AN LTS SQUID-BASED HIGH PRECISION MEASUREMENT TOOL FOR NUCLEAR PHYSICS

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Abstract

This paper describes an LTS SQUID-based high precision measurement tool for nuclear physics. This device makes use of the Cryogenic Current Comparator (CCC) principle and is able to measure e.g. the absolute intensity of a high energy ion beam extracted from a particle accelerator or the so-called dark current, generated by superconductive RF accelerator cavities at high voltage gradients.

The CCC mainly consists of a high performance LTS-DC SQUID system, a special toroidal pick-up coil, and a meander-shaped superconductive magnetic ring structure. The design of the CCC requires a thorough knowledge of several noise contributions to achieve a high current resolution. As the SQUID and the pick-up coil are extremely sensitive to external magnetic fields it is necessary to shield both sufficiently against any disturbing field sources. Theoretical investigations showed that with strong attenuation of external noise sources an improvement of the sensor performance is dependent on the ferromagnetic core material imbedded in the pick-up coil. Several materials were investigated and the temperature and the frequency dependence measured. The current results will be presented and discussed.

CONCEPT AND MOTIVATION

In principle, the CCC [1] comprises three main components (see Fig. 1):

- the superconducting pick-up coil,
- the highly effective superconducting shield, and
- the high performance LTS-SQUID system.

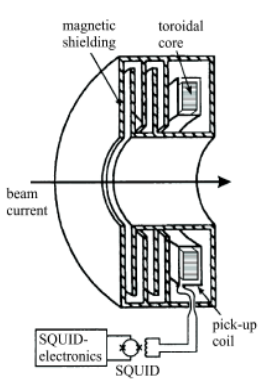


Figure 1: Simplified schematic view of the magnetic shielding, the toroidal pick-up coil, and the SQUID.

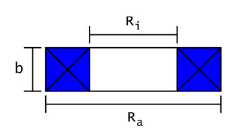
The CCC, first developed by Harvey in 1972 [2], is a non-destructive method to compare two currents with high precision using a meander shaped flux transducer. Thus only the magnetic field component, which is proportional to the current in the wires, will be sensed by the pick-up coil. All other field components are strongly suppressed. In our apparatus the signal current induced in the pick-up coil is fed into the input coil of a high performance DC SQUID.

Thermal noise in ferromagnetic core material generates a noise current which in connection with the inductance L of the pick-up coil causes a magnetic flux noise. For a signal to noise ratio of unity this magnetic flux noise cannot exceed the magnetic flux due to the beam current:

$$\Phi_{beam} = \int_A \vec{B} \cdot d\vec{f} \geq \Phi_{thermal} = L \cdot \sqrt{\langle I_N{}^2 \rangle}$$

For a given pick-up coil the minimum detectable current I_S depends on the geometry of the coil parameters (R_a, R_i, b), the temperature T and the relative permeability μ_r of the ferromagnetic core material according to:

$$I_s = \frac{2\pi\sqrt{k_b T L}}{\mu_0 \mu_r f(R_a, R_i, b)} \qquad L = n^2 \cdot \frac{\mu_0 \mu_r b}{2\pi} \ln \frac{R_a}{R_i}$$



This leads to a possible optimization for better noise performance using materials with a high and frequency independent μ_r, because the signal to noise ratio is proportional to the square root of the relative permeability of the core:

$$B, L \propto \mu_r \Rightarrow \frac{I_s}{I_n} \propto \sqrt{\mu_r}$$

EXPERIMENTAL RESULTS

Temperature and Frequency Dependence

Recent developments in the area of magnetic materials with high permeability, especially the nanocrystalline materials such as Vitroperm [3] and Nanoperm [4], may permit further noise reduction. The materials to be tested were manufactured in the form of thin metal tapes which were wounded up to form toroidal-shaped cores of different dimensions.

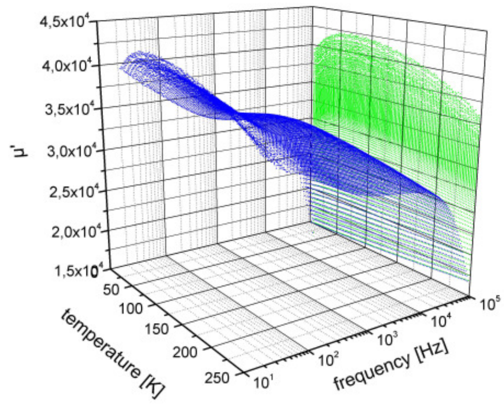


Figure 2: Real part μ' of the relative permeability of Nanoperm M033 (50 windings) in the temperature range between 4.2 and 250 K.

Low Temperature Properties

The properties of magnetic materials at low temperatures are mostly not known. Therefore we investigated these materials in the temperature range between room temperature and 4.2 K in dependence on the measurement frequency (see Fig. 2).

Above all, the serial inductance L_S and serial resistance R_S of the samples were measured using a commercial LCR-Bridge (Agilent E4980A), whereas the real and imaginary parts of the relative permeability are calculated using the equations below:

$$\mu' = \Re\{\mu_r\} = \frac{1}{N^2}\frac{2\pi}{\mu_0 b \ln \frac{R_a}{R_i}} \cdot L_s(f) \qquad \mu'' = \Im\{\mu_r\} = \frac{-1}{2\pi \cdot f}\frac{1}{N^2}\frac{1}{\mu_0 b \ln \frac{R_a}{R_i}} \cdot R_s(f)$$

The real part μ' and the imaginary part μ'' of the relative permeability of different nanocrystalline samples of Vitroperm and Nanoperm at 4.2 K with one superconducting winding are plotted in the Fig. 3 and 4. The red curve shows the amorphous cobalt-based material Vitrovac 6025 [3] also at 4.2 K with one superconducting winding.

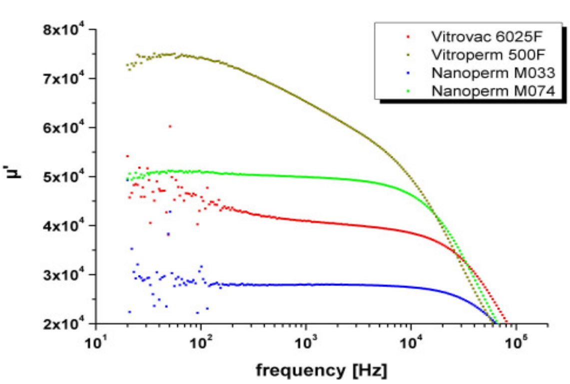


Figure 3: Real part μ' of the relative permeability of different nanocrystalline samples of Vitroperm and Nanoperm at 4.2 K.

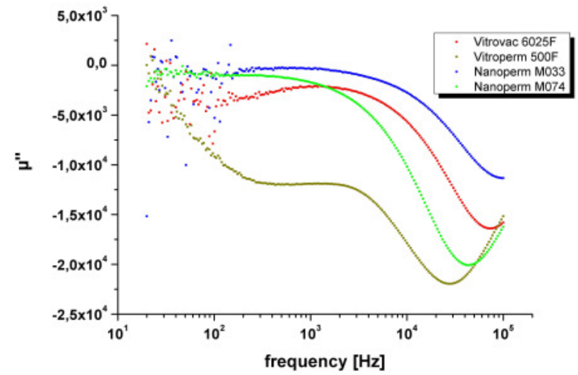


Figure 4: Imaginary part μ'' of the relative permeability of differnet nanocrystalline samples of Vitroperm ans Nanoperm at 4.2 K.

Flux Noise

The spectral flux noise density of different magnetic cores in the frequency range between 1 and 10^4 Hz was measured using a HP spectrum analyzer in the laboratory at Jena University. Fig. 5 gives an example for the toroidal cores made of Vitrovac 6025 and Nanoperm M074. The spectra were achieved using a single turn superconducting coil wounded around the toroidal cores under test and connected across the pick-up coil of an LTS DC-SQUID *UJ 111* of Jena University.

The black curves in Fig. 5 show the intrinsic flux noise of the SQUID only measured with a commercial (upper black curve at a level of 2.2×10^{-5} $\Phi_0/\sqrt{\text{Hz}}$) and a noise optimized SQUID electronics of Jena University (lower black curve at a level of 6.8×10^{-6} $\Phi_0/\sqrt{\text{Hz}}$).

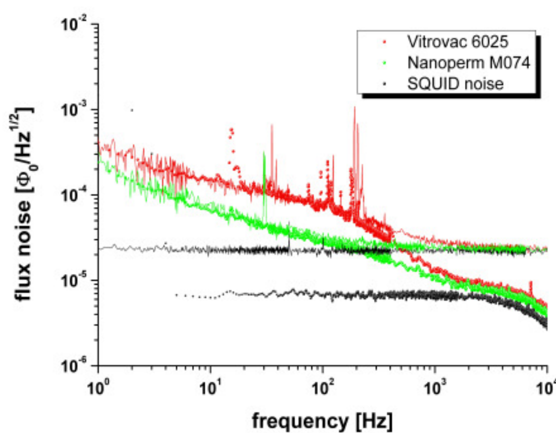


Figure 5: Spectral flux noise density of Vitrovac 6025 and Nanoperm M074 toroidal cores generated by one superconducting turn connected across the SQUID input coil. The black curves show the intrinsic noise of the SQUID using two different electronics (see text for details).

All measurements were carried out in a magnetically shielded room to avoid interferences with external disturbing magnetic and electric fields. In spite of this, numerous peaks were detected caused by external machines and mechanical vibrations in the Laboratory.

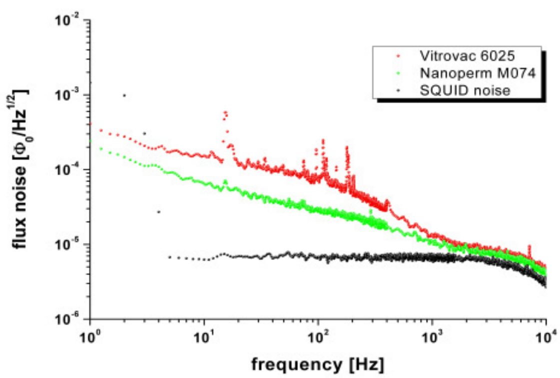


Figure 6: Measured noise contribution of amorphous Vitrovac 6025 and nanocrystalline Nanoperm M074.

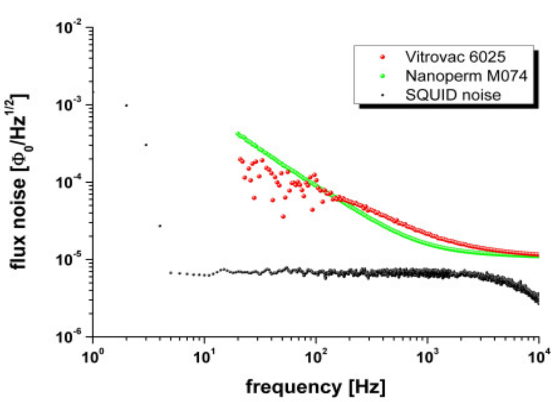


Figure 7: Calculated 1/f magnetization noise of Vitrovac 6025 and Nanoperm M074 using the Fluctuation-Dissipation Theorem.

With the Fluctuation-Dissipation-Theorem it is possible to calculate the 1/f-magnetization noise from the measured serial inductance L_s and resistance R_s [5]. In Fig. 6 is plotted the measured noise contribution of amorphous Vitrovac 6025 and nanocrystalline Nanoperm M074, whereas Fig. 7 shows first calculations using the Fluctuation-Dissipation-Theorem. As it is clearly visible, the general tendency is quite similar to the achieved experimental values. But further investigations are necessary to improve the conformity between experimental and calculated data.

SUMMARY AND OUTLOOK

The resolution of the Cryogenic Current Comparator is limited above all by the magnetic properties of the ferromagnetic core material in the pick-up coil. Here we have presented temperature and frequency dependent measurements of the complex relative permeability of several materials and associated noise figures. For the pick-up coil of the CCC we are looking for materials with the highest possible permeability which is constant over a wide frequency range.

The nanocrystalline Nanoperm tapes fulfil these requirements and show a lower noise contribution than other materials tested. In a future test set-up these results should be verified and approved. In further investigations, the calculation of the intrinsic noise of ferromagnetic core materials using the Fluctuation-Dissipation Theorem and a calibrated LCR-meter to measure the serial inductance L_S and serial resistance R_S should be improved.

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