# DIFFERENT VERSIONS OF CRYOGENIC CURRENT COMPARATORS WITH MAGNETIC CORE FOR BEAM CURRENT MEASUREMENTS*

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## *Abstract*

For more than 20 years Cryogenic Current Comparators (CCC) are used to measure the current of charged particle beams with low intensity (nA-range). The device was first established at GSI in Darmstadt and was improved over the past two decades by the cooperation of institutes in Jena, GSI and CERN. The improved versions differ in material parameters and electronics to increase the resolution, and in dimensions in order to meet the requirements of the respective application.

The device allows non-destructive measurements of the charged particle beam current. The azimuthal magnetic field which is excited by the beam current is detected by a low-temperature Superconducting Quantum Interference Device (SQUID) sensor. A complex shaped superconductor cooled down to 4.2 K is used as magnetic shielding and a high permeability core serves as flux concentrator.

Three versions of the low-temperature superconducting CCC shall be presented in this work: (#1) GSI-Pb-CCC which was running at GSI Darmstadt in a transfer line, (#2) CERN-Nb-CCC currently installed in the Antiproton Decelerator at CERN and (#3) GSI-Nb-CCC-XD which will start operation in the CRYRING at GSI 2019. Noise, signal and drift measurements were performed in the Cryo-Detector Lab at the University of Jena.

## INTRODUCTION

The first CCC with magnetic core for beam current measurements #1 was running at GSI in the late 90's. The motivation to build such a device was the necessity of a non-destructive online beam diagnostics instrument for small beam currents. Based on extraction times of 1 – 10 s, the currents of a high energy beam transport system can widen to some hundreds of nanoamperes. Many detector working principles, i.e. scintillators or ionization chambers, are based on the interaction between a material and the beam which affects the beam. The CCC was the only device which was able to fulfil all requirements for non-destructive, online, radiation resistant measurements with a device which is suitable for vacuum and enables an absolute calibration [1].

The good functionality of this prototype triggered further development of CCC's for beam current measurement. To measure other beam low particle beam intensities and slow extraction processes it was necessary to increase the resolution. Additionally, further improvement of the bandwidth was achieved. Two improved version of the CCC accommodating a larger beam diameter, presenting a better shielding against external fields, and using different material for the shielding and the core were developed (#2) (#3). The shielding efficiency in dependence of the inner and outer diameter of the magnetic shield was investigated and optimized by extensive simulations [2, 3].

Table 1: CCC Dimensions

| CCC- Sensor | (#1) | (#2) | (#3) |
|---|---|---|---|
| Completed | 1992 | 2013 | 2017 |
| Diameter (mm) | | | |
| inner/ outer | 147/ 260 | 185 / 280 | 250 / 350 |
| Length (mm) | 95 | 193 | 207 |

## OPERATION PRINCIPLE

The operation principle is the same as for a commercially available AC current clamp measuring the current flowing in an electrical conductor using the transformer principle (see Fig. 1). Here the primary winding is the conductor to be examined and the signal in the secondary winding serves as a measure of the current in the conductor.

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A magnetic core is mostly used to enhance the coupling between windings.

To make sure that only the magnetic-flux change due to the beam current is measured, the system should be shield from other external time-varying magnetic fields. The Meissner effect is exploited to set up a shielding. Furthermore, a high resolution is achieved by measuring the secondary current with a SQUID which is an extremely sensitive DC- and AC-ampere meter.

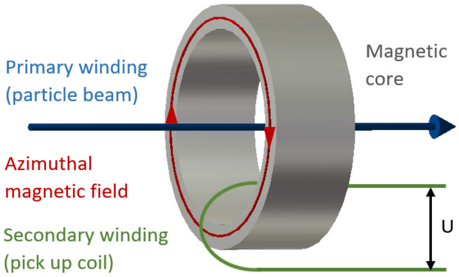

Figure 1: Basic operation principle of AC current clamps.

### *Superconducting Pick-Up Coil*

For all three CCC-sensors, the pick-up coil is made of niobium and has one winding around the core. Because the permeability of the core material can vary along the circumference, due to mechanical stresses during cool down or fabrication, a fully enclosing toroid with a slit on one side was placed around the core. Hereby an averaging of the signal is realized which minimizes the influence of permeability variations on the measurement signal [4]. It is important to note that the pick-up coil is superconducting to enable the measurement of a DC beam due to the flux conservation in superconducting loops.

### *Core Material*

Different core materials were tested to find the most appropriate one with a high permeability at liquid helium temperatures. According to [5] Vitrovac 6025 and the nanocrystalline Nanoperm are the most promising candidates. The material Vitrovac 6025 has a higher relative permeability than Nanoperm and was used for the GSI-Pb-CCC (#1). Further measurements showed that Nanoperm could be more adequate for low temperature current transformers. It is more convenient because of a lower noise contribution and the lower frequency dependence of the permeability [5].

### *SQUID*

The sensor for detecting the small magnetic fields produced by the particle beam is a DC-SQUID which is based on the principle of flux quantization and the Josephson effect. A DC-SQUID consist of a superconducting loop interrupted by two Josephson junctions - small barriers which can be overcome by the cooper pairs due to quantum tunneling [6]. The magnetic flux in the SQUID loop determines the current through the Josephson junctions which is measured by SQUID electronics. If the SQUID is used as an ampere meter, an input coil generating a flux in the SQUID loop is integrated in the SQUID. For the coupling between the high-inductance pick-up coil and the low-inductance input coil of DC-SQUID a matching transformers can be used.

### *Shielding*

In an accelerator environment, background fields need to be minimized in order not to hide the small magnetic fields generated by the particle beam. This can be achieved using a superconducting shielding. The simplest variant of the shielding is a long tube open on both sides. The screening current flowing on the tube surface prevents the external fields to enter inside the shielding. The attenuation factor of such a shielding depends on the tube length. Because of space constraints, the tube can be squeezed as a meander as shown in Fig. 2. It is either made of a lead (#1) or niobium (#2 and #3) and is cooled down to 4.2 K. The advantages of niobium over lead as material for applications with large beam tube diameters and many meanders is the material stiffness.

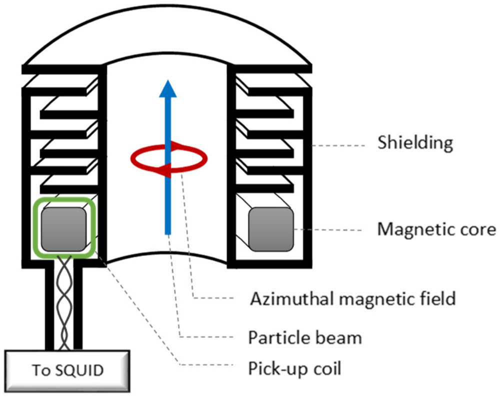

Figure 2: Basic components of CCC's used for beam current measurements.

## MEASUREMENTS

All three versions of the CCC were measured in a wide neck cryostat at the Cryo Detector Lab in Jena.

### *Noise Measurements*

The noise measurements between 0.1 Hz and 100 kHz for all versions are shown in Fig. 3. The spectra of (#1) and (#3) were measured in a magnetically shielded room at least 72 h after cool down in 2018. In the frequency range below 2 kHz (1/f-region), (#1) shows up to four times higher noise values than (#3). The different core materials used for the two versions can explain the different noise behaviour [7]. Amorphous Vitrovac was used for (#1) and nano-crystalline Nanoperm for (#3). Between 5 Hz and 100 Hz the core material Vitrovac shows less acoustic sensibility than Nanoperm, thus (#3) measures all the noise induced by the air conditioning engines of a cleaning room based in the same building. The white noise floor at 10 kHz is below 5 pA/√Hz for all three versions.

The measurement conditions of the noise spectra for (#2) were different compared to the tests with (#1) and (#3). The device was measured in a normal lab environment in 2014, but not in the magnetically shielded room. Furthermore, the measurement was performed less than 72 h after the cool down and during the day while (#1) and (#3) were measured during night. Investigations showed improved performance of the system 72 h after the cool down. These differences in the measurement procedure make it difficult to directly compare (#2) with (#1) and (#3). But the spectrum of (#2) shows also the typical nano-crystalline core behaviour. For the implementation of (#2) in the CERN AD ring a 1 kHz RC - low pass parallel filter was added later in front of the SQUID to decrease the rate of the signal change [8]. Hence, the resulting noise spectrum, shown in [8], is thus dominated by resistor thermal noise.

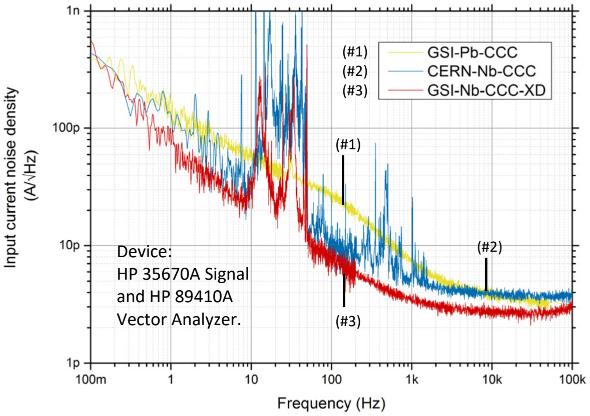

Figure 3: Noise measurements from 0.1 Hz to 100 kHz.

### *Pulse Response and Beam Measurements*

Pulse response measurements in a lab environment can be performed by using a wire representing the particle beam pass through the CCC or by an additional wire wound around the pick-up coil. A well-defined signal is applied to this wire and the CCC response is measured. The additional wire is also used to calibrate the device remotely.

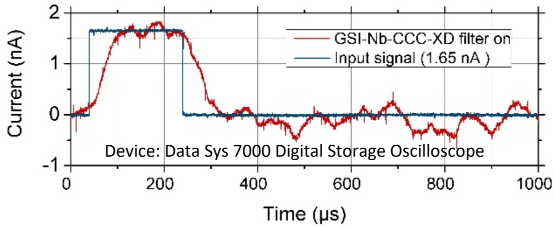

Figure 4: Pulse signal response of (#3) with SQUID electronics and 10 kHz low-pass filter switched on [9].

An example measurement is shown in Fig. 4 for a rectangular 1.65 nA pulse of 200 µs applied to the calibration wire. The pulse form is distorted due to the low-pass filter having a time constant of 16 µs.

In addition to lab signal measurements, successful beam measurements were performed with (#1) at GSI and with (#2) at CERN Antiproton Decelerator. Figure 5 shows a beam intensity measurement of (#2) in the CERN AD in comparison to a Schottky monitor. The improvement of the measurement obtained using a CCC is clearly visible with observed resolution of 3 nA, and maximum long-term drift of 25 nA over a cycle of ~100s [8,10].

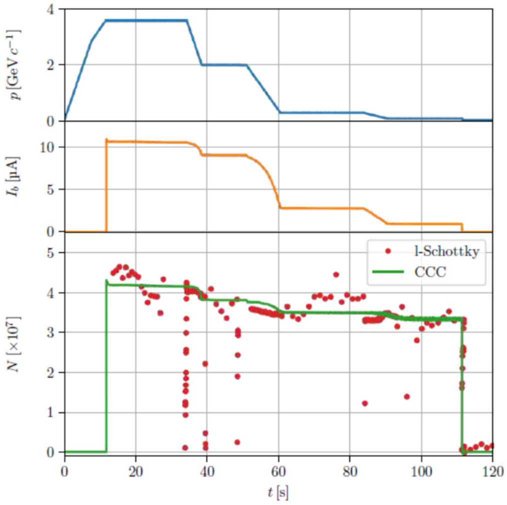

Figure 5: CCC beam intensity measurement and comparison with Schottky monitor. Top: magnetic cycle; Middle: measured beam current; Bottom: beam intensity measurements by (#2) and with Schottky monitor [8].

### *Thermal Drift*

For the application of SQUID together with a highly permeable core, the core material dominates the thermal drift [2,11]. During systematic tests at the Cryo-Detector Lab, the temperature drift measurement of (#1) and (#3) was realised by changing the pressure in the cryostat and monitoring the resulting change in temperature and the SQUID signal. For (#3) the thermal drift was measured also monitoring the SQUID signal during warm up from 2.16 K to 4.20 K at atmospheric pressure. A drift of 30 nA/mK (#1) and 15 nA/mK (#3) was measured. Pressure drifts while keeping the temperature constant were not observed.

## CONCLUSION

The first prototype (#1) was installed in the HEBT transport line at GSI with a beamline diameter of 100 mm. Due to other beam line requirements at FAIR (diameter 150 mm), the device dimensions needed to be increased. Based on the simulations for magnetic shielding efficiency, the investigations of core material and the adaption of the SQUID circuit this increase was successful without any loss of system performance. The second version CERN-Nb-CCC is running in a storage ring at CERN. By optimizing the core material, the white noise decreased down to 3 pA/√Hz. Even further improvement would be possible by cooling the device below 2.16 K. The GSI-Nb-CCC-XD showed good performance in the lab environment. Pulses of 1.65 nA can be measured with the device and the installation in the GSI CRYRING is in preparation. Further optimization of the system is planned by testing an active vibration control system. In addition a new CCC type without core is in preparation [12].

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