# THERMAL AND MECHANICAL EFFECTS OF A CLIC BUNCH TRAIN HITTING A BERYLLIUM COLLIMATOR

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*Abstract*

Beryllium is being considered as an option material for the energy collimators in the CLIC Beam Delivery System. Its high electrical and thermal conductivity together with a large radiation length compared to other metals makes Beryllium an optimal candidate for a long tapered design collimator that will not generate high wakefields, which might degrade the orbit stability and dilute the beam emittance and, in case of the beam impacting the collimator temperature rises will not be sufficient enough to melt the metal. This paper shows results and conclusions from simulations of the impact of a CLIC bunch train hitting the collimator.

## INTRODUCTION

The Compact Linear Collider (CLIC) will collide beams with transverse energy density of the order of GJ/mm$^2$ resulting in a very high damage potential of the beam. Therefore, protection is necessary against mis-steered or errant beams, which can hit and damage components of the machine. In CLIC a postlinac energy collimation system is dedicated to intercept these mis-steered beams. This collimation system consists of a thin spoiler and a thick absorber downstream. The purpose of the spoiler is to increase the angular divergence of an incident beam. This increases the beam size at the downstream absorber and therefore reduces the risk of material damage in the absorber. The spoiler design has to survive the impact of the 312 bunches from the train. Each bunch is composed of 3.72E9 electrons at an energy of 1.5 TeV and needs to be made of a material that will not reach any dangerous temperature that could fracture, or melt, due to the energy deposited by the 156 ns of bunch train.

The spoiler effect on the beam during normal operation due to wakefield effects has to be reduced to a minimum. To achieve this, both the geometric as well as the resistive contributions to the wakefield need to be minimised. A geometry with shallow leading and trailing tapers is used to reduce the impact of the geometry contribution and a high conductive material is recommended for the latter one.

## NEW ENERGY COLLIMATOR SPOILER DESIGN REQUIREMENTS

To ensure the spoiling of the beam by Multiple Coulomb Scattering after hitting the spoiler the calculations presented in [1] show that it must traverse at least 0.007 radiation lengths ($X_0$) of material at any point.

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For CLIC a thin spoiler, 0.01 radiation lengths, made of beryllium, located at a position with non-zero horizontal dispersion equal to 0.27 m, and a thick downstream absorber (20 radiation lengths) are dedicated to protect against off-energy beams of about ±1.5 % of the nominal energy [2]. We have set the collimator aperture to intercept beam with energy deviation larger than 1.3 %.

Table 1: Overall parameters of CLIC for 3 TeV centre-of-mass energy.

| Parameter | Value |
|---|---|
| Centre-of-mass energy (TeV) | 3 |
| Particles/bunch at IP (x10$^9$) | 3.72 |
| Bunch/pulse | 312 |
| Bunch separation (ns) | 0.5 |
| Bunch train length (μs) | 0.156 |
| Unloaded/loaded gradient (MV/m) | 120/100 |
| Beam power/beam (MW) | 14 |

Fig. 1 and Table 2 describe all the different geometrical values used in the spoiler design. The flat part is changed from 0.5 $X_0$ from our previous design [3] to 0.01 $X_0$.

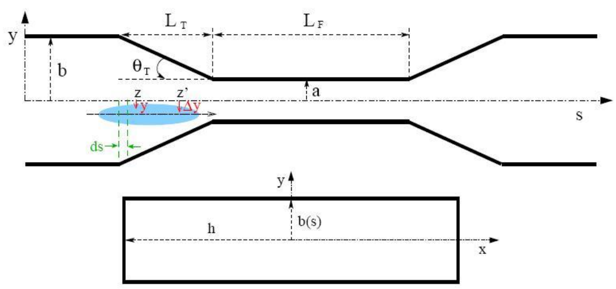


Figure 1: Longitudinal view of a tapered collimator. An oncoming particle bunch is schematically represented by the solid ellipse. Not to scale.

Table 2: Geometrical parameters of the CLIC energy spoiler.

| Parameter | Value |
|---|---|
| Vertical half gap $h$ [mm] | 8.0 |
| Horizontal half gap $a$ [mm] | 3.51 |
| Tapered part radius $b$ [mm] | 8.0 |
| Tapered part length $L_T$ [mm] | 90.0 |
| Taper angle $\theta_T$ [mrad] | 50.0 |
| Flat part length $L_F$ [$X_0$]/[mm] | 0.01/3.53 |

A spoiler model with 50 mrad taper angle and 0.01 $X_0$ made fully of beryllium, a material with good thermal and electrical properties, was used to simulate the energy density deposition a CLIC bunch train would generate using FLUKA [4, 5]. Table 1 summarizes the principal properties of a CLIC beam. The FLUKA output was transformed into a power density, using the bunch train length, and used as an input for an ANSYS [6] calculations.

## ENERGY DEPOSITION ON THE SPOILER DUE TO A BUNCH TRAIN HIT

The horizontal and vertical beam sizes at the spoiler's position are 796 and 21.9 microns respectively. The bunch train impact was simulated options using FLUKA. Fig. 2 shows the energy density deposition on the spoiler as the beam traverses it. A deep position for the beam was chosen, 4 mm from the top, to maximize the total amount of material that it would face in case of a worse case accident scenario. Fig. 3 shows the peaks of energy density along the beam track.

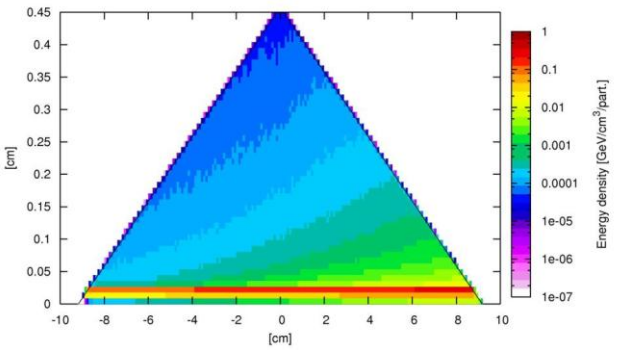


Figure 2: Energy density deposition normalised per incident particle for a CLIC beam hitting the spoiler.

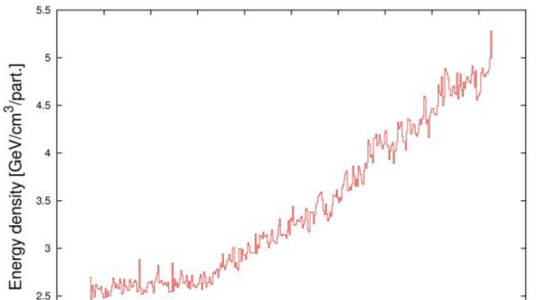


Figure 3: Peaks of energy density deposition normalised per incident particle a for a CLIC beam hitting the spoiler.

The peak of energy deposition happens in the edge of the trailing taper and is ~5.4 GeV/cm$^3$/part.; using the specific heat and density values of beryllium, shown in Table 3, and the total number of particles in a CLIC bunch train we obtain a temperature increment of around 300 °C.

An analytic formula often used to calculate how large an increment of temperature a material can withstand without cracking is:

$$\Delta T_{fr} \cong \frac{2 \cdot \sigma_{UTS}}{\alpha_T \cdot Y} \qquad (1)$$

Where $\sigma_{UTS}$ is the ultimate tensile strength, $\alpha_T$ is the thermal expansion coefficient and Y is the Young modulus of the material. A summary of some mechanical and thermal properties of the beryllium together with its $\Delta T_{fr}$ are given in Table 3. We can see how the 300 degrees of temperature increment we obtain from the simulation are above the $\Delta T_{fr}$ for beryllium.

Table 3: Summary of material properties for beryllium.

| | |
|---|---|
| $T_{melt}$ [K] | 1560 |
| Y [$10^5$ MPa] | 2.87 |
| $\alpha_T$ [$10^{-6}$ K$^{-1}$] | 11.3 |
| $\sigma_{UTS}$ [MPa] | 370 |
| $\Delta T_{fr}$ [K] | 228 |
| Yield Tensile Strength [MPa] | 240 |
| Yield Compressive Strength [MPa] | 270 |
| Specific Heat Capacity [J/g°C] | 1.925 |
| Density [g/cm$^3$] | 1.844 |

The Eq. 1 itself may be a good approximation to give the temperature at which the material may crack; however it is commonly used with quasi-static material data and for fatigue purposes. In this case we are not involved in a fatigue process but in a “one-time” accident scenario. It is known that when a beam hits a material the energy is deposited very quickly into it. This causes a rapid expansion of the material hence quasi-static material properties will not give an accurate answer, the materials under study need to be characterised dynamically in order to give more valid results.

## TRANSIENT ANALYSIS OF A CLIC TRAIN HITTING THE BERYLLIUM ENERGY SPOILER

The FLUKA output was transformed into an ANSYS input and applied in a spoiler model for a time of one bunch train (156 ns). The results of the stress calculations in the beryllium can be compared with the mechanical stress limits of the material by means of a certain failure criterion expressed by the equivalent stress value $\sigma_{eq}$, which can be defined as:

$$\sigma_{eq} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2} \qquad (2)$$

At a given position $\sigma_1$, $\sigma_2$ and $\sigma_3$, the first, second and third components of stress, which are the stress components in the three main directions of the given coordinate system, which in our case is Cartesian. Fig. 4

shows the equivalent stress on the spoiler body after the full CLIC train has hit it.

Fig. 5 shows the equivalent stress together with its first, second and third components of stress. Since $\sigma_{eq}$ is always a positive value it can be judged by the sign of the contributing stress components whether the material has to withstand a compressive or tensile load. Compression forces correspond to a negative sign in ANSYS results while tension forces correspond to a positive sign result.

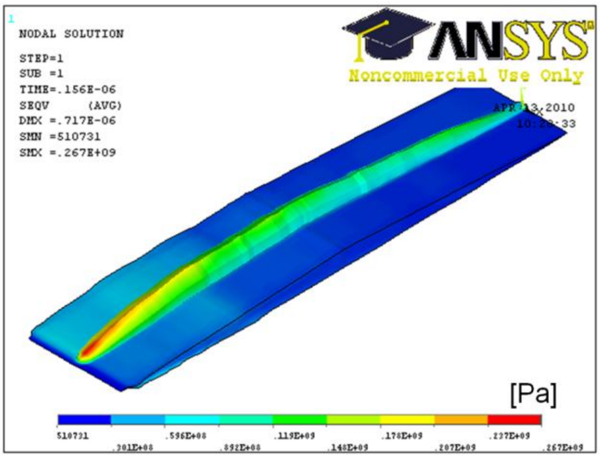


Figure 4: Equivalent stress on the spoiler body after a CLIC train hits it. The total time is one bunch train.

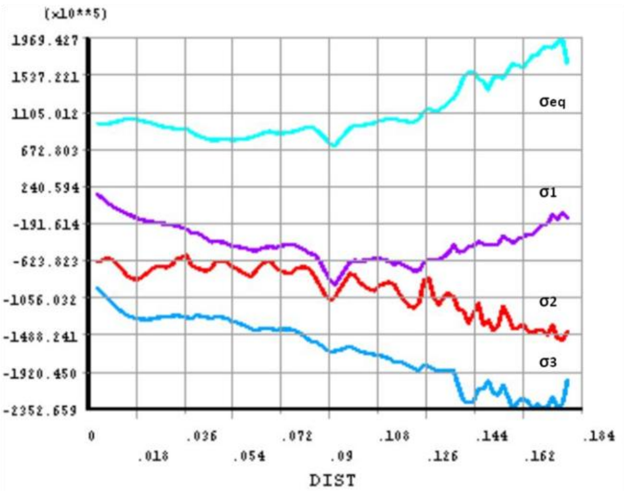


Figure 5: Equivalent stress ($\sigma_{eq}$), and its components ($\sigma_1$, $\sigma_2$, $\sigma_3$) along the path of the beam in the beryllium spoiler.

We obtain a top equivalent stress value of ~267 MPa, red area in Fig. 4 which ranges from 237 to 267 MPa. This stress is compressive and therefore we need to compare it with the Yield Compressive Strength given in Table 3 to assess if there would be any permanent deformation. We observe that we are just below it. We are also well below the ultimate tensile strength, which sets our limit for fractures. Therefore it all seems to indicate that the material would survive a bunch train hit without fracturing or suffering any permanent deformation.

## CONCLUSIONS

The ANSYS study performed to the new collimator geometry with the length for the flat top of $0.01X_0$ shows that a full CLIC bunch train hitting a beryllium spoiler will not imply any fracture. Nevertheless we need to take into account the fact that the study was performed for a perfect beryllium structure, i.e. without any imperfections or impurities in its structure that could act as a stress concentrator. This means that the beryllium samples will need to be tested to compressive stresses up to 200 MPa to assess their suitability for spoiler manufacturing.

## REFERENCES


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