MERIT Experiment Window Study

- Proton Beam Windows
- Optical Windows

N. Simos, PhD, PE

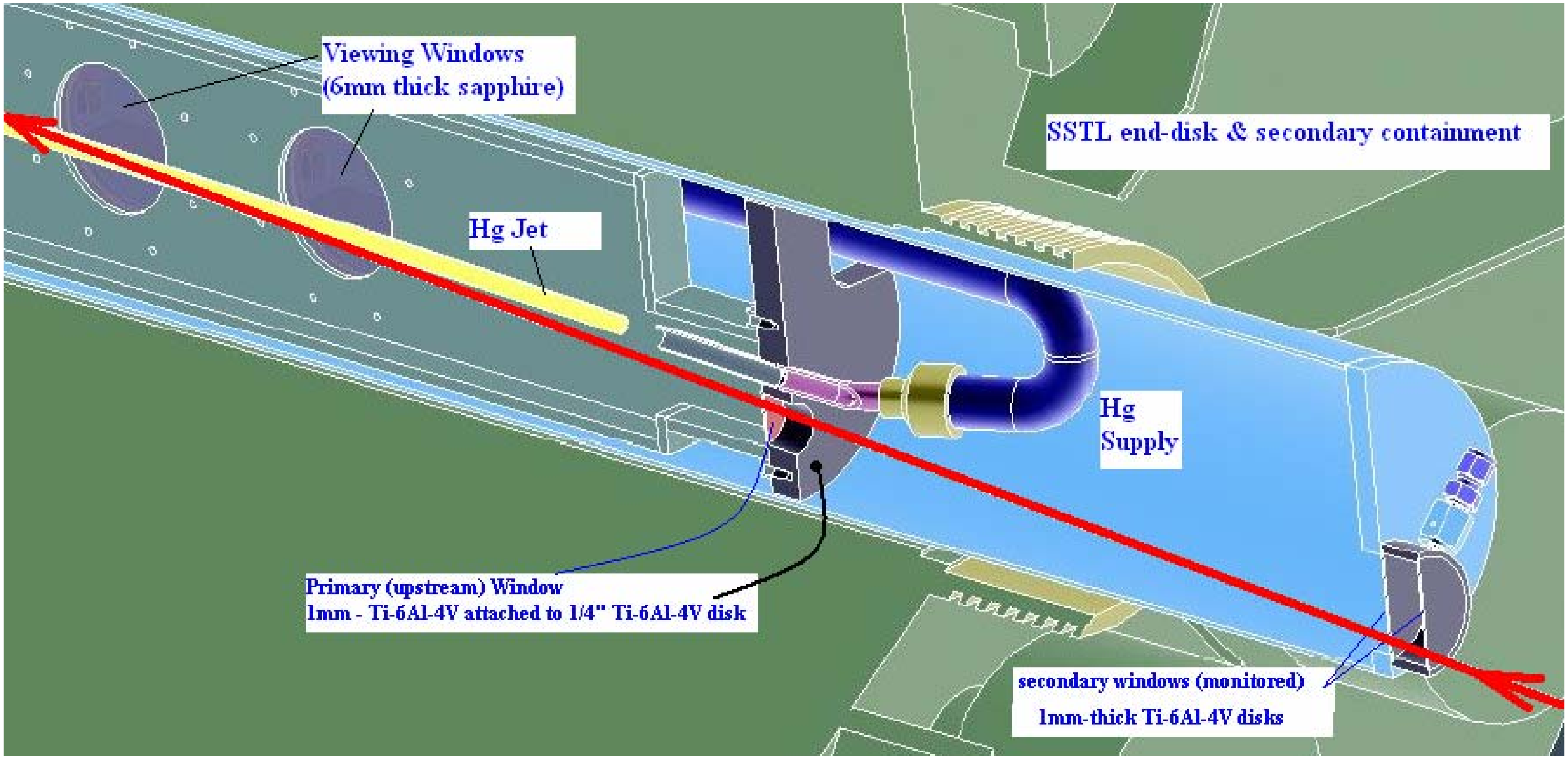
Energy Sciences & Technology Department

Brookhaven National Laboratory

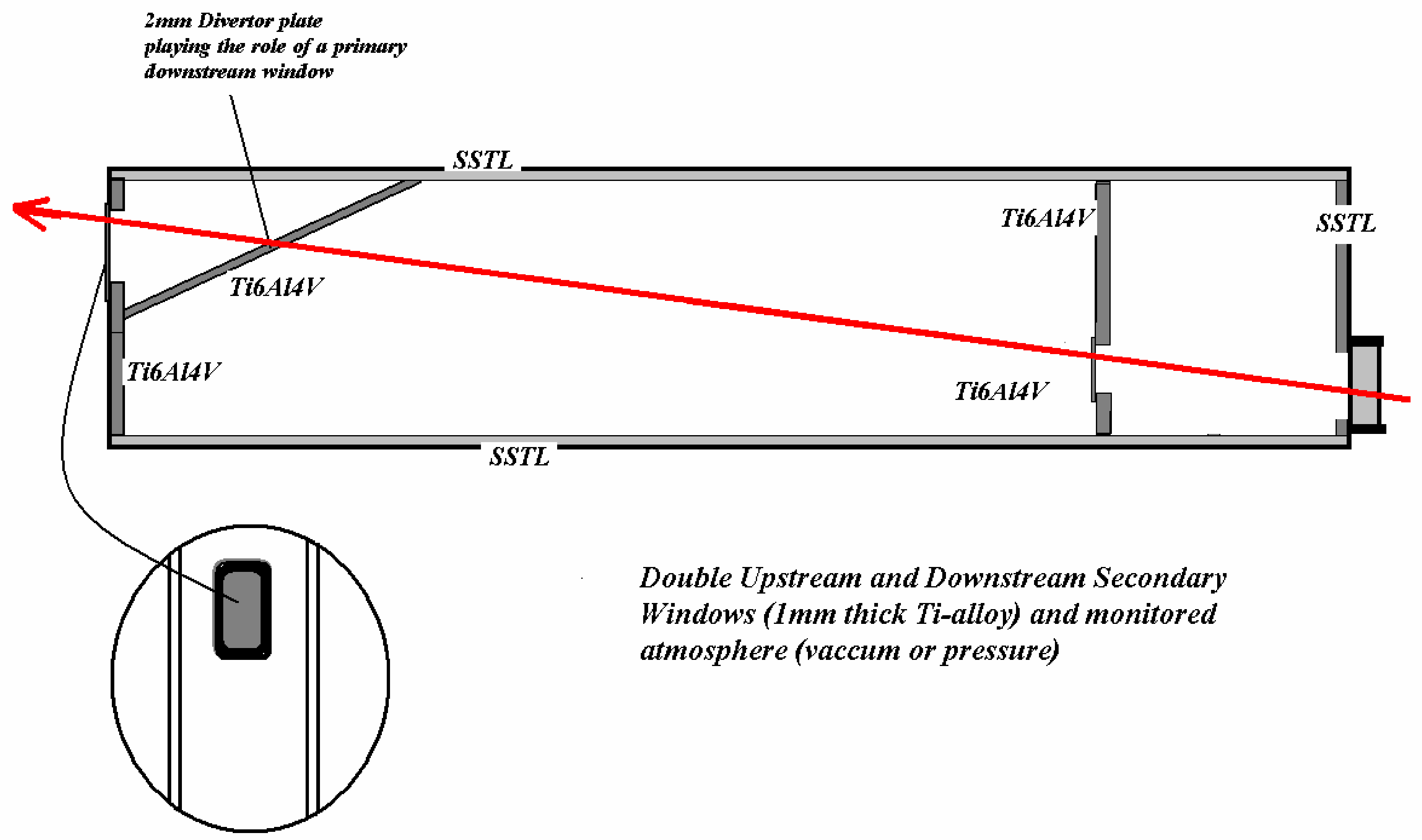
simos@bnl.gov

BNL Review - December 12, 2005

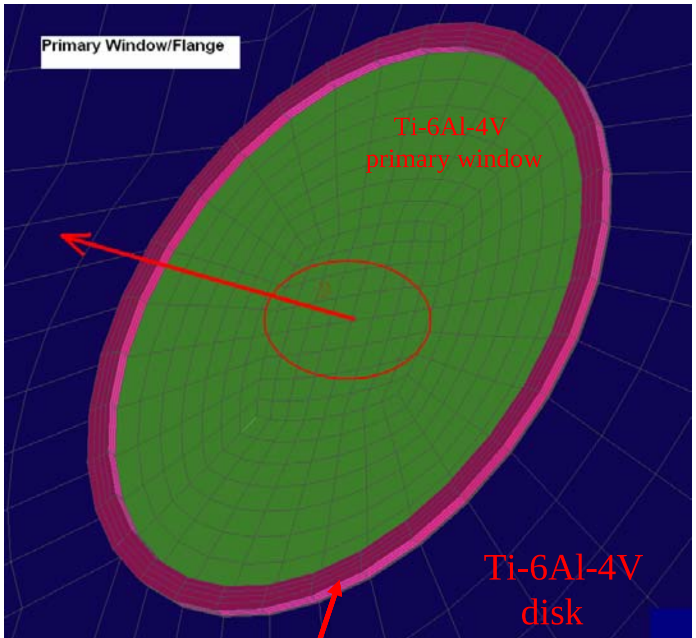
MERIT Hg Jet Target Concept & Window Integration



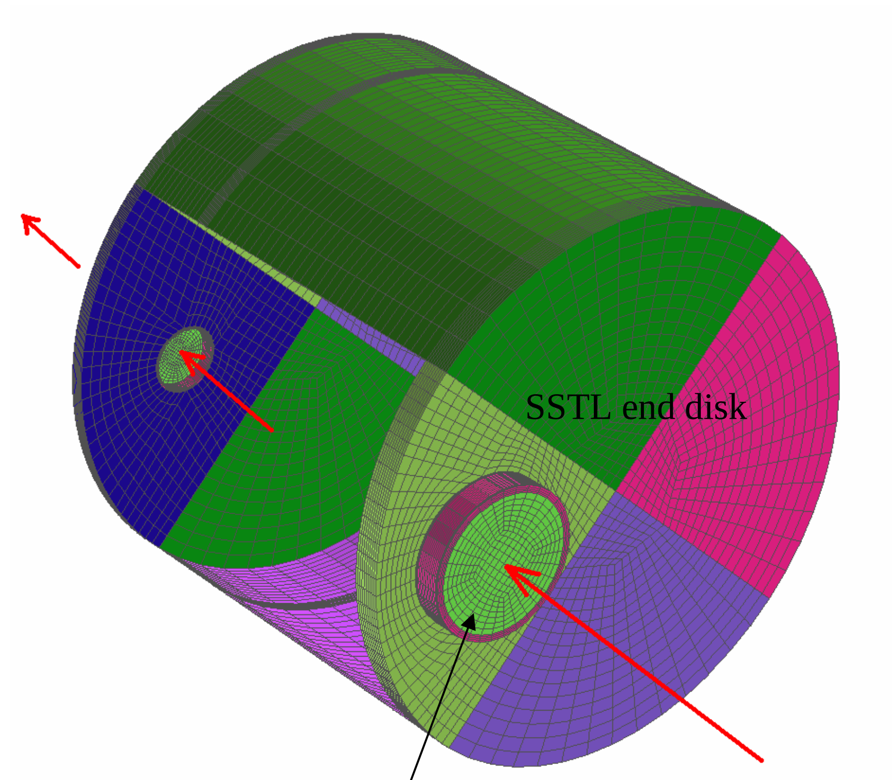
Baseline Target Assembly Concept



Primary & Secondary Beam Windows - Baseline

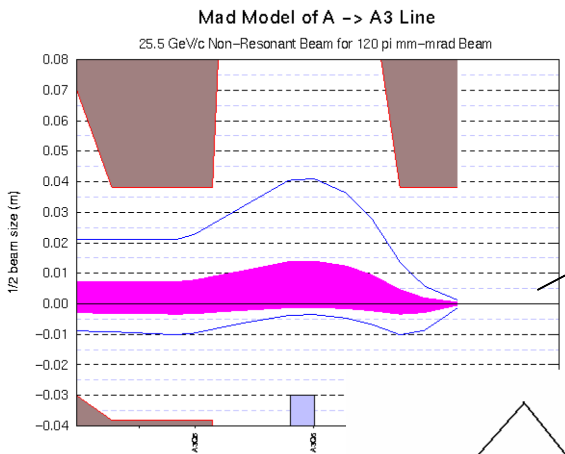


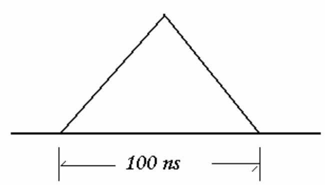
Primary window “collar” to allow welding onto the thicker disk



Secondary window pair (1mm Ti-6Al-4V)

ENSURING THAT Hg is HERMETICALLY ISOLATED
E951 experiment experience





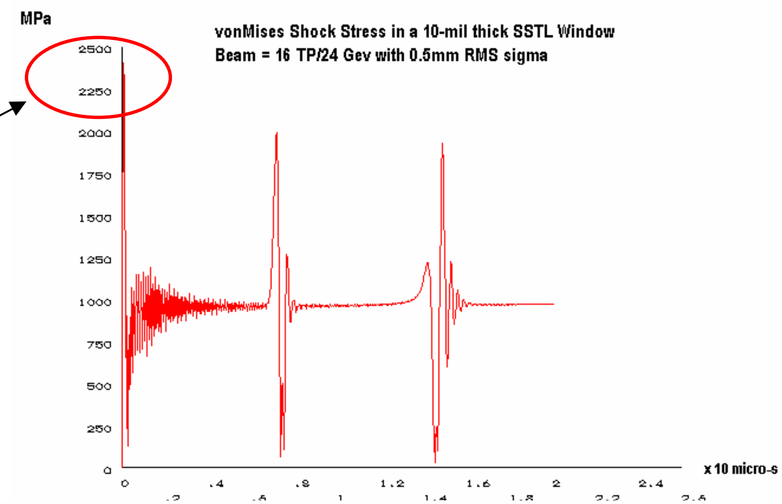
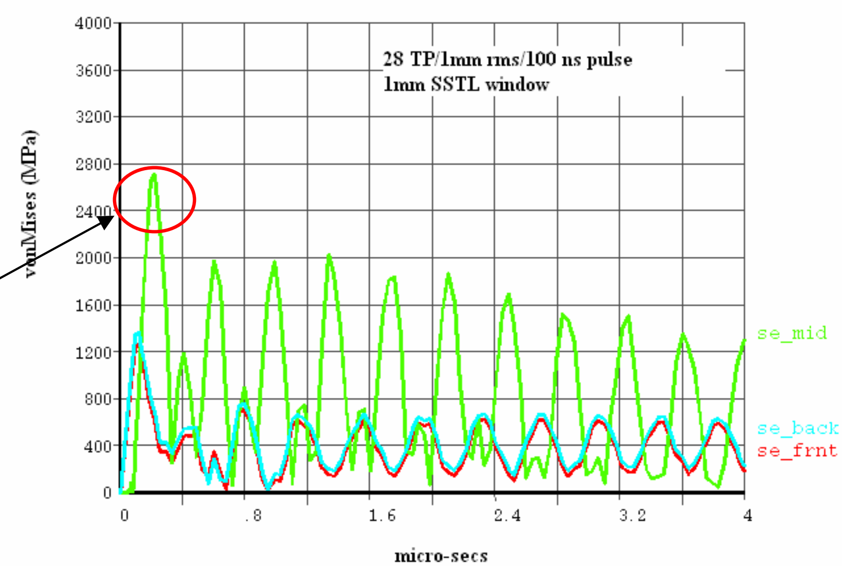


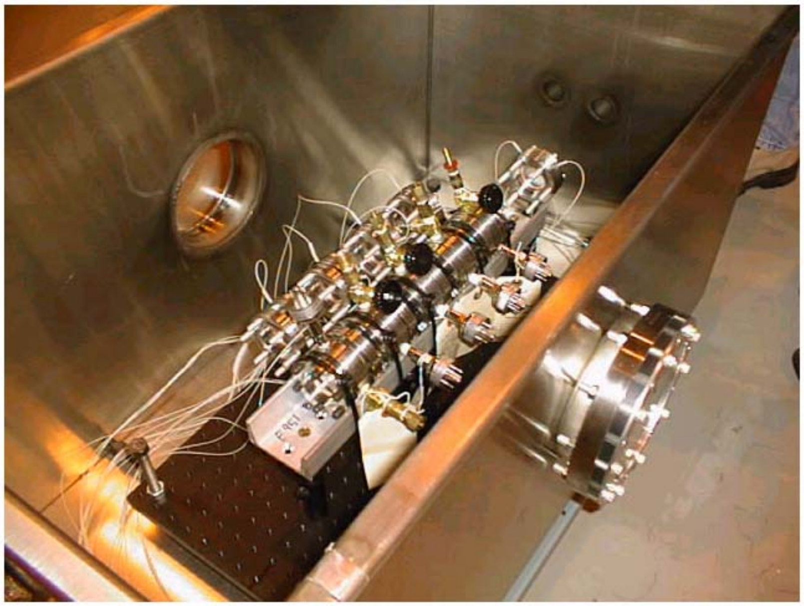
Figure above depicts the tight beam spot requirement (0.5 x 0.5 mm rms) for target experiment at AGS

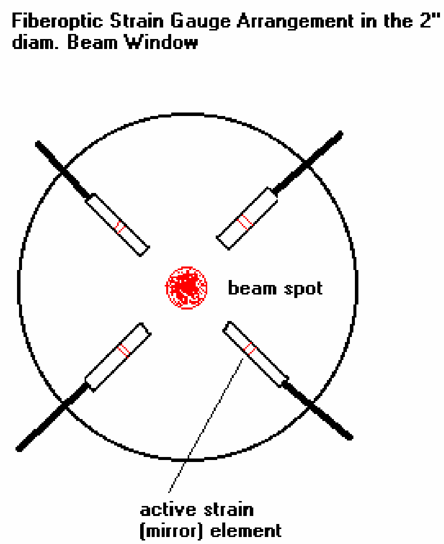
Induced shock stress in a window structure by 16 TP intensity beam and the spot above will likely fail most materials in a single short pulse (~ 2 ns)



MERIT Experiment Issues with SSTL Windows

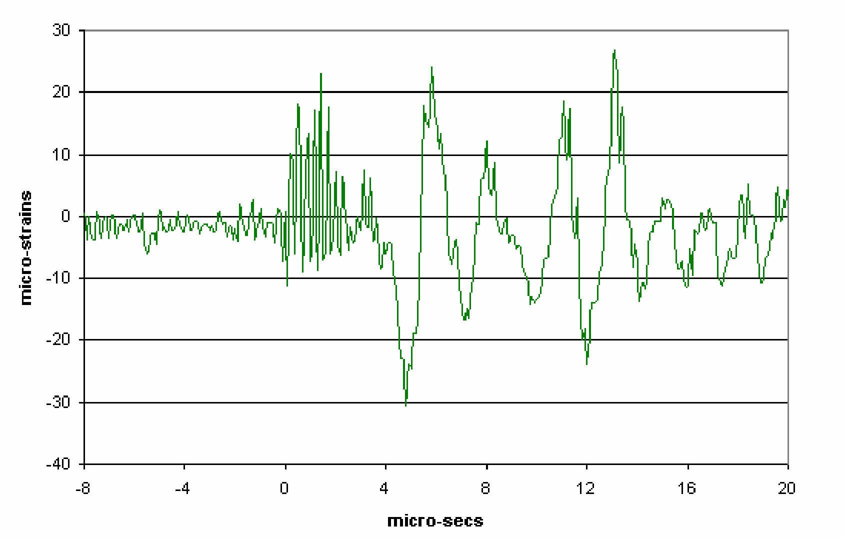
E951 Beam Window Testing (Al-6061; Ti-6Al-6V; Havar; Inconel-718)

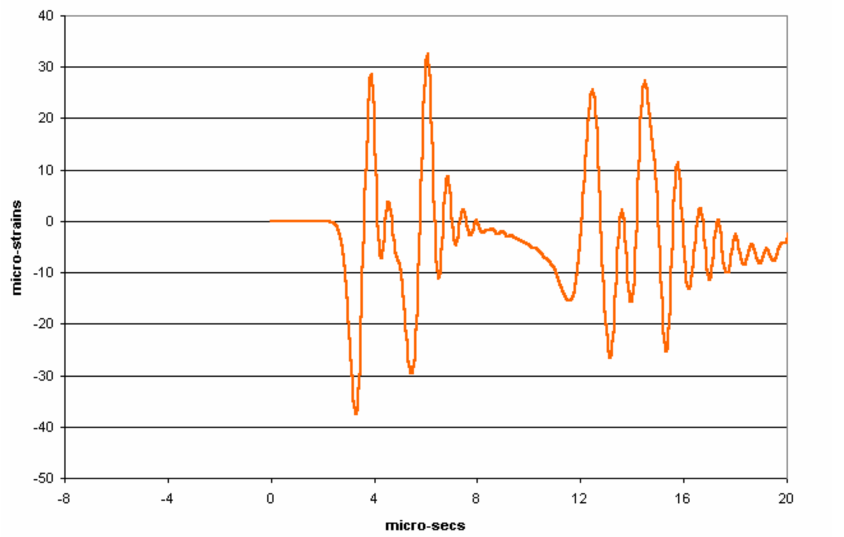


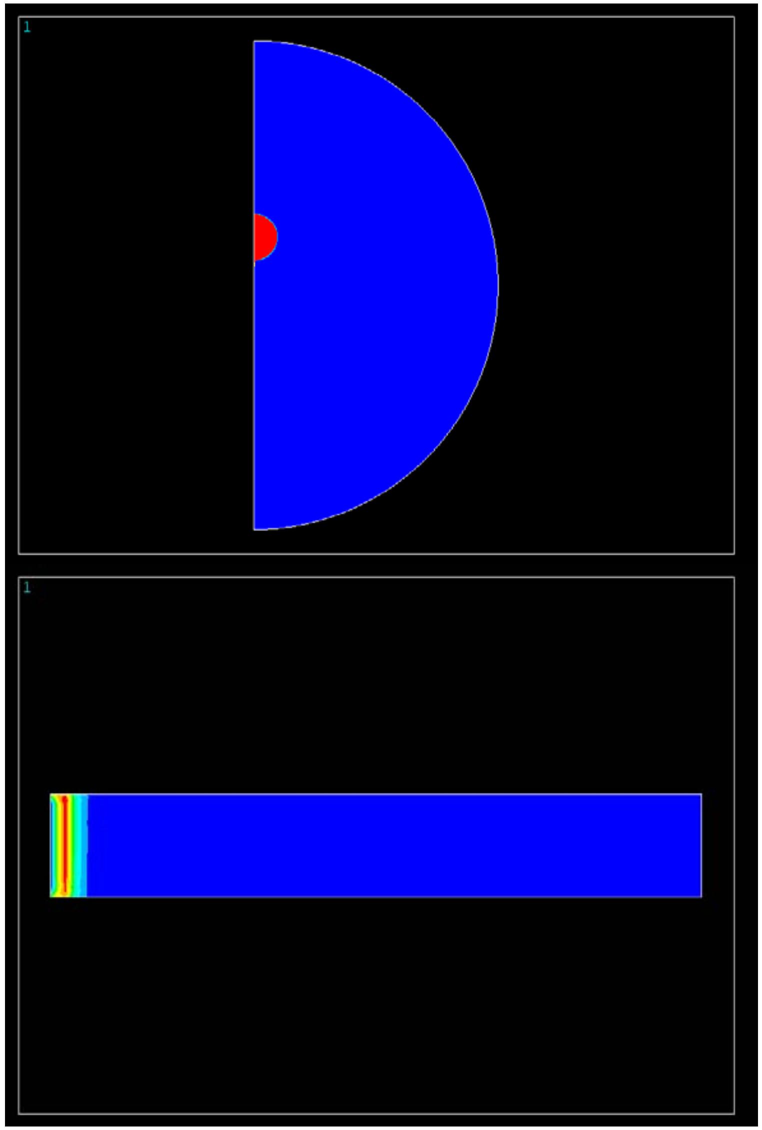


Beam Window Experimental Studies(E951)

Experimental Strain Data vs. Simulation







Ti-6Al-6V tested as beam window with the24 GeV AGS Beam (3.5 TP)

MERIT experiment ➔ Ti-6Al-4V

Important: Tests at BNL showed that Hg does not attack the aluminum of the alloy composition.

The composition of Ti6Al4V Grade 5

	Content
C	<0.08%
Fe	<0.25%
N_2	<0.05%
O_2	<0.2%
Al	5.5-6.76%
V	3.5-4.5%
H_2(sheet)	<0.015%
H_2(bar)	<0.0125%
H_2(billet)	<0.01%
Ti	Balance

Fabrication

- Weldability – Fair
- Forging – Rough 982°C (1800°F), finish 968°C (1775°F)
- Annealing - 732°C (1350°F), 4hr, FC to 566°C (1050°F), A.C. F.C. not necessary for bars
- Solution Heat Treating – Forgings
- Ageing – 904-954°C (1660-1750°F), 5 min-2hrs, W.Q. 538°C (1000°F), 4hr, A.C.

Physical Properties

Typical physical properties for Ti6Al4V.

Property	Typical Value
Density g/cm^3 (lb/ cu in)	4.42 (0.159)
Melting Range °C±15°C (°F)	1649 (3000)
Specific Heat J/kg.°C (BTU/lb/°F)	560 (0.134)
Volume Electrical Resistivity ohm.cm (ohm.in)	170 (67)
Thermal Conductivity W/m.K (BTU/ft.h.°F)	7.2 (67)
Mean Co-Efficient of Thermal Expansion 0-100°C /°C (0-212°F /°F)	8.6x10^{-6} (4.8)
Mean Co-Efficient of Thermal Expansion 0-300°C /°C (0-572°F /°F)	9.2x10^{-6} (5.1)
Beta Transus °C±15°C (°F)	999 (1830)

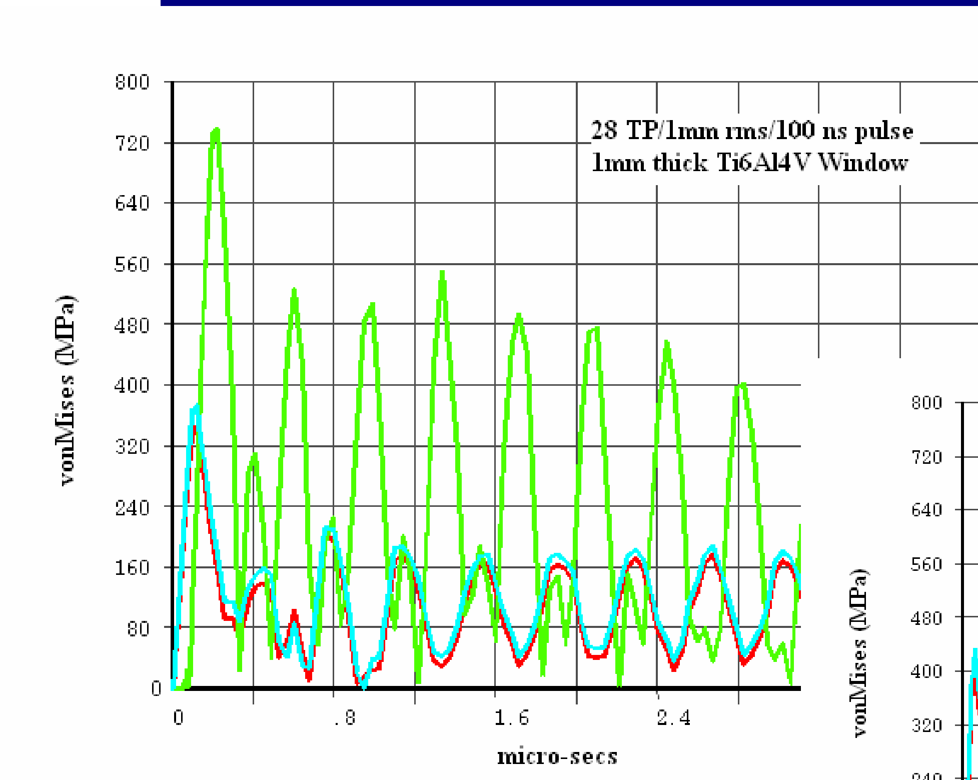
Mechanical Properties

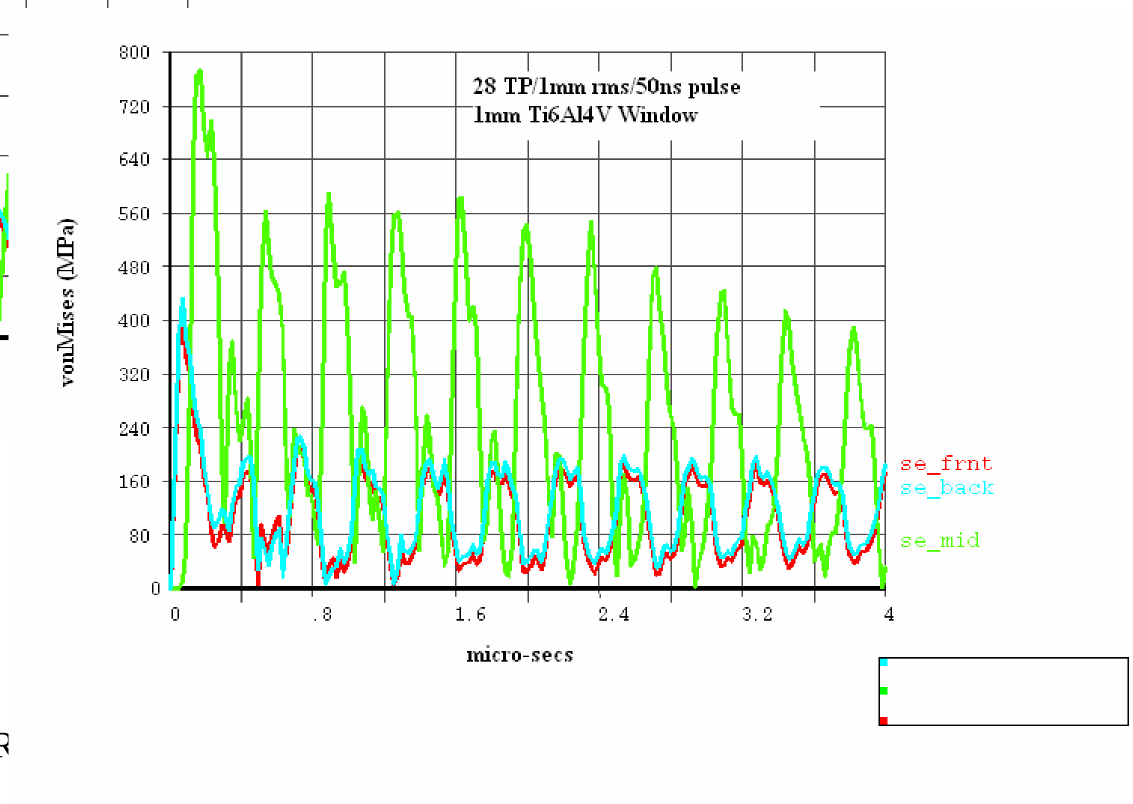
Typical mechanical properties for Ti6Al4V.

Property	Minimum	Typical Value
Tensile Strength MPa (ksi)	897 (130)	1000 (145)
0.2% Proof Stress MPa (ksi)	828 (120)	910 (132)
Elongation Over 2 Inches %	10	18
Reduction in Area %	20	
Elastic Modulus GPa (Msi)		114 (17)
Hardness Rockwell C		36
Specified Bend Radius <0.070 in x Thickness		4.5
Specified Bend Radius >0.070 in x Thickness		5.0
Welded Bend Radius x Thickness	6	
Charpy, V-Notch Impact J (ft.lbf)		24 (18)

Beam Window Study on T-6Al-4V: Establishing Thicknesses

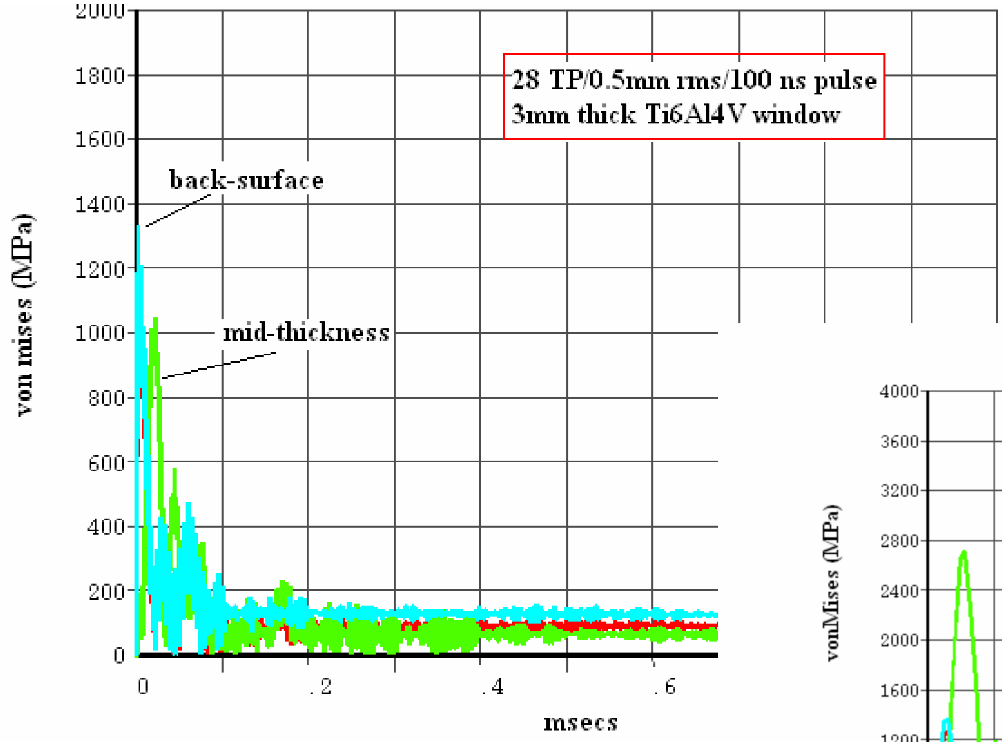
1mm rms spot assumed in analysis (smaller than what will be actually seen by the experiment Windows thus allowing for SF in the calculations)

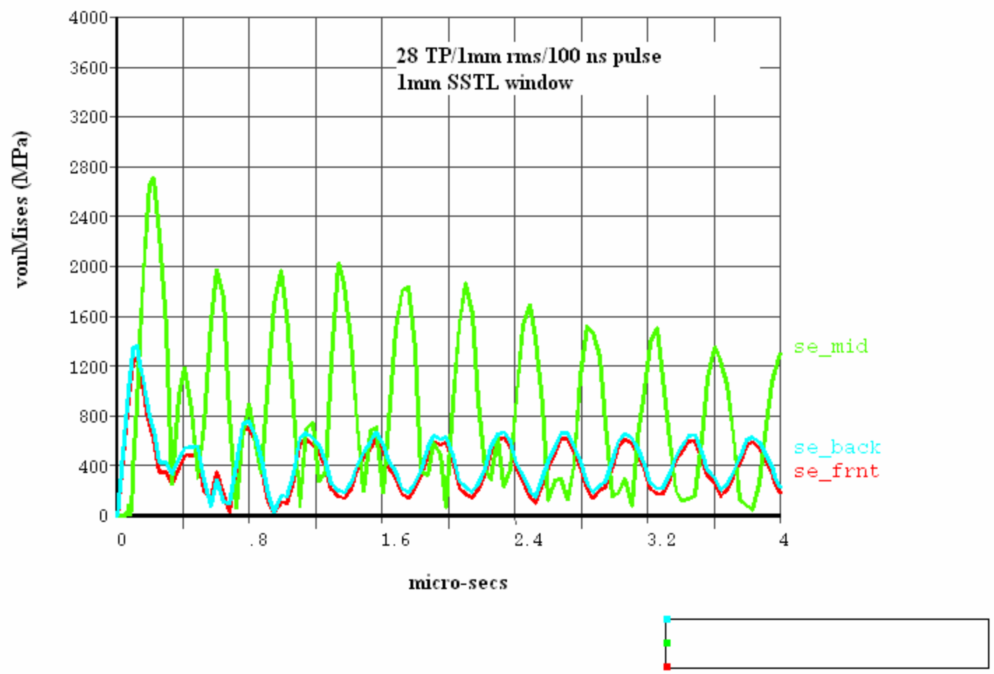




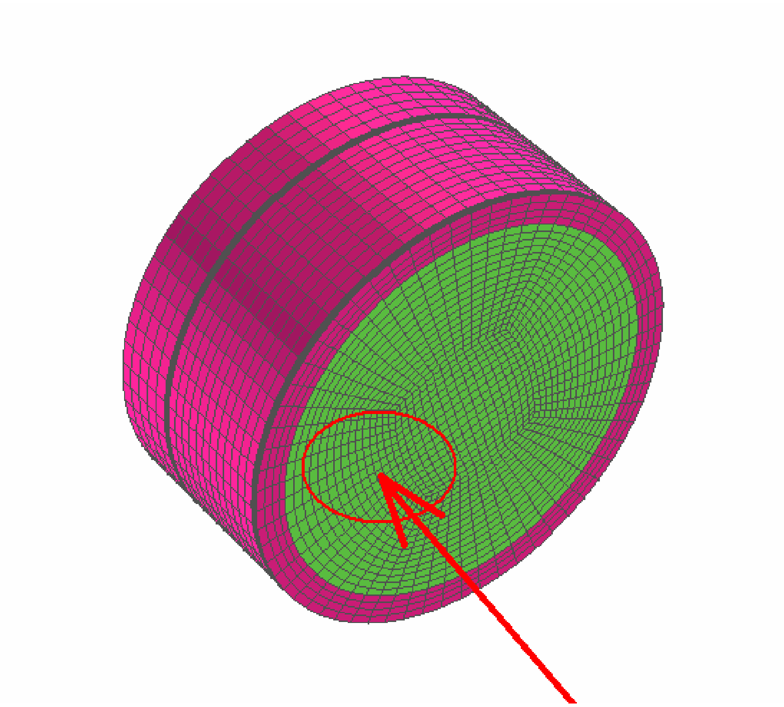
BNL R

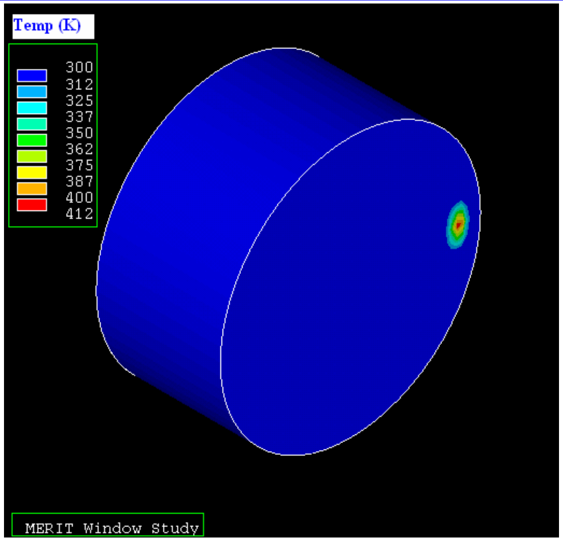
Beam Window Study on T-6Al-4V and SSTL choices

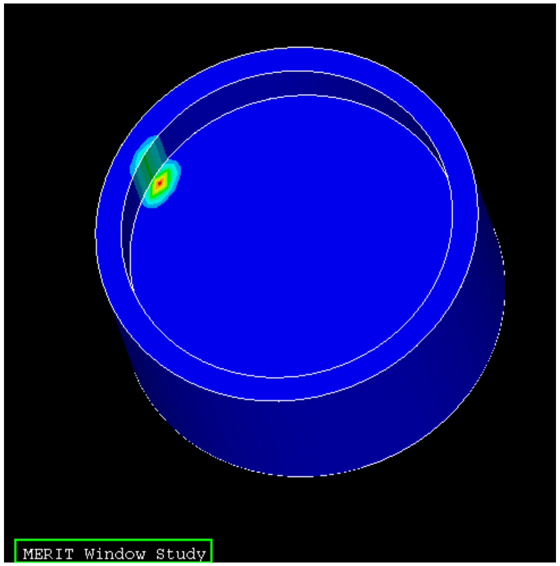




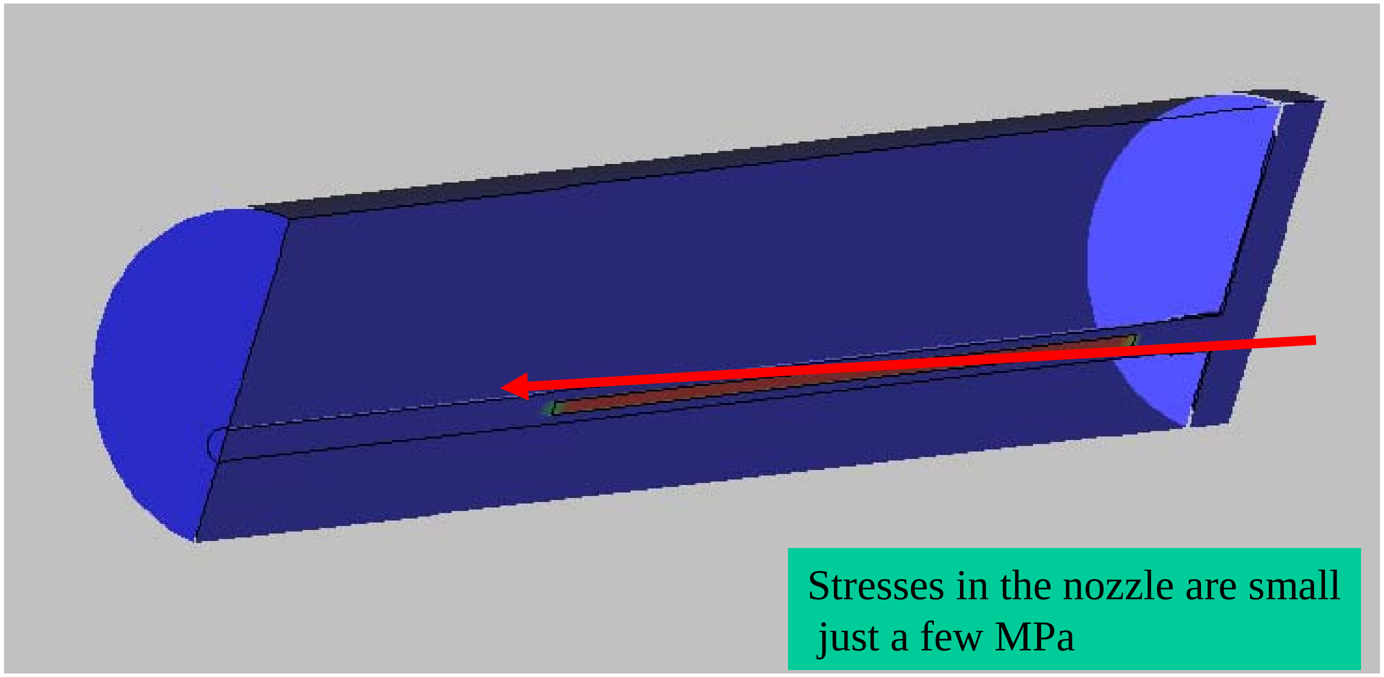
Beam/Window Interaction Analysis
What happens if beam wobbles and catches the edge

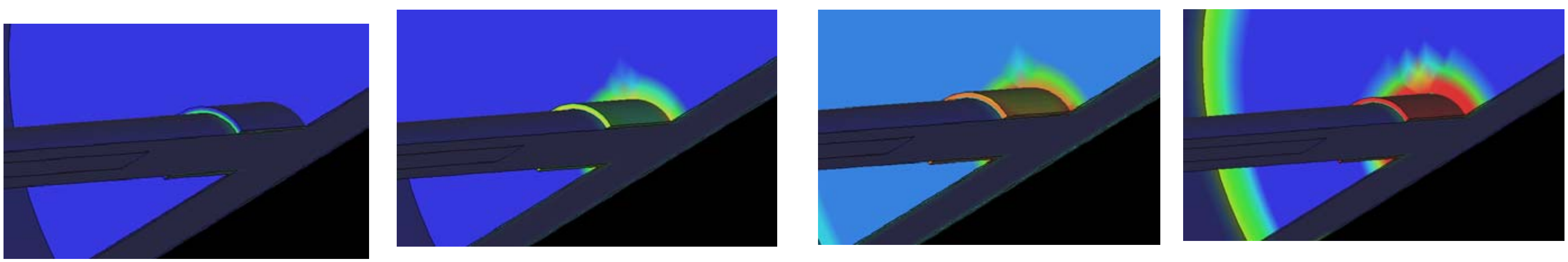






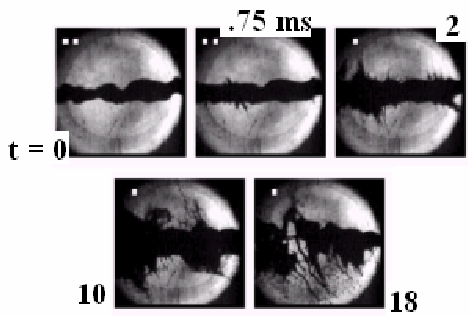
Beam/Jet Interaction Analysis
Nozzle damage from waves in mercury?





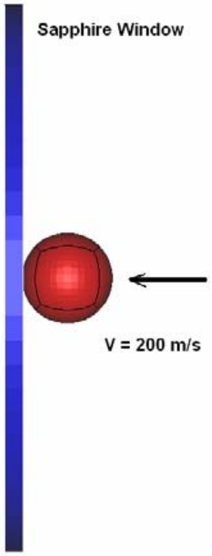
Hg Jet Destruction & Viewing Window Safety Analysis

Optical Window Vulnerability Study



Mercury jet interaction with 24 GeV 3.8 TP beam of the E951 experiment

Entering into BALLISTICS !!!!



Beam-induced Hg jet destruction

In the “bigger picture” goal is to benchmark a simulation of the event with test data. The benefit will be a clear understanding of how quickly jet destructs and thus provide information as to how close micro-pulses in the real muon collider can be stacked

What are we dealing with? Projectile velocity estimates

$$K.E. = \tfrac{1}{2}\,\rho\, dV\, \boldsymbol{U}_r^2 = \Delta P\, \delta(dV)$$

$$\Delta P \approx \alpha_v\, \Delta T / k$$

$$\alpha_v = (\partial V / \partial T)_P$$

$$\delta(dV) = \alpha_v\, dV\, \Delta T$$

$$\boldsymbol{U}_r^2 / \boldsymbol{c}^2 = 2\, \alpha_v^2\, \Delta T^2$$

$$\boldsymbol{U}_r = \sqrt{2}\, [\alpha_v\, \Delta T]\, \boldsymbol{c}$$

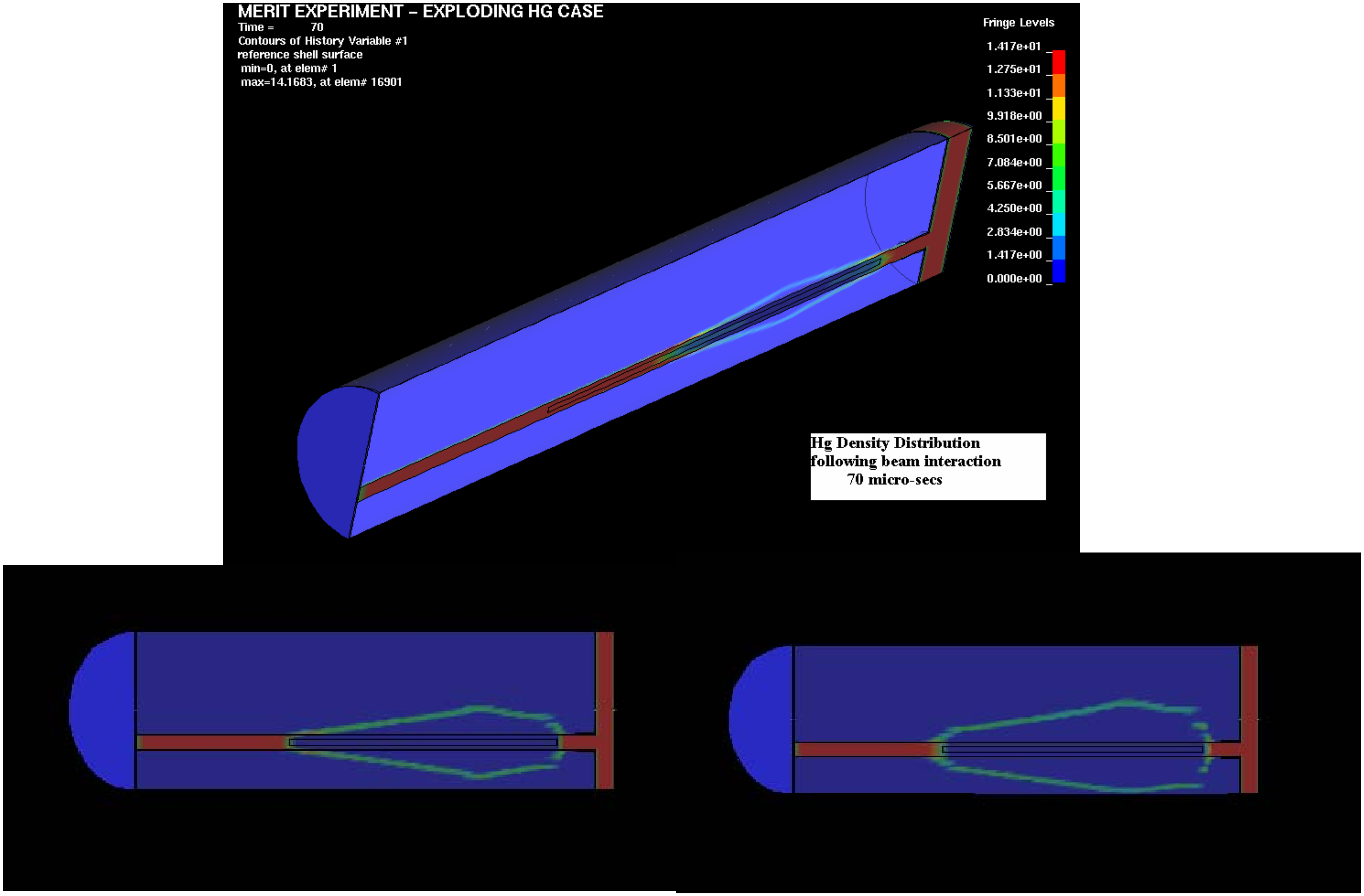
Physical Properties of Mercury

Density: $\rho = 13.5$ x gm/cm^3
Compressibility: $\kappa = 0.45 \times 10^{-10}$ m^2/N
Volumetric Thermal expansion: $\alpha_v = 18.1 \times 10^{-5}$ K^{-1}
Specific Heat: $c_v = 140$ J/Kg K
Velocity of Sound = 1300 m/s
Critical Point Temperature: $T_{cr} = 1593^\circ$ C
Critical Point Pressure: $P_{cr} = 185$ MPa

Based on beam energy deposition & Hg properties

Velocities of ~ 200 m/s are expected

Preliminary beam-induced jet destruction analysis – NO Magnetic Field



Selecting the appropriate material and thickness to protect against the worst-case scenario (projectile with max momentum)

•Sapphire has been selected as the optical window (excellent strength properties including fracture ~ 8 Joules/m^2) – protect against thru cracks

•6mm thickness (such thickness does not impede the optics)

•Explore other thicknesses for future applications (2mm & 4mm)

Mechanical			
Compressive Strength	MPa @ R.T.	ASTM C773	2000
Tensile Strength	MPa @ R.T.	ACMA Test #4	250 - 400
Modulus of Elasticity (Young's Mod.)	GPa	ASTM C848	250 - 400
Flexural Strength (MOR)	MPa @ R.T.	ASTM F417	760 - 1035
Poisson's Ratio, υ	-	ASTM C818	0.29
Fracture Toughness, K_{Ic}	MPa x $m^{1/2}$	Notched Beam Test	1.89

OVERVIEW OF Sapphire Window Vulnerability

Expertise in ballistics/impacts and ALE formulations allowed the modeling and analysis of a series of cases that included the formation of cracks in the sapphire window

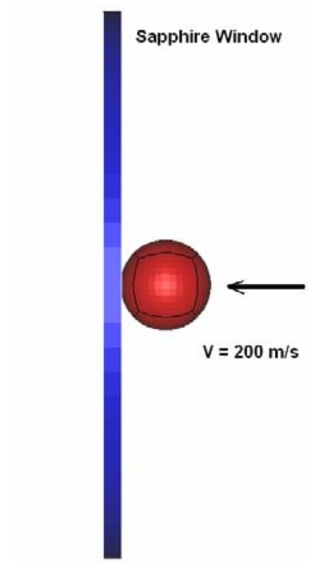
The nominal (6mm) sapphire window does not experience any kind of failure when subjected to a mercury droplet of 5mm diameter (~half the jet diameter) traveling at 200 m/s

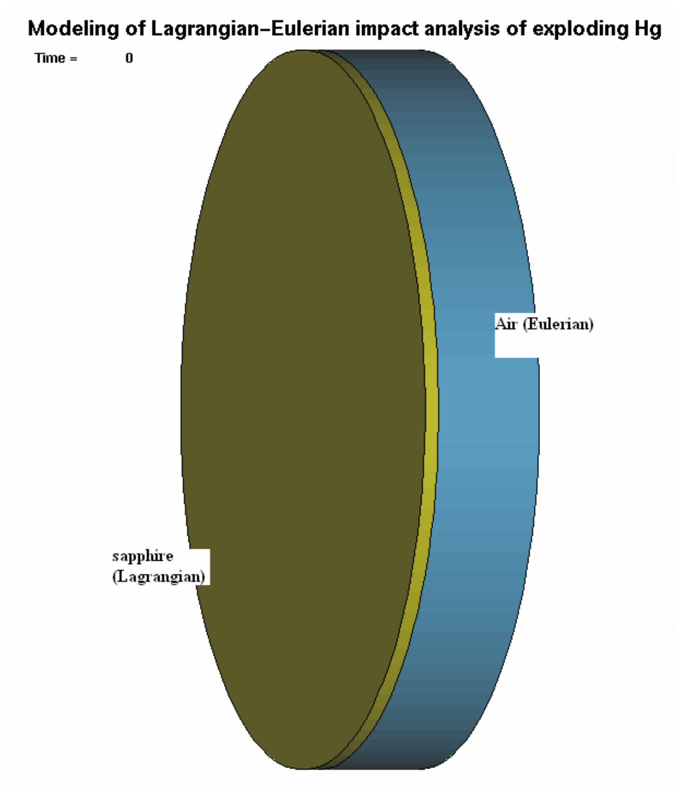
For the same projectile, neither the 4mm nor the 2mm experience failure in the form of cracking or penetration

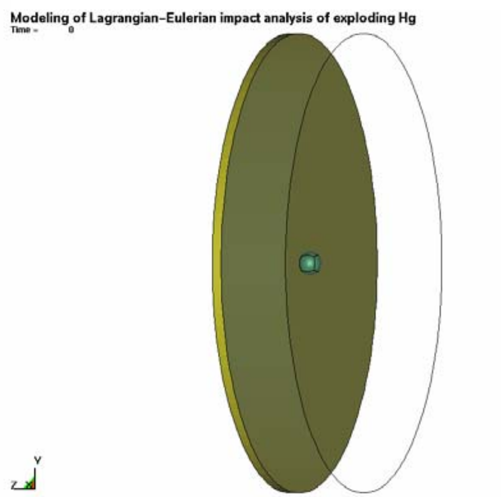
Penetration of the 4mm thick window is possible with a 2cm diam. Mercury projectile traveling at 400 m/s

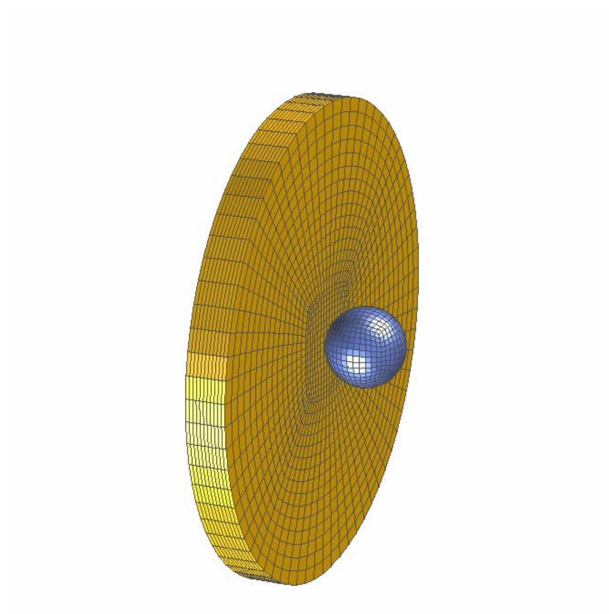
Hg Droplet IMPACT on Sapphire Window Formulation

- Employ ALE formulation (LS-DYNA)
- Hg modeled as fluid enclosed in a hyper-thin hyper-elastic membrane (surface tension) that bursts upon impact
- Hg spills and mixes with the surrounding fluid
- Sapphire is specially modeled so cracks can be traced if they develop
- Mesh adaptation in the impact region for sapphire & mercury is employed
- Examined: 2mm; 4mm and 6mm sapphire windows

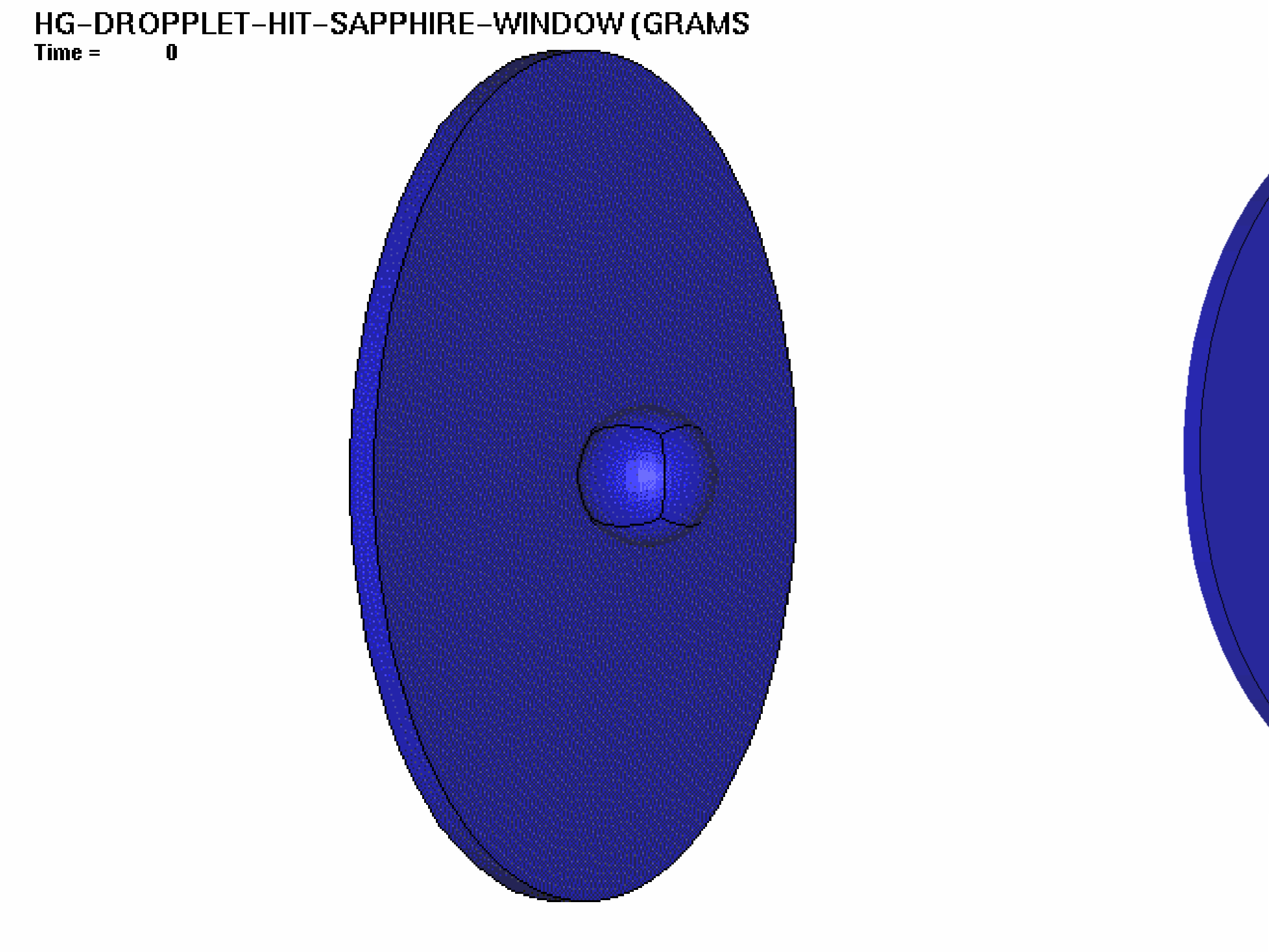


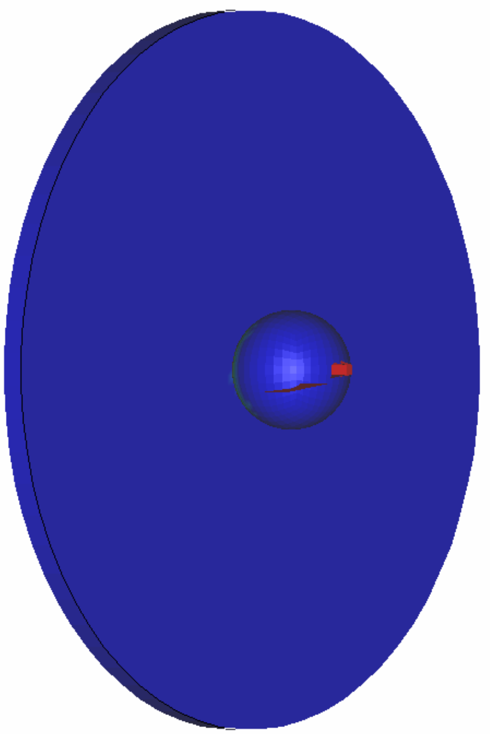




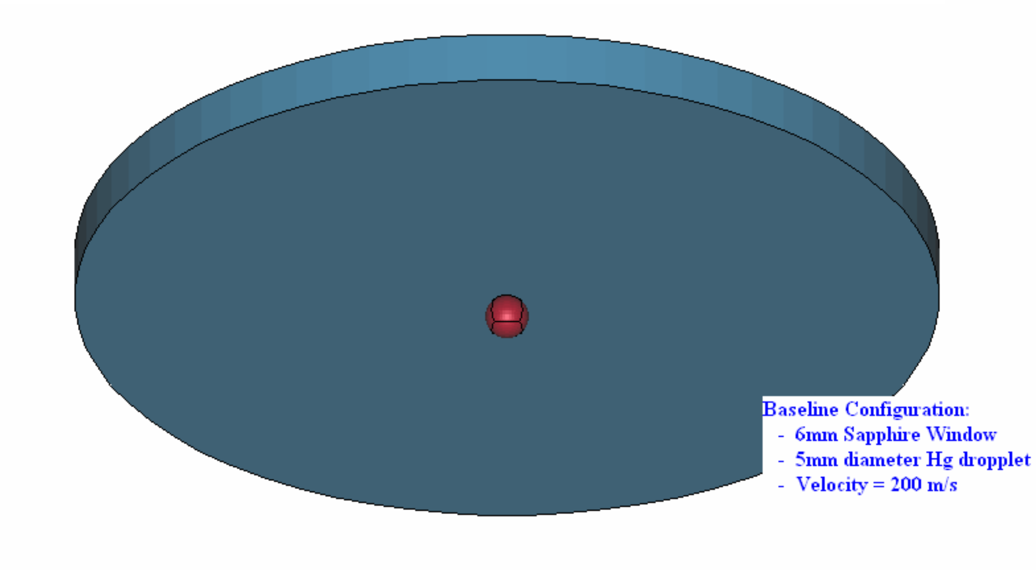


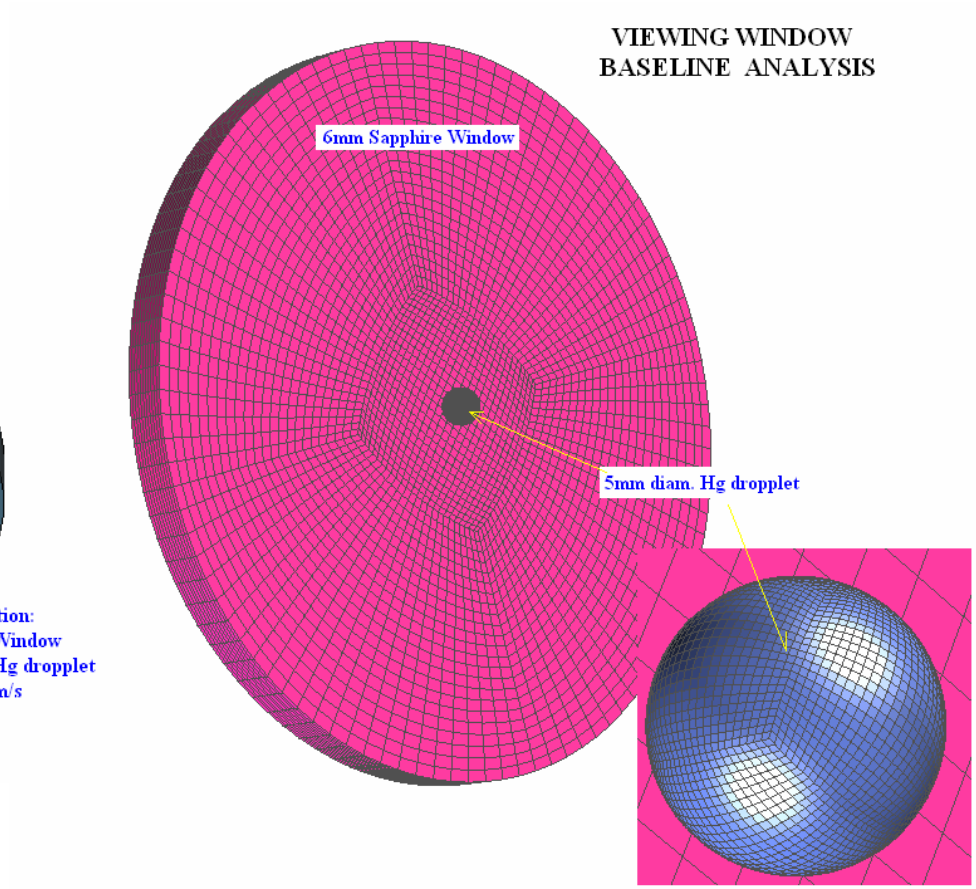
2cm Hg Droplet IMPACT on Sapphire Window: Benchmarking simulations with a planned experiment



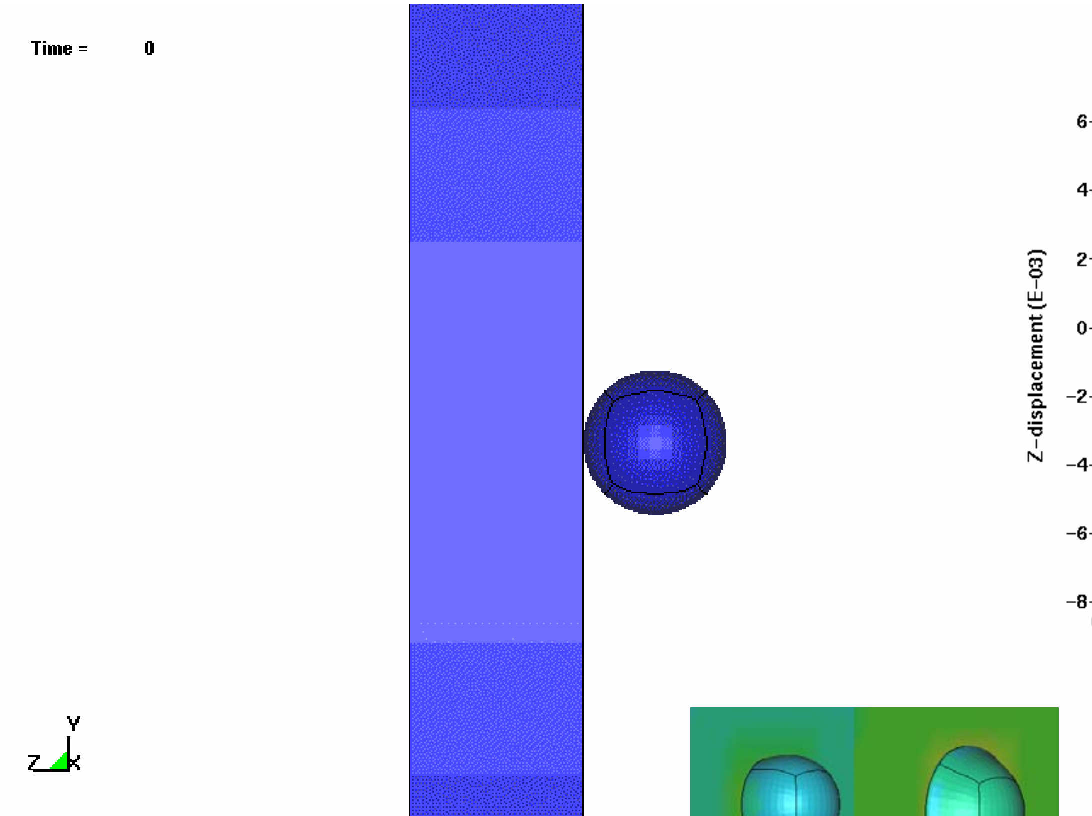


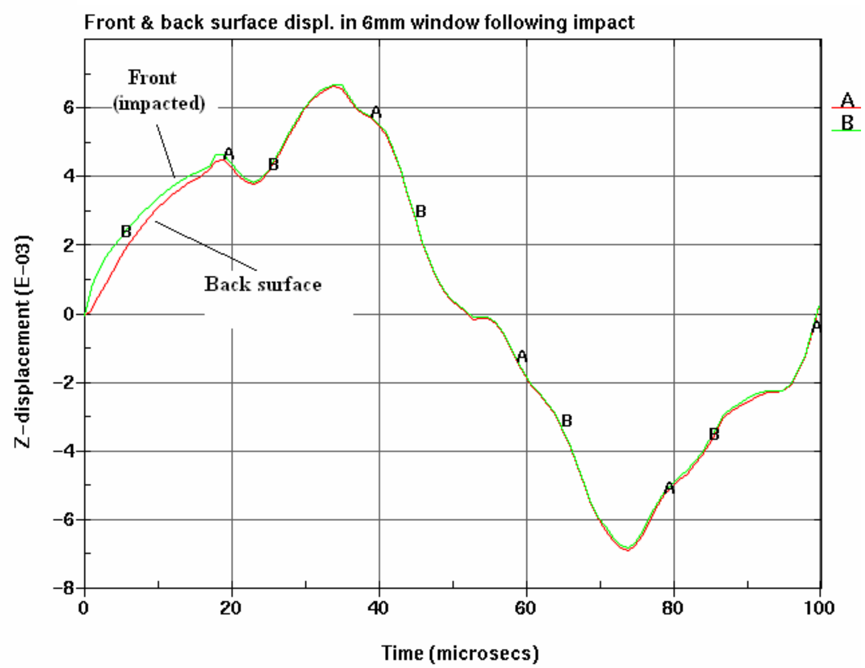
BASELINE
6mm sapphire window & 5mm diam. Projectile at 200 m/s

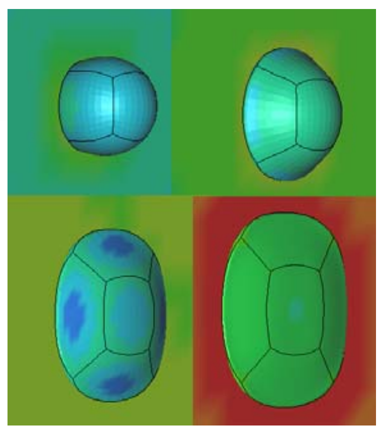




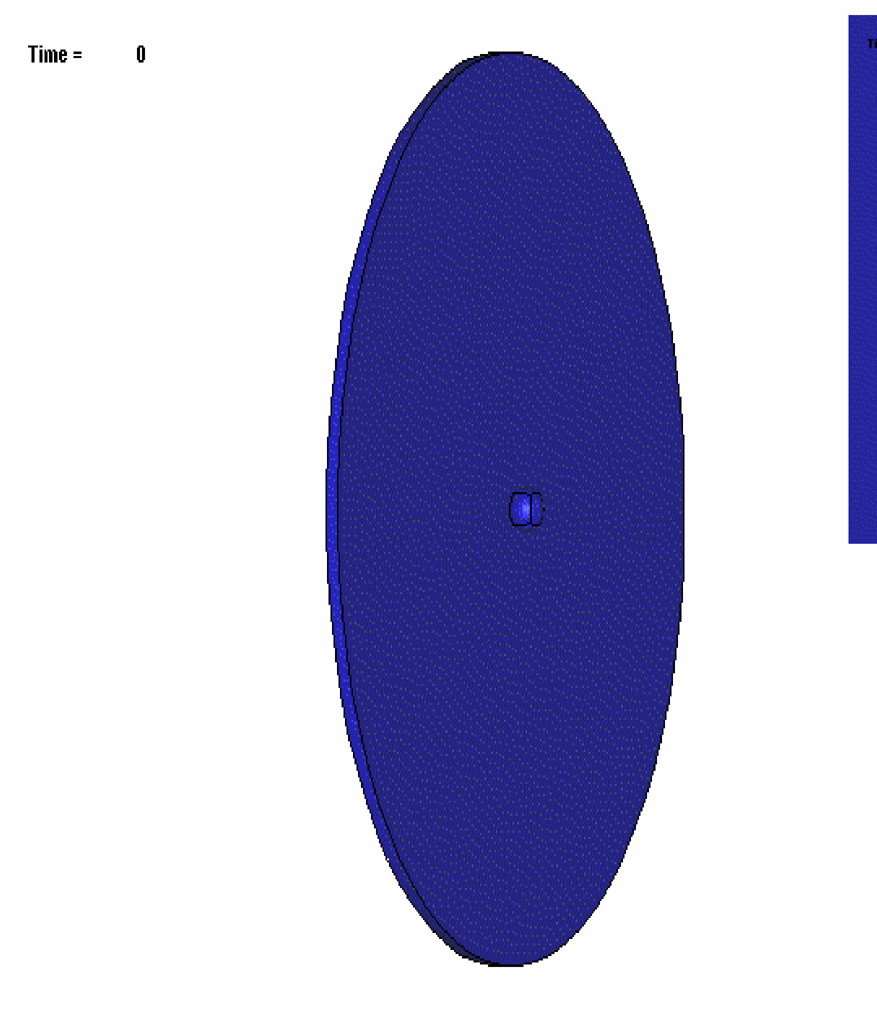
6mm sapphire window & 5mm diam. Projectile at 200 m/s

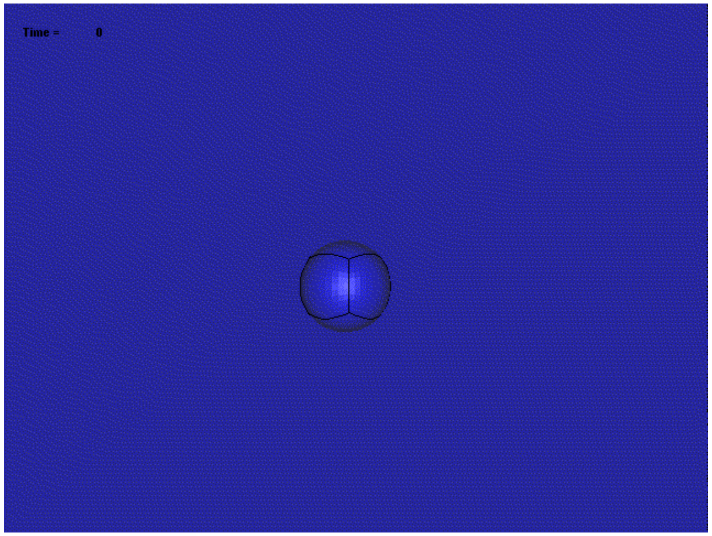


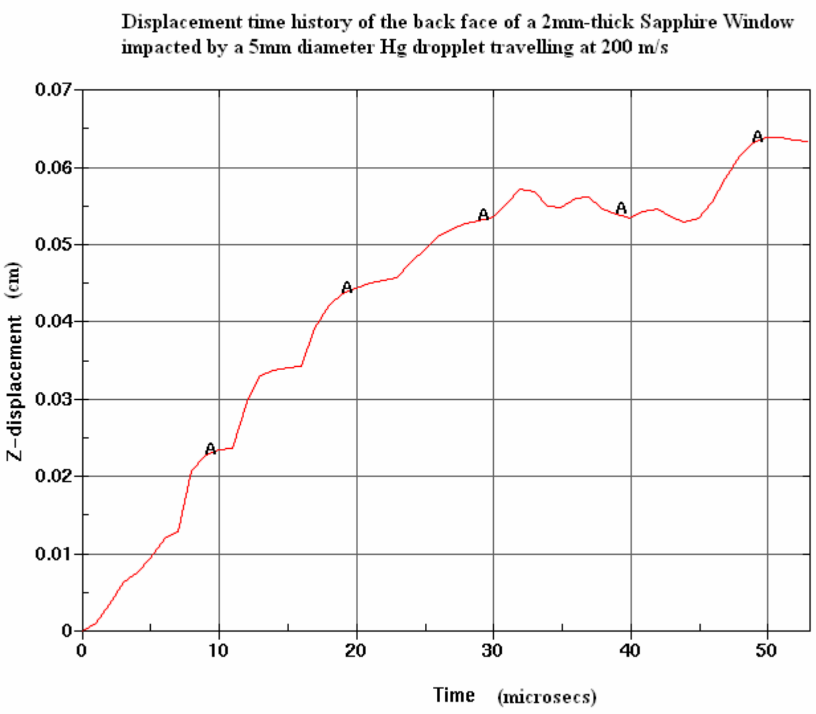




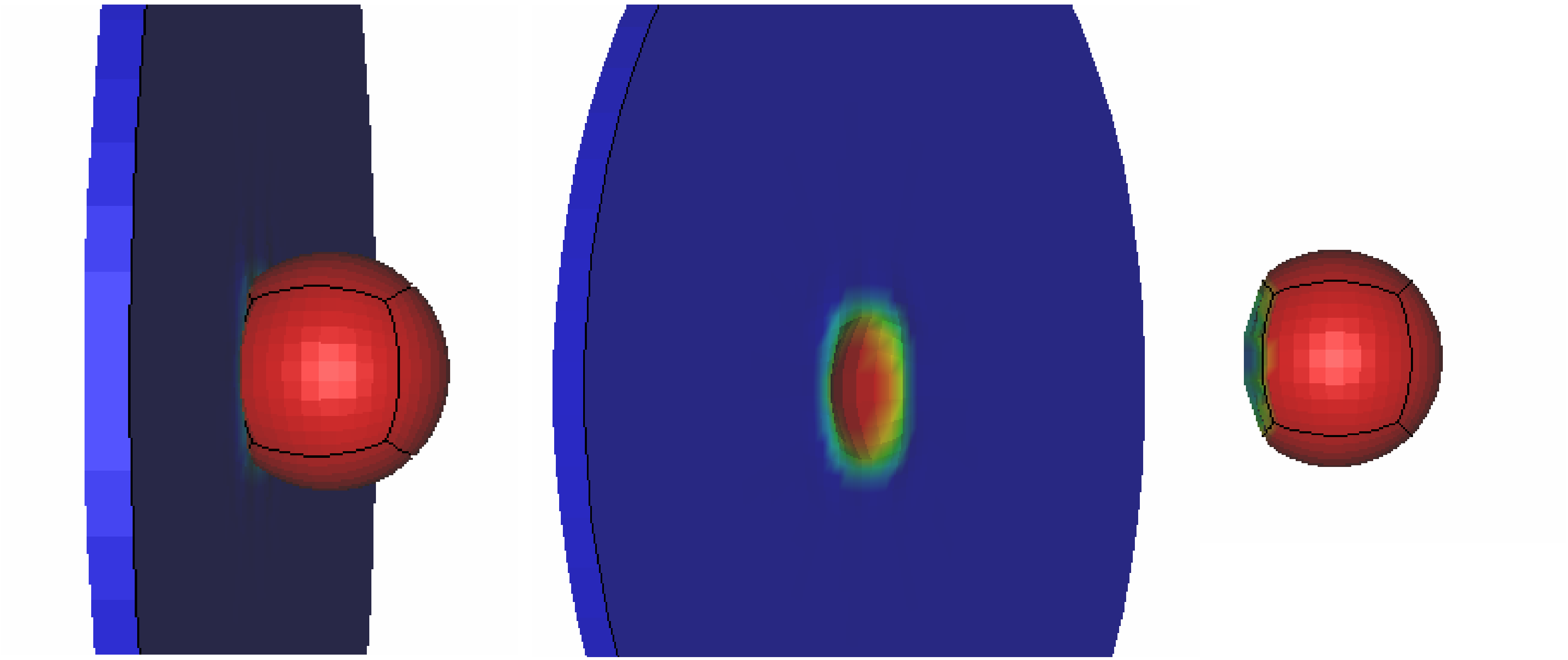
2mm sapphire window & 5mm diam. Projectile at 200 m/s



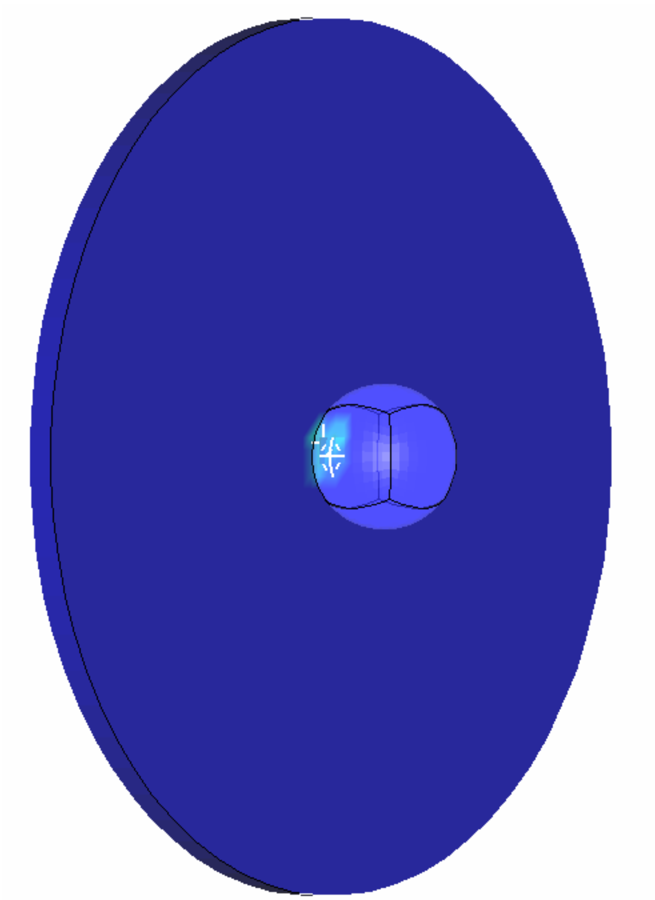




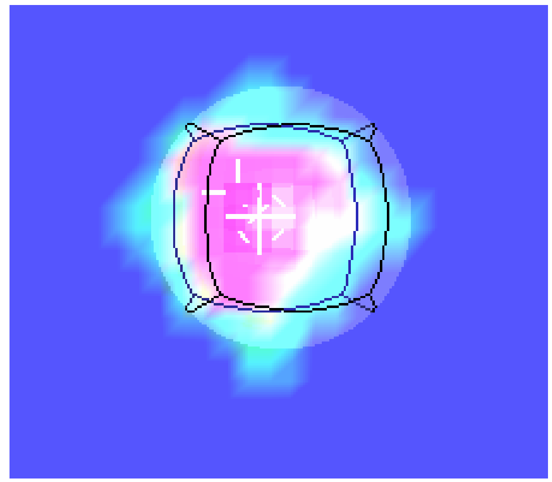
4mm sapphire window & 2cm diam. projectile at 200 m/s
ZOOM IN the region of plastic deformation (adaptive meshing)

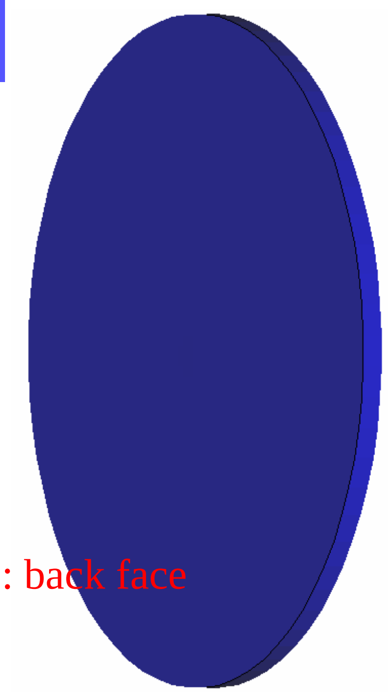


Looking for CRACKS: 4mm window impacted by a 2cm diam. Hg-like projectile

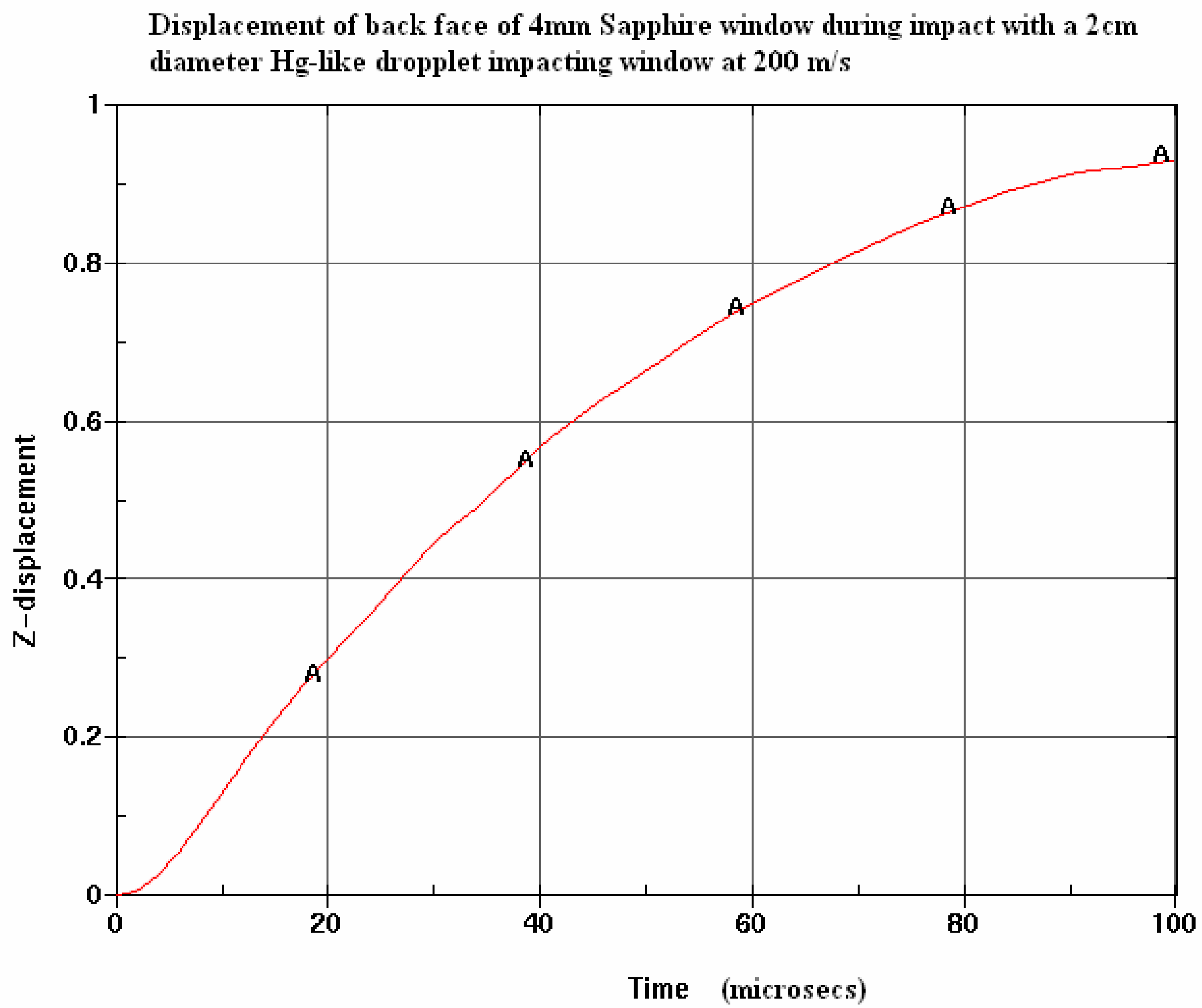


4mm sapphire & 2cm diam. projectile:
IMPACTED face shown small surface cracks

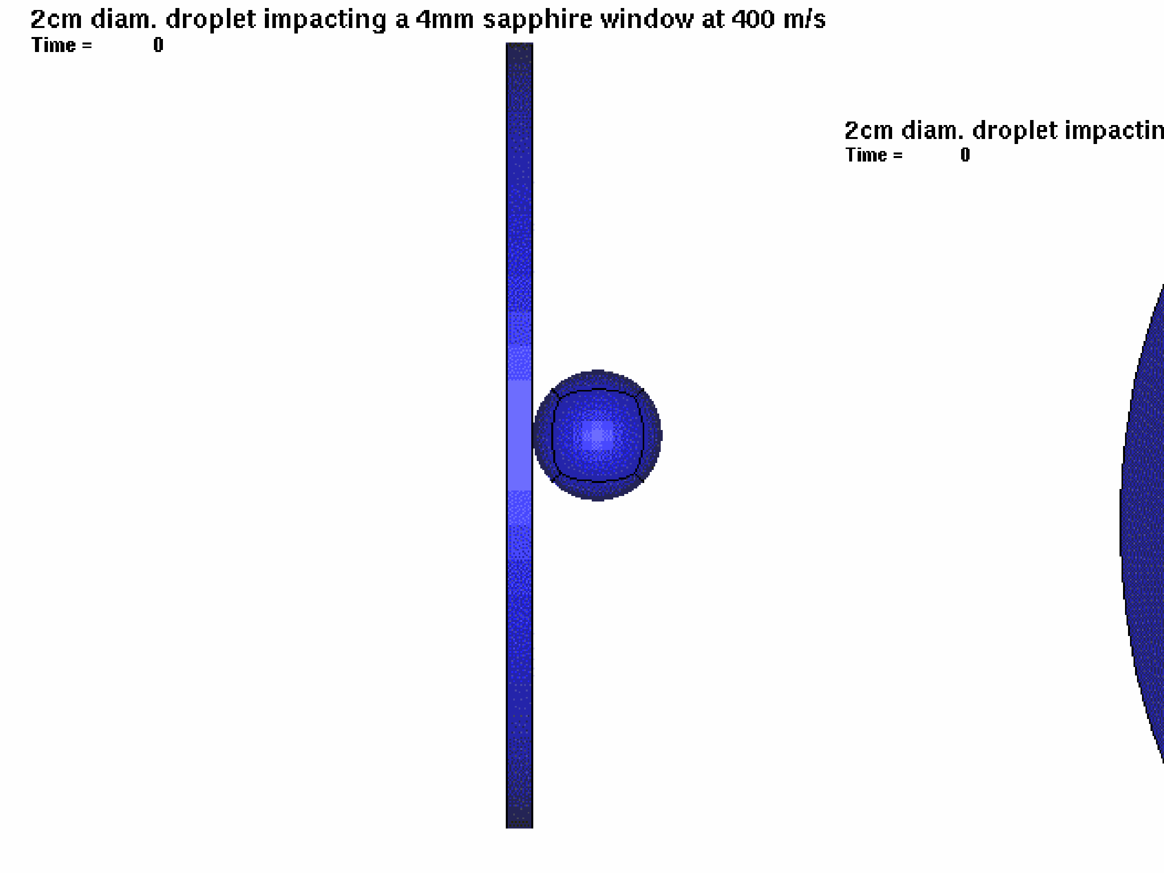


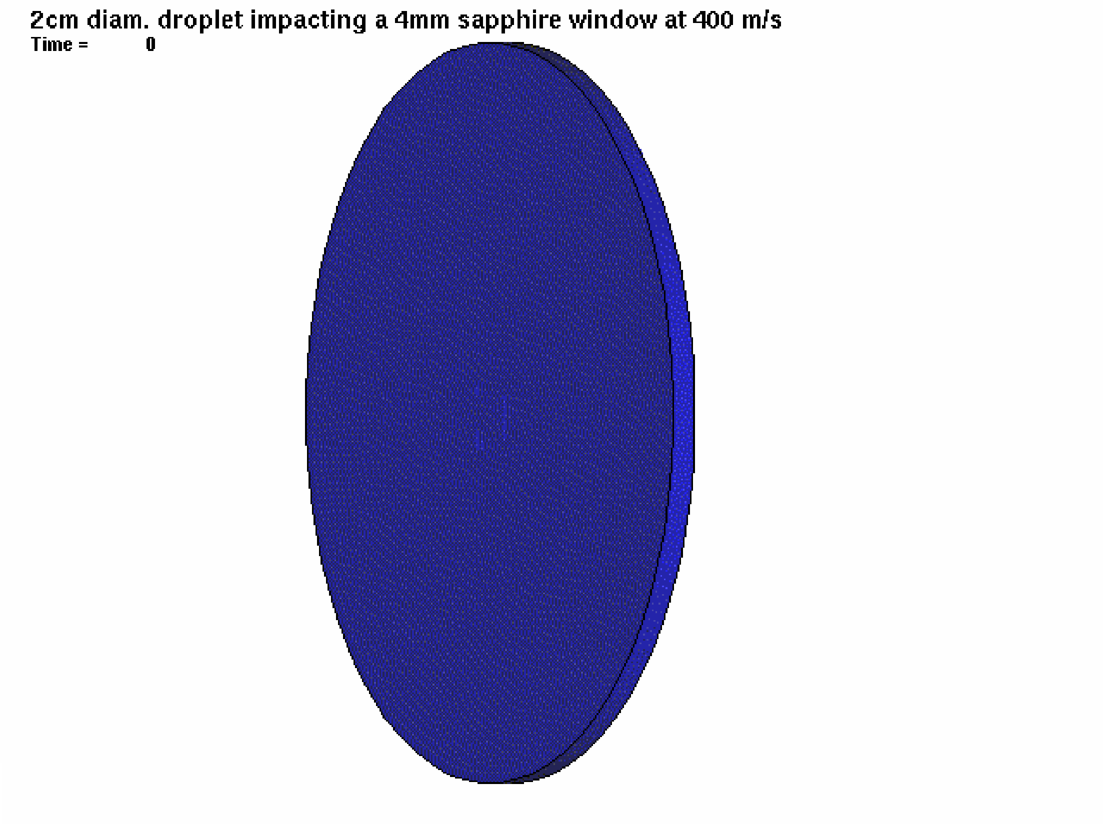


4mm sapphire: back face
and no cracks

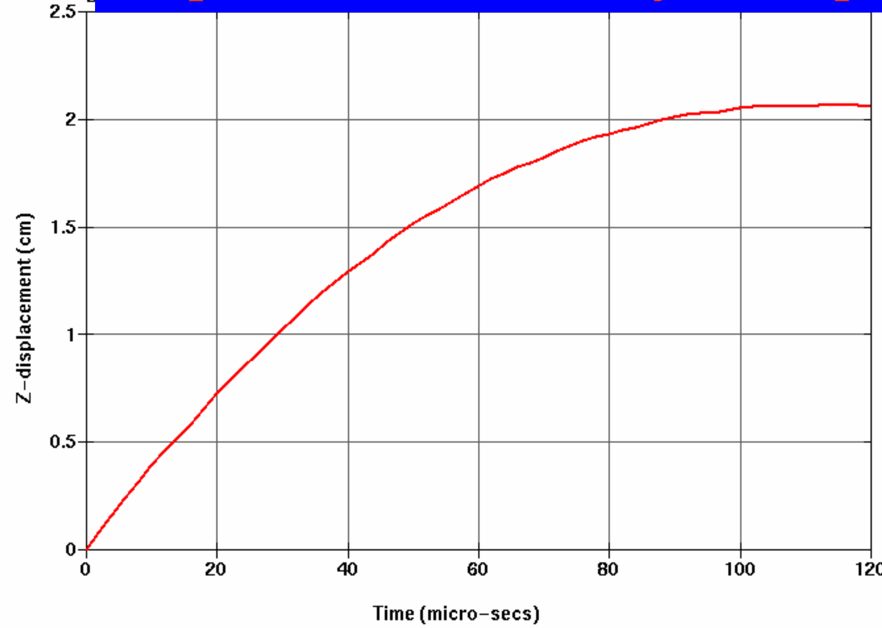

Displacement of back face of 4mm Sapphire window during impact with a 2cm diameter Hg-like dropplet impacting window at 200 m/s
Z–displacement
Time (microsecs)
0
0.2
0.4
0.6
0.8
1
20
40
60
80
100
A

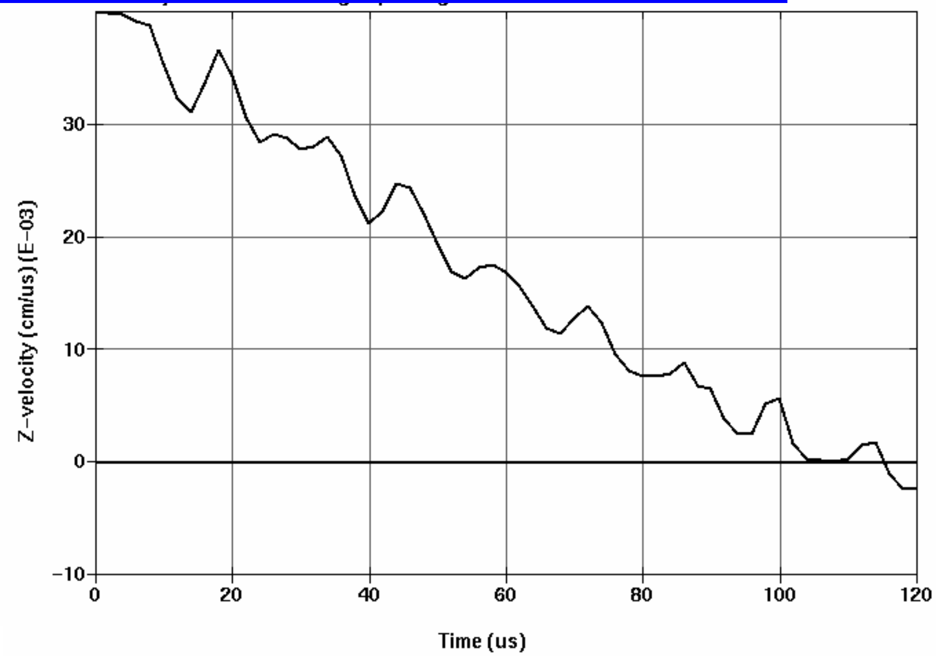
4mm sapphire window & 2cm diam. Hg projectile at 400 m/s
Looking for penetration limits





Displacement & Velocity of the projectile tail





CONCLUSIVE REMARKS

Windows are SAFE from beam & mercury splatter

Actual IMPACT tests on sapphire will be performed to ensure confidence in the simulations

Challenges of Titanium-to-Stainless welding will be met (there is always the fall back position of "*titanionizing*" the whole assembly