CREATION OF THE FIRST HIGH-INDUCTANCE SENSOR OF THE NEW CCC-Sm SERIES*

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Abstract

Cryogenic Current Comparators (CCC) for beamlines are presently used at CERN-AD and in the FAIR project at CRYRING with 100 mm and 150 mm beamline diameter, respectively, for non-destructive absolute measurement of beam currents in the amplitude range of below 10 µA$_{pp}$ (current resolution 1 nA$_{pp}$). Both sensor versions (CERN-Nb-CCC and FAIR-Nb-CCC-XD) use niobium as a superconductor for the DC-transformer and magnetic shielding. The integrated flux concentrators have an inductance below 100 µH at 4.2 Kelvin. The new Sm-series (Smart & Small) is designed for a beamline diameter of 63 mm and is using lead (Pb) as superconductor. The first implemented sensor (IFK-Pb-DCCC-Sm-200) has two core-based pickup coils (2 x 100 µH at 4.2 K) and hence the option to use two SQUID units. During construction, some basic investigations such as on noise behaviour (fluctuation–dissipation theorem, white noise below 2 pA$_{rms}$/√Hz) and the magnetic shielding in terms of L$_{core}$-C$_{meander}$-resonance and additional mu-metal shielding were undertaken. These results are presented herein. Finally, a current resolution of 0.5 nA$_{pp}$ was achieved without additional shielding measures in laboratory environment.

INTRODUCTION

Cryogenic Current Comparators (CCC) measure the azimuthal magnetic field of a charged particle beam non-destructively. By using superconducting components such as magnetic shielding, DC transformer, and SQUIDs, a current resolution in the nA range can be achieved [1]. After the development of large CCCs for the CERN Antiproton Decelerator (CERN-Nb-CCC) [2] and FAIR-project (FAIR-Nb-CCC-XD) [3], both with a current pulse resolution >1 nA, some new concepts are currently being tested on smaller size CCCs - the so-called Small & Smart series (CCC-Sm, <1 nA).

PICKUP COILS

To increase system availability and enable comparison experiments, the setup is carried out with two superconductive pickup coils (Dual-core CCC or DCCC). Standard Magnetec M-616 cores [4] were used for the first DCCC-Sm (see Fig. 1), which achieve an inductance of about 100 µH in a package of three cores per coil (see Fig. 2).

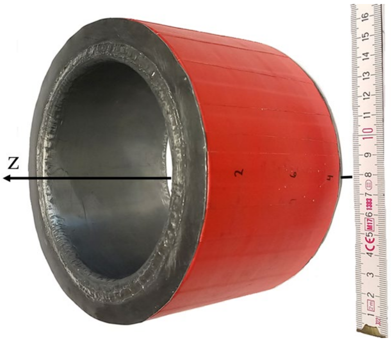

Figure 1: Pickup coil #1, one full-faced single-turn coil made of lead through three M-616 cores with z-axis as later beam direction.

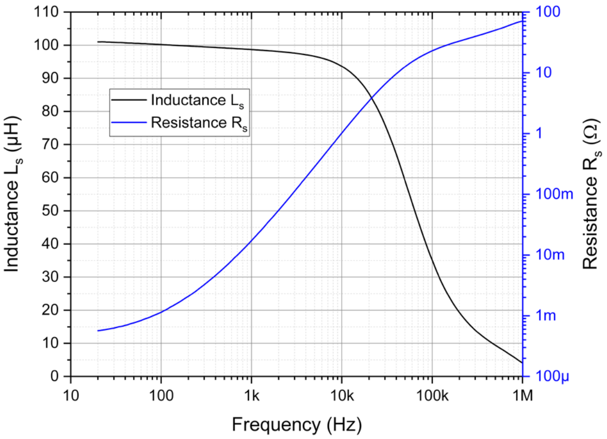

Figure 2: Pickup coil #1, serial inductance L$_s$ and serial resistance R$_s$ measured at 4.2 K.

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Fluctuation-Dissipation Theorem

Following the fluctuation-dissipation theorem (FDT), an expected value for the current noise density $i_{rms}/\sqrt{(\Delta f)}$ can be calculated by the serial inductance L_s and the serial resistance R_s of the pickup coil as functions of the frequency *f*, the fixed input coil inductance L_i (1 µH) of the SQUID, at a fixed temperature T (4.2 K) and a fixed frequency interval Δf, shown in Eq. (1) [5]:

$$\frac{{i_{rms}}^2}{\Delta f} = 4k_BT\cdot\frac{R_S(f)}{\left(2\pi f\cdot(L_i+L_S(f))\right)^2+\left(R_S(f)\right)^2} \qquad (1)$$

Figure 3 shows the good agreement of the directly measured spectral current noise density with the calculation via the FDT in the white noise range > 1 kHz. The slight overestimation of the current noise density in the frequency range < 1 kHz (1/f noise) may be due to a systematic error in determining the resistance R_s (< 10 mΩ) for low frequencies.

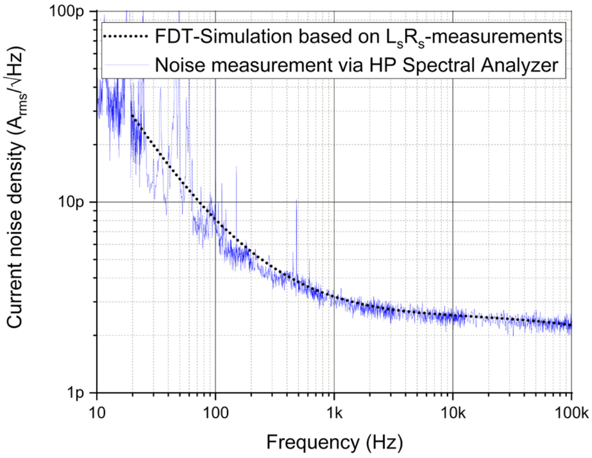

Figure 3: Pickup coil #1, spectral current noise density.

DUAL-CORE CCC

Two pickup coils then have been equipped with common superconducting shielding against magnetic interference signals (Fig. 4).

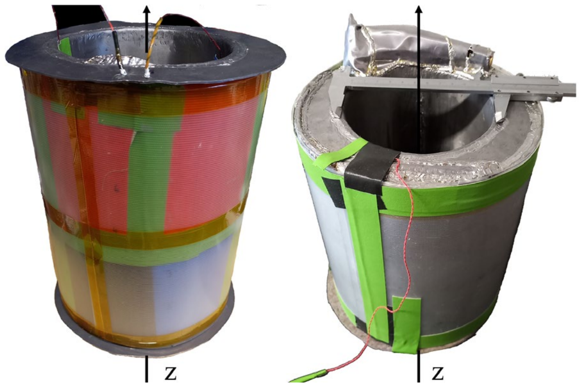

Figure 4: Left: Pickup coils #1 and #2 with inner loop of the shielding. Right: DCCC completed by the outer meander shielding, SQUID, and calibration coil.

Magnetic Shielding and LC-Resonances

Of course the magnetic shielding should not suppress the signal to be measured. Therefore, shielding consists of two superconductive coaxial tubes comprising the pickup coils connected to each other at one end. The longer the tube package, the better the suppression of interference signals [6]. Since long tubes would be impractical, the tubes are folded into a meander structure.

The opposite surfaces of the meander structure also form an electrical capacitance $C_{meander}$, which increases with increasing number of meanders or effective length of the tube package. The inner loop (see Fig. 4 left) creates an inductance L_{core}, which together with $C_{meander}$ forms a parallel LC-resonance circuit. It should be borne in mind that the inductance L_{core} is in fact caused by an additional winding through both pickup coils. Hence, the total inductance is the sum of L_{s1} and L_{s2} of about 200 µH.

Figure 5 shows the shift of the meander LC-resonance measured via the current noise density with 2, 6, and finally 12 full meander pairs (effective length of the shielding tube package: 240 cm). With increasing number of meanders, the parasitic capacitance is enlarged and thus the resonance frequency lowered which may negatively affect the stable work of the SQUID in flux locked loop mode.

The main part of the magnetic shielding is taken over by the superconducting meandering structure. As a first step, a shield with two full meander pairs (40 cm) was installed. As a result, an external, axially magnetic interference field B_z of 1 µT generated an apparent beam current of about 15 nA. This means even in the laboratory common 50 Hz magnetic fields the SQUID fully overrides in amplifier mode. An incomplete shielding with cryogenic mu-metal (4 mm thick, but 100 mm holes on both sides for the beamline) brought an improvement in shielding by a factor of 9.5 @ 1 Hz. More efficient is the use of further superconducting meanders. The final value of 12 full meander pairs (240 cm) leads to a damping below the currently existing detection limit in the laboratory of 5 pA/µT in z-direction.

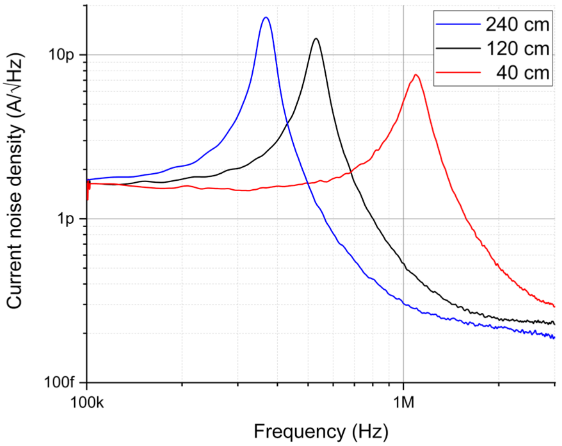

Figure 5: LC-resonance peaks of the DCCC at three processing stages with increasing number of full meander pairs or effective length of the shielding tube package.

Current Noise and Current Pulses

The current noise is a decisive parameter for the later achievable pulse current resolution. The noise measurements were carried out in the frequency range < 100 kHz with a HP 35670A and up to 5 MHz with a HP 89410A. An additional calibration coil and a certified multimeter Keithley 2002 were used for current calibration. Figure 6 shows the measured current noise density in the frequency range of 50 mHz to 5 MHz for the entire DCCC-Sm-200.

The high frequency range above 100 kHz is determined by the discussed meander LC-resonance and the frequency limitation of the core material. The medium frequency range (1 kHz to 100 kHz) has a close to constant noise behaviour (white noise). With $< 2\ \mathrm{pA_{rms}}/\sqrt{\mathrm{Hz}}$ (min. $1.7\ \mathrm{pA_{rms}}/\sqrt{\mathrm{Hz}}$) the absolute values are $1/\sqrt{2}$ times smaller than values from the FDT studies, exactly as expected. A parallel connection of both pickup coils leads to an increase in noise, which is describable with the Pythagorean addition of the single independent noise sources. For two identical pickup coils, the noise increases by a factor of $\sqrt{2}$. At the same time, the current sensitivity doubles due to the simple addition of the two partial currents during calibration, so that ultimately a factor of $1/\sqrt{2}$ results.

The low frequency range < 1 kHz shows a significant increase in noise density, which ultimately (< 1 Hz) results in a $1/f^2$ behaviour, as it leads to Brownian noise (20 dB or current factor of 10 per decade). In addition, in the range between 3 Hz and 80 Hz, other interference signals become visible, most of which can be traced back to building vibrations.

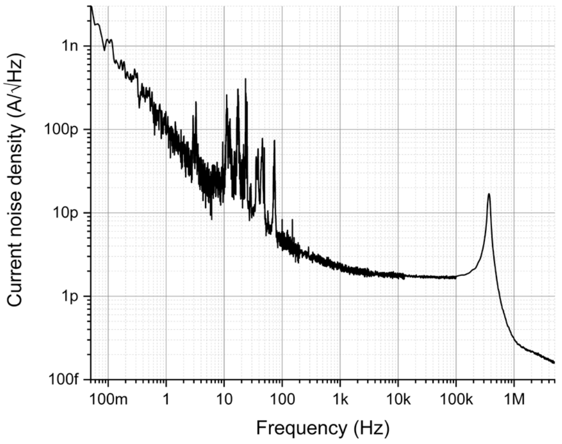

Figure 6: Total current noise density spectrum of the final DCCC-Sm-200, both pickup coils on one SQUID with input inductance of 1 µH.

The ultimate criterion for the application as a beam current meter is the achievable pulse current resolution. Measurements were performed by application of defined current pulses on the calibration coil (single wire through the DCCC). Figure 7 shows the 500 pA current pulses to be measured (dotted line) and the SQUID responses (blue line), smoothed with a 10 kHz low-pass filter and calibrated to current values. For similar measurements, the FAIR-Nb-CCC-XD required 1.6 nA current pulses.

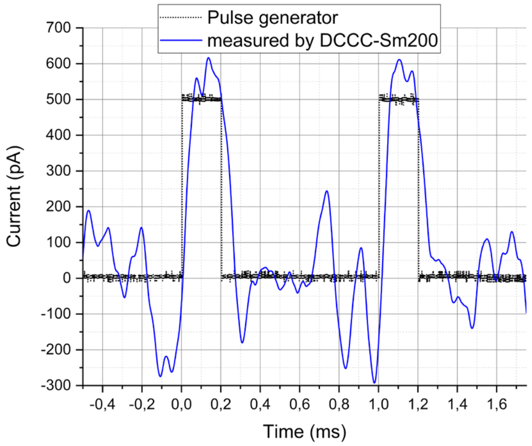

Figure 7: Pulse current resolution of the final DCCC-Sm-200, both pickup coils on one SQUID with input inductance of 1 µH.

CONCLUSION

It was shown that L_sR_s-measurements and the fluctuation-dissipation theorem are suitable for making predictions about the later current noise of CCCs. It was possible to create a lead foil-based Dual-core Cryogenic Current Comparator in smaller dimensions with a very high magnetic meander shielding factor below 5 pA/µT. This IFK-Pb-DCCC-Sm-200 with its 200 µH total inductor achieved a minimum current noise density of $1.7\ \mathrm{pA_{rms}}/\sqrt{\mathrm{Hz}}$, the smallest ever measured value for beamline CCCs at 4.2 K at the Cryo Detector Lab in Jena. This allowed for the first time the detection of a single current pulse below 1 nA with a CCC for beamlines.

OUTLOOK

In the meantime, Magnetec has produced special cores that geometrically have the dimensions of M-616, but use the core material developed for the FAIR-Nb-CCC-XD with improved low-temperature properties. Thus, it is possible to achieve 13% more inductance for the same geometry. With an additional core per pickup coil, the construction of the IFK-Pb-DCCC-Sm-300 could be started. It may have a total inductance 300 µH @ 4.2 K. The expected minimum white current noise density is accordingly $1.5\ \mathrm{pA_{rms}}/\sqrt{\mathrm{Hz}}$ – a similar R_s behaviour assumed. Because of the expected better performance, the full final SQUID setup (two SQUIDs with $L_i = 1$ µH to reduce Barkhausen noise and increase system availability, one SQUID for dynamic expansion with $L_i = 27$ nH) and the installation into a new beam-line cryostat will probably no longer take place with the Sm-200, but with the Sm-300.

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