Beam Window Analysis
Muon Collider Project
Experiment 951

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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
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  - pulse structure and length

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
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 = \( \frac{E \cdot \alpha \cdot DT}{1-2\cdot pr} \)
Two-dimensional simplification of a thin structure does not quite apply
  - directional stress in 2-D = \( \frac{E \cdot \alpha \cdot DT}{1-pr} \)
  - \( 1-D = E \cdot \alpha \cdot DT \)
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
  - \( \text{stress}(t) = f(x-ct) + f(x-ct) \) \[c = \text{speed of sound in material} \]
  - \( \text{period of ringing} = 2h/c \) \[h = \text{window thickness} \]
Thermal Shock Analysis of the Exp951 Windows
A3 Line 3-inch diameter and 6-mil thick Aluminum Window

FIGURE: VonMises Shock Stress in Aluminum Window [R=1.5" t=6mil]
Beam spot = 1mm rms sigma
Pulse width = 34 ns
Beam = 16 TP @ 34 GeV

\[ S_{\text{eqv}} \times 10^{11} \text{[N/cm}^2] \]
\[ S_{\text{eqv max}} = 326 \text{ MPa} \]
\[ S_{\text{eqv max near surface}} = 260 \text{ MPa} \]

boundary/centerline
mid-thick centerline
mid-radius [r=1.5"]

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

FIGURE: Radial Shock Stress in Aluminum Beam Window [D=3" t=6mil]
Beam spot size = Gaussian with 1mm RMS sigma
Pulse Length = 34ns
Beam Properties = 16 TP @ 24 GeV

- $S_{rr}$ @ $R=r/2$
- $S_{rr}$ @ $r=0$
- $S_{rr}$ min = 333 MPa
Thermal Shock Analysis of the Exp951 Windows
A3 Line 3” 3-mil Aluminum Window

FIGURE: Radial Shock Stress in a 3-mil Aluminum Window
Beam = 1mm RMS sigma
Pulse = 34 ns
Thermal Shock Analysis of the Exp951 Windows
A3 Line 3-inch diameter and 3-mil thick Aluminum Window

FIGURE: Equivalent Shock Stress in a 3-mil Aluminum Window
Beam = 1mm RMS sigma
Pulse = 34 ns

max = 270 Mpa
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
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Inconel-718 Window Analysis
Effect of ratio [pulse/period] on shock stress development
Thermal Shock Analysis of the Exp951 Enclosure Window

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

Shock stress in Inco-718 Window at 0.23 micro-secs after the 2-ns pulse

Shock wave in Inco-window 1.2 micro-secs after pulse
Thermal Shock Analysis
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

Von-Mises Stress in INVAR window (frnt & back surface)
Flange radius = 10 cm
Flange thickness = 0.6 cm
Thermal Shock Analysis
Von-Mises stress profiles for INVAR window

Von Mises stress for INVAR window at centerline locations.
Flange $R = 10\, \text{cm}$
Flange $t = 0.6\, \text{cm}$
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 $S_y = 255$ Mpa & $S_u = 290$ 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
  $\sim 100$ 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)