

# NEXT GENERATION CRYOGENIC CURRENT COMPARATOR (CCC) FOR nA INTENSITY MEASUREMENT\*

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## Abstract

A Cryogenic Current Comparator (CCC) is an extremely sensitive DC-Beam Transformer based on superconducting SQUID technology. Recently, a CCC without a toroidal core and with an axially oriented magnetic shielding has been developed at the Institute of Photonic Technologies (IPHT) Jena/Germany. It represents a compact and light-weight alternative to the ‘classical’ CC, which was originally developed at PTB Braunschweig/Germany and is successfully in operation in accelerators at GSI and CERN. Excellent low-frequency noise performance was demonstrated with a prototype of this new CCC-type. Current measurements and further tests are ongoing, first results are presented together with simulation calculations for the magnetic shielding. The construction from lead as well as simplified manufacturing results in drastically reduced costs compared to formerly used Nb-CCCs. Reduced weight also puts less constraints on the cryostat. Based on highly sensitive SQUIDS, the new prototype device shows a current sensitivity of about  $6 \text{ pA/Hz}^{1/2}$  in the white noise region. The measured and calculated shielding factor is  $\sim 135 \text{ dB}$ . These values, together with a significant cost reduction - resulting also from a compact cryostat design - opens up the way for widespread use of CCCs in modern accelerator facilities.

## INTRODUCTION

The Cryogenic Current Comparator measures the beam intensity via detection of the beam azimuthal magnetic field. It consists of a superconducting shielding, which provides an attenuation of non-azimuthal external fields of  $< -100 \text{ dB}$  and guides the Meissner-Current to the internal pickup loop, which is basically a one-winding coil around a high permeability ring core, acting as a flux concentrator. The latter is used in the ‘classical’ CCC shown in Fig. 1 to ensure efficient coupling of the beam magnetic field to the SQUID circuit. The arrangement can be regarded as a transformer with the particle beam being the primary winding and the pickup coil the secondary winding. The signal

from the pickup coil is fed (via a matching transformer for impedance matching) to a DC SQUID (Superconducting Quantum Interference Device) current sensor [1], which is operated in a compensation circuit, using a so called Flux Locked Loop (FLL) electronics [2]. Figure 1 shows the currently used arrangement, originally developed at the PTB (Physikalisch-Technische Bundesanstalt) [3].

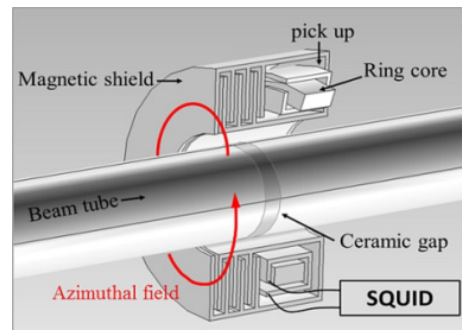


Figure 1: Principle of the CCC, shielding with radial mandrels and high permeability ring core.

The ‘classical’ CCC, as it is shown in Fig. 1, has been operated successfully in accelerator beamlines at GSI [4] and CERN [5], measuring currents  $< 10 \text{ nA}$  at bandwidths  $2 - 10 \text{ kHz}$ . For the FAIR project at GSI, where significantly larger detector dimensions are required, a so called CCC-XD (eXtended Dimensions, inner/outer diameter:  $250\text{mm}/350\text{mm}$ ) relying on the classical design has been developed and was in the meantime extensively tested in the laboratory [6]. Despite the fact that shielding efficiency is anti-proportional to shielding inner diameter, the CCC-XD showed - due to careful shielding design [7], toroid material choice [8] and SQUID circuit design - a performance comparable to its predecessors. The magnetic shielding is (like for the CERN/AD CCC, inner/outer diameter:  $185\text{mm}/280\text{mm}$ ) made from Niobium, which is - simply regarding its mechanical properties - considered the best choice for CCCs at large dimensions. The much smaller GSI CCC prototype (inner/outer diameter:  $147\text{mm}/260\text{mm}$ ) was built from Lead. Recent developments at IPHT Jena have shown that it is possible to build a CCC without toroidal core, using at the same time a

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shielding with axial meander shape [9]. Figure 2 shows this new design in comparison to the classical CCC, it has again two varieties, in version A the pickup-volume is located close to the beamline while in version B the meanders are at the inner side. It was found that version A provides better coupling of the beam to the detector but suffers from lower shielding factor, while version B behaves exactly the other way round. So principally the two versions are equivalent concerning current resolution, however, for practical and mechanical reasons, version A is preferred. As a matter of fact, the pickup wire can no longer be a winding around the toroid, but is connected directly to the shielding, which now fulfills function of shield and pickup at the same time.

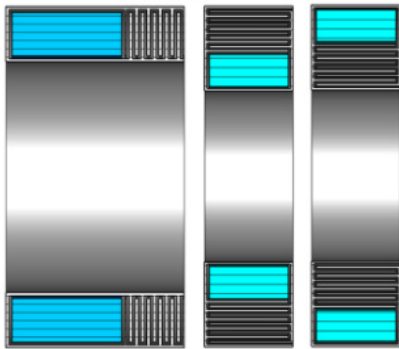


Figure 2: Magnetic shieldings wit radial (left) and axial meanders. Version A (middle), version B (right). The ring-core of the radial CCC is indicated in blue, the detector volume of the axial CCC in turquois.

From this new shielding/pickup design a number of advantages are expected, like reduced magnetic noise and baseline drift from the toroidal core, drastically reduced costs and weight by inherent better mechanical stability (which allows for lead as shielding material). Furthermore, the axial structure offers an easy manufacturing and an increased shielding efficiency (verified by simulations, see below). It is currently investigated, to what extent these advantages can be found in practice, first results look promising. The ultimate test will be to build an axial CCC with dimensions identical to the FAIR XD-CCC and compare the performance of the two systems in CRYRING at GSI.

## NUMERICAL SIMULATIONS

Numerical simulations (Comsol Multiphysics<sup>®</sup>, CST EM Studio<sup>®</sup>) have been performed in the first place to scale the attenuation factor of the GSI prototype shielding to larger CCC dimensions. This resulted in the CCC-XD for FAIR, which ended up with a length of 240 mm, resulting from four additional meanders, necessary to maintain the required shielding factor at larger inner diameter. Recent calculations and theoretical developments have been performed to compare the properties of the two competing, radial and axial shielding geometries [7]. Since the required Nb mass and welding efforts are a significant cost-factor of the total system, the required Nb volume at a given attenuation factor has been calculated. Figure 3 shows the result of an extensive mapping. In this matrix-like depiction, iso-

lines for identical number of meanders (dotted) and identical shielding volume in liters (solid, orange) are plotted in a diagram showing outer radius vs. length. The color of each point represents an attenuation value from low attenuation (blue) to high attenuation (yellow). Since the damping is proportional to the meander path length, it is evident, that in the radial case a large number of short meanders is required for high attenuation, while in the axial case a small number of long meanders provides equivalent damping. Since welding effort is proportional to the number of meanders, this represents a clear advantage for the axial design. Moreover, the calculations show, regarding the span of the two spectra, that the shielding efficiency at similar outer dimensions and shield volume is in general higher at the axial version.

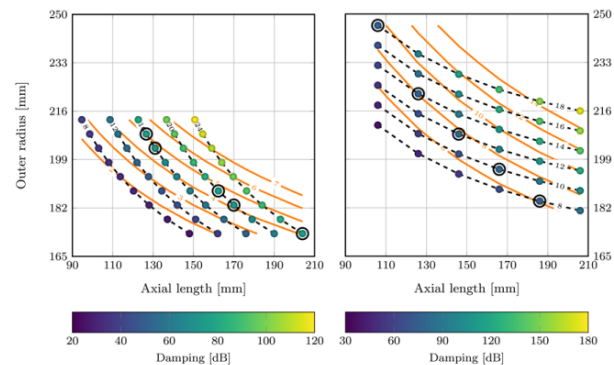


Figure 3: Encircled values represent a  $75 \pm 5$  dB attenuation. Left: radial meanders, right: axial meanders, version A. The inner radius was kept constant at 120 mm. The pickup area is fixed to  $60 \text{ cm}^2$  [7].

## CORELESS CCC DEVELOPMENT

If the path of the Meissner current along the magnetic shielding is interrupted by the input coil of a SQUID, the magnetic field resulting from the screening current can be directly detected with the SQUID. Figure 4 shows how this is realized in the new CCC [9].

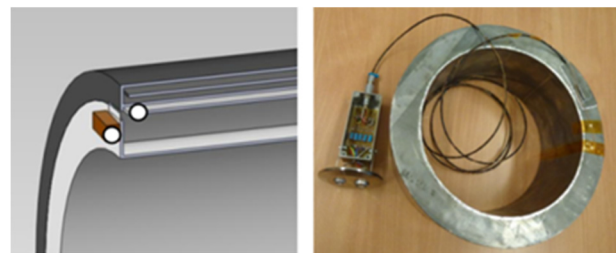


Figure 4: Left: Connection points of the SQUID sensor housed in the brown box. Right: Photo of an axial CCC prototype made from lead, inner diameter 270 mm, 330 mm, length 222 mm, with filter box connected and calibration wire fixed with capton tape.

The SQUID (including the coupling loop and the feedback loop) are located inside the little brown box at the side of the shielding. The interruption of the Meissner current path is indicated by the two white dots. From here the screening current is coupled directly to the SQUID. The transfer of beam current to magnetic flux through the

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SQUID can be described with the inductances of the contributing components like:

$$\frac{\Delta\Phi_{SQ}}{I_{Beam}} = \frac{\sqrt{M_A \cdot L_T \cdot L_{in} \cdot L_{SQ}}}{L_T + L_{in} + L_{par}} \quad (1)$$

where  $L_{in}$  and  $L_{SQ}$  are the inductances of input coil and SQUID,  $M_A$  ( $\equiv L_T$ ) is the coupling of the beam current to the shielding,  $L_{par}$  is the parasitic inductance by cables etc. and  $\Phi_N$  is the magnetic flux through the SQUID. It is obvious, that the flux through the SQUID at a given beam current (and consequently the sensitivity of the detector) depends strongly on the coupling of the beam current to the shielding. Since the relative permeability of the toroidal core, used in the classical CCC, is in the order of  $10^5$ , parasitic inductances play a much larger role in the new, coreless design. Moreover, one can – considering a square-root dependence – expect a loss in sensitivity by a factor of  $\sim 100$  due to the weaker coupling. However, with a significantly reduced background noise, usage of new, specially adapted and highly sensitive SQUIDs with cross-type Josephson junction technology [10] and also without the necessity of a matching transformer between pickup and SQUID, we expect to reach the sensitivity level of the classical CCC with a much simpler and economic device. Numerous noise spectra have been measured under various conditions, clearly showing a noise reduction  $< 5$  Hz of at least one order of magnitude. Recently tests with pulsed currents have been performed in the Jena cold lab, which proved the capability of measurements in the region of several nA with the coreless CCC (see Fig. 5).

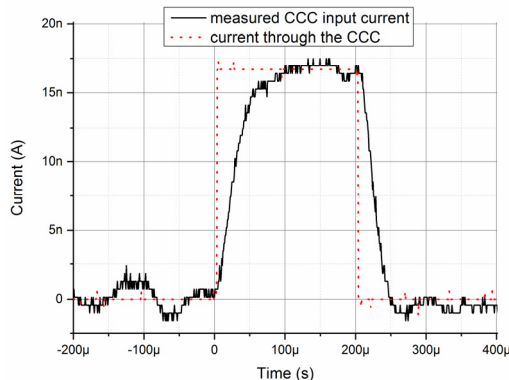


Figure 5: Measurement of a 200  $\mu$ s, 17 nA current pulse from calibration wire with the coreless CCC.

### CCC CRYOSTAT FOR CRYRING

For the test of the new CCC and as a prototype for the CCCs in the FAIR facility a dedicated cryostat has been designed and is currently under production. The outer dimensions of the isolation vacuum vessel are 1.2m x 0.8m x 0.8m. It consists of a stainless steel frame, covered by numerous Aluminum windows, which allow access to all components of cryostat and CCC. A LHe container is located in the center, surrounded by a thermal shielding made from copper. It is fixed by suspension wires, anchored in the corners of the isolation vacuum tank. Figure 6 shows the design of the cryostat. It includes a cold head on the

bottom of the tank, which can be used to support the enthalpy cooling of the thermal shield by evaporated Helium. However, the strong mechanical vibrations of the cold head require switching it off during measurement, therefore strong efforts have been made to realize the system with enthalpy cooling only, similar to the cryostat of the CERN AD-CCC.

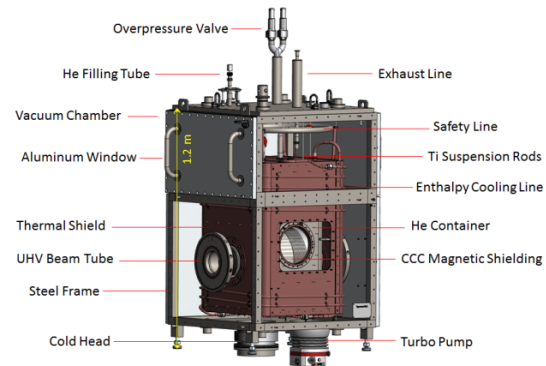


Figure 6: Design of the cryostat for the CRYRING and FAIR CCCs.

In our case, the cooling line around the thermal shield has a length of  $\sim 15$ m at an inner diameter of 10 mm, we expect a shielding temperature of  $\sim 100$  K at an evaporation rate of maximum 15 liters/day. Due to the well-known sensitivity of the CCC to temperature- and pressure fluctuations [11], stability of the system is our main concern. A complex cryo-system for gas handling and re-liquefaction is currently under construction. Our cryostat will work in connection with a Cryomech<sup>®</sup> HeRL15 He-liquefier, which has recently been tested at the old GSI prototype CCC, showing excellent handling and performance. In a second stage, additionally to the cryogenics tests, the mechanical properties of the combination cryostat/liquefier will be investigated, using the SQUID system of the prototype to measure vibrations from pulse tube coolers, pumps and magnets.

### SUMMARY AND OUTLOOK

The CCC-XD for FAIR has been tested and showed excellent performance in the laboratory. At the same time, the cryostat for the installation of the CCC-XD in CRYRING is in production. It is designed to serve as a testbench for CCC development and will work as a stand-alone system in connection with a He-liquefier. At IPHT Jena, a new type of CCC without toroidal core and with an axial meanders has been developed. This new variety offers several advantages compared to the classical PTB- design, like reduced magnetic noise, easy manufacturing, low weight and (last not least) low costs. Measurement of pulsed nA currents has been demonstrated. Our goal is to test both CCC-types under accelerator conditions in CRYRING in 2020.

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