ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG42

FINAL DESIGN OF THE CRYOGENIC CURRENT COMPARATOR FOR FAIR*

T. Sieber†, H. Braeuning, M. Schwickert, GSI, Darmstadt, Germany
L. Crescimbeni[1], F. Schmidl, M. Stapelfeld, Friedrich-Schiller-University Jena, Jena, Germany
R. Stolz[3], M. Schmelz[3], V. Zakosarenko[4], Leibniz IPHT, Jena, Germany
T. Stoehlker[1,2], V. Tympel[1], Helmholtz Institute Jena, Jena, Germany
J. Tan, CERN European Organization for Nuclear Research, Geneva, Switzerland
[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 Technical University Ilmenau, Ilmenau, Germany
[4]also at supracon AG, Jena, Germany

Abstract

Cryogenic Current Comparators (CCC) are ultrasensitive DC-Beam Transformers based on superconducting SQUID technology. With the aim to provide a robust and high resolution intensity measurement for application at FAIR and CERN machines, numerous steps of optimization were carried out over the last years by a collaboration of institutes specialized on the various subtopics. Different types of CCCs with respect to pickup, magnetic shielding, SQUID types and SQUID coupling have been developed and were tested in the laboratory as well as under beamline conditions. In parallel, the cryogenic system has steadily been optimized, to fulfil the requirement of a standalone liquid helium cryostat, which is nonmagnetic, fit for UHV application, vibration damped, compact and accessible for maintenance and repair. We will present the particular development steps and describe the final version of the CCC for FAIR as their outcome. The latest beamtime results are shown as well as recent tests with the cryogenic system. The CCC for FAIR will be a so called Dual-Core CCC (DCCC), which runs two pickups in parallel with independent electronics for improved noise reduction and redundancy. The magnetic shielding will have an axial meander geometry, which provides superior attenuation of external magnetic noise.

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. The shielding guides the superconducting Meissner-Current (which can be a DC current) to the internal pickup loop. The pickup loop is basically a one-winding coil around a high permeability ring core, which acts as a flux concentrator. The ring core is used in the 'classical' CCC as shown in Fig. 1 to provide an efficient coupling of the beam magnetic field to the SQUID circuit. The arrangement is basically a transformer with the particle beam as primary winding and the pickup coil as 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. A second coil is added to apply a calibration current. Figure 1 shows the currently used arrangement, originally developed at the PTB (Physikalisch-Technische Bundesanstalt) [1] and adapted to the accelerator application at GSI [2].

The SQUID is operated in a compensation circuit, using a so called Flux Locked Loop (FLL) electronics, which generates via a feedback system a compensation field to the magnetic field from the pickup circuit. If the working point of the FLL system is locked to the steepest slope of the flux/voltage curve of the SQUID, the resolution can be in the order of $\mu\Phi_0$ (Φ_0 = magnetic flux quantum).

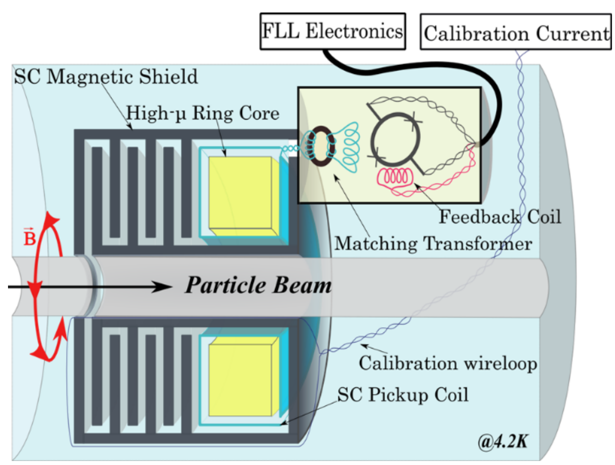

Figure 1: Classical CCC, shielding geometry with radial meanders and high permeability ring core.

Hence the current resolution of the CCC is very much dependent on the stability of the SQUID flux/voltage curve. Another important aspect of the system is its slew rate limitation (min. rise time at a given current), which derives primarily from limited speed of the compensation circuit but is also strongly dependent on background noise and eigenfrequencies of the cold part of the CCC. Figure 2 shows schematically the FLL electronics and the corresponding voltage curve [3, 4].

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG42

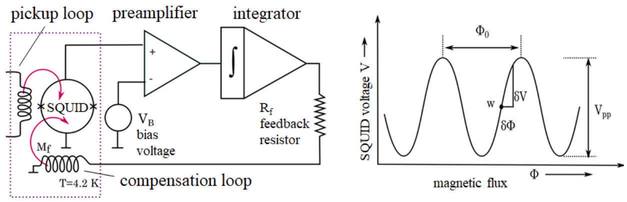

Figure 2: Left: schematic of the FLL electronics. Right: SQUID characteristic flux/voltage curve, W marks the working point of the FLL.

Investigations at IPHT Jena have shown that it is possible to build a CCC without toroidal core, using a shielding with axial meander geometry [5], consequently the device is called coreless or axial CCC, see Fig. 3, middle. This shielding/pickup design provides a several orders of magnitude higher attenuation of external magnetic disturbances due to the increased meander path length. Moreover, it allows for easy manufacturing, significantly reduced costs and weight due to inherent better mechanical stability (which allows for lead as shielding material). However, so far the coreless axial CCC could not be operated in the CCC cryostat due to its weak coupling to beam (resp. calibration) current and its sensitivity to external noise [6].

A third CCC type has been developed and tested in the laboratory at HIJ Jena over the last years. It combines the axial meander geometry with a doubled classical toroidal core pickup [7]. This version, called the dual core CCC or DCCC, is an attempt to combine and improve the positive features of the two earlier types. Figure 3 shows the three CCC varieties at one glance. The DCCC represents our final choice for the CCC systems for FAIR. Beam tests with slow extracted beams from SIS18 synchrotron have been performed.

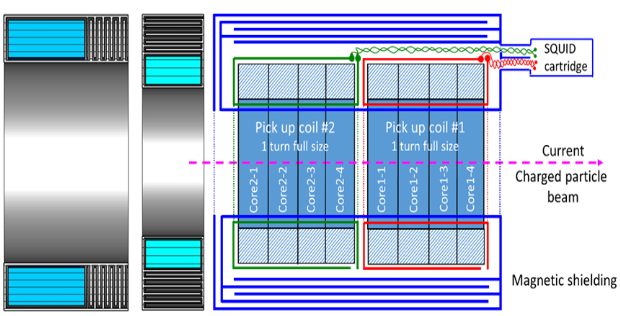

Figure 3: Magnetic shieldings with radial (left) and axial (middle) meanders. The ring-core of the radial CCC is indicated in blue, the detector volume of the axial CCC in turquois. Right: Schematic sectional view of the DCCC with axial meanders and two independent, fourfold segmented (due to material width limitations) toroidal cores.

DUAL-CORE CCC

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. To match the requirements of the FAIR 150 mm beamline and to fit into the cryostat of the FAIR CCC-XD [8, 9], the prototype for beam experiments was designed with a length of 200 mm. inner diameter 250 mm, outer diameter 350 mm. The lead structure has a weight of 39 kg. The magnetic shielding comprises 7 axial meander pairs, each with a total path length of 140 cm. The resulting attenuation of non-azimuthal magnetic fields was determined by Helmholtz coil measurement to < -140 dB (compared to -70 dB with the radial meander shielding).

Since the CCC-XD for FAIR had shown excellent noise behavior and current resolution [10], the components chosen for the pickup (ring core) and SQUID system of the DCCC were identical to the CCC-XD.

During the following optimization process, the DCCC was extensively tested to investigate the influence of different geometries and magnetic core materials on the current noise density and in particular on resonant behavior and eigenmodes of the system, which have strong influence on the current resolution as well as on operation stability. 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 can 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 [11]. Figure 4 shows the noise density spectra of the DCCC compared to an advanced axial CCC prototype.

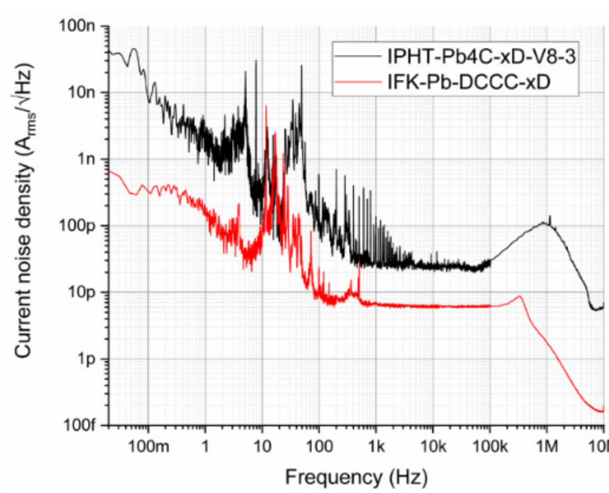

Figure 4: Comparison of current noise from an advanced axial CCC prototype (black) and a dual core CCC (red) at XD-dimensions (outer diameter: 350 mm).

BEAM TESTS

The DCCC was installed in an experimental cave at a SIS18 extraction line to record noise spectra in the

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG42

accelerator environment and to perform spill measurements of slow extracted beams. Besides this a basic FESA class developed for integration of the CCC in the FAIR control system could be tested. We used in a first campaign a 400 MeV/u Erbium 57+ beam with a nominal intensity of $5*10^8$ particles per spill and later a 400 MeV/u Ar 18+ beam with $2*10^9$ particles per spill. Already without beam it was obvious, that the noise behavior of the two SQUIDS was not identical, which is a result of individual material differences and nonsymmetric setup - mainly different orientation of the pickup coils with respect to noise sources and different cable lengths between the two SQUIDS and pickup coils. Figure 5 shows the twofold noise spectrum of the DCCC. The two pickups/SQUIDS are named due to the color of their cables in "red" and "yellow". Remarkably the SQUID with worse noise behavior showed a higher slew rate, means higher stability at fast current changes, which is currently under discussion.

The SIS18 spills had nominal lengths between 100 ms and 1 s. Since the Erbium intensity was quite low, preferably short spills were used to reach reasonable intensities. Figure 6 shows a 30 ms spill at a current of 300 nA with noise filtered and unfiltered. The general noise floor was in the range of 10 nA for the yellow squid and doubled for the red squid, while the 8.4 Hz noise (6^{th} harmonic of the 1.4 Hz liquefier pulse) could even reach 150 nA for the red Squid. While the white noise is random, the main (periodic) perturbation at 8.4 Hz and 30 Hz could be filtered out. The strongest perturbation (8.4 Hz) occurred due to mechanical coupling between liquefier and detector and could be eliminated mechanically.

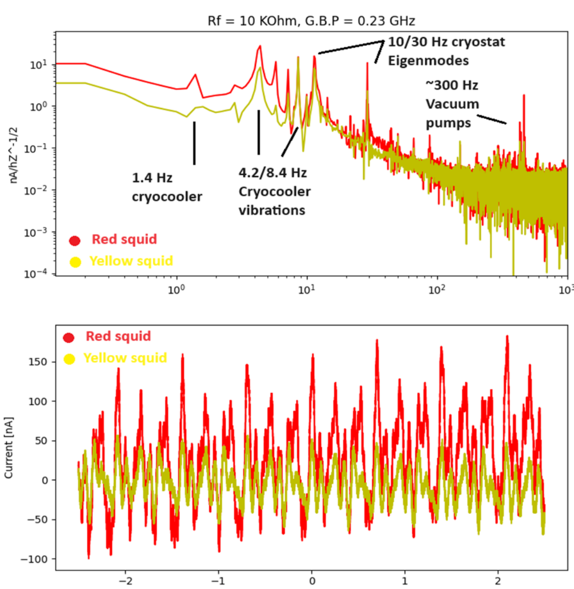

Figure 5: Current noise from the FAIR DCCC prototype, for its two squids. Upper: FFT with main noise sources highlighted. Lower: Noise in time domain.

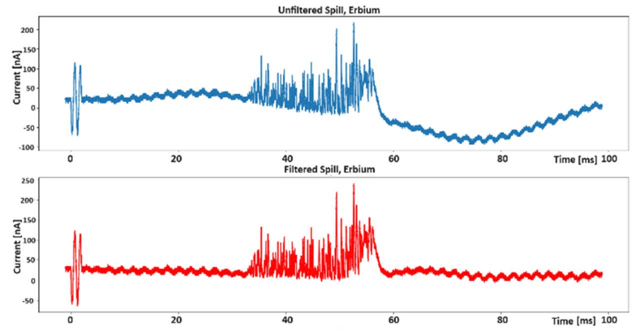

Figure 6: 30 ms spill (Er 57+, $1*10^8$ particles). Upper: unfiltered, lower: filtered (software), both with 120 nA calibration sine-pulse on the left. Periodic noise can be removed in FESA without deforming the spill structure.

The DCCC could be used for analysis of the spill quality and as a detector for an automatic spill optimization system, which was developed at GSI [12], the latter with some limitation because of slew rate problems and bad spill quality. Figure 7 shows an example for the so called "tune wobbling" technique [13], which is applied to quadrupole driven extraction. A periodic signal is superimposed to the steering voltage of the quadrupole, which drives the particles to betatron resonance. Due to the "wobbling" the effect of the power supply noise is reduced, which results in a more homogeneous spill structure and therefore higher detector efficiency at the physics experiments.

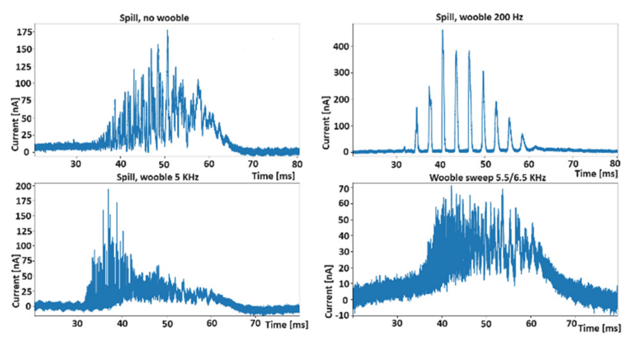

Figure 7: 30 ms spill ($5*10^8$ Ar 18+ per spill). Top left: uncorrected spill. Top right: 200 Hz wobbling frequency, spill modulation. Bottom left: 5 kHz, spill starts to smoothen out (frequency higher than beam cutoff frequency, around 4 KHz). Bottom right: Optimal setting for spill quality (6 kHz $\Delta f = 500$ Hz).

SUMMARY AND OUTLOOK

A new dual core type CCC has been tested in the laboratory and in the beamline. It showed excellent magnetic shielding properties and proved the possibility of noise reduction by combination of two SQUID signals. The costs of a Pb DCCC are less than 1/10 of a Niobium system. We will further improve the performance by making the DCCC more symmetric, slew rate problems can be solved by using matching transformers like for the CCC-XD. We consider the DCCC as the most promising candidate for CCC at FAIR. Concerning controls, our FESA class and filtering is operational on a basic level.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG42

REFERENCES

[1] K. Grohmann, H. D. Hahlbohm, D. Hechtfischer, and H. Lübbig, "Field attenuation as the underlying principle of cryocurrent comparators 2. Ring cavity elements", *Cryogenics*, vol. 16, no. 10, pp. 601–605, 1976.

[2] A. Peters *et al*., "A Cryogenic Current Comparator for the absolute Measurement of nA Beams", *AIP Conf. Proc.* 451 pp.163-180 (1998)

[3] F. Kurian, "Cryogenic Current Comparators for precise Ion Beam Current Measurements", PhD thesis, University of Frankfurt, Germany, 2015

[4] `http://www.magnicon.com/squid`-electronics

[5] V. Zakosarenko *et al*., "Coreless SQUID-based cryogenic current comparator for non-destructive intensity diagnostics of charged particle beams", *Supercond. Sci. Technol*., vol. 32, Dec. 2018, pp. 014002. `doi: 10.1088/1361-6668/aaf206`

[6] L. Crescimbeni *et al*., "Axial Cryogenic Current Comparator (CCC) for FAIR", in *Proc. IBIC'23*, Saskatoon, Canada, Sep. 2023, pp. 259-262. `doi:10.18429/JACoW-IBIC2023-TUP034`

[7] V. Tympel *et al*., "Creation of the First High-Inductance Sensor of the New CCC-Sm Series", in *Proc. IBIC'22*, Kraków, Poland, Sep. 2022, pp. 469-472. `doi:10.18429/JACoW-IBIC2022-WEP30`

[8] V. Tympel *et al*., "Cryogenic Current Comparators for 150 mm Beamline Diameter", in *Proc. IBIC'17*, Grand Rapids, MI, USA, Aug. 2017, pp. 431-434. `doi:10.18429/JACoW-IBIC2017-WEPCF07`

[9] T. Sieber *et al*., "Optimization Studies for an Advanced Cryogenic Current Comparator (CCC) System for FAIR", in *Proc. IBIC'16*, Barcelona, Spain, Sep. 2016, pp. 715-718. `doi:10.18429/JACoW-IBIC2016-WEPG40`

[10] D. M. Haider *et al*., "Commissioning of the Cryogenic Current Comparator (CCC) at CRYRING", in *Proc. IBIC'21*, Pohang, Korea, Sep. 2021, pp. 349-352. `doi:10.18429/JACoW-IBIC2021-WEOB02`

[11] Max Stapelfeld, „Experimentelle Untersuchungen zum Systemdesign von Kryogenen Stromkomparatoren", PhD thesis Friedrich Schiller University Jena, Germany, 2022

[12] P.J. Niedermayer, R. Singh, and R. Geißler, "Software-Defined Radio Based Feedback System for Beam Spill Control in Particle Accelerators", *in Proc. GRCon23*, 2023, Tempe, Arizona, USA, `https://pubs.gnuradio.org/index.php/grcon/article/view/133`

[13] R. Singh, P. Forck and S. Sorge, "Reducing Fluctuation in Slow Extraction Beam Spill using Transit-Time-dependent Tune Modulation", *Phys. Rev. Applied 13*, 044076, April 2020, `https://journals.aps.org/preapplied/abstract/10.1103/PhysRevApplied.13.`