A cryogenic current comparator for beam diagnostics in the FAIR project *

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The non-destructive measurement of beam currents has been successfully achieved using DC beam transformers[1]. A much higher accuracy for the FAIR project can only be achieved using cryogenic current comparators (CCC) with superconducting technologies.

Principle of a CCC

A cryogenic current comparator is based on the properties of ideal superconductors to expel magnetic flux from the bulk material through shielding currents on the surface of the material. As this effect is only dependent on the magnetic field of the beam currents, they can be measured non-destructively with a high precision.

In figure 1 the main components of a CCC are shown. The magnetic field of the beam current creates shielding currents on the superconducting magnetic ring structure, which are converted with a torodial single turn pick-up coil and its ferromagnetic core. The signal from the pick-up coil is feed to a LTS DC SQUID and measured via the external electronics.

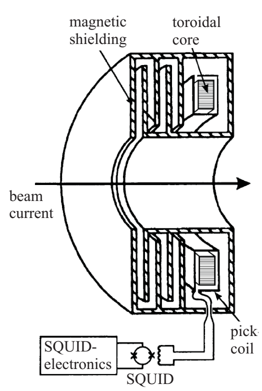

Figure 1: Principle of a cryogenic current comparator

Noise contributions

The design of a CCC requires a thorough knowledge of several noise contributions to achieve a high beam current resolution. As the SQUID and the pick-up coil are very sensitive to external magnetic fields it is necessary to shield both sufficiently against any field sources other than the magnetic field of the ion beam. Grohmann et al.[4, 5] analyzed coaxial cavity structures to suppress unwanted field components. Using this knowledge the current CCC uses a superconducting niobium shield to attenuate non-azimuthal field components by a factor of 120 dB [6].

* Supported by GSI Darmstadt under contract name JVODEL

As external disturbances can be effectively reduced we looked at the influence of thermal noise and the ferromagnetic core material to the overall system resolution. The thermal noise generates a noise current $\sqrt{\langle I^2 \rangle}$, which in connection with the inductance L generates a magnetic flux noise $\Phi_{thermal}$ which cannot exceed the magnetic flux due to the beam current for a signal to noise level of unity.

$$\Phi_{beam} = \int_A \vec{B} \cdot \mathrm{d}\vec{f} \geq \Phi_{thermal} = L \cdot \sqrt{\langle I^2 \rangle} \quad (1)$$

For a given pick-up coil the minimum detectable current I_s is dependent on the geometry of the coil ($f(R_a, R_i, b)$), the temperature T, the geometric inductance L and the relative permeability μ_r of the ferromagnetic core material according to:

$$I_s = \frac{2\pi\sqrt{k_b T L}}{\mu_0 \mu_r f(R_a, R_i, b)}. \quad (2)$$

In figure 2 we calculated the resolution or the minimum current, which can be detected for different temperatures and relative permeabilities with the currently used single turn toroidal pick-up coil.

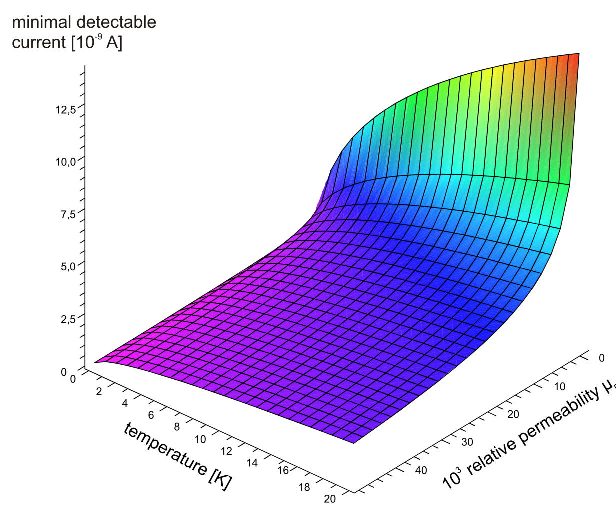

Figure 2: Minimum detectable current in dependence on temperature and relative permeability of the core material

Measurements of ferromagnetic materials

The basic analysis of the detectable current shows a strong dependency on the relative permeability of the core material. As the pick-up coil is fully embedded within the superconducting shield, the core material has to operate at temperatures in the range of 4.2 K. In standard ferromagnetic materials the permeability decreases by about two orders of magnitude from room temperature to these low temperatures. Our first measurements showed a reduction of inductance of coils using Amidon iron powder cores from 450 μH to 4 μH at 4,2 K. Using this knowledge it is necessary to investigate a wide range of ferromagnetic materials at low temperatures in respect to their permeability.

The measurement setup includes a high-precision inductance bridge (Agilent E4980A LCR-Meter) connected to our dipstick in a helium cryostat. A temperature sweep can be achieved with a computer controlled stepper motor, which adjusts the level of the dipstick in respect to the helium bath. With this setup the material Vitrovac VC6025[1], was measured over a temperature range from 290 K to 1,9 K, which is shown in figure 3. The inductance of the test coil decreases by 52% over the whole temperature range which shows that the currently used material is already a large improvement over sintered iron powder cores. The high permeability in group of Vitrovac materials is highly dependend on the heat treatment of the final material which influences for example the size of the magnetic domains. For the application of a specific ferromagnetic material not only the relative permeability at low temperatures but also the frequency dependence needs to be investigated. Materials like Cryoperm-10 (VAC, Hanau) exhibit a high permeability which decreases rapidly with increasing frequencies[7].

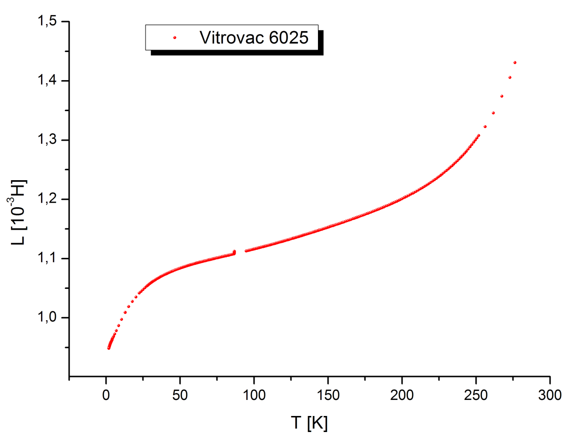

Figure 3: Inductance of a test coil with Vitrovac VC6025 as the core material in dependence on temperature

In the new class of nanocrystalline ferromagnetic materials we measured the temperature- and the frequency-dependence of Vitroperm 500F (VAC, Hanau). While the temperature stability is improved compared with former materials, first measurements show a significant drop of permeability for frequencies above 1 kHz, see figure 4. Similar frequency dependencies have also been measured in other nanocrystalline materials, e.g. Magneperm[2]. The current results show the different ferromagnetic materials exhibit significant temperature- and frequency dependencies, which have to be evaluated to achieve a high accuracy of the CCC in the final application.

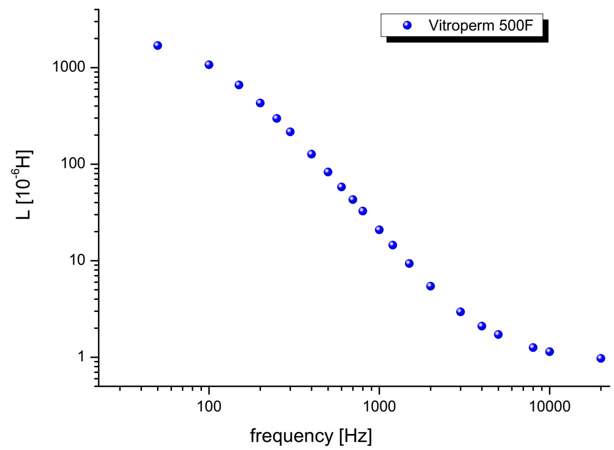

Figure 4: Inductance of a test coil with Vitroperm 500F as the core material at different frequencies at room temperature

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[2] MAGNETEC GmbH, Industriestraße 7, D-63505 Langenselbold

Summary and Outlook

The theoretical investigations showed that with a strong attenuation of external noise sources an improvement of the sensor performance is dependent on the ferromagnetic core material. The current approximation for the minimum detetctable current needs to be further extended with the fluctuation-dissipation theorem to analyse the frequency dependence of the thermal noise. With the first measurements of different core materials we could characterize the inductance over a wide temperature range and show first frequency dependencies. Future measurements will include a direct noise measurement using a DC SQUID to readout thermal noise signals at low temperatures.

References

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