AN IMPROVED CRYOGENIC CURRENT COMPARATOR FOR FAIR*

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Abstract

Online monitoring of low intensity (below 1 µA) charged particle beams without disturbing the beam and its environment is crucial for any accelerator facility. For the upcoming FAIR project a beam monitor based on the Cryogenic Current Comparator principle with an enhanced resolution was developed. The main focus of research was 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 dc Superconducting QUantum Interference Device (LTS-DC-SQUID). The penetration of the pick-up coil by interfering magnetic fields is highly attenuated by a meander shaped superconducting shielding. The Cryogenic Current Comparator is able to measure DC beam currents, e.g. as required for slow extraction from a synchrotron, as well as bunched beams. In this contribution we present first results of the improved Cryogenic Current Comparator working up to now in a laboratory environment.

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 parameter.

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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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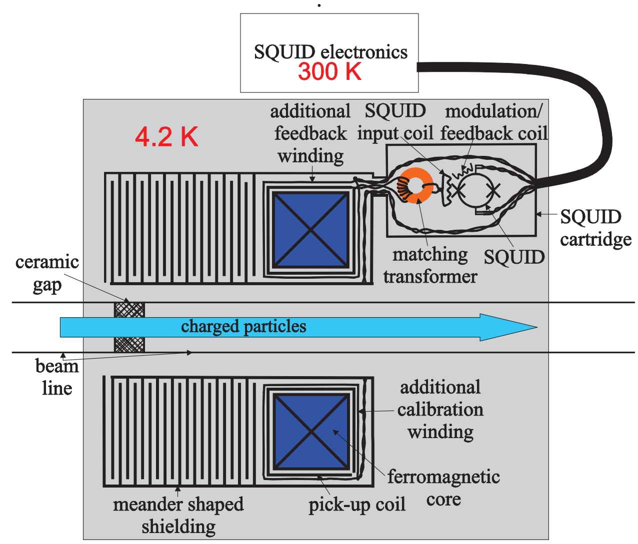

Figure 1: Circuit diagram of the CCC.

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.

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]:

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

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 have 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 considered frequency range. From preliminary investigations we found that Vitrovac 6030 [6] is well suited as core material for matching transformers at 4.2 K with a linear transfer function and low flux noise contribution. That's why we focused our investigation on ferromagnetic core material for the usage in the pick-up coil. 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. Therefore we are searching for core materials with highest possible permeability at liquid helium temperatures with the highest possible cut-off frequency. Unfortunately these two requirements are inversely proportional.

CORE MATERIAL

For the previous installation of the CCC, we used Vitrovac 6025F [6] as core material for the pick-up coil which is also well known for many other cryogenic applications. The CCC developed as a dark current monitor for DESY Hamburg achieved a current resolution of 5 nA with a Vitrovac pick-up coil using a 10 Hz low pass filter [7]. The properties of the DESY-CCC pick-up coil will be the reference for the material investigations presented in the following paragraphs.

From preliminary investigations we found that the nanocristalline ferromagnetic material Nanoperm [8] shows highly satisfying results which matches our requirements [4].

These investigations were done using smaller test samples. Based on these results cores of Nanoperm M764-01 with the final dimensions (outer diameter: 260 mm, inner diameter: 205 mm, width: 97 mm) were ordered. After welding the single-turn toroidal niobium winding the coil, herein after referred to as Nanoperm pick-up coil, was characterized at 4.2 K in a customized wide-neck cryostat.

Measurement of L_S and R_S

The serial inductance and the serial resistance of the coils were measured with the help of a commercial Agilent E4980A LCR-Meter. The coil is connected to a four wire measurement terminal at the level of the coil. Two identical wiring from the top of the cryostat are also applied to the terminal whereas one is shortened by a niobium wire to execute a short respectively open correction of the test setup. After the performance of the correction, L_S (ν) and R_S (ν) of the shortened wiring were measured and these data were subtracted from the measured values of the coil which cancel out parasitic components remaining after correction.

Noise Measurements

The noise measurements were performed with a SQUID UJ111 and a SQUID Control 5.3 electronics of Jena University [9]. The pick-up coils were directly coupled to the SQUID input coil by superconducting wires. The output voltage noise density of the SQUID electronics was measured by a HP 35670A dynamic signal analyser. The current noise density was calculated using the flux and current sensitivity of the SQUID sensor. The flux sensitivity of 10 V/Φ_0 was fixed by the adjustment of the working point. The current sensitivity was tested with the help of a battery driven current source and an additional calibrating winding applied to the pick-up coil (see Fig. 1). In the case of the Nanoperm pick-up coil the current sensitivity was measured to be 430 nA/Φ_0 and it was shielded against external magnetic field with the help of two niobium pots fitted into each other. The DESY-CCC pick-up coil was already enclosed into the meander-shaped shielding and the current sensitivity was measured to be 450 nA/Φ_0.

RESULTS

The serial inductance as well as the serial resistance of the Nanoperm pick-up coil and the DESY-CCC pick-up coil is depicted in Fig. 2.

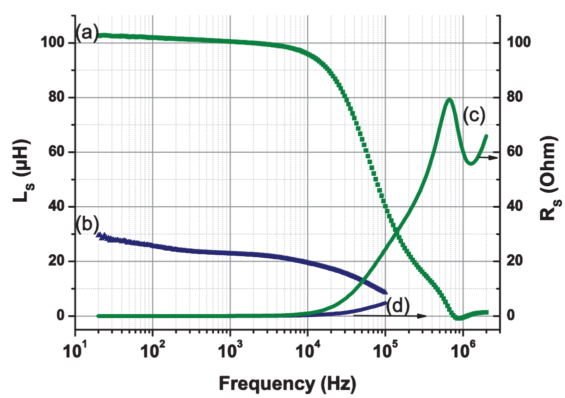

Figure 2: Comparison L_S (ν) and R_S (ν) of the welded pick-up coil with Nanoperm M-764-01 core ((a) and (c)) and the DESY-CCC pick-up coil with Vitrovac 6025F core ((b) and (d)) 4.2 K.

One can see 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.

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The measured current noise density of the Nanoperm pick-up coil (see (a) in Fig. 3) is lower by a factor of 2 - 5 than the current noise density of the DESY-CCC pick-up coil (see (d) in the inset of Fig. 3). It was decreased to 35 $pA/Hz^{1/2}$ compared to 110 $pA/Hz^{1/2}$ at 7 Hz and to 2.7 $pA/Hz^{1/2}$ compared to 13.3 $pA/Hz^{1/2}$ at 10 kHz. Above 1 kHz the current noise density of the Nanoperm coil is in the same range as the intrinsic current noise density the SQUID sensor (see (c) in Fig. 3). The total noise of the Nanoperm coil is calculated to be 1.2 nA in the frequency range from 0.2 Hz to 10 kHz.

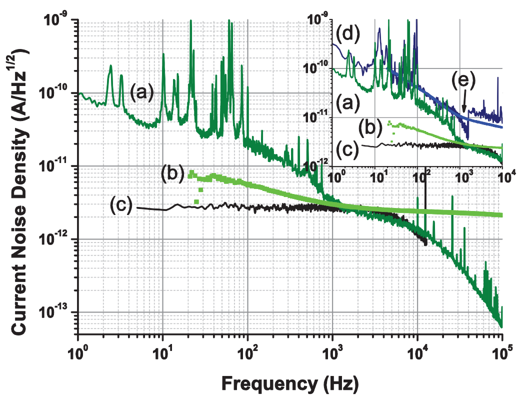

Figure 3: Measured (a) and calculated (b) current noise of the welded pick-up coil with Nanoperm M-764-01 core as well as the measured current noise of the SQUID sensor with rf-shunted input (c). The inset compares the measured (a) and calculated (b) current noise of the welded coil with Nanoperm M-764-01 core with the measured (d) and calculated (e) current noise of the DESY-CCC pick-up coil with Vitrovac 6025 F core.

In the case of the DESY-CCC pick-up coil the predictions from the FDT (see (e) in the inset of Fig. 3) matches very well to the noise measurements. But there is seen an additional noise contribution in the low frequency range up to 1 kHz compared to the FDT (see (b) in Fig. 3) in the case the Nanoperm coil. This arises from the less effective shielding of the coil due to the two niobium pots during the noise measurement compared to the meander-shaped shielding. That means by enclosing the Nanoperm pick-up coil into the meander-shaped shielding this additional noise contribution should be reduced and the current noise should converge the predictions of the FDT. Above all this points out the significance of an accurate shielding.

Fig. 4 shows the response of the Nanoperm coil connected to the SQUID sensor to a rectangular current signal of 220 nA (approximately 0.5 Φ_0) enclosed into the niobium pots. There is no low pass filter or time-averaging used. The signal-to-noise ratio is approximately 10.

CONCLUSION AND OUTLOOK

The Cryogenic Current Comparator has shown its capability as 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 should be possible This would enable the detection of beam currents below 1 nA which means approximately 10^9 ions/spill of $238U^{28+}$ respectively 28×10^9 protons/spill for slow extraction with t_{spill} = 5 s. With this resolution, the CCC is well suited for the beam diagnostics of FAIR. In subsequent experiments, measurements of the current noise distribution of the Nanoperm coil enclosed in the meander-shaped shielding are planned to verify the results from the FDT. Thereafter the complete commissioning, the functional test, and the characterization of the CCC in a noise reduced laboratory environment will be done.

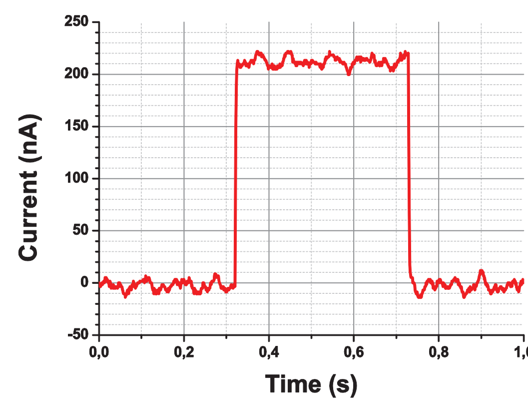

Figure 4: Response of the welded pick-up coil with Nanoperm M-764-01 core connected to the SQUID sensor enclosed into the niobium pots to a rectangular current signal of 220 nA (approximately 0.5 Φ_0). There is no low pass filter or time-averaging used. The signal-to-noise ratio is approximately 10.

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