Beam Window Analysis
Muon Collider Project
Experiment 951

N. Simos, PhD, PE

Accelerator and Novel Technologies Group
ES&T Department

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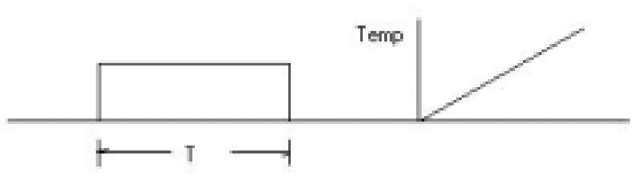
E951 Window Analysis Overview

- **Proton Beam Structure**
  - 15 TP, 24 GeV, Gaussian profile
  - smallest beam spot size assumed = 1mm RMS sigma
  - pulse structure and length
- **Beam/window interactions**
  - A3 Line Windows
  - E951 Target enclosure windows
  - thermal shock
  - material behavior
- **Benchmark analysis and simulation verification using experiment 951 targets**

Proton Beam Structure

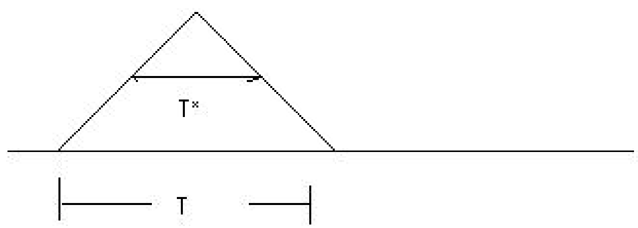
- **Proton Beam Structure**
  - 15 TP, 24 GeV, Gaussian profile
  - smallest beam spot size = 1mm RMS sigma
  - pulse structure and length



T = pulse length

Proton distribution uniform in time
Beam profile is Gaussian

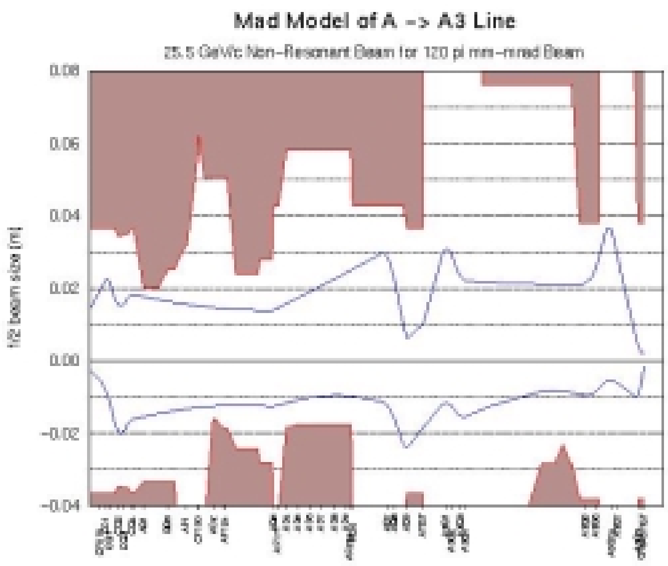
Energy deposition (thermal input rate) constant

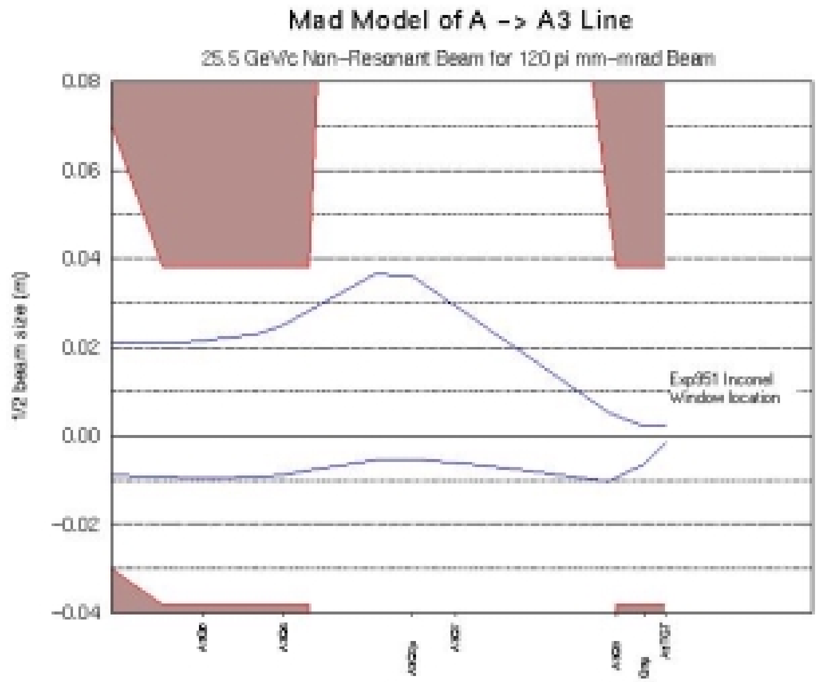


Proton distribution in time space (real beam !!)
Beam = Gaussian in space

T for AGS beam ~ 100 ns
T* 30 ~ 40 ns

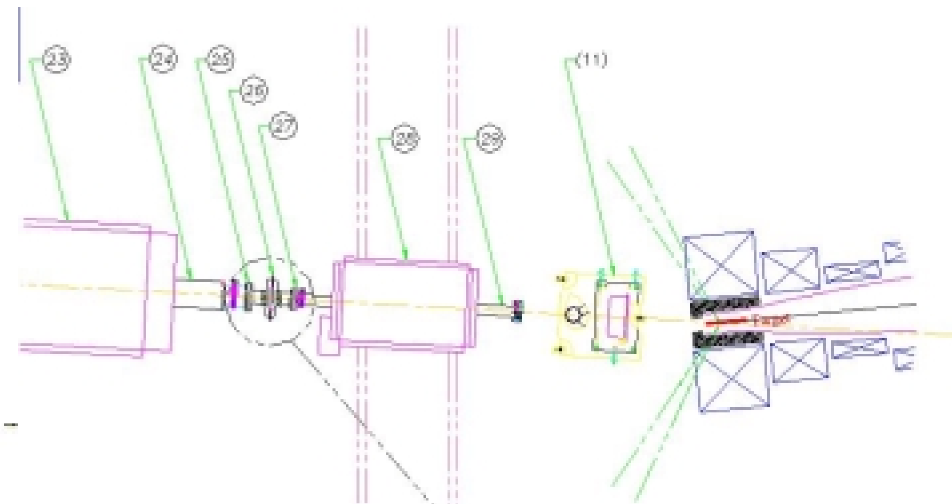
A3 Line Beam Size

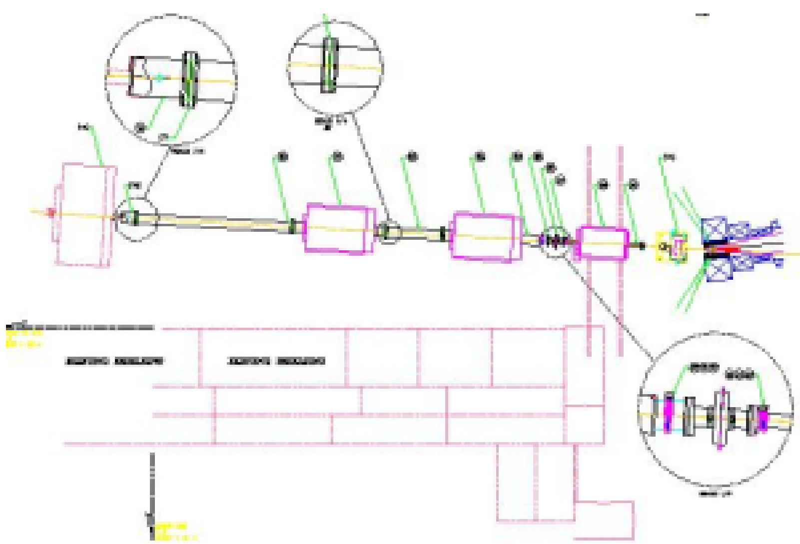




A3 Line

- **A3 Line near E951**





A3 Line Windows

- **Material used is different series Aluminum**
  - 5052 series available in 3-mil thickness
- **Concern is the TP per pulse coupled with a small spot size**
- **Experience from previous experiments showed good window response**
  - an order of magnitude higher in single-pulse TP for E951

E951 Enclosure Windows

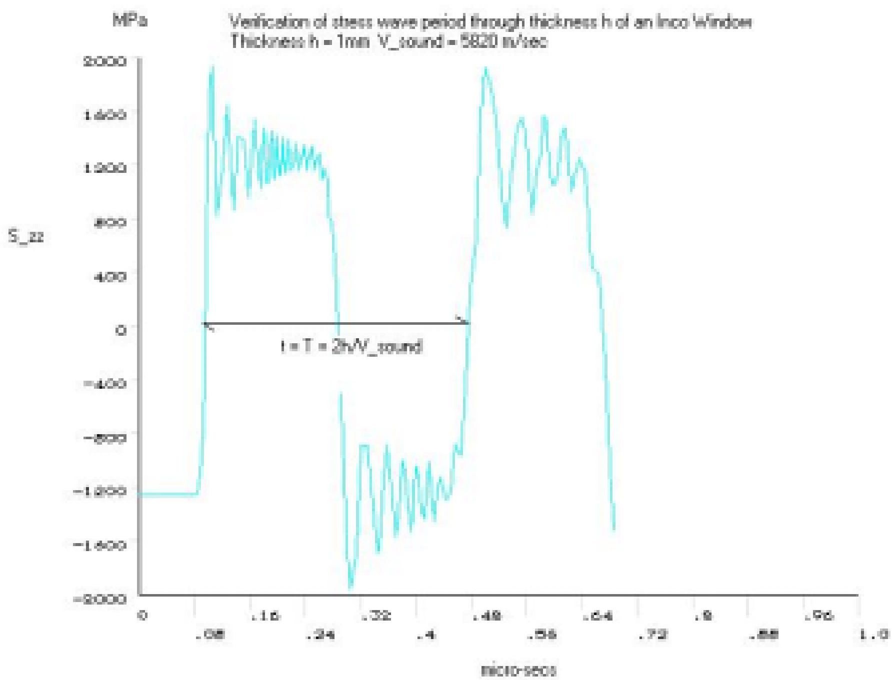
- **Family of materials assessed**
  - INVAR
  - SS316
  - Inconel-718
- **Beam spot size same as on target**
  - Estimates based on 1mm RMS sigma
  - Beam spot may actually be SMALLER !!
  - E951 window positioning
  - Window material monitoring and failure verification

Background on Thermal Shock and Window Failure Estimation

- Quasi-static thermal stress from energy deposition is a 3-D affair no matter how thin the window is
  - directional stress in 3-D world = E*alpha*DT/1-2*pr
- Two-dimensional simplification of a thin structure does not quite apply
  - directional stress in 2-D = E*alpha*DT/1-pr
  - 1-D = E*alpha*DT
- Of concern is NOT the level of directional stress but the deviation from the hydrostatic state of stress (VonMises stress)
- Directional stresses are coupled through the Poisson's ratio
  - dynamic changes in one direction affect all others

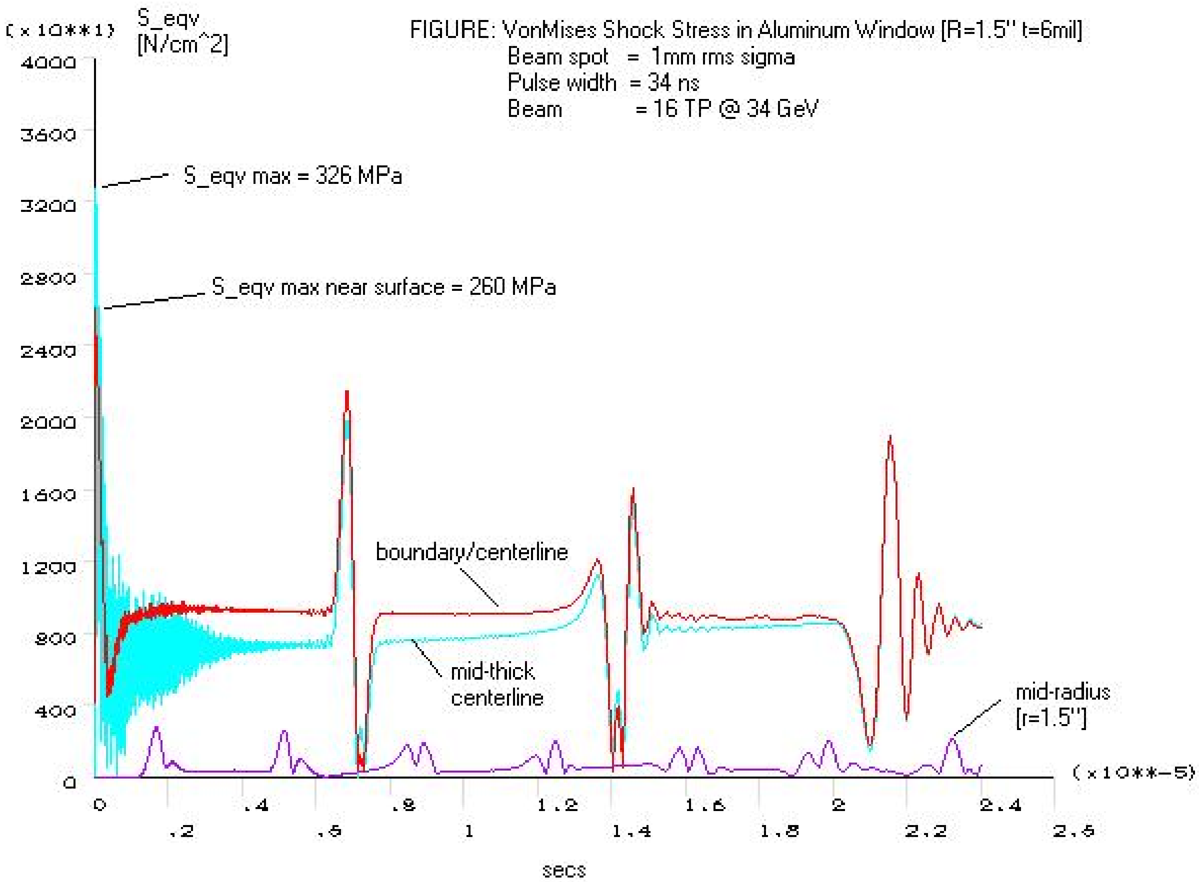
- Build-up of thermal stress in the course of proton pulse
- Propagation and attenuation of shock or dynamic stress

Background on Thermal Shock and Window Failure Estimation



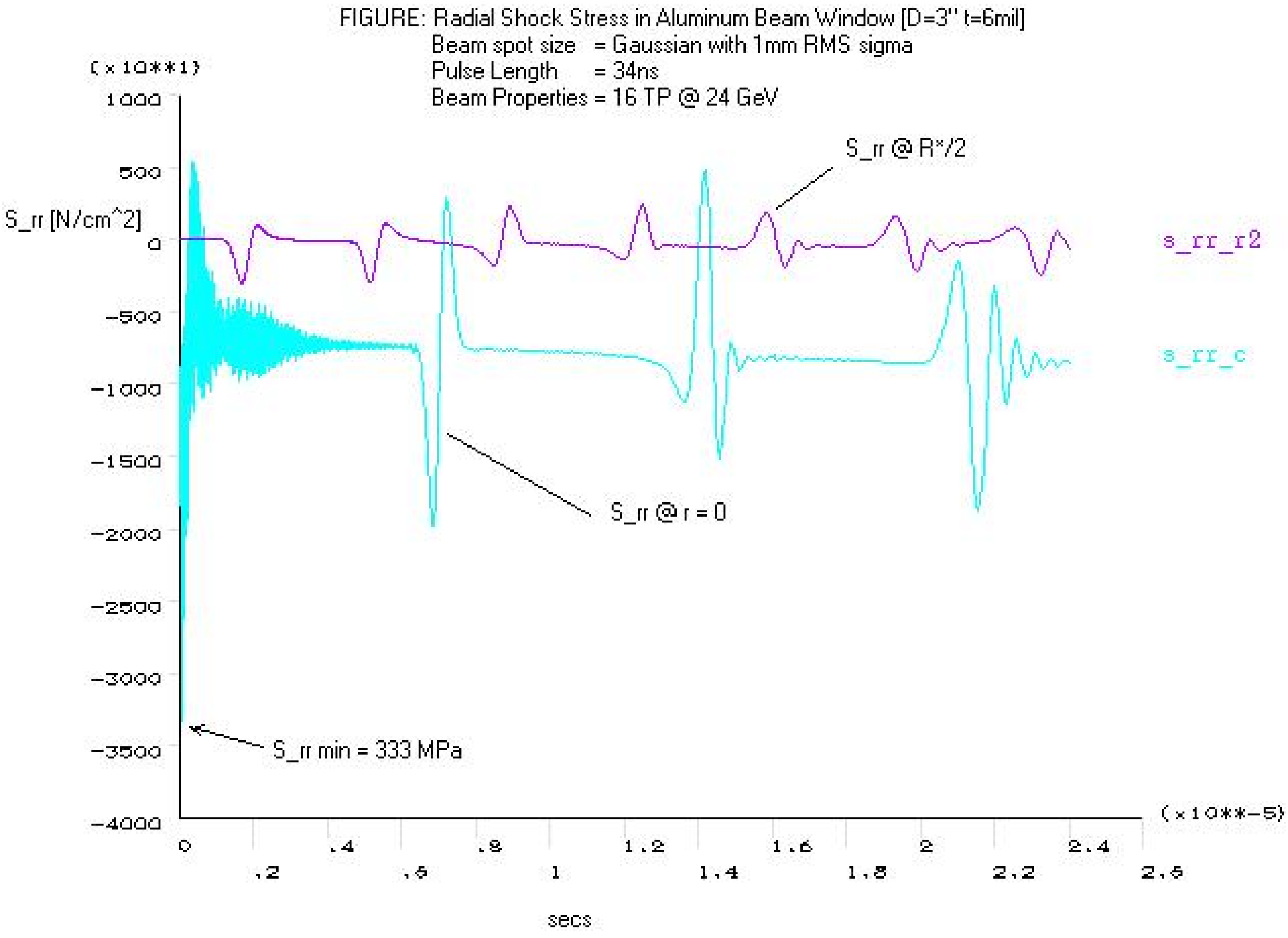
- Based on 3-D stress state the effect of through-thickness RINGING is accounted
- Its effect is **dominant** in the response of the heated window region
- Governed principally by the propagation of stress waves in 1-D space
  - **stress**(t) = f(x-ct) + f(x-ct) [c = speed of sound in material]
  - **period** of ringing = 2*h/c [h = window thickness]

Thermal Shock Analysis of the Exp951 Windows
A3 Line 3-inch diameter and 6-mil thick Aluminum Window

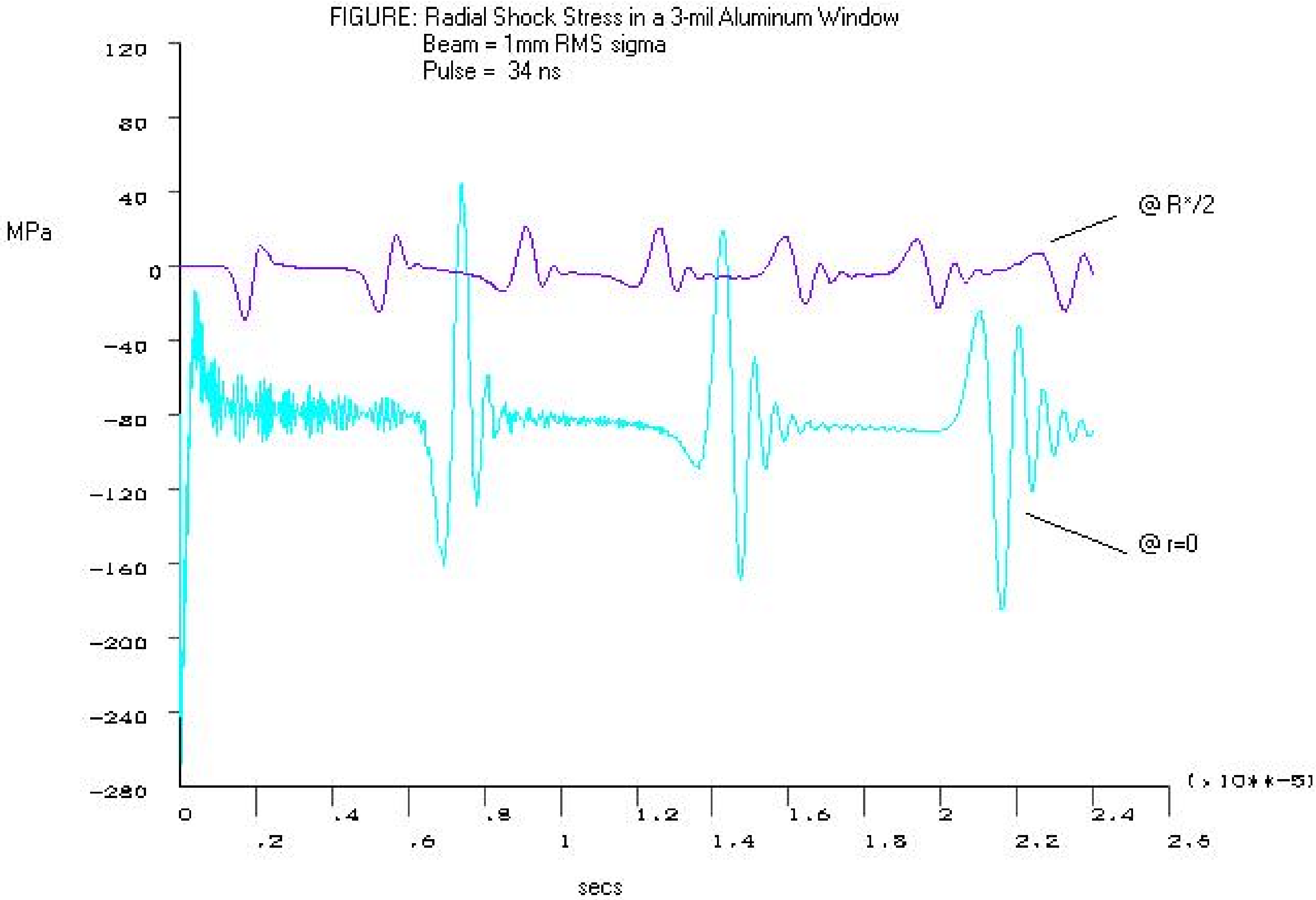


Thermal Shock Analysis of the Exp951 Windows

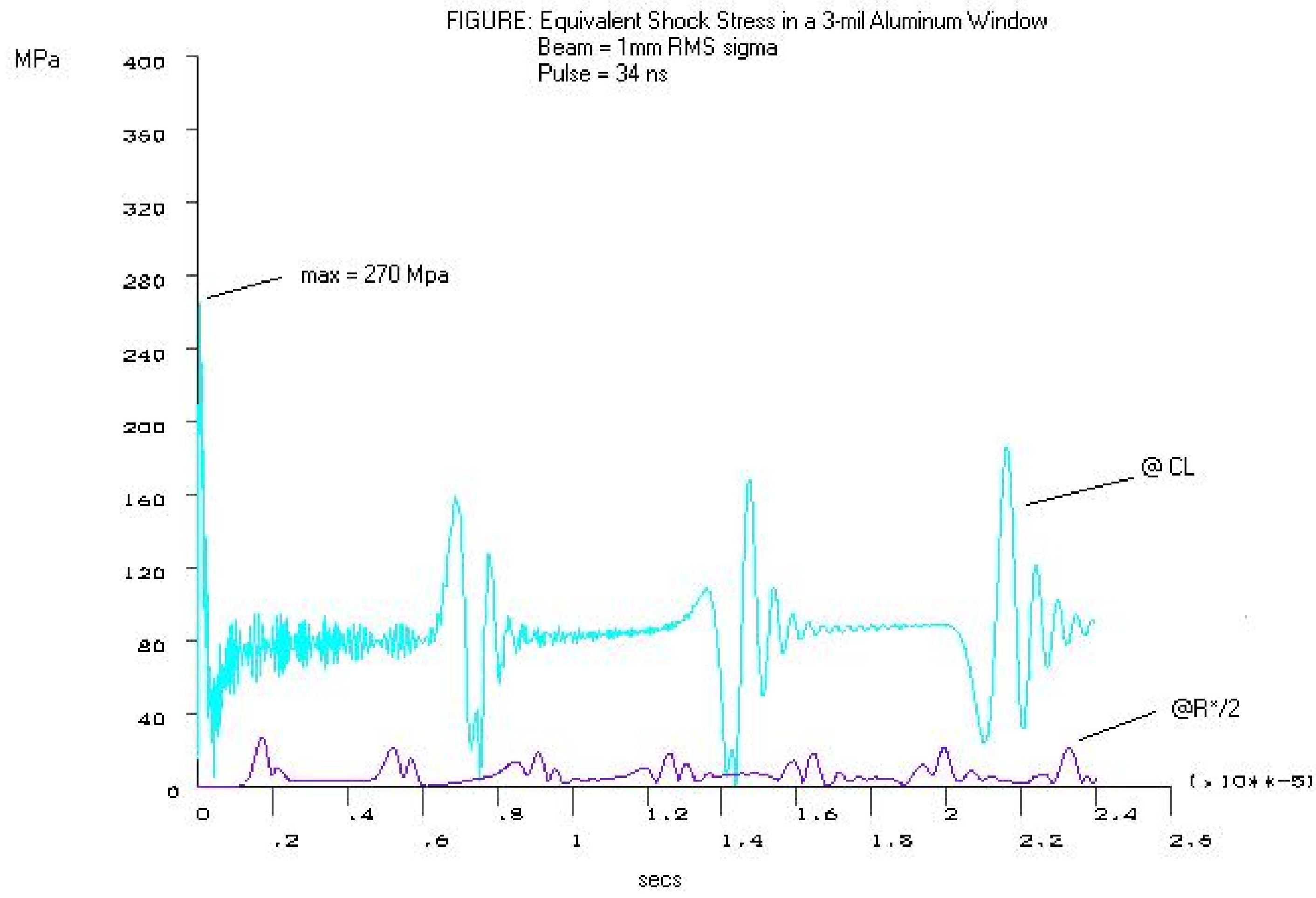
A3 Line 3-inch diameter and 6-mil thick Aluminum Window



Thermal Shock Analysis of the Exp951 Windows
A3 Line 3” 3-mil Aluminum Window

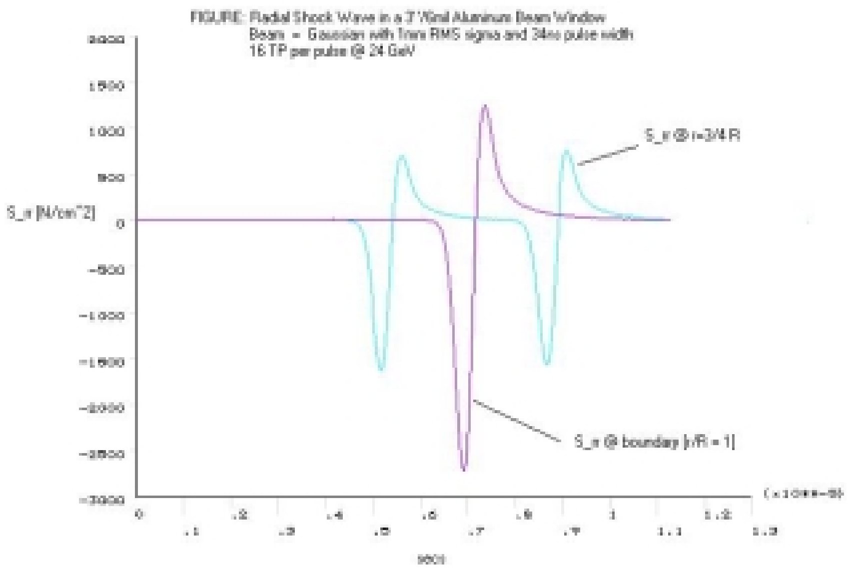


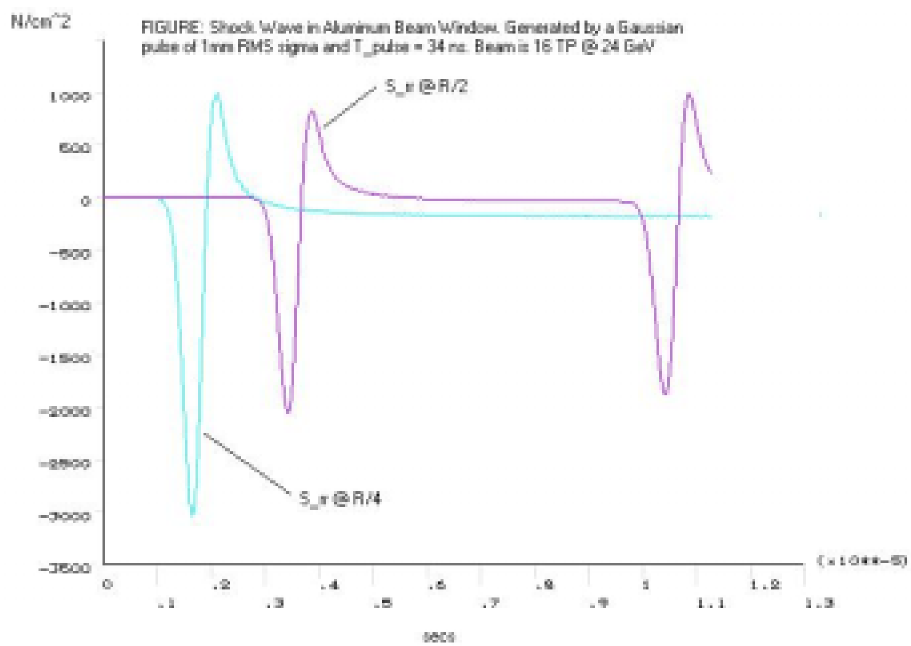
<u>Thermal Shock Analysis of the Exp951 Windows</u>
A3 Line 3-inch diameter and 3-mil thick Aluminum Window



Thermal Shock Analysis of the Exp951 Windows

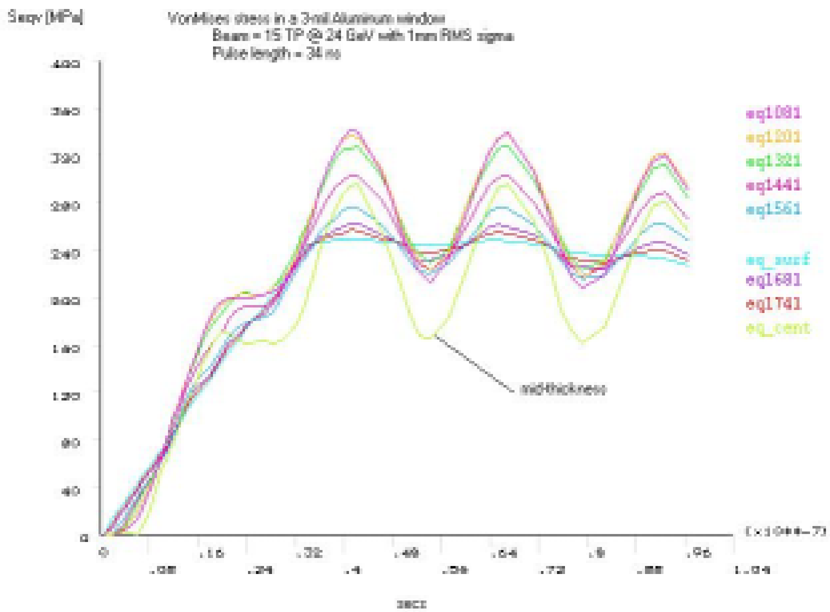
A3 Line 3-inch diameter ; 6-mil Aluminum Window

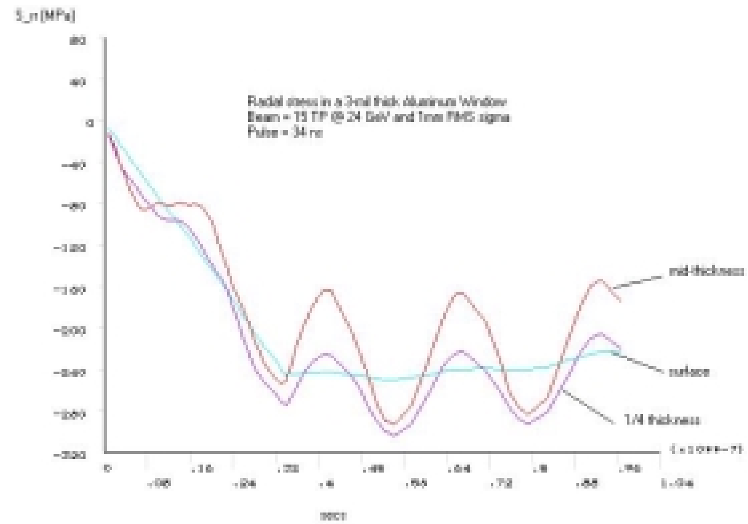


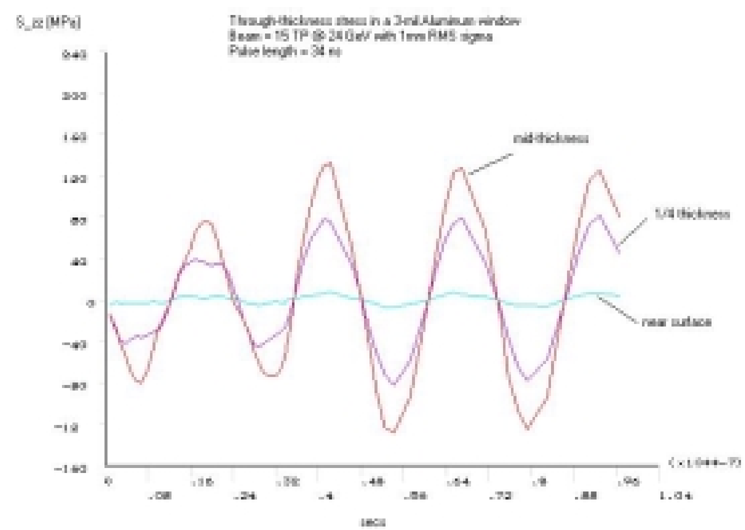


Thermal Shock Analysis of the Exp951 Windows

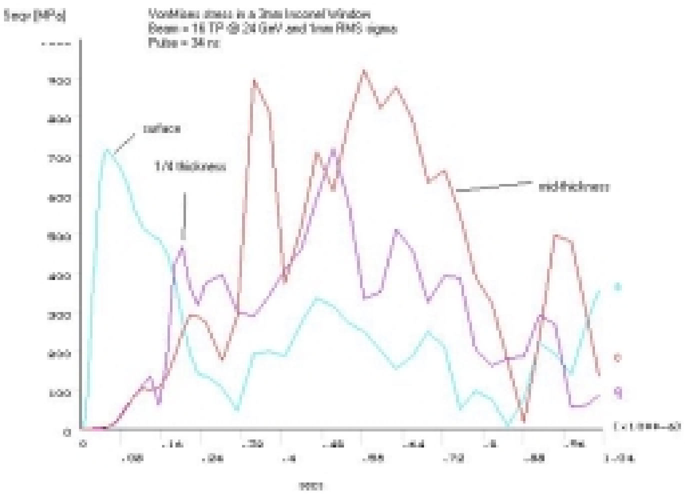
A3 Line 3-inch diameter ; 3-mil Aluminum Window

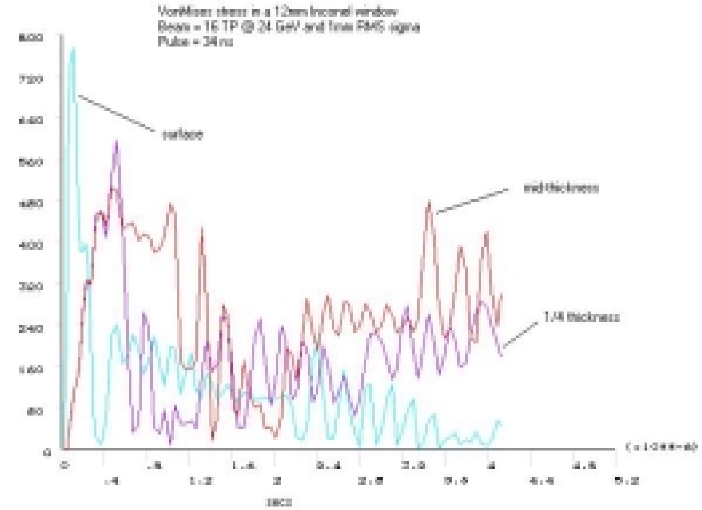


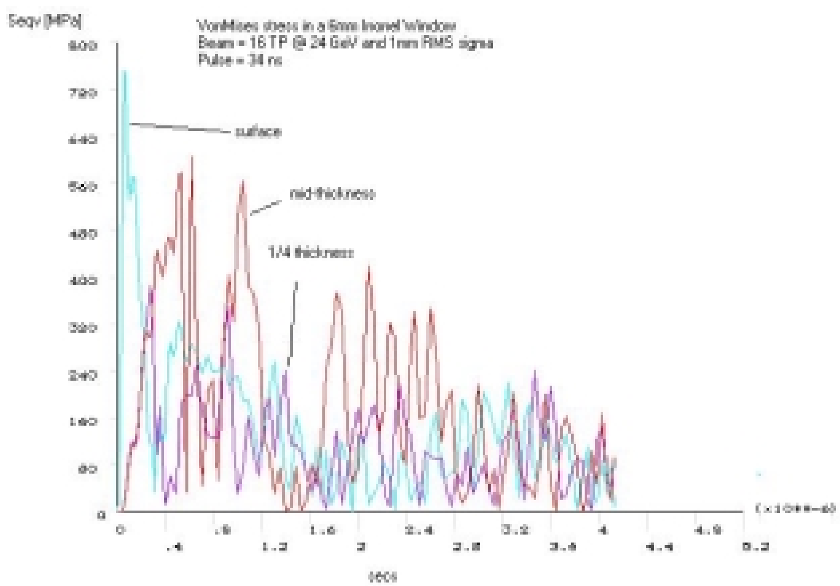




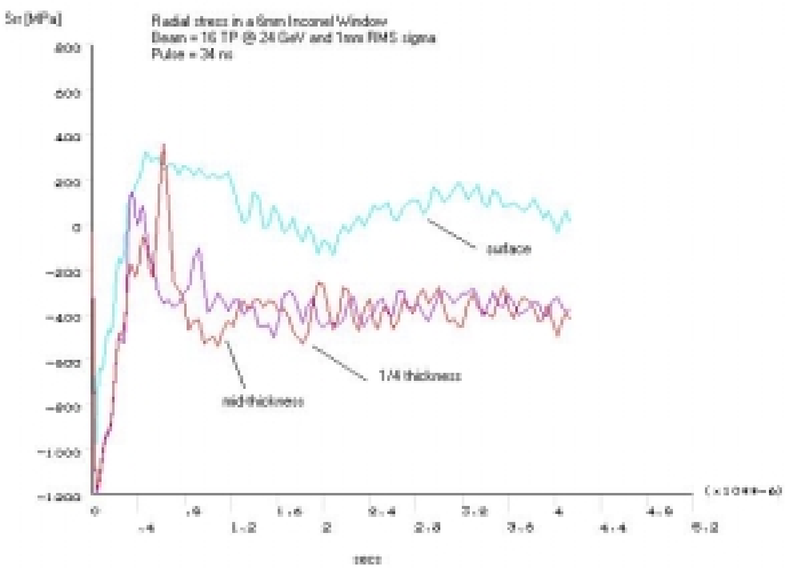
Thermal Shock Analysis of the Exp951 Windows
Inconel-718 Window Analysis

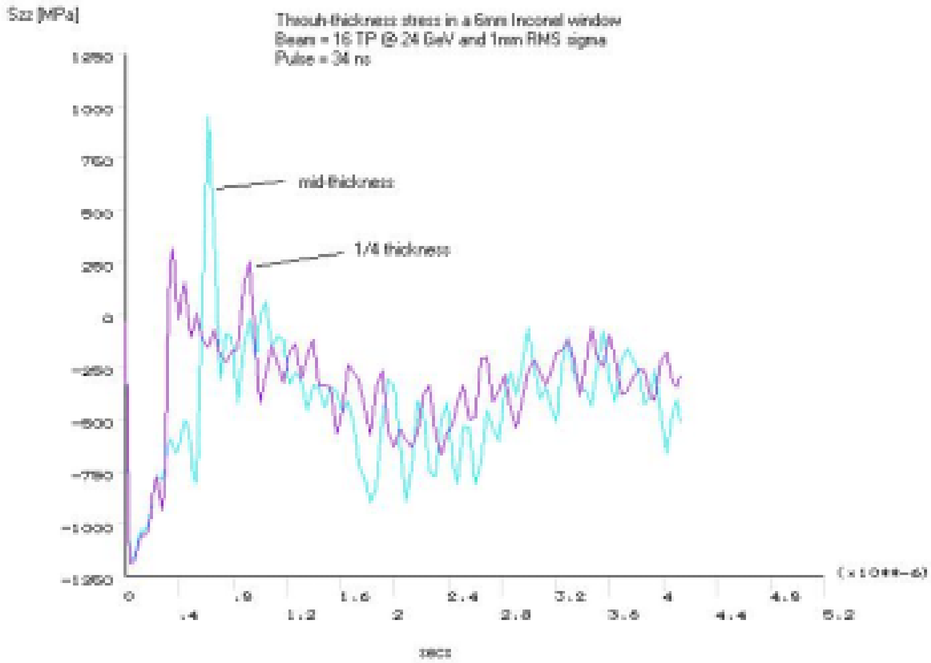




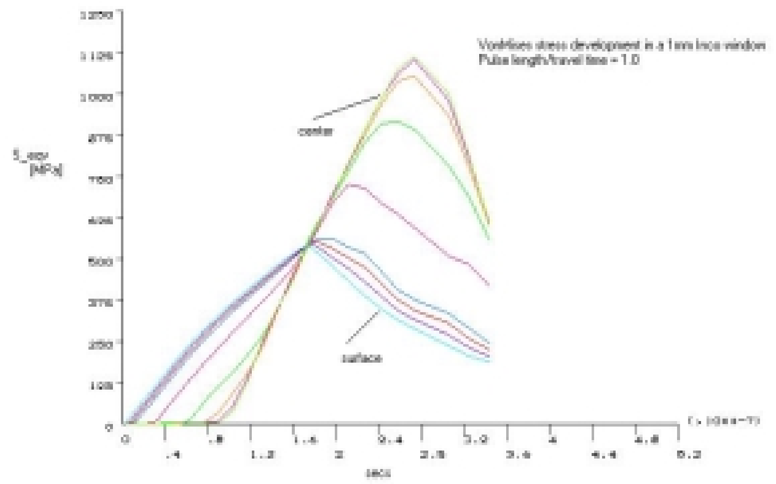


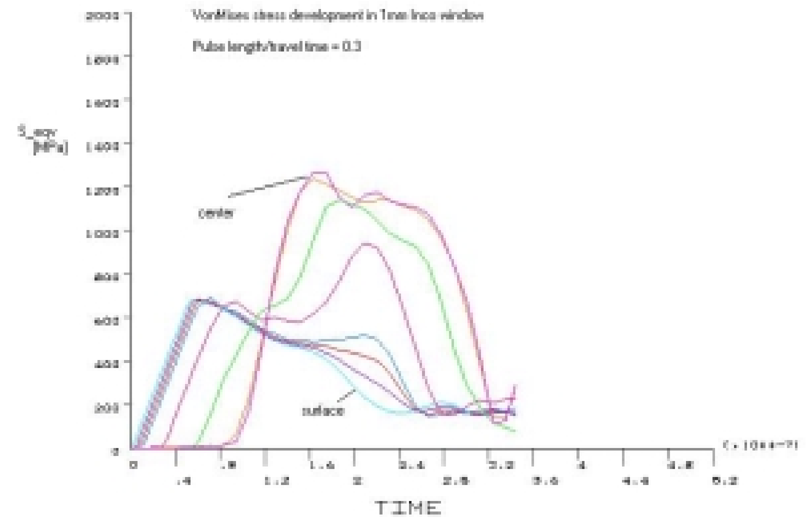
Thermal Shock Analysis of the Exp951 Windows
Inconel-718 Window Analysis

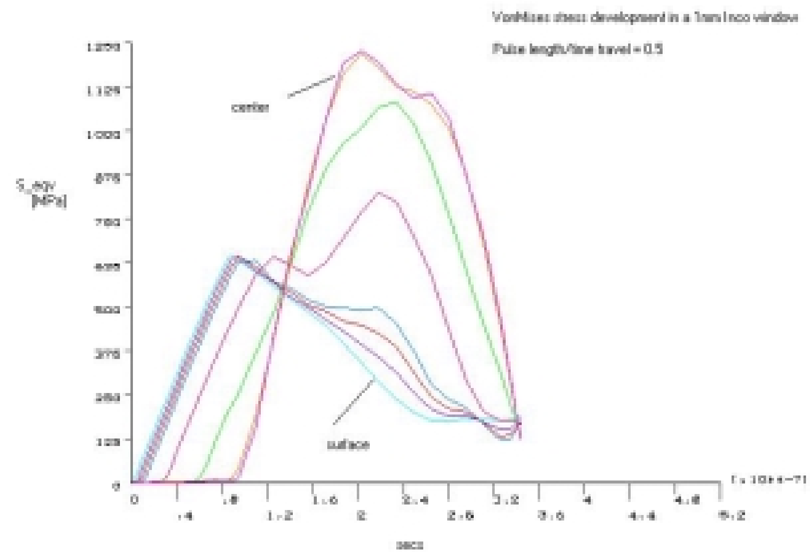




<u>Inconel-718 Window Analysis</u>
Effect of ratio [pulse/period] on shock stress development

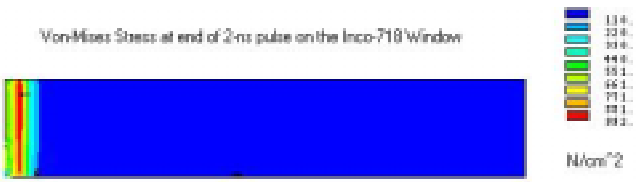


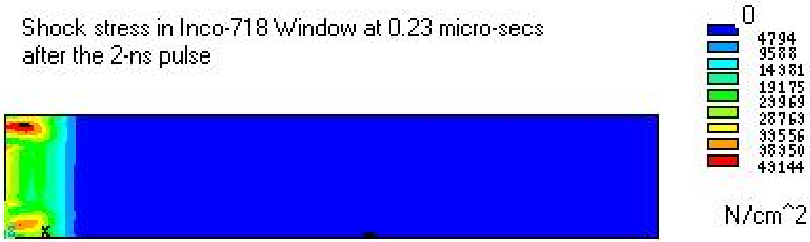




<u>Thermal Shock Analysis of the Exp951 Enclosure Window</u>

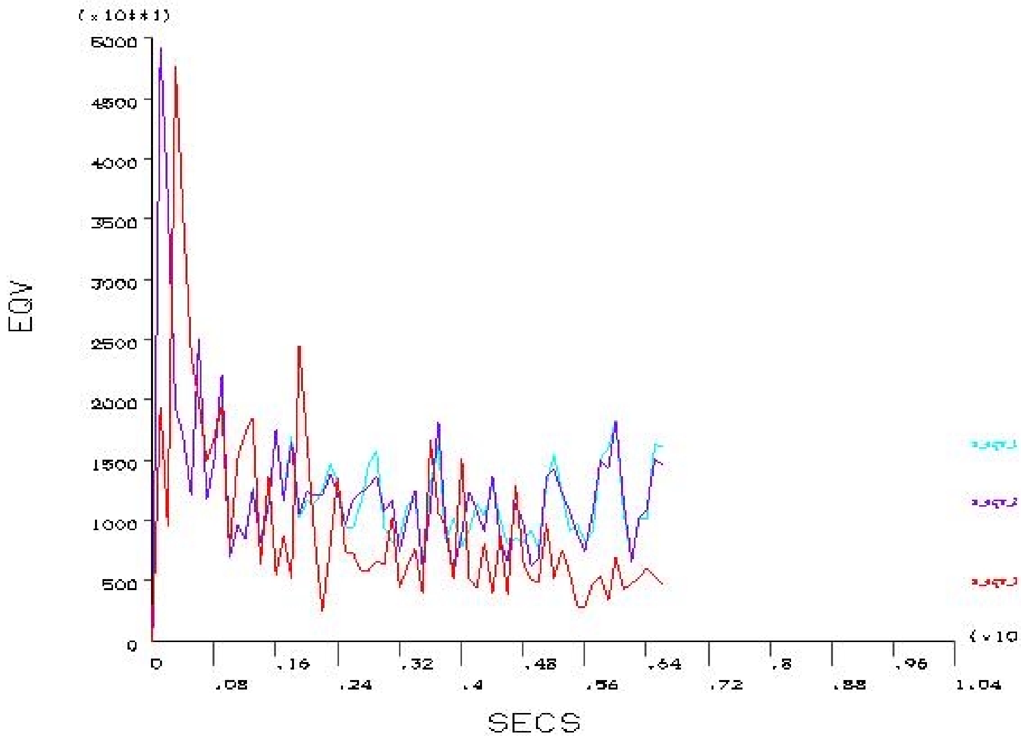
Von-Mises stress profiles for Inco -718 window and 2-ns pulse length

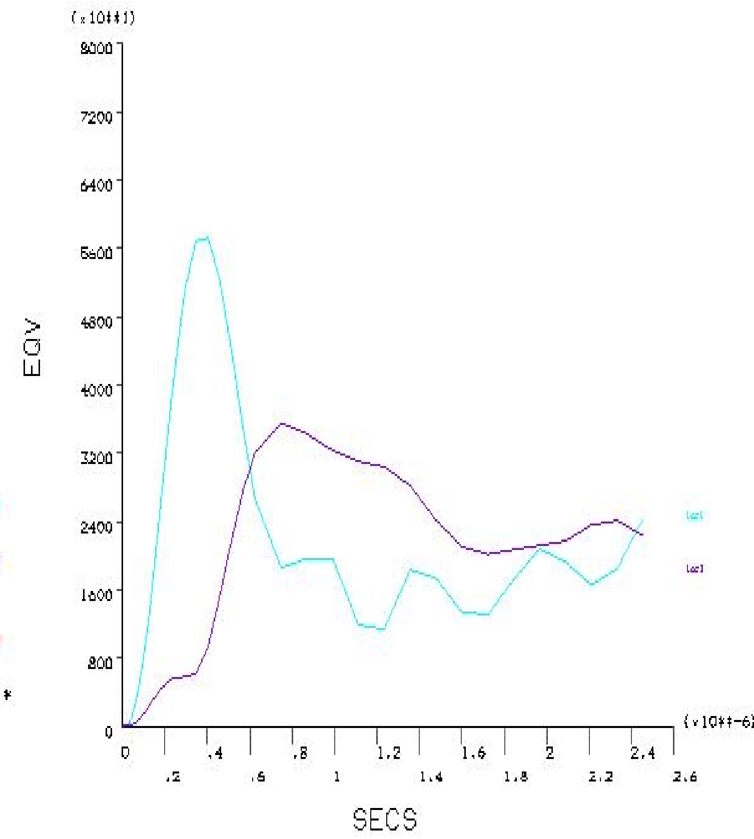




<u>Thermal Shock Analysis</u>

Von-Mises stress profile for steel window

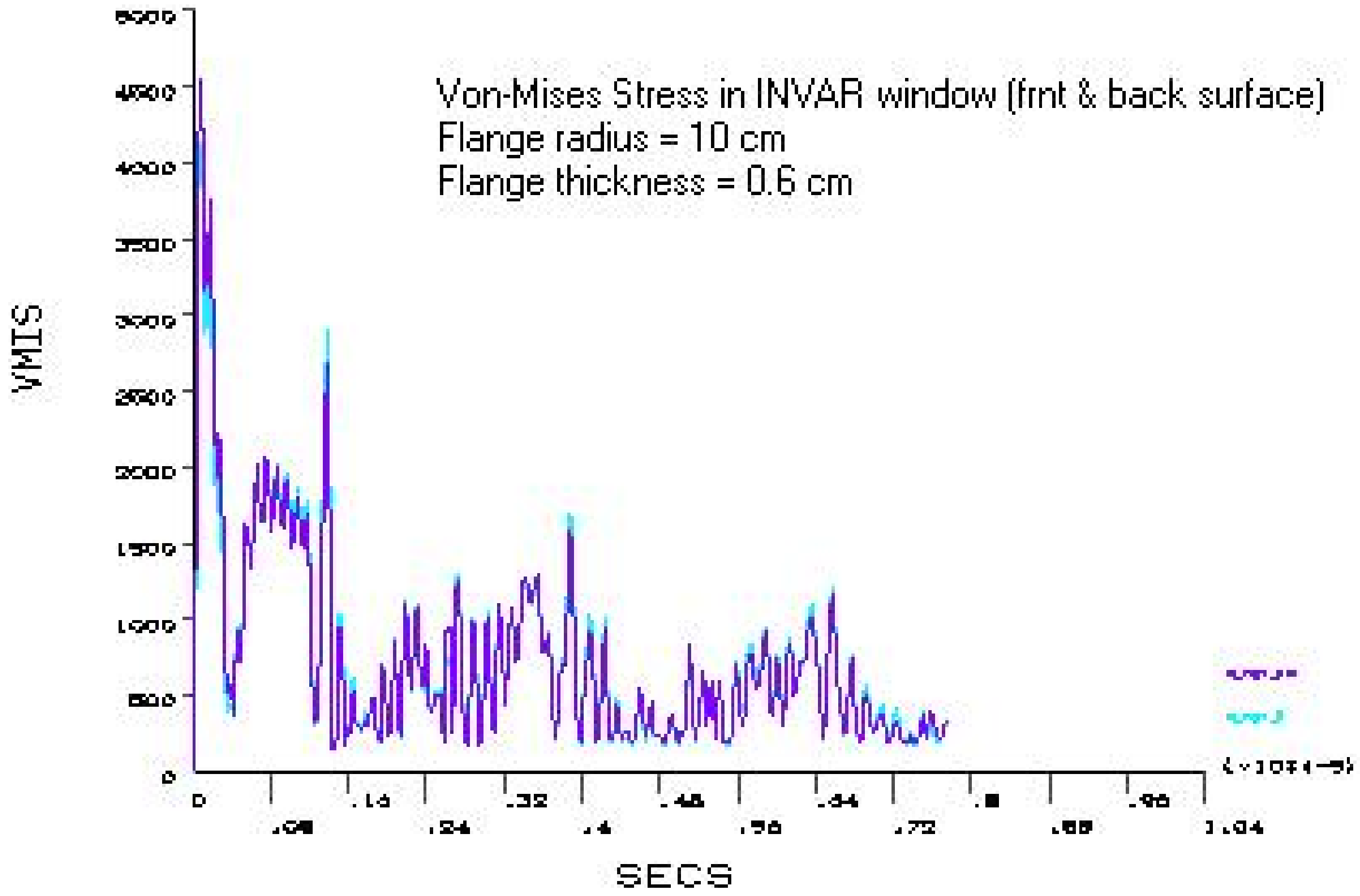




-Mises Stress at locations 1 & 3 following pulse

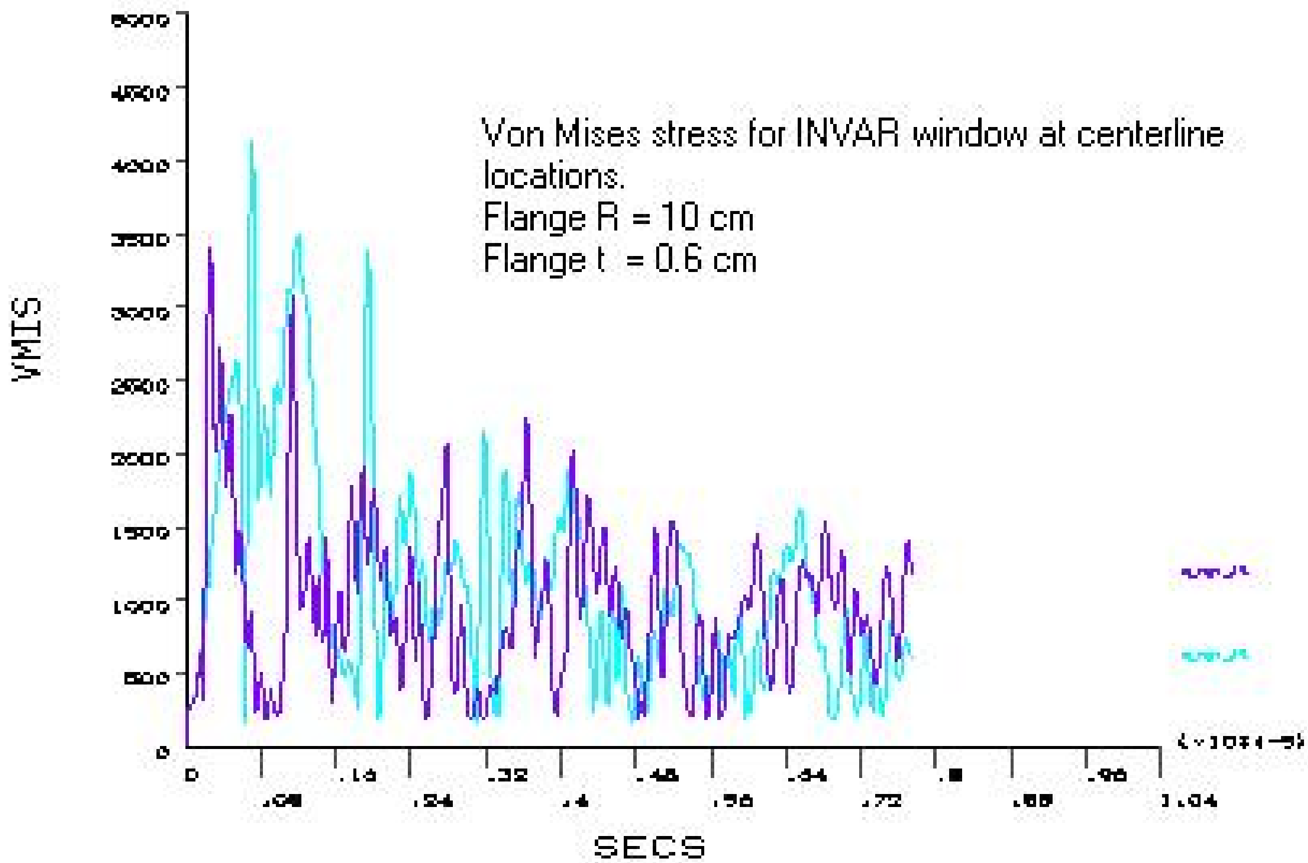
Thermal Shock Analysis

Von-Mises stress profiles for INVAR window



Thermal Shock Analysis

Von-Mises stress profiles for INVAR window



What is Window Failure and how it Impacts on Material Selection & Design

- **Vacuum Window Safety Factor dictated by Buckling Failure**
  - A safety factor of 4 is typical
- **Thermal Shock Failure**
  - enable material to withstand a single pulse
  - design against fatigue failure
- **Conservative estimate of trouble is exceeding the yield strength of material**
  - for catastrophic failure need to exceed ultimate strength
- **Fatigue failure can be short or long-term process**
  - one can barely overcome single-pulse safety and fatigue failure can arise after just few pulses !
  - Through-thickness ringing very important in estimating fatigue due to many cycles of stress it introduces before it dies out

Failure Assessment of E951 Windows
A3 Line Aluminum Windows

- Based on 16 TP/24 GeV beam, **1mm RMS sigma** & pulse = 34ns the peak vonMises stresses are for various thicknesses:
  - 3-mil = 303 Mpa
  - 6-mil = 360 Mpa
  - 12-mil = 436 Mpa
  - 24-mil = 368 Mpa
- Aluminum 5052 has Sy = 255 Mpa & Su = 290 Mpa

- Based on latest optics calculations, smallest beam spot in the Aluminum windows of A3 line are much larger than the 1mm RMS sigma providing ample safety factor

- Real beam pulse is triangular (in time space) with larger width (base ~ 100 ns)

Failure Assessment of E951 Windows
Experiment Windows

- Based on 16 TP/24 GeV beam, **1mm RMS sigma** & pulse = 34 ns
  - 1-mm (inconel) = 1360 Mpa
  - 2-mm = 1172 Mpa
  - 3-mm = 920 Mpa
  - 6-mm = 736 Mpa (640 MPa for 68 ns pulse !)
  - 12-mm = 860 MPa
- **Inconel 718 Strength: Sy = 1034 MPa & Su = 1240 MPa**

- **Based on latest optics calculations, smallest beam spot at target is smaller than 1mm sigma [0.5mm for x and y]**
  - this will leave no safety factor
  - windows may move upstream and downstream
  - re-consider INVAR or Beryllium
- **Real beam pulse is triangular (in time space) with larger width (base ~ 100 ns)**