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MEASUREMENT OF STRAY MAGNETIC FIELDS AT CERN FOR CLIC

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Abstract

Simulations have shown that the Compact Linear Collider (CLIC) is sensitive to external dynamic magnetic fields (stray fields) to the nT level. Magnetic fields are not typically measured to this precision at CERN. Past measurements of the background magnetic field at CERN are limited. In this paper new measurements are presented.

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Abstract

Simulations have shown that the Compact Linear Collider (CLIC) is sensitive to external dynamic magnetic fields (stray fields) to the nT level. Magnetic fields are not typically measured to this precision at CERN. Past measurements of the background magnetic field at CERN are limited. In this paper new measurements are presented.

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 [2–5] have shown nT tolerances to remain within a 2 % luminosity loss budget.

To characterise the expected level of stray fields that CLIC would experience, a campaign to measure a power spectrum was initiated in 2016. These power spectra are expected to be dependent on the local environment and therefore measurements on the CERN site are required. In 2017, the background magnetic field on the CERN site was measured to a sub-nT precision [3]. These measurements were done with a single fluxgate magnetometer with a frequency range of 0-20 Hz. However, this was not enough to measure the full spectrum due to the limited frequency range of the sensor. Measurements of the background magnetic field over the frequency range 0.1-300 Hz in the vicinity of non-operating accelerators are presented in [4]. In this paper further measurements over a wider frequency range are presented.

STRAY FIELD SOURCES

Sources of stray fields can be classified as man-made or natural. Natural sources, such as the Earth's magnetic field, typically produce stray fields of frequencies less than 1 Hz. Such stray fields can be effectively mitigated with the use of a beam-based orbit correction. Stray fields from natural sources with frequencies greater than 1 Hz are typically within the tolerance or occur infrequently (less than once a month) [6]. Therefore, natural sources do not pose the greatest danger for CLIC.

Man-made sources can either be an environmental source, which is a piece of equipment that produces a stray field, but is not an element of CLIC, or a technical source, which is an element of CLIC. Examples of environmental sources are the electrical grid and railways. Other running accelerators can act as an environmental source, particularly on the CERN site where there are several running experiments. Technical sources, such as RF systems, vacuum pumps and power cables, pose the greatest risk. Technical sources are capable of producing stray fields across a wide frequency range. This paper focuses on measurements of environmental and technical sources.

MAGNETIC FIELD SENSOR

The magnetic field sensor used was a three-axis fluxgate magnetometer (Mag-13Z) produced by Bartington Instruments [7]. The specifications of this sensor are summarised in Table 1.

Table 1: Mag-13Z Specifications [7]

Technical Parameter	**Value**	**Unit**
Frequency range	0-1	kHz
Noise level (at 1 Hz)	<7	pT/$\sqrt{\text{Hz}}$
Resolution (24-bit DAQ)	6	pT
Magnetic field range	±100	μT

ENVIRONMENTAL SOURCES

The Proton Synchrotron

The Proton Synchrotron (PS) is a 630 m circular accelerator on the CERN site. The PS injects protons into the Super Proton Synchrotron, which then feeds the Large Hadron Collider. In this accelerator the bending magnets are pulsed every 1.2 s.

A regular pattern was observed in the recorded magnetic field at several locations in proximity to the PS. Previous measurements [4] correlated the magnetic field to the pulsing of the bending magnets in the PS ring.

The PS was modelled as a ring of 100 equally spaced bending magnets each with a dipole field of the form [8]

$$\boldsymbol{B}(\rho_i) = \frac{C_1}{(\rho_i + C_2)^3} \left\{ \frac{3}{2}\hat{\boldsymbol{\rho}}_{\boldsymbol{i}} - \hat{z} \right\} \tag{1}$$

where $\hat{z}$ is a unit vector in the vertical direction, $\hat{\boldsymbol{\rho}}_{\boldsymbol{i}}$ is a unit vector pointing from the i^{th} magnet to the measurement location, ρ_i is the distance from the i^{th} magnet to the measurement location and C_1 and C_2 are constants. The total magnetic field measured at a single location is the summation of the dipole fields from each magnet,

$$B(r) = \left| \sum_{i=1}^{100} \boldsymbol{B}(\boldsymbol{\rho}_i) \right|, \tag{2}$$

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where r is the radial distance from the centre of the PS ring.

Figure 1 shows the peak magnetic field recorded as a function of radial distance from the centre of the PS ring. From the measurements the fit parameters were calculated to be $C_1 = (6.8 \pm 0.4) \times 10^3\,\mu\text{T}{\cdot}\text{m}$ and $C_2 = (9.4 \pm 0.4)\,\text{m}$. In the absence of any shielding material a distance of approximately 1 km would attenuate the magnetic field to a sub-nT level.

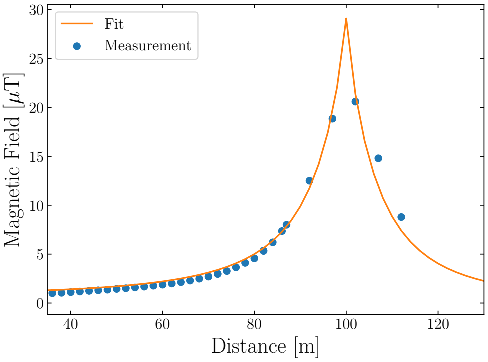

Figure 1: Peak magnetic field on 11/09/18 as a function of radial distance from the centre of the PS ring. Error bars on data points are too small to be seen.

Electrical Grid

Typically the largest contribution to the magnetic field measured comes from the electrical grid. Such magnetic fields characteristically consist of a fundamental frequency of 50 Hz, which has the largest amplitude, as well as harmonics of the fundamental frequency 100 Hz, 150 Hz, etc., which diminish in amplitude with increasing frequency. The odd harmonics typically have larger amplitudes compared to the even harmonics.

To understand the frequency content of magnetic fields from the electrical grid, measurements were taken near the high-voltage transmission lines that run across the Meyrin CERN site. The system consists of a 400 kV line, a 130 kV line and a 18 kV line, which powers the Swiss electrical grid. The power in these lines does not feed the CERN network or accelerators, instead the usage of these lines is from domestic consumption. These lines run over the planned interaction point of CLIC in Prevessin.

The power spectrum of the total magnetic field measured directly underneath the power lines in shown in Fig. 2. The harmonics of 50 Hz are clearly visible, however there are additional peaks surrounding the even harmonics and a significant peak at 16.7 Hz. This suggests stray fields from the electrical grid can have a complicated frequency content and do not solely consist of 50 Hz harmonics.

Figure 3 shows the power spectral density over the same period as a function of time. There appears to be a regular pattern over a period of about 20 s. Figure 4 shows the precise value of the 50 Hz fundamental as a function of time. This fundamental is not exactly 50 Hz. Small fluctuations of ±0.005 Hz occur over time scales of seconds and larger variations of 0.02 Hz occur on time scales of tens of seconds.

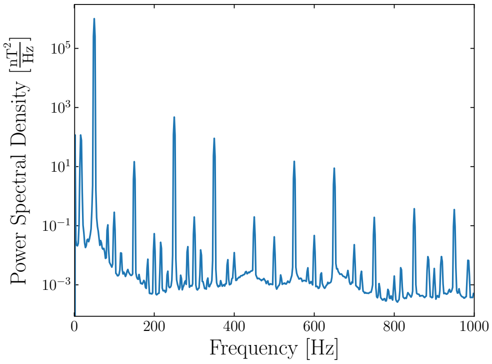

Figure 2: Average power spectral density measured over one minute underneath the power lines at 15:02 on 10/09/18.

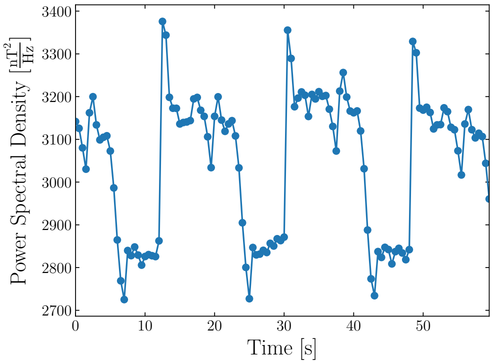

Figure 3: Mean power spectral density over all frequencies underneath the power line at 15:02 on 10/09/18.

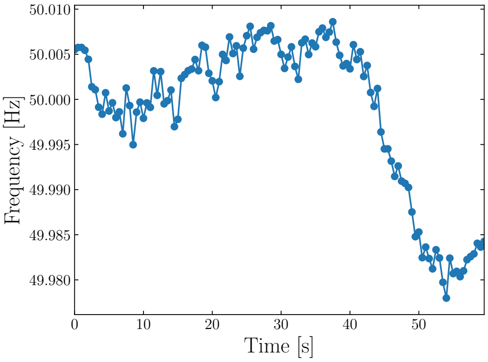

Figure 4: Stability of the 50 Hz signal over one minute underneath the power line at 15:02 on 10/09/18. Error bars too small to be seen.

TECHNICAL SOURCES

CLEAR

The CERN Linear Electron Accelerator for Research (CLEAR) facility — formerly known as the CLIC Test Facility 3 — is somewhat representative of a CLIC beamline. The magnetic field along the beamline was mapped out on the 10/12/18. Figure 5 shows the smallest and largest total power spectrum measured. These measurements occurred at a time without beam and without RF systems running.

Harmonics of 10 Hz have been regularly observed in the CLEAR beamline, but also in the surrounding areas, e.g. in

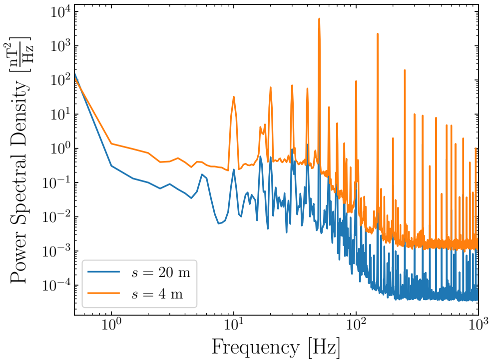

Figure 5: Smallest and largest total power spectrum measured in CLEAR. s is the position along the beamline from the electron gun.

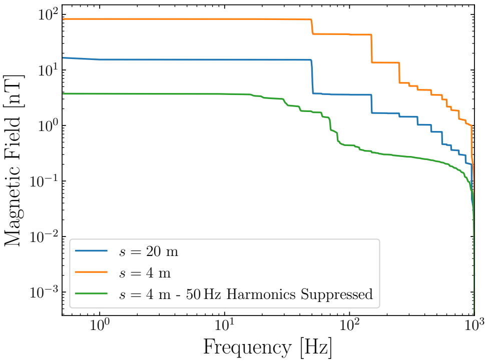

Figure 6: Smallest and largest integrated magnetic field measured in CLEAR. s is the position along the beamline from the electron gun.

the CLEAR klystron gallery, which is located directly above the beamline. These harmonics are suspected to be due to the ventilation system.

There is approximately an order of magnitude difference in the smallest and largest magnetic field measured. The largest magnetic field was approximately 100 nT integrated over the frequency range of the sensor.

CLIC operates with a repetition frequency of 50 Hz, as a result of this magnetic fields at the harmonic frequencies of 50 Hz appear static. Figure 6 shows the integrated magnetic field with the harmonics of 50 Hz suppressed. Removing this contribution, the integrated field is less than 5 nT.

XBOX-3 Test Stand

The XBOX-3 test stand [9] is used for the R&D of CLIC accelerating cavities at CERN. It provides 200-300 ns RF pulses of 60 MW peak power at a repetition rate of up to 400 Hz.

The test stand consists of four Toshiba 6 MW klystrons, which provide 5 µs pulses, and four Scandinova modulators. The peak power of 60 MW is produced using a combination scheme, which compresses and combines the pulses from a number of klystrons [9].

The magnetic field was measured in the proximity of the XBOX-3 test stand on 06/12/18. At the time the klystron was pulsing at 16.7 Hz. Harmonics of 16.7 Hz are clearly visible in the power spectrum when the klystron is running, shown in Fig. 7.

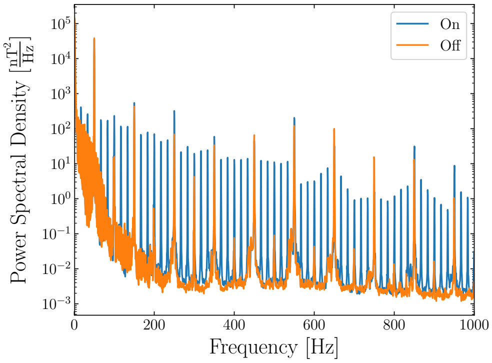

Figure 7: Magnetic field power spectrum measured at the XBOX-3 test stand on 06/12/18 with and without the klystron running. The klystron was operating at 16.7 Hz.

The frequency bandwidth of the Mag-13 is up to a few kHz. Therefore, it is insensitive to high frequency variations O(MHz) that would be produced by the final 200-300 ns pulses provided by the test stand nor is able to resolve the 5 µs pulses from the klystrons. It is suspected the harmonics of 16.7 Hz are excited by currents from the recharging of the modulators.

CONCLUSIONS

Several environmental and technical stray field sources have been identified and measured. CLIC will be sufficiently far from the PS for it not to be a concern. Most of the power in stray fields from the electrical grid is in the harmonics of 50 Hz. The 50 Hz repetition rate of the beam ensures that these stray fields appear static and do not affect performance.

An integrated magnetic field of approximately 5 nT remains in CLEAR after suppressing the 50 Hz harmonics. This is an issue for sensitive regions of CLIC such as the long transfer line in the Ring to Main Linac and Beam Delivery System, where there are 0.1 nT tolerances for particular spatial distributions [5]. Magnetic shields can be used to bring the integrated magnetic field to within the 0.1 nT tolerance [10].

The magnetic field power spectrum at XBOX-3 has large contributions at harmonics of 16.7 Hz. However, this is the result of operating the modulator and klystron at this frequency. In CLIC, these systems will operate at 50 Hz and therefore the harmonics of 16.7 Hz will not be present.

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