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Spoilers in the ILC Beam Delivery System are required to survive without failure a minimum of 1-2 direct impacts from each energetic electron or positron bunch of charged particles, in addition to maintaining low geometric and resistive wall wake fields. The transient shock wave resulting from rapid localised beam heating and its implications for spoiler design are studied using ANSYS. Stress wave propagation is modelled in 2 dimensions showing the effect of dilatational shockwaves striking free surfaces, producing reflected dilatational and distortional waves. The implication of these reflected waves on the damage of the collimators is also discussed.

INTRODUCTION

The International Linear Collider (ILC) is a proposed electron positron Collider with planned collision energy of 500GeV and a possible upgrade to 1000GeV. The beam will be delivered in pulsed bunches, these bunches are of non-uniform distribution and have 'halo' particles which need to be removed to avoid unacceptable background readings in the detectors. To remove the halo particles the beam will be collimated in the beam delivery system. The baseline design requires two-part collimators made up of spoilers 0.5-1 radiation length thickness close to the beam, with downstream absorbers 30 radiation lengths thick. Occasionally errant bunches might hit the spoiler of a collimator, the baseline design requires that the spoilers can survive two bunches at 250GeV and 1 bunch at 500GeV [1] [2]. When a bunch strikes a collimator jaw it creates an electromagnetic cascade and deposits energy mainly through Bremsstrahlung and pair production [3]. The ILC bunch is tightly packed with energetic particles but only covers a small volume. When it strikes material this deposits energy very quickly within a small volume of material. The heated volume expands rapidly but is constrained by its own mass and that of the unheated volume of the spoiler. This creates stress, and a stress wave that propagates through the material. A further consideration is that of wake fields caused by the having the bunch passing so close to the spoiler. To reduce this a taper or curve needs to be incorporated into the spoiler [4].

PROTOTYPE COLLIMATORS

The requirements of having a constant radiation length of material and a tapered or curved surface can be considered to conflict. These are shown in Figure 1 a and b respectively. One possible solution to this problem has been considered here and is shown as figure 1 c. This is a hollow spoiler that manufacturing studies have shown can be manufactured using wire electrical discharge machining. This design has two main benefits the first being a near constant radiation length, so the heat deposition will be similar no matter where the collimator is hit. The second benefit is that the tapered profile reduces geometric wake field effects.

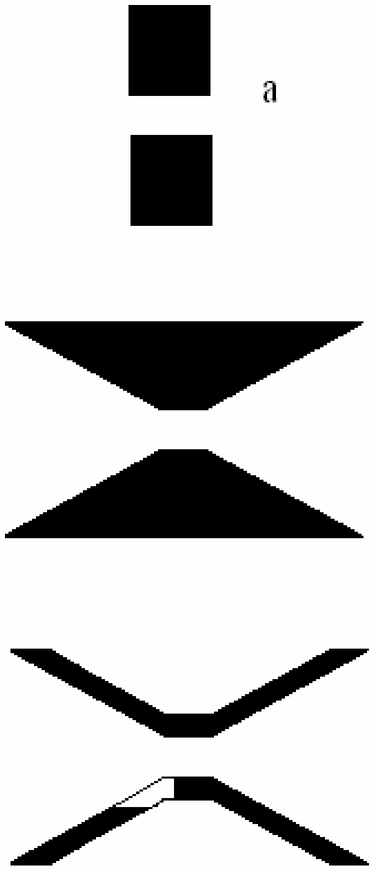

Figure 1: a) constant radiation length spoilers, b) tapered spoilers, c) hollow spoilers, highlighted region modelled in ANSYS

FINITE ELEMENT ANALYSIS OF PROTOTYPES

A basic 2D model was created using the finite element software ANSYS. To save computation time a small section of the collimator was modelled. This is the highlighted region in figure 1.c). This is an important region to model as it covers the transition from the tapered section of the spoiler to the flat top section. The material chosen was Ti-6Al-4V as this is a candidate material for the spoiler. The taper angle chosen was ~19°

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as this is similar to those recently tested for geometric wake fields. The model was meshed with an 8µm element size. Although it would have been possible to model the heat transfer in the material and the affect this had on the stress within the spoiler using a coupled field analysis, this was found not to be necessary as very little heat transfer takes place during the short timescales under consideration. Therefore, only the mechanical analysis was performed. The model has been assumed to be linearly elastic without yield or failure stress.

Boundary and Loading Conditions

The model was set to be in plane stress, all stresses are in the x-y plane displayed therefore the model is allowed to move in z. The bottom surface of the model was fixed in x and y. A small area of the spoiler approximately 3mm in x and 1µm in y was heated to a uniform temperature. This is an oversimplification as in reality the heated region would extend over a larger area but there would have a non uniform temperature gradient. This is a fair simplification because the maximum stress seen is a function of the maximum temperature rise, rather than the area or shape of the heated zone, and it would be inefficient to model these minor details [5]. The large aspect ratio of the heated zone would be a feature of an ILC beam strike due to the small spot size and high energy of the beam, and this has been modelled.

The heated zone was heated from 0°C to 300°C in 1ps, as this is the ILC bunch size. Previous work had indicated that 300°C is approximately the temperature that Ti-6Al-4V would reach. After this initial heating the model was allowed to run for 400ns, to watch the propagation of stress waves.

RESULTS

As the material was heated this produced thermal expansion within the heated zone. The heated region was constrained by its own mass and the mass of the unheated region surrounding. This leads to a compressive stress which passes from the heated region and propagates into the unheated region as a compressive wave. The compressive stress was 328MPa, as would be expected for a material with Modulus of Elasticity of 113.8GPa and thermal expansion coefficient of 9.8µm/m/°C.

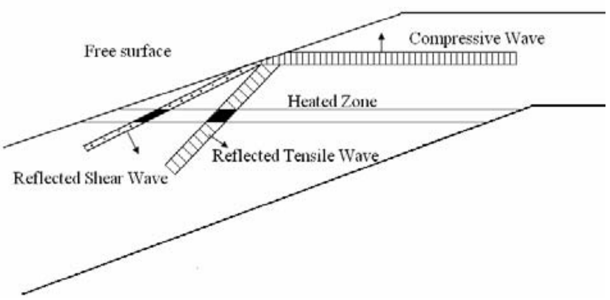

Figure 2: Schematic showing wave propagation, arrows indicate direction of each wave

Stress Waves at Free Boundaries

As had been seen previously when a compressive stress wave reaches a free boundary a tensile wave is reflected [5]. The angle of reflection of the tensile wave is equal to the angle of incidence of the compressive wave. However in this case a secondary shear wave was also reflected. This is shown in figure 2. This hadn't been seen in previous analyses because the boundary was always perpendicular to the stress wave direction. The maximum reflected tensile wave was 286MPa, and the shear stress wave was 56.2MPa. This shear stress wave is a transverse wave, whereas in the compressive and tensile waves the particle motion is longitudinal to the wave direction. This reflected shear wave needs to exist, at angles of incidence other than 0° and 90°, in order to satisfy the boundary conditions that the free surface is both free from shear and normal stresses; a more detailed explanation of this can be found in [6]. The angle at which the shear wave is reflected is related to the relative speeds of the two types of wave and is given by the equation below where c1 and c2 are the longitudinal and transverse wave speeds respectively and α_1 is the incident angle of the longitudinal wave.

$$\sin\beta_2 = \frac{c_1}{c_2}\times\sin\alpha_1$$

FRACTURES PRODUCED BY STRESS WAVES

Large stress pulses through materials can cause fracture. These fractures are different from those produced by static loading.. The maximum velocity of a propagating crack will always be a fraction of the longitudinal wave speed [7]. The heated area is small in comparison to the area of the rest of the spoiler and the heating is for a very short time period. This leads to a very short stress pulse propagating through the material. This short stress pulse acts on a material for a short period of time before passing, so any cracks formed do not have time to propagate far before the stress pulse has passed. This leads to a series of small cracks as opposed to one large crack that would be seen in a statically loaded structure. Materials are generally less strong in tension than in compression [8]. This can also cause failure of the spoiler. The initial stress wave generated will be compressive but could be beneath the compressive failure limit, but when it reaches a free surface it will be reflected back as a tensile wave. This tensile stress could be of a magnitude that is greater than the tensile failure stress, thus causing the spoiler to fail at a surface remote from the beam.

The creation of shear waves at the free surface could also lead to failure of the spoiler. Ductile materials fail in shear at lower shear stresses than the associated direct stresses (by the Von Mises effect). Thus the shear failure stress is lower than the direct failure stress [9]. A further concern is that the shear waves travel slower than the longitudinal waves, so any cracks formed will have longer to propagate before the stress is removed.

Additionally fracture may occur by reinforcement of several reflected pulses, even though each pulse itself would be below the failure criteria of the material. This phenomenon can be tracked using ANSYS so the spoiler design can be modified if this would appear to be a problem.

CONCLUSIONS

The ILC collimation system faces two main challenges, to collimate the beam without inducing unwanted wake field effects and to survive up to two beam strikes. The spoilers will have a tapered or curved profile. The beam strikes will lead to large amounts of energy being deposited in a small volume of the spoiler in a short period of time. This will lead to large compressive stresses and related stress waves. Once these stress waves reach the free surfaces they will be reflected back as tensile and shear waves. Both tensile and shear waves could cause fracture at lower stress level than a compressive wave would cause fracture. There is a danger of reinforcement of stress waves that could cause fracture. The fractures caused are likely to be different to those observed in statically loaded structures. It will be likely there will be many small fractures rather than one larger fracture running the length of the spoiler. From the work done so far it would appear that the ILC collimators will survive one bunch strike if it raised the temperature of the spoilers to a maximum of 300°C, this is approximately the temperature rise due to one bunch at 250GeV. Further work needs to be done to characterise these effects in the chosen material for the spoilers.

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