A CRYOGENIC CURRENT COMPARATOR FOR FAIR WITH IMPROVED RESOLUTION *

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Abstract

A Cryogenic Current Comparator is a highly sensitive tool for the non-destructive online monitoring of continuous as well as bunched beams of very low intensities. The noise-limited current resolution of such a device depends on the ferromagnetic material embedded in the pickup coil of the CCC. Therefore, the main focus of research was on the low temperature properties of ferromagnetic core materials. In this contribution we present first results of the completed Cryogenic Current Comparator for FAIR working in a laboratory environment, regarding the improvements in resolution due to the use of suitable ferromagnetic core materials.

INTRODUCTION

The measurement of the absolute and exact intensity of the beam current is one of the most important challenges for each accelerator facility. A non-intercepting detection of high brightness, high intensity primary ion beams as well as low intensities of rare isotope beams is required for the high-energy transport beam lines at FAIR. The expected beam currents in these beam lines are in the range of few nA up to several μA [1].

This requires a detector with a low detection threshold and a high resolution. The online monitoring of the longitudinal beam profile of continuous as well as bunched beams requires a high bandwidth from DC to several kHz. Superconducting pick-up coils allow the detection of dc magnetic fields created by continuous beams. A SQUID acting as current sensor for the pick-up coil enables the detection of lowest currents. A superconducting pick-up coil and a high performance LTS-DC-SQUID are some of the main components of a Cryogenic Current Comparator. Therewith the CCC optimally fulfils the requirements for the FAIR beam parameters.

DESIGN AND WORKING PRINCIPLE

The design of the CCC is depicted in Figure 1. The CCC [2, 3, 4] consists of a meander shaped shielding, a toroidal pick-up coil with a ferromagnetic core, a toroidal matching transformer also including a ferromagnetic core and an LTS-SQUID with the appropriated SQUID-electronics acting as a precise current sensor.

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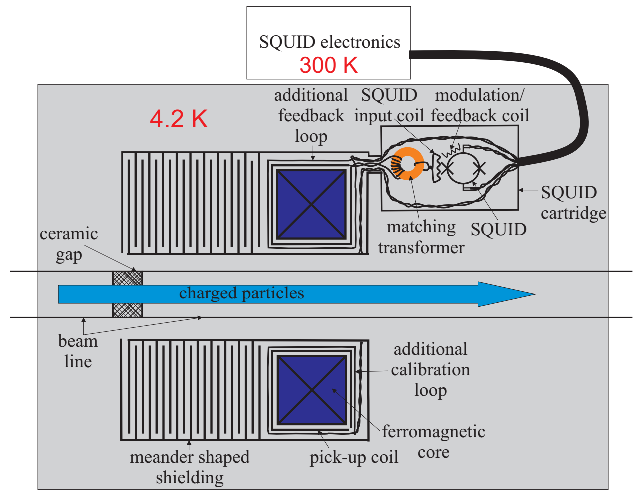

Figure 1: Circuit diagram of the CCC.

The azimuthal magnetic field of the particle beams passes the ceramic gap in the beam line and is guided to the pick-up coil by the meander-shaped shielding whereby all other external magnetic field components are highly attenuated [3].

Sensitivity

Since the CCC is an assembly of different parts with own noise contribution, the total intrinsic noise of the complete CCC is composed by the intrinsic noise of the SQUID itself and its electronics as well as the magnetization noise of the embedded coils. Using a SQUID sensor with an adequate low noise level the sensitivity depends on the pick-up coil and the matching transformer. The current spectral density $\langle I^2 \rangle$ of a coil at a temperature T could be calculated with the Fluctuation-Dissipation-Theorem (FDT) and the measured frequency dependent serial inductance L_S (ν) respectively serial resistance R_S (ν) in the equivalent circuit diagram of a real coil, whereas R_S (ν) represents the total losses [5]:

$$\left\langle I^2 \right\rangle = 4k_B T \int \frac{R_S(\upsilon)}{\left(2\pi\upsilon\left(L_{SQUID} + L_S(\upsilon)\right)\right)^2 + \left(R_S(\upsilon)\right)^2} d\upsilon \qquad (1)$$

For the presented noise measurements the pick-up coil is directly coupled to the input coil of the SQUID. That means that the total noise calculation has to include the SQUID's input coil inductance L_{SQUID}. The input coil does not contain a lossy core material. Therefore the serial resistance could be neglected and the serial inductance is assumed to be frequency independent in the

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considered frequency range. As one can see in Equation (1) the current noise decreases while L_S (ν) is as high as possible and R_S (ν), which means the losses in the core material, remains low over the whole frequency range.

CORE MATERIAL

From preliminary investigations we found that the nanocrystalline ferromagnetic material Nanoperm [6] shows highly satisfying results matching our requirements [7].

The frequency dependent measurements of serial inductance L_S (ν) and the serial resistance R_S (ν) of the coils were measured with the help of a commercial Agilent E4980A LCR-Meter [8].

Figure 2 shows the results of the L_S (ν) - R_S (ν)-measurements at 4.2 K of the FAIR-CCC's single-turn toroidal pick-up coil with Nanoperm M-764-01 core. The Nanoperm pick-up coil has an outer diameter 260 mm, an inner diameter of 205 mm and a width of 97 mm.

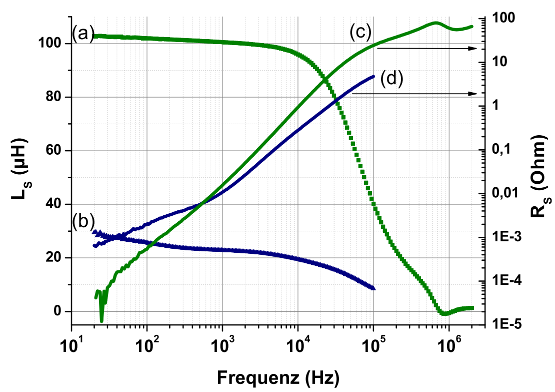

Figure 2: Comparison L_S (ν) and R_S (ν) of the welded pick-up coil with Nanoperm M-764-01 core ((a) and (c)) and the DESY-CCC pick-up coil with Vitrovac 6025F core ((b) and (d)) 4.2 K.

The corresponding curves of L_S (ν) and R_S (ν) of the pick-up coil embedded in a CCC acting as dark current monitor (DESY-CCC) [9] are used for reference purposes. In this installation amorphous Vitrovac 6025F [10] was used as core material for the pick-up coil which is also well known for many other cryogenic applications.

It could be shown that the inductance of the welded coil with the Nanoperm M-764-01 core is almost constant for frequencies below 10 kHz (see (a) in Fig. 2). That would provide a linear transfer function in this frequency range. Moreover, it is shown that the inductance of the Nanoperm M-764-01 coil is four times higher at 4.2 K than the inductance of the DESY-CCC pick-up coil (see (b) in Fig 2). Regarding Equation (1) this should lead to an approximately four times lower current noise with a serial resistance in the same range.

EXPERIMENTAL RESULTS

Noise Measurements

In the case of the FAIR-CCC a SQUID sensor CP2 blue and JESSY SQUID electronics, both from the manufacturer Supracon [11], were used whereas the DESY-CCC used a SQUID UJ111 and a SQUID Control 5.3 electronics of Jena University [12]. The pick-up coils were directly coupled to the SQUID input coil by superconducting wires and already enclosed into the meander-shaped shielding. The output voltage noise density of the SQUID electronics was measured by an HP 35670A dynamic signal analyser. The current noise density was calculated using the flux and current sensitivity of the SQUID sensor. The current sensitivity was tested with the help of a battery powered current source and an additional calibrating loop applied to the pick-up coil (see Fig. 1). In the case of the FAIR-CCC the flux sensitivity was measured to be 0.137 V/Φ_0 and the current sensitivity was 190 nA/Φ_0. The flux sensitivity of the DESY-CCC was measured to be 10 V/Φ_0 and the current sensitivity was 450 nA/Φ_0.

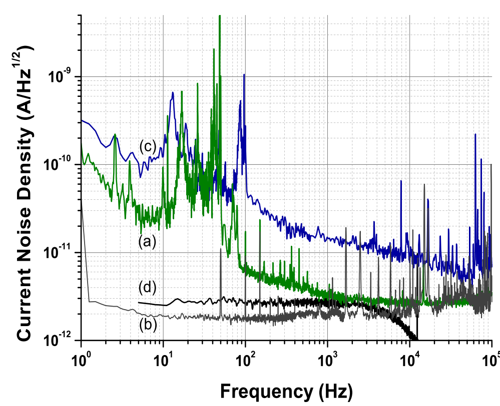

Figure 3: The figure above shows the measured current noise density of the improved FAIR-CCC with Nanoperm M764 core (a) whereas plot (b) represents the intrinsic current noise density of the Supracon SQUID sensor CP2 blue. For comparison the measured current noise density of the DESY-CCC pick-up coil including a Vitrovac 6025F core is shown (c) whereas plot (d) represents the intrinsic current noise density of the SQUID sensor UJ111 from Jena University.

The measured current noise density of the FAIR-CCC (see (a) in Fig. 3) is lower by a factor of 2 - 6 than the current noise density of the DESY-CCC (see (c) in Fig. 3). It was decreased to 21 pA/Hz$^{1/2}$ compared to 110 pA/Hz$^{1/2}$ at 7 Hz and to 2.4 pA/Hz$^{1/2}$ compared to 9,6 pA/Hz$^{1/2}$ at 10 kHz. Above 10 kHz the current noise density of the FAIR-CCC is in the same range as the intrinsic current noise density the SQUID sensor (see (b) in Fig. 3). The total noise of the Nanoperm coil is calculated to be 0.97 nA in the frequency range from 0.2 Hz to 10 kHz.

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Step Function Response

Figure 4 shows the full-bandwidth response of the FAIR-CCC to a rectangular current signal of 1.438 µA (a), 185 nA (b), and 42.5 nA (c) applied to the additional calibrating loop. There is no low pass filter or time-averaging used. The step function response for lower currents is quite linear as one can see from curves (b) and (c). From this curves it is also visible that there is no drift in the CCC signal during a time span of at least 15 s. At higher currents (curve (a)) an overshooting appears at the rising edge of the signal. The reason for this appearance has to be clarified in subsequent experiments.

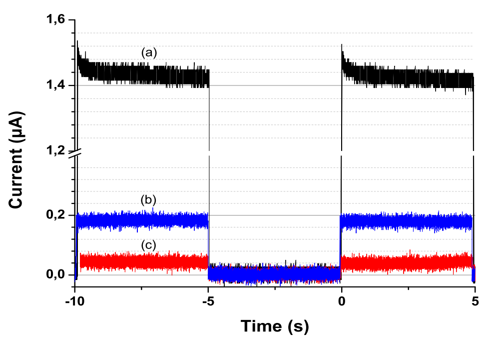

Figure 4: Full-bandwidth response of the FAIR-CCC to a rectangular current signal of 1.438 µA (a), 185 nA (b), and 42.5 nA (c) applied to the additional calibrating loop.

Magnetic Field Attenuation

The attenuation factor of CCCs with a meander-shaped shielding was analytically calculated by Grohmann et al. in great detail [3].

The measurements of the attenuation factor were done by applying a homogenous magnetic field which was created by a modified Helmholtz coil outside of the cryostat. The direction of the magnetic field could be set either perpendicular (transvers field) or parallel (longitudinal field) to the beam axis. The magnetic flux density was varied sinusoidal with a frequency of 0.1 Hz. The peak-to-peak values ΔB_o were measured to be $\Delta B_{o,t} = 51$ µT for the transverse field and $\Delta B_{o,l} = 100$ µT for the longitudinal field. The attenuated magnetic field ΔB_i inside the meander-shaped shielding in the area of the pick-up coil could be calculated from the measured response ΔU of the CCC to the external magnetic field.

$$\Delta B_i = \frac{\Delta U \cdot dI/d\Phi_0 \cdot L_S}{\mu_r \cdot A \cdot dU/d\Phi_0} \qquad (2)$$

Here $dI/d\Phi_0 = 190$ nA/ Φ_0 denotes the current sensitivity of the SQUID sensor, $L_S = 100$ µH the inductance of the pick-up coil at 4.2 K, $\mu_r = 5.4\times10^4$ the relative permeability of the pick-up coil at 4.2 K, $A = 37.5$ cm^2 the cross-section area of the pick-up coil, and $dU/d\Phi_0 = 0.137$ V/ Φ_0 the flux sensitivity of the SQUID sensor. The response of the CCC to the transvers field was measured to be $\Delta U_t = 0.032$ V which gives an attenuation factor $A_t = 20 \cdot log(\Delta B_{o,t}/ \Delta B_{i,t}) = 188$ dB. The response of the CCC to the longitudinal field was measured to be $\Delta U_l = 0.016$ V which gives an attenuation factor $A_l = 20 \cdot log(\Delta B_{o,l}/ \Delta B_{i,l}) = 199$ dB.

CONCLUSION AND OUTLOOK

The Cryogenic Current Comparator has shown its capability as a beam monitor for ions as well as electrons. With the usage of the presented material Nanoperm M-764-01 a linear transfer function up to 10 kHz could be expected. The current noise density of the pick-up coil was reduced by a factor of two to five. With the increased attenuation factor of the meander-shaped shielding a further noise reduction in the low frequency range up to 1 kHz was achieved. This would enable the detection of beam currents below 1 nA which means approximately 10^9 ions/spill of $^{238}U^{28+}$ respectively 28×10^9 protons/ spill for slow extraction with $t_{spill} = 5$ s. The improved resolution as well as the sensitivity to continuous and bunched beams qualifies the CCC as a well suited instrument for the beam diagnostics of FAIR.

There are still some challenges regarding the wiring from the SQUID cartridge to the SQUID electronics. In the presented measurements the wiring is at least in its final configuration with all necessary feedthroughs but there are some perturbances from interfering rf-signals which causes an increased noise level. In subsequent experiments the wiring should be optimized and the matching transformer will be embedded, which again increases the current sensitivity. Simultaneous to these experiments which could be done in a wide neck bath dewar the cryostat for the implementation of the CCC in a beam line should be designed and fabricated.

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