Linear Collider Collaboration Tech Notes

NLC Polarized Positron Photon Beam Target Thermal Structural Modeling

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Abstract: The NLC polarized positron photon beam target is a 0.4 radiation length thick titanium target. Energy deposition from one pulse occurs over 266 nanoseconds and results in heating of the target and pressure pulses straining the material. The 22.1 MeV photon beam has a spot size of 0.75 mm and results in a maximum temperature jump of 233 °C. Stresses are induced in the material from thermal expansion of the hotter material. Peak effective stresses reach 19 ksi (1.34x108 Pa), which is lower than the yield strength of a titanium alloy by a factor of six.

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THERMAL STRUCTURAL MODELING

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ABSTRACT

The NLC polarized positron photon beam target is a 0.4 radiation length thick titanium target. Energy deposition from one pulse occurs over 266 nano-seconds and results in heating of the target and pressure pulses straining the material. The 22.1 MeV photon beam has a spot size of 0.75 mm and results in a maximum temperature jump of 233 °C. Stresses are induced in the material from thermal expansion of the hotter material. Peak effective stresses reach 19 Ksi (1.34×10^8 Pa), which is lower than the yield strength of a titanium alloy by a factor of six.

INTRODUCTION

The next generation of linear colliders require positron beams at greater intensities than in previous collider designs. The NLC polarized positron design[1] utilizes a wiggler to generate a high energy photon beam. A thin titanium target (0.4 radiation lengths) placed in the path of the beam is used to convert the photons into positrons.

Peak shock stresses in the target and energy dissipation are major considerations in the design of the target.

To avoid excessive heating and to reduce thermal stresses in the target, the target is rotated to avoid individual pulses impinging on the same spot on the target. The beam pulses occur 120 times per second and the design goal is to rotate the target to maximize the time before beam pulses overlap on the same region of the target.
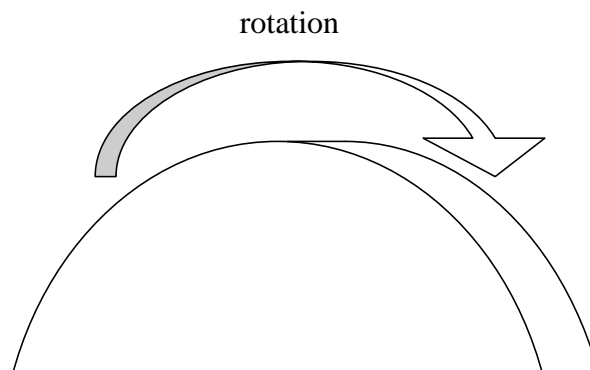
The energy deposition in the target is calculated using the EGS4[2] photon energy deposition code. The code calculates the volumetric rate of energy deposition as a function of axial and radial position along the beam trajectory.

The temperature response of the target due to the energy deposition is calculated with the LLNL three-dimensional finite element heat transfer code, Topaz3d[3].

The structural response of the target is calculated with the LLNL finite element dynamic structural analysis code, Dyna3d[4], which calculates material stresses from the thermal expansion of the material using a coefficient of thermal expansion and the temperature change calculated by Topaz3d. Stresses are calculated from relations of titanium material properties of stress and strain.

TARGET GEOMETRY

The NLC photon beam target, figure 1, is a rotating wheel of titanium alloy, with a thickness of 1.42 centimeters and a radius of 0.13 meters (5 inches). The wheel is rotated so that each individual beam pulse impacts a new spot region on the target.
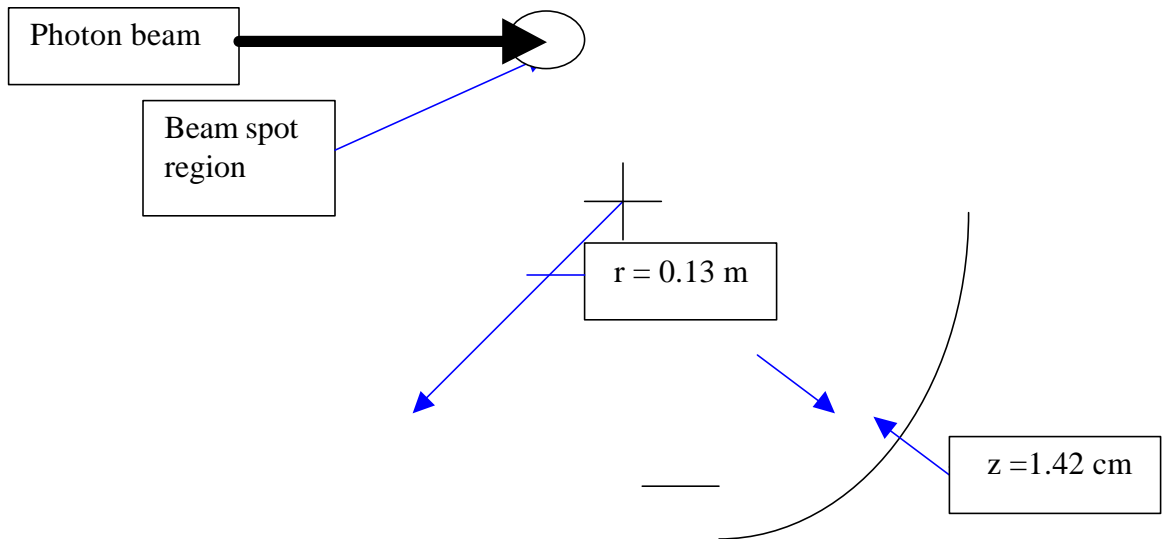
rotation

Figure 1. Target wheel schematic

PHOTON BEAM ENERGY DEPOSITION

The photon beam is produced using a K=1 undulator. The cutoff energy for the first harmonic radiation is 28 MeV and the average photon energy is 22.1 MeV. The full photon spectrum is used to calculate the energy deposition. The beam consists of 190 bunches per pulse, spaced 1.4 ns apart, with a pulse frequency of 120 hertz. The beam has a spot size radius of 0.75 mm. Table 1 lists beam parameters.

Table 1: NLC Positron Source Photon Beam

Parameter Name	Symbol	Value	Units
Undulator Type		Helical	
Undulator Parameter	K	1	#
First Harmonic Cutoff Energy	E_{c10}	28	MeV
Average γ Energy	$\langle E_\gamma \rangle$	22.1	MeV
Bunch Energy	U_b	3.8	J
Average Number of γ per Bunch	$n_{\gamma b}$	1.1×10^{12}	#
Number of Bunches per Pulse	N_b	190	#
Repetition Rate	f	120	Hz
Incident γ-beam size (rms)	$\sigma_x = \sigma_y$	0.75	mm
Target Material		Ti-alloy	
Target Thickness	L_T	0.40	Rad. Length

3

The energy deposition in the target is determined from the electromagnetic shower effect occurring as the photons pass through the titanium target[5]. The EGS4 electromagnetic shower code was used to model the problem and figure 2 shows a maximum energy deposition per gram of material of 1.5 J/g for an incident photon beam energy of 9.6 J. For the NLC photon beam paramenters, the NLC beam has an energy of 3.8 J per bunch and for 190 bunches/pulse the beam has an energy of 722 J per pulse, and a maximum energy deposition of 113 J/g per pulse. The energy deposition is maximum at the back side of the target along the centerline of the beam. The target was modeled with eight regions in the axial direction, with K=1 representing the first region as the beam enters the target and K=8 representing the last or back region of the target.
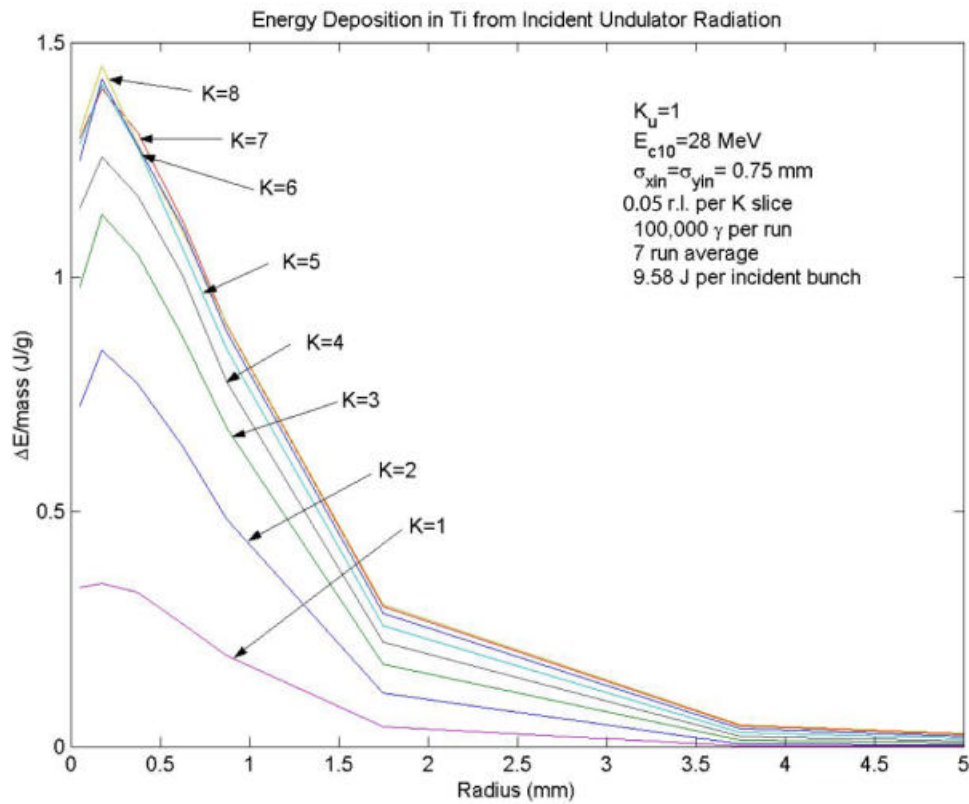

Figure 2. Energy deposition (J/g) in a titanium target[5] as a function of radius from the beam axial centerline, and axial distance for eight regions from the front (K=1) to the back (K=8).

THERMAL ANALYSES

The temperature profile in the target is modeled with an energy per unit volume heat source. The heat source mimics the Gaussian radial profile and axial profile shown in figure 2 and results in a maximum energy depositon of 113 J/g.

From material properties of density, specific heat, and thermal conductivity and the volumetric energy deposition rate, the temperature of the material is calculated. The time scale for the energy deposition (265 nanoseconds) is relatively small versus the time for any energy to conduct into the surrounding material. The temperature profile that exists in the material initially after 265 nanoseconds of pulse energy deposition is thus the profile that is used to determine the resultant material thermal stress. Over a time scale of seconds, the temperature and stress relax to low values until another pulse strikes the same region.

Material thermal properties assumed for the titanium alloy are given in table 2.

Table 2.   Typical Titanium alloy thermal properties

Property	Density, Kg/m^3	Specific heat, J/Kg°K	Thermal conductivity, W/m°K
Value	4,500	530	21

The energy deposition results in a spot region on the target that heats up from an initial assumed temperature of 30 °C to a peak value of 263 °C. Figure 3 shows the temperature profile on the back side of the target. Each mesh square in the z-x plane has a dimension of 0.38 mm. The temperature profile in cross section is shown in figure 4.
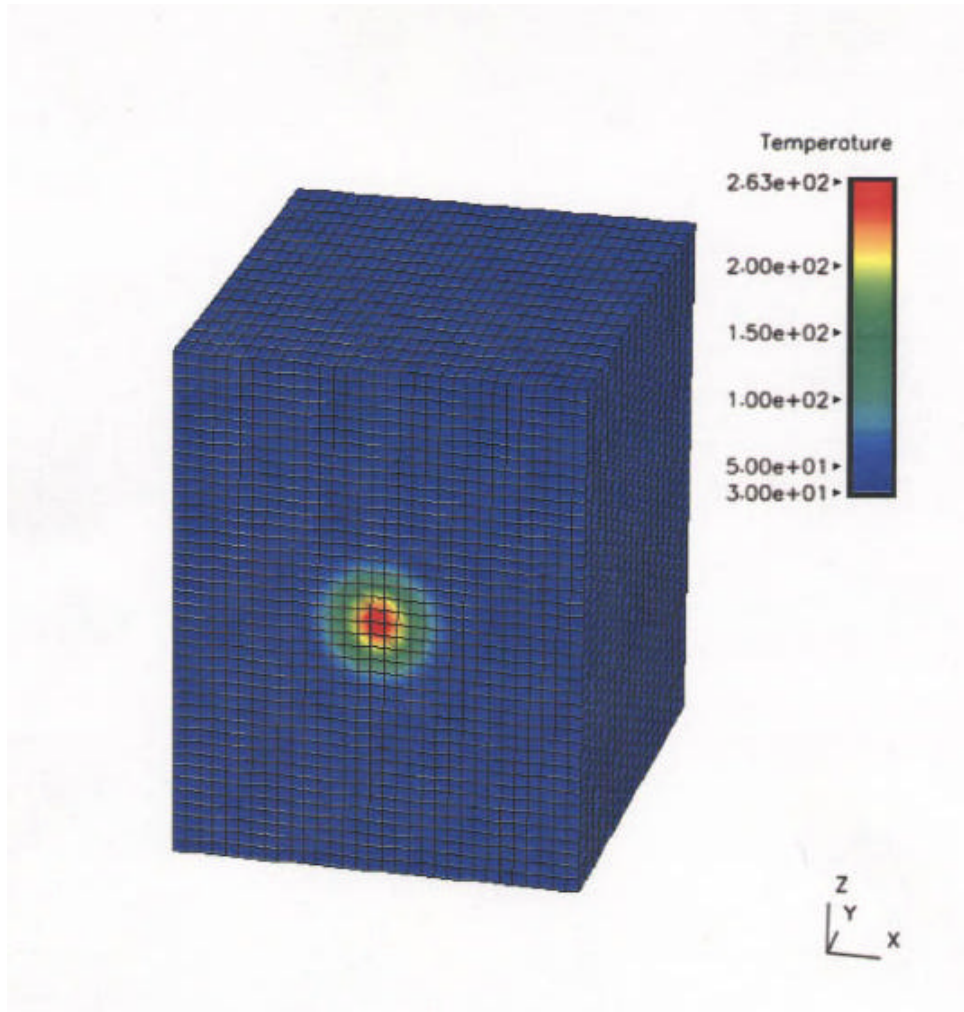
Figure 3. Target temperature profile, °C, from energy deposited by one
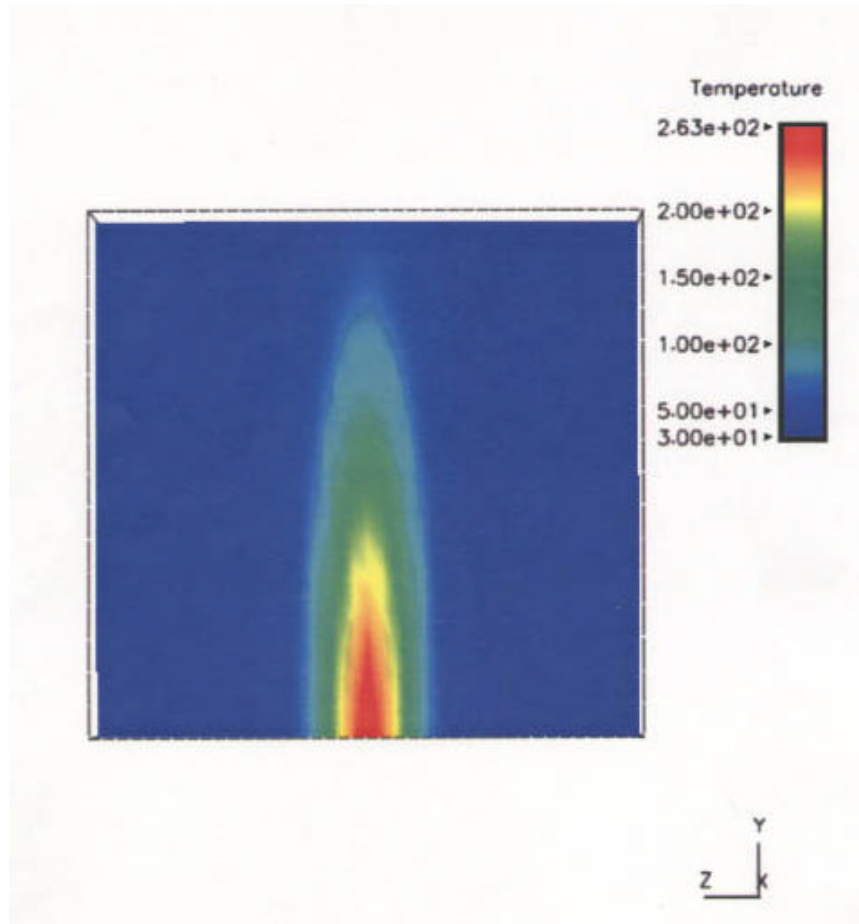Photon beam pulse.

Figure 4. Target temperature cross section, °C, after energy deposition from
one beam pulse.

STRUCTURAL ANALYSES

The heating of the target results in thermal expansion of the heated target material and pressure pulses traveling out from the heated region. The stresses resulting from the expansion are calculated using the LLNL three-dimensional finite element dynamic structural mechanics code, Dyna3d, with temperature input from the results of the Topaz3d thermal analyses. The Dyna3d code calculates the thermal expansion by use of a coefficient of thermal expansion and a change in target temperature. Stresses are determined from stress and strain relationships for the titanium material. For these analyses, a linear elastic material model is assumed.
The problem is modeled over a small rectangular portion of the target that includes the region that a beam pulse impinges upon.   Figure 5 shows the peak effective
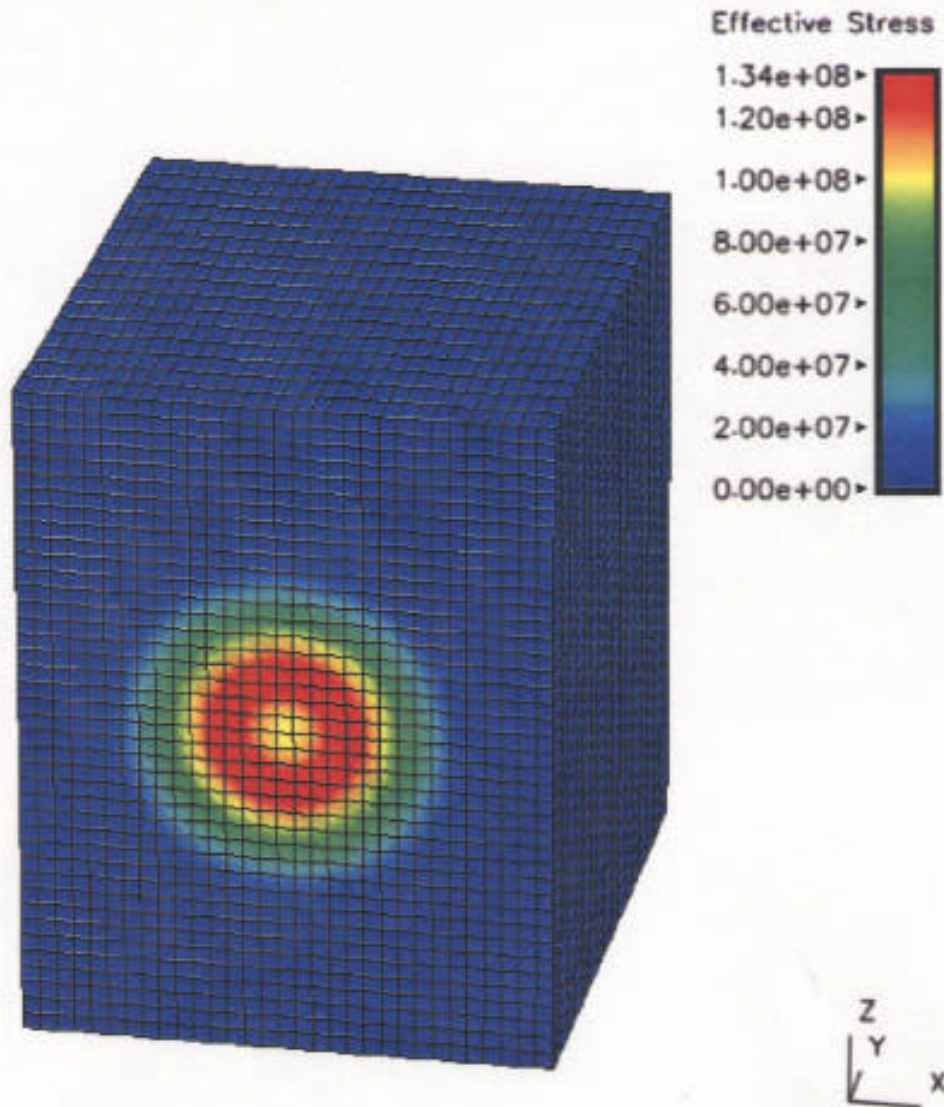
Figure 5. Peak effective stress (Pa) due to one beam pulse.

stress on the back side of the target with a value of 19 Ksi (1.34x10^{+8} Pa). This maximum value varies as the pressure pulses move in the target. Figure 6 shows a cross section of this peak effective stress. The effective Von Mises stress is a correlation of the stress components in the part that can be compared to material yield and strength properties. The yield strength of typical alpha-beta titanium alloys at a temperature of 263 °C is in the range of 90 to 110Ksi (6.2 to 7.6 x10^{+8} Pa). A time history of the peak effective stress, at a location on the back side of the target is shown in figure 7. The

pressure waves dissipate after several microseconds and the material goes into a semi-static lower level stress state due to the temperature induced strain in the material, figure 8, with a maximum effective stress of 11 ksi (7.71e+07 Pa).
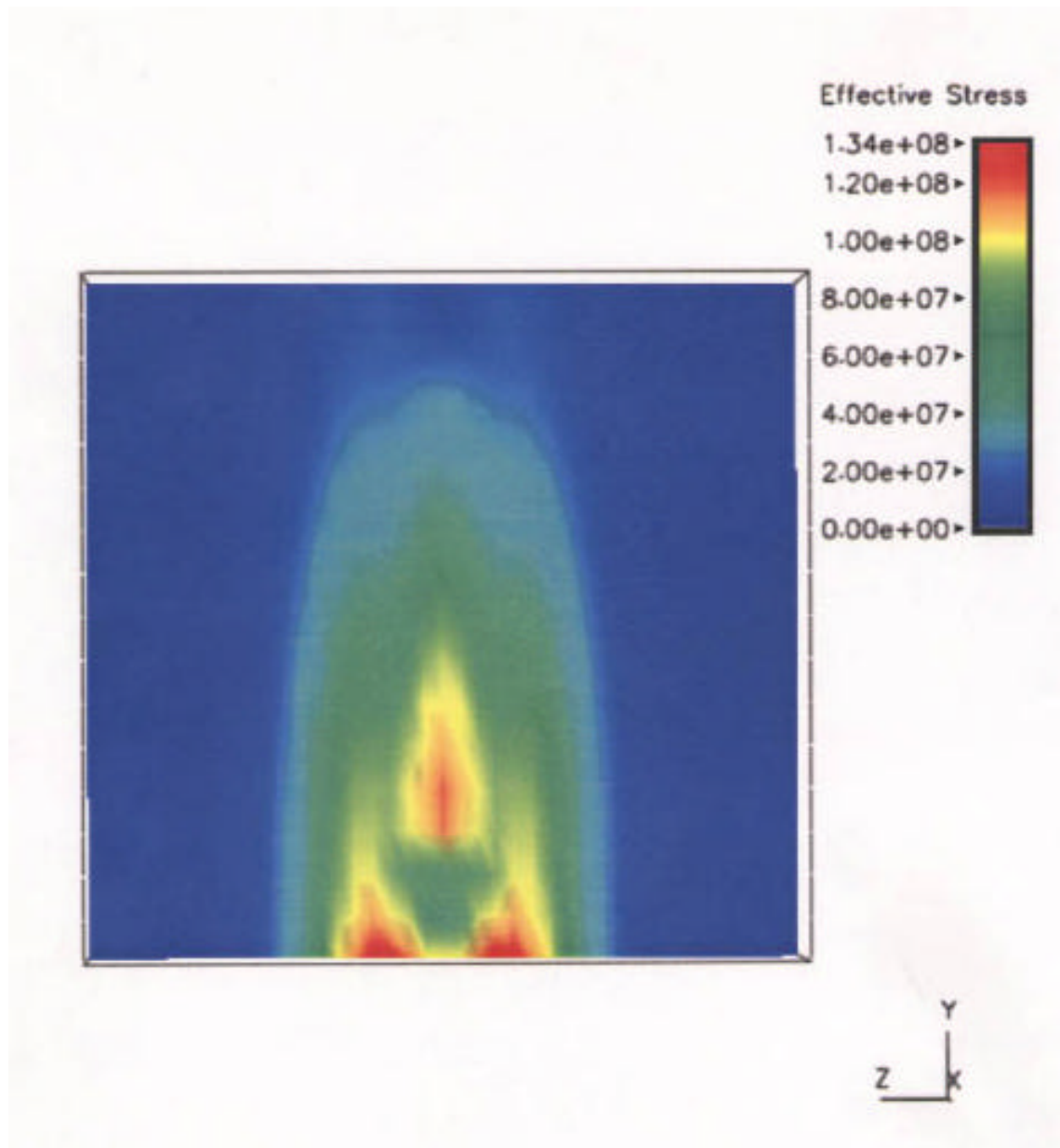

Figure 6. Cross section for the peak effective stress, Pa, shown in figure 5.
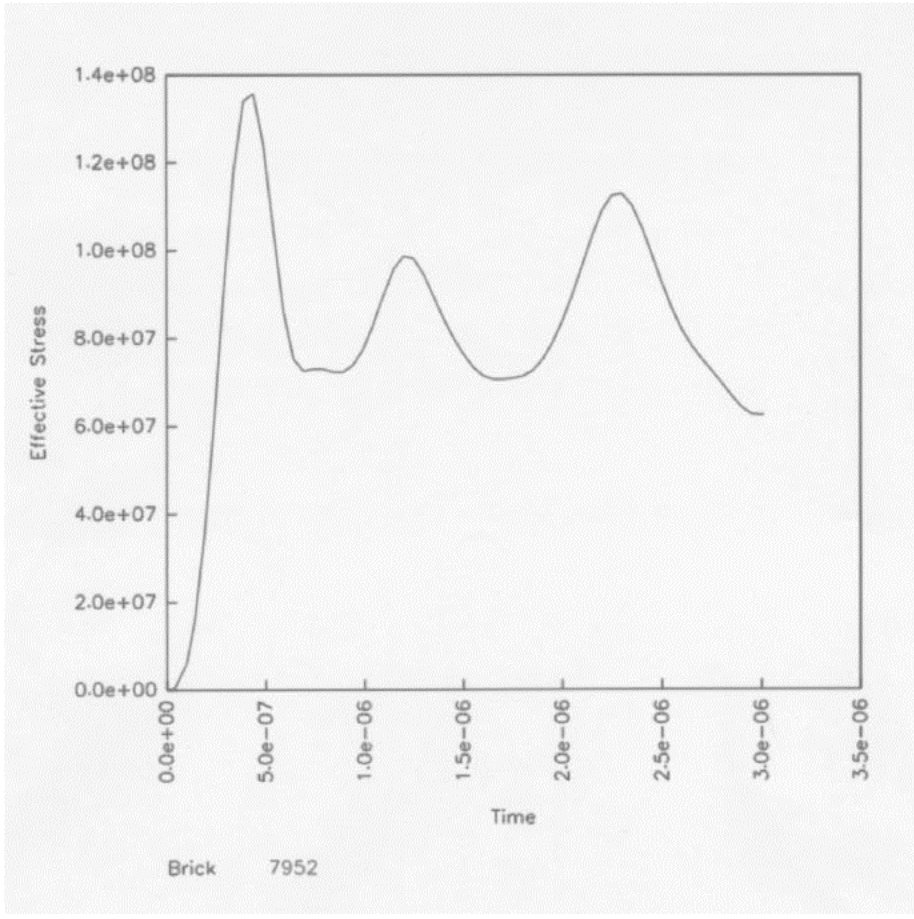
Figure 7. Maximum effective stress, Pa, versus time, s, on the back side of the target.
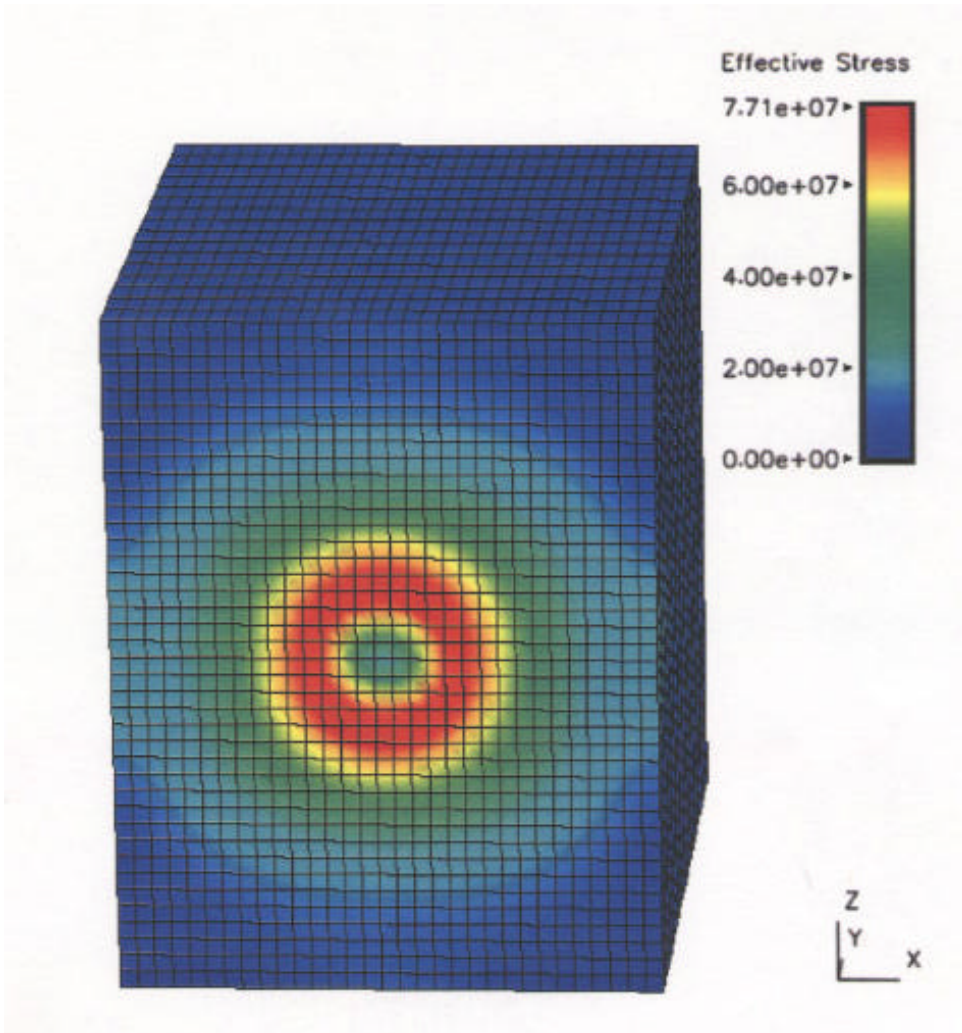
Figure 8. Steady state stress, Pa, in the target due to one beam pulse, after the pressure pulses have relaxed.

TITANIUM STRUCTURAL PROPERTIES

Structural properties assumed for the alpha-beta titanium alloy are given in Table 2. The alpha-beta titanium material contains a few percent of other elements such as aluminum and iron.

Table 2. Typical Titanium alloy structural properties.

property	Young's modulus, Psi (Pa)	Thermal coefficient of expansion, $°C^{-1}$	Poisson's ratio
Value	15×10^6 ($1 \times 10^{+11}$)	9×10^{-6}	0.3

SUMMARY

The above analyses presented information as to energy deposition in a target due to an impinging photon beam. The resultant thermal stress due to the thermal expansion of the target material is relatively low and about 0.2 of the material yield strength. Due to the cyclical nature of the beam pulses and the target stress, the material fails at a fatigue stress that is some fraction of the yield stress. Generally stresses below one third to one half of the yield stress may be considered adequate to avoid fatigue failure. For our case, the stresses are well below yield stress and low enough to avoid fatigue failure.

Other considerations that may affect target performance is radiation damage of the material due to the high energy photons impinging on the target and causing dislocation defects. The defects may cause brittleness in the material and may lead to lower fatigue failure stresses. One way to avoid this problem is to design the target so the beam exposure per unit volume of material is kept low and below normal radiation damage exposure levels.

REFERENCES

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