IMPACT OF DYNAMIC MAGNETIC FIELDS ON THE CLIC MAIN BEAM

J. Snuverink, W. Herr, C. Jach, J.-B. Jeanneret, D. Schulte, F. Stulle, CERN, Geneva, Switzerland

Abstract

The Compact Linear Collider (CLIC) accelerator has strong precision requirements on the position of the beam. The beam position will be sensitive to external dynamic magnetic fields (stray fields) in the nanotesla regime. The impact of these fields on the CLIC main beam has been studied by performing simulations on the lattices and tolerances have been determined. Several mitigation techniques will be discussed.

INTRODUCTION

The Compact Linear Collider (CLIC) accelerator [1] requires a small vertical emittance to achieve its nominal luminosity. Due to this, the vertical beam position is susceptible to external dynamic magnetic fields (stray fields) at the nanotesla level.

A schematic layout of CLIC is shown in Figure 1. In this study, the focus is on the long transfer line, the main linac and the beam delivery system (BDS).

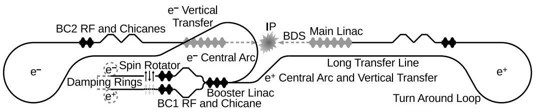

Figure 1: Schematic CLIC layout (not to scale).

Examples of possible sources of stray fields are the earth magnetic field, the RF system, nearby equipment (e.g. vacuum systems, power cables inside the tunnel), other external sources (e.g. railways, power lines) or the drive beam.

Not all fields are of equal importance. The impact of stray fields with frequencies below about 1 Hz will be strongly reduced by feedback systems, e.g. steering the beams into collision with train-to-train feedback. Furthermore, at high frequencies (> kHz) structures and beam pipes provide shielding.

It is important to note that the CLIC beamline will not be sensitive to stray fields with a frequency of 50 Hz (and its harmonics), e.g. fields related to the power grid, due to its 50 Hz repetition rate.

DRIVE BEAM

A source of magnetic field that is unique to CLIC is the drive beam. The CLIC drive beam is a short pulsed (243.7 ns) high current (101 A) beam. The magnetic fields induced by the drive beam at the main beam position will be repeated with 50 Hz and thus look like static fields, except for drive beam current fluctuations. We use a simple two-dimensional model of the magnetic field that leaks out of the beam pipe. The limit frequency ω_0 is the frequency for which the combined thickness of the beam pipes of the source beam and of the kicked beam correspond to one skin depth. Assuming 2 mm of copper one finds $\omega_0 = 7$ kHz. We approximate the magnetic field generated by a Dirac delta beam pulse of charge Q. The case for the CLIC drive beam is shown in Figure 2, with $r \approx 0.5$ m the distance between main and drive beam. The maximum of the field is reached after about 50 μs, so the main beam, which has a train length of 156 ns, will not see the maximum of the field. At the next pulse after 20 ms the field has decayed to 20 pT.

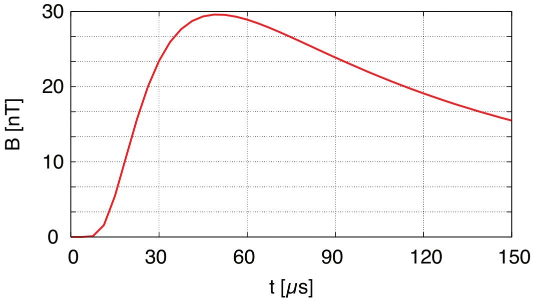

Figure 2: The magnetic field induced by a drive beam at a distance $r = 0.5$ m with 2 mm copper shielding.

The main beam in the long transfer line arrives earlier than the drive beam, while the main beam in the main linac will also see almost no field from the drive beam pulses in the decelerators since the field maximum occurs only after it has passed. However, it will see some field from the drive beam pulses when these are still in their long transfer line. Taking into account the 24 drive beam pulses and their radial distance to the main beam of $r \approx 3$ m the maximum field would be 120 nT, which is still acceptable since variations of the kick in the main beam pulse will be small as can been from the time response to a delta pulse. High bandwidth kickers in the main linac will remove any residual distortion of this seemingly static effect. A further reduction can be achieved by increasing the material thickness thereby reducing and delaying the maximum field. More detailed 3D calculations of the tunnel will be needed to improve the pulse shape calculation.

SIMULATIONS

The simulations are performed with the particle tracking code PLACET [2]. To simulate the stray fields, a grid of dipole kickers is placed in the beamline with a spacing of 1 m. The strength of each dipole is varied, both with a constant field and with sinusoidal fields with a varying wavelength.

Simulations are performed for the long transport line and the main linac including the BDS. As a figure of merit a 2% loss in luminosity is chosen to be allowed.

Transfer Line

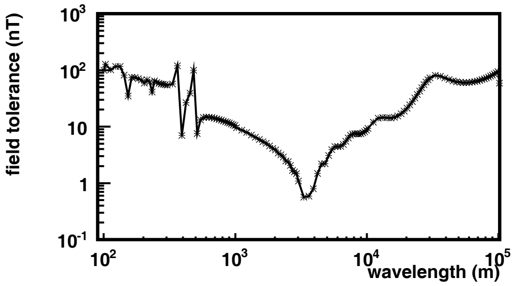

Figure 3: Stray field tolerance for a 0.4 nm emittance growth in the long transfer line versus the wavelength.

For the transfer line this corresponds roughly to a maximal normalized emittance growth of 0.4 nm. It is foreseen to correct an eventual beam offset by a feed forward mechanism after the turnaround. Therefore, for the transfer line the emittance growth is the limiting factor. The field tolerance for a 0.4 nm emittance growth is shown in Figure 3. It can be seen that the beam is most sensitive at the betatron wavelength of about 3 km.

A beam offset will induce no significant emittance growth in the linear parts of CLIC. However the turnaround loop is potentially a source of emittance growth [3]. The CLIC turnaround loop is currently being improved and is discussed in reference [4].

Main Linac and BDS

For the main linac and BDS the geometric luminosity is directly calculated using GUINEA-PIG [5]. There is a clear distinction between symmetric, with respect to the interaction point (IP), and anti-symmetric stray fields. For the former fields the luminosity loss will be dominated by emittance growth, as the offsets of both beams will be the same. While for the latter, the luminosity loss will be due to both the beam offsets and emittance growth.

The tolerances for the main linac including the BDS for the symmetric and anti-symmetric fields are shown in Figure 4. As expected the beam is more sensitive to anti-symmetric fields.

Similar simulations have been performed using a constant field. The sensitivity for the RTML and for the main linac with the BDS are both about 1 nT. The main linac is much more robust.

Discussion

To improve the understanding of the nature of the stray fields, measurements are essential. In the past, some measurements have been performed [6], [7]. Dedicated measurements are planned at CERN on several equipment structures and accelerator lines. Though real field power spectra are currently missing, it is certain that the required dynamic field tolerances are tight and mitigation techniques will be required.

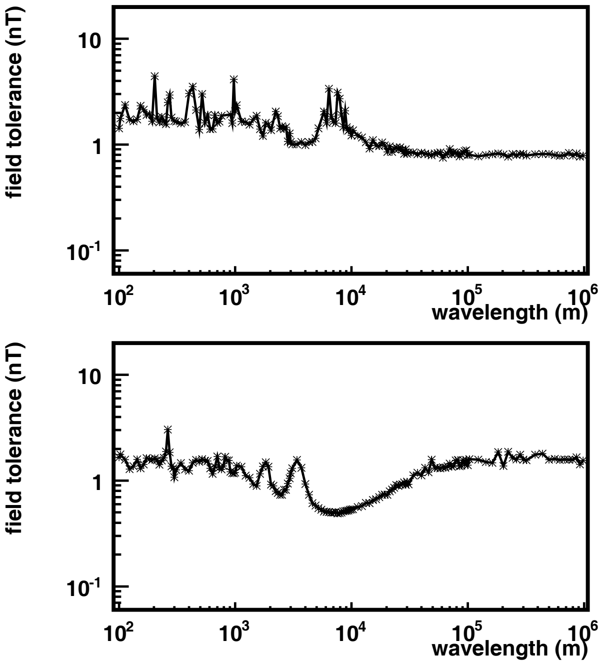

Figure 4: Stray field tolerance in the main linac and BDS for a 2% luminosity loss versus the wavelength. Above for symmetric fields with respect to the IP and below for anti-symmetric fields.

POTENTIAL MITIGATION TECHNIQUES

Stronger Focusing

The CLIC transfer line currently has a relatively weak focusing. By increasing the focusing, the betatron wavelength will be shorter, which will decrease the sensitivity for an orbit jitter proportional to the square root of the betatron wavelength.

Avoid Resonances

It has been shown that the sensitivity varies greatly with respect to the wavelength of the stray fields. Therefore, resonances should be avoided, this can be achieved by placing equipment aperiodicly with respect to the betatron wavelength in the tunnel or by changing the lattice.

Feed Forward Mechanism after Turnaround

It is foreseen to correct the beam offset at the end of the transfer line with a feed forward mechanism. Simulations have shown that by measuring the beam offset just before the turnaround loop, the beam offset can be nearly fully corrected with a system of two dipole kickers.

Shielding the Beamline

The amount of magnetic shielding is determined by the material and the thickness of the beam pipe and the RF structures. The skin depth of a conductor is proportional to the inverse square root of the frequency, so that higher frequencies are damped significantly. The current design is about 2 cm for the copper RF structures (effective shielding for about $f > 10$ Hz) and a 0.3 mm copper coated stainless steel beam pipe (shielded for about $f > 3$ kHz). For the transfer line the design is a 1.5 mm copper beam pipe (shielded for about $f > 2$ kHz). Note that the main linac consists for 80% of structures, while the transfer line mostly consists of beam pipe. Additional passive shielding with high permeability materials, such as mu-metal, can decrease the stray fields in the lower frequency range by several orders of magnitude. However these materials are less effective for low level field fluctuations and very expensive.

BDS

The tight tolerance of the BDS to stray fields is mainly due to the bends of the collimation system as shown in Figure 5, where the sensitivity of the beam is shown along the BDS. If this area would be shielded, the field tolerances, shown in Figure 6, improve significantly by at least one order of magnitude compared to the unshielded case of Figure 4. An option for shielding is to use superconducting bends for this area, with a maximum field of only about 10 mT. In the cryostat of the bends one can then integrate a superconducting container that would shield external magnetic fields.

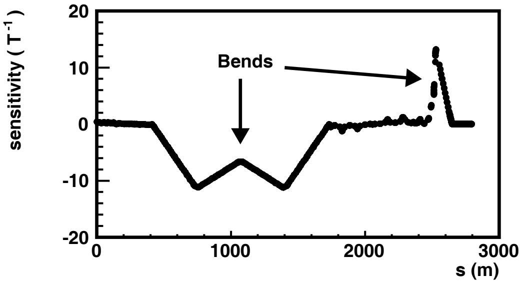

Figure 5: Point sensitivity function of the CLIC BDS.

Shielding the Sources

Another mitigation possibility is to reduce the stray fields at their origin, in particular those that come from technical sources. By eddy current and high permeability shielding the resulting external magnetic fields can be reduced significantly. Shielding the sources is easier compared to the beamline, because of stronger fields, smaller shielding surface and less spatial constraints. A shielding strategy should be investigated for each stray field source.

Active Compensation

An external active compensation system could be deployed. By using coils that generate an antiphasic magnetic field around the beamline, the stray fields can in theory be completely compensated for frequencies from DC up to several kHz. This has been demonstrated for particle beams at LIPSION with a final resolution of about 10 nT [8]. In more dedicated experiments sub-picotesla have been reached [9]. Integration in the tunnel has to be studied.

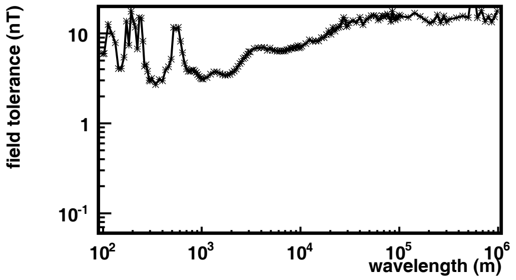

Figure 6: Stray field tolerance in the main linac and BDS for a 2% luminosity loss versus the wavelength (antisymmetric fields) with perfect shielding of the bend regions.

CONCLUSIONS

In this paper the sensitivity of several parts of the CLIC beamline to dynamic external magnetic fields (stray fields) has been discussed. It has been shown that the long transfer line is most sensitive to these fields, while also the BDS will be affected. The high sensitivity to the stray fields will require mitigation techniques, and several options have been discussed. A feed-forward system after the turnaround loop to correct the beam position is conceived to be essential. Furthermore, shielding of the individual magnetic field sources should significantly reduce the stray fields.

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