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Abstract

Simulations have shown the Compact Linear Collider (CLIC) is sensitive to external dynamic magnetic fields (stray fields) to the nT level. Due to these extremely tight tolerances, mitigation techniques will be required to prevent performance loss. A passive shielding technique is envisaged as a potential solution. A model for passive shielding is presented along with calculations of its transfer function. Measurements of the transfer function of a promising material (mu-metal) that can be used for passive shielding are presented. The validity of passive shielding models in small amplitude magnetic fields is also discussed.

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MITIGATION OF STRAY MAGNETIC FIELD EFFECTS IN CLIC WITH PASSIVE SHIELDING

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Abstract

Simulations have shown the Compact Linear Collider (CLIC) is sensitive to external dynamic magnetic fields (stray fields) to the nT level. Due to these extremely tight tolerances, mitigation techniques will be required to prevent performance loss. A passive shielding technique is envisaged as a potential solution. A model for passive shielding is presented along with calculations of its transfer function. Measurements of the transfer function of a promising material (mu-metal) that can be used for passive shielding are presented. The validity of passive shielding models in small amplitude magnetic fields is also discussed.

INTRODUCTION

The Compact Linear Collider (CLIC) [1] is a proposed e^+e^- collider, which targets an extremely small beam size O(nm) at the interaction point. This makes CLIC susceptible to the effects of external (referred to as stray) magnetic fields, which primarily induce a relative offset between the colliding beams. Only dynamic magnetic fields pose a danger as static fields are removed by tuning. Simulations of sinusoidal stray fields [2–6] have shown nT tolerances to remain within a 2 % luminosity loss budget. Stray fields above the nT level have been measured at several locations on the CERN site [4, 5] therefore mitigation techniques will be required to prevent significant performance loss.

A combination of active beam-based feedback and passive shielding is envisaged for CLIC. A mu-metal shield is being considered for key areas of CLIC, specifically the long transfer line in the Ring to Main Linac and drifts in the Beam Delivery System.

PASSIVE SHIELDING

There are two mechanisms for magnetic shielding: *eddy-current cancellation*, which occurs in materials with high electrical conductivities and *flux shunting*, which occurs in materials with high magnetic permeabilities [7]. Flux shunting is an effective mechanism for shielding static magnetic fields and eddy-current cancellation is effective for time-varying magnetic fields. As only dynamic magnetic fields are of concern to CLIC, eddy-current cancellation is the more important shielding mechanism.

Of interest to this work is the amplitude transfer function through a material, which is given by

$$\mathrm{TF}(f) = \frac{B_i(f)}{B_o(f)}, \tag{1}$$

where B_o is the magnetic field outside of a shield, B_i is the magnetic field inside and f is the frequency of the magnetic field. This is similar to a standard quantity often calculated for magnetic shields referred to as the *shielding factor* given by

$$\mathrm{SF}(f) = 20\log_{10}\left(\frac{B_o(f)}{B_i(f)}\right). \tag{2}$$

In this paper, only the transfer function in Eq. (1) will be calculated.

In general, electromagnetic finite element method codes (e.g. Opera2D, CST Microwave Studios) are used to calculate transfer functions. However, for simple geometries such as an infinitely long cylinder, it is possible to solve Maxwell's equations directly to find analytical formulas for the transfer function. A methodology for analytical calculations is outlined in [8]. For a non-magnetic but electrically conductive cylinder, the transfer function is given by

$$\mathrm{TF}(f) = \frac{1}{1 + j\frac{2\pi f \mu_0 \sigma r t}{2}}, \tag{3}$$

where μ_0 is the magnetic permeability of free space, σ is the conductivity of the cylinder, r is the inner radius of the cylinder, t is the thickness of the cylinder and j is the imaginary unit.

SENSORS AND MEASUREMENTS

Two three-axis fluxgate magnetometers (Mag-13) produced by Bartington Instruments, UK [9] were used to measure the transfer function of different materials. These sensors have a frequency response up to 5 kHz beyond which measurements cannot be made.

By placing one sensor inside the shield and the other sensor outside, the transfer function can be measured directly. The transfer function is calculated as the frequency response of the shield,

$$\mathrm{TF}(f) = \frac{P_{xy}(f)}{P_{xx}(f)}, \tag{4}$$

where $P_{xy}(f)$ is the cross spectral density of the input signal x to output signal y and $P_{xx}(f)$ is the power spectral density of the input signal. In measurements, the magnetic field outside the material is the input signal $x = B_o$ and the magnetic field inside is the output signal $y = B_i$.

LHC BEAM SCREEN

A typical beam pipe in accelerators for particle colliders consists of O(1 mm) of steel with an inner coating of

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O(100 µm) of copper. The copper is included to damp wakefield effects. An example of such a beam pipe is the Large Hadron Collider (LHC) beam screen, whose geometry can be approximated as a cylinder of inner radius of 2.2 cm consisting of 50-100 µm of copper and 1 mm of steel [10].

As the LHC beam screen consists of non-magnetic materials, Eq. (3) can be used to calculate a theoretical transfer function. Another consequence of using non-magnetic materials is that magnetic shielding can only occur via the eddy-current cancellation mechanism. Therefore, it is expected that the LHC beam screen will only be effective for shielding high frequency magnetic fields. This feature is also by design, it is undesirable to attenuate static fields from the magnets that guide a particle beam.

Prior to this work the transfer function of the LHC beam screen was calculated from simulations [11]. Figure 1 shows the measured transfer function calculated with Eq. (4) compared to Eq. (3).

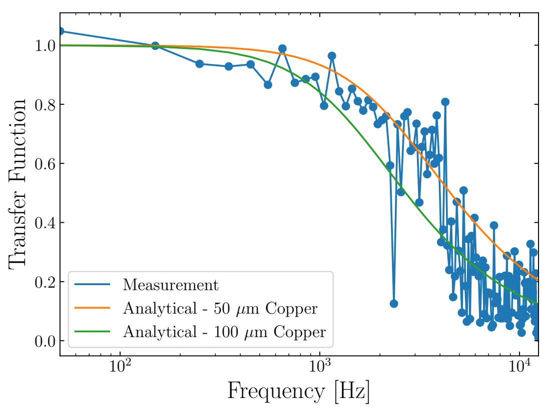

Figure 1: Transfer function of the LHC beam screen measured at room temperature along with theoretical calculations performed with Eq. (3). The LHC beam screen was modelled as an infinitely long cylinder consisting of 1 mm of standard steel and 50-100 µm of standard copper at room temperature.

MU-METAL SHIELDS

CLIC shows nT level sensitivities to stray fields. To maintain a nT level stability requires very effective magnetic shields. Surrounding the beam pipe with a high permeability material, such as mu-metal, is being considered to mitigate the effect of stray magnetic fields.

The shielding factor of an annealed mu-metal foil (MU004-12) provided by Magnetic Shield Corporation, USA [12] was measured. The foil was used to produce a number of cylindrical mu-metal shields. Figure 2 shows the measured transfer function calculated with Eq. (4). Two measurements were performed: with a single mu-metal shield of thickness 0.1 mm and with two nested layers of mu-metal shields, equivalent to a cylinder of thickness 0.2 mm.

The magnetic permeability of the mu-metal was fitted to the measurement. The measured transfer function in Fig. 2 is consistent with a material with relative permeability

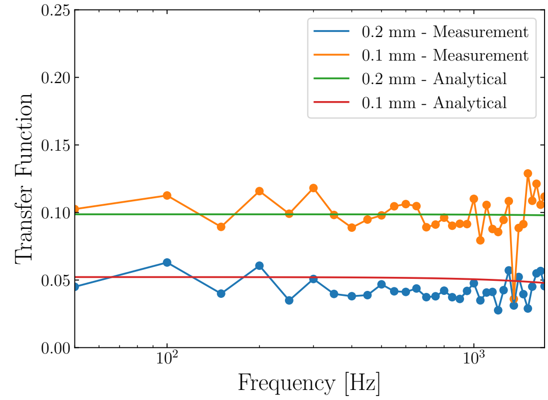

Figure 2: Transfer function of a mu-metal cylinder measured at room temperature along with theoretical calculations performed with the model outlined in [8].

$\mu_r = 5{,}000$. The transfer function appears to have a linear dependance on the shield thickness, this is consistent with the formulae for shielding presented in [13].

The expected relative permeability the mu-metal sample is approximately $\mu_r = 50{,}000$. The discrepancy is suspected to be due to the deformation of the material when producing the shields. The effect of rolling the material is likely to have damaged its material properties. This damage can be reversed by re-annealing the material. Roughly an order of magnitude improvement in relative permeability can be expected from re-annealing. Measurements with re-annealed shields are planned. From the formulae presented in [13] the shielding factor should increase linearly with permeability.

SMALL AMPLITUDE EXTERNAL FIELDS

Magnetic shielding via the flux shunting mechanism often uses ferromagnetic materials with high magnetic permeabilities. This shielding mechanism relies on the external magnetic field supplying sufficient energy to reorientate the magnetisation in the material. This suggests that there exists a minimum amplitude below which the external field does not contain enough energy to reorientate the magnetisation and flux shunting cannot occur.

The magnetic permeability dictates the ease at which a material is magnetised. Measurements of the magnetic permeability of different ferromagnetic materials as a function of external DC magnetic field strength are presented in [14]. The measured relative permeability of mu-metal in a DC field of 10 µT was 20,000. This dropped to 6,000 for fields of 1 µT. These measurements confirm there is an amplitude dependent behaviour of magnetic permeability.

For small amplitude external fields (less than 0.1 mT) the magnetic permeability is governed by Rayleigh's law, [15]

$$B = \mu_i H + \nu H^2, \tag{5}$$

where B is the magnetic induction, H is the external magnetic field strength, μ_i is the initial permeability and ν is Rayleigh's constant. The permeability of a material in the

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Rayleigh region is

$$\mu(H) = \mu_i + \nu H, \tag{6}$$

i.e. a function of the external field strength. For very small external fields, the material responds linearly,

$$B = \mu_i H \tag{7}$$

and its magnetisation is governed solely by its initial permeability. Provided the initial permeability is sufficiently high, ferromagnetic materials can still be effective for shielding small amplitude magnetic fields.

The analytical model in [8] does not account for an amplitude dependent permeability. However, this model has been extended by P. Sergeant et al. for hysteretic materials in [16] and in the Rayleigh region in [17].

The eddy-current cancellation mechanism usually utilises non-magnetic materials with high conductivities, therefore it is unaffected by the external field strength. However, there can be a benefit to eddy-current cancellation provided by high magnetic permeabilities. A high magnetic permeability reduces the skin depth, which improves the effectiveness of eddy-current cancellation.

PASSIVE SHIELDING FOR CLIC

Simulations have shown tolerances down to 0.1 nT for CLIC [2–6], therefore an effective mitigation with passive shielding should reduce the magnetic field seen by the beam to within this tolerance.

Figure 3 shows the largest magnetic field power spectrum measured at the CLEAR facility at CERN [5]. The effect of a beam-based feedback system and different shields is also included. The integrated magnetic field as a function of frequency is shown in Fig. 4.

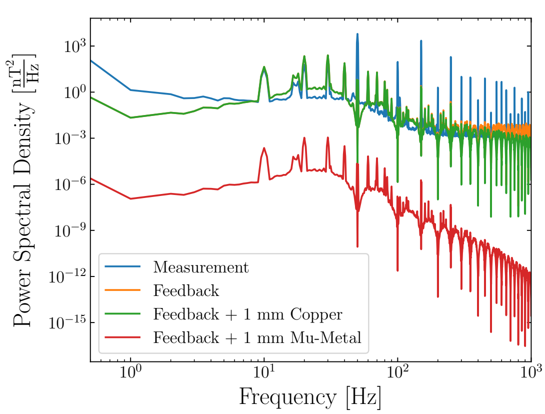

Figure 3: Largest power spectrum measured at CLEAR, CERN [5].

The effect of the feedback is to suppress the harmonics of 50 Hz, which is the largest contribution to the magnetic field, but is not enough to reduce the magnetic field to within the tolerance. Therefore, a magnetic shield surrounding the beam pipe is required. Two magnetic shields were considered: a copper cylinder of thickness 1 mm and inner radius

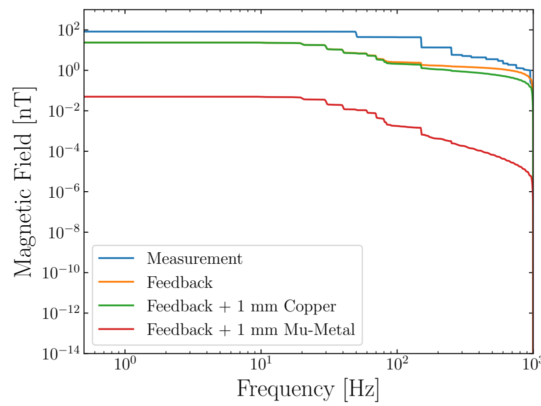

Figure 4: Integrated magnetic field calculated from the power spectrum in Fig. 3.

1 cm and a mu-metal cylinder of thickness 1 mm and inner radius 1 cm. Both shields were modelled using the methodology outlined in [8].

The effectiveness of each shield is shown in Figs. 3 and 4. The copper shield has no effect on low frequency magnetic fields and begins to have an effect for frequencies greater than 100 Hz. The mu-metal shield is much more effective and brings the integrated magnetic field to within the 0.1 nT tolerance. However, the effectiveness of the mu-metal shield is highly dependent on the relative permeability of the material. A constant relative permeability of 10,000 was used in this calculation, i.e. hysteresis was not modelled.

In an accelerator environment the shield is expected to be exposed to the Earth's magnetic field, which is a DC field O(50 μT) [18]. A relative permeability O(10,000) should be expected for mu-metal for this external field strength. The Earth's field ensures there is sufficient energy in the external magnetic field to reorientate the magnetisation in a ferromagnetic shield and results in a large enough permeability to produce an effective shield. Also, if the magnetic field variations are small compared to the DC field, the material will have an approximately constant relative permeability.

CONCLUSIONS

Analytical models for passive shielding have been verified experimentally and have shown good agreement. Passive shielding appears to be an effective mitigation strategy for the effects of stray magnetic fields in CLIC. It is expected from the theory that mu-metal shields with sufficiently high permeabilities will be able to attenuate magnetic fields down to the sub-nT levels required by CLIC, i.e. the amplitude dependent behaviour of the permeability will not prevent shielding to sub-nT levels.

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