ISBN: 978-3-95450-201-1 doi:10.18429/JACoW-IBIC2018-MOPC06

COMPARATIVE MEASUREMENT AND CHARACTERISATION OF THREE CRYOGENIC CURRENT COMPARATORS BASED ON LOW-TEMPERATURE SUPERCONDUCTORS*

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Abstract

A Cryogenic Current Comparator (CCC) is a non-destructive, metrological-traceable charged particle beam intensity measurement system for the nano-ampere range. Using superconducting shielding and coils, low temperature Superconducting Quantum Interference Devices (SQUIDs) and highly permeable flux-concentrators, the CCC can operate in the frequency range from DC to several kHz or hundreds of kHz depending on the requirement of the application. Also, the white noise level can be optimized down to 2 pA/sqrt(Hz) at 2.16 K.

This work compares three different Pb- and Nb-based CCC-sensors developed at the Institute of Solid State Physics and Leibniz Institute of Photonic Technology at Jena, Germany: CERN-Nb-CCC, optimized for application at CERN Antiproton Decelerator (AD) in 2015 with a free inner diameter of 185 mm; GSI-Pb-CCC, designed for GSI-Darmstadt with a free inner diameter of 145 mm, 1996 completed, 2014 upgraded; GSI-Nb-CCC-XD, designed for the GSI/FAIR-project with a free inner diameter of 250 mm, 2017 completed. The results of noise, small-signal, slew-rate, and drift measurements done 2015 and 2018 in the Cryo-Detector Lab at the University of Jena are presented here.

THE SYSTEM

After 25 years of development the Cryogenic Current Comparator (CCC) has been established as a useful tool for non-destructive and metrological-traceable beam intensity measurement in the nano-ampere range [1]. The principle behind the CCC is to pick up the azimuthal magnetic field of the moving charged particles. Figure 1 shows a superconducting meander structure which shields the non-azimuthal magnetic field components. The following pickup coil, enclosing a highly permeable flux-concentrating core, and the particle beam build up a current-transformer. The very low pickup coil current can be measured, via matching electronics, by a Low-Temperature Superconducting Quantum Interference Device (SQUID). The measured raw voltage of the SQUID electronics can be linked to a corresponding CCC input current using a calibration factor defined with a metrological-traceable calibration current.

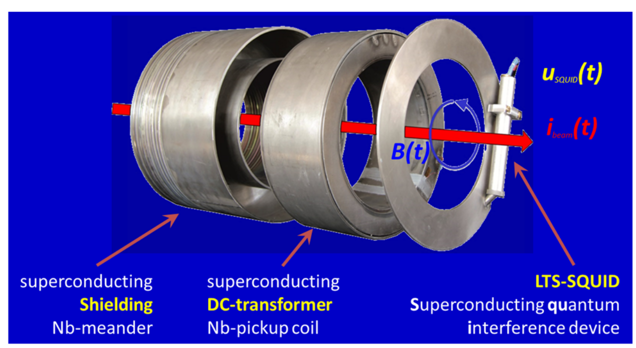

Figure 1: Components and operating principle of the CCC-sensor shown on a niobium-based system before it is assembled.

Measurement Setups

Three CCC sensors (see Table 1) with different dimensions, varying meanders, and core materials were characterized by a setup consisting of a Dynamic Signal Analyzer HP35670A, a Vector Signal Analyzer HP89410A, an Agilent Function / Arbitrary Waveform Generator 33210A and a DAkkS (Deutsche Akkreditierungsstelle)-certified Keithley 2002 Multimeter. The lab measurements are done in a shielded chamber (see Fig. 2, left).

* Work supported by BMBF, project numbers 05P15SJRBA and 05P18SJRB1.
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Figure 2: Wide-neck bath cryostat in an acoustically and magnetically shielded chamber for the electrical CCC-testing at the Cryo-Detector Laboratory at the University of Jena (left), beamline cryostat of the GSI-Pb-CCC at GSI Darmstadt (middle), beamline cryostat and He-reliquefier of the CERN-Nb-CCC at CERN-Antiproton Decelerator (AD) (right).

Two sensors have a dedicated beamline cryostat (see Fig. 2 middle and right). The beamline cryostat for the GSI-Nb-CCC-XD is currently in production. For the 2-K-temperature range two dry scroll pumps SC15D were used.

Table 1: CCC Specifications

CCC-Sensor	GSI-Pb	CERN-Nb	GSI-Nb-XD
Completed	1996	2015	2017
Diameter (mm)			
inner	147	185	250
outer	260	280	350
Length (mm)	95	193	207
Meander	Pb	Nb	Nb
Pickup coil	Nb	Nb	Nb
Core	Vitrovac 6025	Nanoperm M764	Nanoperm GSI328+
Inductance (µH)			
@1 kHz, 4.2 K	25	100	80

MEASUREMENTS

The measurements were done in 2015 (CERN-Nb-CCC) [2] and 2018 (GSI-Pb-CCC, GSI-Nb-CCC-XD) at the Cryo Detector Laboratory at the University of Jena.

Noise

The graph in Fig. 3 can be divided in three frequency regions. The 1/f-region below roughly 2 kHz indicates the differences between the amorphous Vitrovac (GSI-Pb-CCC) and the nano-crystalline Nanoperm (GSI-Nb-CCC-XD) core material. Vitrovac shows up to four times higher noise values, but has a lower acoustic sensibility between 5 Hz and 50 Hz and less spontaneous current jumps (noise below 100 mHz). The next region up to 100 kHz or 500 kHz is characterized by an almost constant level of white noise below 5 pA/√Hz. The last region starts with small resonance peaks and a falling low-pass edge. The smaller bandwidth of the GSI-Nb-CCC-XD is a result of the balanced SQUID coupling described in [3].

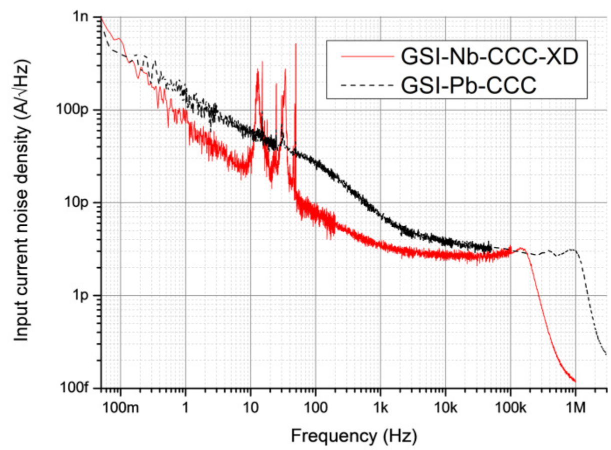

Figure 3: Current noise of the GSI-CCCs @ 4.2 K.

The original CERN-Nb-CCC also shows also typical nano-crystalline core behaviour (see Fig. 4, blue line). For the application in the CERN AD ring a 1 kHz RC-low-pass was added in front of the SQUID to realise an integration (see Fig. 4, green dots). Unfortunately the noise is therefore dominated by a thermal resistor noise.

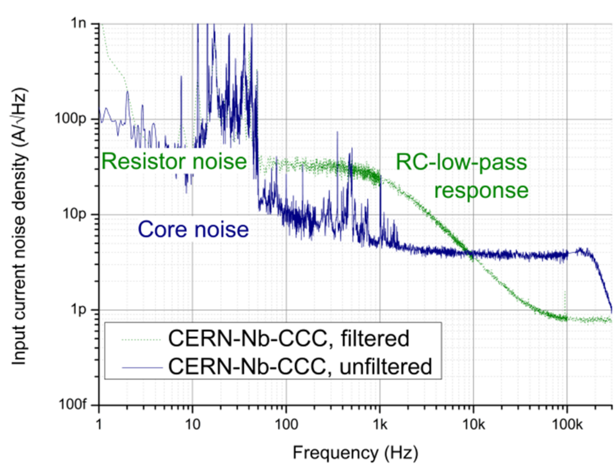

Figure 4: Current noise of the CERN-CCC before (blue line) and after optimization with a RC-low-pass (green dots) of the SQUID coupling.

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Superfluidity

To improve the measurement of thermal drifts and to isolate the influence of He bubbles the GSI-Nb-CCC-XD was cooled down below the λ-point at 2.1768 K @ 50.36 hPa. A transition to superfluid helium II without any gas bubbles takes place at the λ-point. Figure 5 shows that, with bubbles, the noise baseline and the building vibration peak @ 11.5 Hz are up to five times higher than without bubbles. That corresponds to the behaviour that on the way down to the λ-point it was impossible to make any reasonable measurements with the SQUID but below the λ-point and also on the way up to 4.2 K a normal SQUID flux locked loop (FFL)-mode is problem-free.

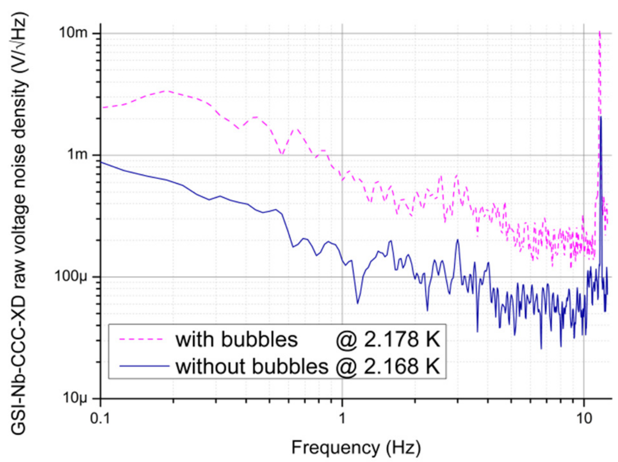

Figure 5: Change of the noise near the λ-point (SQUID amplifier-mode), above the λ-point with gas bubbles (magenta dashes) and below without bubbles (blue line).

Below the λ-point a decrease of white noise down to a value of 2 pA/√Hz is detectable (see Fig. 6). In general it is possible to improve the performance of the system with superfluid helium but the effort can be high and we have to avoid additional acoustic disturbances.

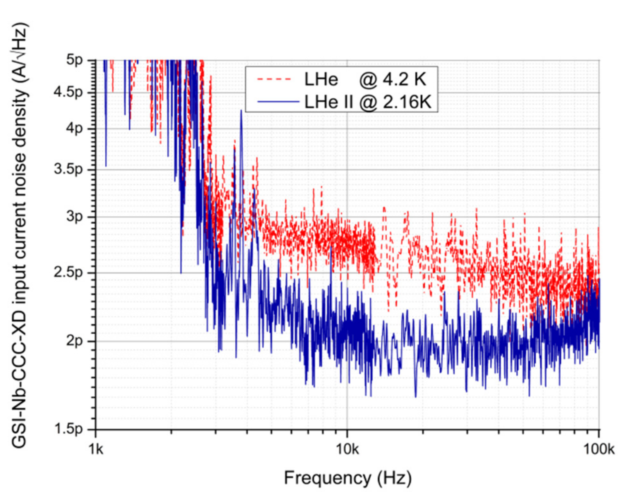

Figure 6: White noise current density of the GSI-Nb-CCC-XD between 3 kHz and 100 kHz (SQUID FLL-mode) at 4.2 K (red dashes) and below the λ-point at 2.16 K (blue line).

Small Sine Signals and Slew-Rates

More important than the noise level by itself is the signal-to-noise ratio. At first we have compared the small-signal behaviour using sinusoidal current waves. A current in an electrical wire through the centre of the CCC sensor is used to simulate the charged particle beam. The SQUID signal was analysed with a HP89410A in average mode for the noise measurement and peak-hold mode for noise and swept sine current inputs. As shown in Fig. 7 (GSI-Nb-CCC-XD) and in Fig. 8 (GSI-Pb-CCC) the small-signal response follows the noise densities. Using additional signal processing it should be possible to achieve a bandwidth of up to 1 MHz (GSI-Nb-CCC-XD) or up to 3 MHz (GSI-Pb-CCC) for small signals.

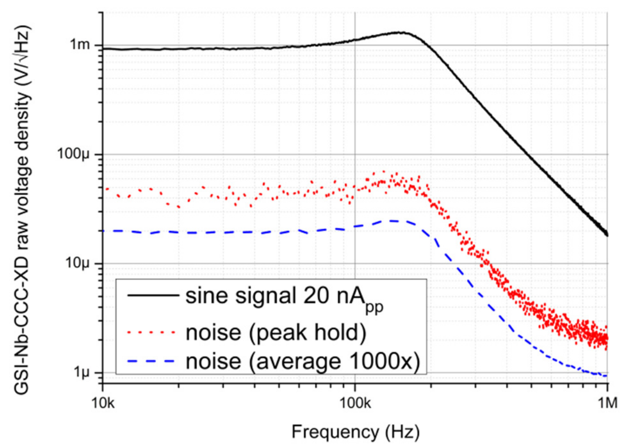

Figure 7: Correlation between noise and signal of the GSI-Nb-CCC-XD.

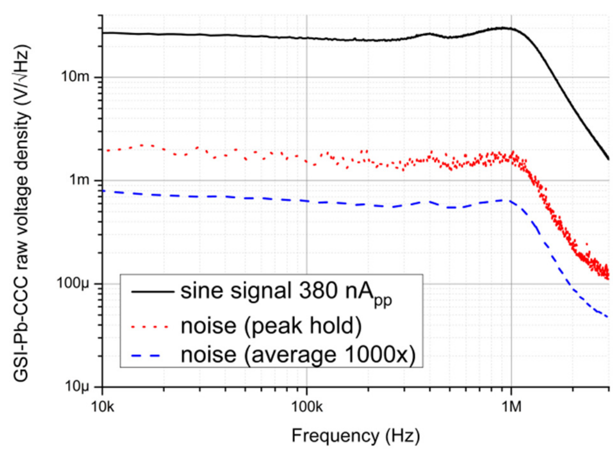

Figure 8: Correlation between noise and signal of the GSI-Pb-CCC.

For the application in a beamline the large-signal response is very important. Using a sine current a slew-rate (SR) can be defined as the product of a given circular frequency and maximum current amplitude for a stable CCC operation. At a frequency of 200 kHz the balanced GSI-Nb-CCC-XD reached SR = 0.16 A/s (direct version: 0.33 A/s) and the GSI-Pb-CCC reached SR = 0.30 A/s. The CERN-AD beam injection with 8.6 kA/s requires a 1 kHz low-pass in the CERN-Nb-CCC [1].

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Thermal Drift

Naturally, the SQUID by itself has a temperature-dependence in its electrical parameters. In a classical beamline CCC with a large, highly permeable core the thermal drift of the SQUID output voltage is dominated by the properties of the core [4]. Via pressure and temperature changes close to 4.2 K and measurements during the warm-up from the λ-point to 4.2 K at atmospheric pressure conditions for the GSI-Nb-CCC-XD a drift of 15 nA/mK and for the GSI-Pb-CCC a drift of 30 nA/mK was measured.

In a second experiment, the temperature of the helium bath was kept constant with the help of the large specific thermal capacity of liquid helium at the λ-point and the pressure was changed rapidly from 50 hPa to 1000 hPa. Despite the dramatic change in pressure a drift below 1 nA/mK could be found. Therefore, the drifts close to 4.2 K are generated by the temperature changes and not by the pressure changes.

ACKNOWLEDGEMENT

We thank our former staff member René Geithner for the raw measurement data and exploded view image of the CERN-Nb-CCC from 2015.

CONCLUSION

It was possible to extend the dimensions of the CCC-sensor for the use in beamlines with a large diameter without losing any system performance. With a core that is optimized for low-temperature applications is it possible to achieve a white noise of 3 pA/√Hz. Unfortunately, the influence of acoustic disturbances is increasing too. Cooling with bubble-free superfluid helium leads to a better performance. Using additional data processing, small-signal bandwidths in the MHz-range are possible by core-based CCCs. The best achieved slew-rate at the moment is below 0.4 A/s. With a low-pass in front of the SQUID the application in storage rings with slew-rates of kA/s can be realized. The lowest thermal current drift that was measured is 15 nA/mK. Therefore, a constant baseline current can only be achieved by a strong temperature stabilisation or with a core-less CCC design [5].

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