LCC-0090
UCRL-ID-148938
July 2002

Linear Collider Collaboration Tech Notes

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June 20, 2002

This work was performed under the auspices of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48 and by the Stanford Linear Accelerator Center under Contract No. DE-AC03-76SF0051

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Abstract

The power deposition of an incident multi slug electron beam in a tungsten-rhenium target and the resultant thermal shock stresses in the material have been modeled with a transient, dynamic, structural response finite element code. The Next Linear Collider electron beam is assumed split into two parts, with each part impinging on a 4 radiation lengths thick target. Two targets are required to avoid excessive thermal stresses in the targets. Each of the two beam parts is assumed broken up into four slugs, each two microseconds apart. Energy deposition from each slug occurs over 265 nanoseconds and results in heating of the target and pressure pulses straining the material. The rapid power deposition of the electron beam and the resultant temperature profile in the target generates stress and pressure waves in the material that are considerably larger than those calculated by a static analysis. The 6.22 GeV electron beam has a spot radius size of 1.6 mm and results in a maximum temperature jump of 438°C. Stress pressure pulses are induced in the material from the rapid thermal expansion of the hotter material with peak effective stresses reaching 78 Ksi (5.3×10^{8} Pa) on the back side of the target, which is less than one half of the yield strength of the tungsten/rhenium alloy and below the material fatigue limit.

A. Introduction

The next generation of linear colliders require positron beams at greater intensities than in previous collider designs. The NLC[1] positron design utilizes a wiggler to generate a high energy electron beam. A Tungsten-26%Rhenium target placed in the path of the beam is used to convert the electrons into positrons.

The NLC electron beam for these analyses is assumed split into two parts, with each part impinging on one of two targets. Two targets are required to avoid excessive heating and to reduce thermal stresses. Each of the two beam parts is further assumed broken up into four slugs, each two microseconds apart, to help mitigate the pressure pulse stresses of the target.

Peak thermal shock stresses in the target and energy dissipation are major considerations in the design of the target. The beam pulses occur 120 times per second and the design goal is to rotate each target to avoid excessive heating and to reduce thermal stresses and 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 stress pressure pulses from the thermal expansion of the material.

B. Target Description

Each NLC target, figure 1, consists of a 10 inch (254 mm) diameter ring of W-26Re, four radiation lengths thick (13 mm), surrounding an inner wheel of silver material. The target is cyclically rotated during operation in a way that the impinging beam pulses strike a different part of the target after every pulse.

The electron beam impinges on the target approximately 7 mm from the target outside edge. Each pulse of electrons causes a large increase in temperature in a local spot on the target.

The target is cooled by water cooled tubes imbedded in the silver material, and they maintain the tungsten-rhenium target at a nominal 315 °C[5]. This temperature can be readily decreased by 100°C by changes in target size and/or cooling tube arrangement. To avoid ductile/brittle temperature transition problems with the material, a nominal minimum temperature of 200°C should be maintained in the target. During daily beam shut down times, some external heating may be required. The individual spots on the target heat up an additional maximum amount of 438 °C to 753°C and relax back down to the 315 °C temperature before another electron pulse impinges.

The time scales of this problem are such that the target material, where the beam impinges, heats up in 265 nanoseconds and this temperature profile essentially doesn't relax until seconds have elapsed. Thermal stress wave effects are initiated from the nanosecond initial pulse and relax to a steady stress state after several microseconds. After a time period of seconds, however, the spot temperature profile and the thermal stresses have essentially relaxed down to the nominal disc steady state temperature of 315 °C and a near zero stress state.

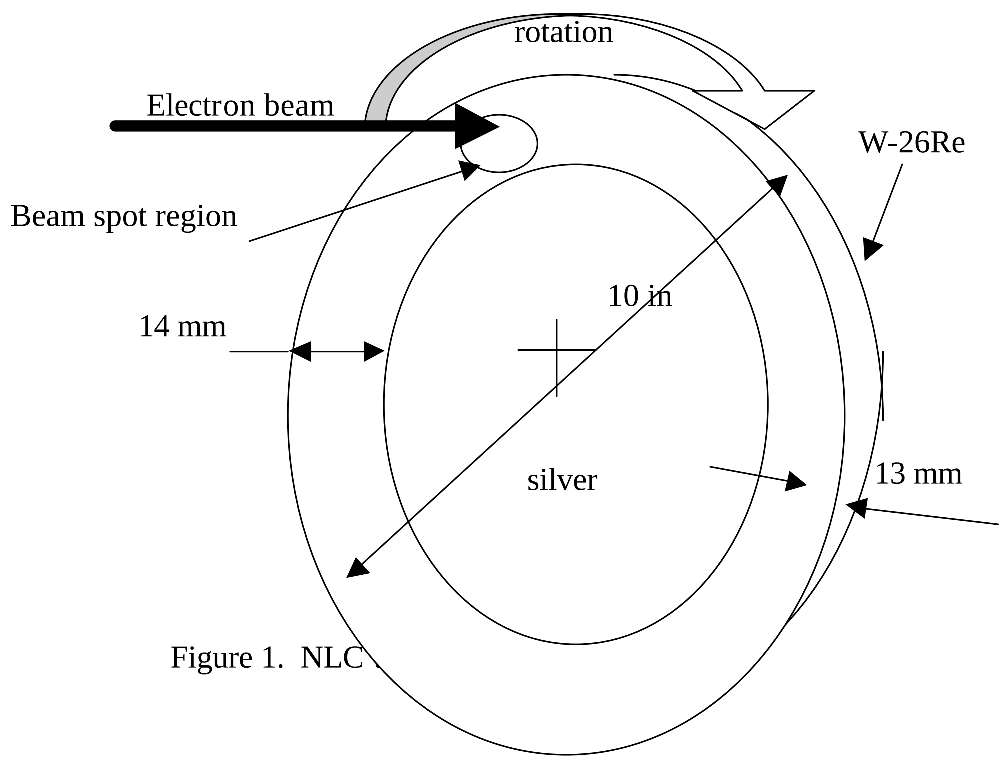


Figure 1. NLC

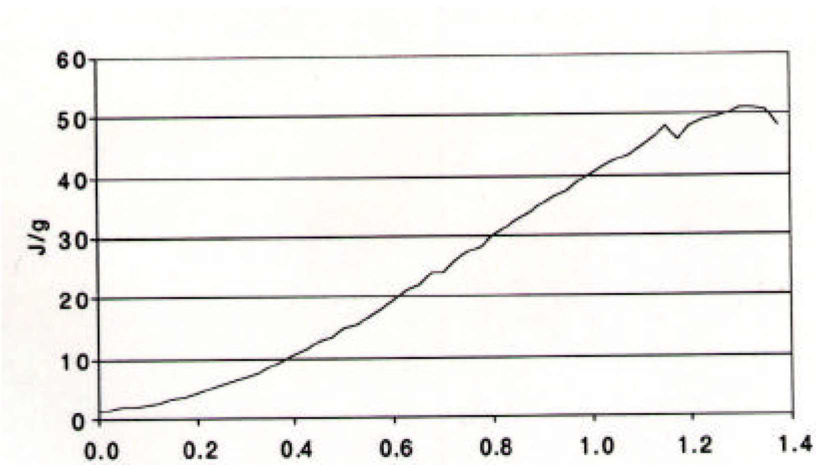
C. Analyses

The analyses are described in the following steps. The first step consists of defining the beam energy deposition as a function of radial and axial position and time for use in determining the temperature distribution in the target. The second step describes the thermal analyses due to the pulse and the third step describes the transient dynamic structural modeling.

a. Beam energy deposition

The SLAC EGS4 shower code was used to determine the energy deposition profile[6]. Figure 2 shows the energy deposition per gram of material profile along the beam centerline into the material for $95x10^{10}$ electrons per bunch. The energy deposition has a radial Gaussian profile with a spot radius size of 1.6 mm. The full NLC beam is composed of 190 bunches of electrons per pulse, each bunch is spaced 1.4 nanoseconds apart, with a pulse frequency 120 pulses per second. Each pulse contains $2.28x10^{12}$ electrons and corresponds to a maximum energy deposition of 125 J/g. The maximum energy deposition occurs on the back side of the targets, along the beam centerline. The average power deposited by the beam in the targets is approximately 37 kW.

The NLC electron beam is assumed split into two parts, with each part impinging on a 4 radiation lengths thick target. Each of the two beam parts is assumed broken up into four slugs, each two microseconds apart. The power absorbed by each target is assumed to be 20 kW, corresponding to $1.2\ x10^{12}$ electrons per bunch, and the maximum energy deposition in a target is 66 J/g. The two targets can thus absorb more than the full NLC beam.



Target depth, cm.

Figure 2. Target energy depostion, J/g, along beam centerline for $9.5x10^{+10}$ electrons at 6.2 GeV, 1.6 mm sigma radius.

b. Thermal Analyses

The temperature profile in the target is modeled with an energy per unit volume heat source. The heat source mimics the beam Gaussian radial profile and the axial profile shown in figure 2 for the case of a maximum energy deposition of 66 J/g.

From material properties, table 1, of density, specific heat, and thermal conductivity and the volumetric energy deposition rate, the temperature of the material is calculated using the LLNL three-dimensional finite element heat transfer code, Topaz3d. 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.

Table 1. Tungsten-26%Rhenium thermal properties.

property			
Temperature, °C	0	500	1000
Density, Kg/m^3	19800	19800	19800
Specific heat, J/Kg°C	135	149	165
Thermal conductivity, J/m^2°C	68	67	66

Figure 3 shows a temperature profile through the target after four slugs of one pulse have deposited their energy in the target. Figure 4 shows the peak temperatures calculated on the back side of the target from the energy deposited by the four slugs of one pulse. The target peak temperature increases by 438°C, from an assumed initial temperature of 315 °C to a spot peak temperature of 753°C.

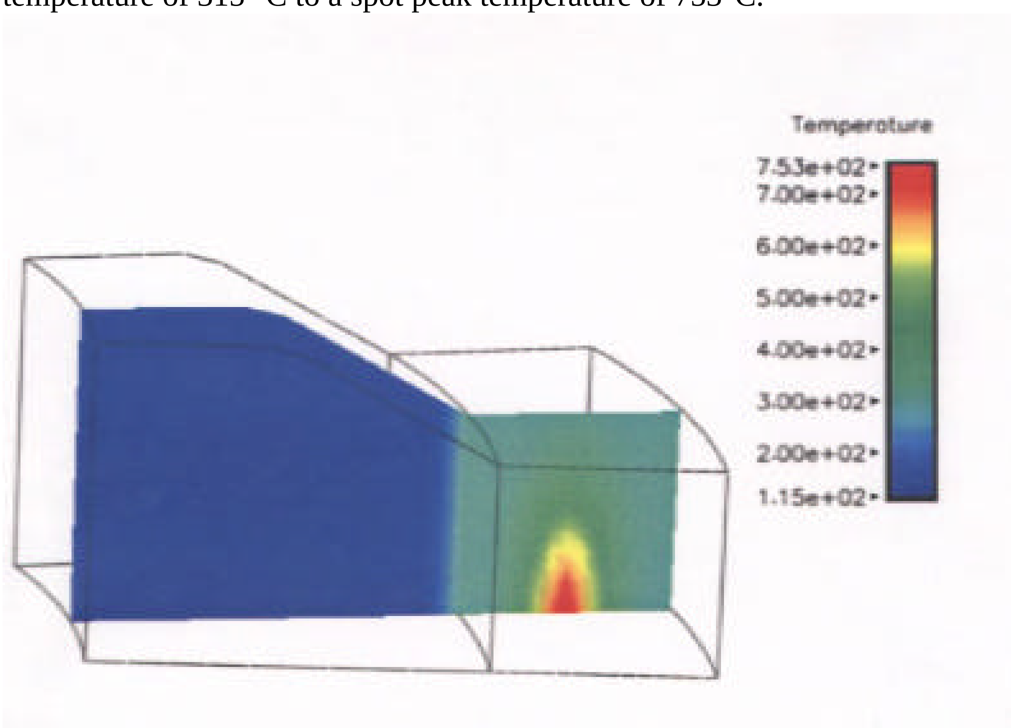


Figure 3. Target temperature, °C, cross-section after one beam pulse.

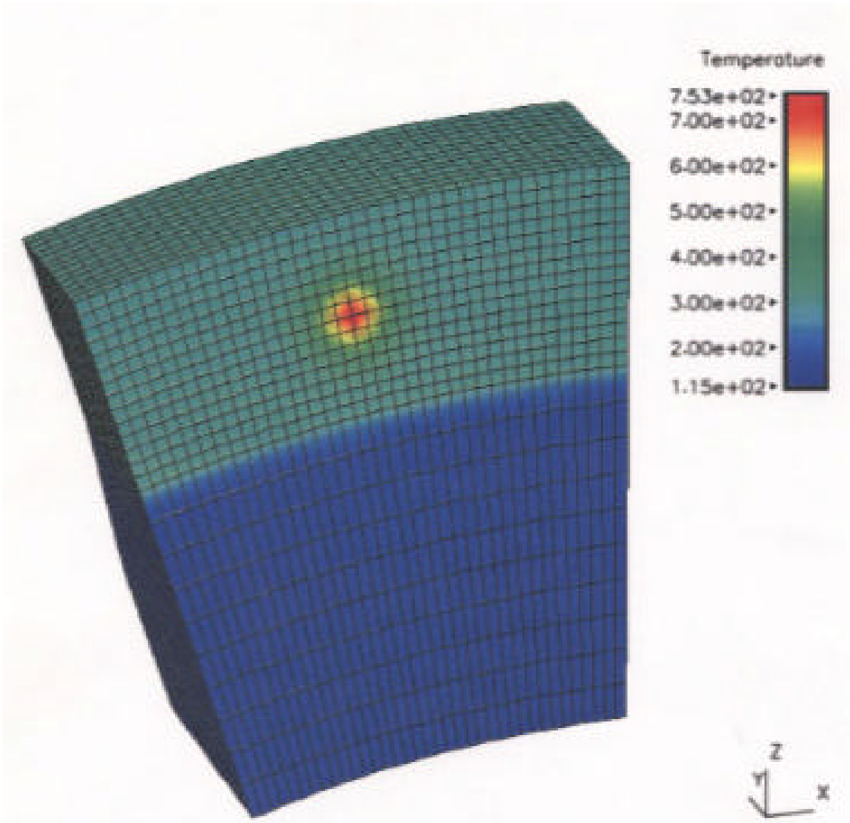
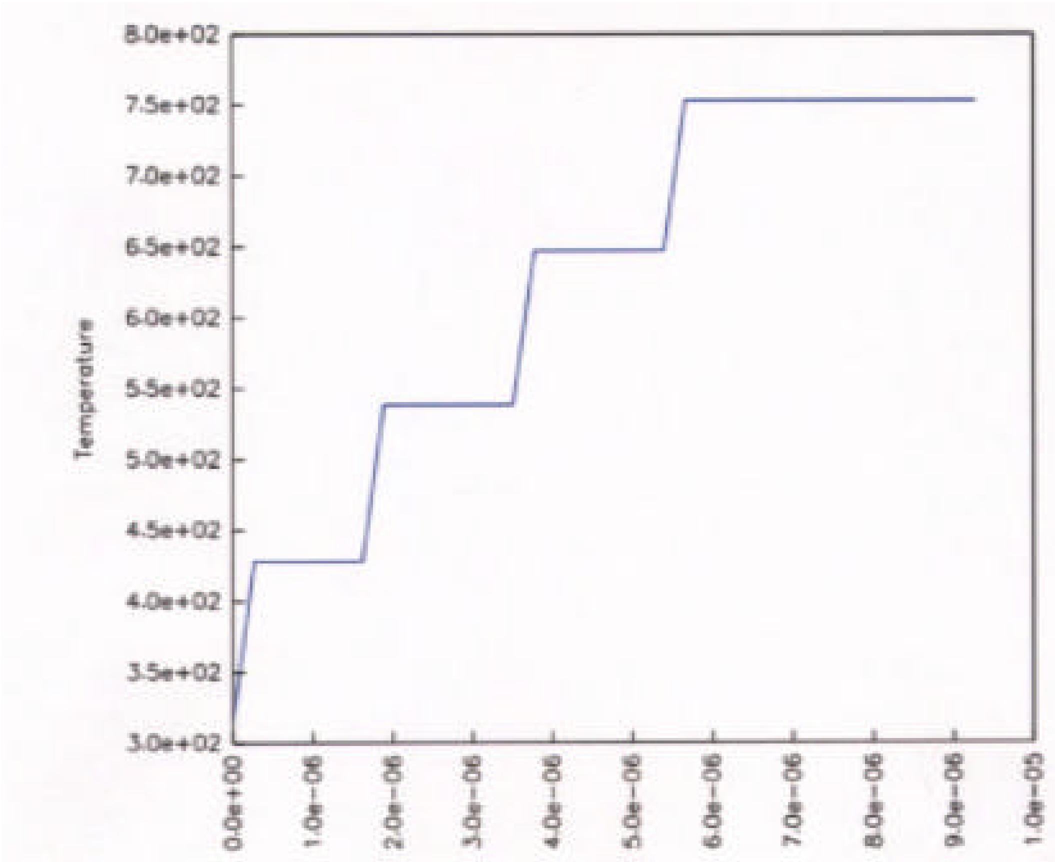


Figure 4. NLC target temperature, °C, contour due to four slugs of one pulse of the impinging electron beam.

The temperature in the target jumps by 110°C after each of the four slugs hits the target. Figure 5 shows a plot of peak target temperature versus time for the four slugs impinging on the target.

c. Structural modeling

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 tungsten/rhenium material.



Time, seconds

Figure 5. Peak target temperature, °C, versus time, s, due to four impinging slugs for one pulse of electrons.

The structural modeling requires developing a calculational mesh of sufficient detail to allow the code to model the physics of the problem. The mesh, shown in figure 4, models a slice of the target disc, including the silver on the inside region of the tungsten-rhenium ring.

The materials in the problem are modeled with a temperature dependent elastic-plastic material model. Properties specified include the elastic modulus, Poisson's ratio, secant coefficient of thermal expansion, yield stress, and plastic modulus and are shown in table 2.

For these analyses, the structural response of the target to one pulse is so fast, less than several microseconds, that only the thermal shock results for one spot location needs to be analyzed. Before a next adjacent spot is impinged upon, 1/120 seconds have elapsed and the previous shock pulses have dissipated and the new spot location does not appreciably affect the adjacent spot temperature or stress state.

Table 2. Tungsten-26 Rhenium material structural properties.

Property			
Temperature	0.0 °C	500.0 °C	1000.0 °C
Modulus, Pa	4.30E+11	4.02E+11	3.95E+11
Poisson's ratio	0.28	0.28	0.28
Secant coef. of thermal exp., C^{-1}	6.66E-06	7.06E-06	7.95E-06
Yield stress, Pa	1.6e+09	1.25e+09	9.0e+08

The rapid beam energy deposition results in stresses that are greatest at the target location where the beam shower exits the target. Von Mises stress is a good measure of the proximity to failure of a material with values below material yield stress usually indicating structural integrity.

Figure 6 shows a contour color plot of the peak Von Mises stress attained on the back side of the target at the impinging beam location. The figure shows a peak value of 5.3e+08 Pa (78 ksi) at a time after the four beam slugs have just impinged on the target.

The structural response of the target material due to the rapid heating of the material results in pressure waves propagating out from the beam location. The material initially goes into a relatively high state of compression followed by a tension stress condition. The pressure waves dissipate somewhat after two microseconds and another slug of electrons again impinges on the target and another set of pressure pulse stresses are added to the previous slug stress condition. The effective stress response in figures 6 is applicable for the time after the four slugs have impinged on the target and represents the highest pressure pulse stress. A plot of Von Mises effective pressure pulse stress at the most severe location on the back side of the target versus time is shown in Figure 7. The material goes into a semi-static lower level stress state after the pulse is done due to the temperature induced strain in the material, figure 8, with a maximum effective stress of 67 ksi (4.6e+08 Pa).

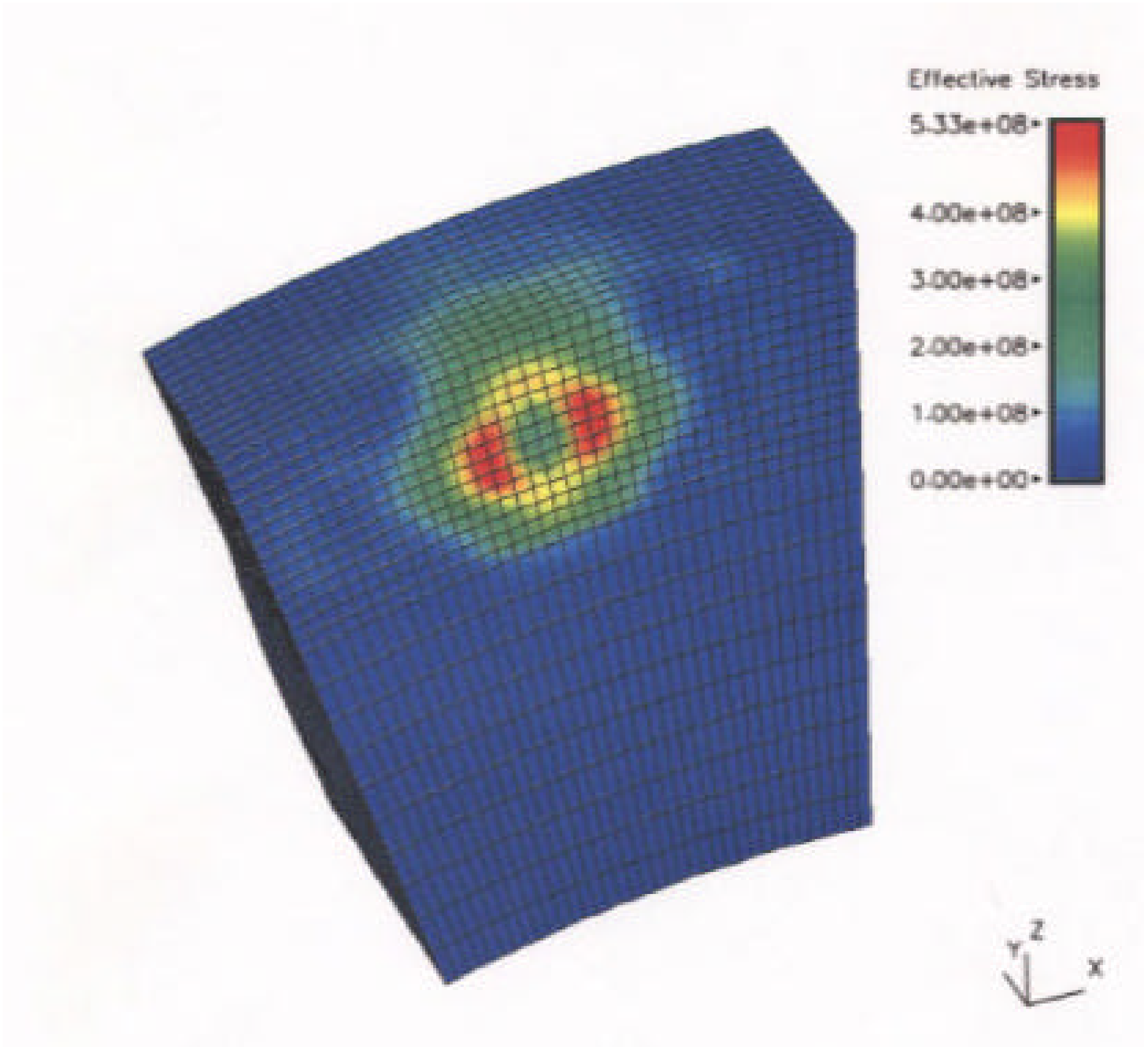


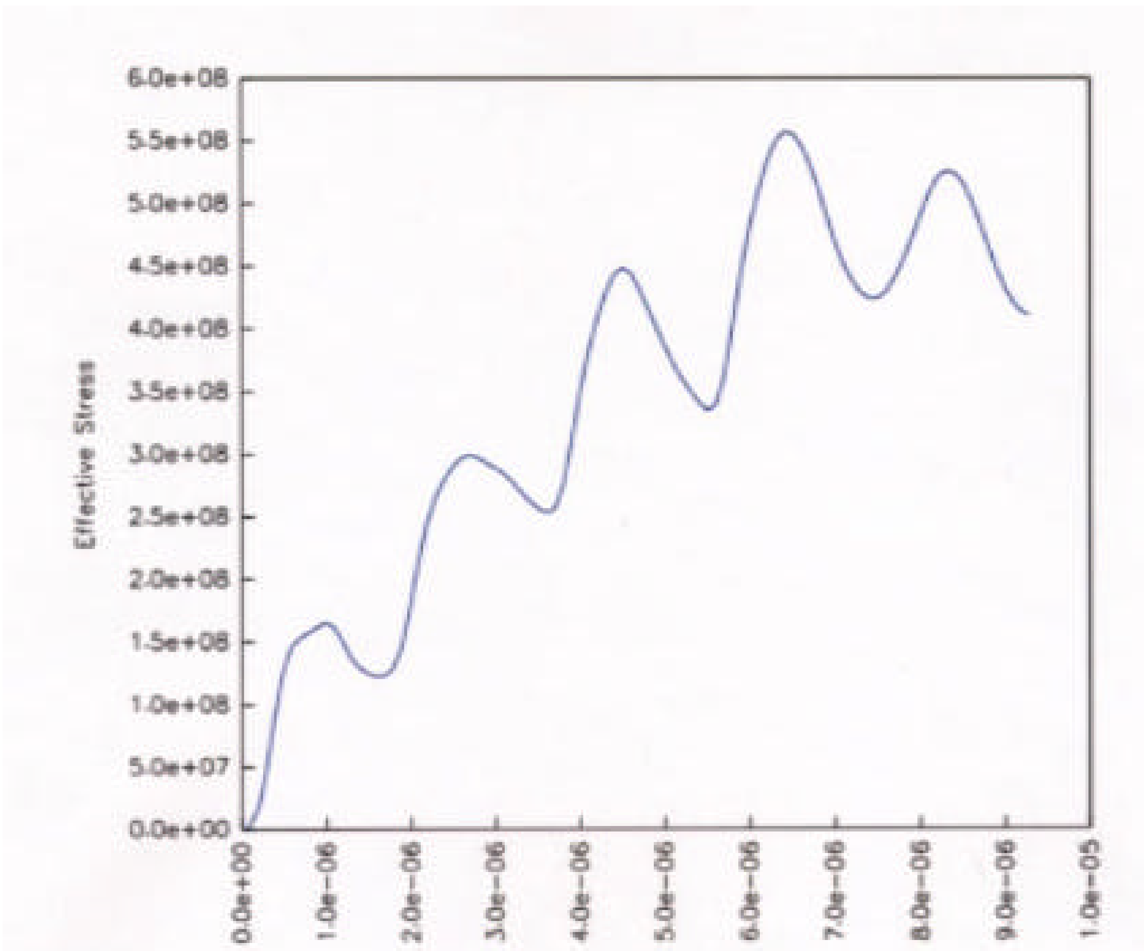
Figure 6. Peak Von Mises stress, Pa, in the target after four slugs of one pulse have just impinged on the target.

D. Conclusions and discussion

The thermal structural response of an NLC target due to a split, multi slug beam was investigated. The four slugs per pulse case was investigated because the time spacing of the slugs was expected to result in lower level pressure pulse stresses in the target. The analyses showed that only two targets were required to absorb the full NLC electron beam.

The analyses show that stresses do not exceed material yield stress. Due to the cyclical nature of the beam energy deposition, failure due to material fatigue must also be considered and may occur at stresses below yield. A general criteria of fatigue failure due to a Von Mises stress of 50 % of yield strength may apply to this target material. Preliminary LLNL fatigue failure data, at elevated temperatures, shows a fatigue limit stress near 100 ksi. The calculated peak Von Mises stress of 78 ksi (5.3e+08 Pa) is below the fatigue limit yield stress and the target should operate satisfactorily.

Another concern for the target's successful operation is that radiation damage due to material dislocations will degrade the material structural properties and thus failure occurring due to enhanced brittleness and lower fatigue limits. From a theoretical study of radiation damage[7] in the NLC and SLC targets, the NLC target may be designed to a wheel size and rotation speed that operation for about one year without excessive radiation damage may be possible.



Time, seconds

Figure 7. Peak Von Misses stress, Pa, versus time, s, at the beam exit location of the NLC target.

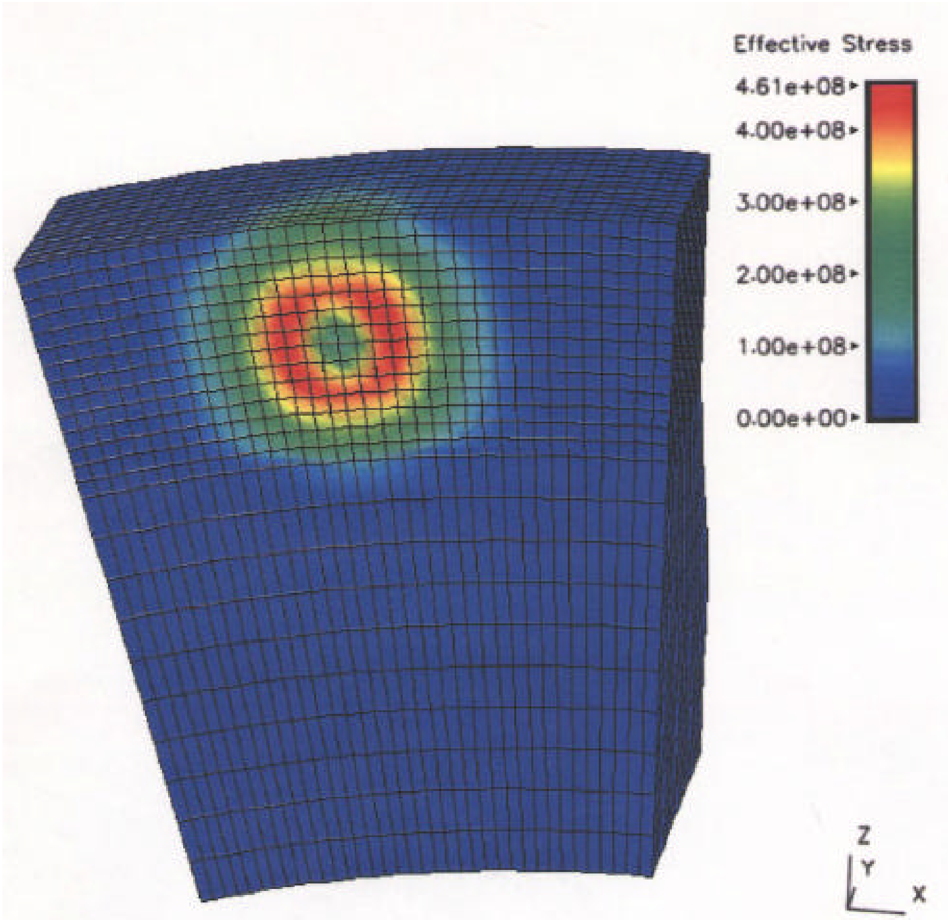


Figure 8. Steady state stress, Pa, in the target due to one beam pulse, after the pressure pulses have relaxed.

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