A FEA STUDY OF THE STRESS WAVES GENERATED IN THE T2K BEAM WINDOW FROM THE INTERACTION WITH A HIGH POWER PULSED PROTON BEAM

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Abstract

The target station of the T2K neutrino facility requires a beam window to separate the target chamber, containing helium at atmospheric pressure, from the vacuum of the secondary beam line. In addition to withstanding this differential pressure, the window must survive induced stresses due to intense heating resulting from interaction with a 0.75 MW pulsed proton beam. The proposed design consists of a hemispherical double window with forced convection helium cooling in between, manufactured from titanium alloy. Preliminary analysis suggested that shock waves induced by the pulsed nature of the beam will form the dominant mode of stress.

The finite element software ANSYS has been used to simulate the effect of beam interaction with a variety of window thicknesses in an attempt to find the optimum geometry. Results have shown that through thickness stress waves can be amplified if successive bunches arrive in phase with the waves generated by previous bunches. Therefore, thickness has been shown to be a critical variable in determining the window's resistance to thermal shock.

INTRODUCTION

The Window

A beam window is required to separate the target chamber, containing helium at one atmosphere, from the vacuum of the final focussing section of the beam line.

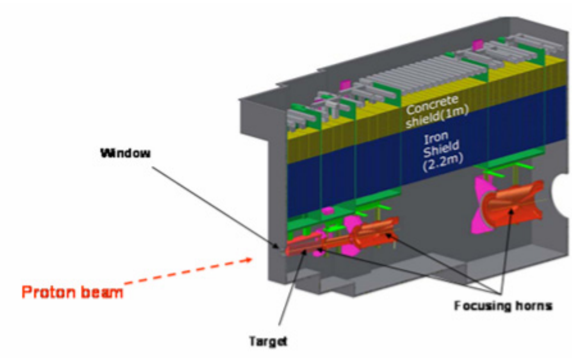

Figure 1: Target station layout.

A hemispherical window design has been chosen as the starting point due to this shapes capacity to withstand pressure. Cooling will be achieved by having two concentric partial hemispheres with pure helium flowing at high velocity through the gap between. After a survey of potential window materials [1], Ti-6Al-4V was chosen as one of few candidates. When mitigating for thermal shock effects, a high ultimate tensile strength (UTS) and a low coefficient of thermal expansion (CTE) are desirable qualities. The UTS of Ti-6Al-4V at room temperature is approximately 900 MPa, and its CTE of 8.8e-6 is low compared with most other metals [2]. Titanium alloy also has a relatively low density, meaning that it will absorb less energy as heat than, say, stainless steel.

Figure 2: Ti-6Al-4V beam window domes.

The Beam

The window is penetrated every 2.1 seconds by a 0.75 MW 30 GeV pulsed proton beam of 5 microseconds duration. The pulse is composed of eight 58 ns bunches, each separated by a 598 nanosecond gap. Heat deposit for an aluminium window had been estimated by GEANT assuming 3.3 x1014 protons. Heat deposit for Ti-6Al-4V has been approximated from this by the ratio of their respective densities. Beam energy is assumed to have a radial Gaussian profile with standard deviation of 4.24 mm. Through thickness energy deposition has been assumed constant in all simulations. Every pulse raises the temperature of the window by 140 K at beam centre. The mean window temperature will depend on the window thickness and the effectiveness of cooling. Fig. 3 shows how incremental temperature rises from each individual bunch combine to achieve the overall heating effect over the 5 microsecond pulse.

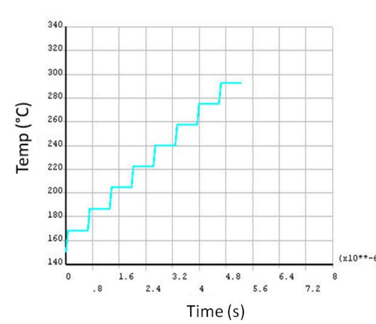

Figure 3: Temperature of window at beam centre over pulse duration

The temperature increase of the window can be assumed to take place instantaneously since, for metals, heating times are in the order of picoseconds, while the acoustic relaxation time* in the window is likely to be in the nanoseconds range [3].

The Model

To simulate the dynamic effect of a pulsed proton beam on the window, an ANSYS [4] model with coupled field (plane 13) elements has been used. To reduce the computational cost, an axisymmetric model has been approximated for all simulations. A crucial factor in obtaining accurate predictions of thermal shock problems using finite element software is using the necessary time step and element size. This has been validated by Zheng *et al* [5]. The guidelines laid out in their paper have been followed for every simulation. In an attempt to further confirm that ANSYS Classic is capable of predicting thermal shock effects, a study was conducted to compare results produced using ANSYS LS Dyna [G. Skoro, *pers. comm.*]. Although the peak stress value was slightly lower using LS-Dyna, almost identical stress plots have been produced using the two methods.

As the window temperature will vary between pulses, temperature dependant properties were used in the simulations [2].

TRANSIENT STRESS ANALYSIS

Transient Stress over Consecutive Pulses

For 30 GeV beam energy, one pulse strikes the window every 2.1 seconds. Because the pulse occurs over such a short time period, the resulting temperature jump will be independent of any cooling applied. Both theoretical calculations and ANSYS simulations have predicted a temperature rise of 140 K with each pulse. Fig. 4 shows how the window heats up and begins to oscillate about an average temperature of about 150 °C after only four pulses. This analysis assumes a heat transfer coefficient of 150 W/m2K on the internal surface. Theoretical calculations and CFX simulations have shown this to be equivalent to a helium flow of approximately 5 m/s [M. Fitton, *pers. comm.*].

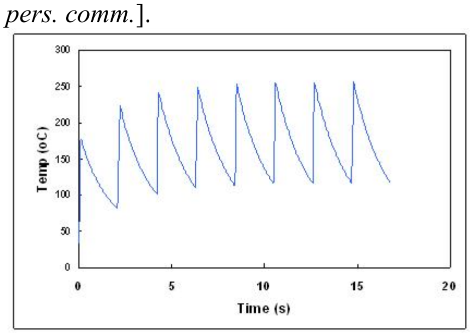

Figure 4: Temperature cycling between pulses at beam centre.

* Acoustic relaxation time is the length of time a sound wave would require to traverse the region of energy deposition. The speed of sound in titanium alloy is approximately 5000 m/s.

Cyclical heating and cooling of the window between pulses will create a corresponding oscillating thermal stress in the window. Fig. 5 shows the variation of beam centre Von Mises stress at the inner and outer surfaces, and at mid-plane. The peak stress due to cyclic heating in this area is about 90 MPa.

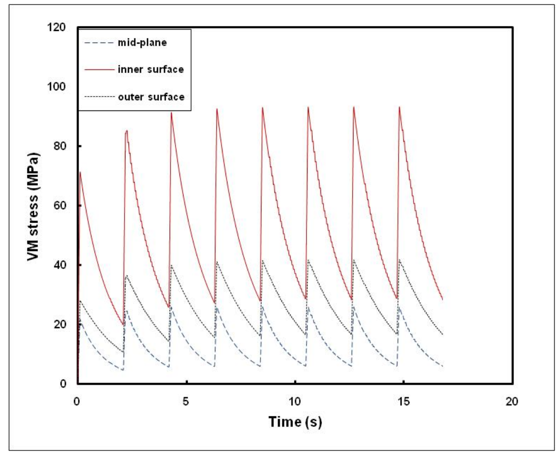

Figure 5: Transient stress at beam centre as a result of temperature cycling.

Stress Waves During and After Pulse

When a material experiences an instantaneous heat rise, mass inertia of the material prevents it from expanding instantaneously to relieve the stress [6]. A quasi-static state of stress results and this may be accompanied by stress waves emanating from the heated zone. In the case of a proton beam striking a metal window, these waves will take two forms: (1) those moving radially outwards from the heated area; and (2) longitudinal stress moving through the material thickness at beam centre. Since a through thickness stress wave is generated by each individual bunch, the next bunch will either interfere in a positive or negative way with the wave that preceded it. If the bunches are exactly in phase with the acoustic transit time of the window then a type of stress resonance will occur in which the longitudinal stresses will continually grow over the duration of the pulse. Stresses are seen to peak at the end of the beam pulse. Subsequently, stress waves oscillate in both longitudinal and radial directions.

As tensile waves reach the free surfaces of the beam window, they change sign and move inwards as a compressive wave. This pattern continues resulting in a period of stress ringing of (2h)/c where h is the window thickness and c is the velocity of the wave. Figures 6 a and b show stress waves in windows of thickness 0.6 mm and 0.3 mm. There is no build up of longitudinal stress in the 0.3 mm window, indicating that successive bunches are 180 degrees out of phase. A window of 0.6 mm thickness has been shown to give a sharp increase in stress over the duration of the pulse. Fig. 6a shows how there are eight jumps in stress over the pulse length, indicating that each bunch is perfectly in phase with that which preceded it.

In Fig. 6, the amplitude of the longitudinal stress waves decrease after the initial heat input due to energy moving out of the region in a radial direction. Taking material damping into account, this effect is likely to be even more pronounced.

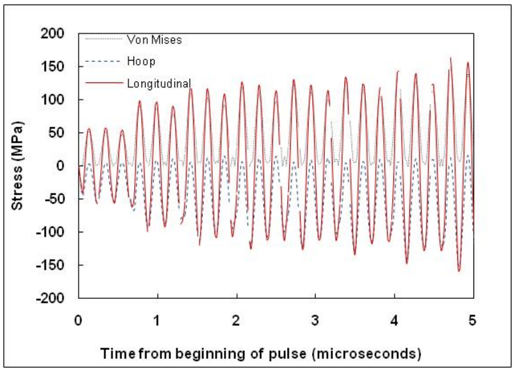

Figure 6a

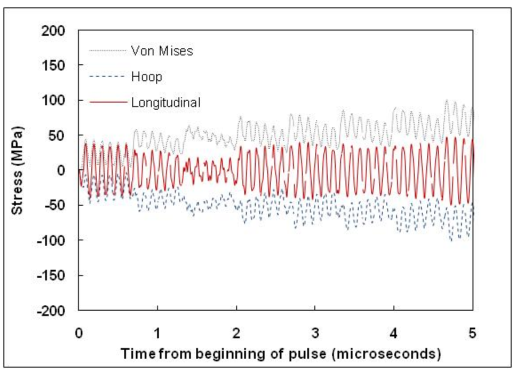

Figure 6b

Figure 6 a and b: Stresses at beam centre, mid-plane in windows of thickness (a) 0.6mm and (b) 0.3mm.

Figure 7 shows the maximum Von Mises stress at the end of the beam pulse in windows with thicknesses ranging from 0.2 mm to 1 mm. Careful choice of thickness results values of below 100 MPa.

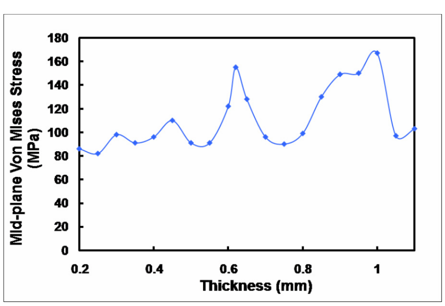

Figure 7: Window max stress with varying thickness.

Peaks of longitudinal stress occur at window thicknesses of 0.45 mm, 0.62 mm and 1 mm. In terms of time, each of these peaks is separated by an increase of two wave traverses. Referring again to the period of oscillation of (2h)/c, this would seem likely. As thickness decreases, the effect of stress resonance becomes less pronounced as, due to an increase in the number of through thickness oscillations between pulses, energy is dissipated more quickly in a radial direction and resonant peaks do not therefore have time to occur.

CONCLUSION

A study of the stress waves resulting in the T2K beam window from the interaction with a pulsed proton beam has been completed using ANSYS FEA software. The study has shown that certain combinations of component geometry and pulse structure can create resonant stress peaks in the material. It is therefore important to take this into consideration when designing any component that will interact directly with a high power pulsed proton beam to prevent premature failure.

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