A Model for Simulating Stray Magnetic Fields in Linear Colliders

C. Gohil\textsuperscript{1,2}, P. N. Burrows\textsuperscript{1}, N. Blaskovic Kraljevic\textsuperscript{*2}, D. Schulte\textsuperscript{2}, and B. Heilig\textsuperscript{3}

\textsuperscript{1}John Adams Institute, University of Oxford, Oxford, United Kingdom
\textsuperscript{2}European Organization for Nuclear Research, Geneva, Switzerland
\textsuperscript{3}Mining and Geological Survey of Hungary, Tihany, Hungary

(September 4, 2020)

Abstract

Future linear colliders target nanometre beam sizes at the collision point. Realising these beam sizes requires the generation and transport of ultra-low emittance beams. Dynamic imperfections can deflect the colliding beams, leading to a collision with a relative offset. They can also degrade the emittance of each beam. Both of these effects can significantly impact the luminosity of a collider. In this paper, we examine a newly considered dynamic imperfection: stray magnetic fields. Measurements of stray magnetic fields in the Large Hadron Collider tunnel are presented and used to develop a statistical model that can be used to realistically generate stray magnetic fields in simulations. The model is used in integrated simulations of the Compact Linear Collider including mitigation systems for stray magnetic fields to evaluate their impact on luminosity.

1 Introduction

There are currently two projects that propose a TeV-scale linear electron-positron collider: the International Linear Collider (ILC) \cite{1,2} and the Compact Linear Collider (CLIC) \cite{3,4}. CLIC incorporates a staged approach with three centre-of-mass energies: 380 GeV, 1.5 TeV and 3 TeV. In this paper, we derive a model for stray magnetic fields and apply it to the 380 GeV stage of CLIC.

1.1 Dynamic Imperfections

Dynamic imperfections in a linear collider can deflect the beams, which leads to a collision with a relative offset, and causes emittance growth. Linear colliders target extremely small beam sizes to maximise the luminosity \cite{5}. This makes the beams in a linear collider particularly sensitive to these effects.

\footnote{Present address: European Spallation Source, Lund, Sweden.}
Beams in linear colliders are generated in pulses. Dynamic imperfections influence consecutive pulses differently. This makes them difficult to correct. The main tool for mitigating the impact of dynamic imperfections is a beam-based feedback system, which measures and corrects the beam offset. Often the beam-based feedback system, whose bandwidth is inherently limited by the beam repetition frequency, is not enough to mitigate the imperfection to the desired level. Dedicated studies are necessary to devise a mitigation strategy for dynamic imperfections. In this paper, we look at the impact of stray magnetic fields and their mitigation.

1.2 Stray Fields

Stray magnetic fields, or simply stray fields, are external dynamic magnetic fields, which influence the beam. They can be classified in terms of their source: natural, environmental and technical [6, 7, 8].

1.2.1 Sources

**Natural** stray fields are from non-man-made objects, e.g. the Earth’s magnetic field. A review of natural stray fields can be found in [9]. Natural stray fields have large amplitudes at low frequencies, which can mitigated with a beam-based feedback system [11]. At higher frequencies the amplitude is small enough that they can be ignored.

**Environmental** stray fields are from man-made objects, which are not part of the accelerator. This includes stray fields from the electrical grid, such as power lines and power stations, and nearby transport infrastructure, such as train and tram lines.

The electrical grid is typically the largest stray field source. In Europe, the electrical grid operates at 50 Hz. This motivates the choice of 50 Hz for the repetition frequency for CLIC. Stray fields at 50 Hz have the same impact on a train-by-train basis. Therefore, stray fields at 50 Hz (and higher-order harmonics) appear as if they are static to the beam and can be removed during beam-based alignment [4].

**Technical** stray fields are from elements of the accelerator, e.g. magnets, RF systems, power cables, etc. These stray fields are the biggest concern because of their proximity to the beam. Measurements at live accelerator facilities, which include stray fields from technical sources are presented in Sec. 2.3.

1.2.2 Sensitivity

Linear colliders are sensitive to extremely small stray fields. CLIC has a sensitivity down to 0.1 nT [7, 8, 12, 13] and the ILC is sensitive to stray fields on the level of 1 nT [1]. These values are several orders of magnitude lower than the typical level of stay fields found in accelerator environments. Therefore, they are a serious consideration in the design and operation of a linear collider.

A realistic model that can be used to simulate stray fields is needed to evaluate the effectiveness of different mitigation strategies. In this paper, we work towards developing such a model.

2 Measurements

The magnetic field sensors used in this work are described in Sec. 2.1. The calculation of useful quantities to characterise stray fields is described in Sec. 2.2.
Measurements in a realistic magnetic environment for an accelerator are presented in Sec. 2.3. These measurements were taken in the Large Hadron Collider (LHC) tunnel. The LHC [14] is a circular proton-proton collider that uses superconducting bending magnets. It is housed approximately 100 m underground.

2.1 Magnetic Field Sensors

Four fluxgate magnetometers (Mag-13s) produced by Bartington Instruments, UK [15] were used in the measurements. The key specifications of these sensors are summarised in Table 1. Further details can be found in [16, 17].

| Specification                      | Value | Unit  |
|-----------------------------------|-------|-------|
| Frequency range                   | 0-3   | kHz   |
| Noise level (at 1 Hz)             | <7    | pT/√Hz |
| Resolution (24-bit DAQ)           | 6     | pT    |
| Magnetic field range              | ±100  | µT    |

Table 1: Mag-13 specifications [16].

The sensors require a power supply unit (PSU) [18], which is also provided by Bartington Instruments. The Mag-13 sensors output an analogue voltage. A National Instruments (NI) data acquisition system was used to digitise the signal. This was a 24-bit NI 9238 module [19]. The data was recorded using a NI LabVIEW script [20] running on a laptop [21].

A schematic diagram of the full measurement setup is shown in Fig. 1. All devices are powered using batteries to ensure currents from the mains do not contaminate the measurement. The setup is highly portable, which is necessary for surveying stray fields.

2.2 Power Spectral Density and Correlation

There are two useful quantities that can be used to characterise stray fields: the power spectral density (PSD) and correlation. The PSD is the average power density as a function of frequency. This is useful for characterising the amplitude of stray fields. The correlation describes the phase difference as a function of frequency and location. This is useful for characterising the spatial variation of stray fields.
2.2.1 PSD

The magnetic field sensors output a voltage $v(t,s)$, which is measured as a function of time $t$ and location $s$. A periodogram can be estimated as

$$p_V(f,s) = \frac{1}{\Delta f} V^*(f,s)V(f,s),$$

(1)

where $V(f,s)$ is the normalised Fast Fourier Transform (FFT) of the signal $v(t,s)$, $\Delta f = f_s/N$ is the frequency bin width of the FFT, $f_s$ is the sampling frequency, $N$ is the number of data points in $v(t,s)$ and $^*$ denotes the complex conjugate.

A FFT assumes a signal is repeated infinitely many times. This often leads to discontinuities that the interface between repetitions, which causes spectral leakage. A windowing technique is applied to the voltage $v(t,s)$ to minimise spectral leakage [22]. In this work, we apply a Hann window [22] to all voltage measurements.

A FFT describes a signal in the frequency domain over the range $[-f_s/2, f_s/2]$. FFTs are conjugate symmetric functions, i.e. $V^*(-f) = V(f)$. Therefore, negative frequencies are redundant. In this paper, the FFT and PSD of a signal will only be defined for positive frequencies.

PSDs were calculated using Welch’s method [23]. Here, the signal $v(t,s)$ is split into $M$ overlapping segments. Each segment contains a 50% overlap with its neighbours. A periodogram is calculated for each segment $p_V^{(m)}(f)$. The estimate for a PSD is calculated by averaging each periodogram,

$$P_V(f,s) = \frac{1}{M} \sum_{n=1}^{M} p_V^{(m)}(f,s).$$

(2)

The PSD of the voltage is converted into a PSD of the magnetic field by using the transfer function of the magnetometer $S(f)$, which was provided by the manufacturer. The PSD of the magnetic field is given by

$$P_B(f,s) = \frac{P_V(f,s)}{|S(f)|^2}.$$

(3)

A property of a PSD is that its integral gives the variance,

$$\sigma_B^2(s) = \int_{0}^{\infty} P_B(f,s) \, df.$$  

(4)

In this paper, we normalise PSDs such that Eq. (4) is true. The square root of Eq. (4) is the standard deviation. To examine the frequency content of a signal, it is useful to calculate the standard deviation as a function of frequency range,

$$\sigma_B(f,s) = \sqrt{\int_{f}^{\infty} P_B(f',s) \, df'}.$$

(5)

2.2.2 Correlation

A correlation spectrum can be calculated for two simultaneous measurements at different locations $v(t,s_0)$ and $v(t,s)$, where $s_0$ is a reference location. The correlation for each frequency and location is given by

$$C_B(f,s) = C_V(f,s) = \frac{\text{Re}\{P_V(f,s_0,s)\}}{\sqrt{P_V(f,s_0)P_V(f,s)}},$$

(6)
where $P_{V}(f, s_0, s)$ is the cross spectral density of $v(t, s_0)$ and $v(t, s)$, which can be calculated using Welch’s method by averaging correlograms,

$$p_{V}(f, s_0, s) = \frac{1}{\Delta f} V^*(f, s_0)V(f, s).$$

(7)

The correlation describes whether two signals are moving in phase or anti-phase. Signals with a phase difference of 0° ($C_B(f, s) = 1$) are said to be highly correlated, signals with a phase difference of 90° ($C_B(f, s) = 0$) or signals that vary independently are said to be uncorrelated and signals with a phase difference of 180° ($C_B(f, s) = -1$) are said to be anti-correlated.

2.3 The LHC

The ambient magnetic field was measured near the Compact Muon Solenoid (CMS) detector \cite{24}. Specifically, the measurements were taken in LSS5, which is a long straight section that precedes the detector. The measurements were taken on 29/04/2019, during long shutdown 2, over the course of one hour.

The measurements were taken at a time where accelerator elements were operational. This includes magnets, vacuum pumps, cooling, ventilation, cryogenics, lighting, etc. Of interest in this work is the stray field seen by the beam. Therefore, measurements should be taken with the sensor inside the beam pipe. However, measuring inside the beam pipe is impractical due to the limited space and access. Accurately positioning and moving the sensors inside a beam pipe is also difficult. The measurements presented in this section were taken outside of the beam pipe. All known stray field sources are located outside of the beam pipe in an accelerator.

2.3.1 Measurement Procedure

Four sensors were placed at different longitudinal positions on a parallel line adjacent to the beamline (see Fig. 2). They were approximately 1 m away from the beamline axis. The magnetic field in three orthogonal directions: $x$, $y$ and $z$ (see Fig. 2) was simultaneously measured for one minute by each sensor.

![Figure 2: Placement of the sensors relative to the beam pipe.](image)

In between measurements three sensors were moved to a new position along the beamline ($s$ in Fig. 3), mapping out a 40 m section of the beamline at intervals of 1 m. The fourth sensor was kept stationary as a reference.
2.3.2 Beamline Description

A schematic diagram of the elements in the beamline is shown in Fig. 3. The beamline includes:

- Two roman pots (XRPT), which are particle detectors used for machine protection [25].
- Three vacuum pumps (VAC), which are used to maintain the vacuum inside the beam pipe.
- Two quadrupoles (Q5, Q4). These are the fifth and fourth closest quadrupoles to the collision point at CMS.
- One concrete shielding block (JBCAE).
- One collimator (TCL), which is used to collimate the beam before collision.
- One beam position monitor (BPTX).

![Schematic diagram of the elements in LSS5. Relative lengths are to scale.](image)

Figure 3: Schematic diagram of the elements in LSS5. Relative lengths are to scale.

2.3.3 PSD and Standard Deviation

The PSD of the magnetic field in the x, y and z-direction and total PSD (sum of all three components) is shown in Fig. 4. The amplitude of the x and y-components is relatively constant over the length of the beamline. The z-component has the smallest amplitude. The most prominent peaks are at harmonics of 50 Hz, which are from the electrical grid. The standard deviation of the magnetic field as a function of position is shown in Fig. 5.

2.3.4 Correlation

The correlation of the magnetic field in the x, y and z-direction with respect to the reference sensor at s = 30 m is shown in Fig. 6. The magnetic field is highly correlated for low frequencies (below 10 Hz) in the x and y-direction. In the z-direction, the magnetic field flips direction several times. This is consistent with elements in the beamline with a high iron content attracting the magnetic field. The locations of anti-correlated magnetic fields coincide with the minima of standard deviation shown in Fig. 5.
Figure 4: PSD of the magnetic field $P_B(f, s)$ (RH scale) vs location $s$ (LH scale) and frequency $f$.

Figure 5: Standard deviation of the magnetic field $\sigma_B(s)$ in the $x$-direction (blue), $y$-direction (orange), $z$-direction (green) and total (red) vs location $s$. 
3 Modelling

This section develops a two-dimensional PSD model for stray fields based on the LHC measurements. There are two characteristics of stray fields that must be accurately captured in the model: the amplitude and the spatial correlation.

In this paper, we follow the same approach used to simulate ground motion in linear colliders described in [26]. Ground motion is modelled as a set of travelling waves of differing wavenumber \( k \) and frequency \( f \). The amplitude of each wave is determined by a two-dimensional PSD \( P(f, k) \) as

\[
a_{ij} = \sqrt{2} \sigma_{ij} = \sqrt{2 \int_{f_i}^{f_{i+1}} \int_{k_j}^{k_{j+1}} P(f, k) \, dk \, df} \approx \sqrt{2P(f_i, k_j)\Delta k \Delta f}. \tag{8}
\]

The displacement of an accelerator element at a particular location and time is calculated from the superposition of each wave.
3.1 Amplitude

The amplitude of the magnetic field measured in the LHC tunnel was similar in the two transverse directions to the beam (x and y in Fig. 4). The y-component measurements were used to develop the model.

The average PSD of the magnetic field in the y-direction measured by the reference sensor is given by

\[ P_{B,y,\text{ref}}(f) = \frac{1}{M} \sum_{i=1}^{M} P_{B,y,i}(f,s_{\text{ref}}), \quad (9) \]

where \( P_{B,y,i}(f,s_{\text{ref}}) \) is the PSD of the magnetic field in the y-direction of the \( i \)-th measurement made by the reference sensor at \( s_{\text{ref}} \) and \( M \) is the number of measurements. This is shown, along with the standard deviation, in Fig. 7.

Figure 7: (a) Stray field PSD \( P_{B,y,\text{ref}}(f) \) vs frequency \( f \) and (b) standard deviation \( \sigma_{B,y,\text{ref}}(f) \) vs frequency \( f \).

Fig. 4 shows that the amplitude is approximately constant over the measured section. Therefore, a PSD measured at one location can be representative of the amplitude across the entire section. The PSD shown in Fig. 7a will be used to characterise the PSD of stray fields. The standard deviation of the stray field is approximately 35 nT.

3.2 Correlation

The stray field model should reproduce the correlation shown in Fig. 6b. There are three different regions in Fig. 6b:

- Frequencies below 10 Hz, which are highly correlated over the 40 m section.
- Frequencies between 10 Hz and 400 Hz, which are correlated over length scales of 10 m.
- Frequencies above 400 Hz, which are uncorrelated.

The PSD in Fig. 7 characterises the power distribution over different frequencies. To calculate a two-dimensional PSD, the power in each frequency must be distributed over
different wavenumbers. The distribution over wavenumbers determines the spatial correlation of the stray field. If there are many modes of differing wavenumber, their superposition leads to an uncorrelated stray field. Whereas if the modes have similar wavenumbers, the stray field is highly correlated.

Simultaneous measurements at many locations are required to determine the wavenumber spectrum. However, only a maximum of four sensors was available for measurements. This is not enough to parameterise a wavenumber spectrum from measurements.

A particular functional form for the wavenumber spectrum must be assumed. We propose a Gaussian function for simplicity and because its width is determined by a single parameter. The power density of a mode with frequency \( f_i \) and wavenumber \( k_j \) is given by

\[
P_B(f_i, k_j) = P_B(f_i) \sqrt{\frac{2}{\pi \alpha^2}} \exp \left( -\frac{k_j^2}{2\alpha^2} \right),
\]

where \( P_B(f_i) \) the power density of frequency mode \( i \) and \( \alpha \) is half the width of the distribution. The factor \( \sqrt{2/(\pi \alpha^2)} \) was introduced to ensure that the two-dimensional PSD correctly recovers the one-dimensional PSD \( P_B(f) \) after integrating over all wavenumbers,

\[
P_B(f) = \int_0^\infty P_B(f, k) \, dk.
\]

The width \( \alpha \) is parameterised from measurements to produce a desired spatial correlation. A small value for \( \alpha \) produces a stray field which is correlated over large distances, whereas a large value for \( \alpha \) produces a stray field which is only correlated over short distances. The following widths were found to reproduce the correlation measured in the LHC tunnel, \cite{10}

\[
\alpha = \begin{cases} 
0.002\pi & \text{for } f \leq 10 \text{ Hz}, \\
0.04\pi & \text{for } 10 \text{ Hz} < f \leq 400 \text{ Hz}, \\
0.5\pi & \text{for } f > 400 \text{ Hz}.
\end{cases}
\]

3.3 Generator

The stray field is simulated as a grid of zero length dipoles, which is inserted into the lattice. The purpose of the generator is to calculate the kick applied by each dipole. A dipole spacing of 1 m was used in the simulation. With this dipole spacing, only wavelengths of \( \lambda_{\text{min}} > 2 \text{ m} \) can be represented. This corresponds to a maximum wavenumber of \( k_{\text{max}} = 2\pi/\lambda_{\text{min}} = \pi \).

The stray field is modelled as a standing wave. The stray field at location \( s \) and time \( t \) is given by

\[
B(s, t) = \sum_i \sum_j a_{ij} \cos(k_j s + \theta_j) \cos(2\pi f_i t + \phi_{ij}),
\]

where \( a_{ij} \) is the amplitude determined by the two-dimensional PSD (see Eq. (8)) and \( \theta_j \) and \( \phi_{ij} \) are uniformly distributed random numbers between 0 and 2\( \pi \). The computational efficiency of calculating Eq. (13) can be improved by calculating a time-dependent amplitude,

\[
A_{ij}(t) = a_{ij} \cos(2\pi f_i t + \phi_{ij}),
\]

and calculating the stray field as

\[
B(s, t) = \sum_i \sum_j A_{ij}(t) \cos(k_j s + \theta_j).
\]
This significantly reduces the computation time because $A_{ij}(t)$ only needs to be calculated once per time step. The stray field kick applied by each dipole is calculated using

$$\delta [\mu \text{rad}] = \frac{c [\text{m/s}] \cdot B [\text{nT}] \cdot L [\text{m}]}{E [\text{GeV}]} \times 10^{-12},$$

where $c$ is the speed of light, $L$ is the dipole spacing and $E$ is the beam energy.

The generator was used to sample the stray field in a 40 m section of the beamline. Fig. 8 shows the PSD and correlation of the stray field from the generator. The generator is able to qualitatively reproduce the features measured in the LHC tunnel (Figs. 4b and 6b).

![Figure 8: A sample from the generator of stray fields. (a) PSD $P_B(f, s)$ (RH scale) vs location $s$ (LH scale) and frequency $f$ and (b) correlation $C_B(f, s)$ (RH scale) vs location $s$ (LH scale) and frequency $f$. The correlation was calculated with respect to the stray field at $s = 30 \text{ m}$.](image)

### 4 Integrated Simulations

The two-dimensional PSD model described in the previous section was used in integrated simulations of CLIC at 380 GeV to evaluate the impact of stray fields on the luminosity.

#### 4.1 CLIC

In this work, we combine the Ring to Main Linac (RTML), Main Linac (ML) and Beam Delivery System (BDS) of CLIC into a single tracking simulation, referred to as an ‘integrated simulation’. This is necessary because stray fields can be correlated over the entire length of the machine. Therefore, the entire machine must be simulated to evaluate their full effect.

The particle tracking code PLACET [27] was used to track the electron and positron beams. A full simulation of the collision, including beam-beam effects [5] was performed with GUINEA-PIG [28] to estimate the luminosity.
4.2 Mitigation of Stray Fields

The impact of a mitigation system can be described using a transfer function $T(f)$, which acts on the two-dimensional PSD of stray fields $P_B(f, k)$ to give an effective two-dimensional PSD,

$$P_{B,\text{eff}}(f, k) = |T(f)|^2 P_B(f, k),$$

which is used to generate the stray field. Here, the mitigation system only impacts the temporal variation of the stray field, i.e. all wavenumbers are affected in the same way. Therefore, Eq. (17) is true for mitigation systems that act equally across the accelerator.

In the following sections we look at the impact of two mitigations systems: a beam-based feedback system and a mu-metal shield.

4.2.1 Beam-Based Feedback System

The aim of the beam-based feedback system is to correct the beam offset along the accelerator. This is achieved by measuring the offset of a pulse using beam position monitors and applying a correctional kick to the following pulse using magnets. The transfer function for the CLIC feedback system is shown in Fig. 9 [10]. The feedback system is effective at suppressing low frequency noise, below 1 Hz, but amplifies noise in the frequency range 4-25 Hz. The repetition frequency of the beam is 50 Hz, which corresponds to a Nyquist frequency of 25 Hz. Therefore, noise above 25 Hz is aliased to lower frequencies.

This feedback system was optimised to minimise the luminosity loss from ground motion [10, 11]. The same feedback system was used in stray field simulations to ensure that the proposed mitigation strategy is consistent for the combined effects of ground motion and stray fields.

![Figure 9: Transfer function of the beam-based feedback system $T(f)$ vs frequency $f$.](image)

4.2.2 Mu-Metal Shield

Another approach to mitigate stray fields is to prevent them from reaching the beam. This can be achieved by surrounding the beam pipe with a magnetic shield. The tolerances for magnetic field ripples are larger than the tolerances for stray fields [10]. Therefore,
the magnetic shield does not need to run through the aperture of magnets, shielding the
drifts is sufficient.

Ferromagnetic materials with a large magnetic permeability are commonly used to
shield magnetic fields. Mu-metal offers one of the highest permeabilities. The use of
mu-metal to shield magnetic fields in linear colliders is discussed in [10].

A methodology for calculating the transfer function of a cylindrical magnetic shield is
outlined in [29]. The transfer function for a cylindrical mu-metal shield with a thickness
of 1 mm and inner radius of 1 cm is shown in Fig. 10. A relative permeability of 50,000
was used for this calculation, which is a reasonable estimate for the permeability with
very low amplitude external magnetic fields [10]. The mu-metal shield is very effective at
mitigation.

![Figure 10: Transfer function of a mu-metal cylinder with 1 mm thickness and inner radius of
1 cm T(f) vs frequency f.](image)

Stray field simulations in [10, 13] identified particular sections of CLIC, which are
sensitive to stray fields. The most sensitive regions are the Vertical Transfer and Long
Transfer Line in the RTML and the Energy Collimation Section and Final-Focus System
in the BDS. It is possible to devise an effective mitigation strategy by just shielding these
sections. The ML is the least sensitive section and benefits from shielding from the copper
accelerating cavities.

4.2.3 Impact on the Stray Field PSD

Ignoring the spatial variation, the transfer function can act on the one-dimensional PSD
\( P_B(f) \) to estimate the impact of a mitigation system at a single location. The one-
dimensional PSD in Fig. 7 is used to characterise the PSD of stray fields at a single
location.

Fig. 11 shows the effective PSD and standard deviation of stray fields including the
impact of different mitigation systems. The standard deviations are summarised in Ta-
ble 2.

Without mitigation, there is a large stray field of 35 nT. With a beam-based feedback
system, the effective stray field is 2.1 nT, which is still above the 0.1 nT level required
for CLIC. The mu-metal shield is the most effective mitigation system, which brings the
stray field down to the level of 3 pT without the feedback system and 0.5 pT with the
feedback system.
Figure 11: (a) Effective stray field PSD $P_{B,\text{eff}}(f)$ vs frequency $f$ and (b) standard deviation $\sigma_{B,\text{eff}}(f)$ vs frequency $f$: without mitigation (blue); including a beam-based feedback system (orange); including a 1 mm mu-metal shield (green) and with the feedback system and mu-metal shield combined (red).

| Mitigation                        | $\sigma_{B,\text{eff}}$ [nT] |
|-----------------------------------|--------------------------------|
| None                              | 35                             |
| Feedback System                   | 2.1                            |
| Mu-Metal Shield                   | $3.1 \times 10^{-3}$           |
| Feedback System + Mu-Metal Shield | $0.5 \times 10^{-3}$           |

Table 2: Standard deviation of the stray field $\sigma_{B,\text{eff}}$ with different mitigation techniques.

4.3 Luminosity Loss

Integrated simulations including stray fields were performed using nominal beam parameters; additional details are provided in [10]. Table 3 shows the luminosity loss including a beam-based feedback system and a 1 mm mu-metal shield in sensitive regions (Vertical Transfer, Long Transfer Line, Energy Collimation Section and Final-Focus System).

Without mitigation, there is a significant luminosity loss of 43%. The beam-based feedback system alone is not enough to mitigate stray fields. A luminosity loss of 15% is expected if only the beam-based feedback system is used. With the mu-metal shield only, the luminosity loss is reduced to 2%. The combination of the beam-based feedback system and mu-metal shield is an effective mitigation strategy for stray fields, reducing the luminosity loss to 0.4%.

5 Conclusions

High-precision magnetic field measurements were performed in the LHC tunnel, which characterised a realistic amplitude for stray fields in a live accelerator environment. These measurements were used to develop a two-dimensional PSD model, which could be used to simulate stray fields in linear colliders.

This model was used in integrated simulations of the 380 GeV stage of CLIC. The
| Mitigation                              | $\Delta L / L_0$ [%] |
|----------------------------------------|-----------------------|
| None                                   | 43                    |
| Feedback System                        | 15                    |
| Mu-Metal Shield                        | 2.0                   |
| Feedback System + Mu-Metal Shield       | 0.4                   |

Table 3: Relative luminosity loss $\Delta L / L_0$ due to stray fields. $L_0$ is the nominal luminosity of CLIC.

Simulations show CLIC is robust against the level of stray fields measured in the LHC tunnel provided a beam-based feedback system and mu-metal shield is used.

Acknowledgements

We would like to thank our CERN colleagues Benoit Salvant and Daniel Noll for their assistance in stray field measurements in the LHC tunnel.

References

[1] C. Adolphsen, et al., ILC Report No. ILC-REPORT-2013-040, 2013.
[2] H. Aihara, et al., DESY Report No. DESY-2019-037, 2019.
[3] M. Aicheler, et al., CERN Report No. CERN-2018-010-M, 2018.
[4] M. Aicheler, et al., CERN Report No. CERN-2012-007, 2012.
[5] D. Schulte, ICFA Beam Dyn. Newslett. 69, 237-245 (2006).
[6] C. Gohil, N. Blaskovic Kraljevic, P. N. Burrows, B. Heilig, and D. Schulte, in Proceedings of the 10th International Particle Accelerator Conference, Melbourne, Australia, 2019, (JACoW, Geneva, 2019), p. MOPGW081.
[7] C. Gohil, M. C. L. Buzio, E. Marin, D. Schulte, and P. N. Burrows, in Proceedings of the 9th International Particle Accelerator Conference, Vancouver, BC, Canada, 2018, (JACoW, Geneva, 2018), p. THPAF047.
[8] E. Marin, D. Schulte, and B. Heilig, in Proceedings of the 8th International Particle Accelerator Conference, Copenhagen, Denmark, 2017, (JACoW, Geneva, 2017), p. MOPIK077.
[9] B. Heilig, C. Beggan, and J. Lichtenberger, CERN Report No. CERN-ACC-2018-0033, 2018.
[10] C. Gohil, DPhil thesis, University of Oxford, 2020.
[11] C. Gohil, D. Schulte and P. N. Burrows, CERN Report No. CERN-ACC-2018-0051, 2018.
[12] J. Snuverink, W. Herr, C. Jach, J.-B. Jeanneret, D. Schulte, and F. Stulle, in Proceedings of the 1th International Particle Accelerator Conference, Kyoto, Japan, 2010, (JACoW, Geneva, 2010), p. WEPE023.

[13] C. Gohil, D. Schulte, and P.N. Burrows, CERN Report No. CERN-ACC-2018-0052, 2018.

[14] O. Brüning, S. Oliver, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, P. Proudlock, CERN Report No. CERN-2004-003-V-1, 2004.

[15] Bartington Instruments Ltd, UK, https://www.bartington.com.

[16] Bartington Instruments Ltd, UK, Mag-13 brochure, https://www.bartington.com/wp-content/uploads/pdfs/datasheets/Mag-13_DS3143.pdf.

[17] Bartington Instruments Ltd, UK, Mag-13 operation manual, https://www.bartington.com/wp-content/uploads/pdfs/operation_manuals/Mag-13_OM3143.pdf.

[18] Bartington Instruments Ltd, UK, PSU1 brochure, https://www.bartington.com/wp-content/uploads/pdfs/datasheets/Magnetometer_Power_Supplies_DS2520.pdf.

[19] National Instruments, NI 9238 datasheet, http://www.ni.com/pdf/manuals/376138a_02.pdf.

[20] National Instruments, LabVIEW, https://www.ni.com/en-us/shop/labview.html.

[21] DELL, https://www.dell.com/en-us/work/shop/dell-laptops-and-notebooks/latitude-7480-business-laptop/spd/latitude-14-7480-laptop.

[22] K. Prabhu, Window functions and their applications in signal processing (CRC Press, 2013).

[23] P. Welch, IEEE Trans. Aud. and Electr. 15, 70-73 (1967).

[24] CMS collaboration, J. Instrum. 3, S08004 (2008).

[25] M. Oriunno, M. Deile, K. Eggert, J.-M. Lacroix, S. J. Mathot, E. P. Noschis, R. Perret, E. Radermacher, and G. Ruggiero, in Proceedings of the 10th European Particle Accelerator Conference, Edinburgh, UK, 2006, (JACoW, Geneva, 2006), p. MO-PLS013.

[26] A. Seryi and O. Napoly, Phys. Rev. E 53, 5323-5337 (1996).

[27] The tracking code PLACET, https://gitlab.cern.ch/clic-software/placet/blob/master/doc/placet.pdf.

[28] D. Schulte, Ph.D. thesis, University of Hamburg, 1997.

[29] J. F. Hoburg, IEEE Trans. on Electr. Comp. 38, 93-103 (1996).