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RESISTIVE WALL EFFECTS IN THE CLIC BEAM DELIVERY SYSTEM

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Abstract

Resistive wall wakefields are an important issue to study for future linear colliders. Wakefields in the Beam Delivery System (BDS) might cause severe multi-bunch effects, leading to beam quality and luminosity losses. The resistive wall effects depend on the beam pipe apertures and materials, which are optimised to limit the impact on the beam. This paper presents a study of this issue for the 380 GeV and 3 TeV beam parameters and optics of the Compact Linear Collider's BDS. First, the resistive wall effect and the calculation of the beampipe apertures is shown, then the luminosity and its quality are presented. Finally, the proposed design parameters discussed.

INTRODUCTION

The Compact Linear Collider (CLIC) is a proposed future electron–positron collider with the potential to reach centre-of-mass energies in the TeV scale. The construction and physics programme is assumed to be carried out in three stages: at 380 GeV, 1.5 TeV, and 3 TeV [1].

The Beam Delivery System (BDS) transports electron and positron beams from the linacs to the Interaction Point (IP). First, the beam is cleaned in the energy and betatron collimation sections and then it is focused with the Final Focus System (FFS). The FFS is made of dipoles, quadrupoles and sextupoles that have been optimized to match the desired beam parameters at the IP. The total FFS length is 770 m at all energy stages [2]. An intra-pulse feedback system is installed on both sides of the CLIC detector, each consists of a Beam Position Monitor (BPM) and a kicker. It is designed to iteratively correct the incoming beam position within a single bunch train, with a goal to increase the luminosity with each iteration [3].

To achieve the desired high luminosity nanometre-scale bunch size with a population in the order of 10^9 particles, as well as bunch trains with a large number of bunches, are required. These intense charges give rise to resistive wall wakefields, which may cause significant multi-bunch effects leading to beam quality and luminosity losses.

The resistive wall wakefields pose a limitation on how small the vacuum chamber apertures can be. Larger apertures are not desired due to the increased costs of magnets and the increased complexity of assuring their field uniformity. In the CLIC BDS the use of room-temperature magnets is envisaged. This imposes a limit on the magnetic field in the magnet poles of around 1.5 T, which provides an upper limit on the allowable radii of the apertures. Any design of the apertures to minimise the resistive wall wakefield effect must fall between these two limits on radii.

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RESISTIVE WALL EFFECT

The resistive wall effect is a result of finite vacuum chamber conductivity. The surface current induced on the beampipe wall is delayed with respect to the source and can interact with the following charged particles over short- and long ranges.

In this study, the classical treatment of resistive wall wake was used, and only the fundamental transverse mode is considered, where thick walls, circular aperture shapes, and ultra-relativistic particles are assumed. The formula for the wake potential [4]:

$$W(z) = -L\frac{c}{\pi b^3}\sqrt{\frac{Z_0}{\pi \sigma_r z}}\left[\frac{V}{Cm}\right], \tag{1}$$

where: Z_0 - impedance of the vacuum: $1/\varepsilon_0 c$, z - longitudinal distance between the source and the impacted particle, σ_r - conductivity of the wall material, b - aperture radius, L - length of the considered accelerator element in which the wake propagates.

RESULTS

The bunch trains were created at the beginning of the BDS with a uniform offset of half of the RMS bunch size in both the horizontal and vertical directions for all bunches. Then PyHEADTAIL [5] was used to perform linear tracking through the BDS up to the interaction point (IP), taking into account the multi-bunch and resistive wall effects. The sensitivities to the effect was checked by calculating the luminosity in Guinea-Pig [6]. The scenario used assumed duplicating the beam that was transported through the BDS by PyHEADTAIL and centring one of the copies at (0,0) while leaving the other to remain fully impacted by the resistive wall wake. The statistics used in this study was 30 bunch trains. The conductivity numbers used were $5.96 \cdot 10^7$ S/m and $1.45 \cdot 10^6$ S/m for copper and stainless steel respectively.

The nominal apertures were calculated for each element along the BDS using the following formula:

$$R = max\{r_{min}, 1.1 + max\{15\sigma_x, 55\sigma_y\}\}, \tag{2}$$

where the minimal radius r_{min} was based on a previous study, and was equal to 6 mm at 3 TeV and 15 mm at centre-of-mass energy of 380 GeV, which was scaled from the 500 GeV design [7]. The beam sizes were calculated using:

$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\beta_{x,y} + (D_{x,y}\delta)^2}, \tag{3}$$

where: $\varepsilon_{x,y}$ - geometrical emittance, $\beta_{x,y}$ - beta function, $D_{x,y}$ - dispersion, δ - relative energy spread. The collimation depth of $15\sigma_x$ and $55\sigma_y$ was taken from a collimation study [8].

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The goal of this study is to have a comparable sensitivity to the resistive wall wakefield at both energy stages with a maximal luminosity loss in the order of 1%.

380 GeV CLIC

The aperture distribution along the BDS is shown in Fig. 1. The luminosity distributions along the bunch train where two materials: steel and copper are used for the vacuum chamber walls and compared to the case where there were no wakefields present are shown in Fig. 2. The luminosity loss when stainless steel is used shows a quickly decaying pattern and reaches 13% at the end of the bunch train. Therefore this material is not advised to be used for the inner walls of the vacuum chamber without any additional mitigation method. The luminosity distribution when a copper coating is used is less steep than for steel, and the loss reaches 2.5% in comparison to the no-wakefield hypothesis. These results suggest that there is a significant sensitivity present to the resistive wall effect in the current design of the BDS, which needs to be mitigated (see below).

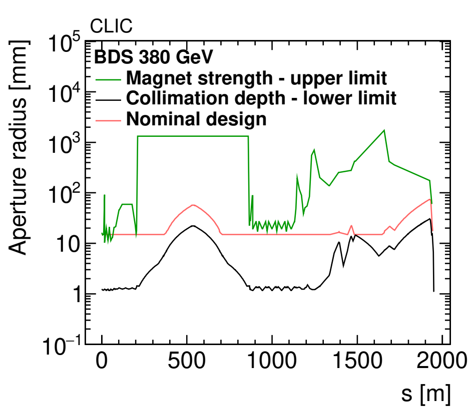

Figure 1: Apertures distribution in the CLIC Beam Delivery System at 380 GeV.

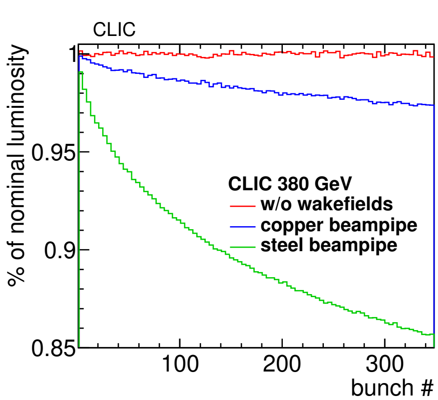

Figure 2: Luminosity distribution along the bunch train with copper and steel beampipes in CLIC BDS at 380 GeV.

3 TeV CLIC

The aperture distribution along the BDS is shown in Fig. 3. The simulated luminosity when copper and steel beam pipes are used and compared to the distribution when the wakefield does not impact the beams are shown in Fig. 4. The luminosity distribution along the bunch train when the copper coating is used shows a slowly decreasing trend. In this case, the luminosity loss reaches 1.2%. This suggests that the assumed minimum aperture radius of 6 mm is optimised and further mitigation of the effect is not required. The remaining loss can be restored using the intra-train feedback.

The use of a steel beampipe leads to a significant luminosity degradation, with a maximum luminosity loss of over 6%, and the emergence of a non-monotinic pattern where there is initially a trough, then the luminosity increases above the nominal value at the assumed offset, that is followed by a steep decrease. The higher rate of change in the luminosity distribution in comparison to when copper is used makes the luminosity more difficult to regain using the IP feedback system.

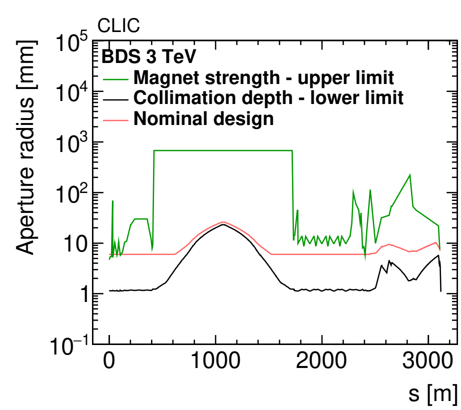

Figure 3: Apertures distribution in the CLIC Beam Delivery System at 3 TeV.

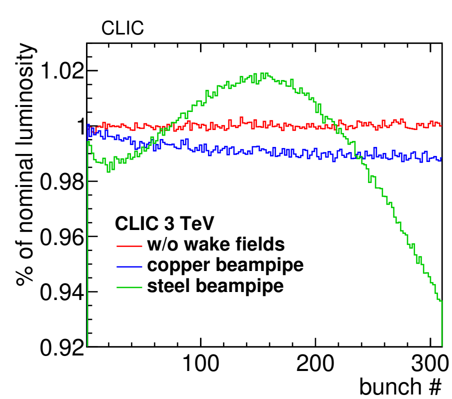

Figure 4: Luminosity distribution along the bunch train with copper and steel beampipes in CLIC BDS at 3 TeV.

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Mitigation

The found sensitivity to the resistive wall effect at 380 GeV can be addressed either by using a material with a higher conductivity or by increasing the aperture radii. The former does not offer a significant improvement in the already assumed simulation conditions, as the only metal more conductive than copper at room temperature is silver. The reduction in the wakefield amplitude, using Eq. (1), would be 2.7%, which would be insufficient mitigation.

Thus an increase in the aperture radii needs to be introduced. Using the formula from Eq. (1), one can calculate that an increase in the radius of 44% should lead to a decrease in the sensitivity by 66%, and limit the luminosity loss to 1%. The luminosity sensitivity to the wakefield impact concentrates in the FFS [9], and thus the aperture increase is proposed to be implemented between the beginning of the FFS and the final doublet. The extended apertures in the FFS are shown in Fig. 5.

The result of the luminosity performance simulation with the extended apertures is shown in Fig. 6. The 44% increase in aperture allows limiting the luminosity loss down to 1%. The 44% extension provides a satisfactory limitation of the lumininosity loss due to the resistive wall effect. The average vertical offset distributions at IP with both the nominal apertures design and the extended radii option for the FFS are shown in Fig. 7. The difference in offset between the first and last bunch for the nominal design is equal to 16% of the vertical bunch size of 2.9 nm and this number is reduced to 7% for the extended radius option.

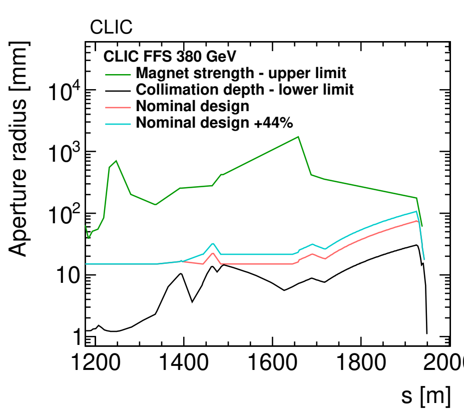

Figure 5: Extended apertures distribution in the Final Focus System at 380 GeV.

CONCLUSIONS

The impact of resistive wall wakes had been checked in the CLIC BDS. The beams at 380 GeV are sensitive to the resistive wall effect when the minimum aperture in the BDS are assumed at 15 mm. Using iron for the vacuum chamber walls leads to a significant luminosity loss and its use in the FFS is discouraged. With copper coating, the luminosity loss can be limited to 2.5%. This can be further reduced by increasing the aperture in FFS. An increase in radii by 44%

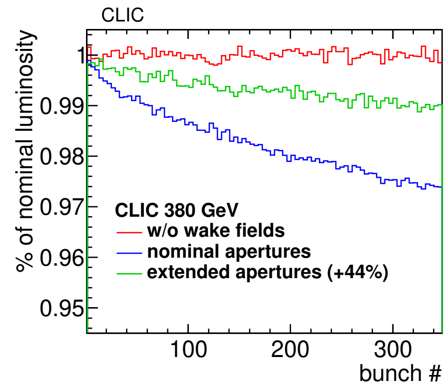

Figure 6: Luminosity distribution along the bunch train with increased apertures options.

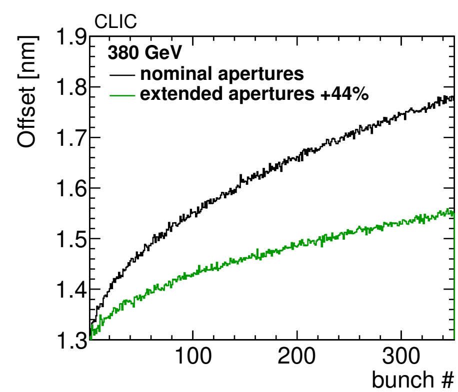

Figure 7: Average vertical offset at the interaction point along the bunch train, with two aperture options, the nominal apertures and the 44% extended option in Final Focus System.

limits the loss to below 1%. The offset distribution with the increased radii is in order of 10% beam size and could be mitigated by intra-train feedback allowing for further improvement.

The resistive wall effect at 3 TeV with a minimum aperture radius of 6 mm and copper beam pipe does not have a significant impact on the beam quality, with the luminosity loss within 1.2%. The remaining loss can be restored using intra-train feedback, and no further optimisation is required. The significant luminosity loss and its non-monotonic distribution makes the use of steel for vacuum chamber walls in the BDS at 3 TeV strongly discouraged.

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