FIELD ATTENUATION OF THE MAGNETIC SHIELD FOR A CRYOGENIC CURRENT COMPARATOR *

F. Kurian, M. Schwickert, H. Reeg, P. Kowina, D. Liakin, P. Huelsmann, GSI, Darmstadt, Germany
R.Geithner, R. Neubert, W. Vodel, FSU, Jana, Germany

Abstract

The upcoming FAIR facility requires measurements of very low ion currents, especially for slow extraction from the SIS100 synchrotron. Cryogenic Current Comparators (CCC), which allow to measure beam currents non-destructively down to the nA range, are foreseen in various locations of the high energy beam transport sections of FAIR [1]. A CCC prototype with improved performance is presently being developed at GSI. The current resolution of the CCC is only limited by the system noise, mainly originating from environmental electromagnetic fields and mechanical vibrations. A meander-shaped superconducting shield geometry is applied to efficiently suppress disturbing field components. In this contribution we present FEM simulations to determine the attenuation of external magnetic fields by the shield geometry for different field directions and various geometrical parameters.

CCC AND THE FAIR PROJECT

One of the unique features of the upcoming FAIR accelerator facility [1] will be the availability of beams of a large variety of ion species which will be accelerated to unprecedented high intensities. However in certain locations of the High Energy Beam Transport (HEBT) sections, such as in the slow extraction lines from the synchrotrons and at the experiments using slowly extracted beams with spill length of several seconds, the beam currents will be very low, i.e. down to few nanoampere. These currents are well below the detection threshold of conventional non-intercepting beam current transformers. Nevertheless, an online measurement device is required and thus CCCs are foreseen in six different locations of the HEBT section. A former prototype study [2] had shown, that the CCC offers an absolute measurement of beam current independent of energy and trajectory of the beam with a current resolution of < 65 pA/$\sqrt{\text{Hz}}$.

WORKING PRINCIPLE

The measurement of beam currents with a CCC is based on the detection of the azimuthal component of the magnetic field produced by the beam current. The beam's magnetic field is measured using a pick-up coil which is surrounding a high-permeability ring core made of the nano-crystalline magnetic alloy Nanoperm™ [3] which acts as a flux concentrator**.** This arrangement ensures efficient coupling of the azimuthal magnetic field into the pickup coil. The signal from the pickup coil is fed into a dc SQUID (superconducting quantum interference device), a high precision magnetic flux sensor. To suppress disturbing magnetic noise fields the pickup coil and ring core are embedded in a meander-shaped magnetic shield (see next section). A schematic of the device is shown in Figure 1. More details on the CCC working principle are given in [2].

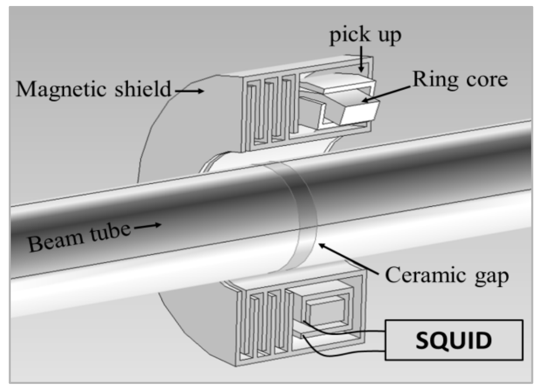

Figure 1: Schematic cross-section of the sensor setup.

A ceramic gap is required to prevent image currents flowing through the surface of the beam tube. The shield geometry, pickup coil, SQUID unit and the matching transformer are immersed in a liquid helium bath. For the preparation of the superconducting magnetic shield geometry, Niobium (Nb) is chosen as the material owing to its better mechanical strength compared to Lead (Pb) which had been used for the previous CCC prototype.

Superconducting magnetic shield

It has been shown previously [4] that the current resolution of the CCC setup presented here is limited by the system noise, mainly given by disturbing external magnetic fields of the accelerator environment. Hence the magnetic shield geometry is an important part of a CCC and has to be optimized for effective attenuation of any non-azimuthal field component. The field attenuation achieved by the shield geometry for different magnetic field directions are studied using FEM simulations. In the following sections two different shield geometries are analysed: a simple coaxial setup is compared to a more intricate meander-shaped geometry, see Fig. 2.

ATTENUATION OF MAGNETIC FIELD COMPONENTS

The field attenuation through a superconducting coaxial cylindrical has been studied by Grohmann et al. [6-8].

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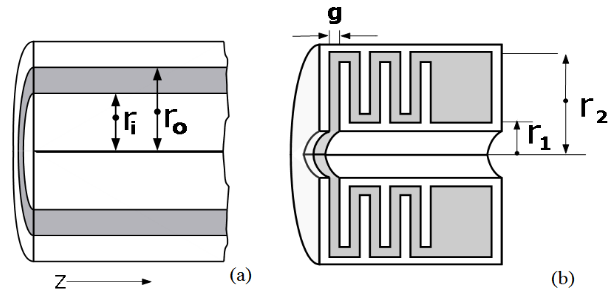

Figure 2: Geometries considered for the simulations.

For a uniform magnetic field B_{out} applied at the opening of a coaxial cylinder, the field attenuation in terms of a scalar potential V is given by the sum of the transverse and longitudinal field components as

$$V(\rho, \emptyset, z) = \left(V_{trans} \exp\left\{\left(\frac{-2}{1+{}^{r_i}/_{r_o}}\right){}^{z}/_{r_o}\right\}\right) + \left(V_{long} \exp\left\{-\left(\frac{\pi}{1-{}^{r_i}/_{r_o}}\right){}^{z}/_{r_o}\right\}\right) \quad (1)$$

Where $(\rho, \emptyset, z)$ represent cylindrical co-ordinates. r_o is the outer and r_i inner radius of the coaxial cylinder. The first and second terms represent the transverse and the longitudinal components of the magnetic field respectively. For the coaxial case Grohmann et al. have shown that, azimuthal magnetic field components are not attenuated for any radius. Following their argument the meander-shaped geometry may be understood as a combination of two coaxial conductors with different radii. Thus Grohmann et al. conclude that also for a meander-shaped geometry the relevant azimuthal components are not attenuated. Also the relative position of the current element will not contribute to a considerable change in the magnetic field measured by the pickup coil.

FEM Simulations and Validation

Detailed FEM simulations were performed using Comsol Multiphysics™ to study the influence of various geometrical shield parameters on the attenuation of the magnetic field inside the shield. As a first step a coaxial geometry (see Fig. 2(a)) was simulated in order to compare the simulation results with attenuation values obtained analytically. Secondly, a model of the meander-shaped shield was simulated to determine the attenuation factor for longitudinal as well as for transverse external fields.

For the superconducting Nb-shield of the present prototype has the skin depth at 4.2 K is in the order of a few nanometers. Hence the perfect conductor approximation is assumed for all simulations. The superconducting boundaries are realized by applying the 'magnetic insulation' boundary condition for the superconducting walls of the shield which sets the tangential component of the magnetic potential to zero.

To confirm the simulation results, we consider the case of a transverse magnetic field applied to a coaxial cylinder. From the first term in equation 1, the field strength inside the coaxial cylinder is given by,

$$B_{in} = B_{out} \exp\left\{\left(\frac{-2}{1+{}^{r_i}/_{r_o}}\right){}^{z}/_{r_o}\right\} \quad (2)$$

In Figure 3 the attenuated field strength inside the coaxial cylinder as given from equation (2) is compared to the simulation results. The simulation is in good agreement with the analytical result up to a length of 700 mm.

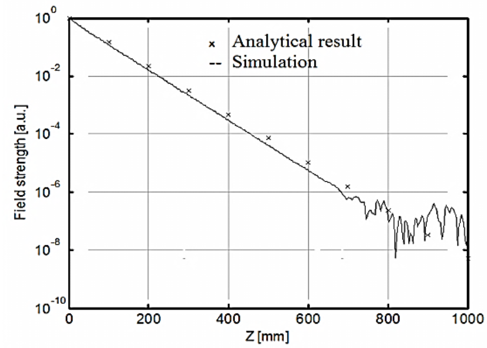

Figure 3: Comparison of the field attenuation by the simulation of a transverse field applied to a coaxial cylinder with the values given by equation 2.

Attenuation of the longitudinal magnetic field

For the simulation of the meander-shaped geometry a model was used containing a set of superconducting plates with a thickness of d=3 mm, a length of l=41 mm, and separated by gap width of g=0.5 mm between the plates. In order to minimize the number of mesh cells the superconducting material has been removed from the simulation leaving only the areas where the field exists. The magnetic field is defined in the inner rectangular domain along the path of the meander shaped shield geometry (See Figures 4 and 5).

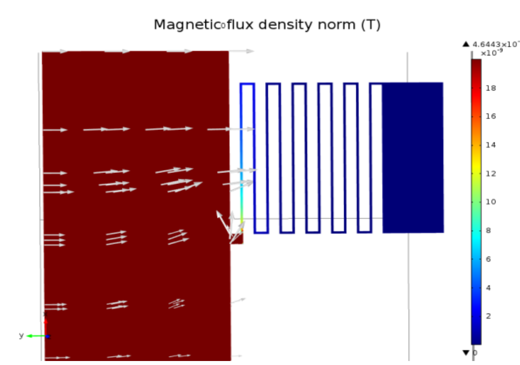

Figure 4: Simulation of a longitudinal magnetic field applied to meander-shaped geometry.

Figure 4 shows the simulation result for a magnetic field applied in longitudinal direction. With the values B_{out}= 1.2×10^{-6} T and B_{in}=2.2×10^{-14} T of the simulation the attenuation factor, defined as

$$A = 20\log_{10}\left(\frac{B_{out}}{B_{in}}\right) \quad (3)$$

yields a very strong attenuation of 155 dB for a field applied longitudinally to the geometry with 6 meanders.

Attenuation of the transverse magnetic field

As depicted in Figure 5, a magnetic field applied perpendicular to the axis of the meander-shaped shield yields an attenuation factor of 55 dB.

For the transverse case additional simulations were carried out varying the gap width g. The field attenuation as a function of gap width between the meanders (Figure 6) shows that minimizing the gap width has only an effect of less than 10% on the attenuation factor. On the other hand, decreasing the gap width has some mechanical disadvantages. Small gap widths increase the risk of possible short circuits due to thermal contraction of the shielding material leading to a breakdown of the current detection. Secondly, trapped flux inside the shield geometry results in current zero drift as reported in the previous CCC installation at GSI [2].

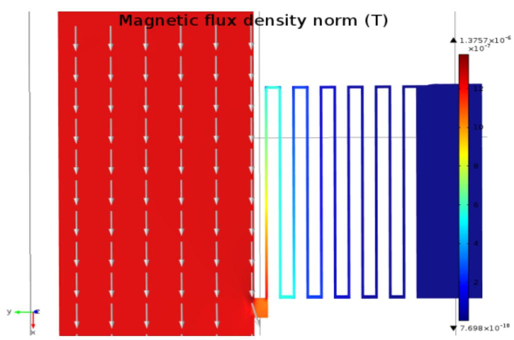

Figure 5: Simulation of a transverse magnetic field applied to a meander-shaped geometry.

Coaxial vs. meander-shaped Geometry

In order to study the advantages of the proposed meander-shaped geometry over the much simpler coax setup an 'effective shield length' was defined as

$$L_{eff} = n \cdot (l + d)$$

where, n: number of meander-plates, l: length and d: thickness of the plate.

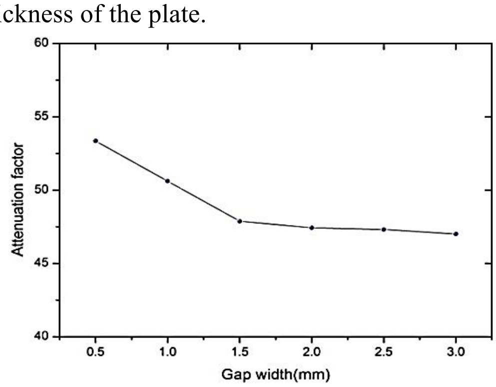

Figure 6: Attenuation factor for varying gap width between two consecutive meanders.

Figure 7 shows the comparison of the magnetic field strength for the case of a simple coaxial geometry having an effective length equal to that of the meander shaped shield geometry. The radii r_1 and r_2 of the coaxial cylinder were selected according to the inner and outer radius of the meander plates. It is found that the attenuation factor for a meander shaped shield has similar value like for a coaxial cylinder. Nevertheless, the coaxial setup would of course require an unfavourably large insertion length for the CCC setup.

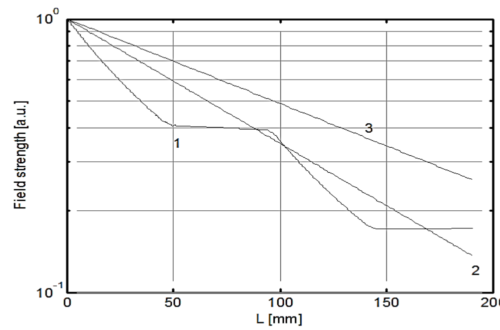

Figure 7: Comparison of field attenuation through a meander shaped geometry with a coaxial cylinder having same effective length. 1: Attenuation through the shield geometry, 2: Coaxial cylinder with a inner radius r_1, 3: Coaxial cylinder with outer radius r_2.

SUMMARY AND OUTLOOK

Magnetic field attenuation through a meander-shaped shield geometry for various field components is studied. It has been found through simulations that the non-azimuthal magnetic field components are attenuated strongly by the shield geometry. In order to compare the attenuation factor of the shield geometry with the experimentally observed values, the coupling of the non-azimuthal magnetic field components with the magnetic alloy ring core has to be taken into account. Also more realistic results can be achieved by investigating the direction of the dominant noise field components present at the installation locations of the CCC.

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