Project X – Kaon Targetry

N. Simos

BNL

SOLID Target Options and Studies Required

SEVERAL Studies conducted at BNL to-date focusing on Solid Targets

Neutrino Factory ➔ entire Z range (graphite, Albemet, Be, super-Invar, Inconel 718, Havar, Ti6Al4V, Gum Metal, Vascomax, Ta, W)

Superbeam ➔ carbon composites, graphite

LHC ➔ Collimation (2D C/C, copper, Glidcop)

LBNE ➔ Various Graphite grades and 3D C/C composite

This wide array of potential candidates was and continues to be evaluated for irradiation damage assessment and life expectancy in a multi MW environment

SOLID Target Studies on Beam Induced Shock and Damage

As part of E951 beam induced shock on several target materials was conducted including:

- 3D Carbon/Carbon fiber composite
- ATJ Graphite
- Aluminum
- Inconel
- Havar
- Ti6Al4V

High-fidelity shock simulations and damage evaluation associated with high strain rate effects (appropriate for these beam/target interactions have been and continue to be conducted).

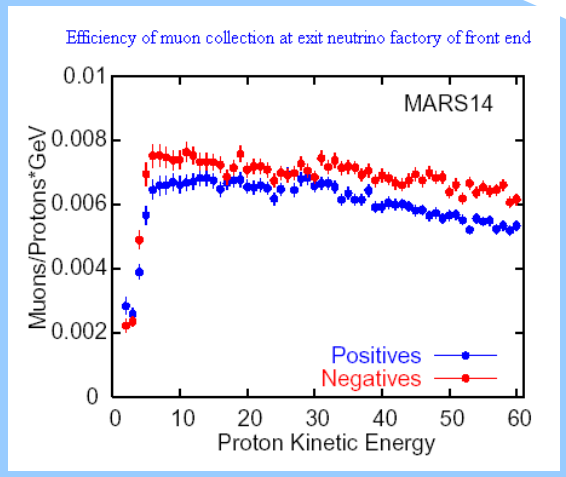
BNL Analyses have gone beyond the ANSYS-type calculations and into the regime of highly non-linear processes and severe consequences on the targets (some examples are attached for reference)

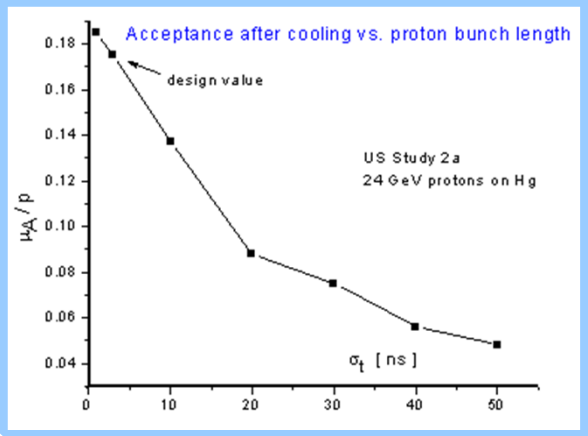
Parameter Space

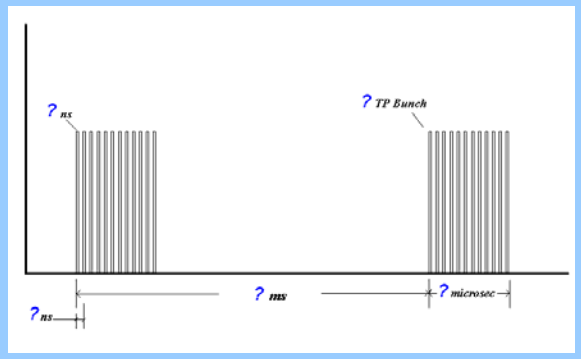
Protons per pulse required for 4 MW

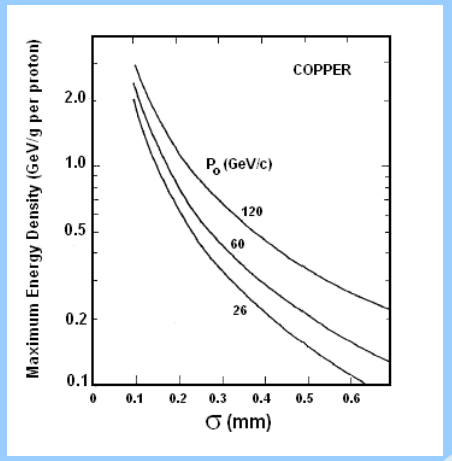
$$\bar{P}_{arc}(w) = E[eV] \times N \times e \times f_{rep}[Hz]$$

	10 Hz	25 Hz	50 Hz
10 GeV	250×10^{12}	100×10^{12}	50×10^{12}
20 GeV	125×10^{12}	50×10^{12}	25×10^{12}

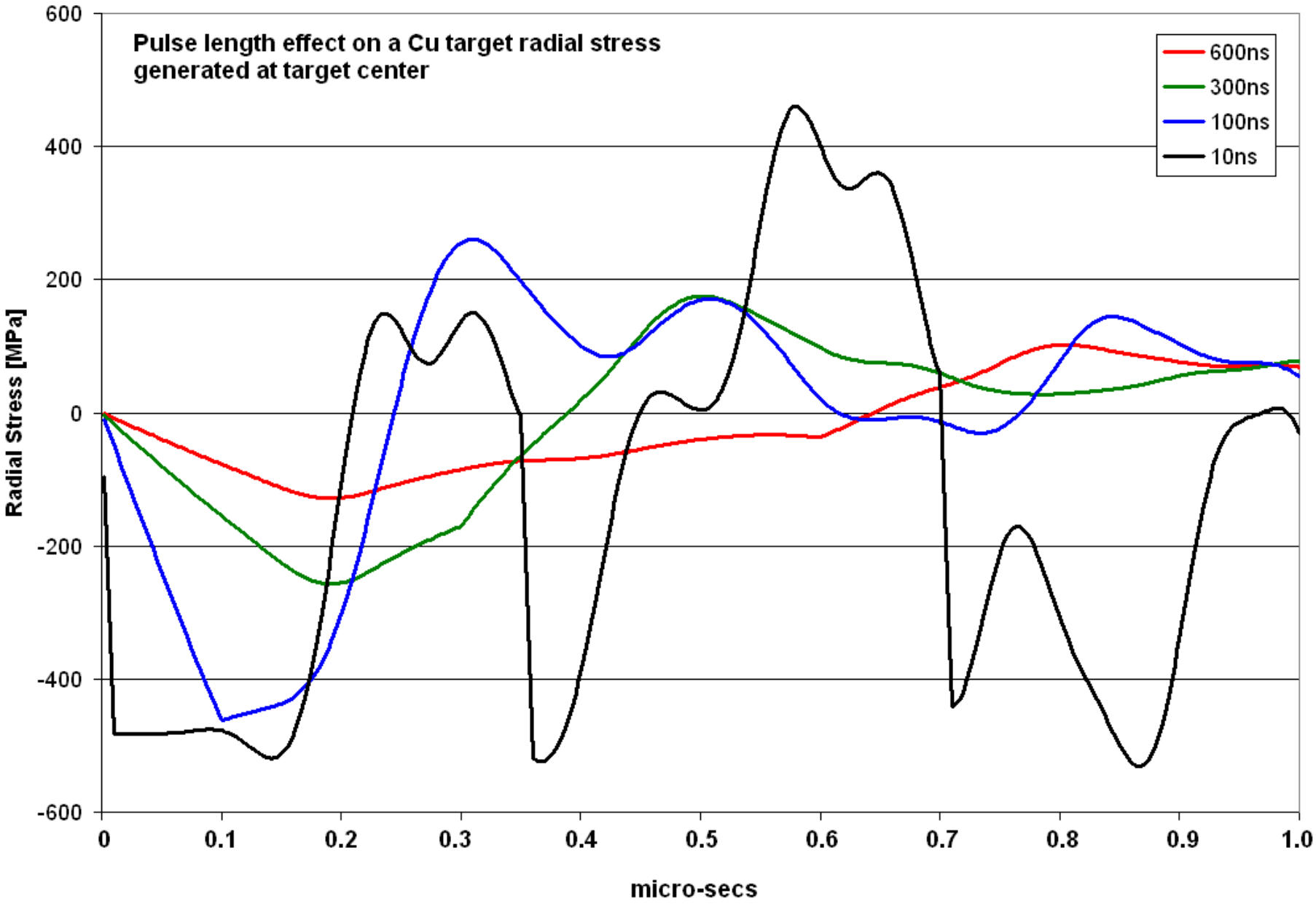




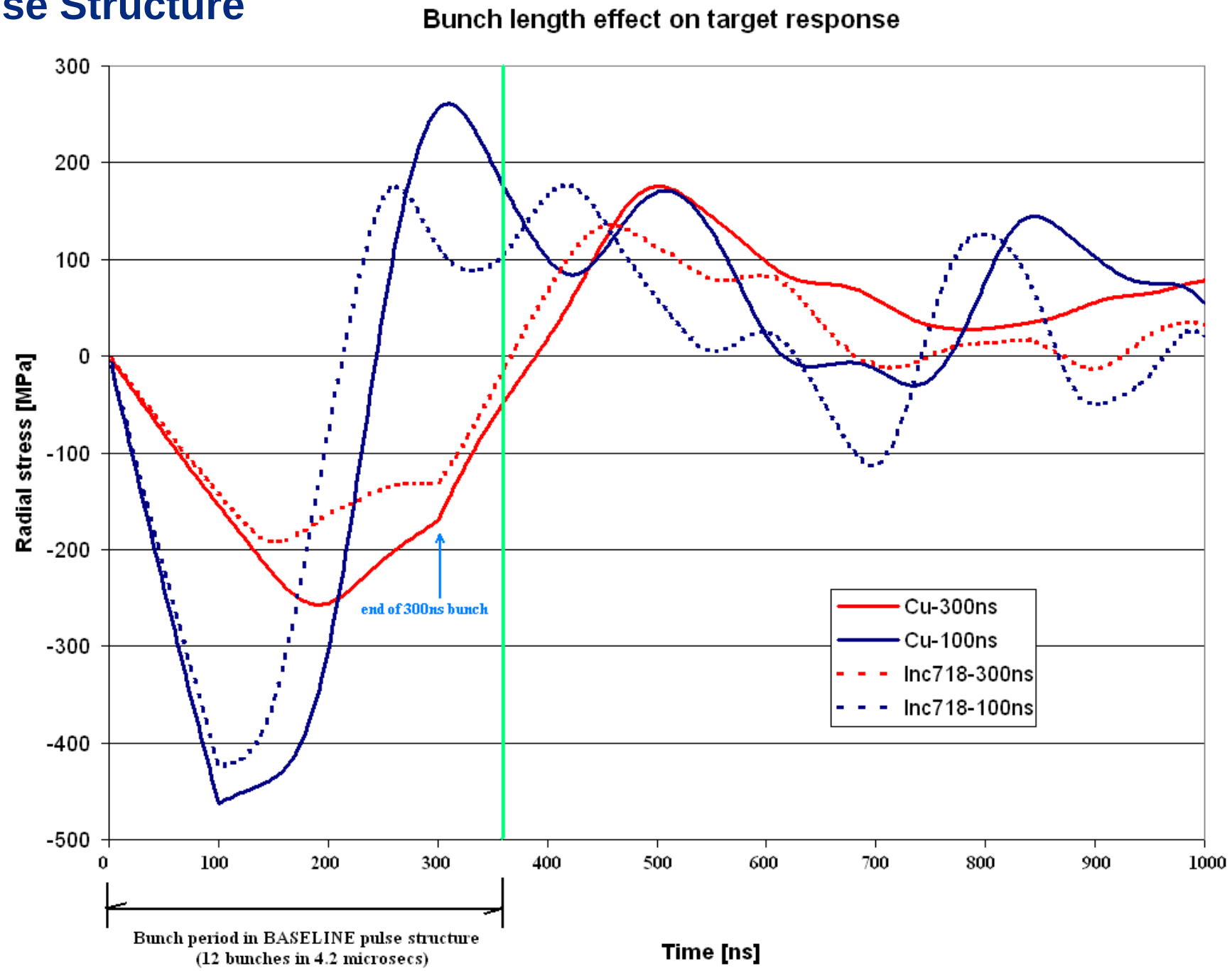




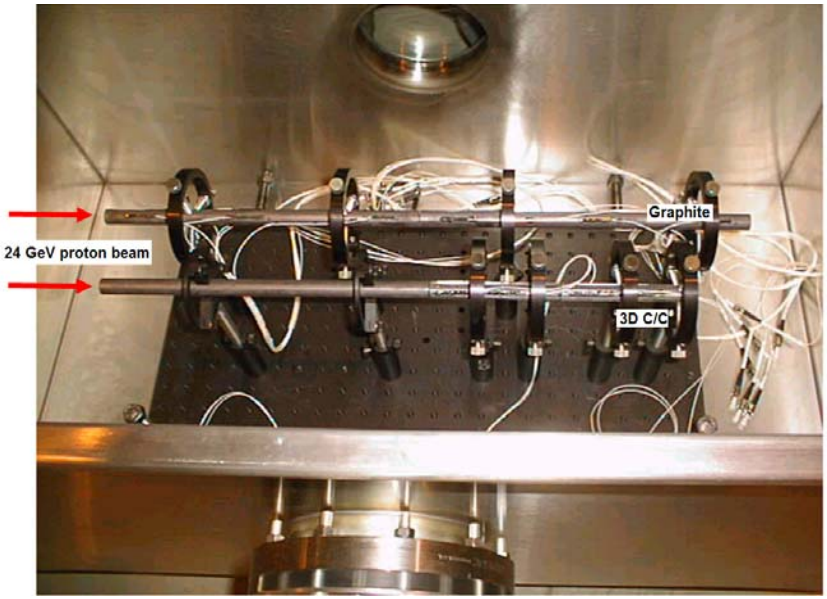
Pulse Structure

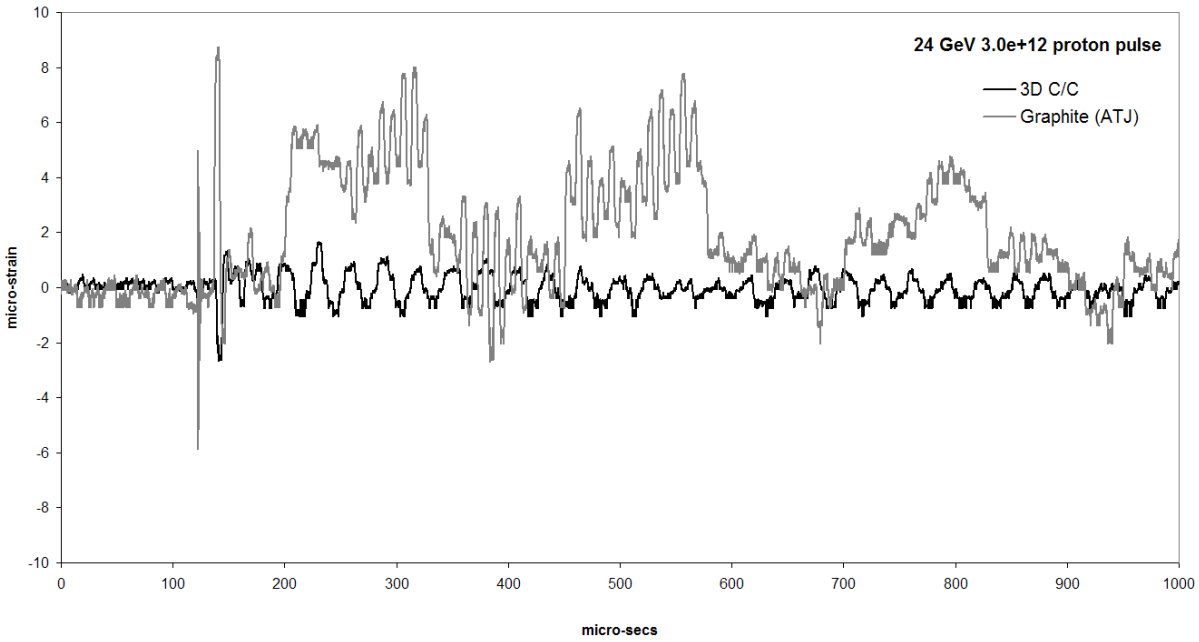


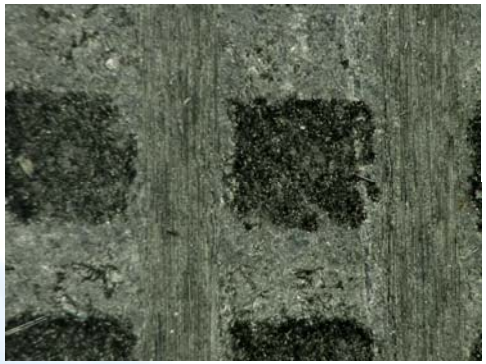
Pulse Structure

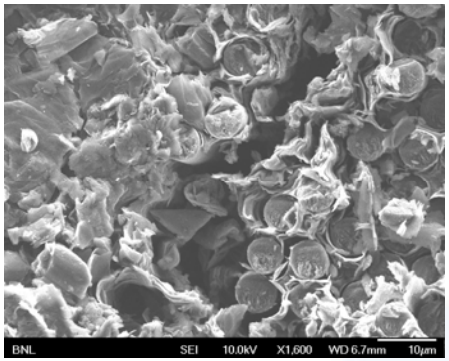


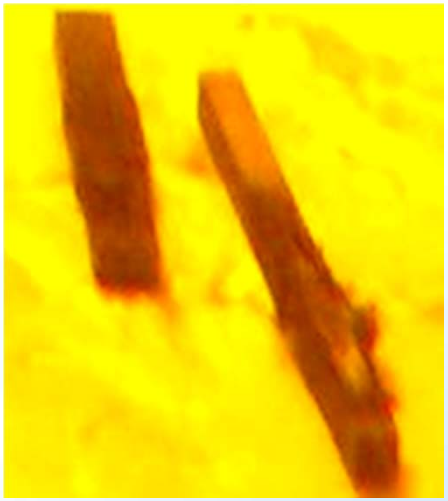
SOLID Target Studies on Beam Induced Shock and Damage











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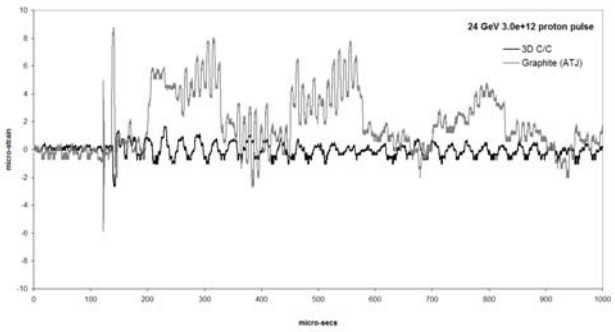
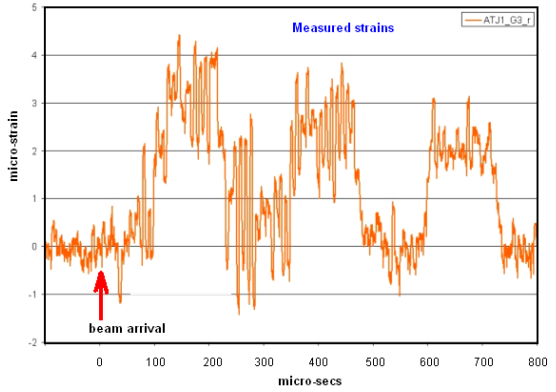
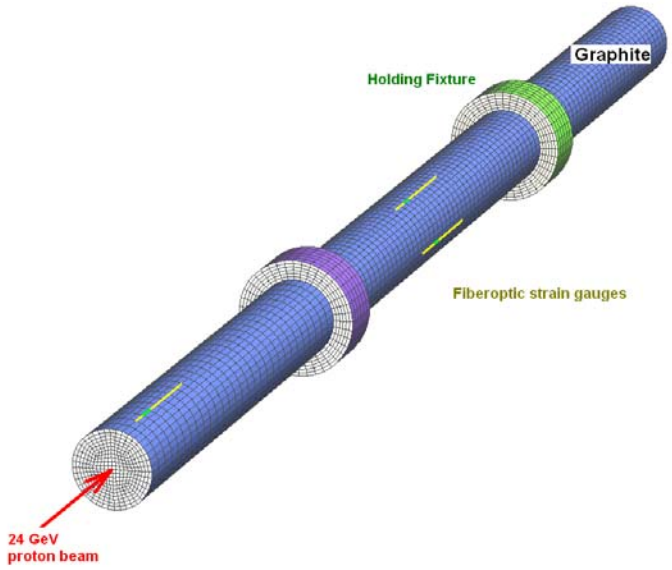
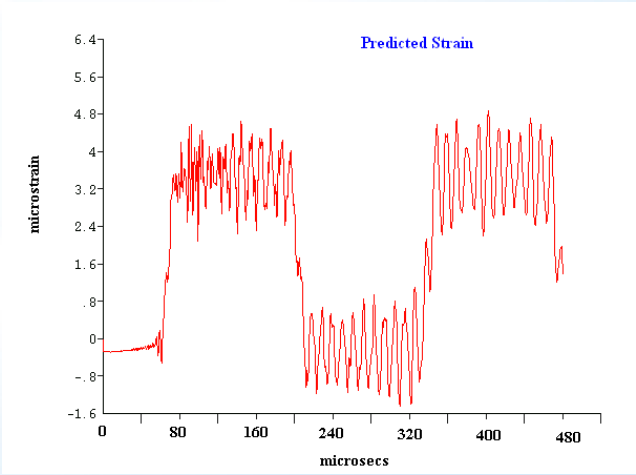
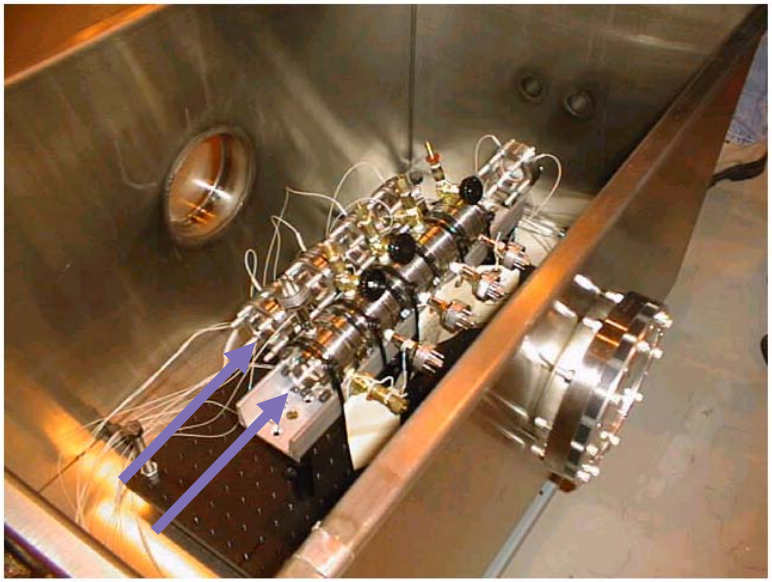


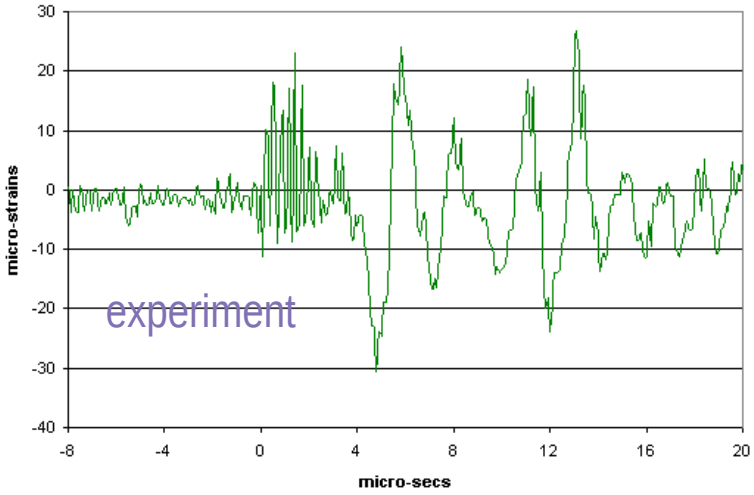


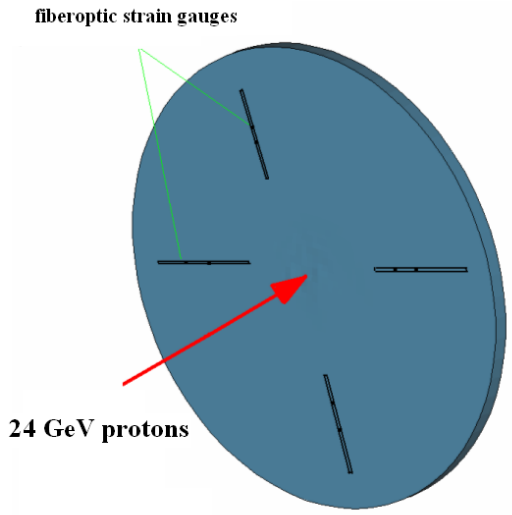


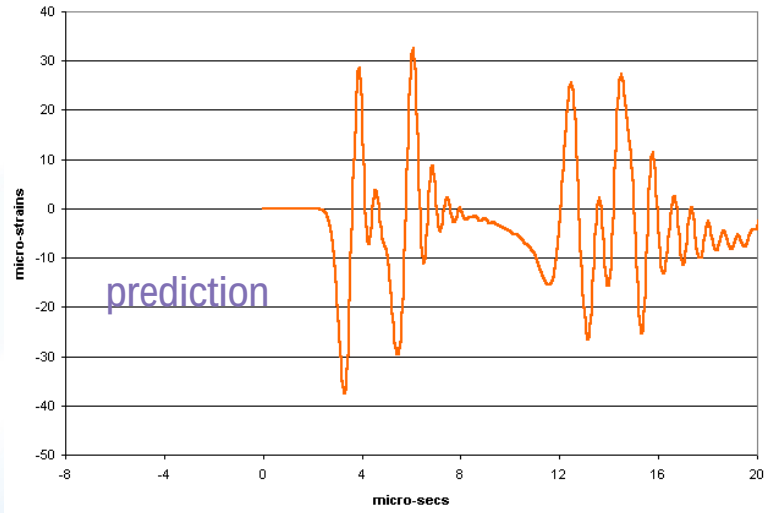


Beam-window interaction test (BNL E951 Experiment)





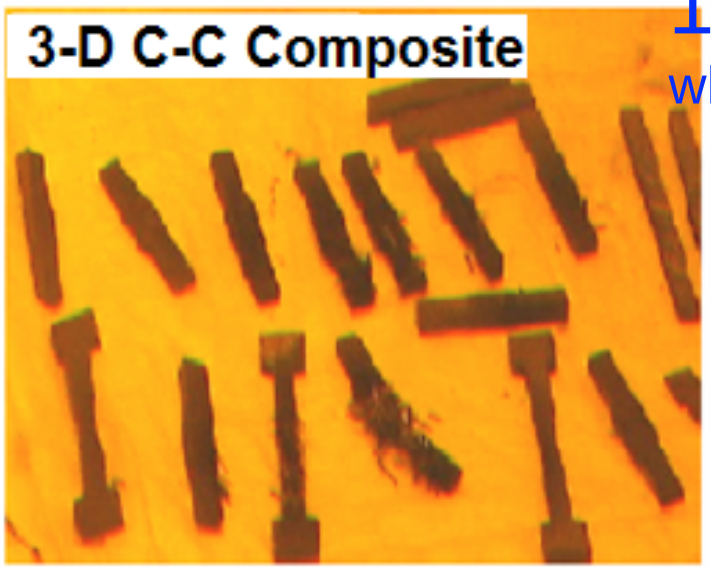


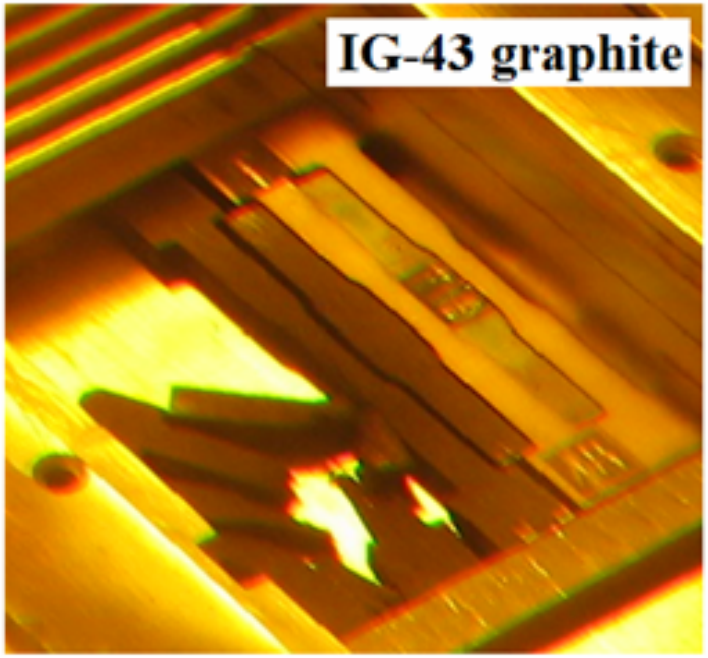


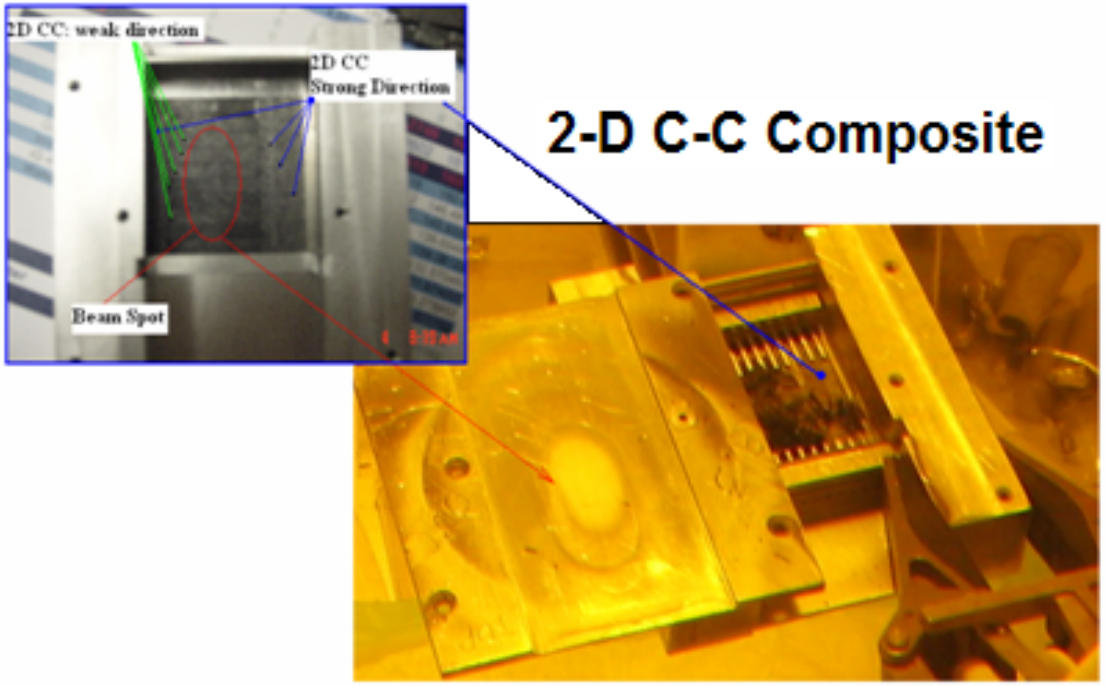
Irradiation Damage Surprises

10^{21} p/cm^2 fluence ➔ 0.2 dpa

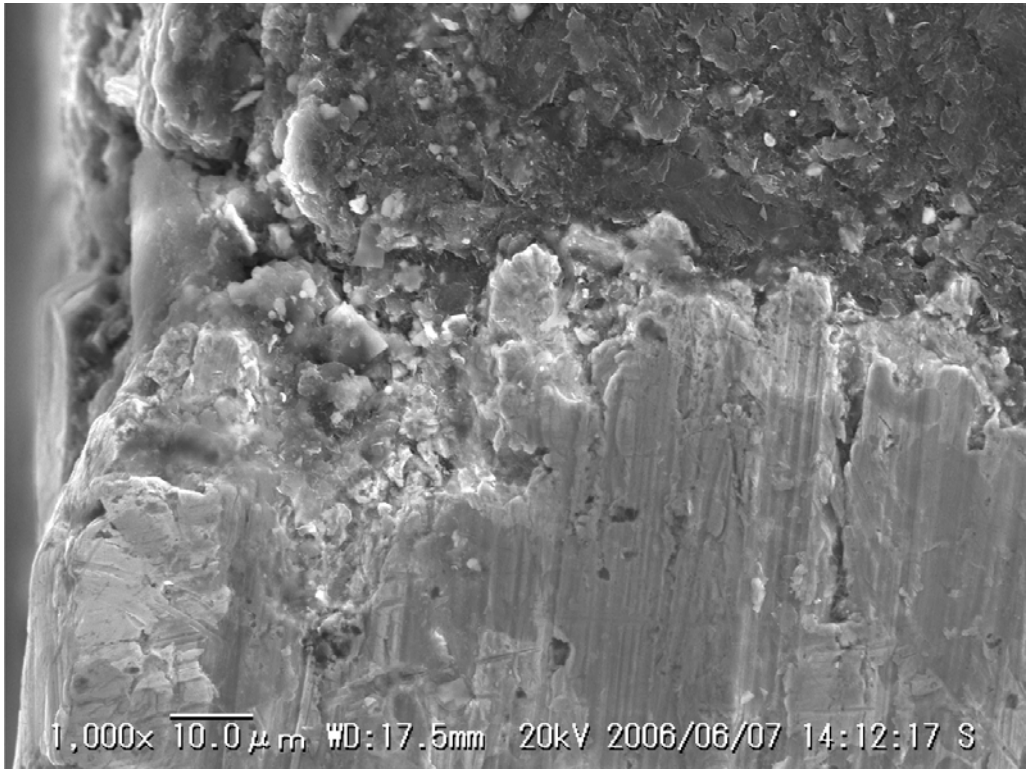
what happened to the 10s of dpa seen in thermal reactors?

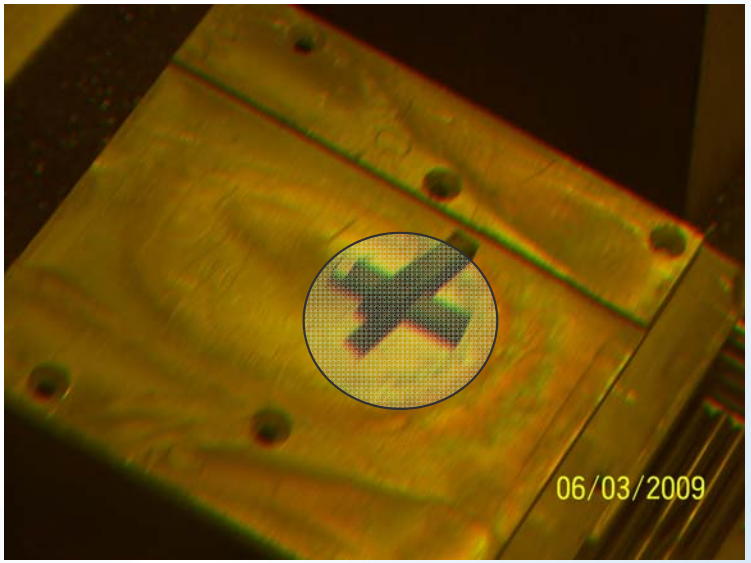


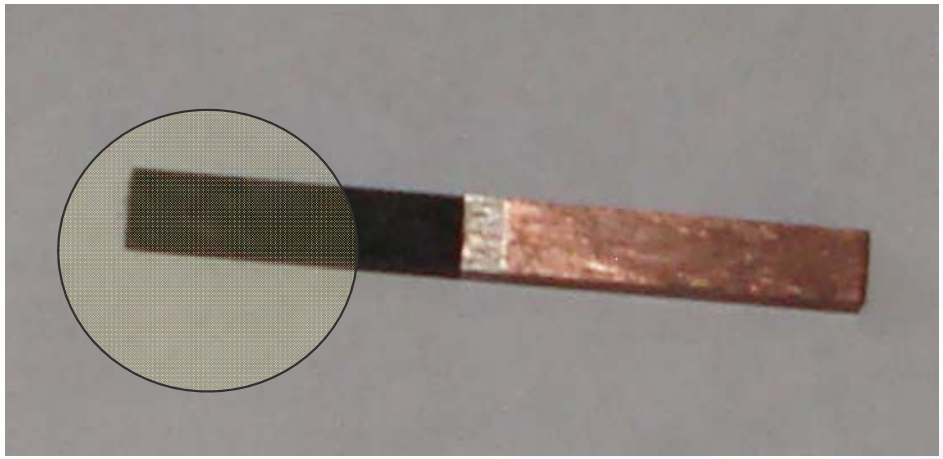




Observations were reproduced 3 times !!


1,000× 10.0μm WD:17.5mm 20kV 2006/06/07 14:12:17 S


06/03/2009

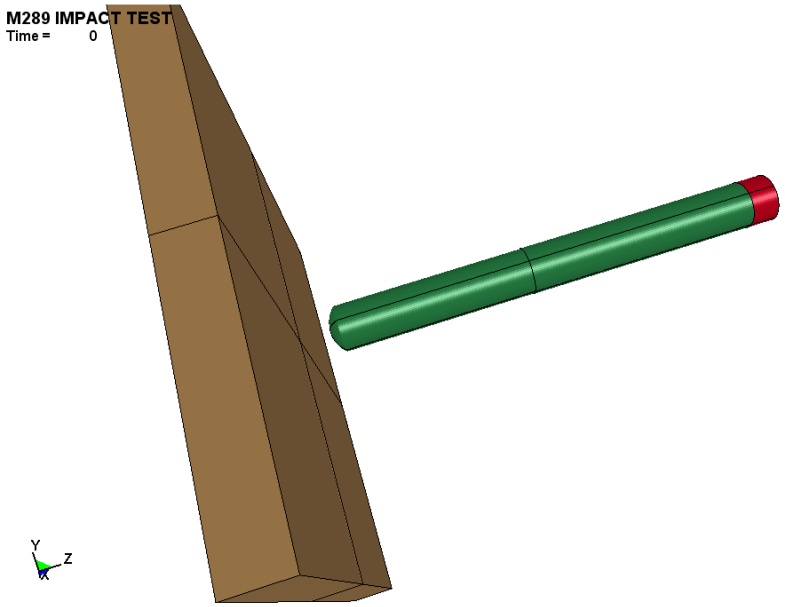


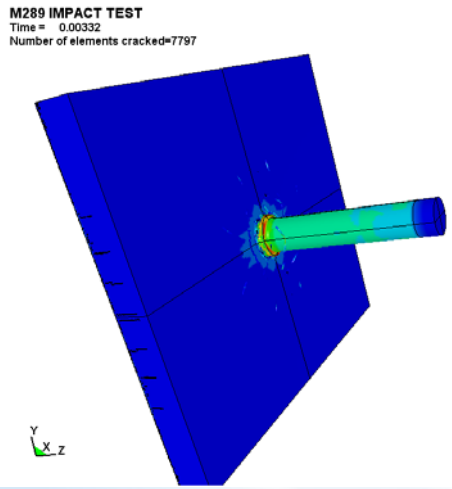
Beam induced Shock - Survivability

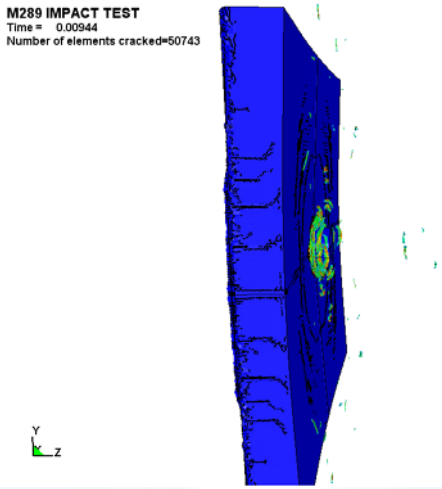
Solving/benchmarking transient problems with EXPLICIT formulation

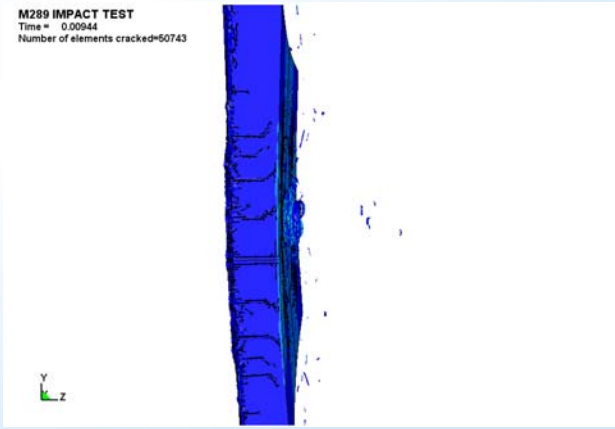
One needs to enter this regime to understand and establish the limitations of targets intercepting the multi-MW beams

Projectile Impact Benchmark Study









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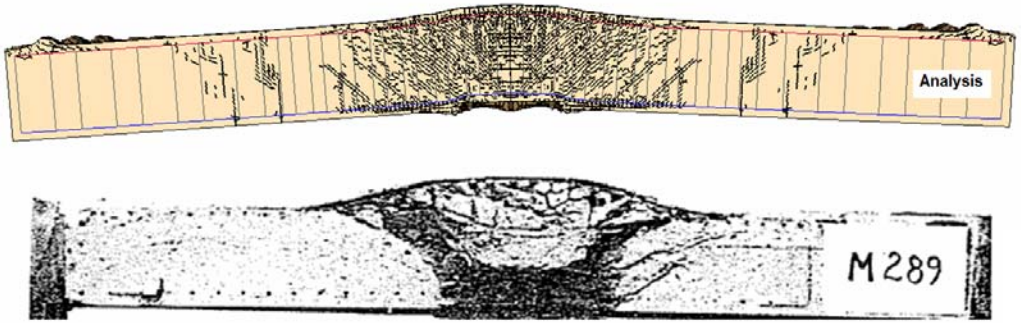
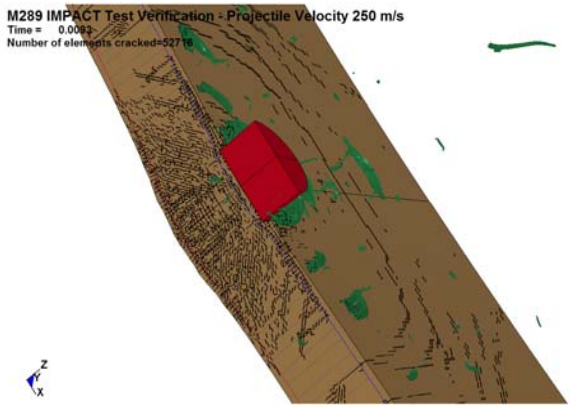
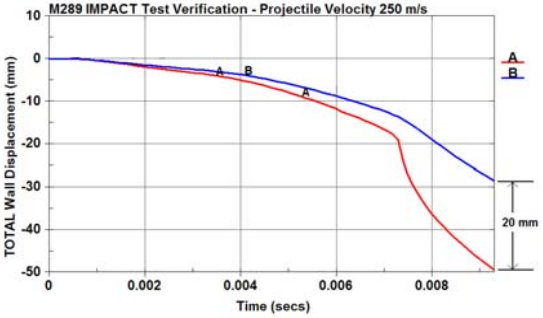
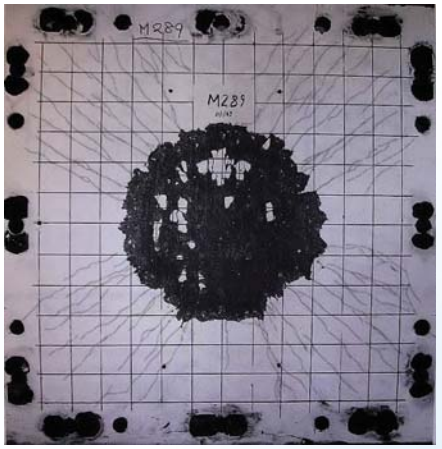
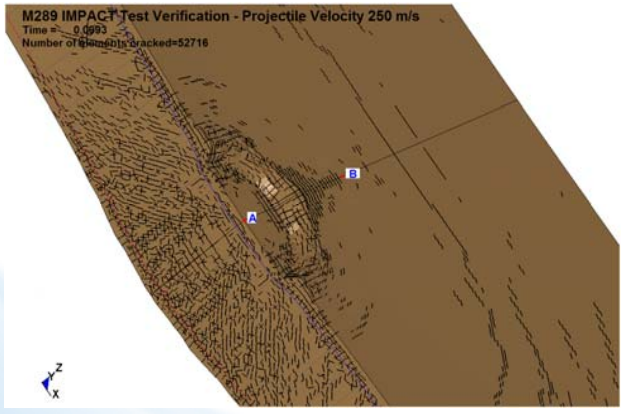
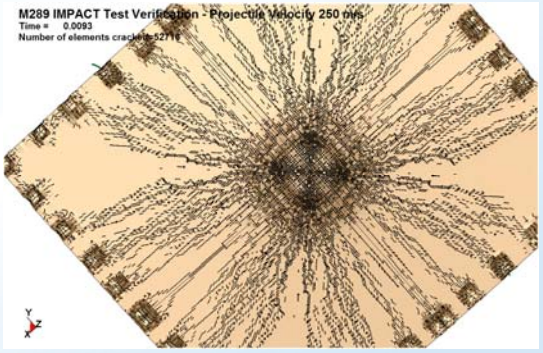








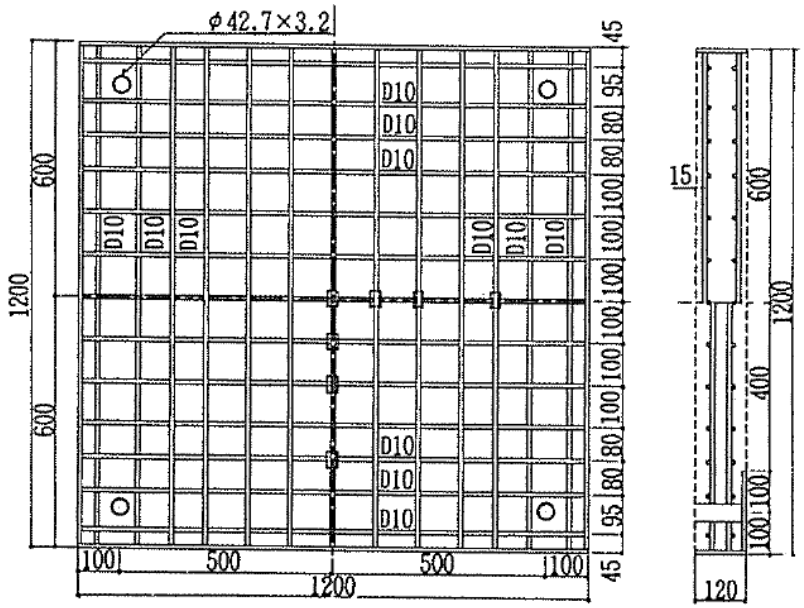


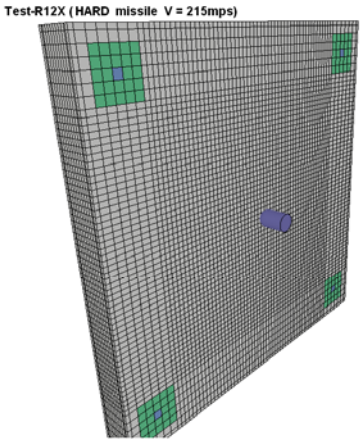


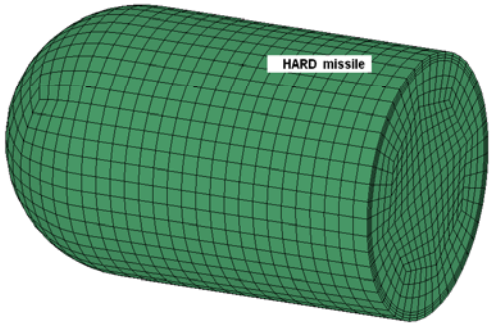
According to test results, missile-induced dent on upstream face of wall = 20 mm

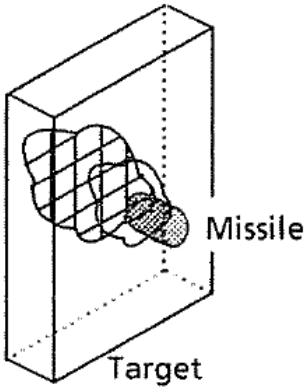
Analysis prediction matched the experimental data precisely !

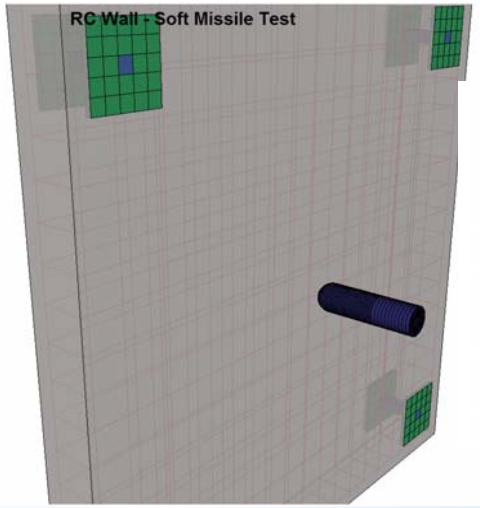
High Velocity Hard & Soft Missile Tests - Benchmarking

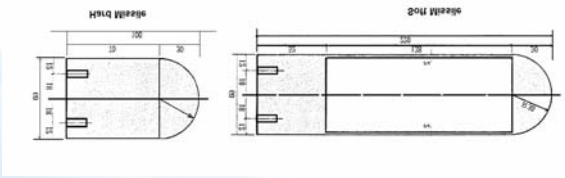




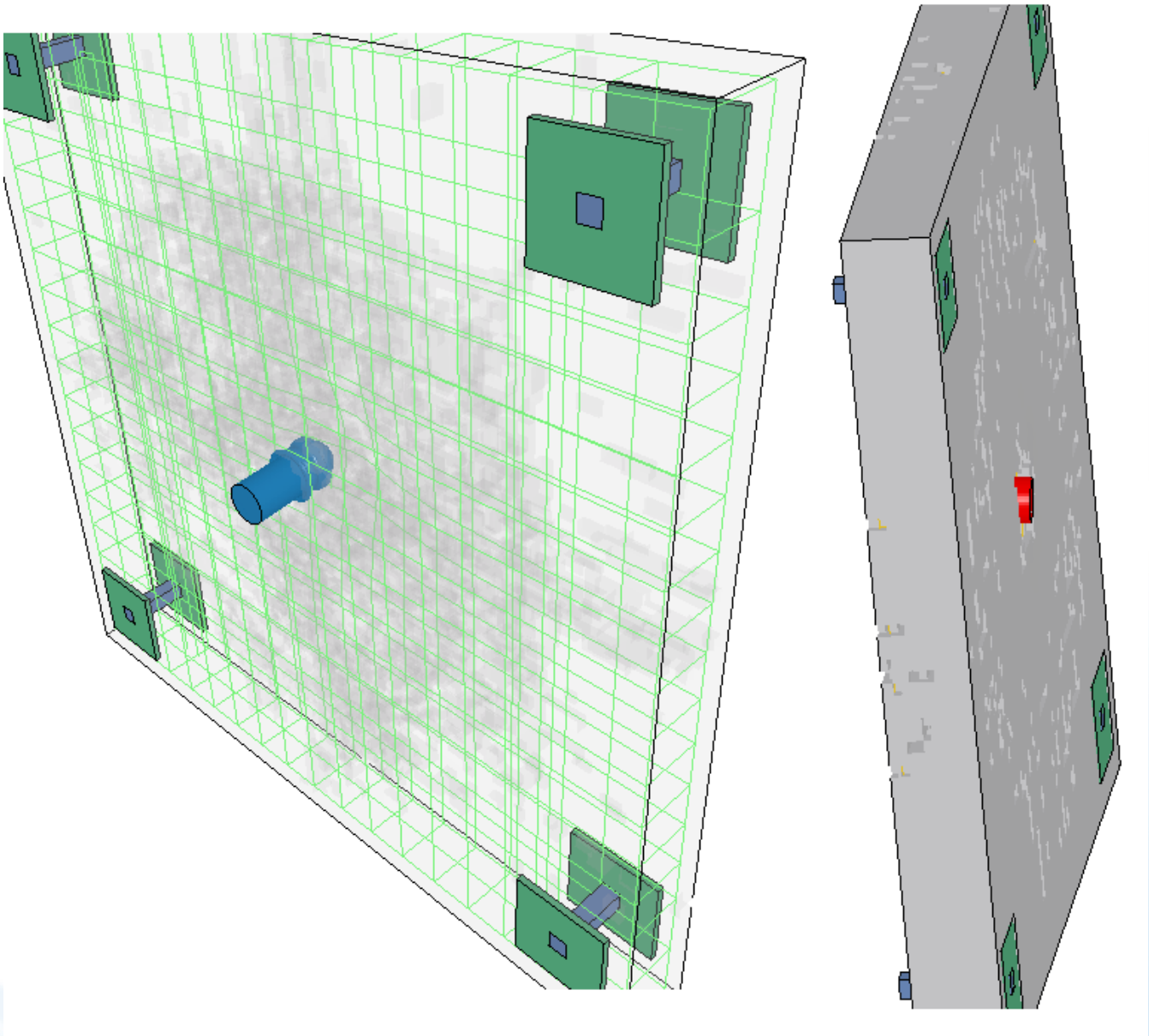




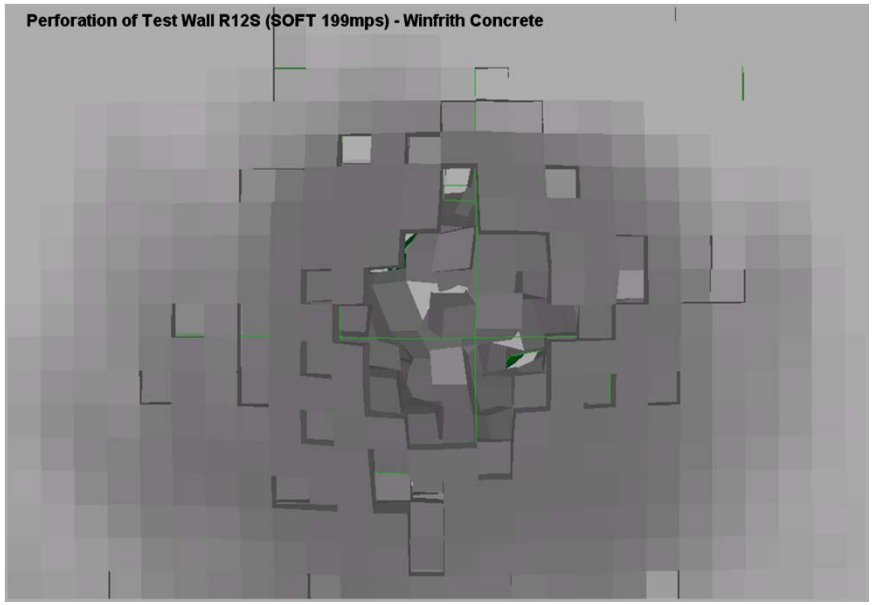


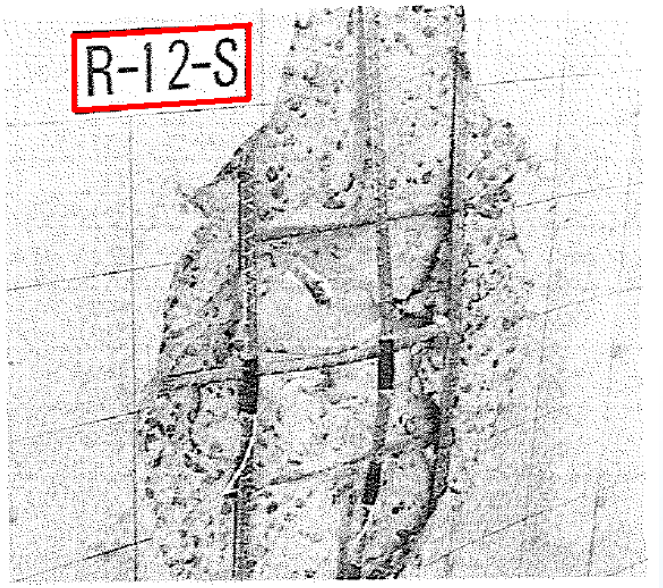


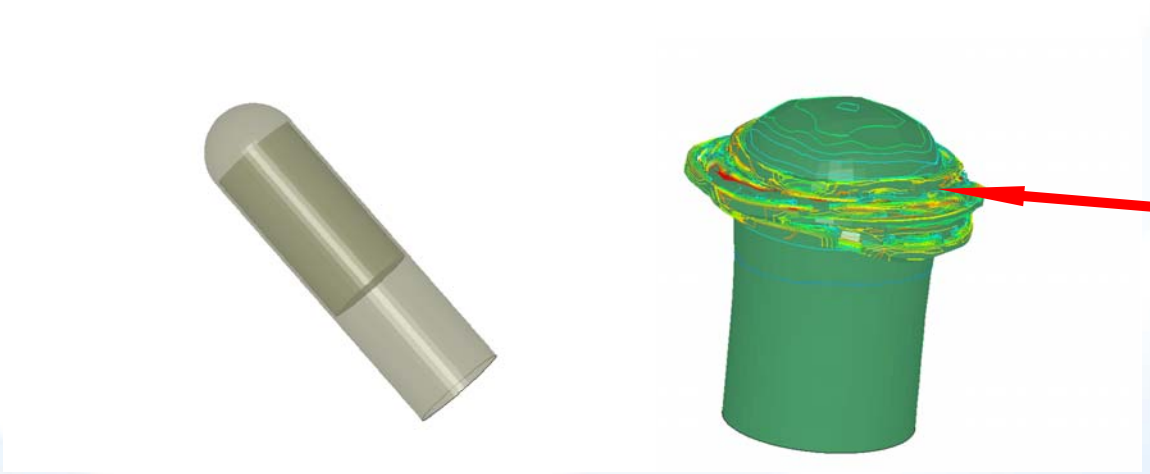
High Velocity Hard & Soft Missile Tests - Benchmarking

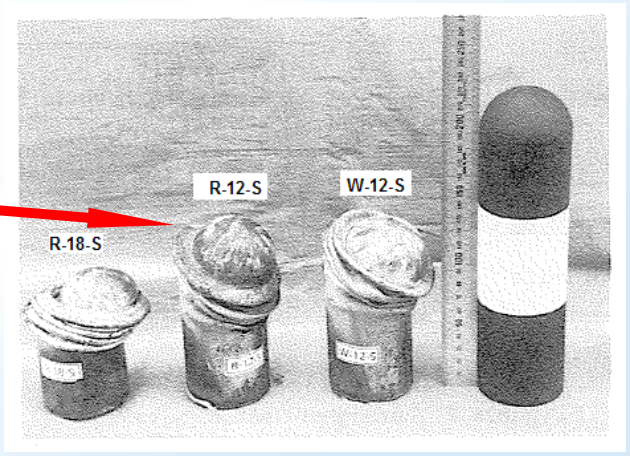


High Velocity Hard & Soft Missile Tests - Benchmarking

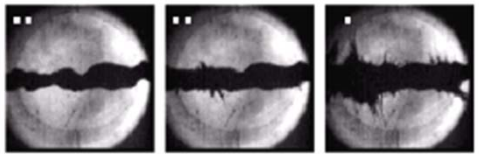


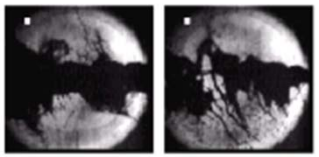


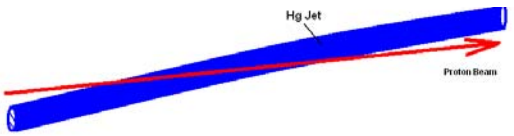


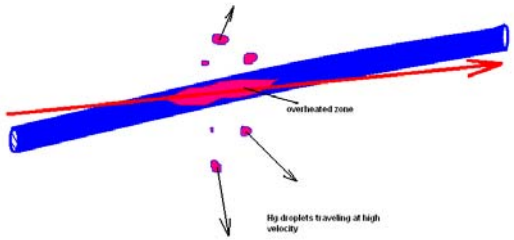


MERIT ALE Analyses – Hg Jet Interaction with Confinement Structure









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

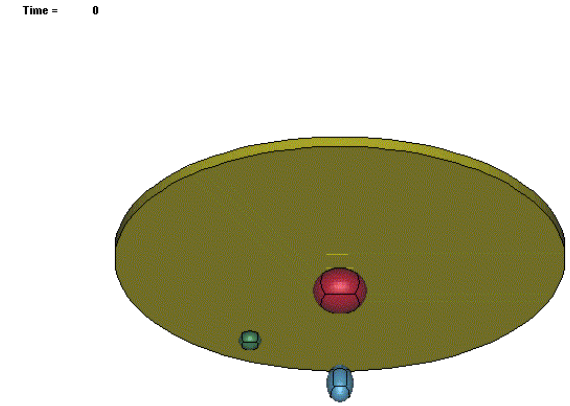
$$\Delta P \approx \alpha_v\, \Delta T/k$$

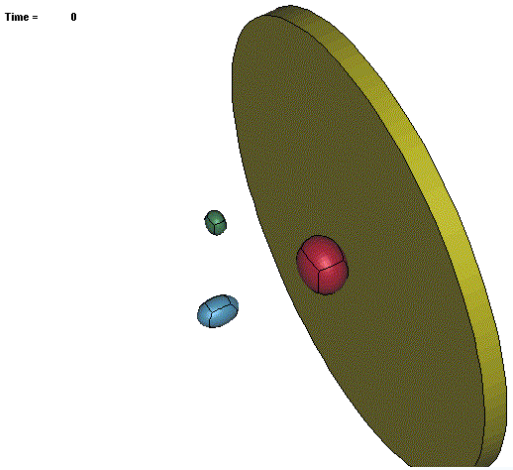
$$\alpha_v = (\partial V/\partial T)_P$$

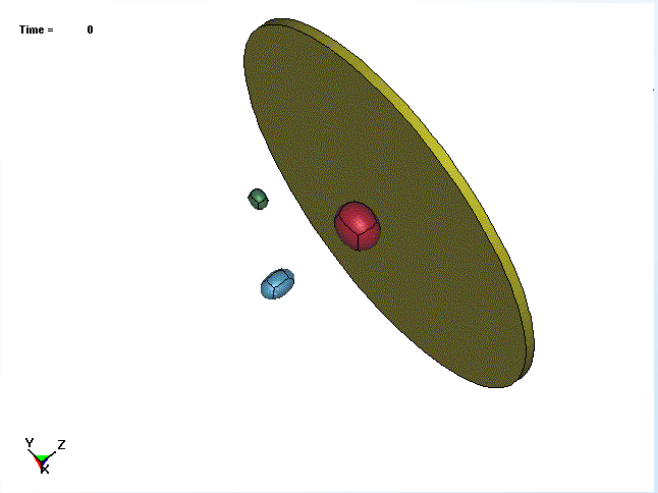
$$\delta(dV) = \alpha_v\, dV\, \Delta T$$

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

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







Conservative velocity estimates ~200 m/s are expected

Liquid Target Options and Studies Required

An ALE Formulation of Beam/Target Thermodynamic Interaction

Neutrino Factory Mercury Jet
Ejected Fluid and Surrounding Envelope Interaction/Damage

Problem Statement:

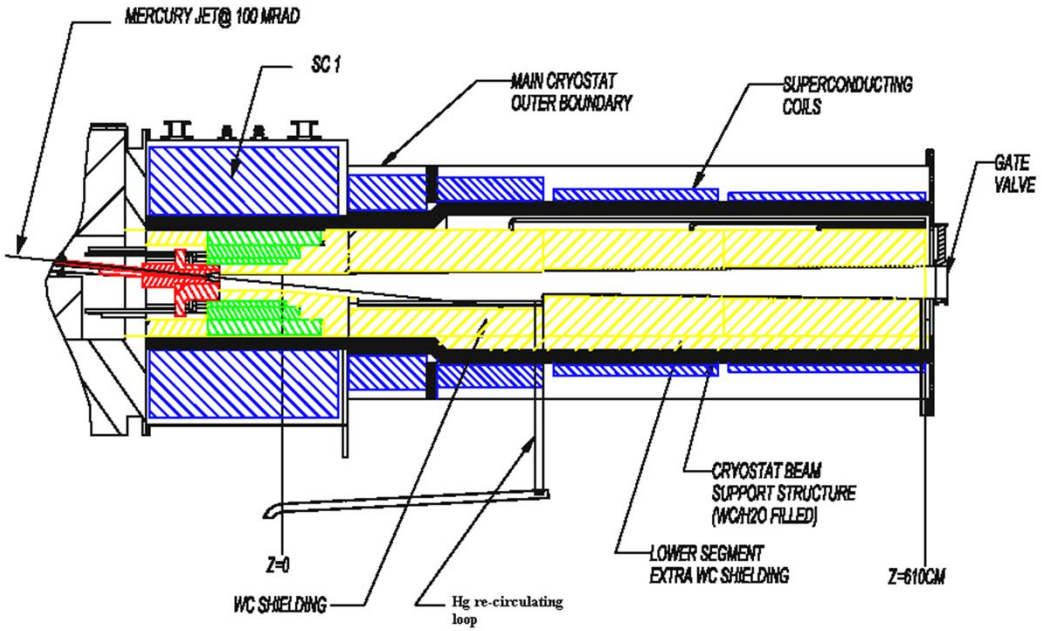
Following the Successful Completion of the E951 and MERIT Experiments regarding Hg Jet Stability and Beam Interaction,

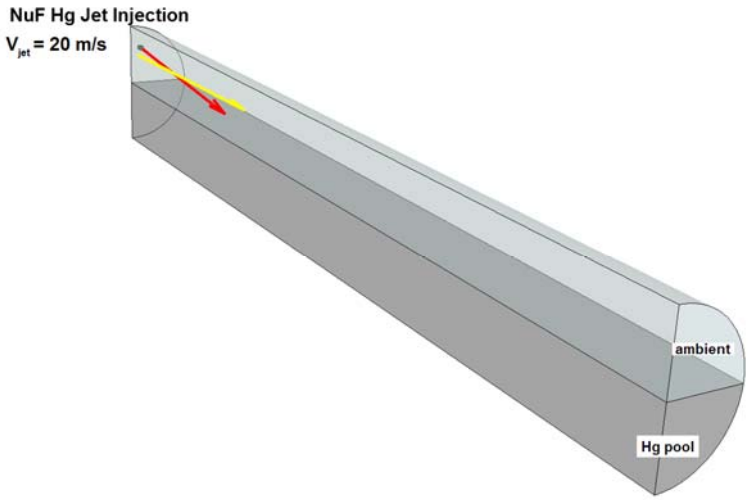
Questions addressed (or attempted to be answered)

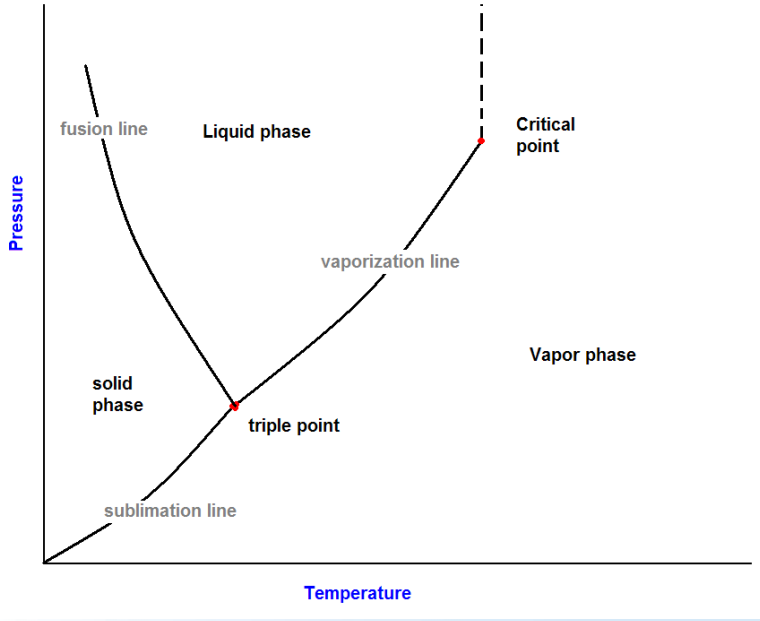
In the real target system where pulses will be arriving, interacting with Hg jet and Hg pool (+ Jet interacting with pool

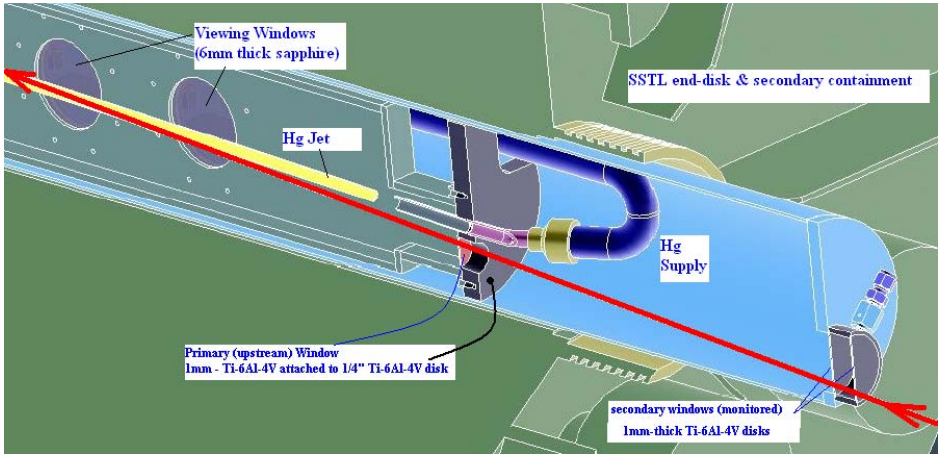
How does the “ambient” volume look after a while?

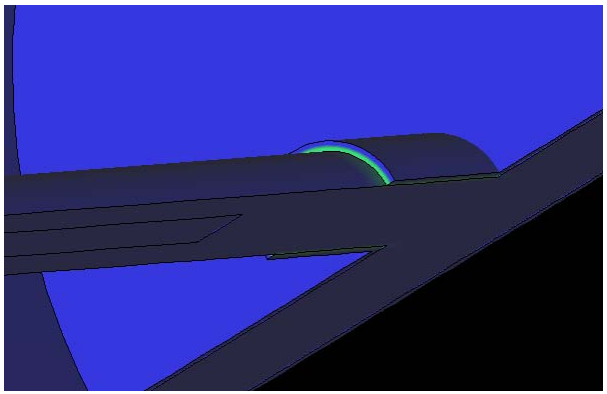
Will Hg vapors end-up occupying the volume impeding pion travel after being produced and coming out of the Hg jet target?

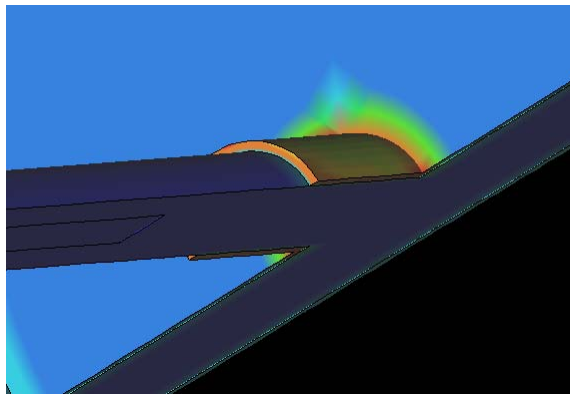

MERCURY JET@ 100 MRAD
SC 1
MAIN CRYOSTAT OUTER BOUNDARY
SUPERCONDUCTING COILS
GATE VALVE
CRYOSTAT BEAM SUPPORT STRUCTURE (WCH2O FILLED)
LOWER SEGMENT EXTRA WC SHIELDING
Z=0
Z=610CM
WC SHIELDING
Hg re-circulating loop

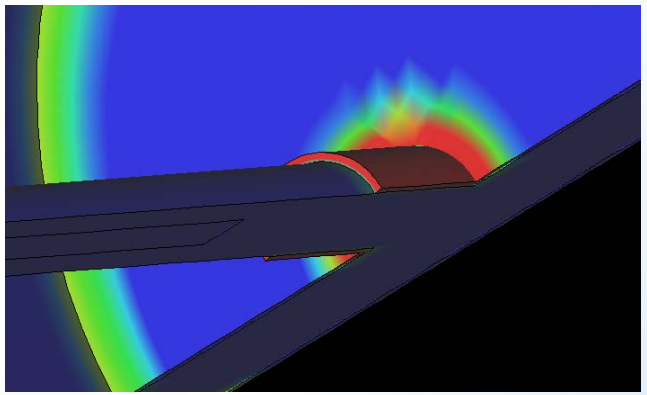

NuF Hg Jet Injection
V_{jet} = 20 m/s
ambient
Hg pool


fusion line
Liquid phase
Critical point
Pressure
vaporization line
Vapor phase
solid phase
triple point
sublimation line
Temperature


Viewing Windows
(6mm thick sapphire)
SSTL end-disk & secondary containment
Hg Jet
Hg
Supply
Primary (upstream) Window
1mm - Ti-6Al-4V attached to 1/4" Ti-6Al-4V disk
secondary windows (monitored)
1mm-thick Ti-6Al-4V disks







Challenges:

Hg EOS that cross phase boundaries

SESAME Library revisited in attempt to numerically describe the Hg phase diagram and introduce it to codes such as LS-DYNA

Energy Deposition introduction into Hg jet/pool system

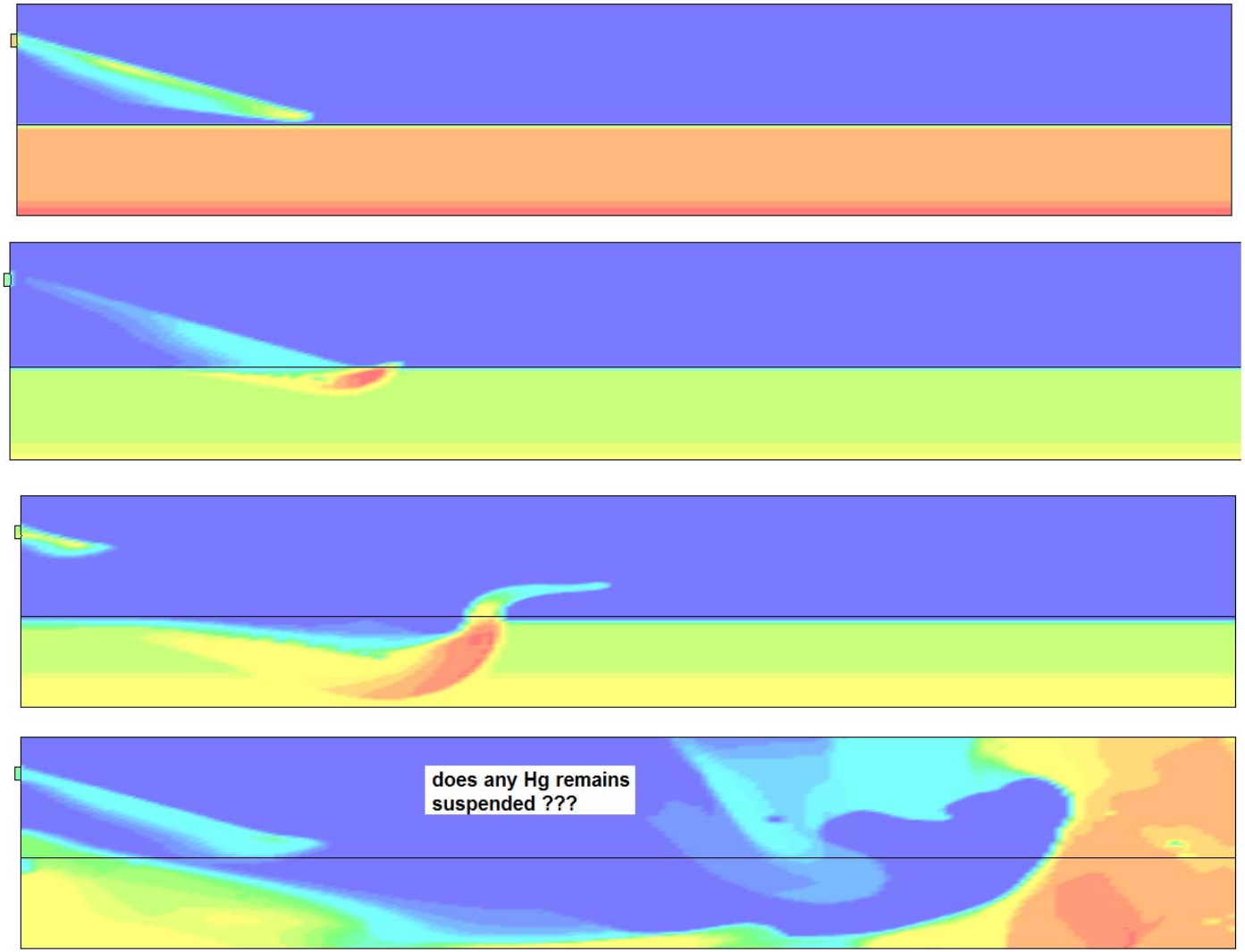
mechanics of it has been solved by utilizing capabilities of different codes

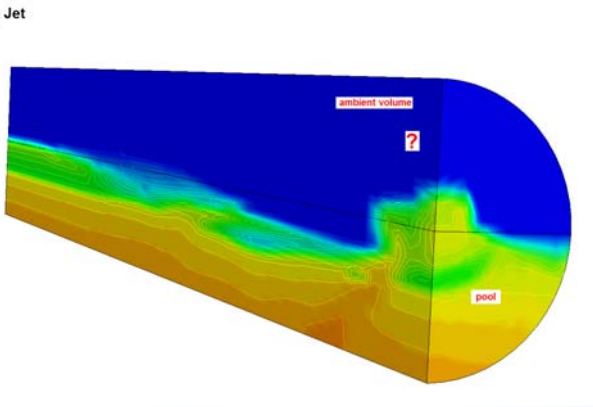
Implementation of Solenoid Tesla Field as part of same analysis

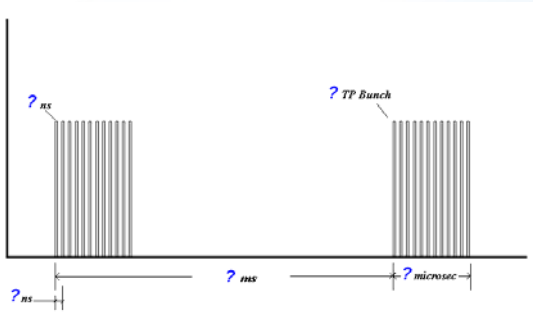
we think we have a solution with “pseudo-angular” rotation of Hg jet providing magneto-confining pressure

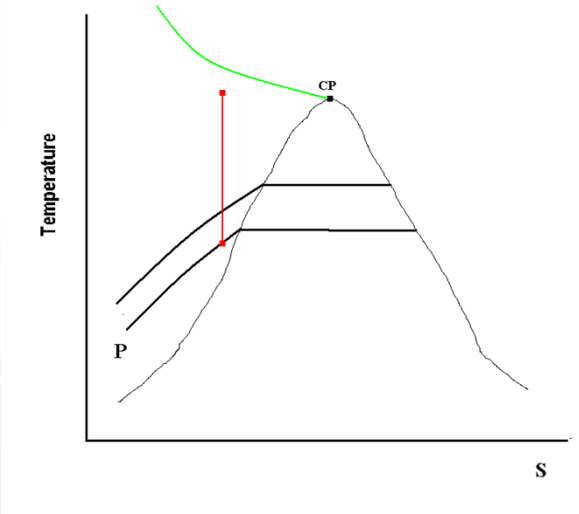
Trusting the predictions of the violent processes that we try to simulate

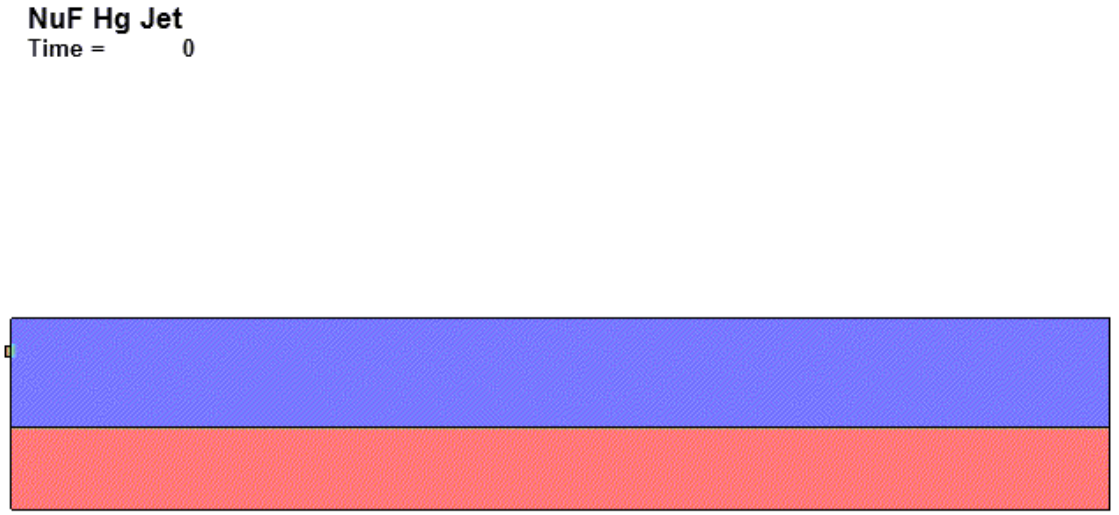
excellent basis due to successful benchmarking of relevant experiments


does any Hg remains
suspended ???


Hg Jet
ambient volume
?
pool

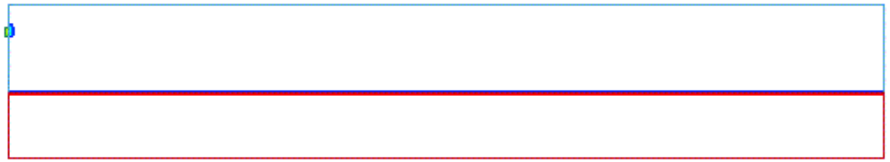

? ns
? TP Bunch
? ns
? ms
? microsec

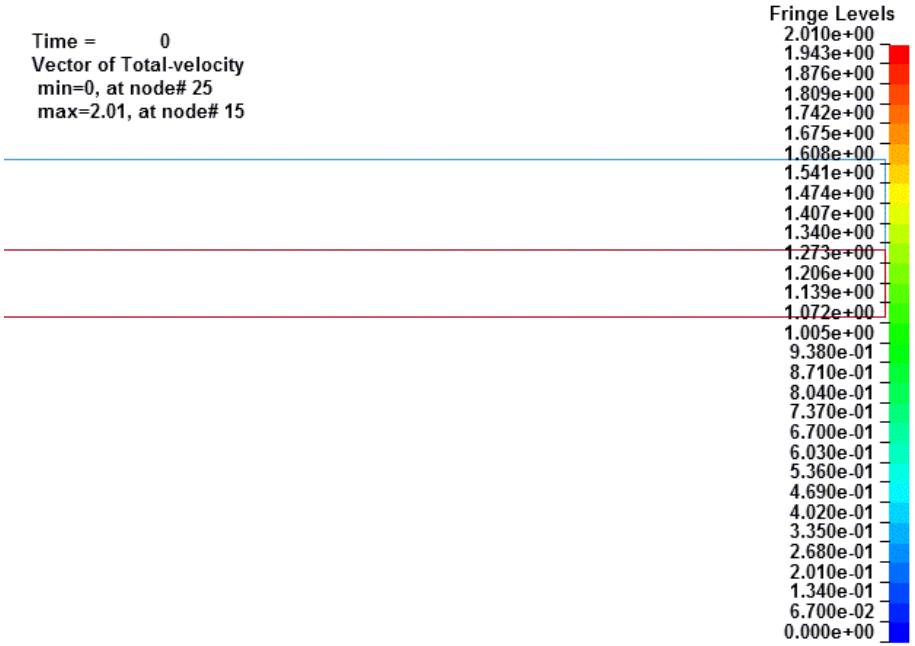

Temperature
CP
P
S

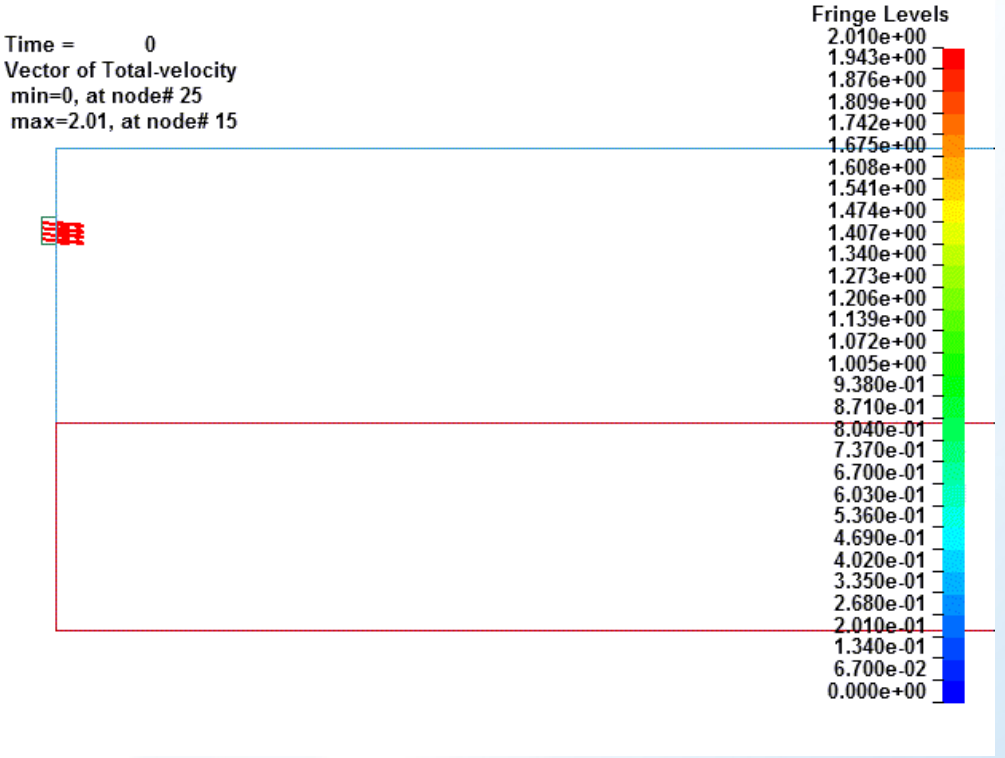

NuF Hg Jet
Time = 0

NuF Hg Jet
Time = 0

NuF Hg Jet
Time = 0




Time = 0
Vector of Total-velocity
min=0, at node# 25
max=2.01, at node# 15
Fringe Levels
2.010e+00
1.943e+00
1.876e+00
1.809e+00
1.742e+00
1.675e+00
1.608e+00
1.541e+00
1.474e+00
1.407e+00
1.340e+00
1.273e+00
1.206e+00
1.139e+00
1.072e+00
1.005e+00
9.380e-01
8.710e-01
8.040e-01
7.370e-01
6.700e-01
6.030e-01
5.360e-01
4.690e-01
4.020e-01
3.350e-01
2.680e-01
2.010e-01
1.340e-01
6.700e-02
0.000e+00


Time = 0
Vector of Total-velocity
min=0, at node# 25
max=2.01, at node# 15
Fringe Levels
2.010e+00
1.943e+00
1.876e+00
1.809e+00
1.742e+00
1.675e+00
1.608e+00
1.541e+00
1.474e+00
1.407e+00
1.340e+00
1.273e+00
1.206e+00
1.139e+00
1.072e+00
1.005e+00
9.380e-01
8.710e-01
8.040e-01
7.370e-01
6.700e-01
6.030e-01
5.360e-01
4.690e-01
4.020e-01
3.350e-01
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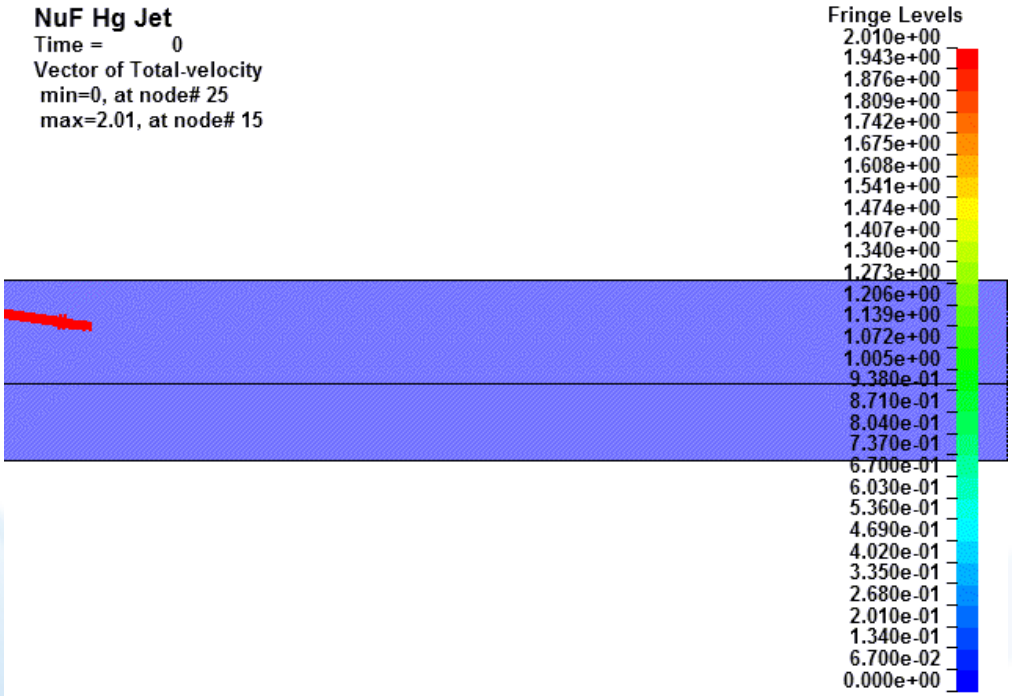
2.010e-01
1.340e-01
6.700e-02
0.000e+00


NuF Hg Jet
Time = 0
Vector of Total-velocity
min=0, at node# 25
max=2.01, at node# 15
Fringe Levels
2.010e+00
1.943e+00
1.876e+00
1.809e+00
1.742e+00
1.675e+00
1.608e+00
1.541e+00
1.474e+00
1.407e+00
1.340e+00
1.273e+00
1.206e+00
1.139e+00
1.072e+00
1.005e+00
9.380e-01
8.710e-01
8.040e-01
7.370e-01
6.700e-01
6.030e-01
5.360e-01
4.690e-01
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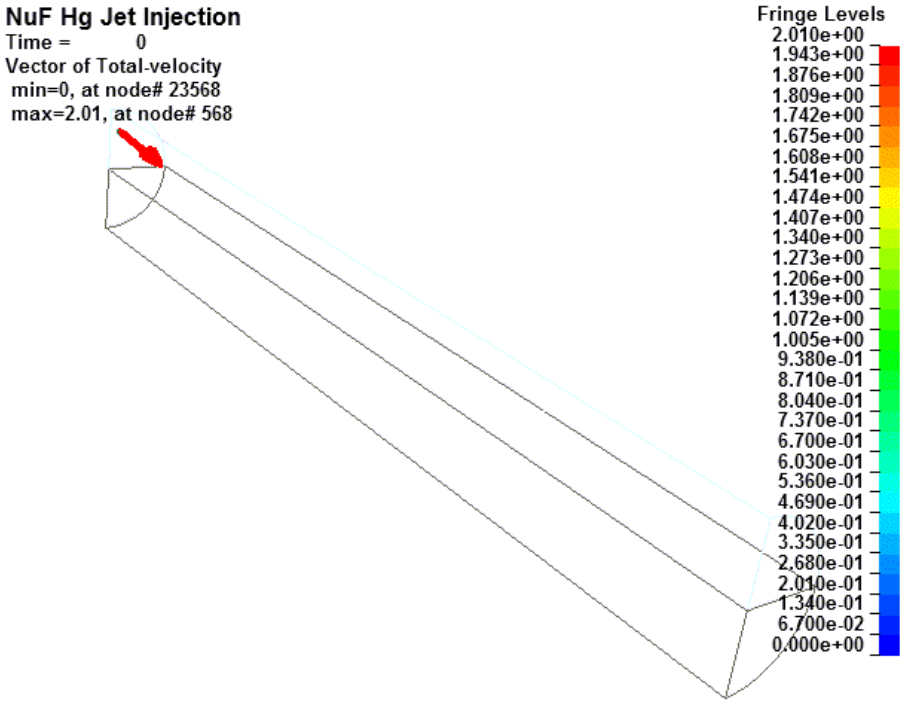
2.010e-01
1.340e-01
6.700e-02
0.000e+00


NuF Hg Jet Injection
Time = 0
Vector of Total-velocity
min=0, at node# 23568
max=2.01, at node# 568
Fringe Levels
2.010e+00
1.943e+00
1.876e+00
1.809e+00
1.742e+00
1.675e+00
1.608e+00
1.541e+00
1.474e+00
1.407e+00
1.340e+00
1.273e+00
1.206e+00
1.139e+00
1.072e+00
1.005e+00
9.380e-01
8.710e-01
8.040e-01
7.370e-01
6.700e-01
6.030e-01
5.360e-01
4.690e-01
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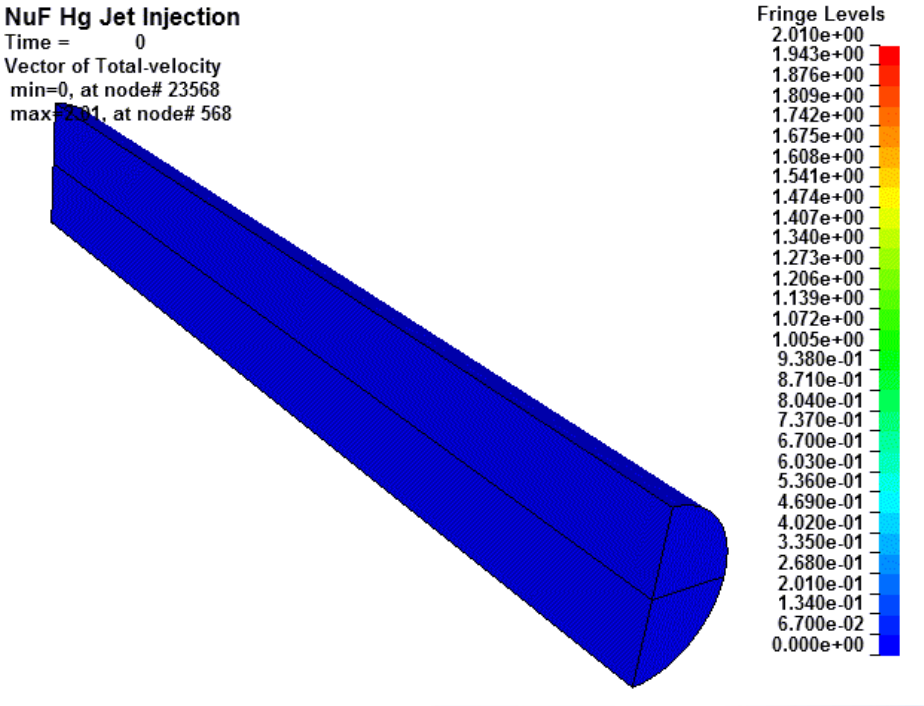
2.010e-01
1.340e-01
6.700e-02
0.000e+00


NuF Hg Jet Injection
Time = 0
Vector of Total-velocity
min=0, at node# 23568
max=2.01, at node# 568
Fringe Levels
2.010e+00
1.943e+00
1.876e+00
1.809e+00
1.742e+00
1.675e+00
1.608e+00
1.541e+00
1.474e+00
1.407e+00
1.340e+00
1.273e+00
1.206e+00
1.139e+00
1.072e+00
1.005e+00
9.380e-01
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8.040e-01
7.370e-01
6.700e-01
6.030e-01
5.360e-01
4.690e-01
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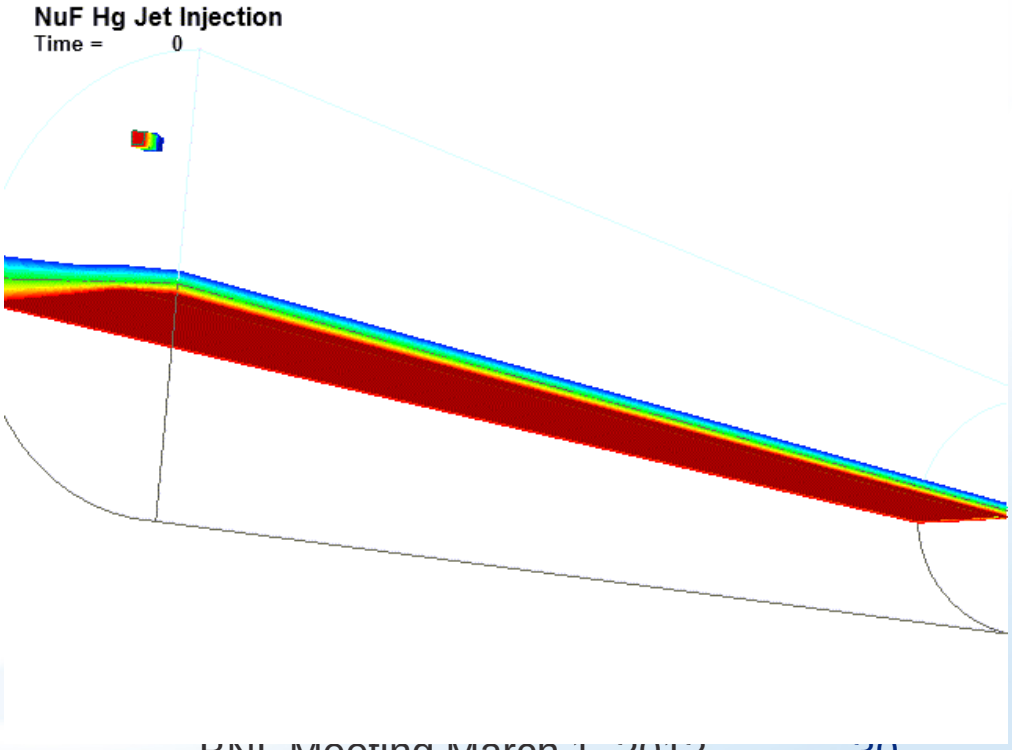
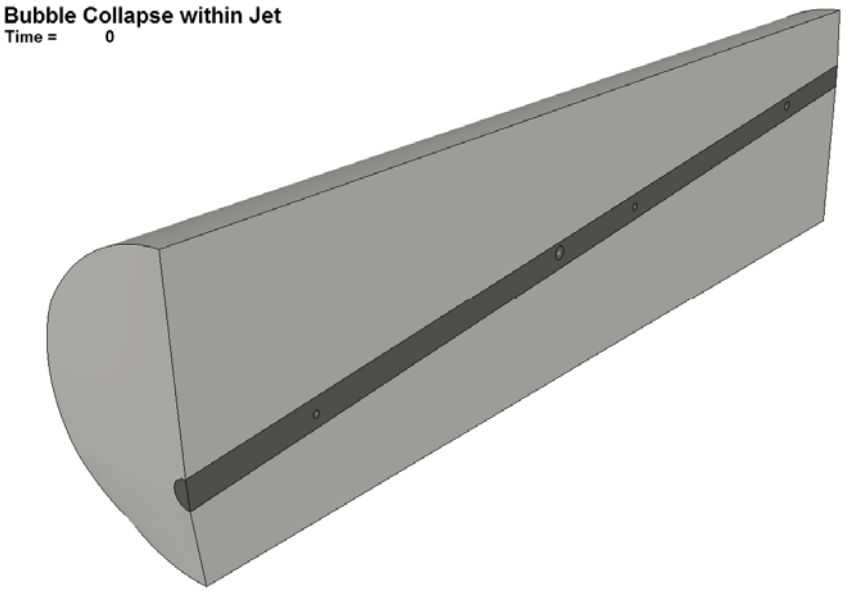
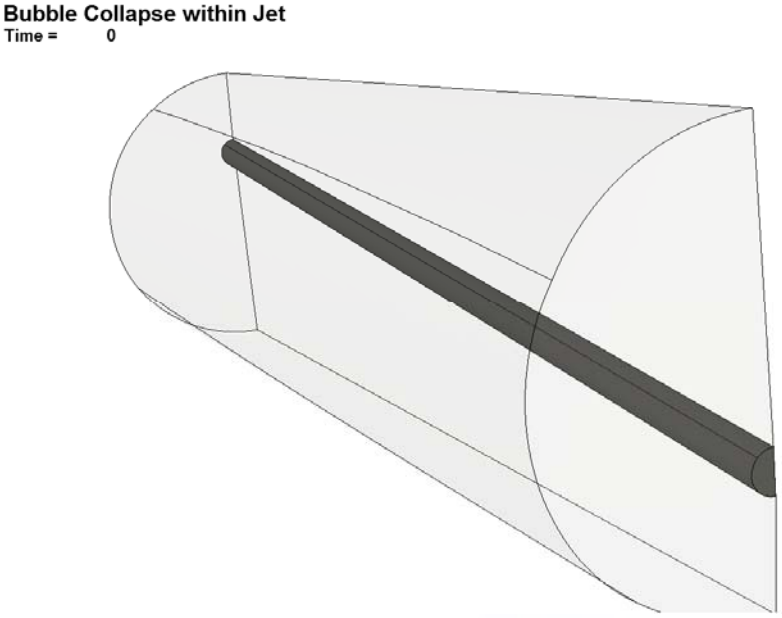
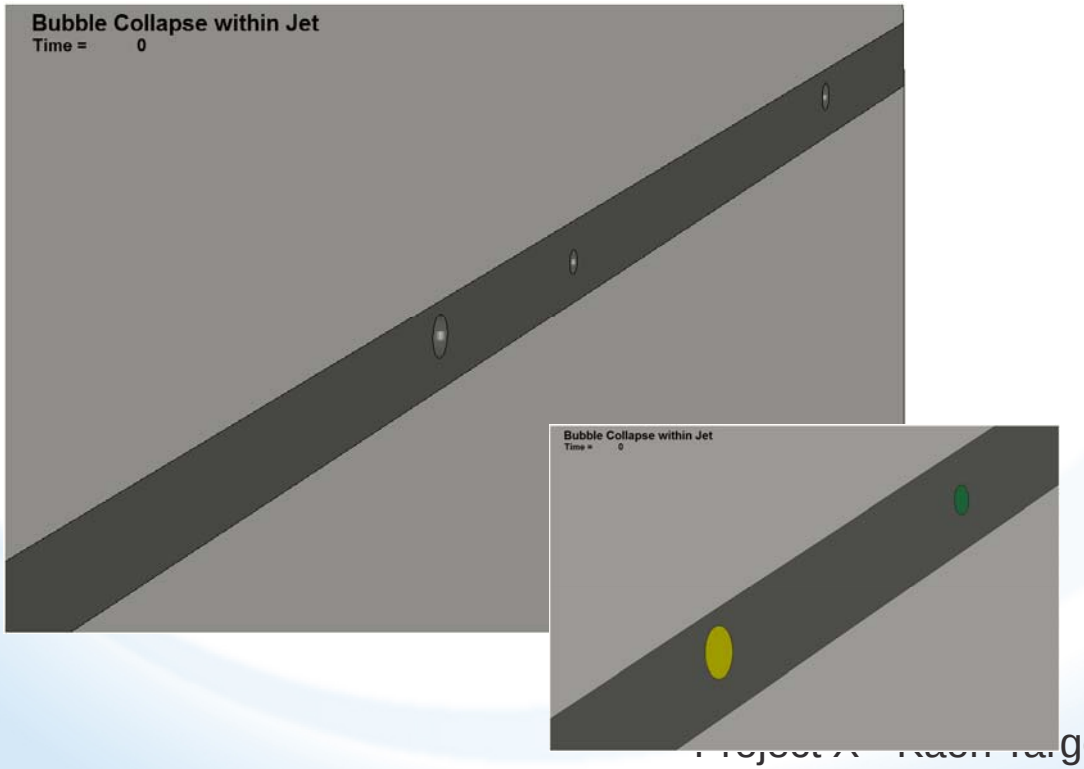
1.340e-01
6.700e-02
0.000e+00

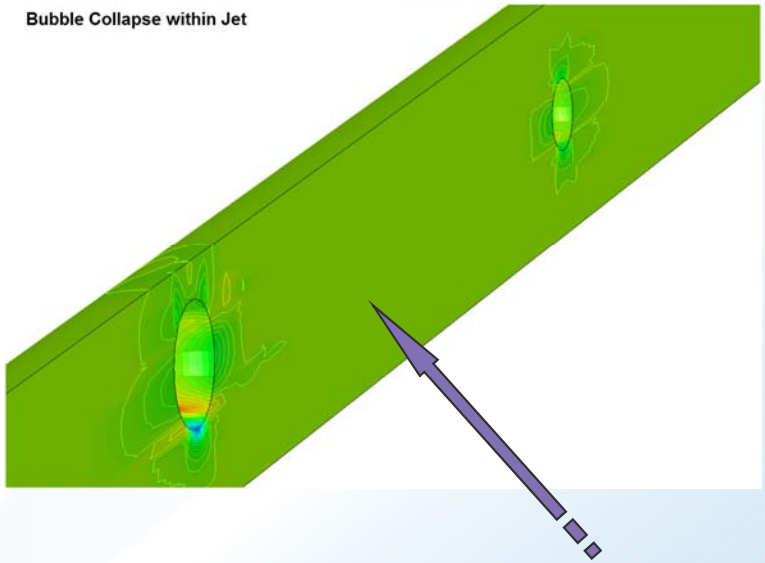

NuF Hg Jet Injection
Time = 0

Bubble Dynamics and Hg Jet/Pool



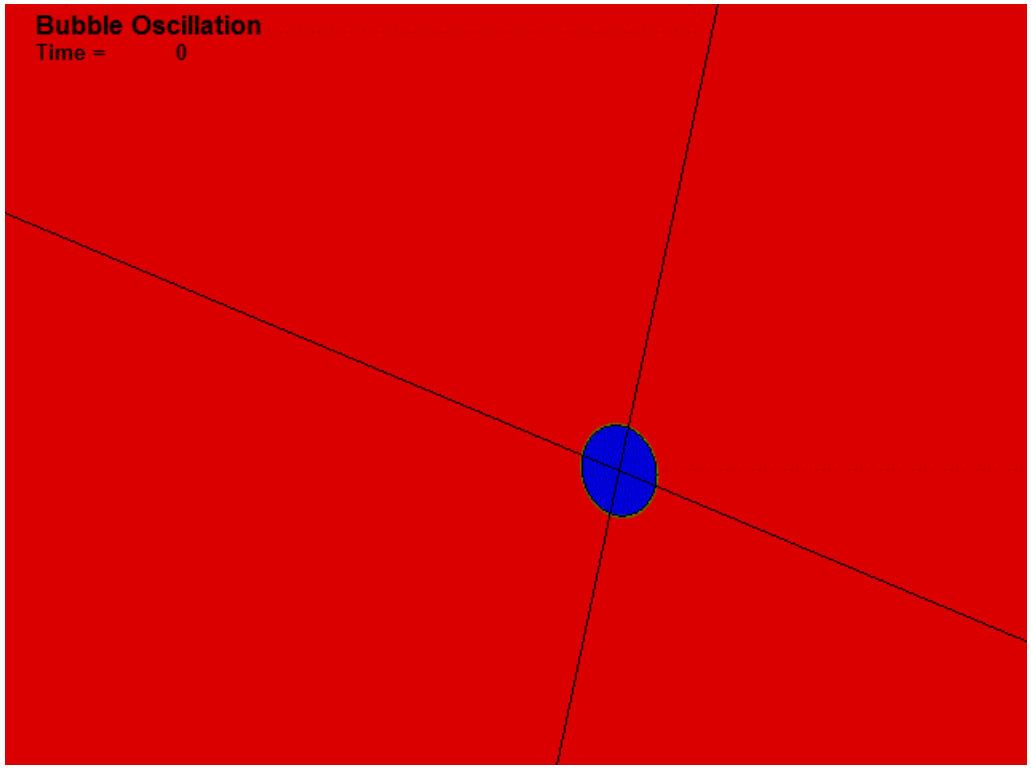


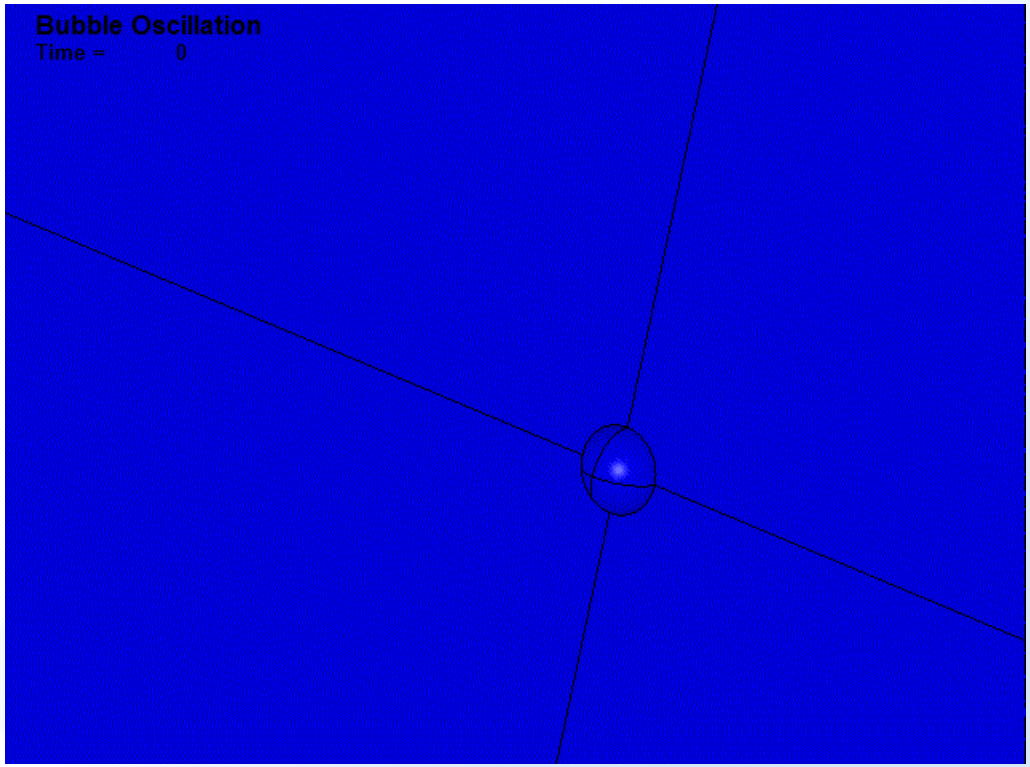


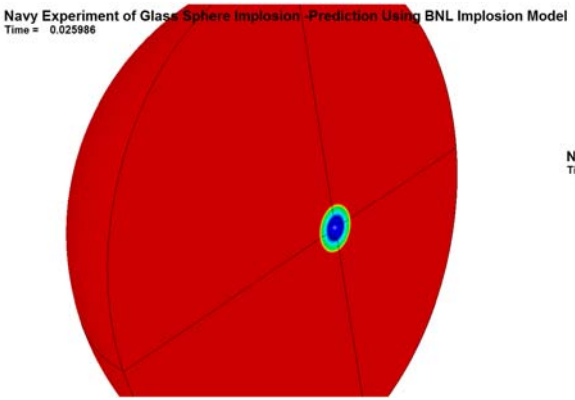


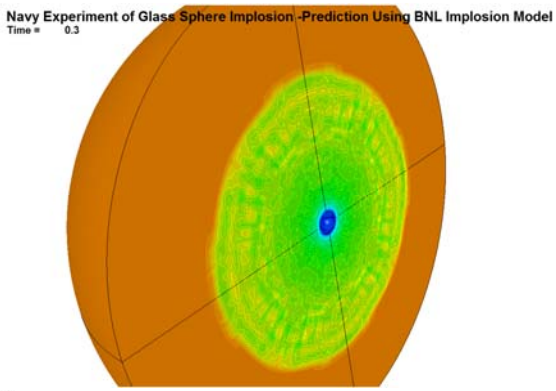
Local pressure outside formed bubble
can be very high from beam energy deposition

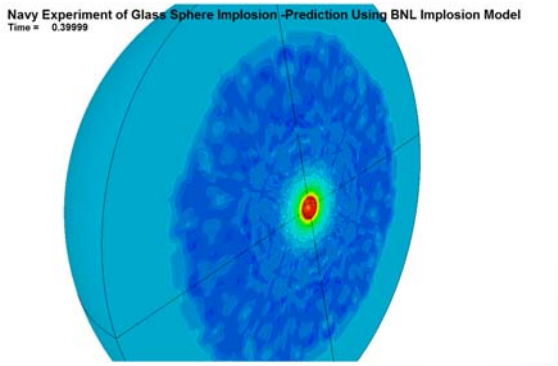
Excellent driver of implosion process

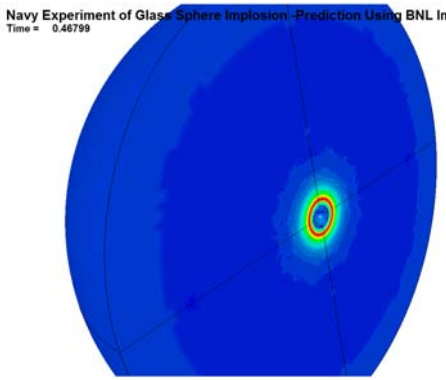

Bubble Oscillation
Time = 0

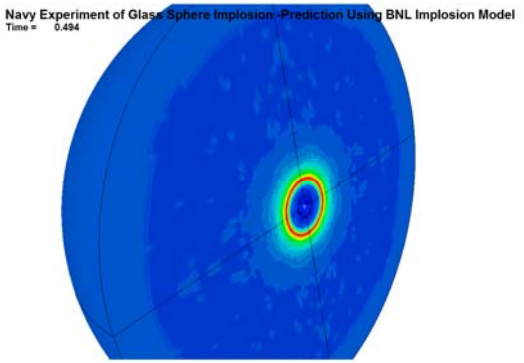

Bubble Oscillation
Time = 0

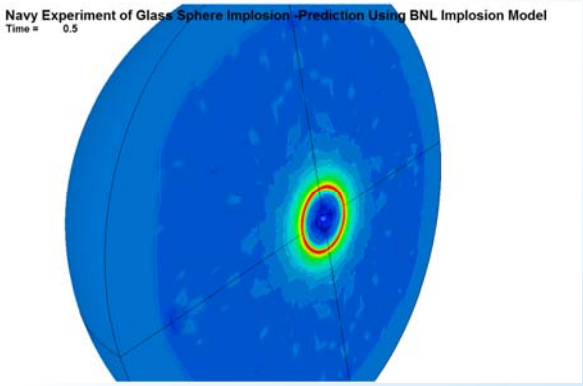

Navy Experiment of Glass Sphere Implosion -Prediction Using BNL Implosion Model
Time = 0.025986

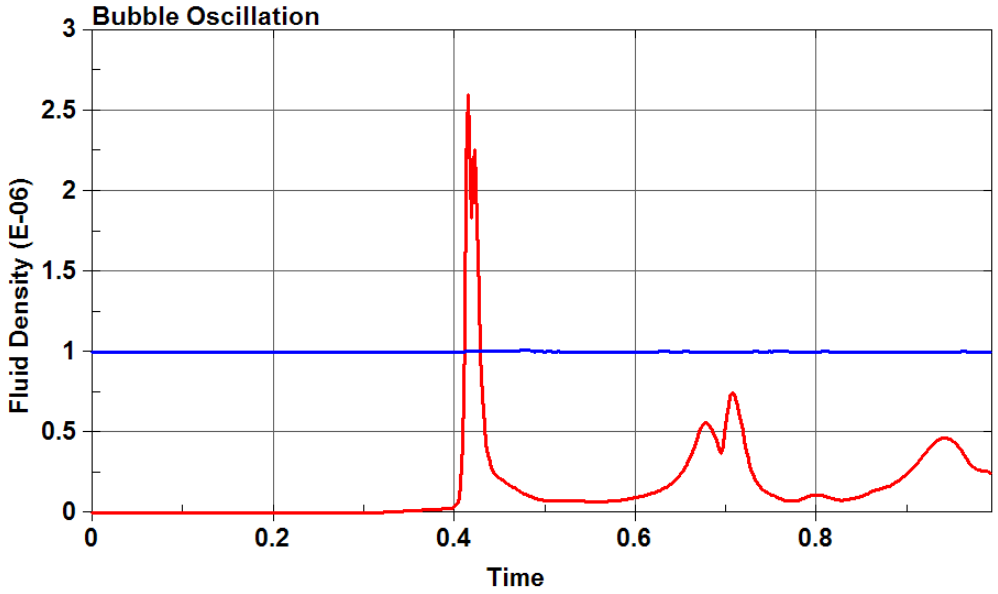

Navy Experiment of Glass Sphere Implosion -Prediction Using BNL Implosion Model
Time = 0.3

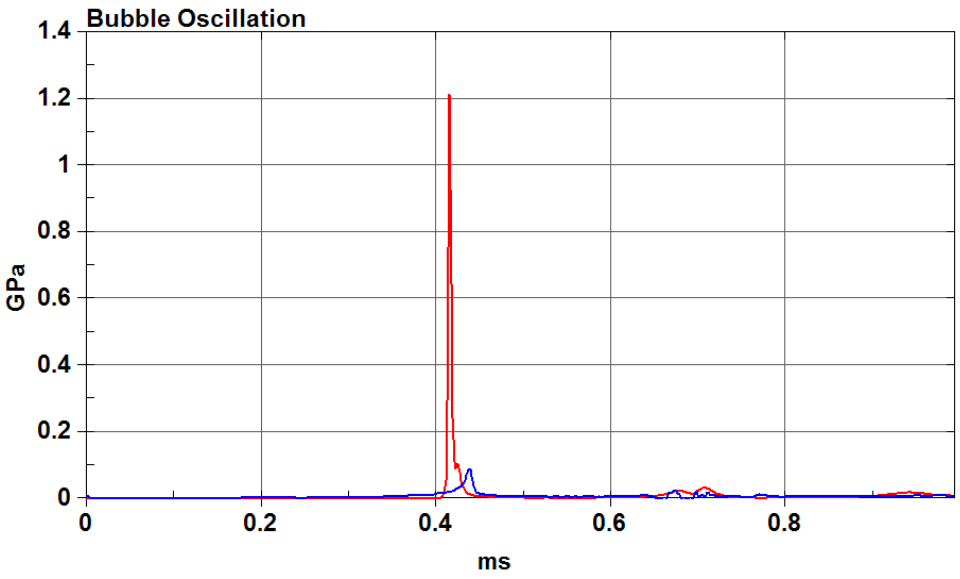

Navy Experiment of Glass Sphere Implosion -Prediction Using BNL Implosion Model
Time = 0.39999

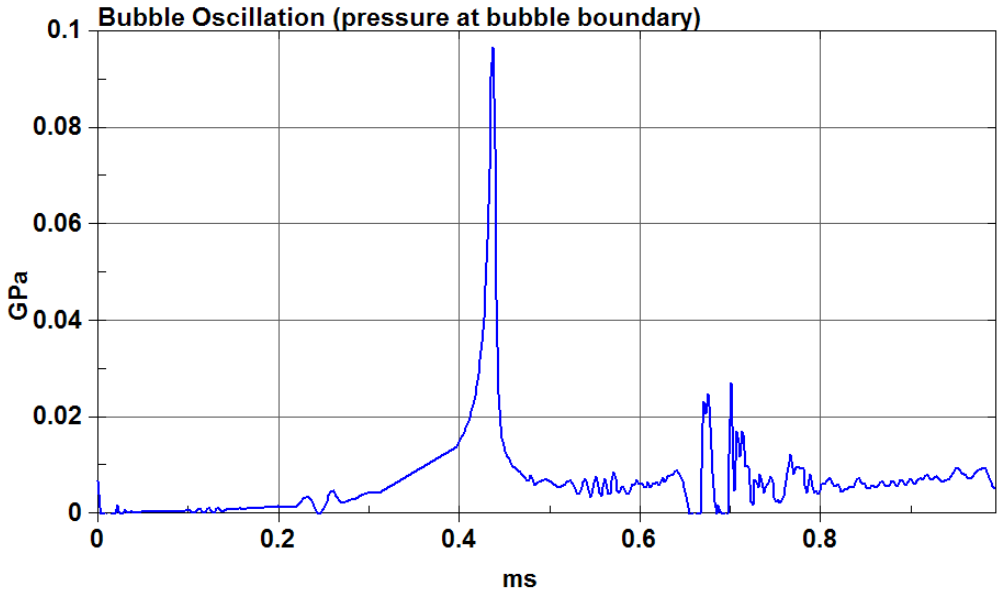

Navy Experiment of Glass Sphere Implosion -Prediction Using BNL Implosion Model
Time = 0.46799


Navy Experiment of Glass Sphere Implosion -Prediction Using BNL Implosion Model
Time = 0.494

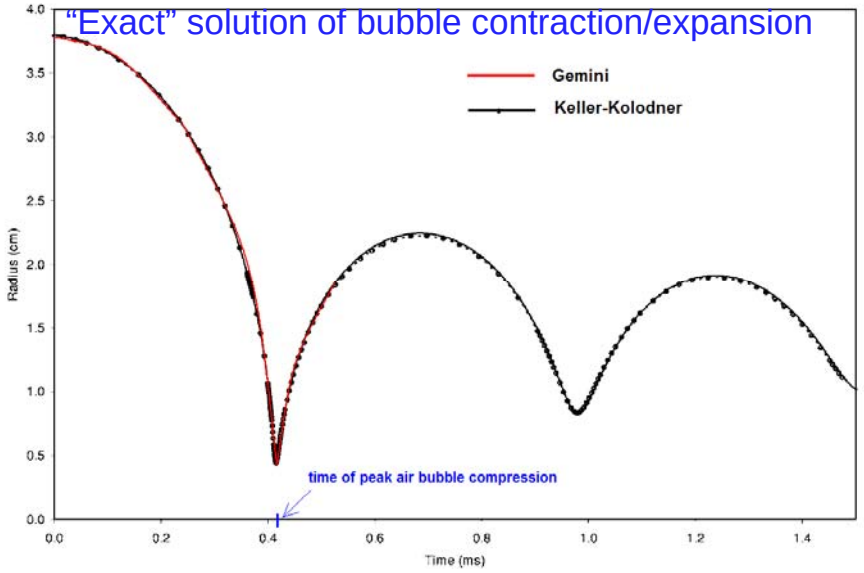

Navy Experiment of Glass Sphere Implosion -Prediction Using BNL Implosion Model
Time = 0.5

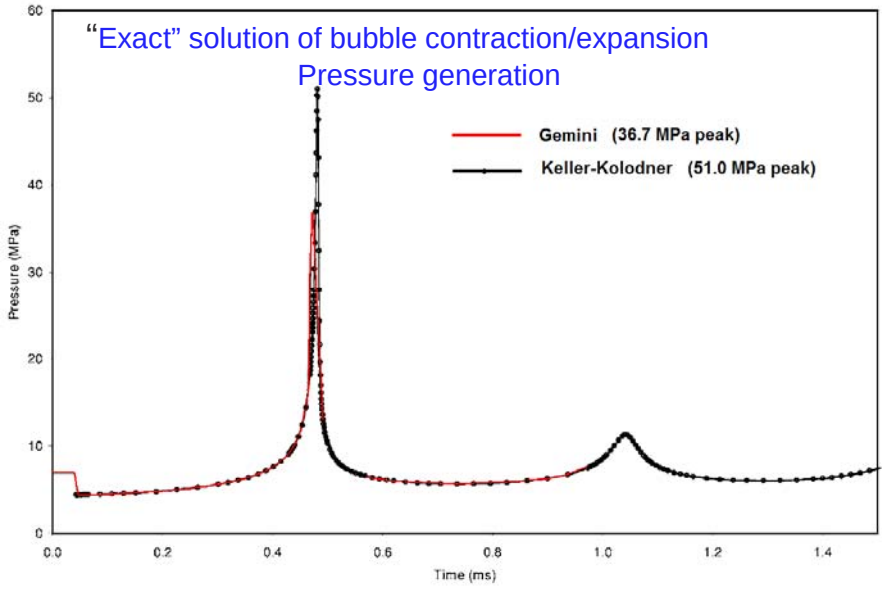

Bubble Oscillation
Fluid Density (E-06)
3
2.5
2
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
Time

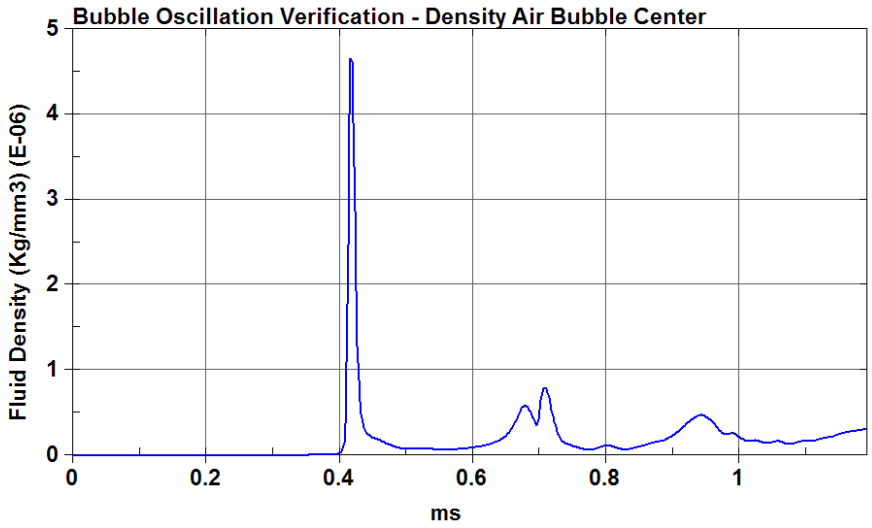

Bubble Oscillation
GPa
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
ms

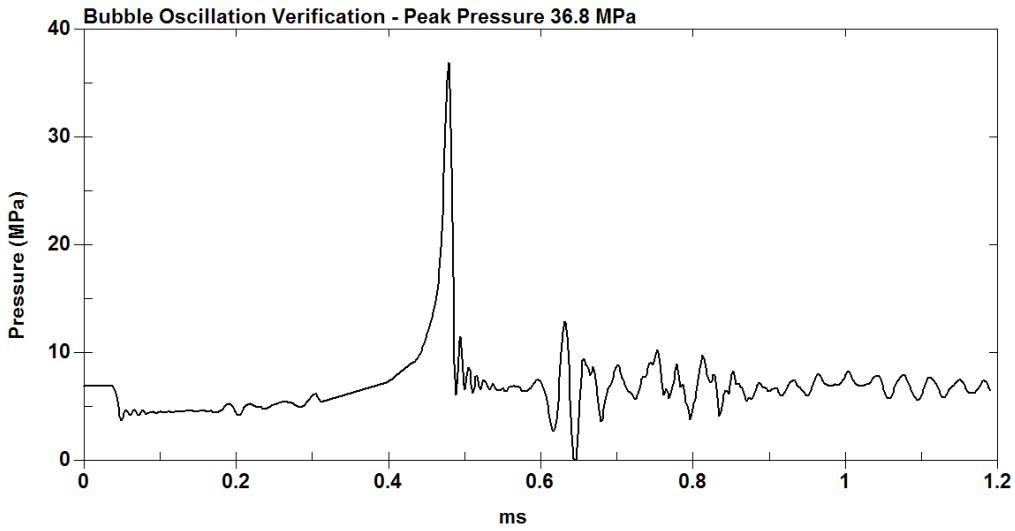

Bubble Oscillation (pressure at bubble boundary)
GPa
0.1
0.08
0.06
0.04
0.02
0
0
0.2
0.4
0.6
0.8
ms

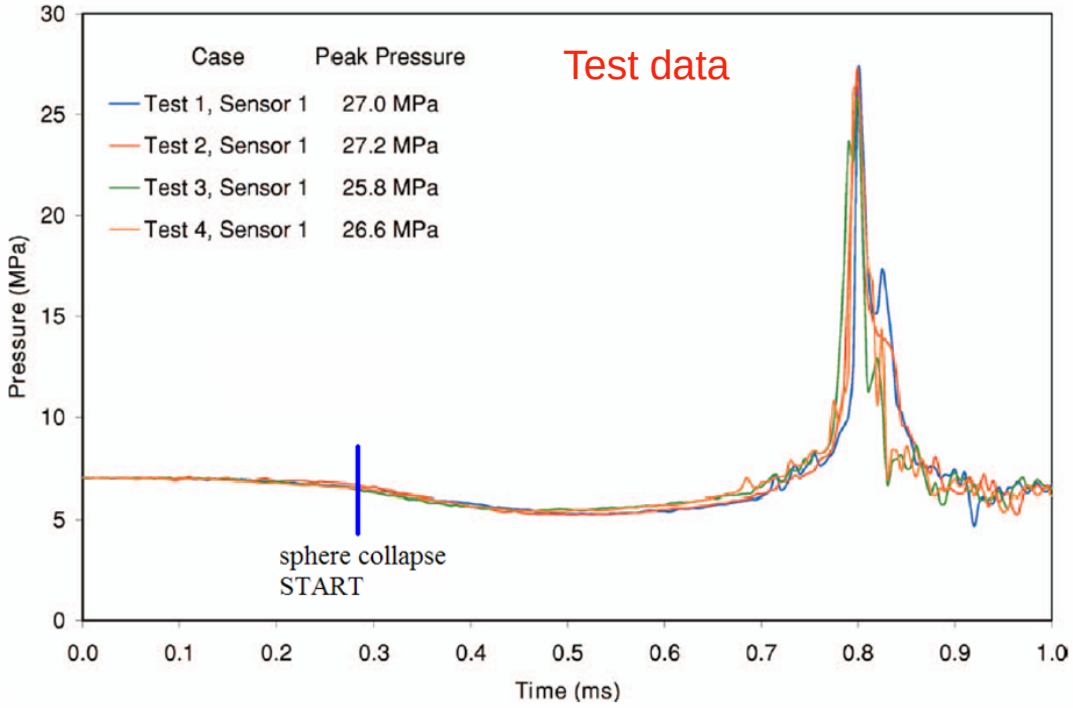
“Exact” Solutions of Air Bubble Collapse/Oscillation

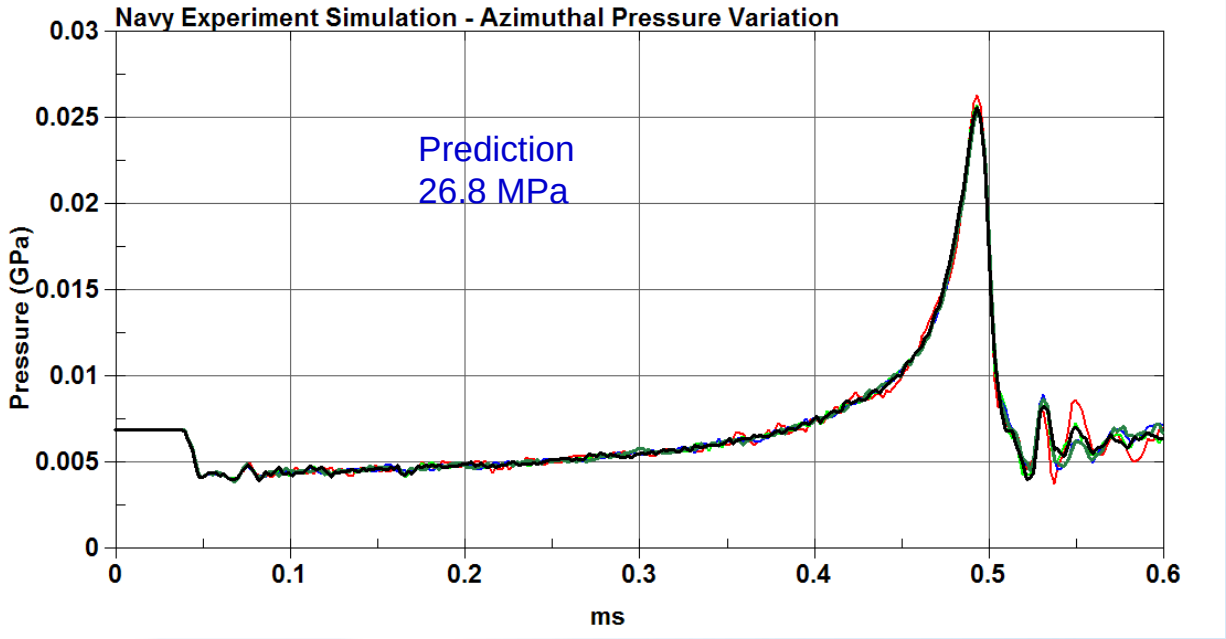


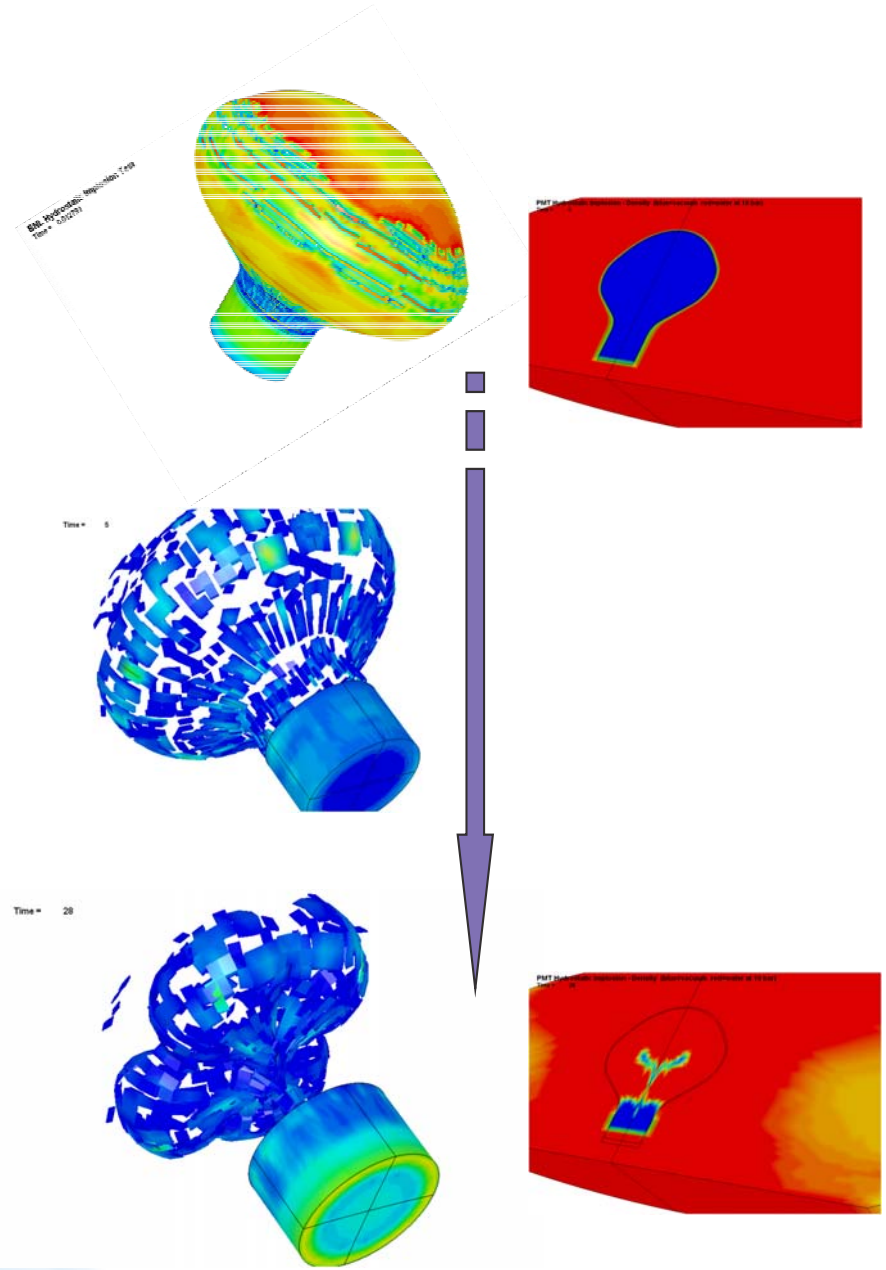







Test data
Case
Peak Pressure
Test 1, Sensor 1
27.0 MPa
Test 2, Sensor 1
27.2 MPa
Test 3, Sensor 1
25.8 MPa
Test 4, Sensor 1
26.6 MPa
sphere collapse
START
Pressure (MPa)
Time (ms)
0
5
10
15
20
25
30
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0


Navy Experiment Simulation - Azimuthal Pressure Variation
Prediction
26.8 MPa
Pressure (GPa)
ms
0
0.005
0.01
0.015
0.02
0.025
0.03
0
0.1
0.2
0.3
0.4
0.5
0.6

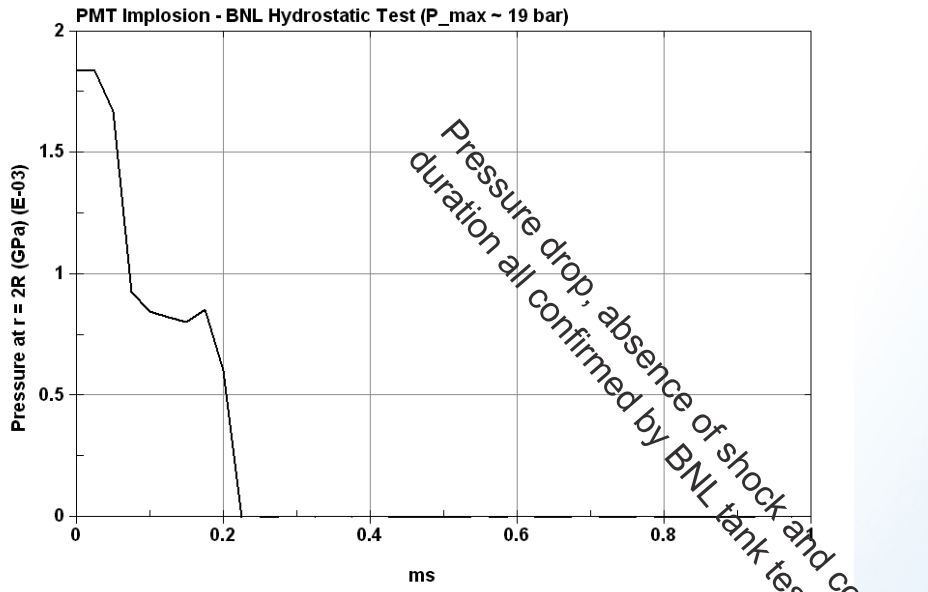


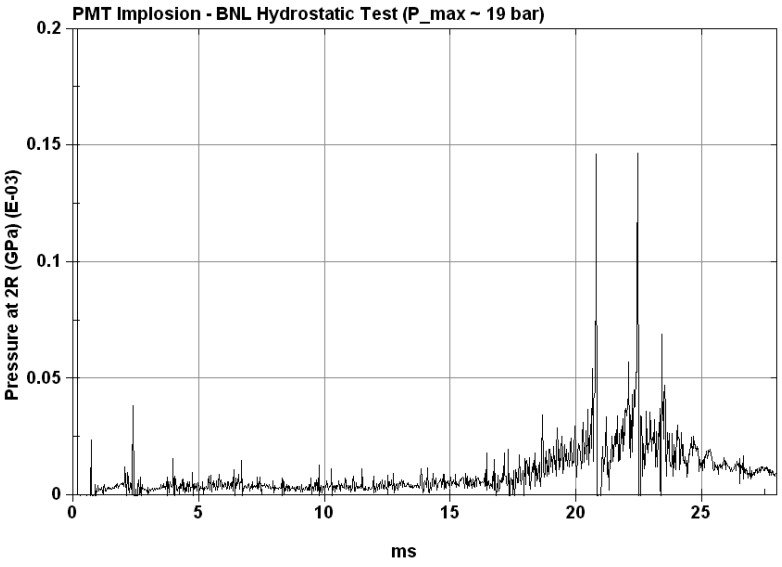
Simulation Predictions confirmed by the BNL Tests:

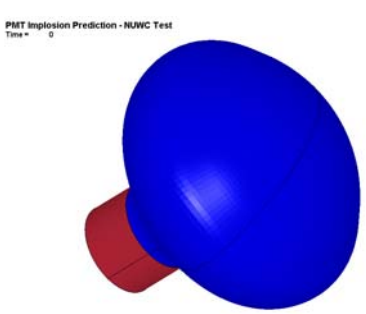
No shock develops !!

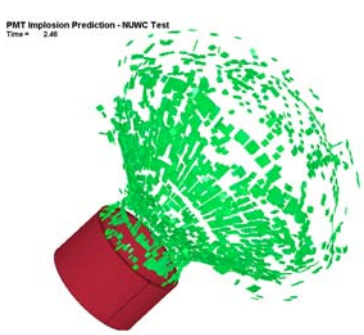
Implosion process very long (20+ ms)

Hydrostatic pressure limit ~270 psi (19 Atm) !!!

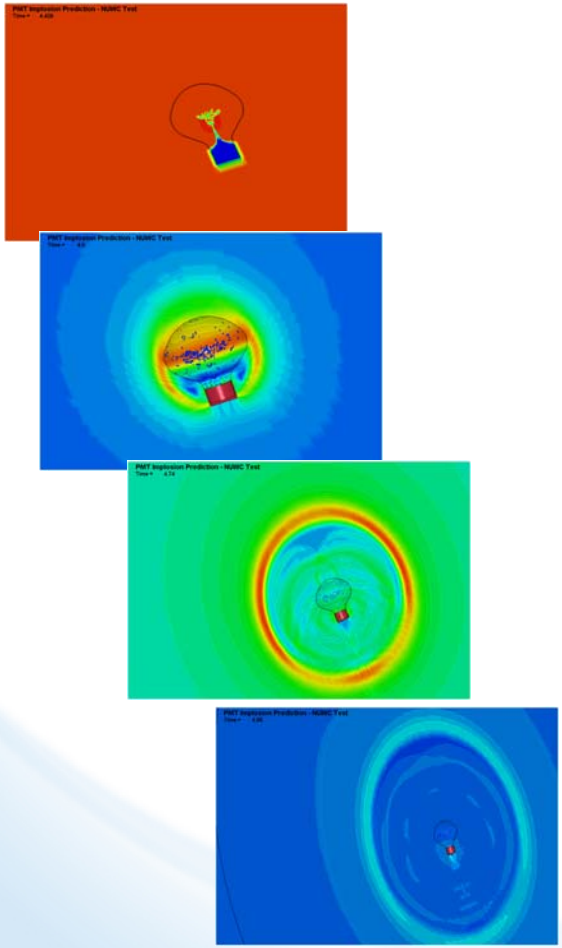


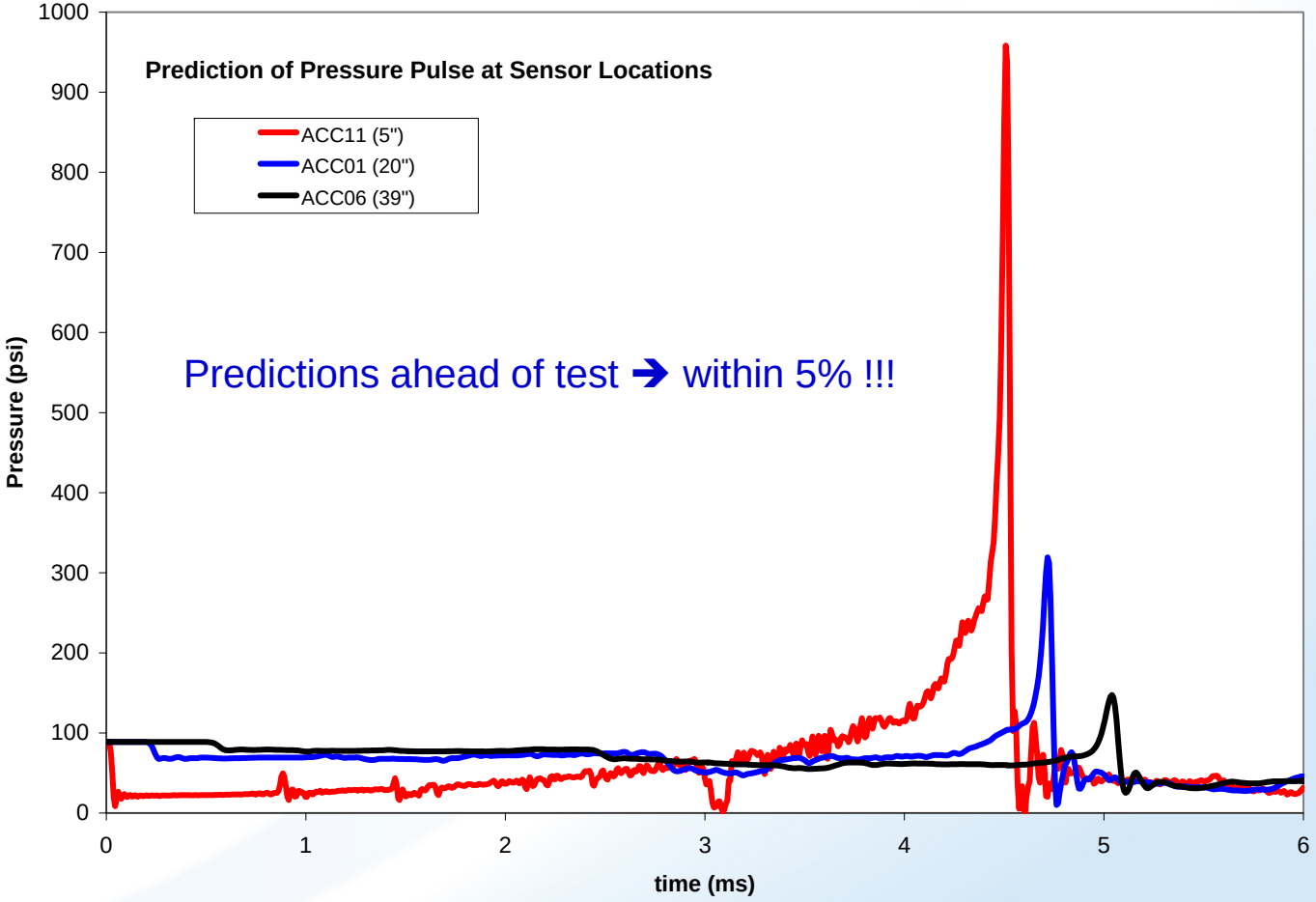



PMT Implosion Prediction - NUWC Test


PMT Implosion Prediction - NUWC Test


PMT Implosion Prediction - NUWC Test




Prediction of Pressure Pulse at Sensor Locations
ACC11 (5")
ACC01 (20")
ACC06 (39")
Predictions ahead of test ➔ within 5% !!!
Pressure (psi)
time (ms)
0
100
200
300
400
500
600
700
800
900
1000
0
1
2
3
4
5
6

Path Forward and Connection to Project X – Kaon Targetry

..... To be discussed in March 1, 2012 meeting