

THE NEXT GENERATION OF CRYOGENIC CURRENT COMPARATORS FOR BEAM MONITORING*

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Abstract

A new *Cryogenic Current Comparator with eXtended Dimensions (CCC-XD)*, compared to earlier versions built for GSI, is currently under development for a non-destructive, highly-sensitive monitoring of nA-intensities of beams for larger beamline diameters planned for the new FAIR accelerator facility at GSI. The CCC consists of a:

- 1) flux concentrator,
- 2) superconducting shield against external magnetic field and a
- 3) superconducting toroidal coil of niobium which is read out by a
- 4) Superconducting Quantum Interference Device (SQUID).

The new flux concentrator (1) comprises a specially designed highly-permeable core made of nano-crystalline material, in order to assure low-noise operation with high system bandwidth of up to 200 kHz. The superconducting shielding of niobium (2) is extended in its geometric dimensions compared to the predecessor CCC and thus will suppress (better -200 dB) disturbing magnetic fields of the beamline environment more effectively. For the *CCD-XD* readout, new SQUID sensors (4) with sub- μm Josephson junctions are used which enable the lowest possible noise-limited current resolution in combination with a good suppression of external disturbances.

The *CCC-XD* system, together with a new dedicated cryostat, will be ready for testing in the CRYRING at GSI in spring 2017. For the application of a CCC in the antiproton storage ring at CERN a pulse shape correction has been developed and tested in parallel. Results from electrical measurements of two components (1 and 4) of the new *CCC-XD* setup will be presented in this work.

INTRODUCTION

Cryogenic Current Comparator (CCC) is a non-destructive, highly-sensitive charged particle beam measurement system using the magnetic field of the moving charged particles, well described in [1, 2]. Figure 1 shows the general principle with the main parts flux concentrator and flux compensator. Using superconducting components for the coils, the transformer and the Superconducting Quantum

Interference Device (SQUID) for the magnetic field measurement it is possible to measure DC currents. That means that it is possible to measure a constant particle flow too. CCCs are in use at GSI [3] and CERN [4]. Figure 2 shows the schematic of a CCC system with the main components: flux concentrator, shielding, pick-up coil and matching transformer, SQUID and cooling.

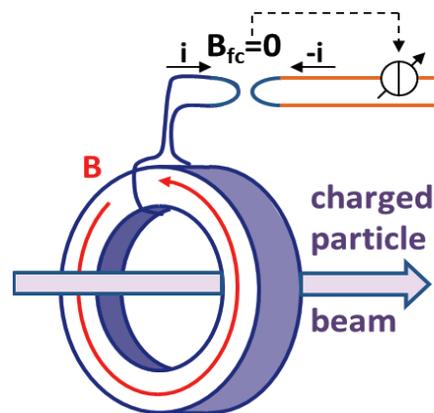


Figure 1: The general principle of a CCC with a flux concentrator and a closed loop current measurement system with compensation current as measurement value.

New Challenges

The CCC application at FAIR leads to two basic challenges: a bakeable ultra high vacuum (UHV) beam tube and a larger beam tube diameter of 150 mm. The required new cryostat is described in [5]. The larger diameter also leads to an extended core diameter of the flux concentrator. Therefore, the new CCC with *eXtended Dimensions* is called *CCC-XD*.

Other challenges of the *CCC-XD* are the desired higher system bandwidth of up to 200 kHz, a higher sensitivity and a better noise immunity. The flux concentrator with its soft magnetic core and the SQUID as magnetic field sensor are the important components to improve the performance of the *CCC-DX* system in this area. Investigation in the field of soft magnetic core materials and the development of a new SQUID design, as described in this work, will ensure the achievement of the forecast targets.

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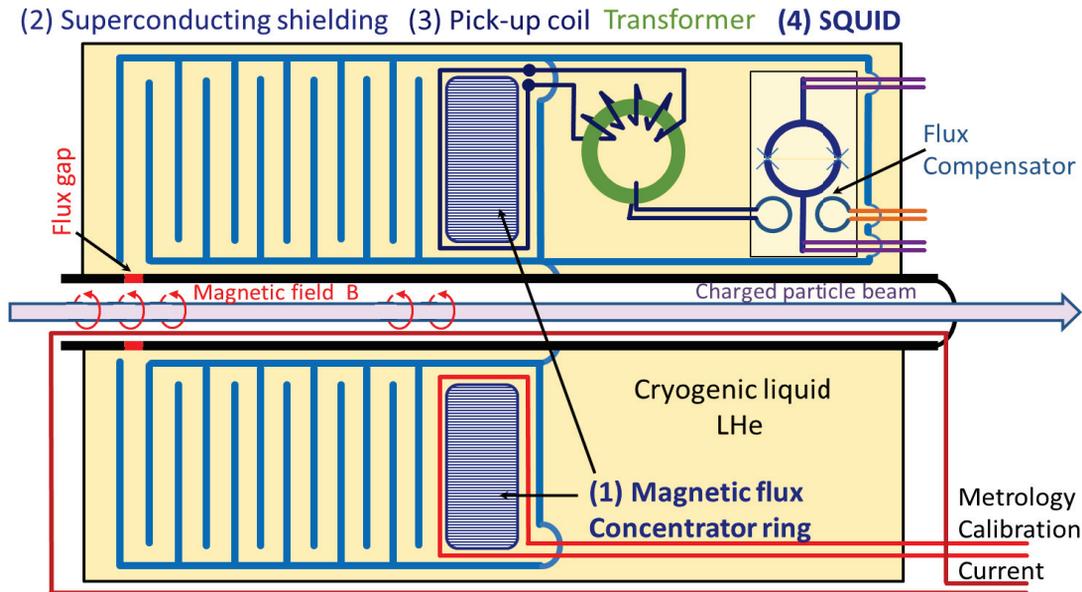


Figure 2: Schematic of a CCC with the main components.

ADVANCED FLUX CONCENTRATOR

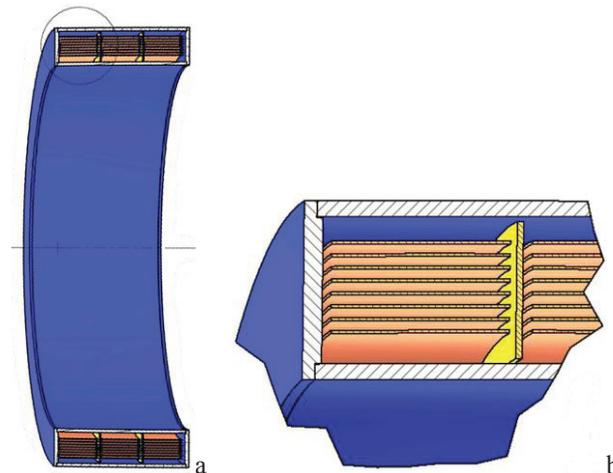
The larger beamline diameter of the new FAIR accelerator facility leads to an inner diameter of 274 mm for the flux concentrator (see Fig. 3). A special three-piece core package was composed by wrapped ribbons of nanocrystalline Soft Magnetics (see Fig. 4). The ribbon thickness itself is very small – only about 15 μm. The material is produced by a specific thermo-magnetic, gas and heat treatment process of amorphous Fe-alloy (NANOPERM® Fe_{73.5} Cu₁ Nb₃ Si_{15.5} B₇) ribbons which defines the magnetic parameters and the temperature dependencies [6, 7]. More than 1000 layers are necessary to create a single core for the CCC-DC flux concentrator.

For the core package characterisation a high precision LS-RS-measurement setup based on an Agilent E4980A LCR-meter, LabVIEW and C++ programs and a wide-neck cryostat was developed.

Two scroll pumps SCROLLVAC SC 15 D allow the extension of the temperature range from room temperature down to below 2 K. Due to thermo-magnetic annealing process a variation of the electrical parameter is possible. The accurately investigations of nanocrystalline Soft Magnetics at low temperatures with smaller cores began in Jena at 2010 [8]. The aim is to create a core material with a high permeability to get a high inductance as well as low magnetic losses to get a low core noise, accompanying with a large bandwidth and at a low temperature. The measured electrical parameters are the series inductance L_s and the series resistance R_s . The materials now can be described by a complex permeability $\mu = \mu' - i\mu''$. The real μ' is proportional to L_s and the imaginary part μ'' is proportional to R_s / f with f as the measured frequency. The complex permeability μ is in fact a function $\mu(f, T)$ with the frequency f and the temperature T .



Figure 3: Real core package GSI328plus with an outer diameter of 330 mm and a depth of 100 mm.



Figures 4: a: Virtual cut through the core package; b: Enlarged cut through a NANOPERM® ribbon core (only schematic: real ribbon thickness ≈ 15 μm).

The recipe of the thermo-magnetic annealing process is very important for the function $\mu(f, T)$. Figure 5 shows the inductance L_s of a single turn coil (in electrical engineering called A_L -value) as a function of the temperature for different core materials. All cores were created from NANOPERM[®] with different annealing recipes by the company MAGNETEC. As shown in Fig. 5 it is necessary to measure $\mu(f, T)$ for each ordered core batch, but there is also a variation in the same core batch as shown in Fig. 6.

Figure 7 (real part μ') and Fig. 8 (imaginary part μ'') show the final measurement results of a GSI328plus core package at 4.2 K. We can see the excellent performance of the measurement system with low 3-sigma errors. The selected GSI328plus No. 1 has at 4.2 K a high and nearly constant μ' -value up to 20 kHz. We can achieve 20 % of the maximum inductance at 200 kHz and still 10 % at 500 kHz. The maximum imaginary part μ'' is in the frequency area of 65 kHz, helpful to get low magnetic losses and low noise.

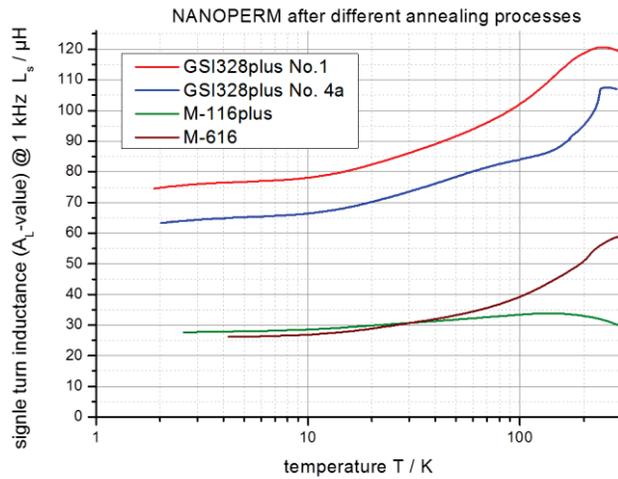


Figure 5: Different recipes of the thermo-magnetic annealing process lead to changed characteristics. GSI328plus No.1 and No. 4a are from different batches.

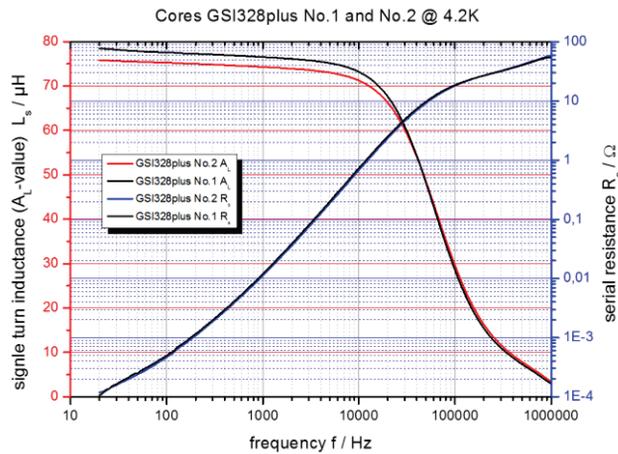


Figure 6: Two core packages of GSI328plus from the same core batch with different A_L -values.

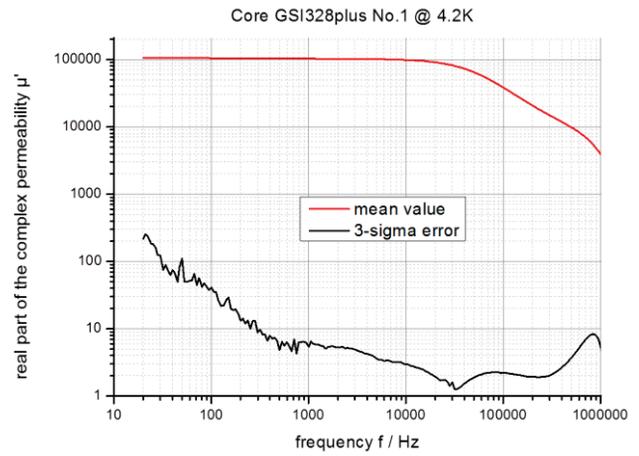


Figure 7: Precision measurement of the real part μ' .

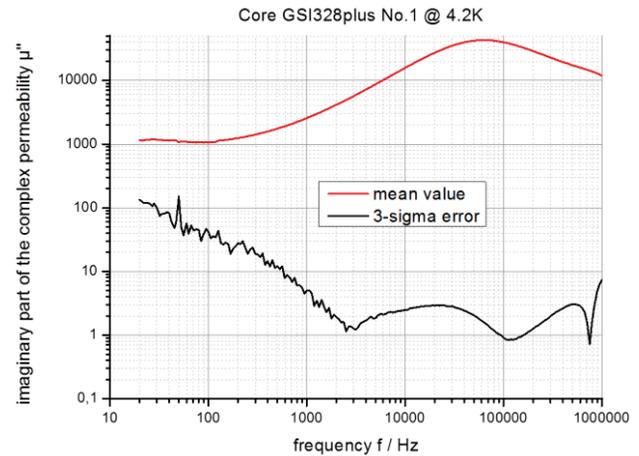


Figure 8: Precision measurement of the imaginary μ'' .

THE NEW SUB- μM SQUID

The SQUID performance is essential for the whole system. Calculations strongly suggest that smaller Josephson junctions could lead to a better SQUID performance.

Estimations

Figure 9 shows the electrical schema with the input current I_A , matching transformer L_A / L_T , coupler coil L_K , SQUID inductance L_{SQ} and the change of SQUID flux $\Delta\Phi_{SQ}$. Equation (1) is used to calculate the relation between $\Delta\Phi_{SQ}$ and I_A as a function of the inductances including an additional parasitic inductance L_{par} :

$$\frac{\Delta\Phi_{SQ}}{I_A} = \frac{\sqrt{L_A \cdot L_T \cdot L_K \cdot L_{SQ}}}{L_T \cdot L_K \cdot L_{par}} \quad (1)$$

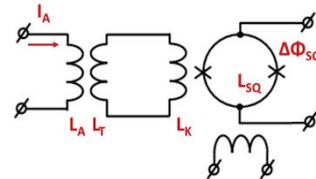


Figure 9: Electrical schematic of the CCC.

Table 1 shows a comparison between standard and sub- μm SQUIDs with its parameters and calculations by $L_A \approx 100 \mu\text{H}$. The calculation leads to a five times better noise performance for the sub- μm SQUID. Figure 10 is a SEM image of a first realisation of the new design.

Table 1: SQUID Specifications

SQUID	Standard CSBlue	Sub- μm CE1K
L_{SQ} [nH]	0.30	0.18
L_K [μH]	0.32	2.7
$\Delta\Phi_{\text{SQ}}/I_A$ [$\mu\text{A}/\Phi_0$]	0.21	0.10
Φ_n [$\mu\Phi_0/\sqrt{\text{Hz}}$]	≈ 5	≈ 2
Noise performance [pA/ $\sqrt{\text{Hz}}$]	1.0	0.2

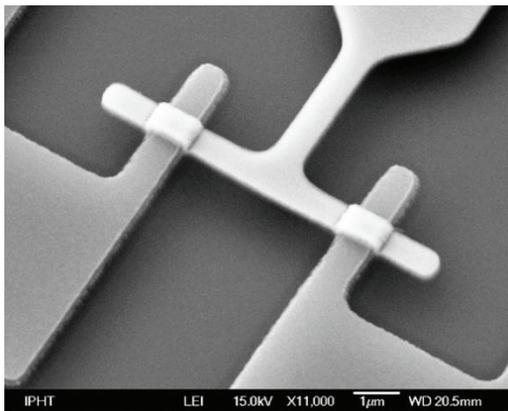


Figure 10: SEM image of sub- μm sized Josephson junctions of the new IPHT CE1K SQUID with critical dimensions below one micron.

Noise Measurement

First noise measurements without flux concentrator are shown in Fig. 11. The white flux noise between 100 Hz and 20 kHz is $1.3 \mu\Phi_0/\sqrt{\text{Hz}}$ with a ratio $\Delta\Phi_{\text{SQ}}/I_A$ of $0.12 \mu\text{A}/\Phi_0$ the noise performance is $0.16 \text{ pA}/\sqrt{\text{Hz}}$.

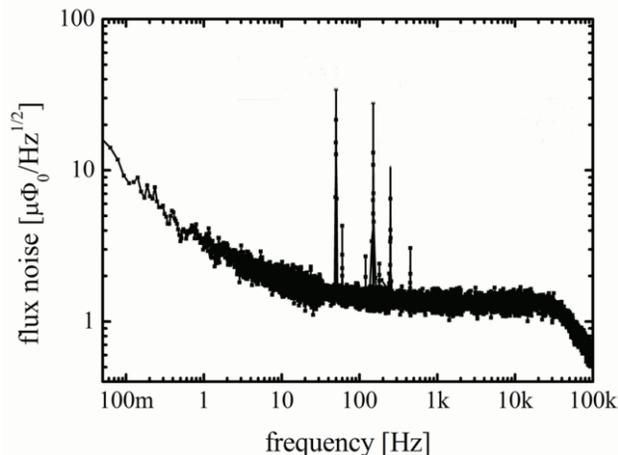


Figure 11: Measurement of the CE1K flux noise with a noise performance of $0.16 \text{ pA}/\sqrt{\text{Hz}}$.

CONCLUSION

The CCCs in operation already have demonstrated their potential at beam lines at GSI and CERN. The newly developed core materials will allow higher signal frequencies and lower noise. The use of new sub- μm -SQUID will enable a decreased noise and higher system bandwidth. Within the current research project the magnetic and acoustic disturbing signals shall be reduced to improve the CCC operations in critical environment. Alternative shielding constructions and their magnetic field suppression will be evaluated. In the meantime the *CCC-XD* for CRYRING is still under construction, the related cryostat - considering AD CCC measuring results - is in preparation.

ACKNOWLEDGEMENT

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