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Safety Committee Presentation
Experiment 951
Beam Window Analysis

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E951 Window Analysis Overview

- **Proton Beam Structure**
  - 15 TP, 24 GeV, Gaussian profile
  - spot size
  - pulse structure and length
- **Beam/window interactions**
  - A3 Line Windows
  - E951 Target enclosure windows

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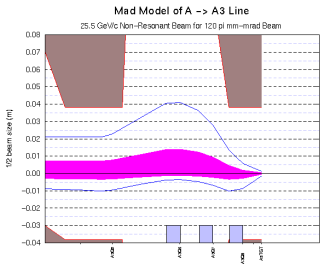
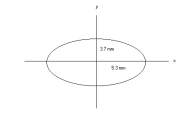
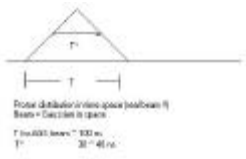
Beam Parameters Used in Window Safety Analysis







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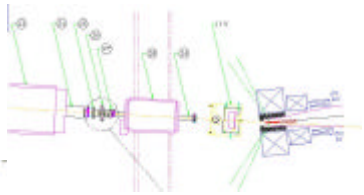
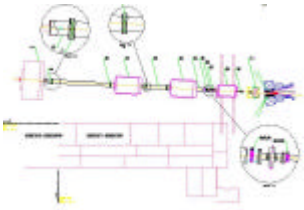
A3 Line

- **A3 Line near E951**





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A3 Line Windows

- **Material used is different series Aluminum**
  - 5052 series available in 3-mil thickness
  - 3000 series available in 5-mil thickness
- **Concern is the TP per pulse coupled with a small beam spot**
- **Experience from previous experiments showed good window response**
  - order of magnitude higher in single-pulse TP for E951

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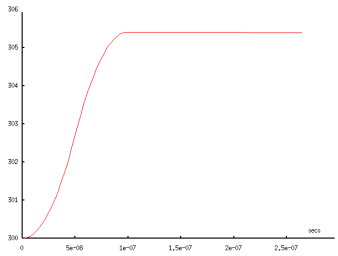
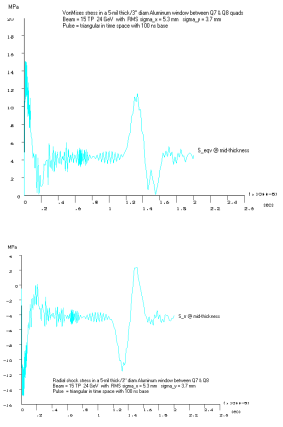
A3 Line Windows Results

- Optimal location between Q7 and Q8
- Delta-T per pulse ~ 5 C
- Von-Mises stress ~ 16 MPa
- Yield strength = 255 MPa





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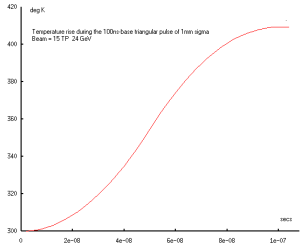
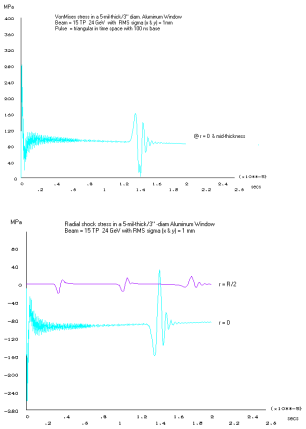
A3 Line Windows Results

- Window past last quad (Q8)
- Delta-T per pulse ~ 110 C
- Von-Mises stress ~ 290 MPa
- Yield strength = 255 MPa





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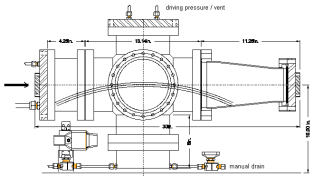
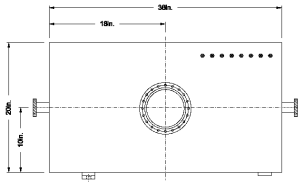
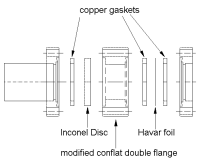
E951 Target Enclosure Windows

- Secondary containment windows
- double window concept for primary containment







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E951 Target Enclosure Windows

- **Family of materials assessed**
  - INVAR
  - SS 316
  - SS 301
  - Inconel-718
  - HAVAR
- **Beam spot size same as on target**
  - 0.5 mm RMS sigma
  - deposition ~ 300 Joules/gram

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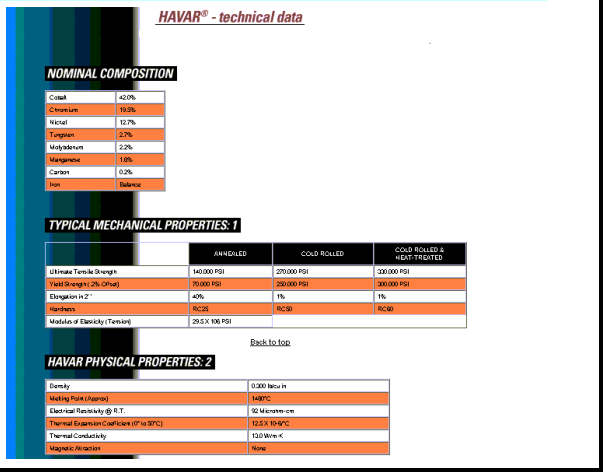
Target Enclosure Window Optimal Material HAVAR



HAVAR® - technical data

NOMINAL COMPOSITION

Cobalt	42.0%
Chromium	19.9%
Nickel	12.7%
Tungsten	2.7%
Molybdenum	2.2%
Manganese	1.6%
Carbon	0.2%
Iron	Balance

TYPICAL MECHANICAL PROPERTIES: 1

	ANNEALED	COLD ROLLED	COLD ROLLED & HEAT-TREATED
Ultimate Tensile Strength	140,000 PSI	270,000 PSI	320,000 PSI
Yield Strength (.2% Offset)	70,000 PSI	250,000 PSI	300,000 PSI
Elongation in 2 "	40%	1%	1%
Hardness	RC25	RC50	RC60
Modulus of Elasticity (Tension)	29.5 X 106 PSI		

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HAVAR PHYSICAL PROPERTIES: 2

Density	0.300 lb/cu in
Melting Point (Approx)	1493°C
Electrical Resistivity @ R.T.	92 Microhm-cm
Thermal Expansion Coefficient (0° to 93°C)	12.5 X 10-6/°C
Thermal Conductivity	13.0 W/m-K
Magnetic Attraction	None

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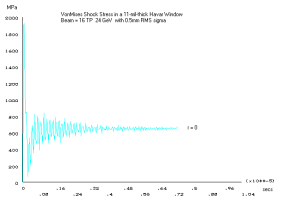
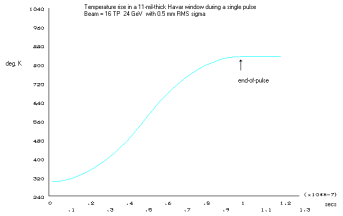
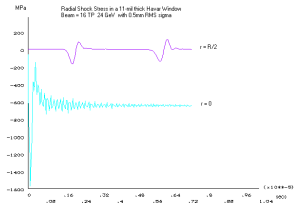
Target Enclosure Window Results
11-mil thick HAVAR

- Beam rms sigma = 0.5 mm
- 16 TP per pulse
- Delta-T per pulse ~ 532 C
- Von-Mises stress ~ 1900 MPa
- Yield strength = 1930 MPa







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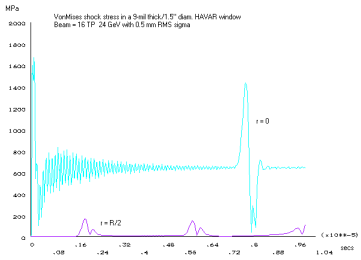
Target Enclosure Window Results
9-mil thick HAVAR

- Beam rms sigma = 0.5 mm
- 16 TP per pulse
- Delta-T per pulse ~ 532 C
- Von-Mises stress ~ 1640 MPa
- Yield strength = 1930 MPa



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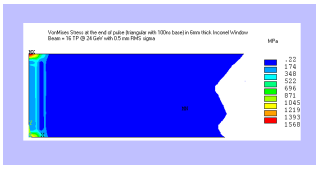
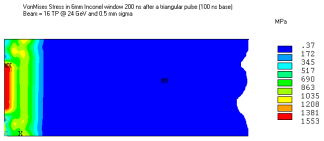
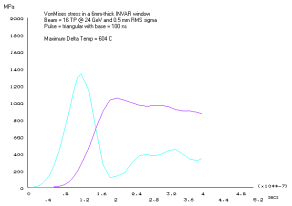
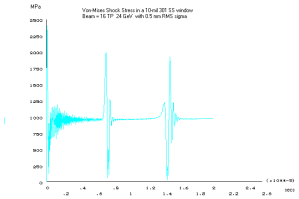
Target Enclosure Window Results
Inconel-718 - SS 301 - INVAR

- Beam rms sigma = 0.5 mm
- 16 TP per pulse









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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
  - directional stress (3D) ó = Å á ÄÔ/1-2í
- 2-D simplification of a thin structure does not quite apply
  - ó = Å á ÄÔ/1-í (2-D)
  - ó = Å á ÄÔ (1-D)
- 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

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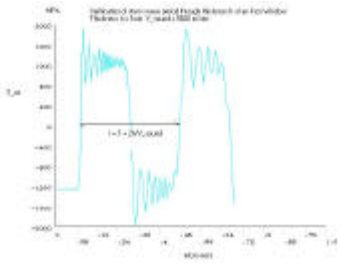
Background on Thermal Shock and Window Failure Estimation



- 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]

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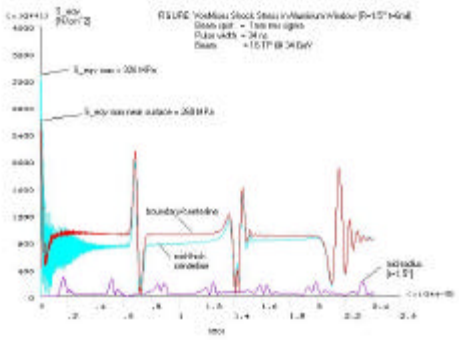
Thermal Shock Analysis
3-inch diameter/6-mil thick Aluminum window



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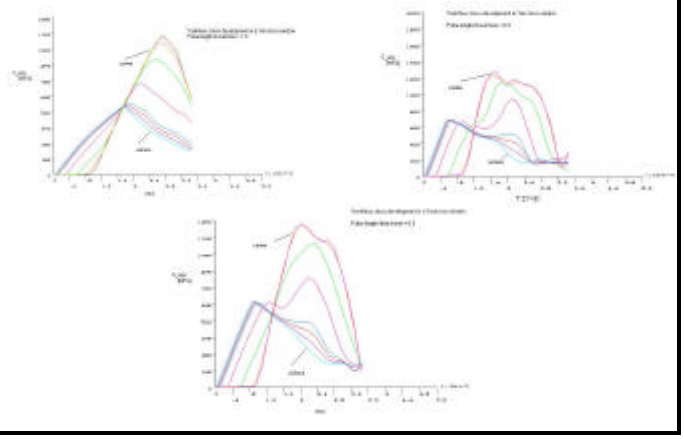
Inconel-718 Window Analysis
Effect of ratio [pulse/period] on shock stress development



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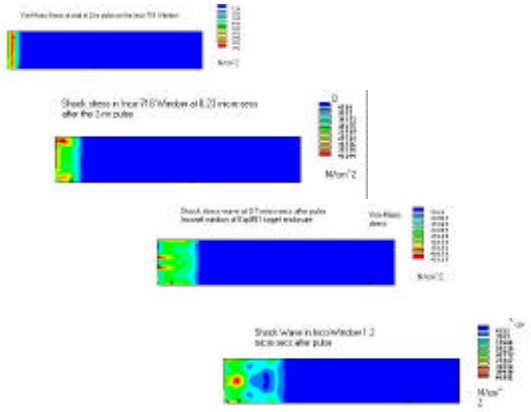
Thermal Shock Analysis of the Exp951 Enclosure Window
Von-Mises stress profiles for Inco -718 window and 2-ns pulse length



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

- **Vacuum Window Safety Factor dictated by buckling failure**
- **Thermal Shock Failure**
  - enable material to withstand a single pulse
  - design against fatigue failure
- **Conservative estimate of exceeding 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

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Assessment of E951 Windows
A3 Line Aluminum Windows

- Based on 15 TP/24 GeV beam, a beam spot **5.3mm x 3.7 mm RMS sigma** & pulse a triangular pulse structure with 100 ns base, the peak shock stress experienced by the most critical aluminum window is of the order of 15 MPa
- Available aluminum 5000-series has S_{yield} = 255 MPa & $S_{ultimate}$ = 290 MPa
- Based on latest optics calculations, all upstream locations from critical beam window will see even larger beam spot, providing even higher safety
- Therefore, all A3 Line aluminum windows will be well within the safety limits

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Assessment of E951 Experiment Windows

- Based on 16 TP/24 GeV beam, **0.5 mm RMS sigma** & pulse structure with 100 ns at base, a window made of HAVAR will be the best candidate given that
  - the temperature rise is in excess of 530 C
  - an 11-mil thick Havar will experience a shock close to the yield strength
- The ACTUAL protons-per-pulse will be significantly less than the 16 TP used for all calculations (~ 6 TP) thus providing a safety factor of almost 3
- Such tight beam spot (0.5 mm RMS sigma) may not be achieved with the current configuration and thus providing further latitude on safety factor
- The double window concept (Havar/inconel-718 combination) on both sides of the target assembly will provide the best defense for maintaining integrity of the enclosure