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A SQUID-BASED BEAM CURRENT MONITOR FOR FAIR*

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Abstract

A Cryogenic Current Comparator (CCC) was developed for the upcoming FAIR-Project, providing a non-destructive online monitoring of the beam current in the nA-range. The CCC was optimized for a lowest possible noise-limited current resolution together with a high system bandwidth. Therefore, the low temperature properties of ferromagnetic core materials used in the pick-up coil were investigated and different Superconducting Quantum Interference Device (SQUID)-systems were tested.

In this contribution we present results of the completed Cryogenic Current Comparator for FAIR working in a laboratory environment, regarding the improvements in resolution and bandwidth due to the use of suitable ferromagnetic core materials and optimized SQUID-system components.

INTRODUCTION

The high energy beam transport lines (HEBT) at FAIR require a non-intercepting detection of the absolute and precise intensity of the beam current of high brightness, high intensity primary ion beams as well as low intensities of rare isotope beams. The expected beam currents in these beam lines are in the range of few nA up to several µA for continuous as well as bunched beams [1]. This requires a detector with a low detection threshold, a high resolution, and as well as high bandwidth from DC to several kHz.

A superconducting pick-up coil and SQUID-system are some of the main components of a Cryogenic Current Comparator. Superconducting pick-up coils allow the detection of DC magnetic fields created by continuous beams without applying modulation techniques. A SQUID acting as current sensor for the pick-up coil enables the detection of lowest currents. Therewith the CCC optimally fulfils the requirements for the FAIR beam parameters.

DESIGN AND WORKING PRINCIPLE

The CCC [2, 3, 4] consists of a meander-shaped niobium shielding, a toroidal niobium 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 (see Fig. 1).

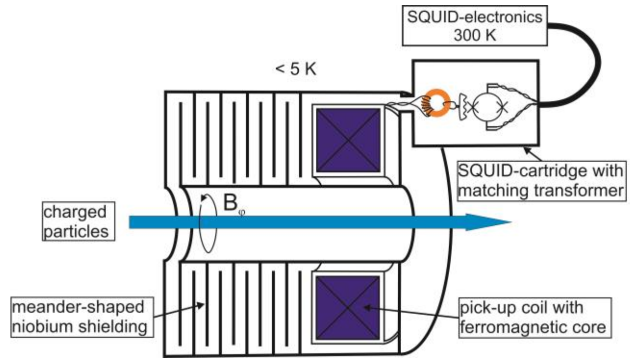

Figure 1: Circuit diagram of the CCC.

The azimuthal magnetic field of the particle beam 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, 5].

Sensitivity Optimization

The total intrinsic noise of the entire CCC is composed by the intrinsic noise of the SQUID itself and its electronics as well as the magnetization noise of the embedded coils. The spectral current density $\langle I^2 \rangle$ of a coil coupled to the input coil L_I of a SQUID at a temperature T can be calculated with the Fluctuation-Dissipation-Theorem (FDT) and the measured frequency-dependent serial inductance $L_S(\nu)$ respectively serial resistance $R_S(\nu)$ in the equivalent circuit diagram of a real coil, whereas $R_S(\nu)$ represents the total losses [6, 7]:

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

As one can see in Equation (1) the current noise decreases while $L_S(\nu)$ is as high as possible and $R_S(\nu)$ remains low over the whole frequency range.

From preliminary investigations [5, 7] we found that the nanocrystalline ferromagnetic material Nanoperm [8] shows highly satisfying results matching our requirements. A single-turn Niobium toroidal pickup coil was e-beam-welded around a Nanoperm M764 core. This pick-up coil has an outer diameter 260 mm, an inner diameter of 205 mm and a width of 97 mm.

A possibility for optimization of the overall current sensitivity is the use of a matching transformer with optimized winding ratio and core material.

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For a transformer the current gain in the short-circuit case only depends on the winding ratio, $I_2/I_1 = n_1/n_2$.

However, the CCC with a matching transformer can be described as a series connection of two burdened transformers (see Fig. 2) [4].

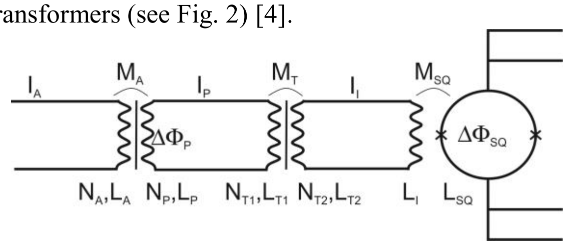

Figure 2: Schematic circuit diagram of the CCC with pick-up coil L_P, matching transformer L_{T1}, L_{T2}, SQUID input coil L_I and SQUID L_{SQ}.

The ratio of the screening currents, I_A, seen by the pick-up coil L_P, to the current through the input coil of the SQUID, I_I, depends on the winding ratio N_{T1}/N_{T2} of the matching transformer, the inductances of the pick-up coil, L_P, the primary, L_{T1} respectively secondary coil, L_{T2}, of the matching transformer, and the input coil of the SQUID, L_I.

$$\frac{I_I}{I_A} = \frac{N_{T1}}{N_{T2}} \cdot \frac{1}{1+\frac{L_I}{L_{T2}}} \cdot \frac{N_A}{N_P} \cdot \frac{1}{1+\frac{L_{T1}L_I}{(L_{T2}+L_I)L_P}} \qquad (2)$$

Setting $N_A = N_P = N_{T2} = 1$, $L_{T1} = N_{T1}^2 \times L_{T2}$, $L_I = 0.46$ µH and $L_P = 103$ µH, I_I/I_A can be plotted as a function of L_{T2} and N_{T1}. There is an optimal number of windings, $N_{T1,\ opt} = 15$, for $L_{T2} = 0.46$ µH where the current gain factor has a maximum of $I_I/I_A = 5.0$. The differences with an unburdened transformer can be seen at this point where the current gain N_{T1}/N_{T2} (= 15/1) should be 15. The dependence on the inductance of the secondary coil of the matching transformer saturates for L_{T2} bigger than 0.46 µH which is the inductance of the input coil of the SQUID.

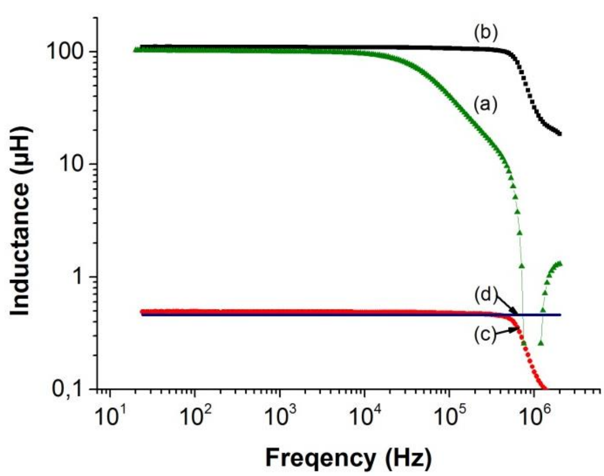

Figure 3: L_S (ν) at 4.2 K for the welded toroidal pick-up coil with Nanoperm M764 core (a), and the primary (b) respectively secondary (c) coil of the matching transformer with Vitrovac 6030 core as well as the SQUID input coil inductance (d).

Regarding these results the matching transformer was customized by applying 15 turns respectively 1 turn of niobium wire to a selected Vitrovac 6030 [4, 9] core.

Figure 3 shows the frequency dependence L_P (ν) at 4.2 K of the FAIR-CCC's single-turn toroidal pick-up coil with Nanoperm M764 core and the primary L_{T1} (ν) with $N_{T1} = 15$ respective secondary coil L_{T2} (ν) with $N_{T2} = 1$ of the matching transformer with Vitrovac 6030 core. The frequency characteristics of serial inductance L_S (ν) and the serial resistance R_S (ν) of the coils were measured with a commercial Agilent E4980A LCR-Meter [8].

The inductance of the pick-up coil of $L_P = 103$ µH matches quite well to the inductance of the matching transformer's primary coil $L_{T1} = 110$ µH as well as the inductance of the matching transformer's secondary coil $L_{T2} = 0.49$ µH to the inductance of the SQUID's input coil of $L_I = 0.46$ µH. Inserting these measured values in Eq. (2) yields an overall current gain factor of 5.1. It could be shown that the inductance of the welded coil with the Nanoperm M764 core is almost constant for frequencies below 10 kHz (see (b) in Fig. 3). L_{T1} respectively L_{T2} (see (b), (c) in Fig. 3) are even constant up to 400 kHz which promises high system bandwidths.

EXPERIMENTAL RESULTS

For the presented results of the completed FAIR-CCC with matching transformer a SQUID sensor CP2 blue from the manufacturer Supracon [10] and a XFF-1 electronics from the manufacturer Magnicon [11] were used.

Step Function Response

Figure 4 shows the response of the completed FAIR-CCC with matching transformer to a rectangular current signal of 2 µA (a), 1 µA (b), 200 nA (c), 100 nA (d), 20 nA (e), and 10 nA (f) applied to a beam simulating wire along the beam axis with the help of a battery powered current source. The response is plotted as the magnetic flux seen by the SQUID in units of the magnetic flux quantum Φ_0 which could be calculated from the output voltage and the flux sensitivity of the SQUIQ-system. The flux sensitivity was adjusted to 0.103 V/Φ_0 and the bandwidth of the SQUID-system to 217 kHz. From the responses to the different current pulses an overall current sensitivity of 42 nA/Φ_0 could be calculated. In the case of the direct coupled pick-up coil the flux sensitivity was measured to be 0.137 V/Φ_0 and the current sensitivity was 190 nA/Φ_0. The overall current sensitivity therefore was enhanced by a factor of 4.5 using the matching transformer compared to the direct coupled pick-up coil. There is no low pass filter or time-averaging used in the output circuit of the CCC. The step function response is quite linear. From this curves it is also visible that there is almost no drift in the CCC signal during a time span of at least 5 s. The smoothing at the rising edge of the signal at higher currents (curve (a)) arises due to the use of a 10 Hz low-pass filter in the input to prevent RF-interferences and is not a characteristic of the CCC.

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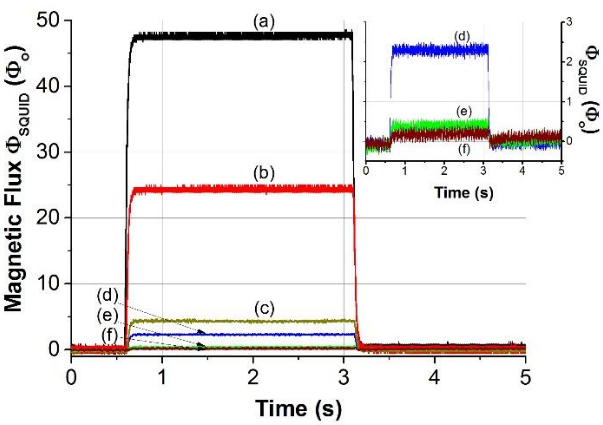

Figure 4: Response of the completed FAIR-CCC with matching transformer to a rectangular current pulse of 2 µA (a), 1 µA (b), 200 nA (c), 100 nA (d), 20 nA (e), and 10 nA (f) applied to a beam simulating wire along the beam axis (insert with magnified scale).

Noise Measurements

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 setup.

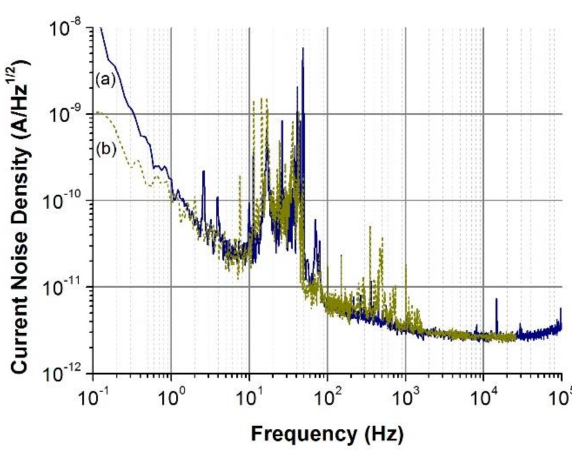

Figure 5: Current noise density of the FAIR-CCC without the matching transformer (a) whereas trace (b) represents current noise density of the FAIR-CCC with matching transformer.

Figure 5 shows the measured current noise density of the FAIR-CCC without the matching transformer (a) using Supracon‘s SQUID sensor CP2 blue and JESSY SQUID electronics [5] in comparison to the current noise density of the FAIR-CCC with matching transformer using the Supracon‘s SQUID sensor CP2 blue and Magnicon‘s XFF-1 SQUID electronics. There is no additional current noise due to the use of the matching transformer. The current noise density was measured to be 21 pA/Hz$^{1/2}$ at 7 Hz and to 2.4 pA/Hz$^{1/2}$ at 10 kHz, cf. Fig. 5. The total noise of the completed FAIR-CCC is calculated to be 0.97 nA in the frequency range from 0.2 Hz to 10 kHz.

CONCLUSION AND OUTLOOK

The Cryogenic Current Comparator has shown its capability as a beam intensity monitor for ions as well as electrons [12, 13]. Using Nanoperm M764 material, the current noise density of the pick-up coil was reduced by a factor of 2 to 5 compared to previous installations. Including the matching transformer enhances the overall current sensitivity by a factor of 4.5 without increasing the current noise density. This enables 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. Using fast SQUID systems as well as broadband core materials enables time resolved measurements to explore the spill structure of the beam. Together with the improved resolution the sensitivity to coasting beams qualifies the CCC as a well suited instrument for the beam diagnostics of FAIR.

The next steps will be the measurements of the step-function response without the low-pass regarding the estimation of the SQUID-system’s slew-rate as well as the design and fabrication of a cryostat for the implementation of the CCC in the CRYRING as a kind of test bench for FAIR.

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