susceptible to external perturbations.

*Work supported by AVA – Accelerators Validating Antimatter the EU H2020 Marie-Curie Action No. 721559 and by the BMBF under contract No 05P21SJRB1.
†l.crescimbeni@gsi.de, d.haider@gsi.de
§ILK Dresden gGmbH, Dresden, Germany
¶Model PT415 from Cryomech Inc, Syracuse, NY, USA

ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TUP31

Therefore, the cryostat provides a very stable operating pressure and temperature, necessary to ensure the stable operation of the detector. The system is equipped with a local helium liquefier¶ which at CRYRING allowed a continuous operating time of 7 days which will be expanded in the future to complete stand alone operation [5].

Moreover, it is necessary to have a mechanical isolation from the accelerator environment to suppress mechanical perturbations, which is achieved using a support system composed of stainless steel filled with sand and equipped with a dedicated dampening mat. The beamline and the liquefier are connected with mechanical bellows, and the vacuum pumps are equipped with damping elements.

After the installation at the beamline, the detector was calibrated with a reference current that simulates the beam. The calibration line is composed of a wire parallel to the beamline that passes through the CCC and is connected to a function generator. This setup allows the in-situ calibration of the CCC with waveforms of chosen shape, intensity and frequency. The calibration showed that the CCC is able to measure currents below 10 nA limited by the fluctuation of the baseline on the scale of several nA. Larger baseline fluctuations were mainly due to two noise sources, the stray field of the ramp of nearby dipole magnets and the vibration of the CCCs own helium liquefier. Using data collected in several “dry runs” it was possible to identify the noise and to develop a correction for these baseline drifts. This is possible because the dipole ramp is strongly deterministic, and the liquefier noise is periodic with a period of 1.4 Hz. This leads to a noise-limited current resolution in the accelerator environment that is not far from the value that was achieved in the laboratory [2].

CRYRING MEASUREMENT

Following the commissioning reported in detail last year [5], the accuracy of the CCC was tested with beam at CRYRING. Figure 2 shows the beam intensity of a bunched deuterium beam throughout the accelerator cycle. Shown in light green is the data collected by the CCC, after applying the liquefier and the dipole ramp correction. Even if the phases of the machine cycle (injection, acceleration, flattop) are clearly visible, the signal is affected by noise. A large part of the noise originates in the bunch structure of the beam, which at the low injection energy of 300 keV/u can partly be resolved by the CCC. The remaining noise contribution is due to the intrinsic noise of the magnetic core and due to external perturbations. For DC beam current measurements both can be strongly attenuated with an analogue low-pass filter (e.g., at 20 Hz) or by performing a digital averaging of the data (Fig. 2, dark green). A noise-limited current resolution of better than 10 nA_{rms} at the full detector bandwidth of roughly 200 kHz could be shown.

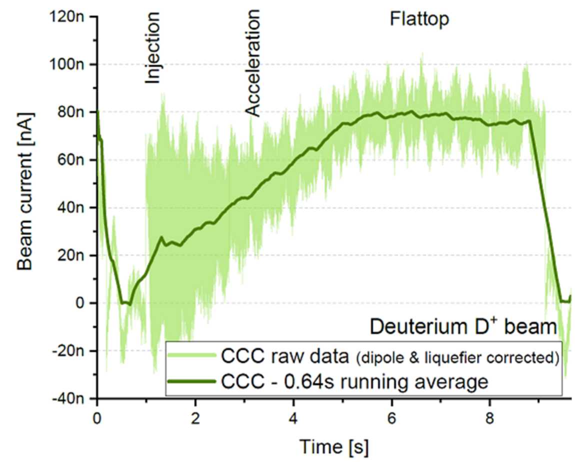

Figure 2: CCC measurement of a low-current bunched beam of deuterium D^+ (5 MeV/u at flattop). Dipole ramp and liquefier noise corrected (light green) with a bandwidth of about 200 kHz [2] and smoothed with a running average (dark green).

Coasting Beam

After this first demonstration of the performance, we proceeded with the comparison of the CCC with existing instrumentations in the CRYRING. The first one shown here is the confrontation with a Parametric Current Transformer (PCT) and with an Ionization Profile Monitor (IPM) for the measurement of unbunched beam. Figure 3 shows the exponential loss of beam current for a coasting $^{238}U^{91+}$ beam with a peak beam intensity of around 18 µA (identical results obtained for $^{208}Pb^{78+}$ beam). Due to the large noise associated with the signal of the PCT and of the IPM, both were smoothed with a running average to allow a sensible comparison. The count rate of the IPM (order of 60kHz) was converted to an absolute current with a linear calibration factor that was determined using the calibrated CCC signal. The 3dB-bandwidth of the CCC was restricted to 11.3 kHz (required due to “high intensity” operation”) but no signal correction (dipole or liquefier) was applied.

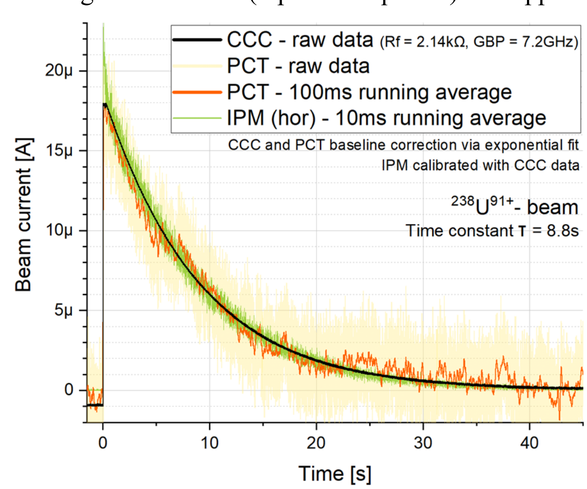

Figure 3: Coasting beam current measurement of a $^{238}U^{91+}$ beam performed with CCC (black), with PCT (orange) and IPM (green). The CCC provides a superior current resolution.

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Figure 3 shows that the current measurement performed by the CCC was affected by substantially less noise and subsequently could provide a significantly better current resolution, even at beam intensities that are rather large for the CCC. For the PCT a current noise of 1.9 μA_{rms} with a bandwidth of 100 Hz was determined while the IPM showed a noise of around one μA_{rms}. For the direct comparison, Table 1 gives a list of the noise-limited current resolution of the intensity diagnostics at CRYRING.

In addition, we must consider the limitations of the PCT and of the IPM. First of all, the PCT – even with averaging multiple accelerator cycles – it not suited for intensities smaller than about 5 μA which means there is no possibility to obtain a calibrated measurement with weaker intensities. The IPM can detect much lower currents, however, it has two main problems. First, the measure is not calibrated and strongly depends on the measurement parameter. The calibration of the IPM can be performed only by referring to another device able to measure the beam current, in the data acquisition at CRYRING the CCC has been used as calibration device. Second, at low beam energies it can significantly affect the beam. For low-energy beam the electromagnetic field used to collect the secondary ions act as a disturbance on the beam, making the IPM a destructive device, even if not completely.

Bunched Beam

Excellent specialized diagnostics already exists for low intensity bunched beams. The second comparison was performed with the intensity signal obtained from the sum signal of a Beam Position Monitor (BPM) and with the calibrated signal of an Integrating Current Transformer (ICT), using bunched $^{2}D^{+}$ and $^{16}O^{6+}$ beam. At CRYRING the optimal current noise of the ICT is 1 nA_{rms} or larger at a bandwidth of 20 Hz [6] which is comparable to the CCC. The noise level of the BPM can be as low as 100 pA_{rms} (@ 20 Hz) which exceeds today's measurement capacity of the CCC (see Tab. 1). However, the BPM signal needs to be calibrated to obtain a current measurement and both the ICT and BPM are restricted to bunched beams which makes the CCC a much more versatile device.

Table 1: Comparison of Intensity Diagnostics at CRYRING

Instrument	Current noise (bandwidth)	Comments
CCC	< 10 nA_{rms} (200 kHz)	Calibrated
PCT	~ 1.9 μA_{rms} (100 Hz)	Calibrated
IPM	~ 1 μA_{rms} (parameter dep.)	Uncalibrated
ICT	≥ 1 nA_{rms} (20 Hz) [6s]	Calibrated, bunched beam
BPM	~ 100 pA_{rms} (20 Hz) [6]	Uncalibrated, bunched beam

LIMITATIONS

The CCC primarily is a diagnostic to monitor small, gradual changes of the beam intensity of (coasting) beams with high precision. When intensities are larger, the associated slew rates during the injection of the bunched beam can easily exceed the slew rate limit of the detector of approximately 0.16 μA/μs (with f ≤ 200 kHz) [2]. Excessive slew rates lead to local artefacts or to a measurement offset. The slew rate limit at higher frequencies depends on the corresponding pick-up sensitivity of the CCC, which significantly drops beyond 200 kHz.

Figure 4 shows the beam current of a deuterium D^{+} beam measured by the CCC and by the PCT, which was used as a reference signal. The signal of the CCC is distorted during most of the accelerator ramp due to a slew rate of the bunched beam that exceeds the limitation of the detector. Once the revolution frequency is larger than the sensitive bandwidth of the CCC of 200 kHz, the signal can be tracked accurately and can be used to obtain the absolute beam current. Any offset of the CCC measurement as a result of the exceeding slew rate can be corrected using the zero-current baseline of the empty accelerator after the beam dump. Effectively, only the information about the beam intensity during the time in which the slew rate was exceeded is lost.

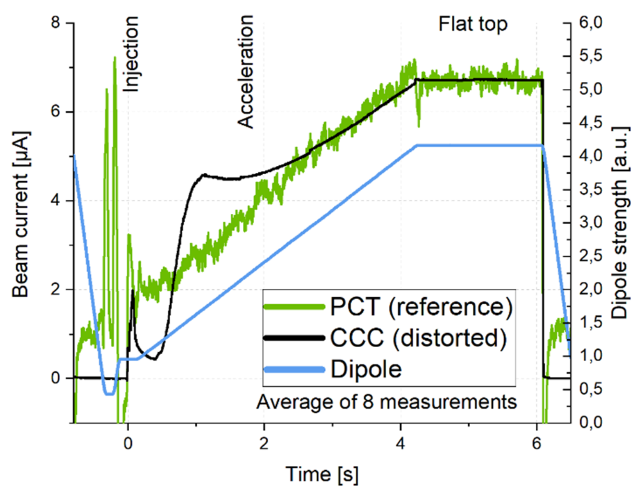

Figure 4: Averaged current measurement of a bunched beam of deuterium D^{+} (5 MeV/u with revolution frequency of 572 kHz at flattop) with the PCT (green) and with the CCC (bandwidth of 200 kHz). The dipole ramp is shown in blue.

In order to increase the slew rate limit of the CCC the sensitive bandwidth of the pick-up can be reduced. Following the first measurements with beam, a low-pass filter with a 3dB-bandwidth of 11.3 kHz was installed to the pick-up of the CCC to reduce the sensitivity at the typical operating frequencies at CRYRING (≥ 130 kHz). In principle, arbitrary signal filters can be installed to adapt the CCC to the required slew rates. However, each resistance adds a thermal noise to the system that can significantly deteriorate the current resolution of the CCC. Therefore, a balance between the required low-current resolution and

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the maximum slew rate must be found depending on the operating scenario. An improvement of the maximum slew rate of the CCC detector itself based on two parallel, specialized SQUIDs is currently under investigation.

CONCLUSIONS

The results of the test of the FAIR CCC prototype at CRYRING is highly satisfactory. The cryostat works as expected, providing a reliable shield for external disturbances (magnetic and mechanical ones) and a stable temperature and pressure environment for the CCC. This allowed us to perform the measurement in the noisy accelerator environment maintaining a resolution almost comparable with the one achieved in the laboratory (better than 10 nA).

The comparison of the measurement collected by the CCC with the ones obtained with standard instrumentation is highly promising. Even if our CCC is still a prototype it showed a better resolution than all the standard detectors used for monitoring coasting beams in CRYRING allowing access to high-precision measurement of beam current also for coasting beams that are often requested by experiments. At the same time, the CCC provides a fast, non-destructive measurement of low-intensity beam currents.

As expected, the measurement performed with the CCC is independent from the ion species. The test performed with a full spectrum of ion species and beam conditions has shown accurate measurement results and better resolution than the one achieved with the standard instrumentation.

FUTURE PLANS

The prototype of the CCC has still an improvement margin. The future plans regarding the development of the new CCC have two main directions that we will discuss briefly: the first is the optimization of the cryogenic support system and the second is the development of a new CCC for better performance of the detector itself.

For the optimization of the cryogenic support system the focus is on the resolution of the problems regarding the limited operation time, which is in contradiction with to the requirement of a stand alone system. With the development of a new thermal shield with improved enthalpy cooling on the helium exhaust line it's possible to maximize the liquefier efficiency. Moreover, an active pressure control system is under development, this system will allow us to keep the pressure at the required value for maximum liquefier performance. Moreover, we are working on reducing the heat load inside the cryostat, thanks to additional placement of Multi-Layer Insulation (MLI) and minimization of the possible heat input sources.

Furthermore, we are working on the development of a new CCC made from lead, coreless and with an axial shield geometry. This new model is expected to be less sensitive to external perturbations, in particular low-frequency ones, caused by magnetic field caught inside the core material [7] (for CCC version with core) and by mechanical disturbances, allowing an increase of the resolution of the detector itself. Moreover, it will also allow us to increase the slew rate limit, thanks to the implementation of two parallel SQUID systems. This allows us to track faster slew rates and therefore to increase the dynamic range of the CCC. Our desired value should be 10 times higher, to cover the full intensity range at all locations of GSI and FAIR. The slew rate limitations that have been found during our measurement in CRYRING will be checked in a new measurement campaign with the coreless lead axial CCC.

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