# Measurement and Characterisation of Three Cryogenic Current Comparators Based on Low-Temperature Superconductors

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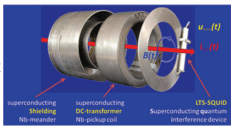
V. Tympel[1], T. Stöhlker[1,2,3], J. Golm[4], R. Neubert[4,5], F. Schmidl[4], P. Seidel[4], F. Kurian[2], D. Haider[2], M. Schwickert[2], T. Sieber[2], M. Schmelz[6], R. Stolz[6], V. Zakosarenko[6,7], N. Marsic[8], W. Müller[8], H. De Gersem[8], M. Fernandes[9,10,11], J. Tan[9], C.P. Welsch[10,11]

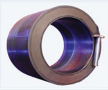
[1]Helmholtz Institute Jena (HI-Jena), Germany; [2]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany; [3]Institute for Optics and Quantum Electronics (IOQ), 07743 Jena, Germany; [4]Institute of Solid State Physics (IFK), 07743 Jena, Germany; [5]Thuringia Observatory Tautenburg (TLS), 07778 Tautenburg, Germany; [6]Leibniz Institute of Photonic Technology (IPHT), 07745 Jena, Germany; [7]Supracon AG, 07751 Jena, Germany; [8]Department of Electrical Engineering and Information Technology (etit), TU Darmstadt, Germany; [9]CERN, CH-1211, Geneva 23, Switzerland; [10]Cockcroft Institute, Sci-Tech Daresbury, WA4 4AD, Daresbury, Warrington, UK; [11]Department of Physics, The University of Liverpool, Liverpool, L69 7ZE, UK.

## 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 (SQUID) 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: 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.



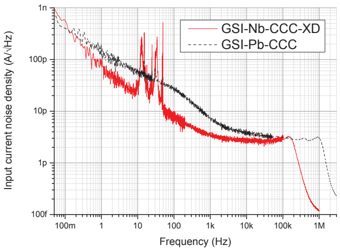

### Three CCCs

| CCC-Sensor | GSI-Pb | CERN-Nb | GSI-Nb-XD |
|---|---|---|---|
| Final location | GSI | CERN-AD | FAIR |
| Completion | **1996/14** | **2015** | **2017** |
| |  |  |  |
| Inner diameter (mm) | 147 | 185 | 250 |
| Outer diameter (mm) | 260 | 280 | 350 |
| Length (mm) | 95 | 193 | 207 |
| Meander | Pb | Nb | Nb |
| Pickup coil | Nb | Nb | Nb |
| Core material | **Vitrovac 6025** | **Nanoperm M764** | **Nanoperm GSI328+** |
| Inductance @1 kHz, 4.2 K (µH) | 25 | 100 | 80 |

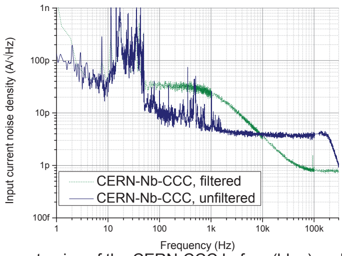
## Measurements

### Noise

The 1/f range between 50 mHz and approx. 2 kHz indicates the differences regarding to the amorphous (GSI-Pb-CCC, black line) and the nano-crystalline (GSI-Nb-CCC-XD, red line) core material. Vitrovac shows higher noise values (up to four times @ 100 Hz) but also a lower acoustic sensibility between 5 Hz and 50 Hz and spontaneous current jumps observable by the better noise values below 100 mHz. A white noise below 5 pA/√Hz and small changes up to 100 kHz/ 500 kHz is following. The last section starts with small resonance peaks [1] and falling low-pass edge. The smaller bandwidth of the GSI-Nb-CCC-XD is a result of the balanced SQUID coupling and described in [3]. The original CERN-Nb-CCC shows also typical nano-crystalline core behaviour (blue line). But for the application in the CERN AD ring a 1 kHz low-pass was added in front of the SQUID to realise an integration (green dots) [2]. Unfortunately the noise is now dominated by a thermal resistor noise.



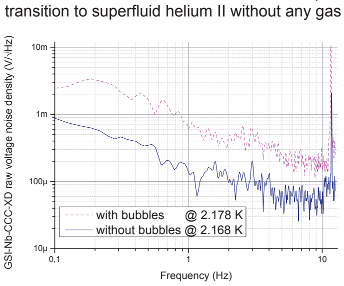

Current noise of GSI-CCCs @ 4.2 K.



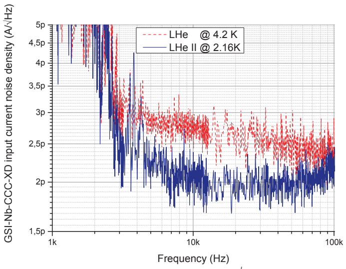

Current noise of the CERN-CCC before (blue) and after optimization (green) of SQUID coupling [3].

### @ λ-point

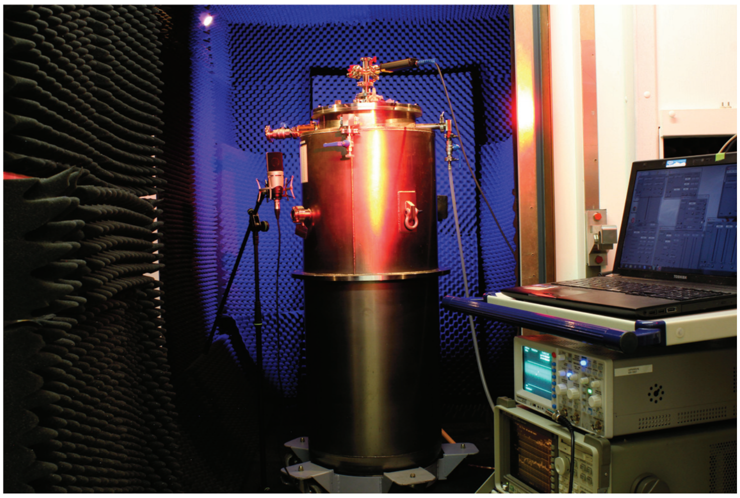
For the better measurements of thermal drifts and to separate the influence of He bubbles the GSI-Nb-CCC-XD was cooled down below the λ-point at 2.1768 K @ 50.36 hPa. At the λ-point we have transition to superfluid helium II without any gas bubbles.



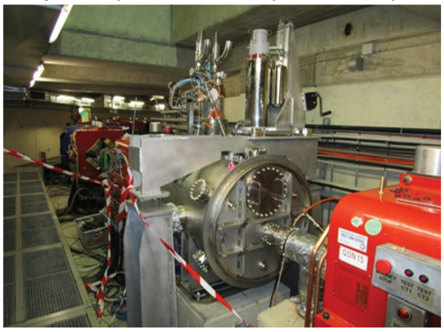

Change of the CCC noise near the λ-point.




White noise density of 2 nA/√Hz @ 2.16 K.



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.

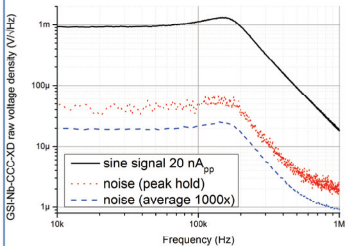


Beamline cryostat and He-reliquefier of the CERN-Nb-CCC at the Antiproton Decelerator (AD) at CERN.

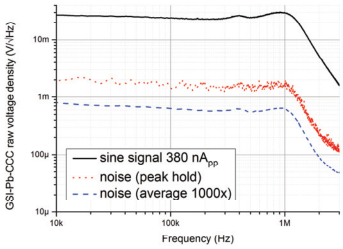
Beamline cryostat of the GSI-Pb-CCC at GSI Darmstadt.

### Sine Signals and Slew-Rates

A current in an electrical wire through the centre of the CCC sensor simulates the charged particle beam. Using additional signal processing it should be possible to achieve a bandwidth of up to 1 MHz for the GSI-Nb-CCC-XD and up to 3 MHz for the GSI-Pb-CCC for small signals. Using a sine current signal 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.




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




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

### Thermal Drift

Via pressure and temperature changing close to 4.2 K and also measurements on the way from the λ-point to 4.2 K under normal 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. With the help of the large specific thermal capacity of liquid helium at the λ-point and a quick pressure change from 50 hPa to 1000 hPa 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.

## Conclusion

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

## References

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Mail to volker.tympel@uni-jena.de

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