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3D Numerical Thermal Stress Analysis of the High Power Target for the SLC Positron Source*

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Abstract

The volumetrically nonuniform power deposition of the incident 33 GeV electron beam in the SLC Positron Source Target is hypothesized to be the most likely cause of target failure. The resultant pulsed temperature distributions are known to generate complicated stress fields with no known closed-form analytical solution. 3D finite element analyses of these temperature distributions and associated thermal stress fields in the new High Power Target are described here. Operational guidelines based on the results of these analyses combined with assumptions made about the fatigue characteristics of the exotic target material are proposed.

I. Background

The results of empirical beam tests conducted on various Positron Source target materials in the early stages of the SLAC Linear Collider (SLC) conceptual design resulted in several target failures.[1] Subsequent inspection of these failed targets indicated that the primary failure mechanism was catastrophic melting of the target material. However, in most of the failures, the estimated local power deposition in the target bodies (from the test beams) was not high enough to cause melting in homogeneous material. Therefore, the failures were hypothesized to be primarily caused by fatigue fracture initiated by the cyclic thermal stressing imposed by the nonuniform shower energy deposition of the incident 33 GeV electron beam. Cracks were thought to have propagated through the material, impeding the heat conduction paths and causing local melting.[2]

The tests provided a good rough idea of target limits, but were carried out over a short period of time and with too few samples to be statistically significant. Numerical calculations of the stresses in the target were deemed necessary and once the stress fields were calculated, some criteria had to be applied to estimate how these could be correlated to target life expectancy. This paper is a summary of the numerical study carried out to better estimate the limits on the new High Power Target (HPT) used in the SLC.

II. Target Description

The first Positron Target was stationary, and proved to be very reliable during the initial SLC operating cycle but was inherently limited in the amount of beam power that it could dissipate reliably. In order to reach the ultimate luminosity design goals of the SLC, it had to be replaced with a more robust version that could handle more than triple the power.

Initial analytical models of the target indicated that higher power levels could be reached if the new target were moved cyclically in the beam. The cycling concept chosen, known as "trolling," is shown (greatly simplified) in Fig. 1.

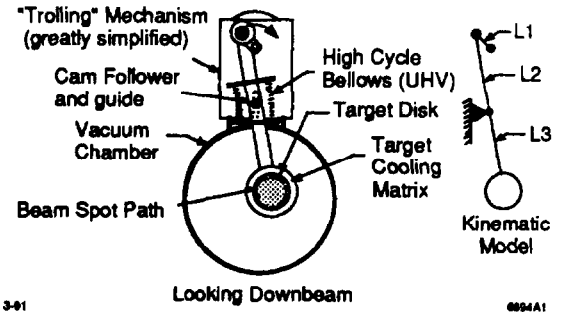

Figure 1. "Trolling" target mechanism.

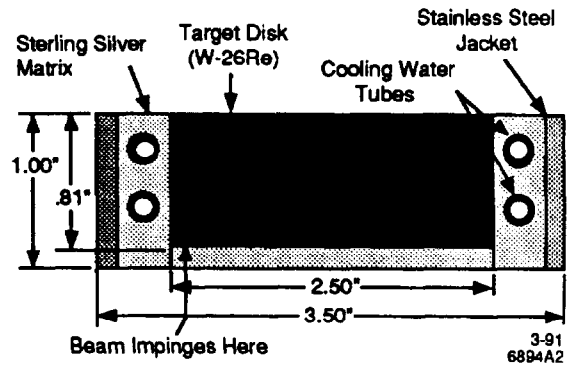

Figure 2. Target disk cross section.

The HPT itself is a 2 1/2 in dia. disk of W-26 Re, arc cast and forged, six radiation lengths long, copper plated and cast in sterling silver. A cross section of the target is shown in Fig. 2. The cooling lines are 0.25 in OD 304 stainless steel (0.020 in wall). They carry $\approx$ 3 gpm of cooling water in a counterflow direction at a differential pressure of $\approx$ 80 psi. The inlet water temperature is controlled (for RF structures in the same water system) at 43°C.

Varying the lengths of the linkage arms in Fig. 1 causes large deviations in the beam path on the target. The positron output of the target (as well as the stresses in the target) could vary greatly depending upon the position of the beam relative to the target edge (due to the difference in material properties between silver and W-26 Re). Therefore, the lengths of the target arms and crank were chosen to maintain a maximum deviation from a circle of about $\pm$0.032 in. The beam at its nominal position impinges on the target $\approx$ 0.125 in. from the outside edge of the target disk. A summary of the mechanical design of the target system is given in [3].

The SLC beam is composed of bunches of electrons which are far apart compared to their length. As each bunch impinges on the target, it generates a hot "spot." The average beam spot-to-spot spacing was set initially at 3 mm. The drive control system was designed to provide this spacing regardless of repetition (rep.) rate. This spacing corresponded approximately to the radius of the beam spot at the exit plane and was chosen (in advance

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of detailed analysis) so that the successive pulses would have minimal influence on each other. If the pulses were moved closer together, component wear would be slightly reduced (due to slower cycle speed). However, a significant increase in both the material temperature and the associated stresses would be developed. In this preliminary analysis, the "worst case" beam-to-target-edge distance was chosen (i.e. with the beam furthest out on the target disk).

III. Analysis

Three basic steps were necessary to complete the analysis.

1. Power Deposition: The first step was to use SLAC's Monte Carlo Electromagnetic Gamma Shower code (EGS) to determine what the power deposition in the target would be (and in what spatial distribution) for a beam with the maximum SLC design parameters of 7×10^{10} electrons per pulse, 120 pulses per second, and a one σ incident beam spot radius of 0.6 mm. [4–5] The 7×10^{10} intensity criterion, along with a 0.8 mm spot size, was used as a goal for the project initially but recent studies and beam experiments have confirmed that a 15% increase in positron yield (for a given intensity) could be obtained if the spot size incident on the target were decreased to 0.6 mm. This tighter bunch was expected to cause a pronounced increase in the single pulse stresses and therefore a reduction in the allowable intensity.

The energy deposition output by EGS is in fractional energy per unit volume per pulse. For all practical purposes, the temperature rise per pulse is instantaneous and is found by scaling the EGS data by a constant (121.5 cm^3 °C). This results in very high temperature gradients being imposed on the target material during every beam pulse.

2. Model Generation and Solution: The second step was to model the geometry and physical properties of the target numerically. ANSYS, a commercial multi-purpose finite element code, was used for this task.

During operation, the beam pulses impinge sequentially on the target as they trace around the disk periphery. Therefore, the entire target had to be modeled as a single meshed entity and then solved iteratively. However, it was only necessary to calculate power deposition data in EGS for a local region cylindrically symmetric about the beam center. In order to map EGS output to thermal model input, temperature-rise values scaled from EGS output were input to a small dummy cylindrical thermal model and transferred, via a 3D interpolater in ANSYS, to a region near the periphery of the full 3D thermal model of the target.

The full model included all the components shown in Fig. 2. The mesh was fine near the edge of the W-Re disk in one area, and was made gradually coarser around the periphery. The initial pulse temperature-rise data was input in the finely meshed area, with the rest of the target set to 0° in order to facilitate future superposition. Convection boundary conditions were imposed on the inside surface of the cooling tubes, with a 0° bulk water temperature, again to facilitate superposition. The temperature distribution was then allowed to relax for 1/120 s, using ANSYS's time-step optimization routine. This took 19 cpu-hrs on a 7-MIP Sun 4 workstation.

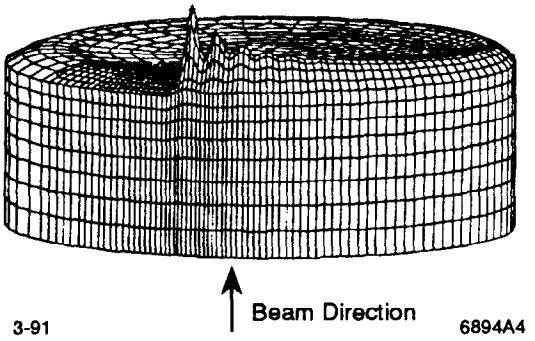

Figure 3. Raised contour temperature map of High Power Target in "steady state," just after a pulse.

A solution file was written at this point and the relaxation resumed. Using time-step optimization, the second 1/120 s of relaxation only took 5.5 cpu-hrs. This was repeated several times and the results used, in conjuction with the temperature interpolater, to create a superposition of temperatures representing ten "pulses," each 1/120 s older than its neighbor.

A seed time step for the new maximum gradient was determined and the ten-pulse superposition allowed to relax for 10/120 s. This took 31 cpu-hrs. A solution file was written and the relaxation resumed for another 10/120 s. By repeating this process several times, superpositions of more and more pulses could be generated until finally a superposition of 9193 pulses was created.

At this point a check of the total heat flowing out of the target model found that 7490 W was exiting, while 7950 W was being deposited. Since the iterative transient analysis only approximately conserves energy, and further iterations resulted in no significant change in the heat conducted through the cooling tubes, it was concluded that the "steady state" of cycling through the same sets of temperatures had been reached. The temperature distribution just after the 9193rd pulse is shown as a raised contour map in Fig. 3. Only the W-Re disk is shown in the figure. The silver cooling matrix and cooling tubes are deleted for clarity. The maximum temperature reached is only 720°C despite the fact that a single pulse creates a peak temperature rise of 530°C, indicating that the "piling up" of overlapping pulses has been reduced to a relatively small effect by the trolling action of the moving target.

To find the thermal stresses due to this temperature distribution a new mesh was generated, coarser than the thermal model everywhere but near the hottest spot, where the stresses were expected to be greatest. Since the silver surrounding the W-Re has a much lower modulus of elasticity, it was left out of this model. The interpolater was used to transfer temperatures from the thermal model to the structural model, and it was solved for stresses.

To accurately solve for the stresses perpendicular to the hot surface, a sub-model of the region around the hottest spot was created with a finer mesh in that direction. Temperatures from the thermal analysis were interpolated to its entirety and displacements from the larger structural model were interpolated to its cut surfaces. The plot in

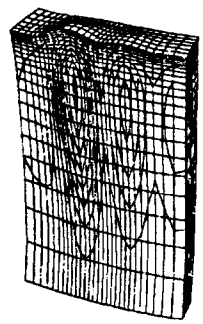

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Figure 4. Axial stress contours in hottest region of High Power Target in "steady state," just after a pulse.

Fig. 4 shows stress contours for the stress in the direction of the beam that resulted from solving the submodel. In this view the submodel is cut-away through the center of the pulses in order to show the most severe stress profiles.

The stress shown in Fig. 4 reaches a maximum of 180 ksi compressive. Where the stress is maximum the temperature is 650°C and so the yield strength of the W-Re is about 150 ksi. However, because the material is "captured" by compressive stresses in all directions, this situation is not the most critical. Distortion strain energy, or "Von Mises stress" is a better measure of the proximity to failure, and its value at that place is only 87 ksi. It is actually highest on the surface between two pulses, where a tensile radial stress of 94 ksi combines constructively with a compressive hoop stress of 63 ksi for a Von Mises stress of 140 ksi. At that place the temperature is 370°C, making the yield strength about 200 ksi.

3. Evaluation of Results: W-26 Re was chosen as a target material because of its excellent physics properties and extremely high strength and ductility at the anticipated target operating temperatures. Unfortunately, due to the relatively limited market for the material, only the most basic engineering properties were available.

Although the Von Mises stresses calculated and summarized above were below the actual yield strength of the material at operating temperature in all areas, the failure mechanism was hypothesized to be thermal stress fatigue fracture. Commonly accepted failure analysis principles state that the stress history of the body (alternating and mean stress values at the operating temperature) should be correlated in an S/N or similar statistical summary of material test data to estimate the safety of the design. However, no such data was available nor was it practical to have the material tested. It was necessary, therefore, to recommend operational limits based on advice from others who have worked with the material under similar conditions before, and empirical operational experience with the previous target. The criterion which was determined applicable was that the Von Mises stresses in all areas must be below 0.5 times the yield strength at the operating temperature (a compromise between suggestions from Dieter Walz (0.3) at SLAC and Prof. Tom Divine (0.8) at UC Berkeley).

III. Conclusion

Based on this criterion, the maximum allowable intensity for a .6 mm spot size is 5.3×10^{10} electrons per pulse. This is lower than the "break even" point (6.1×10^{10}) where the 0.6 mm beam yields the same number of positrons per incident electron as a 0.8 mm beam at 7×10^{10}.

The following is a list of some of the assumptions made and some practical considerations not quantified in the analysis.

- Beam Spot Shape and Path. The beam spot has been assumed to be round and its path circular.
- Surface Defects. The number and position of voids and other defects ultimately will have some effect on the useful lives of the targets. During the fabrication of the targets, the downstream faces are micro-polished to minimize these defects.
- Ductile-to-Brittle Transition Temperature. W-26 Re exhibits a relatively abrupt ductile-to-brittle transition at a temperature of about 90°C. Although the actual yield strength of the material does not change appreciably through this range, the ability of the material to elongate (i.e., absorb energy) does. At temperatures below this transition, the target may be much more susceptible to thermal shock and crack propagation.
- Thermal Shock Focussing. The beam energy deposition in the target occurs virtually instantaneously, causing a compression wave to be generated at the beam center and propagate outward. Some studies have shown that damage (spallation, cracking) may occur if these waves are symmetrically reflected back off an interfacing surface so that they constructively add at the beam axis. [6] However, no noticeable damage was seen on the previous target, which was centered on the beam (but ran at one third the intensity), and the beam does not hit the center of the new trolling target.
- Casting Pre-stress Effects. As the assembly cools after casting, the silver matrix shrinks considerably more than the target disk. However, sterling silver exhibits considerable plasticity and the elastic modulus is low. Therefore, the stresses imposed on the disk from the casting are probably negligible.

Operational experience with the new target has been very successful over the past year. Although the SLC has been unable to deliver beams of design intensity yet, the target has operated reliably at intensities $\approx 60\%$ of design.

IV. References

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[6] J.G. Kelly "Deep Craters Produced by Shock Focussing in Relativistic Electron Beam Diodes." J. Appl. Phys. Vol. 40, No. 10, pp. 1415, (Oct. 1975).