

SENSOR OPTIMIZATIONS FOR A CRYOGENIC CURRENT COMPARATOR*

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Abstract

We present a non-destructive superconducting monitoring system for charged particle beams. The system uses the Cryogenic Current Comparator (CCC) principle with a low temperature DC-SQUID. The Cryogenic Current Comparator has shown its capability in the Horizontal Bi-Cavity Test Facility at the Helmholtz-Zentrum Berlin under noisy conditions. In this test facility for superconducting cavities the CCC setup was able to detect dark currents in the nA range. The suitability of the Cryogenic Current Comparator as a beam monitor for the Facility of Antiproton and Ion Research at GSI Darmstadt as well as for the Cryogenic Storage Ring at MPI Heidelberg will be pointed out and discussed. Special attention will be given to the ferromagnetic core materials embedded in the pickup coil.

INTRODUCTION

High-resolution online monitoring of modulated as well as non-modulated beams of charged particles without affecting the beam is a great challenge in beam diagnostics.

In the high-energy transport beamlines at the Facility of Antiproton and Ion Research (FAIR) there will be transported high brightness, high intensity primary ion beams, e.g. 3×10^{11} ions/spill of 238U^{28+} as well as low intensities ($< 10^9$ ions/spill) of rare isotope beams [1].

The the Cryogenic Storage Ring (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. This will allow 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 [2].

For the detection of the low intensity beams a low detection threshold and a high resolution is necessary. Also

a high bandwidth from DC to several kHz is demanded for the reproduction of the longitudinal beam profile of continuous as well as bunched beams. In addition, a stable high vacuum inside the beamline with a residual gas pressure below 10^{-13} mbar (room temperature equivalent) is required for operation of the CSR. The CCC optimally fulfills these requirements for the FAIR and the CSR beam parameters due to the superconductivity of the sensing parts and its position outside the beamline.

CRYOGENIC CURRENT COMPARATOR

The CCC [3, 4, 5] consists of a superconducting hollow cylinder which is part of a superconducting meander-shaped shielding, a superconducting toroidal pickup coil with a ferromagnetic core, a superconducting matching transformer and a high performance LTS-DC-SQUID-system of the Jena University [6].

Sensitivity

The total intrinsic noise of the CCC is composed of the noise contribution of the SQUID with its electronics and the noise from the pickup coil. Applying a SQUID sensor with an adequate low noise level the sensitivity depends on the pickup coil.

Using the Fluctuation-Dissipation-Theorem for a coil coupled to an input coil of a SQUID, one can calculate the current spectral density [7]:

$$\langle I \rangle^2 = 4k_B T \frac{R_S(\nu)}{(2\pi\nu(L_{SQUID} + L_S(\nu)))^2 + (R_S(\nu))^2}. \quad (1)$$

L_{SQUID} is the inductance of the input coil of the SQUID and is assumed to be frequency independent in the considered frequency range. $L_S(\nu)$ and $R_S(\nu)$ are the frequency dependent serial inductance respectively serial resistance in the equivalent circuit diagram of a real coil, whereas $R_S(\nu)$ represents the total losses. On the basis of Eq. (1) it can be seen that the current noise decreases for coils with a frequency independent inductance because $R_S(\nu)$ increases

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with decreasing $L_S(\nu)$ at higher frequencies (see Fig 1). Therefore the main focus is on core materials with a high, frequency independent relative permeability at cryogenic temperatures.

Results from HoBiCaT

In collaboration with DESY Hamburg a Cryogenic Current Comparator (DESY-CCC) operating as dark current monitor was developed. This device should work as a quality test facility for superconducting cavities and was tested in the Horizontal Bi-Cavity Test Facility (HoBiCaT) at the Helmholtz-Zentrum Berlin. As reported in [8] the DESY-CCC was able to detect dark currents down to 5 nA in a noisy accelerator environment using a 5 Hz low pass filter. The noise limited current resolution in the frequency range up to 5 Hz is $0.2 \text{ nA/Hz}^{1/2}$ with a total noise of 1.8 nA. Between 5 Hz and 500 Hz this increases to $50 \text{ nA/Hz}^{1/2}$ due to external disturbances. An optimization of the meander-shaped shielding is subject of further investigations.

PROPERTIES OF THE COILS

Although the properties of ferromagnetic materials are well characterized at room temperature or above, there is less information for low temperatures. One way to evaluate the frequency dependent low temperature properties of ferromagnetic strip wound cores is the measurement of the inductance of toroidal coils made out of this cores. Beside this the direct measurement of the current noise contribution of the cores is done by connecting the coils to the input coil of a SQUID system.

Materials

The core material used for the DESY-CCC pickup coil is the amorphous Vitrovac 6025F from the manufacturer Vacuumschmelze GmbH&Co. KG Hanau [9]. In the last years many publications deal with nanocrystalline soft magnetic materials [10]. In previous measurements [5] we have characterized several samples of nanocrystalline Nanoperm from the manufacturer Magnetec GmbH Langenselbold [11]. Because of these results it was decided to use Nanoperm as core material for the future pickup coils. Due to the fact that the previous measurements were done on small samples (outer diameter $d_a = 28 \text{ mm}$, inner diameter $d_i = 13 \text{ mm}$ and width $h = 12.5 \text{ mm}$) three cores of Nanoperm M-764-01 with the final dimensions (outer diameter $d_a = 260 \text{ mm}$, inner diameter $d_i = 205 \text{ mm}$ and width $h = 97 \text{ mm}$) were tested. To investigate possible improvements using new core materials they should be compared with the pickup coil from the DESY-CCC tested at HoBiCaT.

Measurement of L_S and R_S

The inductance and the resistance of the coils were measured in a wide neck cryostat at room temperature, 77 K

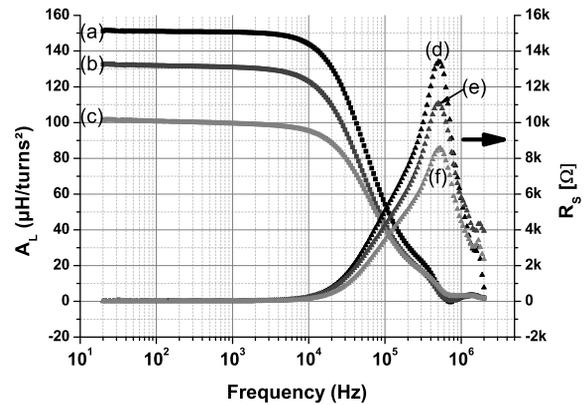


Figure 1: Frequency dependence of the inductance factor A_L at room temperature (a), 77 K (b) and 4.2 K (c) as well as frequency dependence of the serial resistance R_S at room temperature (d), 77 K (e) and 4.2 K (f) of the coil with Nanoperm M-764-01 core.

and 4.2 K with an Agilent 4980A LCR-Meter [5]. The DESY-CCC pickup coil was measured after welding the toroidal niobium winding. For the characterization of the three Nanoperm M-764-01 cores a different number of turns (11,12,13) of normal conducting wire were applied. In the case of the Nanoperm M-764-01 cores the inductance factor A_L will be used in the following to compare the results. The inductance factor A_L is the measured inductance L_S divided by the square of the number of turns. In the case of a single turn coil like the CCC pickup coil, A_L could be equated with L_S for this coil.

Noise Measurements

For the noise measurements the DESY-CCC pickup coil was connected directly to the input coil of the LTS DC SQUID sensor UJ111. The spectral density of the output voltage of the SQUID electronics was measured with an Hewlett Packard 35670A dynamic signal analyzer. With the flux sensitivity of $10 \text{ V}/\phi_0$ and a current sensitivity of $450 \text{ nA}/\phi_0$ one can calculate the corresponding current spectral density.

The noise of the Nanoperm M-764-01 cores is not measured directly, yet. An estimate from the fluctuation-dissipation-theorem (see Eq. 1) is used.

COMPARISON AND ESTIMATE OF THE SENSITIVITY

In Fig. 2 one can see that the inductance factor of the Nanoperm M-764-01 coil is almost constant for frequencies below 10 kHz. That provides a linear transfer function in this frequency range. Moreover, it is shown that the inductance factor of the Nanoperm M-764-01 coil is four times higher at 4.2 K than the inductance factor of the DESY-CCC pickup coil. Regarding Equation (1) this

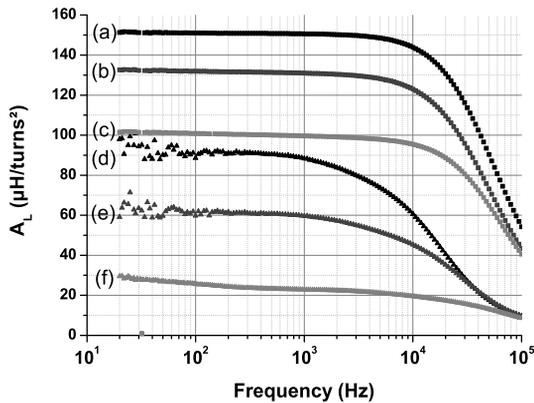


Figure 2: Comparison of the frequency dependence of the inductance factor A_L of the coil with Nanoperm M-764-01 core ((a) - (c)) and the DESY-CCC pickup coil with Vitrovac 6025F core ((d) - (f)) at room temperature (a) (d), 77 K (b) (e) and 4.2 K (c) (f).

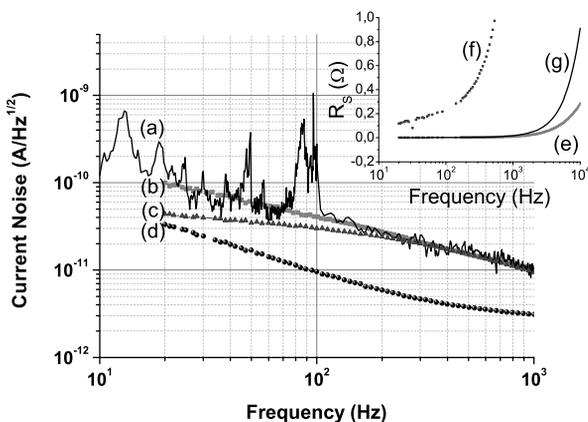


Figure 3: Measured (a) and calculated (b) current noise of the DESY-CCC pickup coil with Vitrovac 6025 F core. (c) is the current noise of the coil with Nanoperm M-764-01 core calculated from A_L and the original R_S (see Fig. 1 and (f) in the inset) and (d) from A_L and the modified R_S (see inset (g)). (e) in the inset is the original R_S of the DESY-CCC pickup coil with Vitrovac 6025 F core.

should lead to an approximately four times lower current noise given that the serial resistance is in the same range. In fact the measured R_S is much higher because of the normal conducting wire used for the multi-turn winding of the Nanoperm M-764-01 coils. The effect on the calculated current noise is shown in Fig. 3 (curve c). It leads to a much higher current noise. Assuming a comparable R_S of the Nanoperm M-764-01 coils in the low frequency regime where A_L is almost constant (frequency between 20 Hz and 1 kHz, see inset Fig. 3) the calculated current noise is in the predicted range (see curve d in Fig. 3). This adjustment was done by dividing the measured R_S through the square of

the number of turns. Using the modified R_S the calculated current noise of the Nanoperm M-764-01 coils (see (d) in Fig. 3) is by a factor of 3 - 5 lower than the current noise of the DESY-CCC pickup coil depending on the differences of $A_L(\nu)$. Assuming similar noise contributions from the other components this would lead to a current noise of approximately $50 \text{ pA/Hz}^{1/2}$ with a total noise of 0.45 nA in the frequency range up to 5 Hz under noisy conditions comparable to HoBiCaT.

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 and a four times lower current noise could be expected. 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 $t_{\text{spill}} = 5 \text{ s}$.

With this resolution, the CCC is well suited for the beam diagnostics of FAIR and CSR.

In subsequent experiments, the measurement of L_S and R_S of the Nanoperm M-764-01 cores with one superconducting turn as well as the direct measurement of the current noise distribution are planned to verify the results from the FDT.

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