20 YEARS OF DEVELOPMENT OF SQUID-BASED CRYOGENIC CURRENT COMPARATORS FOR BEAM DIAGNOSTICS

W. Vodel[1], R. Neubert[2], R. Geithner[1,2], P. Seidel[2], [1]Helmholtz Institute Jena and [2]Institute of Solid State Physics of Friedrich Schiller University Jena, Germany
H. Reeg, M. Schwickert, GSI Helmholtzzentrum für Schwerionenforschung Darmstadt, Germany
K. Knaack, K. Wittenburg, Deutsches Elektronensynchrotron (DESY) Hamburg, Germany,
A. Peters, Heidelberg Ion-Beam Therapy Center (HIT), Germany

Abstract

An absolute and exact measurement of the intensity of charged particle beams - extracted from an accelerator or circulating in a Storage Ring - is one of the major problems of beam diagnostics. Also the measurement of socalled dark currents, generated by superconductive RF accelerator cavities at high voltage gradients to characterize the quality of these components becomes more and more important for the commissioning of new accelerators (XFEL at DESY). The Cryogenic Current Comparator (CCC) based on high precision LTS SQUIDs is an excellent tool to solve these problems.

This contribution gives an overview of the development of highly sensitive SQUID-based Cryogenic Current Comparators (CCC) for nuclear physics from the first successful demonstration of its performance at GSI Darmstadt through the latest improved version for FAIR and the Cryogenic Storage Ring at MPI Heidelberg.

PRINCIPLE OF THE CCC

The first Cryogenic Current Comparator (CCC) was developed by I. K. Harvey (National Standards Laboratory, Sydney, Australia) for precise dc current ratios in 1972 [1]. To compare two currents with high precision a super-conducting meander shaped flux transducer was used. Only the azimuthal magnetic field component, which is proportional to the current in the wires, will be sensed by the pick up coil whereas all other field components are strongly suppressed.

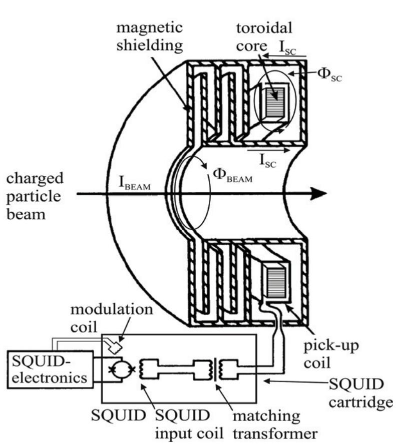

Figure 1: Simplified schematic view of the CCC with magnetic shielding, pick-up coil, and SQUID system.

In principle a CCC consists of the following main components (see Fig. 1):

- a superconducting pick-up coil for the passing high energy ion beam,
- a low noise highly sensitive LTS DC SQUID system, and
- an extremely effective meander-shaped super-conducting shielding.

CCC FOR DARK ELECTRONS (DESY-HAMBURG, TESLA / X-FEL)

The performance of superconducting cavities of accelerators is characterized by the Q-value vs. gradient dependency, measured in a cavity test facility (e. g. "CHECHIA" at DESY or "HOBICAT" at Helmholtz-Zentrum Berlin). But the existence of so-called dark currents (vs. gradient) may have a crucial influence on the accelerator operation. Fig. 2 shows an example for the measurement of dark currents of RF-cavities at "HOBICAT" [2].

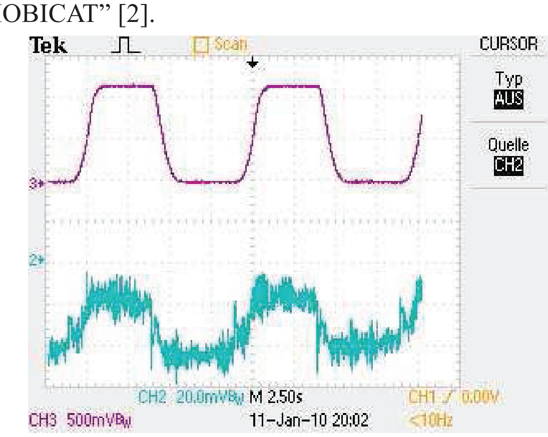

Figure 2: Dark current of about 5 nA measured with the CCC (lower curve) at "HOBICAT" (Helmholtz-Zentrum Berlin) compared with a reference signal of the accelerator voltage (upper curve).

CCC FOR HIGH ENERGY IONS (GSI DARMSTADT / FAIR)

At GSI Darmstadt an LTS SQUID based CCC detector system has demonstrated its excellent capabilities for absolute measurements of the intensity of the extracted ion beam from the synchrotron. The maximum current resolution achieved with this apparatus was 250 pA/√Hz

ISBN 978-3-95450-122-9

[3]. For that reason a special liquid helium bath-cryostat with a "warm hole" of 100 mm for the passing ion beam was designed. Fig. 3 shows the mechanical setup of the cryostat which is nearly 1.2 m high and has a diameter of about 0.66 m. The pick-up coil, a single winding formed as a toroid with a VITROVAC 6025 F core, is made of niobium while the meander shape shielding is produced from lead plates and tubes insulated by Teflon foil. To read out the signal of the pick-up coil a low noise LTS dc SQUID system, developed and manufactured by the F. Schiller University Jena, was successfully employed.

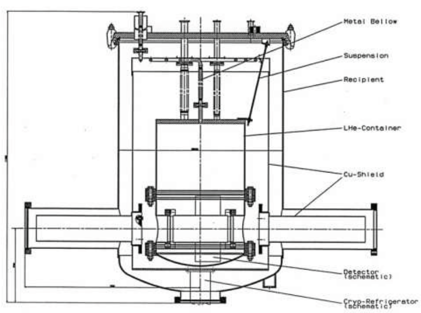

Figure 3: Cross section of the special bath-cryostat for the CCC at GSI.

First measurements were carried out in May 1996 with a $^{20}Ne^{10+}$-beam at 300 MeV/u. About 4 × 10^{10} particles per machine cycle were accelerated in the SIS and were extracted to the beam diagnostics test bench with a transmission of about 50 %. The worldwide first measurement of high energy ions using a CCC is shown in Fig. 4.

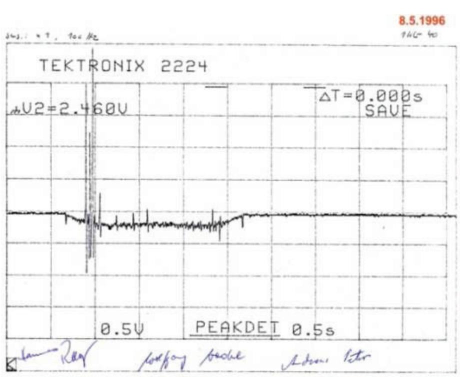

Figure 4: Worldwide first beam measurement of $^{20}Ne^{10+}$ ions using a SQUID-based CCC at GSI.

For the upcoming FAIR project a beam monitor based on the CCC with an enhanced resolution was developed (see Fig.5) [4]. Therefore we focused our investigations on the low temperature properties of the ferromagnetic core material of the superconducting pick-up coil. The pick-up coil transforms the magnetic field of the beam into a current that is detected by a high performance low temperature LTS-DC-SQUID. The penetration of external interfering magnetic fields into the pick-up coil is highly attenuated by an effective meander shaped superconducting shielding.

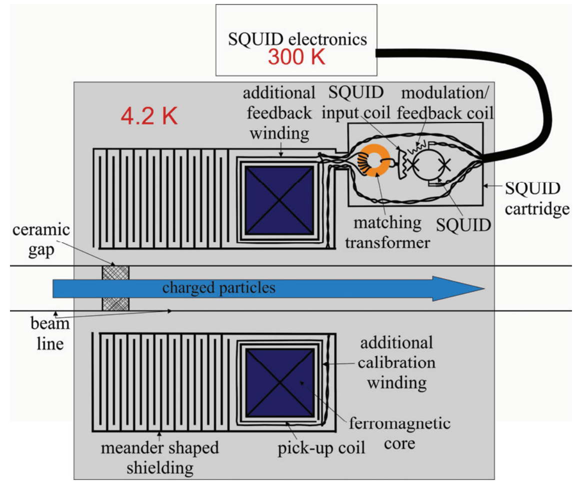

Figure 5: Cross section of the improved SQUID-based CCCfor FAIR.

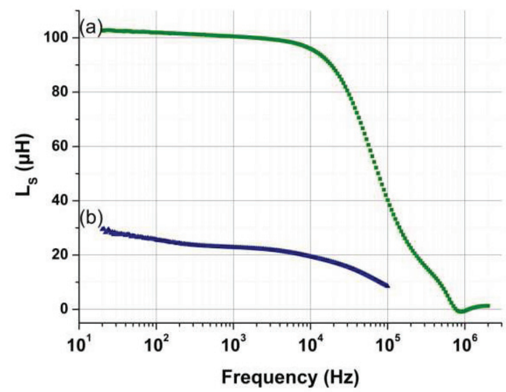

Figure 6: Frequency dependence of the inductance of the Nanoperm pick-up coil for FAIR (a) and VITROVAC 6025 F pick-up coil for DESY (b).

We found that Nanoperm M764 [5] provides much better low temperature performance than VITROVAC 6025 F [6]. In curve (a) of Fig. 6 is shown the inductance of the pick-up coil of the latest CCC for FAIR with Nanoperm M764 core as a function of the frequency. One can see that the inductance of the welded coil is almost constant for frequencies up to 10 kHz. That would provide a linear transfer function of the CCC in this frequency range. Moreover, it is shown that the inductance of the Nanoperm M764 coil is for times higher at liquid helium temperature than the inductance of the DESY-CCC pick-up coil (see curve b in Fig. 6). This should lead to an approximately four times lower intrinsic current noise of the CCC.

The measured current noise density of the Nanoperm pick-up coil (see curve a in Fig. 7) is lower by a factor of 2 – 5 than the current noise density of the DESY-CCC pick-up coil as could be seen in curve b in Fig. 7. The noise level was decreased to 35 pA/√Hz compared to 110 pA/√Hz at 7 Hz. At higher frequencies a noise level of 2.7 pA/√Hz compared to 13.3 pA/√Hz was achieved. Above

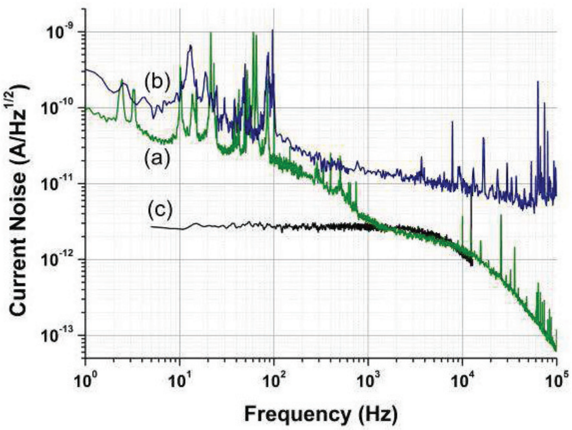

Figure 7: Current noise of the FAIR-CCC with Nanoperm M 764 core (a) in comparison with the DESY-CCC with VITROVAC 6025 F core. The intrinsic noise of the SQUID is depicted in curve (c).

1 kHz the current noise density of the Nanoperm pick-up coil is in the same range as the intrinsic current density of the SQUID sensor itself (see curve c in Fig. 7). The total noise of the Nanoperm coil is calculated to be 1.2 nA in the frequency range from 0.2 to 10 kHz.

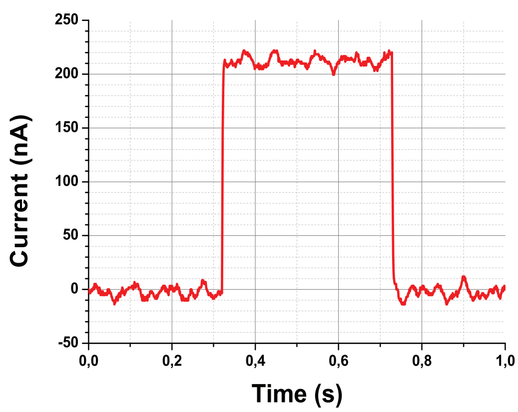

Figure 8: Response of the welded pick-up coil with Nanoperm M-764-01 core connected to the SQUID sensor enclosed into the niobium enclosure to a rectangular current signal of 220 nA (about 0.5 Φ_0).

The response of the Nanoperm coil connected cross the input coil of the SQUID system to a rectangular current signal with an amplitude of 220 nA (corresponding to 0.5 Φ_0) enclosed into a niobium shielding is plotted in Fig. 8. For this measurement no additional low pass filter or time-averaging was used. As could be seen in Fig. 8 a signal-to-noise ratio of approximately 10 was achieved.

In generally, we could show that the CCC is able to measure DC beam currents, e.g. as required for slow extraction from a synchrotron, as well as bunched beams with a noise limited sensitivity of nearly 50 pA/√Hz [2].

SUMMARAY AND OUTLOOCK

In former projects the CCC has shown its capability as beam monitor for ions [3] as well as so-called dark electrons [2]. The resolution of the CCC is limited above all by the magnetic properties of the ferromagnetic core material in the pick-up coil. For the pick-up coil of the CCC we are looking for materials with the highest possible permeability at 4.2 K which is constant over a wide frequency range.

Based on our investigations Nanoperm M764 shows a linear transfer function up to 10 kHz and a four times lower current noise could be achieved. This would allow the detection of beam currents below 1 nA which means 10^9 ions/spill of $^{238}U^{28+}$ respectively 28×10^9 protons / spill for slow extraction with t/spill = 5 s.

IMPORTANT FEATURES OF A SQUID-BASED CCC:

- No back actions
- Highest sensitivity – no alternatives
- Easily calibrated (by an additional electrical current)
- Measurement of absolute current values
- Negligible low drift

REFERENCES

[1] I. K. Harvey, "A precise low temperature dc ratio transformer", Rev. Sci. Instrum. vol. 43, (1972), p. 1626.
[2] R. Geithner, R. Neubert, W. Vodel, P. Seidel, K. Knaack, S. Vilcins, K. Wittenburg, O. Kugeler, and J. Knobloch, Rev. Sci. Instrum. 82 (2011), 013302.
[3] A. Peters, W. Vodel, H. Koch, R. Neubert, H. Reeg, C. H. Schroeder, AIP Conf. Proc. 451 (1998), pp. 163-180.
[4] R. Geithner, W. Vodel, R. Neubert, P. Seidel, F. Kurian, H. Reeg, M. Schwickert, "An improved Cryogenic Current Comparator for FAIR", Proc. of IPAC 2012, New Orleans, Louisiana, USA, MOPPR020, pp. 822, ISBN 978-3-95450-115-1
[5] MAGNETEC GmbH, Industriestrasse 7, D-63505 Langenselbold, Germany.
[6] VACUUMSCHMELZE GmbH & Co. KG, Grüner Weg 37, D-63450 Hanau, Germany.

ISBN 978-3-95450-122-9