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CRYOGENIC CURRENT COMPARATORS (CCC) AS LOW INTENSITY DIAGNOSTICS FOR ION BEAMS*

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Abstract

The Cryogenic Current Comparator (CCC) is a SQUID based superconducting device for intensity measurement. It was firstly proposed as a beam diagnostics instrument in the mid ´90s at GSI. After prove of principle the CCC was introduced into other facilities, showing great potential for high resolution measurements as well as raising considerable mechanical and cryogenics challenges and costs.

In the course of planning for FAIR the CCC has been revitalized. Systematic investigations started - also involving now commercially available SQUID systems - which led to improvements of detector and cryostat. The developments resulted in nA spill measurements at GSI (2014) followed by the installation of a CCC in CERN Antiproton Decelerator (AD), which has become a key instrument.

Since then optimization of the device is ongoing, with respect to various operating conditions, system robustness, current resolution and last but not least system costs. Alternative CCC versions with improved magnetic shielding have been developed as well as ‚Dual Core' versions for background noise reduction. We give an overview of CCC optimization and development steps, with focus on applications at GSI and FAIR.

INTRODUCTION

The Cryogenic Current Comparator measures the beam intensity via the beam azimuthal magnetic field, which is for nA currents in the fT range. The device consists of a superconducting shielding, which provides an attenuation of non-azimuthal external fields in the range -70 dB to -140 dB, depending on the shield geometry (see below). The shielding guides the superconducting Meissner-Current (compensation current for the beam magnetic field) to the internal pickup loop, which allows for DC measurements as a matter of principle. The pickup loop 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) magnetometer, which is operated in a compensation circuit, using a so called Flux Locked Loop (FLL) electronics [1]. Figure 1 shows the currently used arrangement, originally developed at the PTB (Physikalisch-Technische Bundesanstalt) [2] and adapted to the accelerator application at GSI [3].

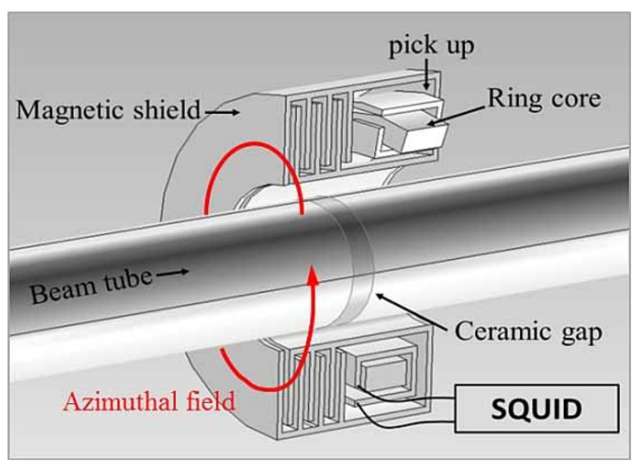

Figure 1: Classical CCC, shielding geometry with radial meanders and high permeability ring core.

Recent developments at IPHT Jena have shown that it is possible to build a CCC without toroidal core, using a shielding with axial meander geometry [4], consequently the device is called coreless or axial CCC (see Fig. 2). This

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new shielding/pickup design promised a number of advantages, like reduced magnetic noise and baseline drift (both mainly caused by the toroidal core), significantly reduced costs and weight due to inherent better mechanical stability (which allows for lead as shielding material). Furthermore, the axial structure offers an easy manufacturing and most of all a significantly increased shielding efficiency.

In addition to the two mentioned CCC varieties, a third CCC type is currently under investigation, which combines the axial meander geometry with a doubled classical toroidal core pickup [5]. This version, called the double core CCC or DCCC, is an attempt to combine and improve the positive features, which have been identified at the different CCC systems so far. Figure 2 shows the three CCC types schematically.

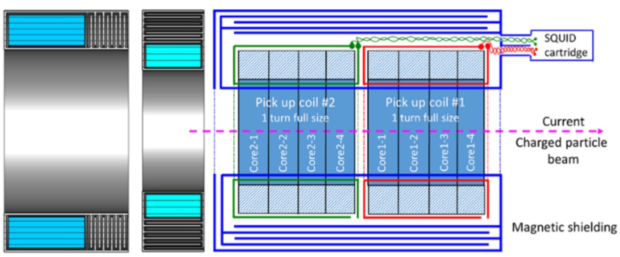

Figure 2: Magnetic shieldings with radial (left) and axial (middle) meanders. The ring-core of the radial CCC is indicated in blue, the detector volume of the axial CCC in turquois. Right: Schematic sectional view of the DCCC with axial meanders and two independent, fourfold segmented (due to material width limitations) toroidal cores.

CLASSICAL (RADAL) CCC

The classical CCC, as it is shown in Fig. 1, has been operated successfully in accelerator beamlines at GSI [6], and CERN [7], measuring currents <10 nA at bandwidths 2-10 kHz. For FAIR, significantly larger detector dimensions are required, therefore a so called CCC-XD (eXtended Dimensions, with inner/outer diameter: 250 mm/350 mm) has been designed and extensively tested in the laboratory [8] and in CRYRING [9]. Although shielding efficiency is anti-proportional to shielding inner diameter, the CCC-XD reached - due to careful shielding design, toroid material choice [10] and sophisticated SQUID electronics and controls [11] - a performance similar or better than its predecessors. The magnetic shielding provides (like for the CERN/AD CCC with inner/outer diameter: 185 mm/280 mm) an attenuation of external fields of -70 dB. It is made from Niobium, which is - regarding its mechanical properties - considered the best choice for CCCs at large dimensions. The much smaller GSI CCC prototype [3] (inner/outer diameter: 147 mm/260 mm) was built from Lead.

The CCC-XD, in combination with its specially designed cryostat [12], was originally considered to be the first of series for five planned CCC systems at FAIR. Nonetheless, already during its construction and assembly, investigations on the coreless axial CCC (see below) started in parallel, with the goal to eliminate unwanted effects (low frequency Barkhausen noise, temperature dependent offset drift, microphony) related to the toroidal core. Moreover, a more efficient magnetic shielding seemed desirable because of the disturbing influence of nearby dipole and quadrupole magnets (see Fig. 3). Despite these drawbacks, the prototype of the CCC-XD was operated successfully in CRYRING@ESR, showing with appropriate filtering of dipole and cryostat effects (see Fig. 3) a current resolution <10 nA at 10 kHz bandwidth. Slew rate problems at higher currents and fast rise-times could be solved by damping the SQUID circuit with an inductive load. Figure 4 shows such a 'high current' measurement in CRYRING with CCC in comparison to standard diagnostics, IPM and DCCT (Bergoz PCT).

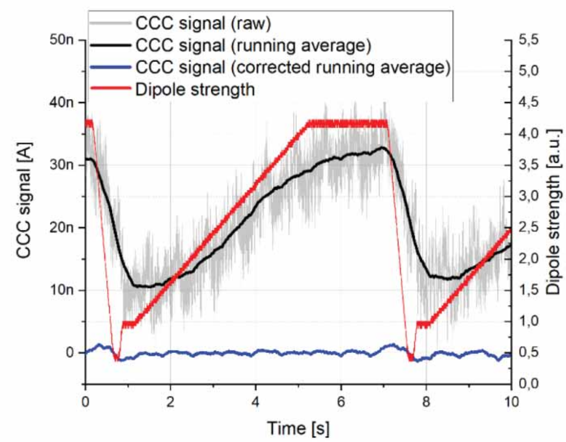

Figure 3: Effect of dipole ramp in CRYRING on CCC-XD measurement. Since the dipole ramp is deterministic it can be subtracted with an appropriate transfer function. The 1.4 Hz pertubation from the cryostat pulse tube cooler, visible on the raw signal, was eliminated by a software bandblock filter (1-3 Hz) [9].

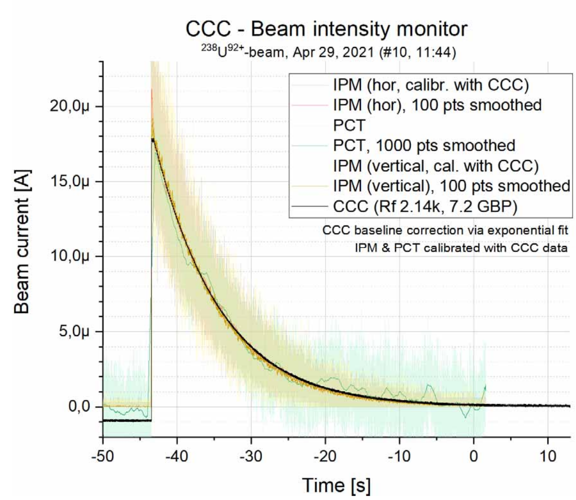

Figure 4: CCC current measurement compared to IPM and PCT in CRYRING. Rf = Feedback resistor value, GBP = Gain Bandwidth Product of the SQUID electronics [9].

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Independent from parallel and future steps of CCC development, it could be demonstrated in CRYRING that the classical CCC system is appropriate for nA current measurement at slow extracted beams in transfer lines and low intensity exotic ion beams in the storage rings at FAIR. Room for optimization was identified in the requirement of filtering external (periodic) disturbances, the necessary slew rate damping (which reduces current resolution) as well as in the high costs of the system, mainly because of the Niobium shielding.

AXIAL CCC DESIGN

As a solution for some of the above mentioned problems a coreless CCC with axial meander geometry has been proposed by IPHT Jena. In this design the SQUID is directly connected to the inner part of the shielding, which becomes therefore pickup coil and shielding at the same time. Figure 5 shows on the left hand side a cross section of the shielding torus.

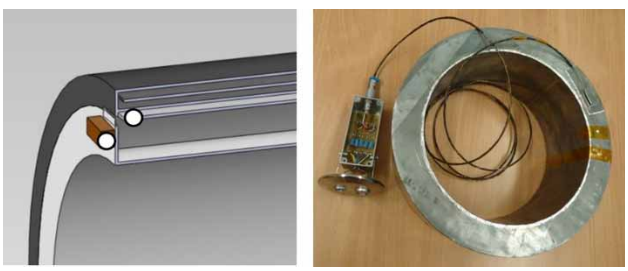

Figure 5: Alternative shielding geometry with axial meanders (left), the SQUID, housed in the little brown box, is connected between the two marked dots. Right: prototype of the Axial CCC made from Lead with attached SQUID electronics.

Compared to the classical CCC, the production of the axial version is much simpler, due to the possibility of wrapping lead sheets around a GFK carrier (compared to electron beam welding of the Niobium meanders). The costs for the shielding/pickup are therefore significantly reduced (to ~1/10). Another big advantage of this design is the improved magnetic shielding. From the analytical model in Ref. [2] as well as from FE simulations [13] it was shown that the shielding efficiency depends basically on the path length of the meanders. Since each of the axial meanders has the full length of the detector, a comparatively small number of meanders is sufficient to provide a much higher damping than with the classical shielding. Realistic values are -140 dB instead of classical -70 dB, the high attenuation factor could be verified in laboratory tests and can to large extent solve the problem of interference from nearby magnetic elements.

Since the high permeability ring core is omitted, the coupling of the axial pickup to the beam is much weaker than in the classical setup. The pickup inductance now depends completely on the detector volume (Fig. 5, left, volume below the meanders) and is in the order of nH, compared to µH with toroidal core. This has on the one hand the advantage of matching the pickup to the SQUID inductance (~10 nH) without necessity of a matching transformer (which might introduce its own thermal noise and slew rate problems), on the other hand, the signal from the beam magnetic field is much weaker (by a factor ~100) and parasitic inductance (e.g. connection cables) play a bigger role. The basic question during axial CCC development was, if the lower signal strength would be compensated by the improved noise properties and SQUID coupling, resulting in an improved SNR. First evidence that this trade off might not work out was the detection of an unexpected high intrinsic noise in the range between 1 Hz and 1 kHz measured on the axial CCC prototype during laboratory tests. Figure 6 shows for comparison a noise spectrum from the CCC-XD (blue) compared to the axial CCC (black). The expected positive effect from the missing core is not evident, even at very low frequencies <1 Hz. Also in the critical region for microphonic effects (~10-100 Hz) the noise of the axial CCC is an order of magnitude higher.

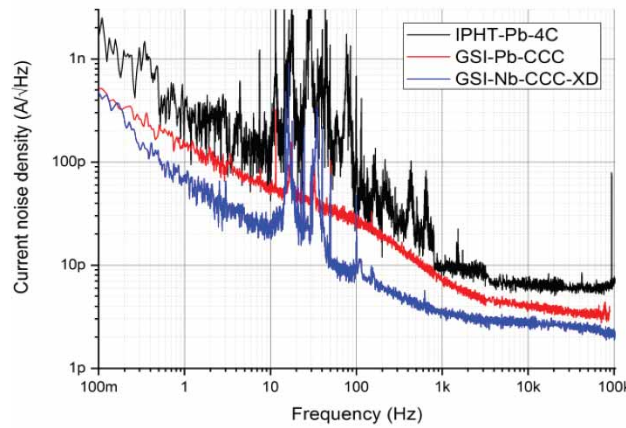

Figure 6: Noise spectra measured at the FAIR CCC-XD (blue), the GSI prototype from [3] (red) and one of the first prototypes of the axial CCC, shown in Fig. 5.

This result is still analyzed and under discussion, damping properties of the matching transformer and the toroidal core might play a bigger role than expected. Also, the exact reproduction of this measurement is quite difficult. Nonetheless, from recent laboratory tests it also seems that the axial pickup is extremely sensitive to rf-disturbances, a kind of influence that can (partially) be shielded in the laboratory, but not in the accelerator environment, since it propagates along the beamtube, through the detector.

A detailed report from development work and latest test measurements can be found in Ref. [14]. The application of the axial detector at FAIR seems at the moment questionable and has to be further investigated. In any case we consider the cost reduction due to axial meander production from Lead and the superior magnetic shielding properties as extremely valuable results from axial CCC development.

DUAL CORE CCC (DCCC)

The DCCC was originally designed to eliminate the low frequency disturbances from magnetization jumps, which have been observed in the Nanoperm© toroidal cores. Since these jumps occur randomly in each core, they can easily be subtracted from the beam current signal (seen by both pickups/cores simultaneously), which leads to an improved SNR.

Since the CCC-XD for FAIR had so far the best noise behaviour and current resolution, the components chosen for the pickup and SQUID system of the DCCC were identical to the CCC-XD. To combine all advantages our CCC systems have shown so far and to facilitate the production (and reduce costs) the magnetic shielding was designed as an axial type, built from lead, which resulted in a setup like shown in Fig. 2, right. Figure 7 shows a completed prototype of the DCCC with 300 mm outer diameter and closed axial shielding.

Figure 7: DCCC prototype, built from lead with diameter 300 mm and length 600 mm. Left: Pickup coils #1 and #2 mounted to the inner cylinder of the shielding (covered with tape). Right: DCCC completed and closed, with the outer meander shielding and the SQUID housing.

The DCCC has been extensively tested to investigate the influence of different geometries and magnetic core materials on the current noise density and in particular on resonant behaviour and eigenmodes of the system, which have strong influence on the current resolution as well as on operation stability [15]. Additional use of mu-metal shielding was tested as well as different ways of connecting the pickup coils (e.g. in series and parallel).

During this process it could be shown that inversely connected SQUIDS will suppress the influence of high frequency noise by adding the SQUID signals either analogue by differential amplifier or digitized via software differentiation. In total the optimization of the CCC LC circuit (L: pickup inductance, C: meander capacitance) together with the elimination of Barkhausen and rf noise lead to a strongly reduced noise floor. Figure 8 shows the noise density spectra of the DCCC compared to an advanced axial CCC prototype. Obviously the DCCC noise density is much lower due to the possibility of noise subtraction by dual core.

Independent from properties of a special CCC type, it could be shown during the same measurement campaign that further noise reduction can be achieved if the system is operated at superfluid Helium temperature (2.1 K), to avoid the disturbances from He boil off.

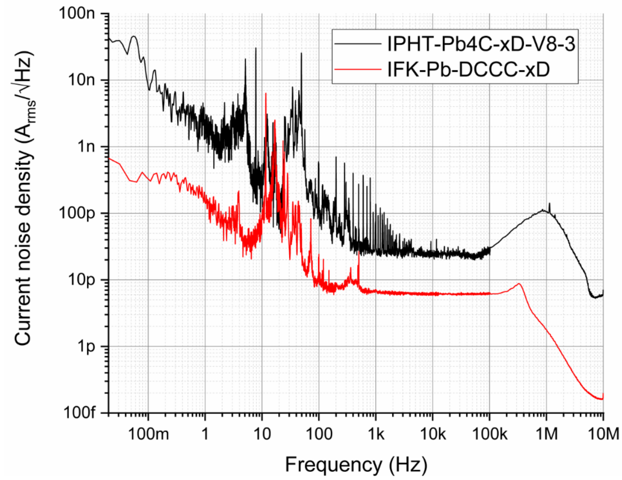

Figure 8: Comparison of current noise from an advanced axial CCC prototype (black) and a dual core CCC (red) at XD-dimensions (outer diameter: 350 mm).

SUMMARY AND OUTLOOK

Two CCC detectors, based on the classical PTB design, made from Niobium, are in standard operation at CERN AD or have shown solid performance in CRYRING at GSI/FAIR. We conclude that our CCC system, the combination of cryostat and classical CCC detector, is appropriate to serve as a basis for nA current diagnostics in FAIR and other machines. In parallel an alternative axial shielding/pickup design has been developed to avoid unfavorable properties of the classical CCC. This axial CCC has recently been tested in the laboratories at Jena and in the beamline cryostat at GSI, it was found to provide a significant improvement concerning magnetic shielding efficiency as well as production effort, materials and costs. However, regarding the current measurement respectively the CCC functionality in general the axial CCC is still suffering from too high sensitivity to background noise and has to be further investigated. As a third variety a dual CCC has been designed to combine the advantages of the two earlier versions. In addition to a high pickup efficiency and superior magnetic shielding properties the usage of two pickups and SQUIDs in parallel provides excellent noise spectra. Beam experiments with the DCCC are planned for 2024.

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