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Low temperature permeability and current noise of ferromagnetic pickup coils

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ABSTRACT

For a non-destructive measurement of intensities of charged particle beams a Cryogenic Current Comparator is used which captures the azimuthal magnetic field of the beam by a superconducting pickup coil at 4.2 K and transforms it into a current which is detected by a SQUID based current sensor. The current noise of the pickup coil and the bandwidth of this transformer depend on the frequency response curve of the complex permeability of the ferromagnetic core material embedded in the pickup coil. A measurement of the series inductance L_S and series resistance R_S of such a coil allows an indirect evaluation of the current noise contribution of the core using the Fluctuation–Dissipation-Theorem. These measurements were done with a commercial LCR-Meter in a frequency range from 20 Hz to 2 MHz. The current noise density was also directly measured using a SQUID-sensor. A comparison with between the direct and indirect measurement showed a good coincidence. Due to the critical temperature of the LTS-SQUID, noise measurements above 4.2 K are not possible apart from using an anti-cryostat. The measurement of the series inductance L_S and series resistance R_S with an LCR-Meter works in the whole temperature range and provides a comfortable access to the magnetic properties of core materials. Compared to direct measurements, the indirect measurement thus allows a technologically simpler and broader determination of the core noise.

1. Introduction

For any particle accelerator facility, a precise measurement of the intensity of charged particle beams is crucial for their generation and controlling. The non-destructive measurement of beam intensities using the magnetic field of the moving charged particles requires the use of pickup coils with a ferromagnetic core to reach a good coupling of the magnetic field to the pickup coil. In the case of bunched beams one wants to measure the rising and the falling slope as well as the flat top. The frequency spectra of the slopes depend on the slew rates and define the required bandwidth of the detector system. The flat top region corresponds to a DC current and therewith to a DC magnetic field. Using normal conducting pickup coils it is not possible to directly detect DC magnetic fields due to the law of induction.

Unser [10] developed the so called DC Current Transformer (DCCT) to measure DC magnetic fields with normal conducting coils. The current resolution of commercially available devices using the DCCT principle like the New Parametric Current Transformer [1] is limited to 1 μA/sqrt(Hz) and a bandwidth of 10 kHz.

With a superconducting coil it is possible to detect DC magnetic fields due to the flux conservation. Another advantage is the performance at low temperatures which reduces the thermal noise and allows the use of highly sensitive sensors like superconducting quantum interference devices (SQUIDs). This device is called Cryogenic Current Comparator (CCC). Geithner et al. [4] gives a detailed description of the setup and working principle as well as a schematic view of the construction of the CCC. Using a SQUID sensor with a low intrinsic noise and a high bandwidth, the sensitivity and the bandwidth of the whole system depends on the pickup coil and therewith the embedded ferromagnetic core material at 4.2 K. Therefore we were searching for materials with a high and frequency independent relative permeability at low temperatures. Magnetic cores commonly used at room temperature are not useful at cryogenic temperatures because they show a significant decrease of their permeability. There are a lot of materials on the market providing a high frequency independent relative permeability at room temperature but there are less data available for cryogenic temperatures provided by the manufacturers. In addition, low losses coming along with a low noise contribution are also crucial for a good current resolution.

In this paper, we present the evaluation of the complex relative permeability and the current noise contribution of candidate materials at 4.2 K using a commercial LCR-Meter and SQUID-based noise measurement equipment. The materials we had chosen for

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this evaluation were the amorphous Co-based Vitrovac 6025F from the manufacturer Vacuumschmelze GmbH Hanau, Germany and the nanocrystalline Fe-based Nanoperm from the manufacturer MAGNETEC GmbH Langenselbold, Germany. Vitrovac 6025F was chosen for comparison because this material is often used for transformers and well known for a high permeability at low temperatures [4]. Nanoperm is providing a high frequency independent relative permeability at room temperature and it would be interesting if these advantages still remain at low temperatures. Both materials are available commercially as tape wound toroidal cores. In the case of Nanoperm there are several types with different μ_r and frequency dependencies available. From preliminary investigation [5] we choose Nanoperm M033 which we present in this paper.

2. Experimental methods

The method to measure the noise is similar to that reported by Quach and Chui [8], and Hutzler et al. [7]. A single turn niobium coil was wound around the toroid and directly connected to the input coil of an LTS DC SQUID sensor using niobium screws. The SQUID and the coil were put into a niobium cartridge to shield them against disturbing external magnetic fields. The cartridge was connected to a dipstick and put into the liquid helium bath. The DC SQUID had detected the current generated by the magnetization noise of the core. The SQUID operates with a modulated flux-locked-loop (FLL) electronics. This technique uses an additional modulation coil to modulate the flux trough the SQUID with the reference frequency and a lock-in amplifier to reduce the $1/f$-noise of the SQUID. The amplified signal is than integrated and fed back via a resistor to the modulation coil to compensate the flux through the SQUID. The transfer function was used to convert the output voltage noise signal of the SQUID electronics to the current noise. We used a UJ111 SQUID and a SQUID-Control 5.3 electronics developed and manufactured by Jena University. The flux sensitivity of the FLL-electronics was 10 V/Φ_0 and the current sensitivity of the SQUID at the input coil is approximately 430 nA/Φ_0 and varies with the inductive load connected to the input coil whereby $\Phi_0 = h/2e$ is the magnetic flux quantum with the Planck constant h and the elementary charge e. The flux sensitivity was adjusted with the working point settings. The current sensitivity was determined by a battery driven current source and an additional single turn coil wound on the toroid.

In contrast to previous measurements [8,7], the complex inductance of the coil was measured with a commercial Agilent E4980A LCR-Meter in the frequency range from 20 Hz to 2 MHz. The LCR-Meter applied a sinusoidal current to the coil and measured the voltage drop over the coil and the resulting phase shift. Due to the characterization of a real coil it uses the series equivalent diagram which means that a real inductance is seen as a series connection of an ideal coil and a resistor which represents all losses. The series inductance L_S and series resistance R_S is calculated from the applied current, the measured voltage drop and phase shift.

The measurement was done in four-point geometry. That means the tested coil was connected to a four-point terminal with twisted wires as short as possible to minimize parasitic areas for flux coupling (Fig. 1, terminal (a)). The terminal was connected to a dipstick and put into the liquid helium bath. The parasitic capacities, inductances and resistances of the test setup were eliminated by the LCR-Meter doing an open (Fig. 1, terminal (b)) and short (Fig. 1, terminal (c)) correction at the certain test frequencies and test currents at 4.2 K. Therefore, three pairs of identical twisted pairs of copper wires were connected to the terminal. Due to the superconducting turn of the coil the series resistance R_S at low frequency was also very low. To correct the remaining parasitic

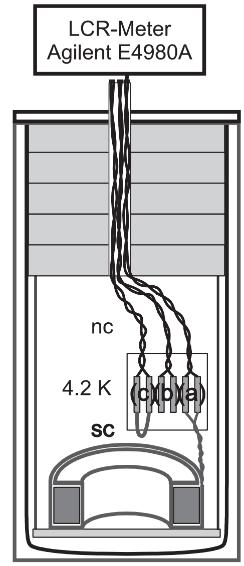

Fig. 1. Schematic setup of the LCR-Meter measurements. The superconducting (sc) wires of the measured coils and the short circuit for the short correction are colored in grey. Each terminal is connected to the top of the cryostat with the help of two twisted pairs of copper wires (colored in black) which enables a measurement in a four-point geometry.

inductances and resistances of the whole corrected setup a test measurement with short circuited terminals using superconducting wire between them was done and the measured remaining series inductances and series resistances were subtracted from the coil measurement results. The geometric inductance $L_0 = (\mu_0 d/2\pi)\ln(r_a/r_i)$ which is the inductance of the coil without the ferromagnetic core was used to calculate the complex relative permeability $\mu_r = \mu' + i\mu''$ from the measured frequency dependent series inductance $L_S(\nu)$ and series resistance $R_S(\nu)$. Here d is the thickness of the coil, r_a its outer radius and r_i its inner radius. Due to the fact, that these materials are very brittle they were encased by epoxy coating by the manufacturer or with Teflon tape. Also there is an insulating layer between the layers of the tape wound cores to reduce eddy current losses. Due to the fact that only a part of the cross-section area of the coil is magnetically active, a correcting factor f_c (see Table 1) was applied to get the true relative permeability of the materials with the real part

$$\mu'(\nu) = L_S(\nu)/L_0 f_c \quad (1)$$

and the imaginary part

$$\mu''(\nu) = -R_S(\nu)/2\pi\nu L_0 f_c \quad (2)$$

The correcting factors $f_c = a_{fe}/((r_a - r_i)d)$ were calculated with the help of the core dimensions and active magnetic areas a_{fe} given by the manufacturer.

According to the Fluctuation–Dissipation-Theorem [2], the current noise density $\langle I_S^2 \rangle$ of the coil could be predicted from the measured series inductance L_S and series resistance R_S. Due to the fact

Table 1
Dimensions and correcting factors of the measured samples.

	Vitrovac 6025F ferromagnetic core including Teflon tape	Nanoperm M033 ferromagnetic core including epoxy coating
Thickness d (mm)	9.1	10.7
Inner radius r_i (mm)	5.75	7.5
Outer radius r_a (mm)	9.9	13.2
Correcting factor f_c ()	0.72	0.59