Proceedings of the 2001 Particle Accelerator Conference, Chicago

THERMAL SHOCK ANALYSIS OF WINDOWS INTERACTING WITH ENERGETIC, FOCUSED BEAM OF THE BNL MUON TARGET EXPERIMENT*

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Abstract

In this paper, issues associated with the interaction of a proton beam with windows designed for the muon targetry experiment E951 at BNL are explored. Specifically, a 24 GeV proton beam up to 16 TP per pulse and a pulse length of 100 ns is tightly focused (to 0.5 mm rms radius) on an experimental target. The need to maintain an enclosed environment around the target implies the use of beam windows that will survive the passage of the proton beam. The required beam parameters in such a setting will induce very high thermal, quasi-static and shock stresses in the window structure that exceed the strength of most common materials. In this effort, a detailed analysis of the thermal/shock response of beam windows is attempted through a transient thermal and stress wave propagation formulation that incorporates energy deposition rates calculated the by hadron interaction code MARS. The thermal response of the window structure and the subsequent stress wave generation and propagation are computed using the finite element analysis procedures of the ANSYS code. This analysis attempts to address issues pertaining to an optimal combination of material, window thickness and pulse structure that will allow for a window to safely survive the extreme demands of the experiment.

1. INTRODUCTION

A tightly focused beam on target is required in the muon collider/neutrino factory study. Specifically, up to 16 TP per pulse of a 24 GeV proton beam are expected to be delivered on target, with a pulse length of a few microseconds and a beam spot of 0.5 mm rms sigma. The proton beam, prior to entering the target space, is to go through a beam window structure. From the required beam parameters it may be concluded that very few, if any, window materials will be able to survive the thermal shock that will be induced. While in the real muon collider target the beam window location can be optimized based on the beta function in order to see a bigger spot, the E951 experiment at BNL will require for the beam window to be close to the target where the beam focuses down to its smaller spot. In order to select the right window material that will survive under such conditions, an extensive effort was undertaken to evaluate different materials that show promise based on their mechanical strength. The effort consisted of the calculation of energy deposition on the different materials using the hadron interaction code MARS [3], the transient thermal analysis resulting from the deposited energy and finally the thermal stress analysis that included the generation and propagation of stress waves. To demonstrate the severity of the beam-window interaction, the thermal stress induced in a 10-mil thick stainless steel window by the beam of the required parameters (24 GeV, 16 TP, 0.5 mm sigma and 100 ns pulse length) is shown. The peak von Mises stresses in the window material, occurring at beam center and mid-thickness, approaches 2500 MPa that is more that twice the yield and ultimate strength of the material. According to this prediction such window will not be able to survive a single pulse let alone multiple pulses.

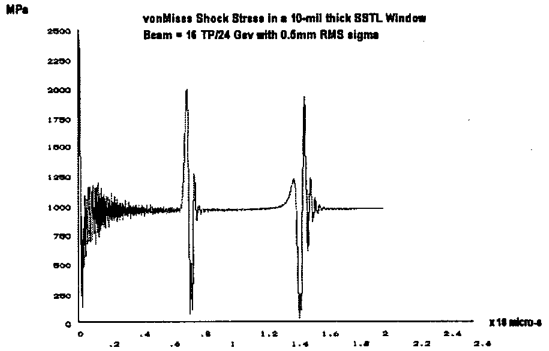

Figure 1. Prediction of von Mises stress in a stainless steel window intercepting a 24 GeV proton beam with 16 TP and 0.5 mm sigma spot.

Given the severity of the problem, an experimental set-up to study the response of window materials as part of the E951 muon targetry experiment was introduced. Four (4) different window materials were selected for testing in the beam line at AGS. Three of the materials, Inconel-718, Havar and Titanium alloy, showed promise of surviving the proton beam pulses. Their selection was based on material properties and extensive thermal shock predictions. The fourth material selected is

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* Work performed under the auspices of the US DOE

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Aluminum (3000-Series). Based on the theoretical predictions, this window material could fail even if 6 TP are delivered on target. Because of the proximity to the failure condition, experimental data that could verify the predictions would be very valuable. Since the calculations show that the window thickness, in conjunction with the material acoustic velocity and the pulse structure and duration, has a dramatic effect on the peak stresses generated in the material, two (2) thicknesses (1-mm and 6-mm) of the Inconel-718 material were selected for study.

2. EXPERIMENT CONDUCT

2.1 Strain Measurement Set-Up

The goal of the strain experiment is to capture the radial strain at a specified distance from the beam spot location. While the governing shock stress in determining the safety of the window material is the von Mises stress at the center of the spot and through the material thickness, there is no measurable quantity in that orientation. However, by predicting the radial strain at a safe distance from the beam (minimize the radiation damage on the strain gauges), the whole stress tensor can be estimated. Figure 2 depicts the arrangement of four (4) fiber-optic strain gauges that were placed on the front surface of each of the tested windows. The strain gauges are designed around an interferometer by FISO Technologies Inc. The basic active element (cavity) consists of two mirrors facing each other. The acquired signal goes through custom-made filtering and at the end of the process a 500 KHz strain signal is deduced. The wavelength of the shock front (uncorrupted in nature) and the ability of recording system to capture it is vital to the analysis of strain amplitude and time structure.

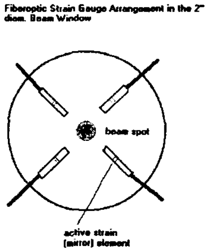

Figure 2. Schematic arrangement of the fiber-optic strain gauges in the test windows.

2.2 Strain Measurements

During the window tests of the E951 experiment a beam intensity of approximately 2.5 TP was delivered on target while the beam spot was approximately 1mm rms sigma. The beam spot closely fit an ellipse rather than the circle that was assumed in the theoretical predictions. While the combination of beam intensity and spot was far from being critical for any of the windows, strain measurements that can be used to verify the predictions have been generated. Shown in Fig. 3 is the radial strain in one of the four gauges of the 10-mil aluminum window. The very first part of the record is the noise in the fiber-optic system. The arrival of the proton beam is indicated by the high frequency noise corruption of the signal. The arrival of the compressive wave at the active element of the gauge (approximately at 0.5-inch from center) is shown by the first dip. What follows is the arrival of the tensile wave phase at precisely the time that is expected.

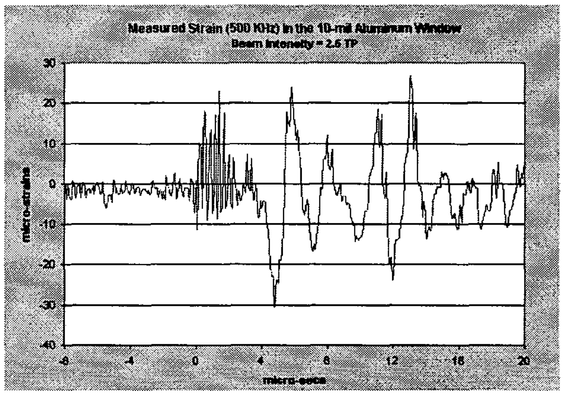

Figure 3. Radial strain measured in the 10mil aluminum window and induced by a 2.5 TP beam with 1mm sigma

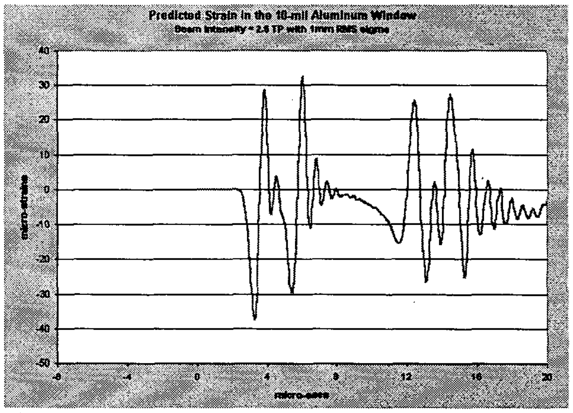

Figure 4. Predicted strains (ANSYS) in the 10mil aluminum window for 2.5 TP and 1mm sigma

Following the rapid thermalization of the affected material (within the beam spot) two waves are generated at the edge of the heated zone. One travels outward as a compressive wave and arrives at the strain gauge first (dip). The second wave travels toward the center of the beam spot as compressive, reflects at the center by changing sign, and travels outward as a tensile wave. The remaining cycles represent reflections at the edge of the window and its center.

Figure 4 depicts the calculated strains for the same beam parameters but with a "true" round Gaussian profile. The agreement between experiment and theory is very good both in terms of amplitude and time structure. Figure 5 shows the strain measurements in two pulses back-to-back and with approximately the same beam intensity. The duplication of the response is a sign of stability in the measurements. However, it should be noted that fiber-optic strain signal is very sensitive to the beam arrival and the ensuing flux of photons. A filtering effort is under way to "clean" the records from the inherent and induced noise.

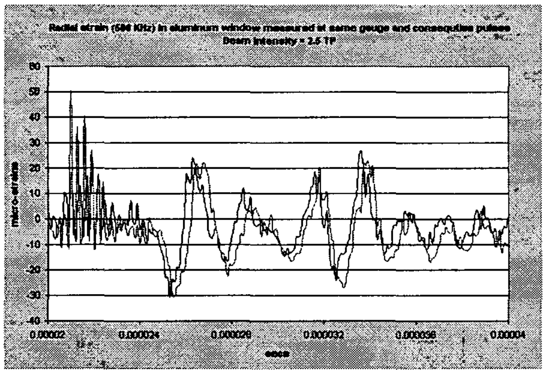

Figure 5. Strain in aluminum window recorded by the same strain gauge and back-to-back pulses

In Figures 6 & 7 the measured and predicted strains in the 1mm-thick Inconel-718 window are shown. It should be noted that based on the "preliminary" analysis and comparison of experimental to theoretical results, it has been observed that the thicker the window gets the higher the deviation between the two. An additional source of discrepancy is the actual position of the beam with regard to the four gauges. A beam shift toward one of them will alter the strain measurements by inducing higher strains in the closest gauge. To estimate the "true" position of the beam, a cross-correlation process of the gauge signals has been introduced that, in first order, indicates the relative arrival of the signal.

3. SUMMARY

The first phase of the targetry experiment E951 at BNL that completed in the spring of 2001 provided the opportunity to test, in addition to targets, window structures that are integral part of any target system and normally experience similar shock conditions. What has been deduced, so far, from the experimental/theoretical results are the following:

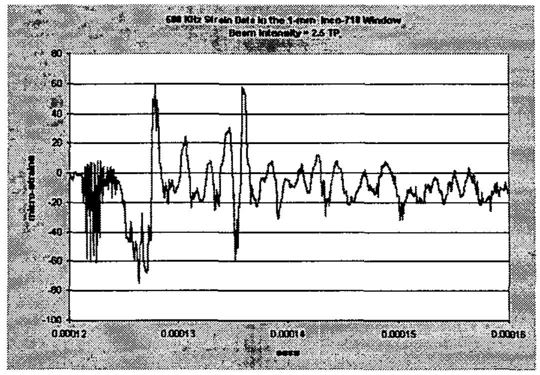

Figure 6. Measured strains in a 1mm Inconel window

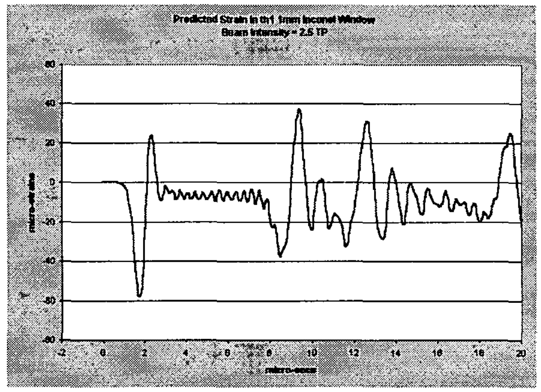

Figure 7. Predicted strains in the 1mm inconel window.

a) Very good agreement is seen in the strains of thin windows. This implies that the energy deposition estimated by the neutronic code agrees with the energy left by the beam

b) Because of the lower than anticipated intensity and larger beam spot, the failure conditions for the weakest window (aluminum) were never approached

c) The thicker the window, the more difficult to predict amplitudes and structure of the signal due to multiple wave phases and reflection

d) Given the nature of shock waves in the materials, an increase in the measuring system bandwidth is desirable

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