An ALE Formulation of Thermodynamic Interaction of the Neutrino Factory Mercury Jet in the Target Envelope

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BNL

Problem Statement:

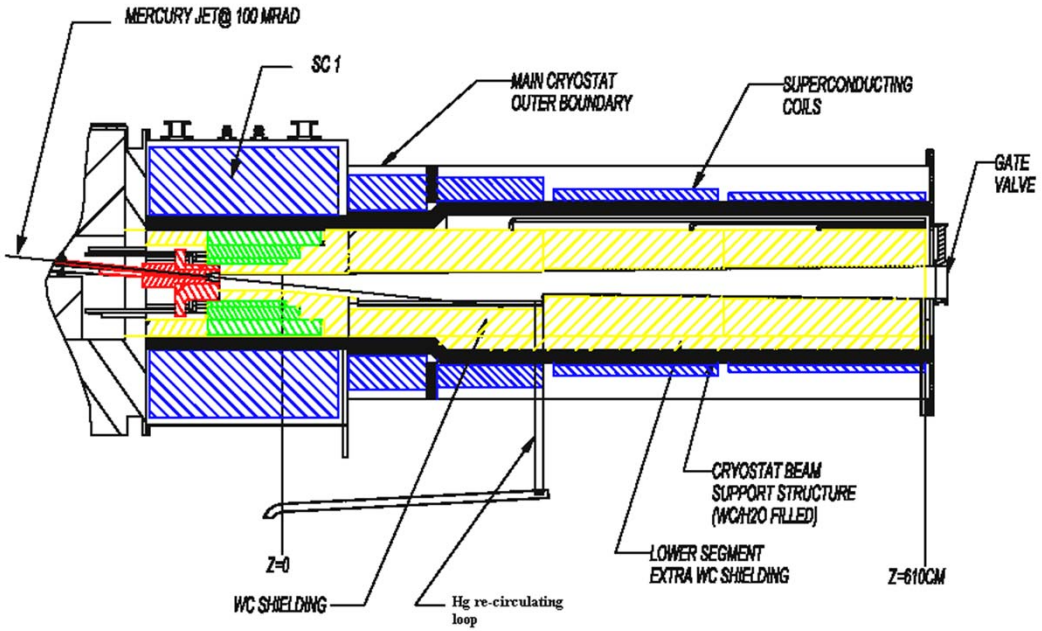
Following the Successful Completion of the E951 and MERIT Experiments regarding Hg Jet Stability and Beam Interaction,

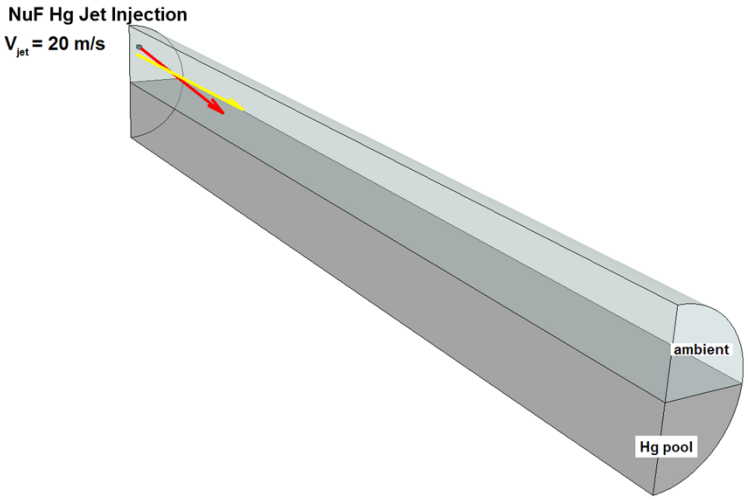
The following question is addressed (attempted to be answered)

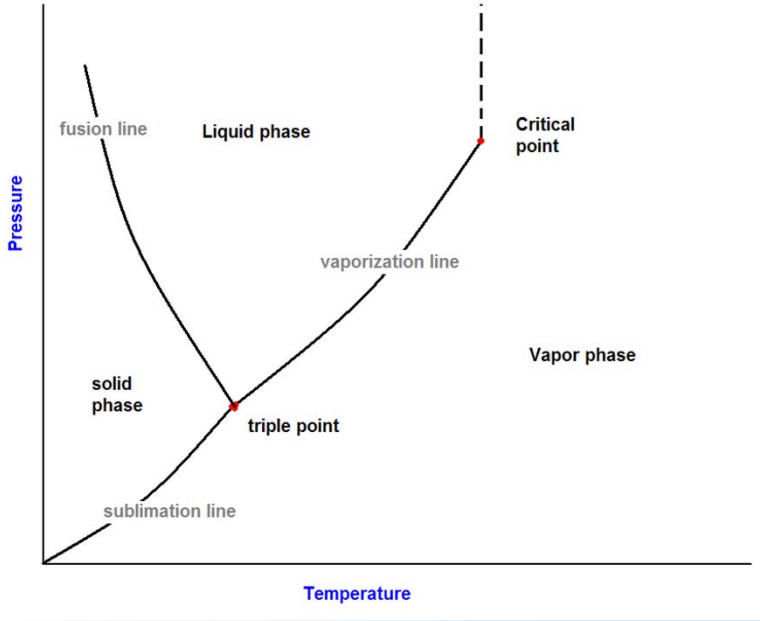
In the real target system where pulses will be arriving, interacting with Hg jet and Hg pool (+ Jet interacting with pool

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

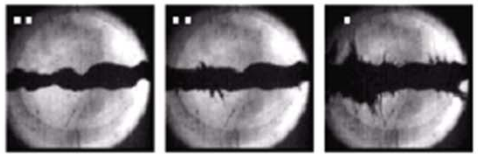
Will Hg vapors end-up occupying the volume impeding pion travel after being produced and coming out of the Hg jet target?

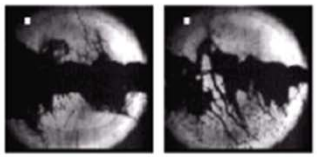

MERCURY JET@ 100 MRAD
SC 1
MAIN CRYOSTAT OUTER BOUNDARY
SUPERCONDUCTING COILS
GATE VALVE
CRYOSTAT BEAM SUPPORT STRUCTURE (WCH2O FILLED)
LOWER SEGMENT EXTRA WC SHIELDING
Z=0
Z=610CM
WC SHIELDING
Hg re-circulating loop

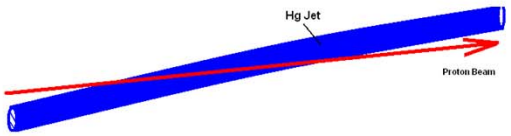

NuF Hg Jet Injection
V_{jet} = 20 m/s
ambient
Hg pool

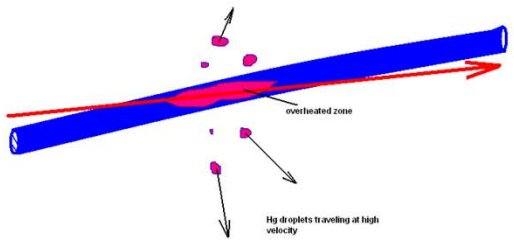

fusion line
Liquid phase
Critical point
Pressure
vaporization line
Vapor phase
solid phase
triple point
sublimation line
Temperature

MERIT ALE Analyses – Hg Jet Interaction with Confinement Structure









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

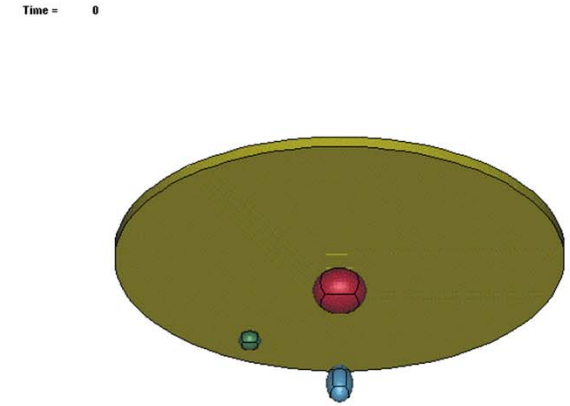
$$\Delta P \approx \alpha_v\, \Delta T/k$$

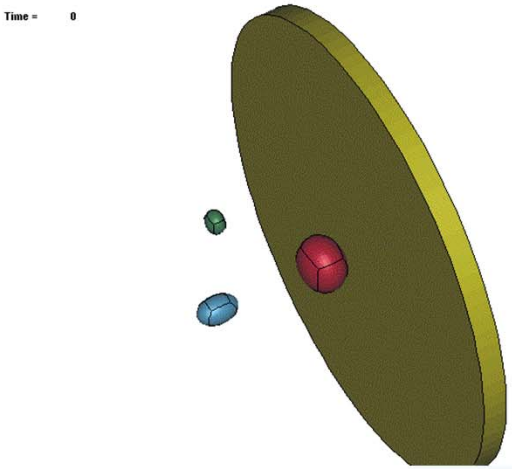
$$\alpha_v = (\partial V/\partial T)_P$$

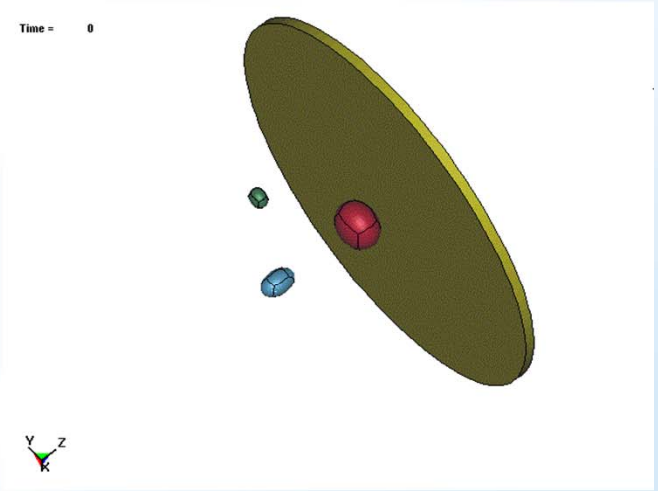
$$\delta(dV) = \alpha_v\, dV\, \Delta T$$

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

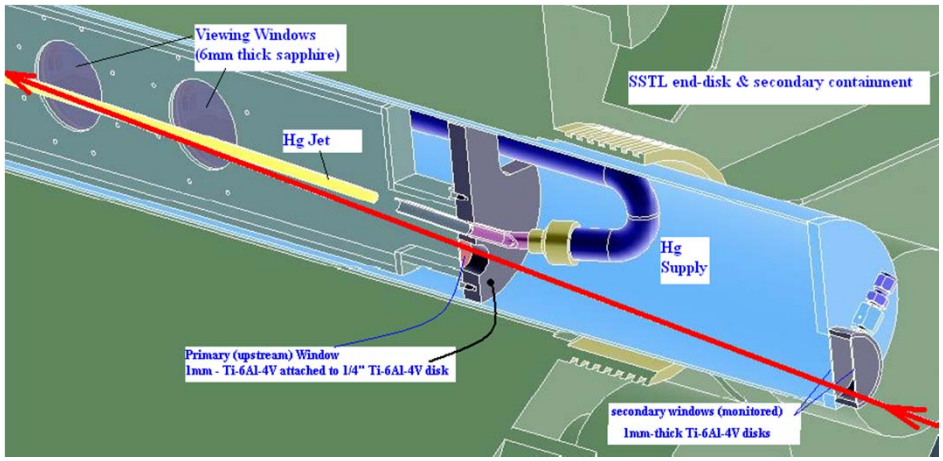
$$\boldsymbol{U}_r = \sqrt{2}\,[\alpha_v\,\Delta T]\,c$$

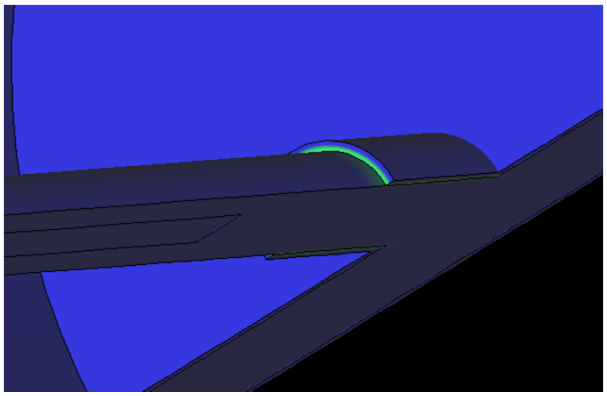


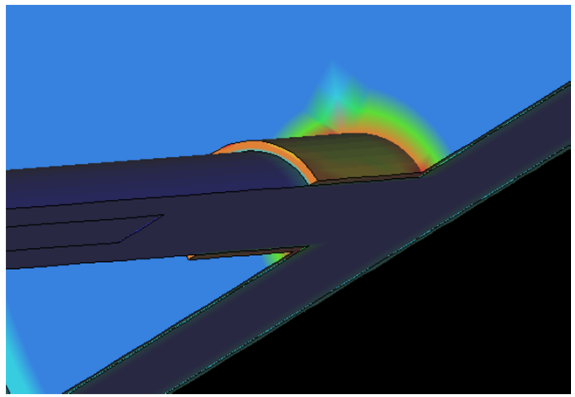


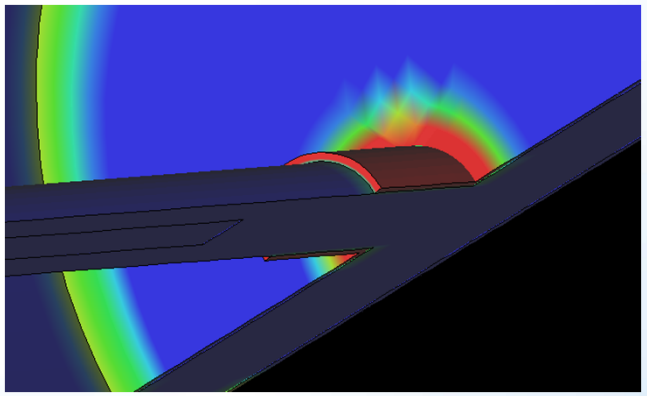


Conservative velocity estimates ~200 m/s are expected


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

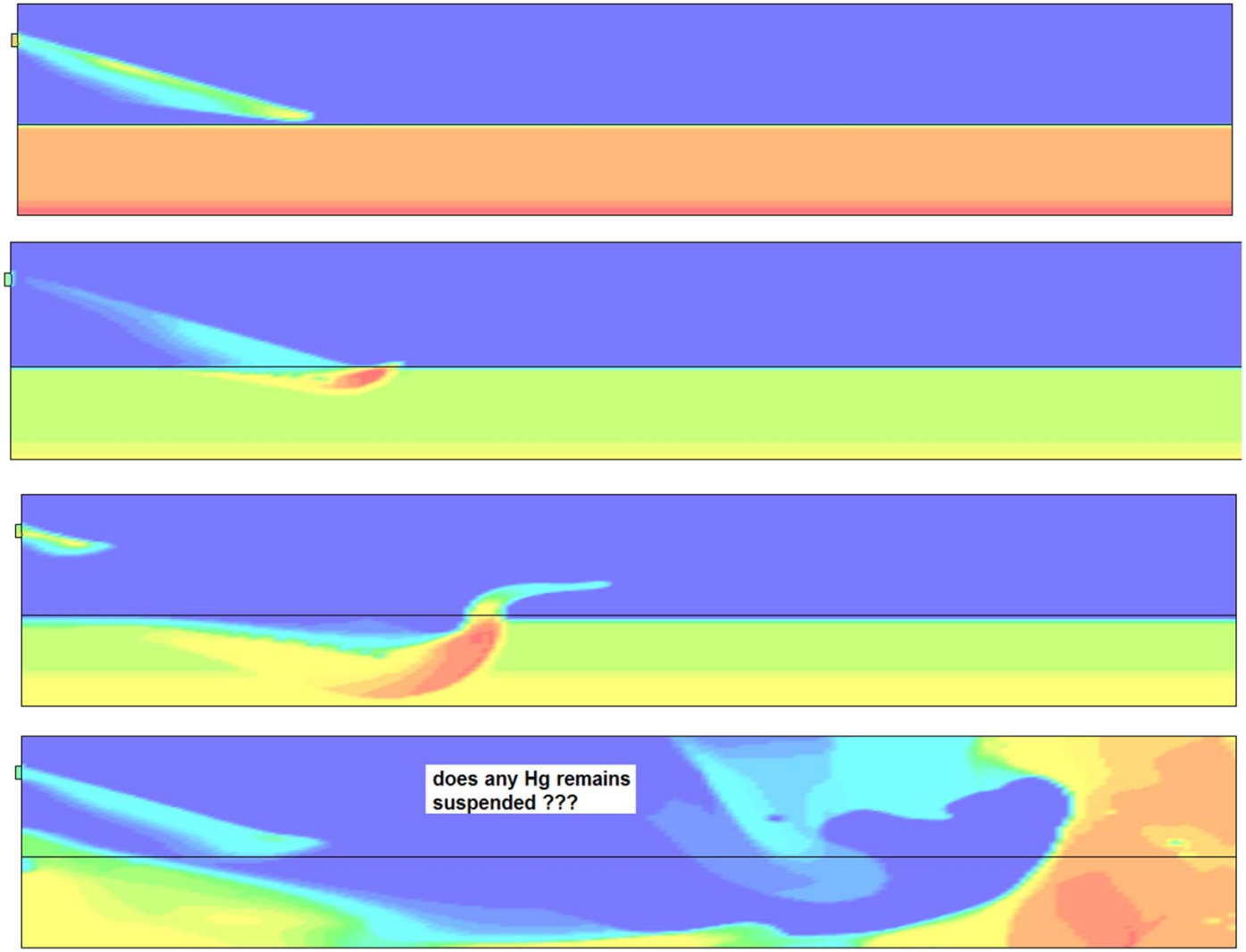
mechanics of it has been solved by utilizing capabilities of different codes

Implementation of Solenoid Tesla Field as part of same analysis

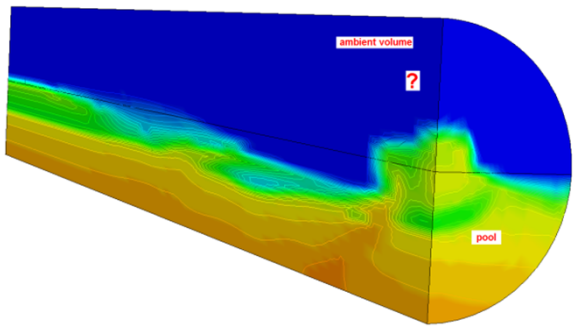
we think we have a solution with “pseudo-angular” rotation of Hg jet providing magneto-confining pressure

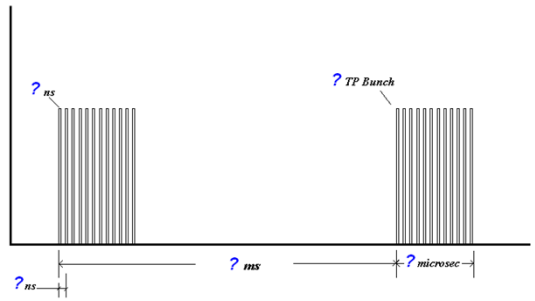
Trusting the predictions of the violent processes that we try to simulate

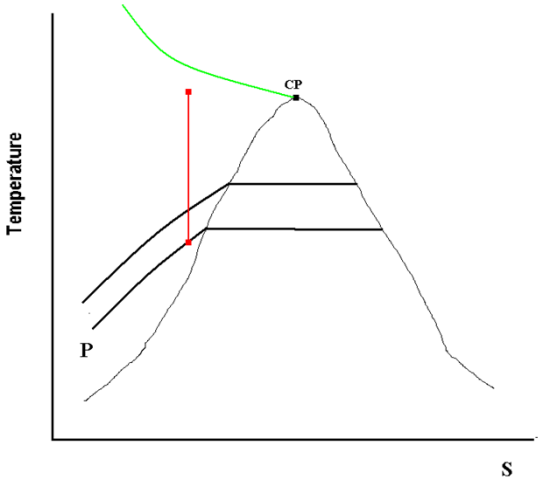
excellent basis due to successful benchmarking of relevant experiments


does any Hg remains
suspended ???

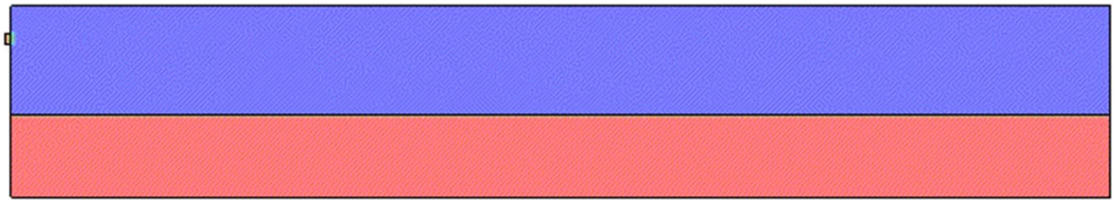
Hg Jet


ambient volume
?
pool


? ns
? TP Bunch
? ns
? ms
? microsec

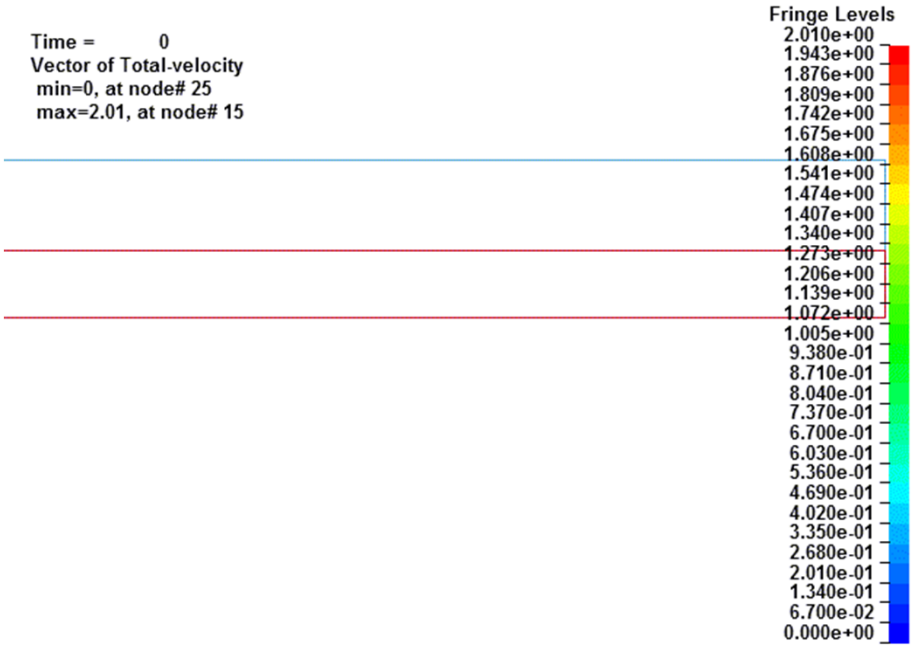

CP
Temperature
P
S

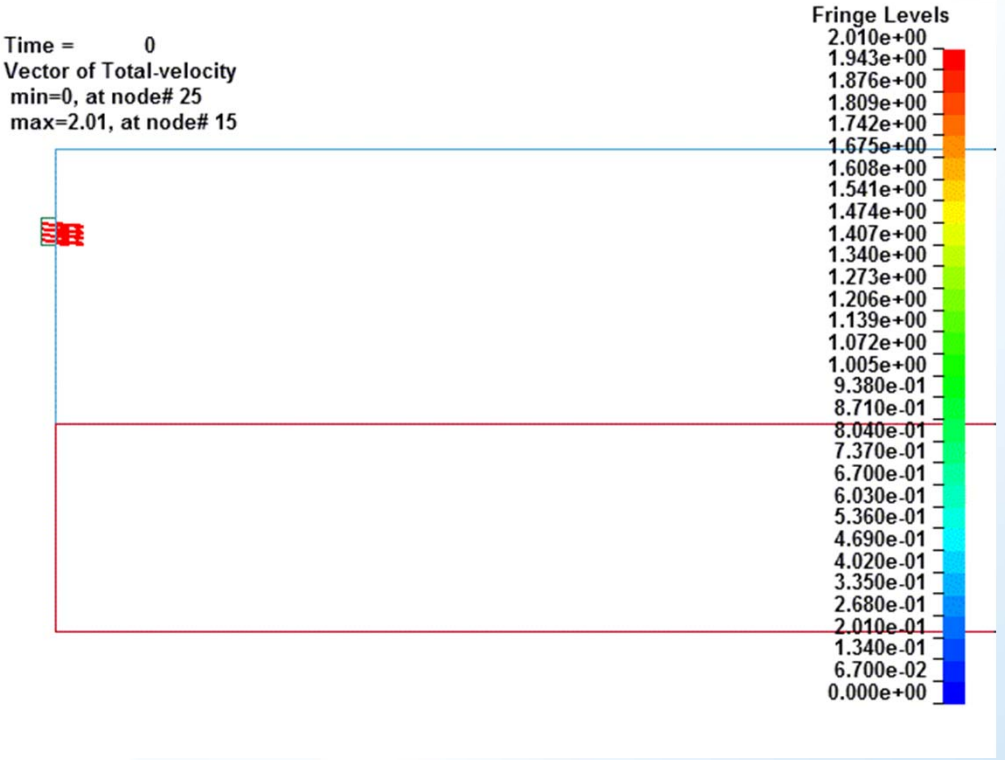
NuF Hg Jet
Time = 0



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
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1.809e+00
1.742e+00
1.675e+00
1.608e+00
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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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3.350e-01
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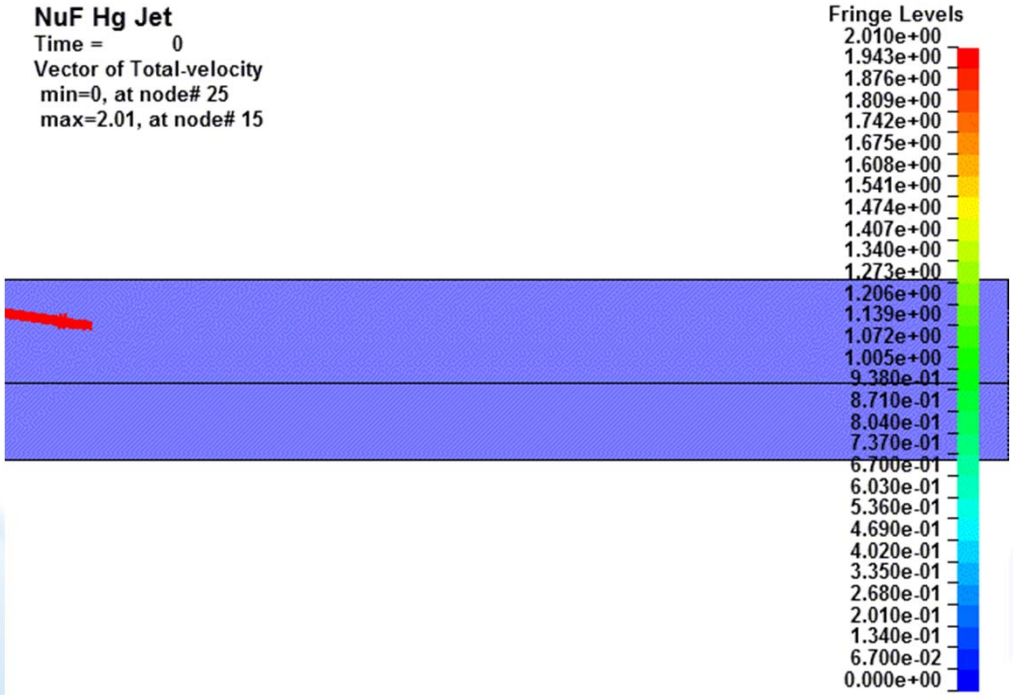
1.340e-01
6.700e-02
0.000e+00


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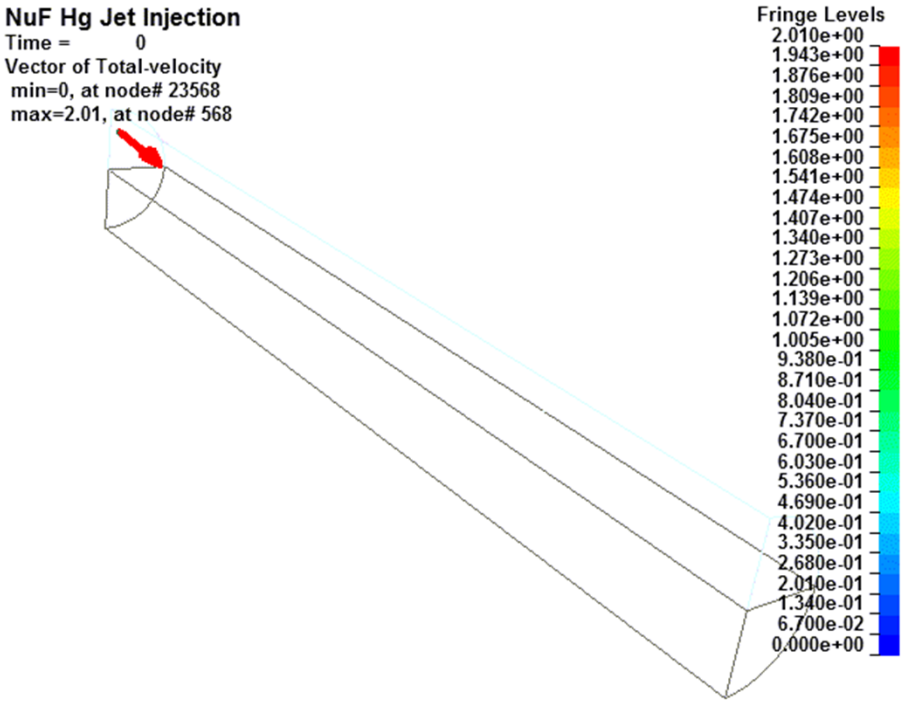
NuF Hg Jet Injection
Time = 0
Vector of Total-velocity
min=0, at node# 23568
max=2.01, at node# 568
Fringe Levels
2.010e+00
1.943e+00
1.876e+00
1.809e+00
1.742e+00
1.675e+00
1.608e+00
1.541e+00
1.474e+00
1.407e+00
1.340e+00
1.273e+00
1.206e+00
1.139e+00
1.072e+00
1.005e+00
9.380e-01
8.710e-01
8.040e-01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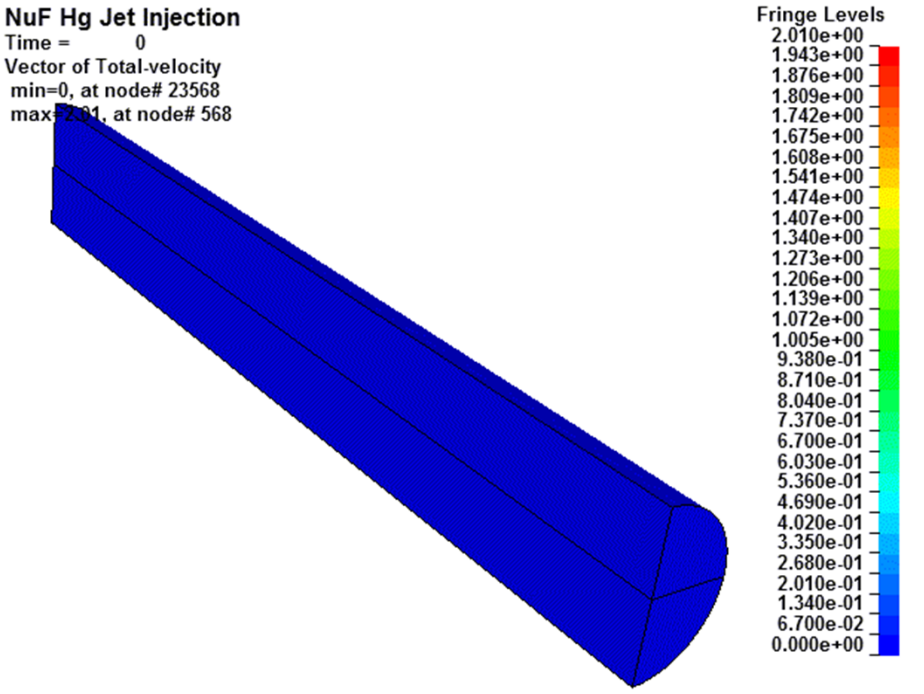
2.010e-01
1.340e-01
6.700e-02
0.000e+00


NuF Hg Jet Injection
Time = 0
Vector of Total-velocity
min=0, at node# 23568
max=2.01, at node# 568
Fringe Levels
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1.943e+00
1.876e+00
1.809e+00
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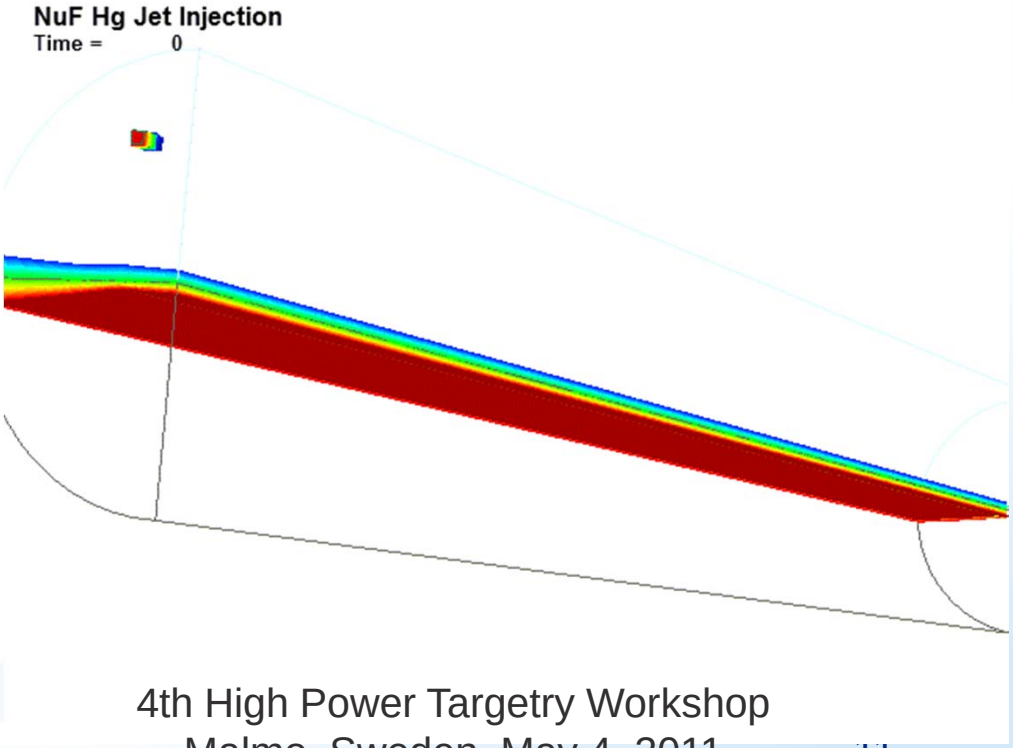
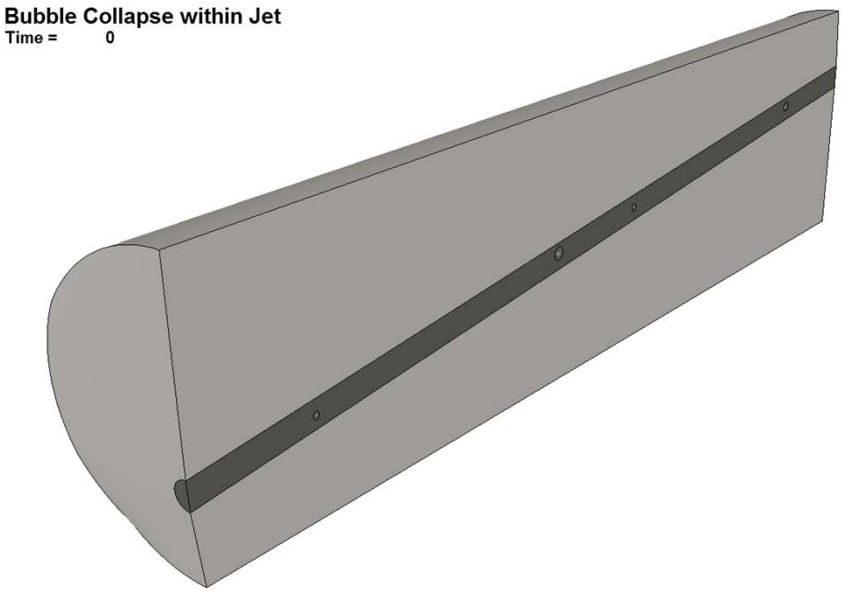
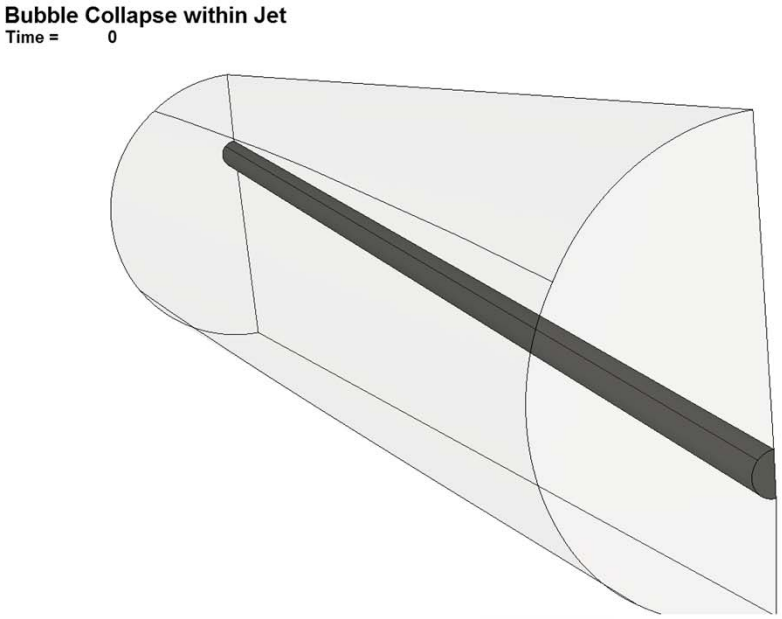
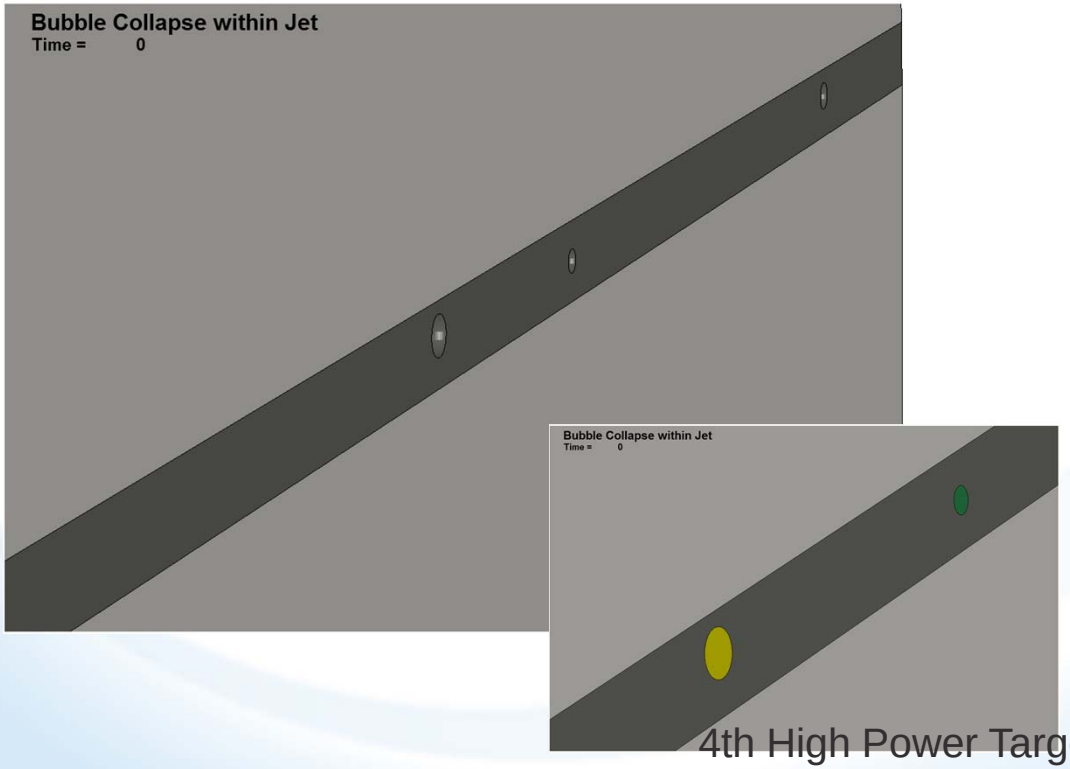
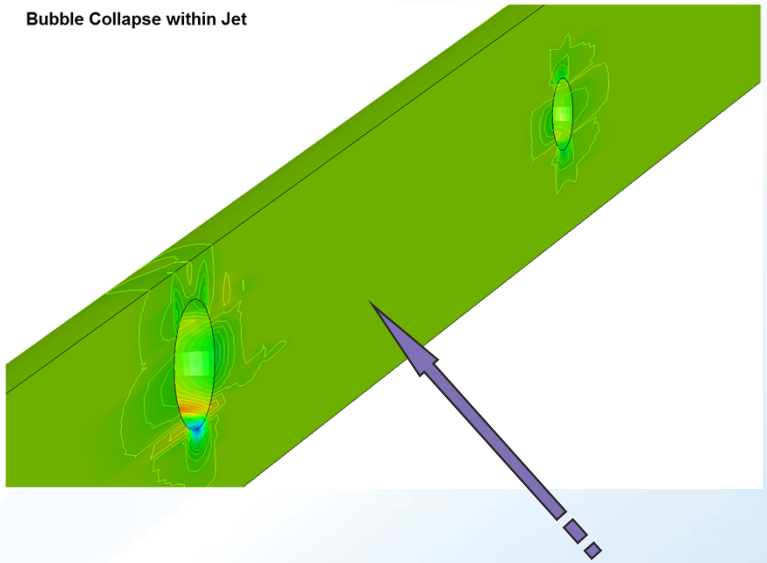

NuF Hg Jet Injection
Time = 0

Bubble Dynamics and Hg Jet/Pool



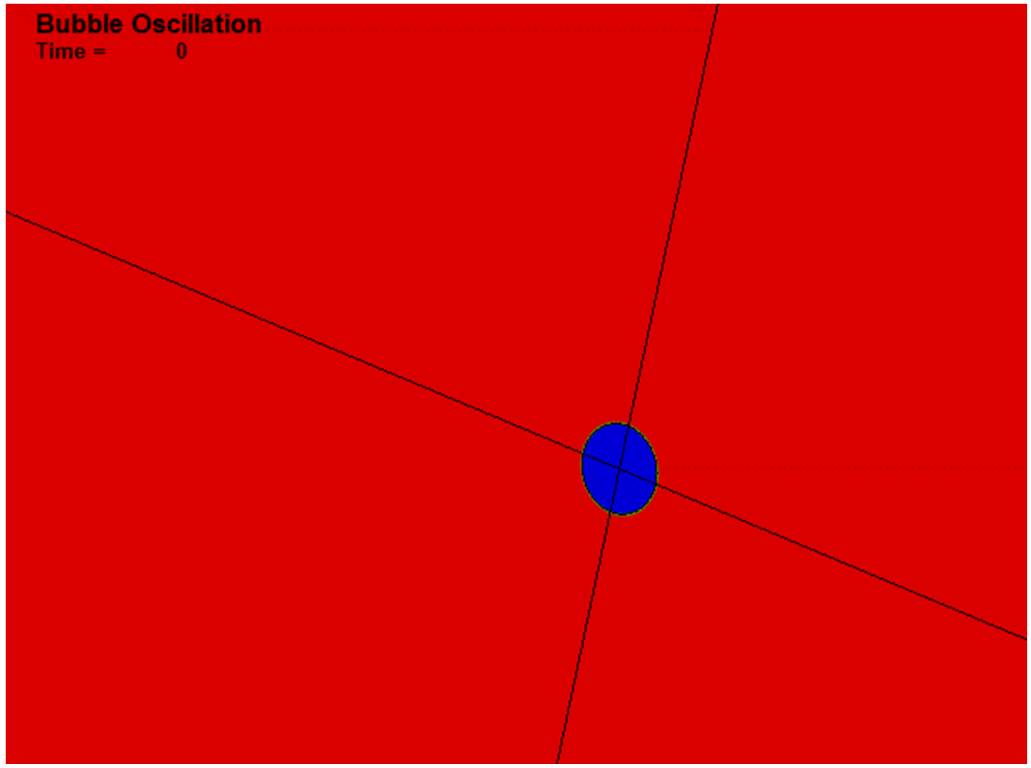


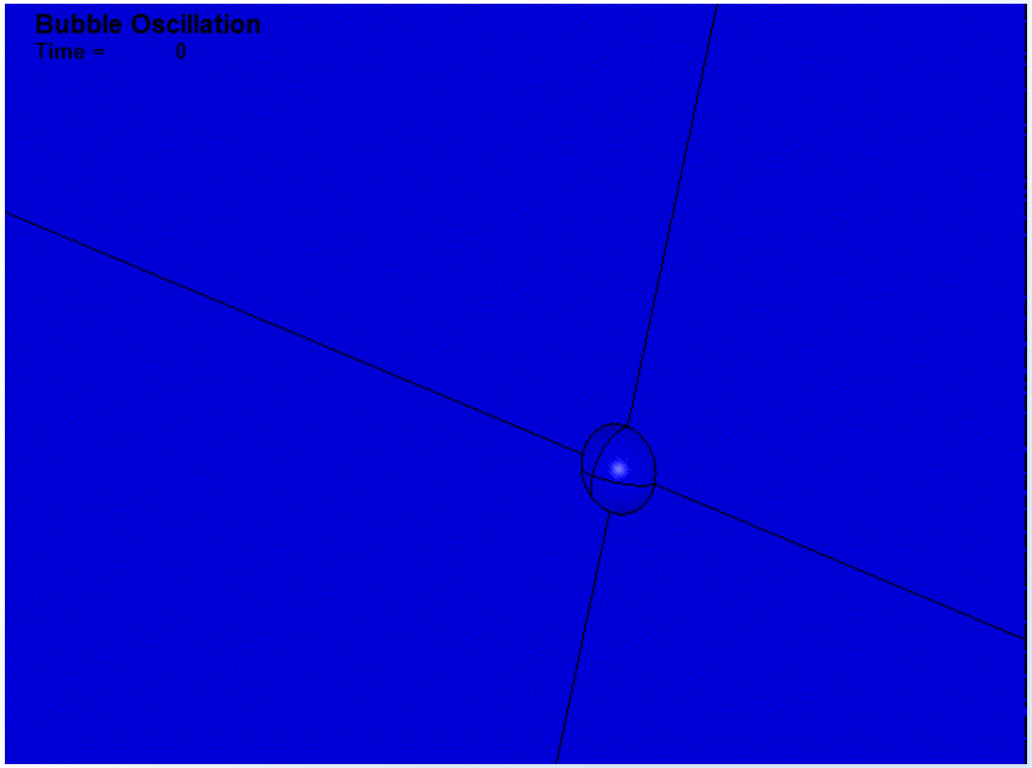




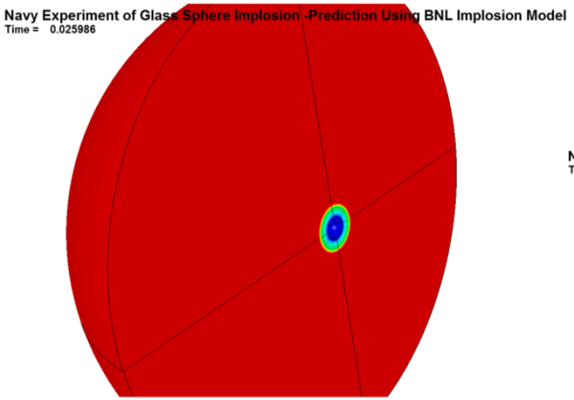
Local pressure outside formed bubble
can be very high from beam energy deposition

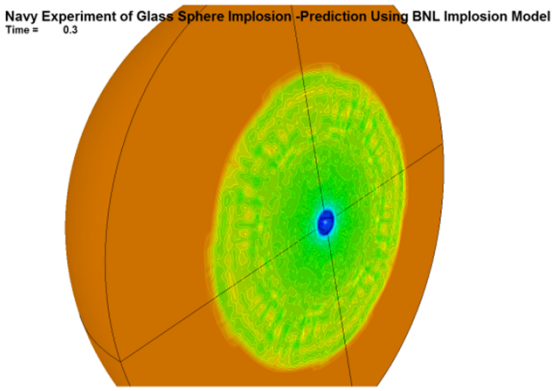
Excellent driver of implosion process

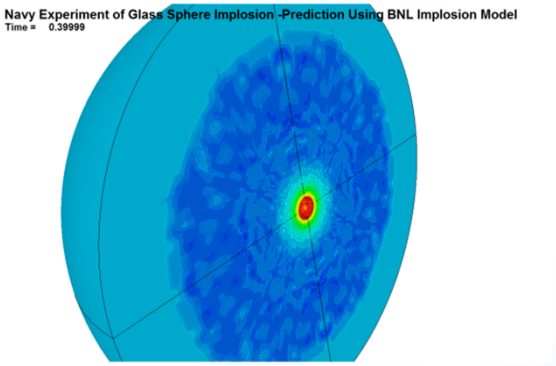

Bubble Oscillation
Time = 0

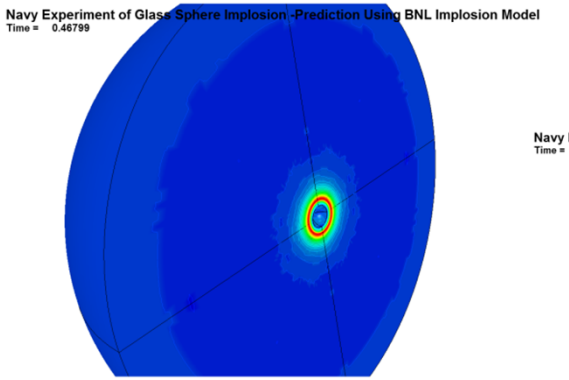

Bubble Oscillation
Time = 0

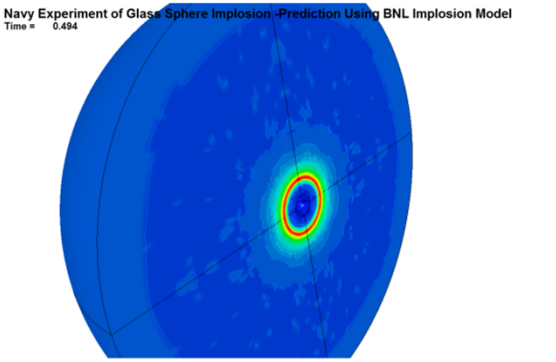
Bubble Implosion

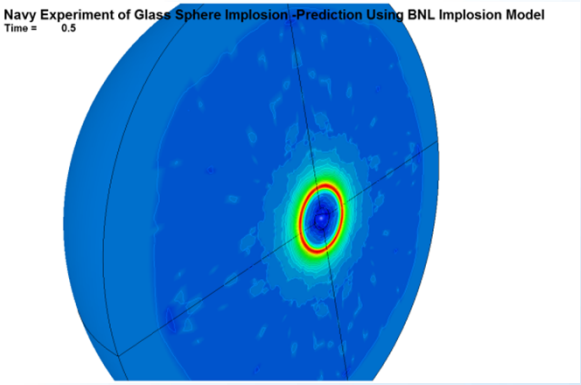


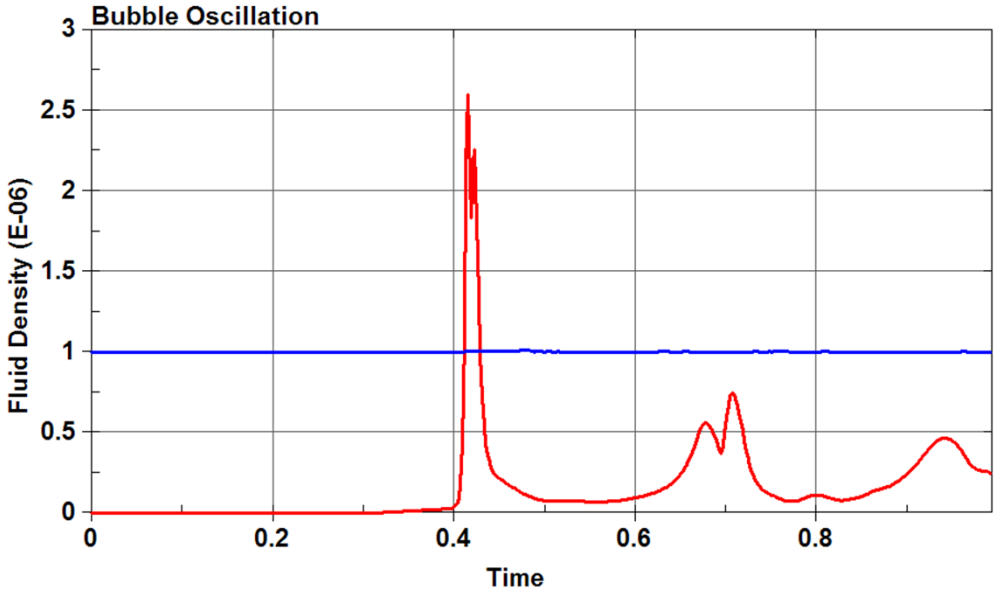


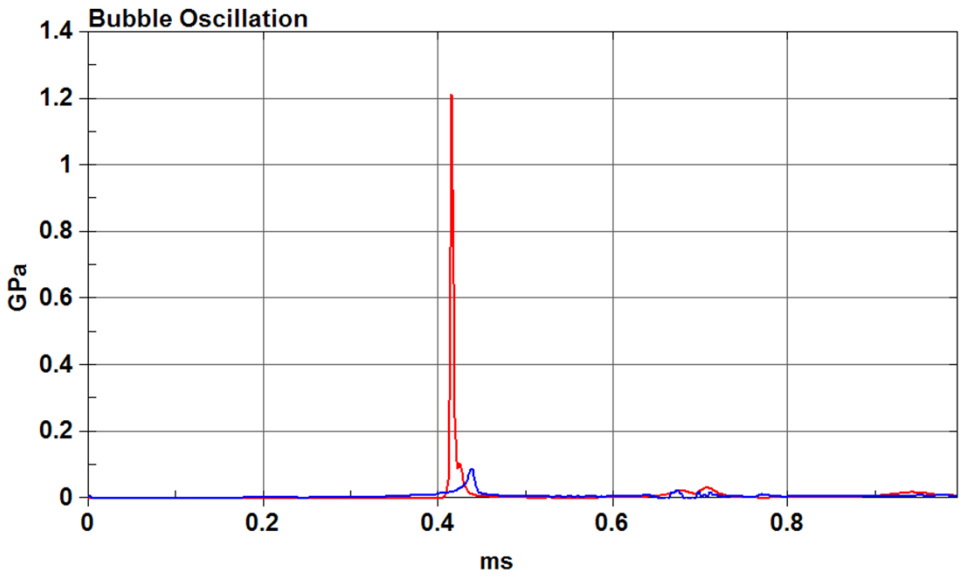


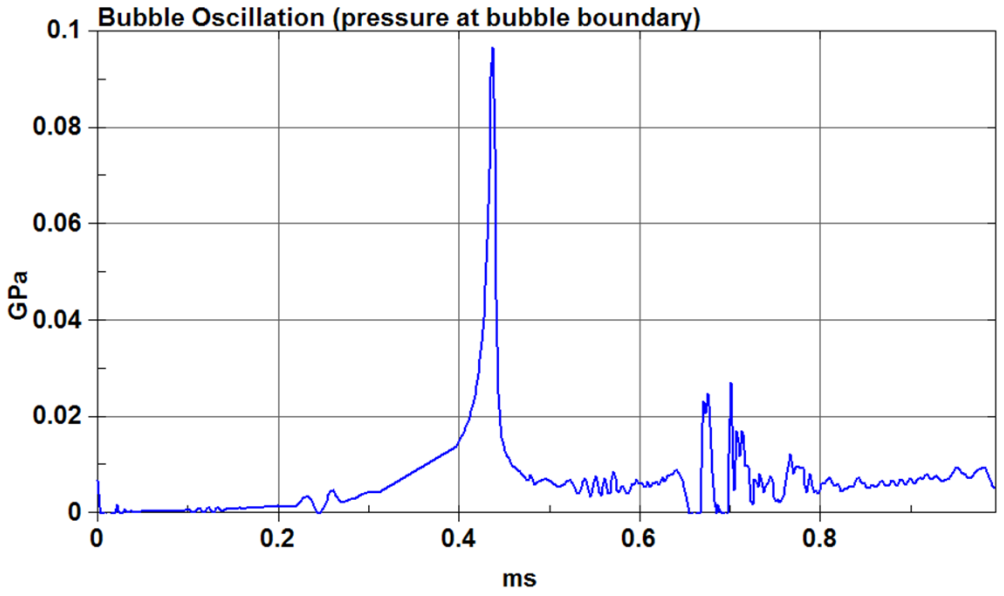




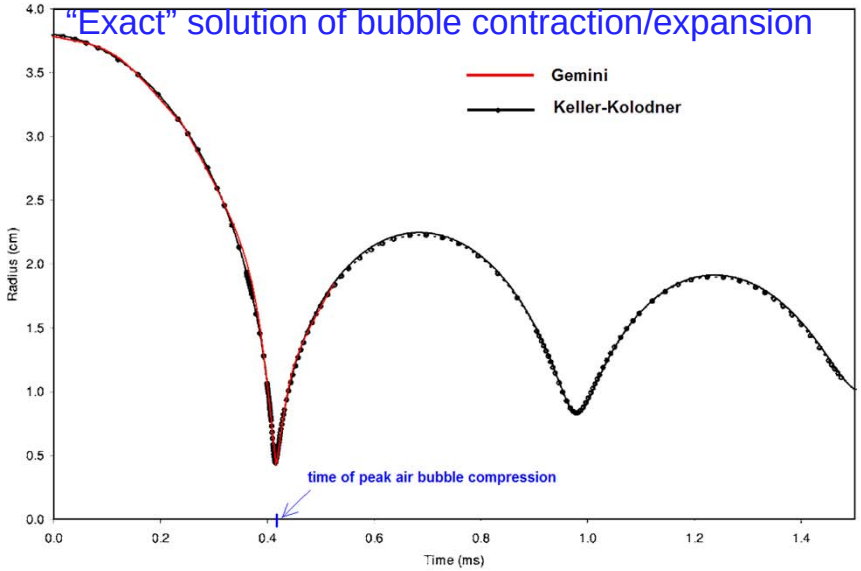


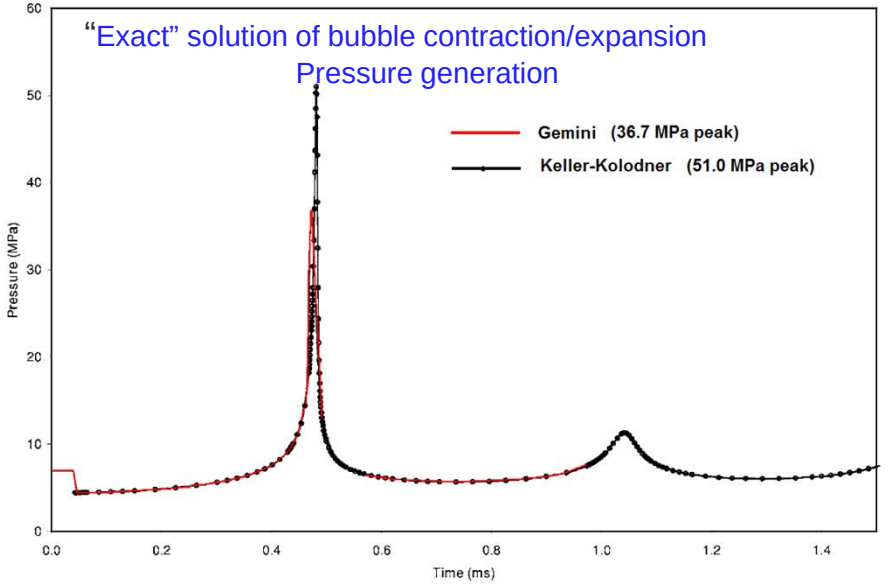

Bubble Oscillation
Fluid Density (E-06)
Time
0
0.5
1
1.5
2
2.5
3
0
0.2
0.4
0.6
0.8

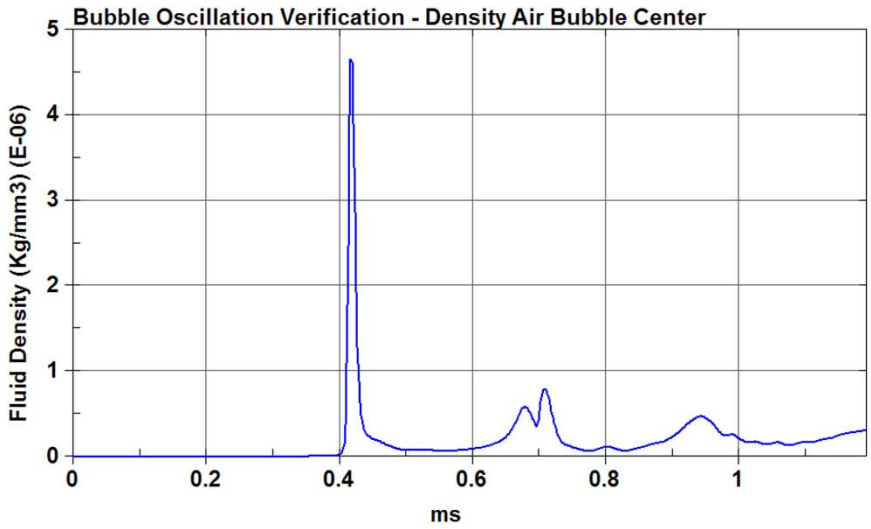

Bubble Oscillation
GPa
ms
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
0.2
0.4
0.6
0.8

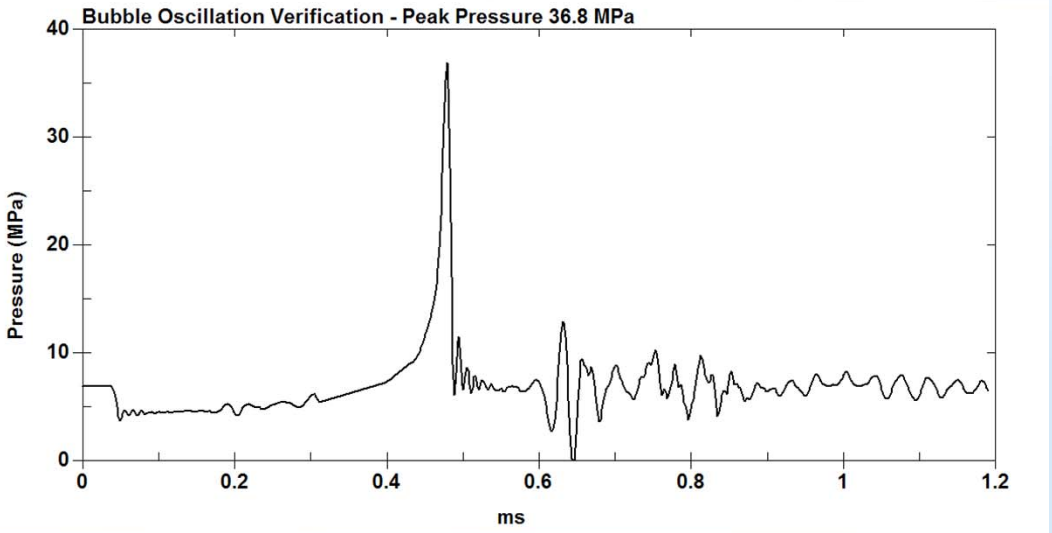

Bubble Oscillation (pressure at bubble boundary)
GPa
ms
0
0.02
0.04
0.06
0.08
0.1
0
0.2
0.4
0.6
0.8

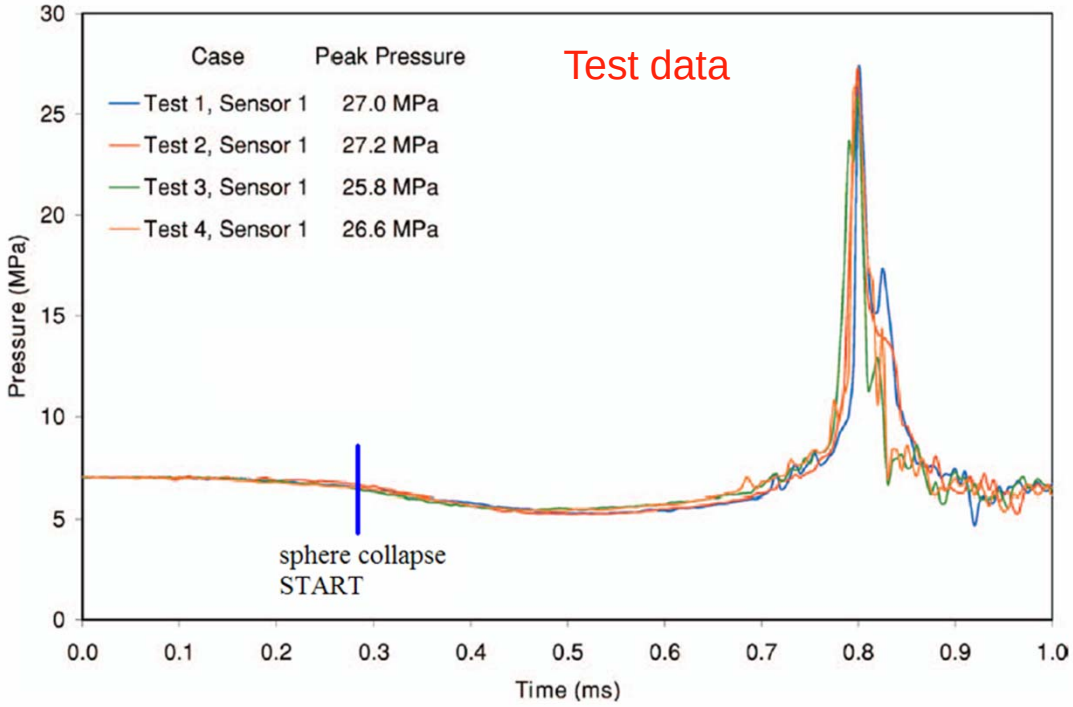
“Exact” Solutions of Air Bubble Collapse/Oscillation

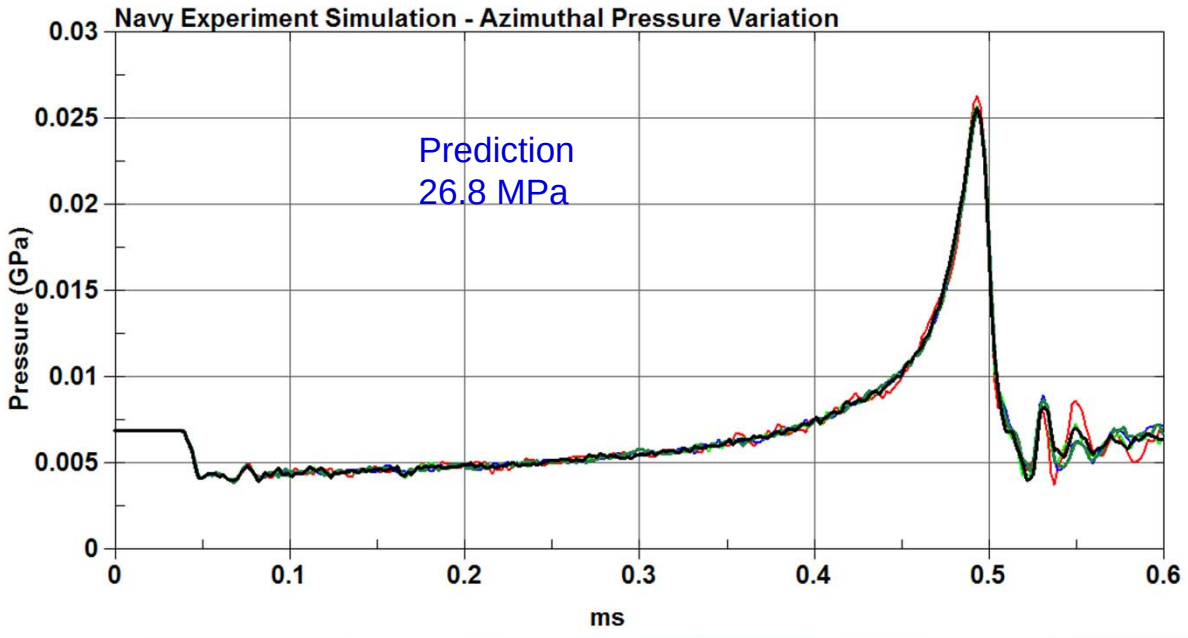


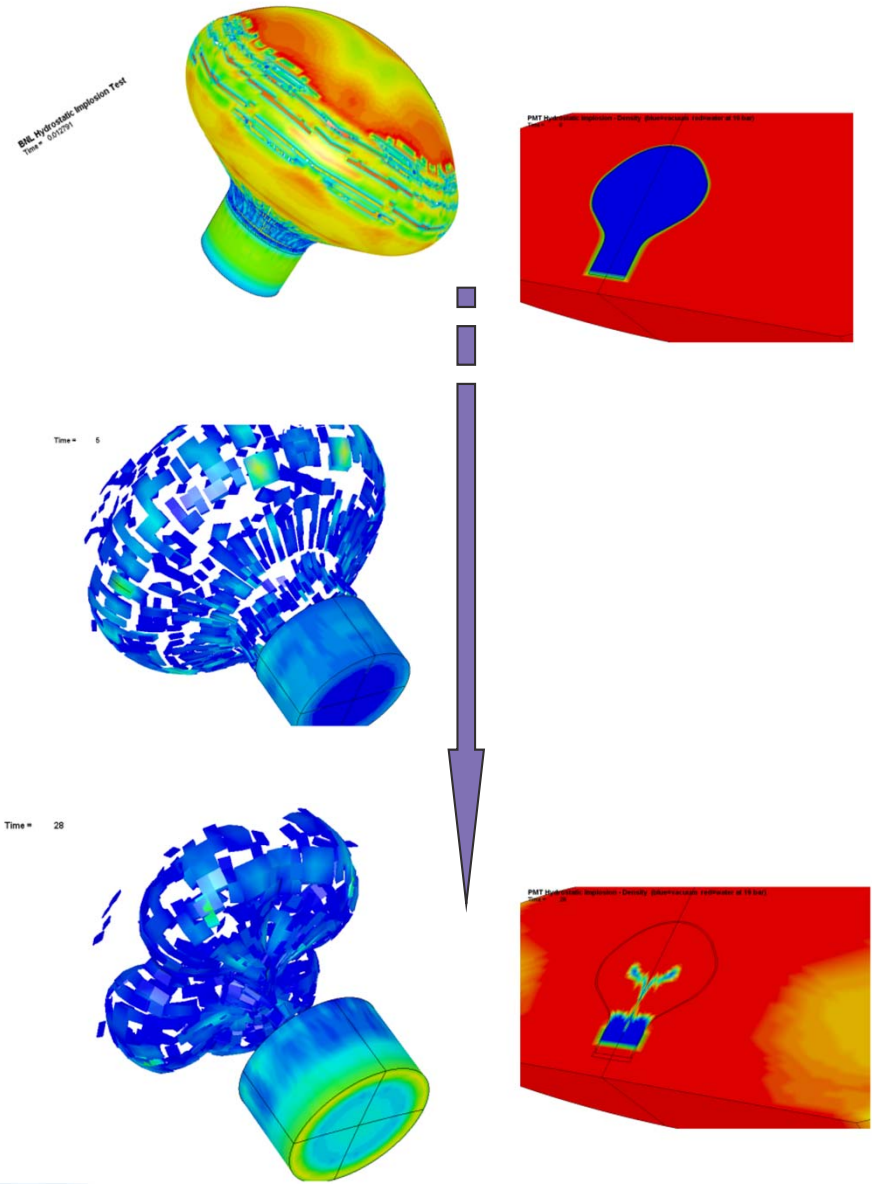







Test data
Case
Peak Pressure
Test 1, Sensor 1
27.0 MPa
Test 2, Sensor 1
27.2 MPa
Test 3, Sensor 1
25.8 MPa
Test 4, Sensor 1
26.6 MPa
sphere collapse
START
Pressure (MPa)
Time (ms)
0
5
10
15
20
25
30
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0


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

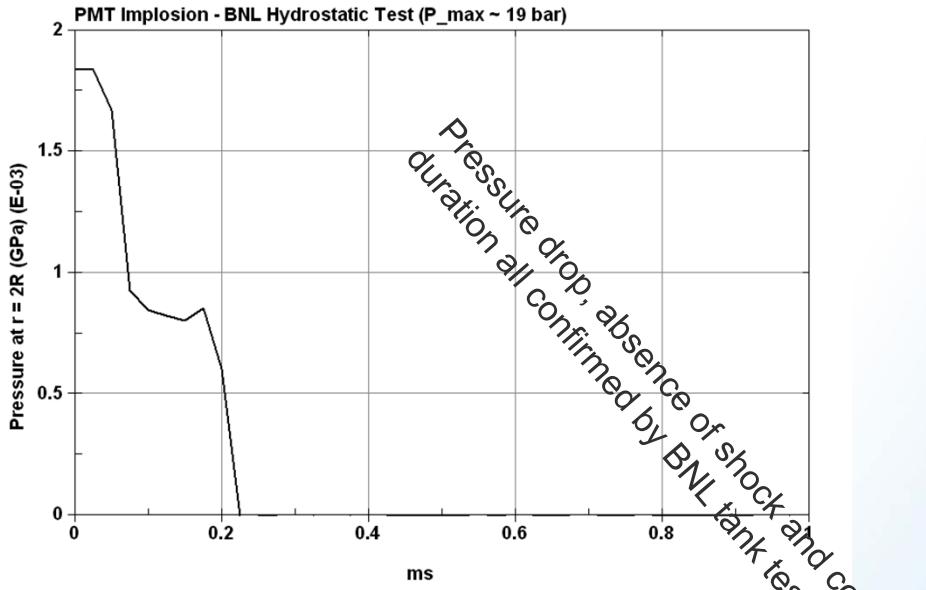


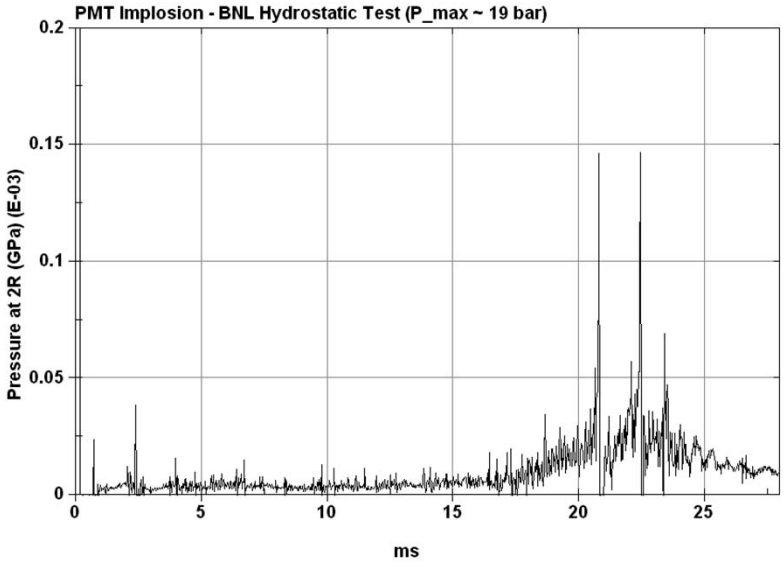
Simulation Predictions confirmed by the BNL Tests:

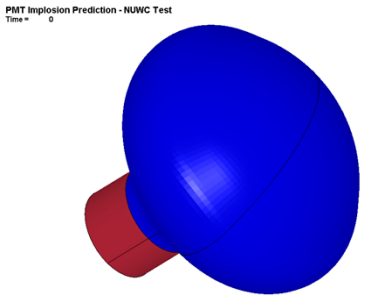
No shock develops !!

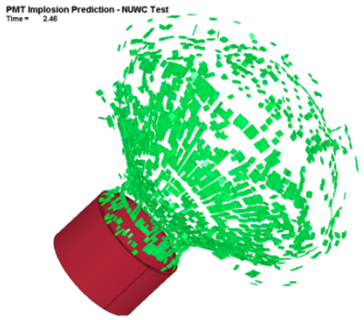
Implosion process very long (20+ ms)

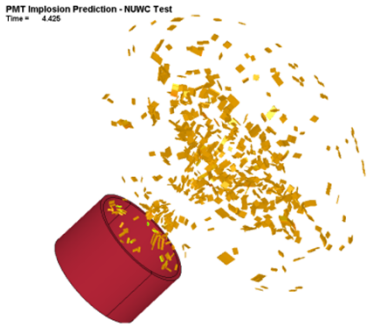
Hydrostatic pressure limit ~270 psi (19 Atm) !!!

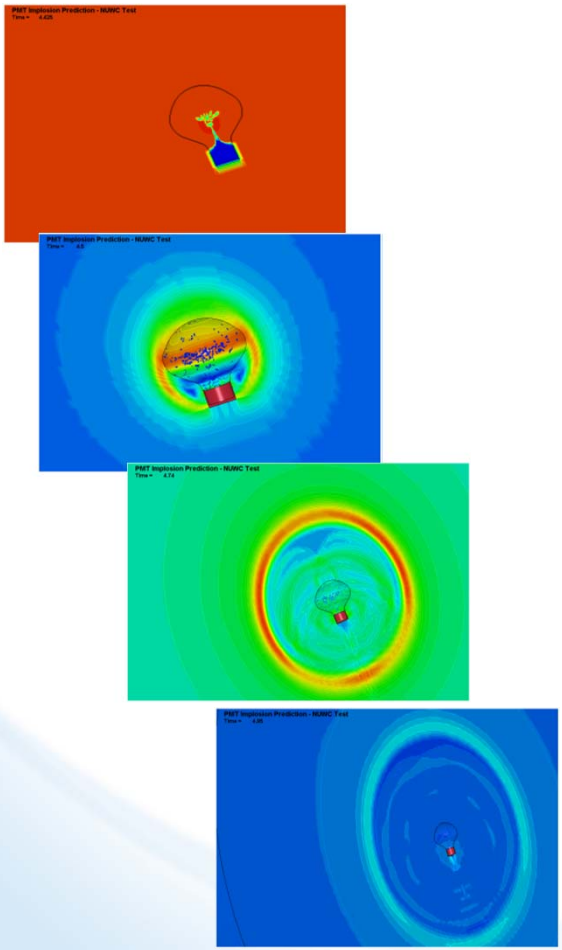


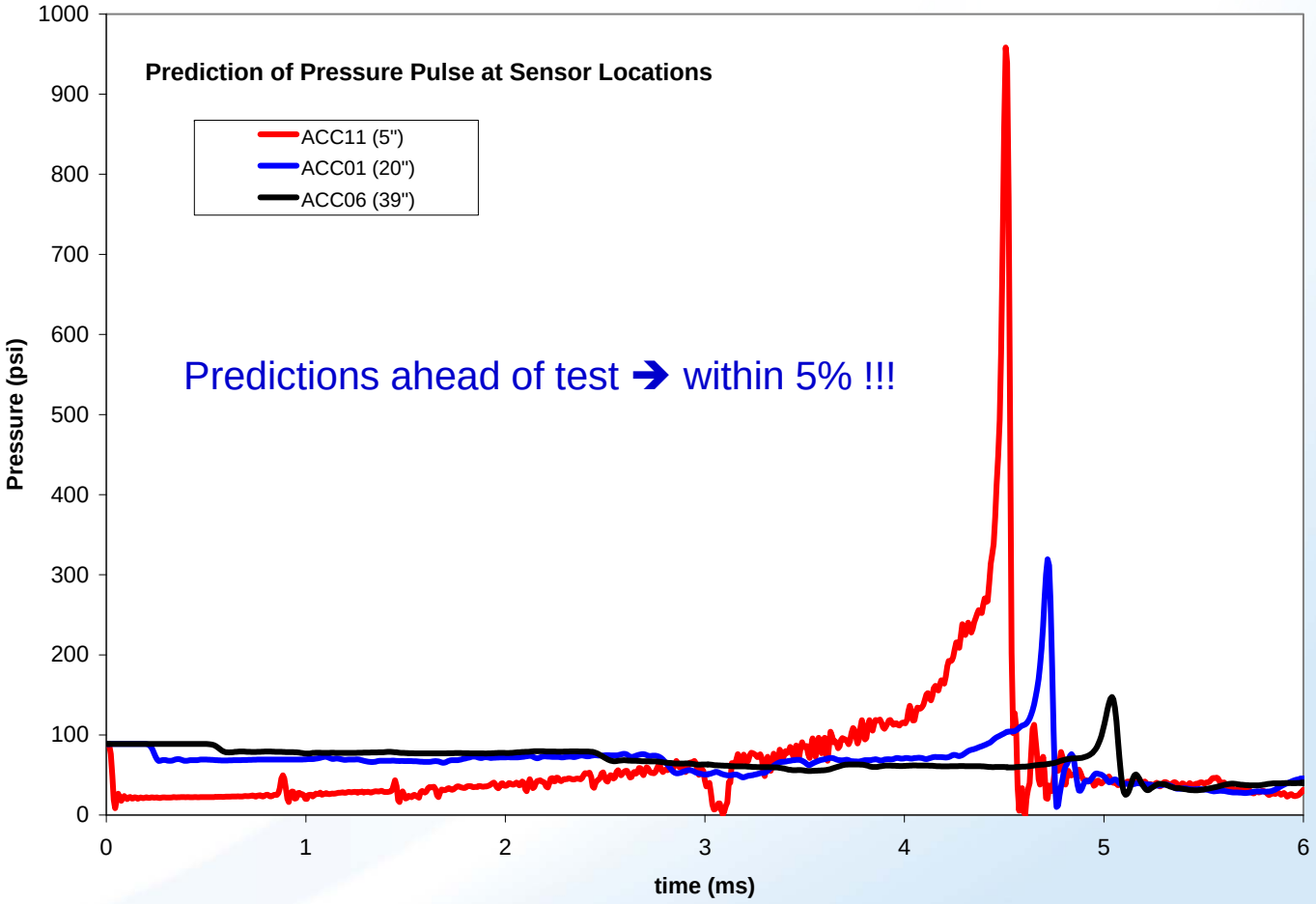



PMT Implosion Prediction - NUWC Test
Time = 0


PMT Implosion Prediction - NUWC Test
Time = 2.46


PMT Implosion Prediction - NUWC Test
Time = 4.425




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:

We feel that the simulation processes have been well benchmarked to extrapolate the analysis into the question of phase transitions

SESAME Library (Hg) EOS described numerically (user input into LS-DYNA)

Incorporate all effects (hydrodynamic, beam, solenoid field)

Quantify the ambient space for operational mode

..... To be continued