NEWS ABOUT THE CRYOGENIC CURRENT COMPARATOR FOR BEAM DIAGNOSTICS*

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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 diagnosis. Also the measurement of so-called 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 (X-FEL). The Cryogenic Current Comparator (CCC) based on high precision LTS SQUIDs is an excellent tool to solve these problems.

This contribution gives an overview on the development of SQUID-based CCCs for high energy physics from the first successful demonstration of the performance at GSI Darmstadt through the latest improved version for FAIR and the Cryogenic Storage Ring at MPI Heidelberg.

INTRODUCTION

Applications of LTS SQUIDs include precision measurement techniques in laboratory research, fundamental physics, biomedicine, and nuclear physics [1]. Monitoring of beam currents in particle accelerators without affecting the beam guiding elements, interrupting the beam or influencing its profile is a major challenge in accelerator technology. Originally developed to compare two currents with one another, CCCs are used in many ways in metrology [2]. Also the detection of the magnetic field generated by the moving high energy charged particles from an accelerator can be successfully done by a CCC.

Exact measurements of beam intensities play an important role for any accelerator facility. At the Facility for Antiproton and Ion Research (FAIR), presently in the planning phase at GSI, the requirements set by beam intensities in the various accelerators, storage rings and transport lines differ significantly. A set of beam diagnostic instruments is foreseen to detect the large variety of ion beams ranging from less than 10^4 antiprotons up to high intensity of 5×10^{11} uranium ions. On-going developments are discussed for non-intercepting devices, such as the cryogenic current comparator, purpose-built for the detection of lowest beam intensities at FAIR and the Cryogenic Storage Ring at the MPI Heidelberg.

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MEASUREMENT SETUP

SQUID-based Cryogenic Current Comparator (CCC)

In principle, the CCC is composed of three main components (see Fig. 1):

- The superconducting pickup coil,
- the highly effective superconducting shield, and
- the high performance LTS-SQUID system.

The CCC, first developed by Harvey in 1972 [3], is a non-destructive measurement method to compare two currents I_1, I_2 (see Fig. 1) with high precision using a meander shaped flux transducer. Only the azimuthally magnetic field component, which is proportional to the current in the wires, will then be sensed by the pick-up coil. All other field components are strongly suppressed. The very small magnetic flux coupled into the coil is mostly detected by a highly sensitive LTS SQUID.

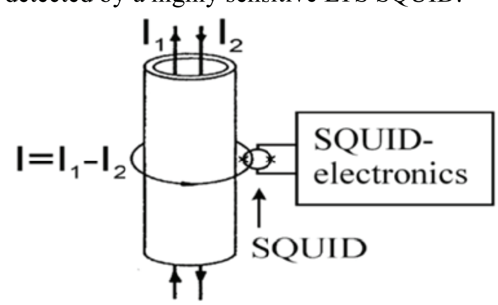

Figure 1: Simplified scheme of an LTS SQUID-based Cryogenic Current Comparator.

The design of the CCC for measuring of dark currents was realized as co-operation of DESY Hamburg, Jena University and GSI Darmstadt. For testing the CCC the whole apparatus was installed in the cavity test stand and operates at 4.2 K.

Pickup Coil

A single turn pickup coil is formed as superconducting niobium toroid with a slot around the circumference. It contains a magnetic core (e.g. Vitrovac 6025-F) providing a high permeability of about 30,000 at liquid helium temperatures. Because the properties of the ferromagnetic core material set the fundamental limits for the achievable intrinsic noise limit of the CCC, numerous materials, such as nanocrystalline Nanoperm, were investigated at low temperatures to find out an optimal candidate. Results are given in [10].

Superconductive Shields

The resolution of the CCC is reduced if the toroidal pickup coil operates in presence of external disturbing magnetic fields. As external fields are in practice unavoidable, an extremely effective shielding has to be applied. A circular meander ("ring cavities") shielding structure (see Fig. 2) allows to pass only the azimuthal magnetic field component of the dark current, while the non-azimuthal field components are strongly attenuated. The attenuation characteristics of CCC shielding were analytically analysed in great detail [4, 5]. Applied to the shielding of the TESLA CCC an attenuation factor of approximately 120 dB for transverse, non-azimuthally magnetic field components is estimated.

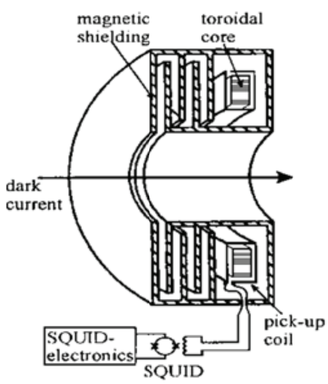

Figure 2: Simplified schematic view of the magnetic shielding, the toroidal pick-up coil, and the SQUID.

SQUID Measurement System

The key component of the CCC is a high performance DC SQUID system developed and manufactured at Jena University. The system makes use of the sensor UJ 111 [6], which is designed in a gradiometric configuration and based on Nb-NbO$_x$-Pb/In/Au Josephson tunnel junctions with dimensions of 3 µm × 3 µm. To couple a signal into the gradiometer-type SQUID an input coil system is integrated on the chip consisting of two coils of 18 turns each, connected in a gradiometric configuration. The input inductance of the SQUID is about 0.8 µH.

The SQUID electronics consists of the low noise preamplifier and the SQUID control and detector unit. The low source impedance of the SQUID (about 1Ω) is stepped up to the optimal impedance of the preamplifier by means of a resonant transformer. The d.c. bias and flux modulation current (modulation frequency 307 kHz) are fed into the SQUID via voltage-controlled current sources situated in the preamplifier and the controller, respectively. The amplification and detection of the SQUID signal is achieved by the state-of-the-art design, i.e. the preamplifier is followed by an AC amplifier and a phase sensitive detector (lock-in) with a PI-type integrator. The output signal returns via a resistor to the modulation coil to close the feedback loop.

In a DC coupled feedback loop, the field of the moving charged particles to be measured is compensated at the SQUID by an external magnetic field generated from the attached electronics. Due to the superconductivity of all leads in the input circuitry (pick-up coil, transformer, SQUID input coil) the CCC is able to detect even DC currents. For an optimum coupling between the 1-turn toroidal pick-up coil (40 µH) and the SQUID a matching transformer is necessary. The overall current sensitivity of the CCC was calculated to 175 nA/Φ_0.

The simplified scheme of the main components of the CCC is shown in Fig. 3.

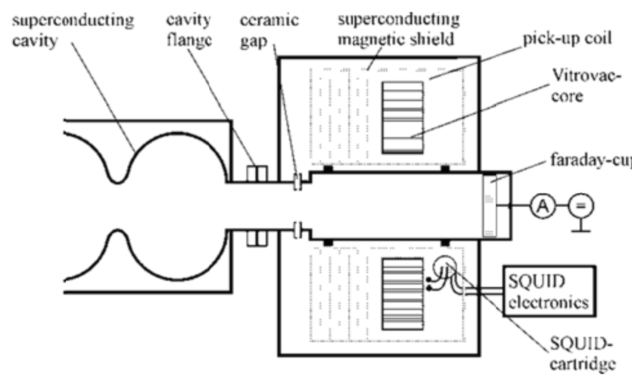

Figure 3: Schematic design of the CCC.

BEAM MEASUREMENTS (GSI-CCC)

At GSI Darmstadt an LTS SQUID based CCC detector system has demonstrated 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 [7]. Based on these promising results new efforts were started in cooperation with GSI Darmstadt and MPI Heidelberg to develop an improved CCC for the upcoming FAIR (Facility for Antiproton and Ion Research) project [8], and for the CSR (Cryogenic Storage Ring) [9], respectively.

FAIR will be one of the leading accelerator facilities. In its final stage FAIR will consist of two fast-ramped superconducting synchrotrons SIS 100 - SIS 300, three storage rings for ion storage and associated experiments (CR, RESR, NESR), a dedicated antiproton storage ring (HESR), and the superconducting fragment separator S-FRS for the production of rare isotope beams. A unique feature of the main FAIR accelerator (SIS100) will be the generation of high brightness, high intensity primary ion beams, e.g. 3×10^{11} ions/spill of $^{238}U^{28+}$. Low intensities ($<10^9$ ions/spill) of rare isotope beams will also have to be transported by the high-energy transport beam lines [8], where installation of the CCCs is foreseen.

The CSR was developed as a novel concept for a storage ring operating below 10 K with only electrostatic ion optical devices for bending and focusing. These electrostatic devices will allow in comparison to magnetic storage rings experiments from light to rather heavy ions or molecules up to organic molecules or even biological samples. The energy of the ions will be variable between 20 to 300 keV per charge state.

A continuous monitoring of the beam currents in the accelerator beam lines requires a non-intercepting measurement method. This method must operate at a wide frequency range in order to sense currents of bunched and continuous beams, from several kHz down to DC. An improved CCC optimally fulfils these requirements for the FAIR and the CSR beam parameters.

DARK CURRENT MEASUREMENTS (DESY-CCC)

The dark current, due to emission of electrons in high gradient fields, is an unwanted particle source. Two issues are of main concern:

- Additional thermal load
- Propagating dark current

Previous studies showed that the second case seems to be the more critical one. It limits the acceptable dark current on the beam pipe "exit" of a TESLA 9-cell cavity to approximately 50 nA.

To demonstrate the function of the CCC and to characterize its current sensitivity test measurements were successfully done at the cryogenic laboratory of Jena University. As signal source a programmable current generator was used to simulate the expected dark electron beam pulses. The solid line in Fig. 4 shows a plot of the beam simulation signal and the dotted line represents the SQUID response of the CCC. The phase shift between both pulses is caused by the measurement bandwidth of the whole system.

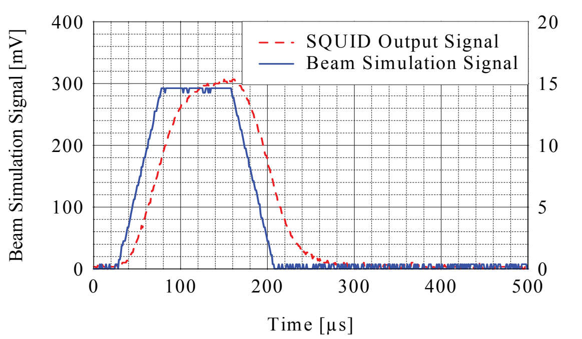

Figure 4: Beam simulation signal (solid line) and output signal of the SQUID based CCC (dotted line).

The spectral flux noise density of the whole system in the white noise region was measured in our laboratory and a level of 8×10^{-5} $\Phi_0/\sqrt{\text{Hz}}$ was observed. This value corresponds to a noise limited current resolution of the CCC of 13pA/√Hz which is much better than required.

In the final test phase the system was installed in the HoBiCat test stand at BESSY, combined with a 9-cell cavity. As a result of additional noise contributions due to the core material of the pick-up coil, mechanical vibrations of the test facility and external disturbing magnetic fields the current resolution was decreased and a resolution of about 1 nA/Hz was achieved [10].

CONCLUSIONS

A SQUID-based CCC is the most sensitive device available for non-destructive low current beam measurements in a wide frequency range from DC to several kHz. To achieve a high resolution, shielding and noise isolation must be highly sophisticated. The properties of the ferromagnetic core material set the fundamental limits for noise reduction. According to our investigations nanocrystalline Nanoperm alloys provide significant advantages for the CCC due to their high permeability and low noise level at liquid helium temperatures. This material allows us to reduce the overall noise by about 40 % in the frequency range from 1 Hz to 2 kHz. Compared to [11], a current sensitivity of 11×10^{-12} A/√Hz against 40×10^{-12} A/√Hz at 100 Hz could be achieved.

At the Facility for Antiproton and Ion Research (FAIR), presently in the planning phase at GSI, a set of beam diagnostic instruments is foreseen to detect the large variety of ion beams ranging from less than 10^4 antiprotons up to high intensity of 5×10^{11} uranium ions.

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