THERMO-MECHANICAL STUDY OF A CLIC BUNCH TRAIN HITTING A BERYLLIUM ENERGY SPOILER MODEL

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Abstract

A thermo-mechanical study of the impact a CLIC bunch train over a beryllium energy spoiler has been made. Beryllium has a high electrical and thermal conductivity which together with a large radiation length compared to other metals makes it an optimal candidate for a long tapered design spoiler that will not generate high wakefields, which might degrade the orbit stability and affect the collider luminosity. This paper shows the progress made from the paper presented last year in IPAC10[1]. While in the aforementioned paper the study of the temperature and stress was made for the duration of the bunch train, the studies described in this paper show the evolution of the stress in the spoiler body 4 µs after the bunch train hit, which has implications to survival of the spoiler.

INTRODUCTION

A post-linac energy collimation system in CLIC is dedicated to intercept mis-steered beams which will have great potential of damaging machine components. 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 and needs to be made of a material that will not reach dangerous temperature that could fracture, or melt, due to the energy deposited by the 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. Therefore for this study we used a design made of beryllium, a material that combines good electrical and thermal properties.

ENERGY COLLIMATOR SPOILER DESIGN REQUIREMENTS

To ensure the spoiling of the beam by Multiple Coulomb Scattering after hitting the spoiler the calculations presented in [2] show that it must traverse at least 0.007 radiation lengths (X_0) of material at any point. A thin spoiler of 0.05 radiation lengths, made of beryllium and a thick downstream absorber (20 radiation lengths) are dedicated to protect against off-energy beams of about ±1.5 % of the nominal energy [3]. However these calculations have to be revised as simulations have shown that the absorber could reach melting temperatures in micrometric volumes after the bunch train being spoiled by 0.05 radiations lengths. Table 1 shows the main parameters of CLIC for 3 TeV centre-of-mass energy.

Table 1: Overall parameters of CLIC.

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 [4] to 0.05 X_0.

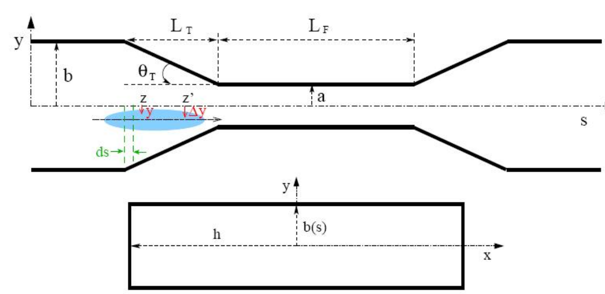

Figure 1: Longitudinal view of a tapered collimator. An oncoming particle bunch is schematically represented by the solid ellipse. Not to scale.

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 θ_T [mrad]	50.0
Flat part length L_F [X_0]/[mm]	0.05/17.65

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THERMO-MECHANICAL STUDIES

A spoiler model with 50 mrad taper angle and 0.05 X_0 made fully of beryllium was used to simulate the energy density deposition a CLIC bunch train would generate using FLUKA [5]. The FLUKA output was transformed into a power density, using the bunch train length, and used as an input for an ANSYS [6] calculations. The calculations shown in this paper are a continuation of the study presented in [1], where results of generated stresses inside the spoiler body were shown for the duration of the bunch train length only. A study of the evolution of these stresses inside the spoiler up to 4 µs after the bunch train length has left was performed and the results are shown below.

A summary of some mechanical and thermal properties of the beryllium are given in Table 3.

Table 3: Summary of material properties for beryllium.

Melting Temperature, T_{melt} [K]	1560
Young modulus, Y [10^5 MPa]	2.87
Thermal expansion coefficient, α_T [10^{-6} K^{-1}]	11.3
ultimate tensile strength, σ_{UTS} [MPa]	370
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 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 σ_{eq}, which can be defined as:

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

At a given position σ_1, σ_2 and σ_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. A positive value of these stress components indicates a tensile stress while a negative value corresponds to a compressive stress. Tensile stress is dangerous as it can potentially fracture the material. Compressive stress can deform it but not fracture it. However, a compressive stress can induce a response in the material body in the form of a tensile stress wave and that is why it is important to calculate the evolution of the stresses even after the thermal influence of the bunch train has gone and when these stress values have stabilized over a peak stress value.

Figure 2 shows the final equivalent stress values in the spoiler 3 µs after the bunch train left. The bunch train hit 0.2 mm from the bottom which represents a deviation from normal orbit of 10σ_x. The peak of stress is 950 MPa and, as shown in Figure 3, it is a tensile stress. From Table 3 we can see that this value is well above beryllium ultimate tensile strength limit (σ_{UTS}) and therefore we would have a fracture.

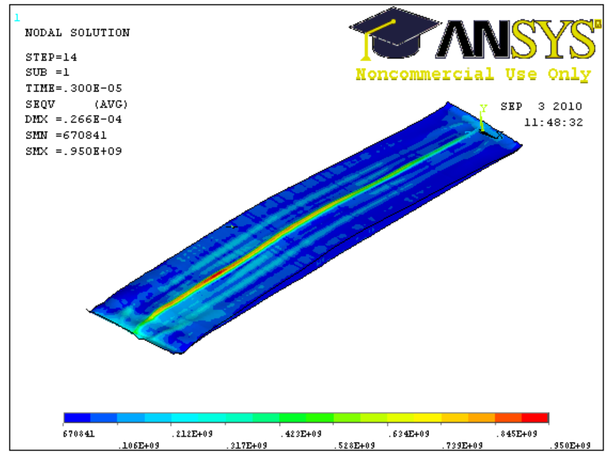

Figure 2: Equivalent stress in the beryllium spoiler 3 µs after the bunch train hit.

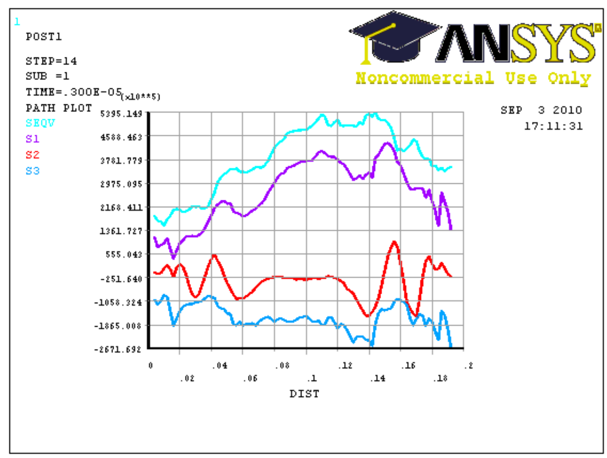

Figure 3: Equivalent stress (σ_{eq}), and its components (σ_1, σ_2, σ_3) along the path of the beam in the beryllium spoiler 3 µs after a bunch train hit. The main contributor to the stress is σ_1 and it is of tensile nature.

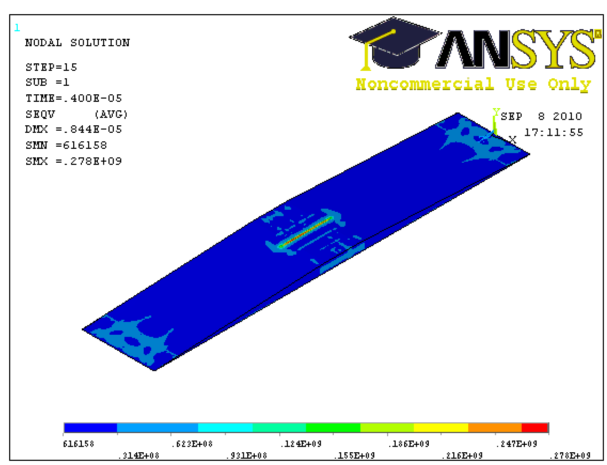

Figure 4: Equivalent stress in the beryllium spoiler 4 µs after the bunch train hit.

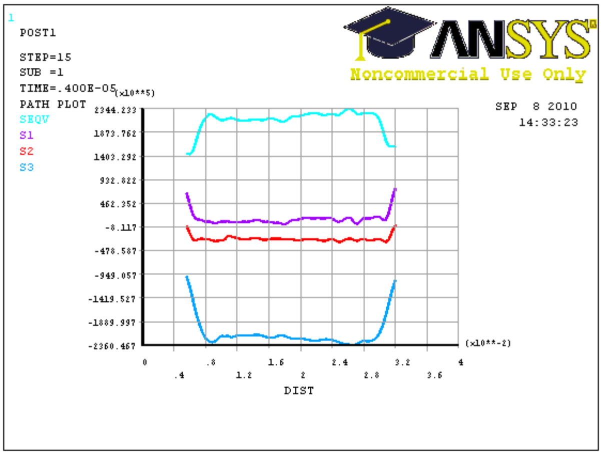

Figure 5: Equivalent stress (σ_{eq}), and its components (σ_1, σ_2, σ_3) along the path of the beam in the beryllium spoiler 4 μs after a bunch train hit. The main contributor to the stress is σ_3 and it is of compressive nature.

Figure 4 shows the equivalent stress on the spoiler body 4 μs after the full CLIC train has hit it 0.2 mm from the top. This represents a deviation of 4.75σ_x from the normal orbit. The peak stress is around 340 MPa and from Figure 5 we can see it is of a compressive nature. Therefore there will not be fracture. However, this value is higher than beryllium Yield Compressive Strength and in this case there will be a permanent deformation. FEA calculations indicate that this deformation would be around 5 μm representing a 0.1% of the gap distance

THE SILICON CARBIDE BODY OPTION

Silicon carbide (SiC) is a material with good thermo-mechanical properties. SiC will be used for LHC collimation phase 2 and it is used in Formula 1 brakes and aerospace applications. It can be used as a core material in its foam form for CLIC spoilers, coated with metal (beryllium in our case).

Table 4 shows a comparison of the different radiations lengths for different materials. The very long radiation length of the foam at 8% of nominal density allows for low energy deposition of the particle beam.

Table 4: Radiation lengths for different materials.

Material	Radiation length X_o [cm]
Copper	1.44
Ti alloy	3.56
Beryllium	35.3
SiC (solid)	8.1
SiC (foam 8%)	337

The advantages of such solution are the following: we ensure that the beam will always impact on 0.05X_o of beryllium without depending of the bunch train impact point, this solution also saves beryllium in the material budget. The disadvantages of such a solution comes mainly from the junction of the two different materials, SiC and Be, which may be mechanically challenging to produce. The different thermal properties can lead to dislocation or fracture of the junction when the bunch train hits. A single material spoiler is more robust in that aspect.

CONCLUSIONS

The study of the evolution of the stresses in the spoiler body has shown that in the case of a deep hit (i.e. 0.2 mm from the bottom) the initial compressive shock wave evolves into a tensile stress that will fracture the material and in the case of a shallower hit (i.e. 0.2 mm from the top) these stresses remain compressive in nature but nevertheless we would have some permanent deformation.

It would be very important to identify the failure modes and accident scenarios to know by how much the bunch train can be deviated from. If these studies reveal that the beam orbit cannot be deviated by more than ~5 σ's (could be more) then the full beryllium body would survive the impact of a bunch train.

Studies on how to attach the spoiler to its vacuum chamber are required to avoid concentration of tensions in the attached points. This is of critical importance as the spoiler could easily fracture in the union points with its mount.

Studies of using a SiC foam core would give us the maximum stress in the material junction and therefore tell us if it would survive a bunch train hit at any depth position.

These simulations and calculations, for the spoiler and the absorber, did not take into account the fact of an imperfect bunch train with energy dispersion and jitter and therefore could be too pessimistic. To be on the safe side for the absorber, incrementing the spoiling length would be advisable but that could mean that the spoiler would not be able to survive the bunch train impact.

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