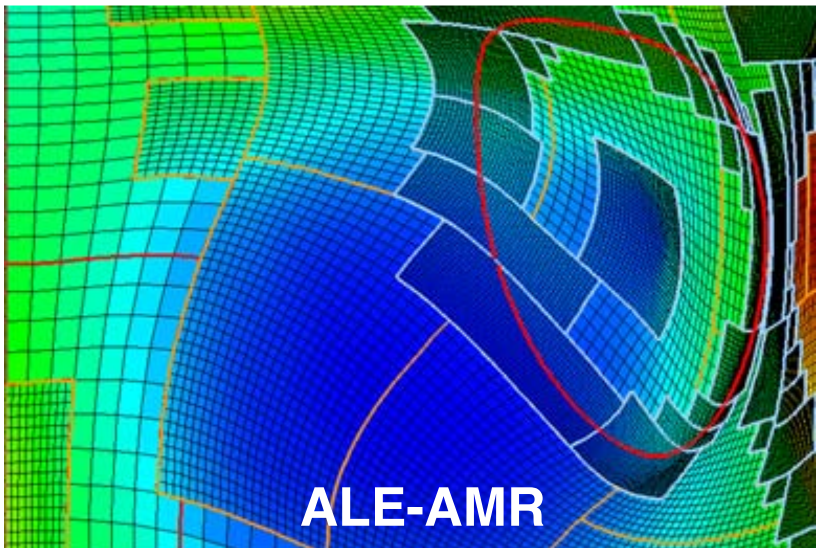
# Late-Time Numerical Simulations of High-Energy-Density (HED) Targets




ALE - Arbitrary Lagrangian Eulerian
AMR - Adaptive Mesh Refinement

**Twenty Second International Conference on Numerical Simulations of Plasmas**

**Long Branch, New Jersey, USA**
**September 7, 2011**

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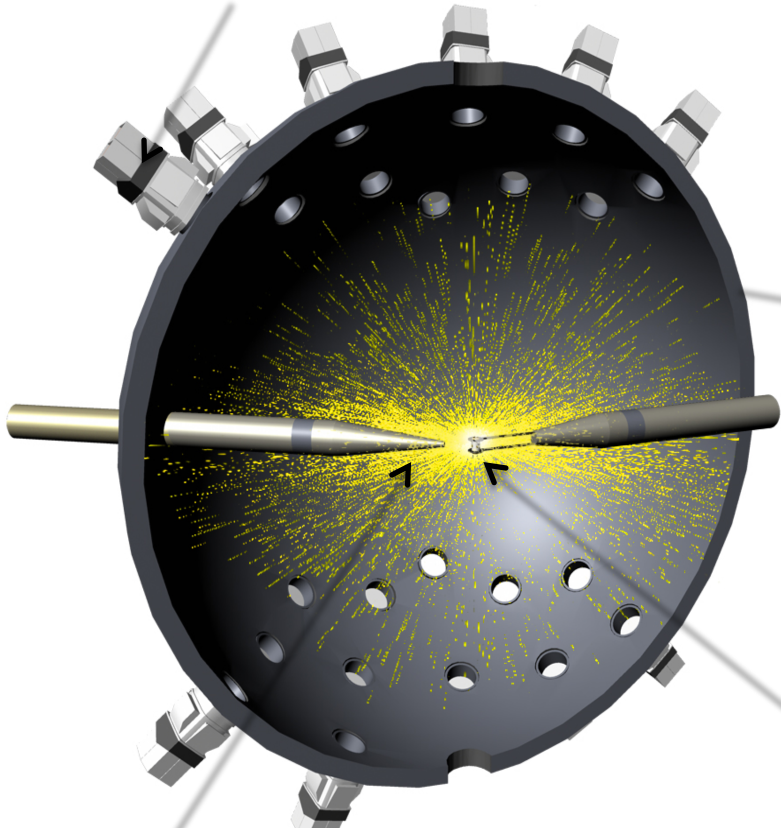
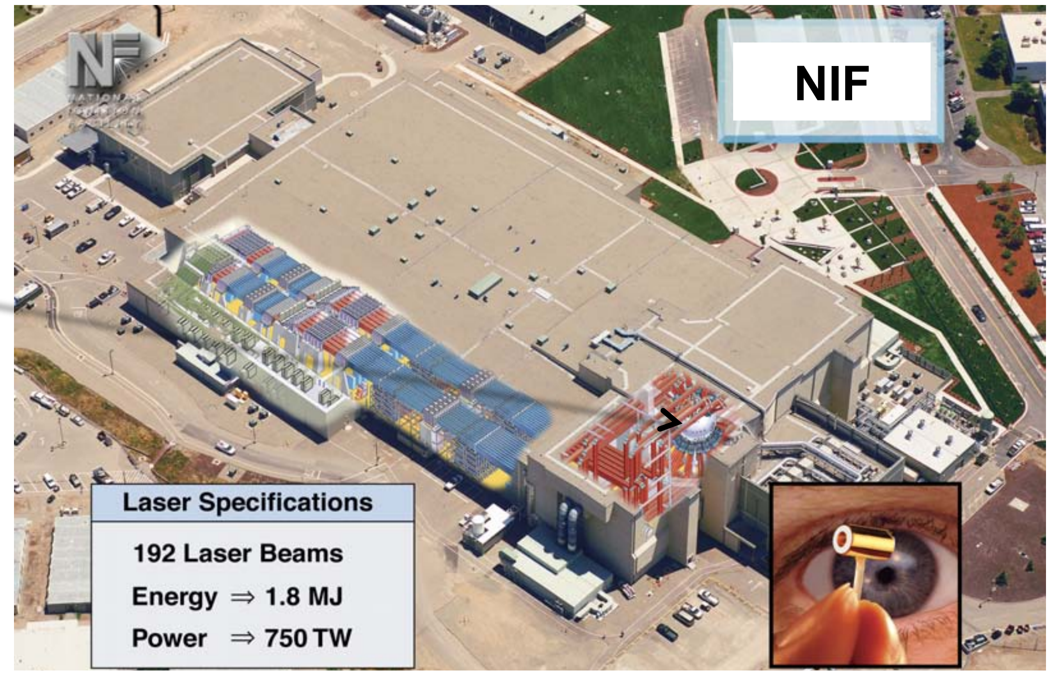
# Outline

- **Motivation for late-time simulations for debris/shrapnel assessment**
- **Numerical issues associated with late-time HED simulations**
- **Overview of the ALE-AMR code capabilities and validation**
- **Application to National Ignition Campaign (NIC) targets**
  - **Focus on higher risk (low-energy) targets**
    - **Simulation of re-emit target using <1% NIF energy**
- **Redesign of various HED targets based on simulations**
- **Role of debris wind on components in the NIF chamber**

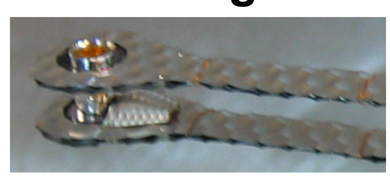
# Late-time simulations are needed to assess impacts to NIF optics and diagnostics from debris and shrapnel

**Optics: 192 3-mm thick DDS's located ~ 7 m from target**






**NIC Target**



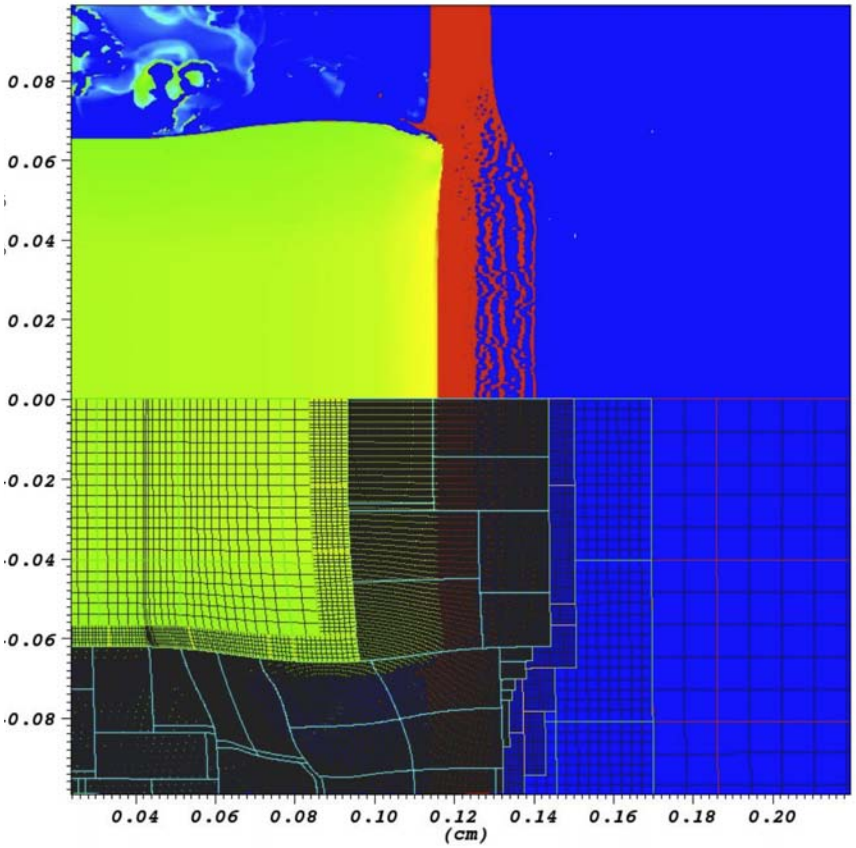
**Diagnostics: components, e.g., pinhole array, ~10 cm from target**

## There are five major differences as compared to conventional HED simulations

1. Generally run simulations ~100X longer in time
2. Additional physics, such as material strength/failure and surface tension, can be required
3. Additional parts of the target, e.g., Al thermal mechanical package and Si cooling rings, must be included
4. Additional sources of input energy, e.g., unconverted laser light, must be included
5. Less symmetry leading to 3D simulations as well as need to resolve shrapnel fragments that also requires 3D

# ALE-AMR developed by DOE labs (LLNL and LBNL) and UC campuses (UCSD and UCLA)

Simulation of soft x-rays striking foil

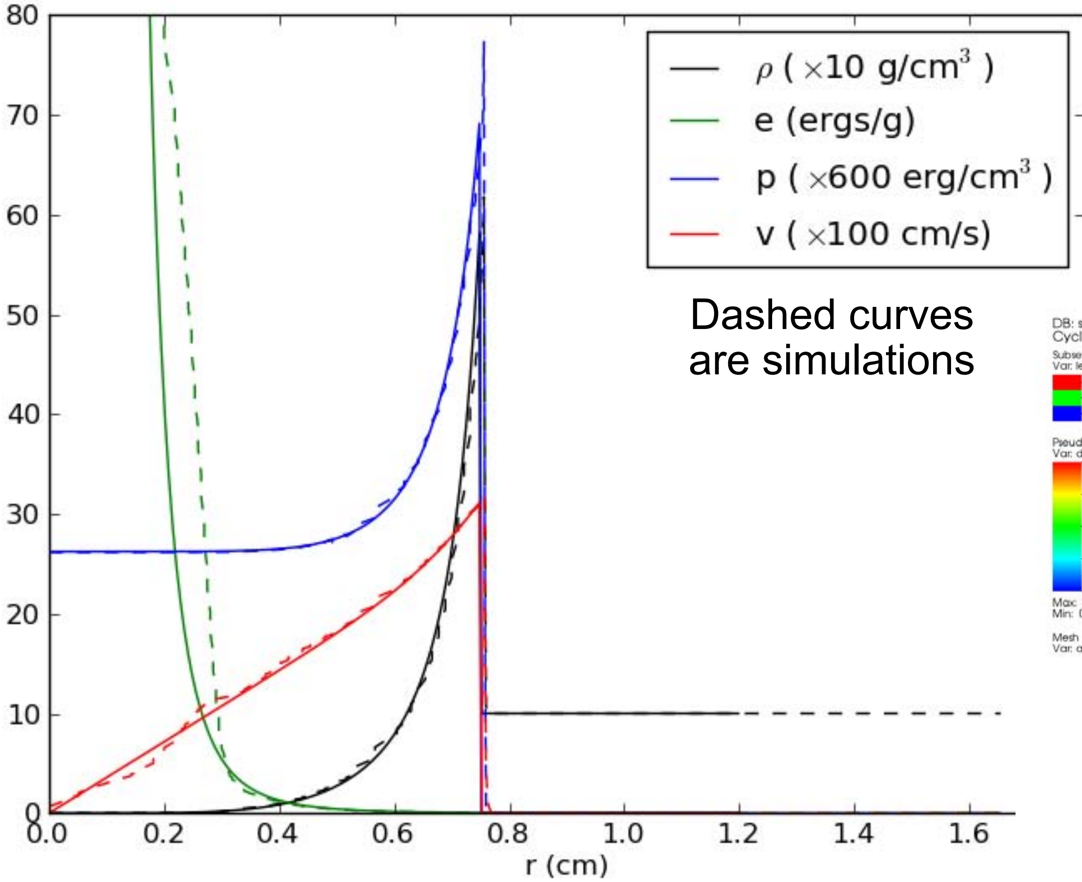



ALE-AMR is an open science code that runs at various computing centers including NERSC and has no export control restrictions

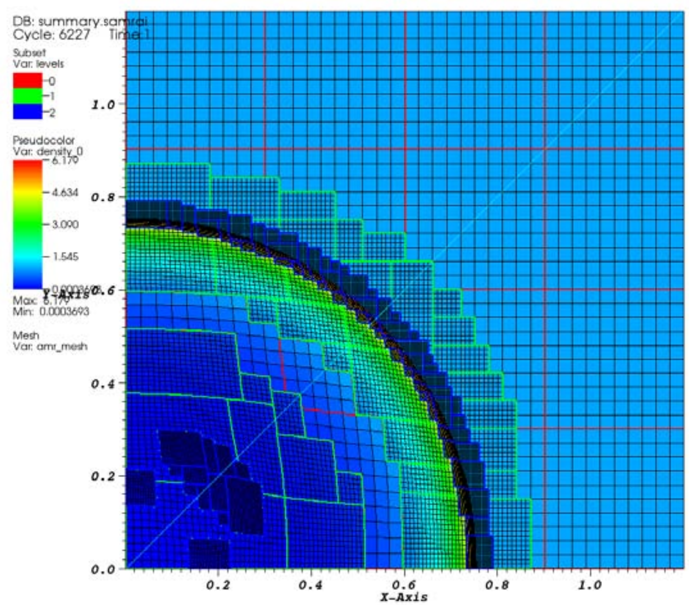
- 3D ALE hydrodynamics
- AMR (use 3X refinement)
  - With 6 levels, vol ratio $10^7$ to 1
- Material interface reconstruction
- Anisotropic stress tensor
- Material failure with history
- Laser ray trace and deposition
- Ion deposition
- Thermal conduction
- Radiation diffusion (new)
- 2D Axisymmetric capability (new)
- AMR with 3X in only 1 direction (new)
- Surface tension (in progress)

# The Sedov blast wave problem has been used to benchmark the code running in various modes

- 2D Cylindrical Blast wave
  - r=1, g=1.4, $E_{Blast}$=0.311357 ergs
  - Domain 1.2x1.2 cm

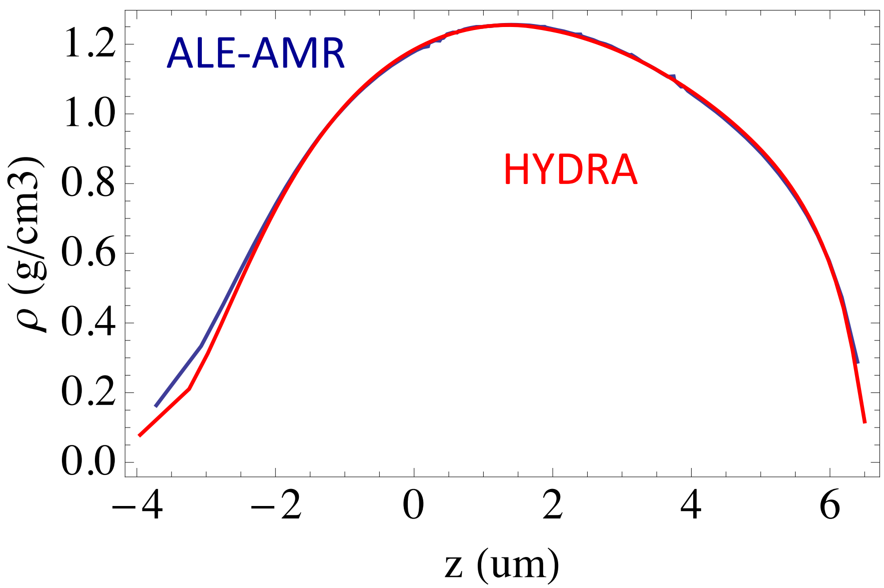


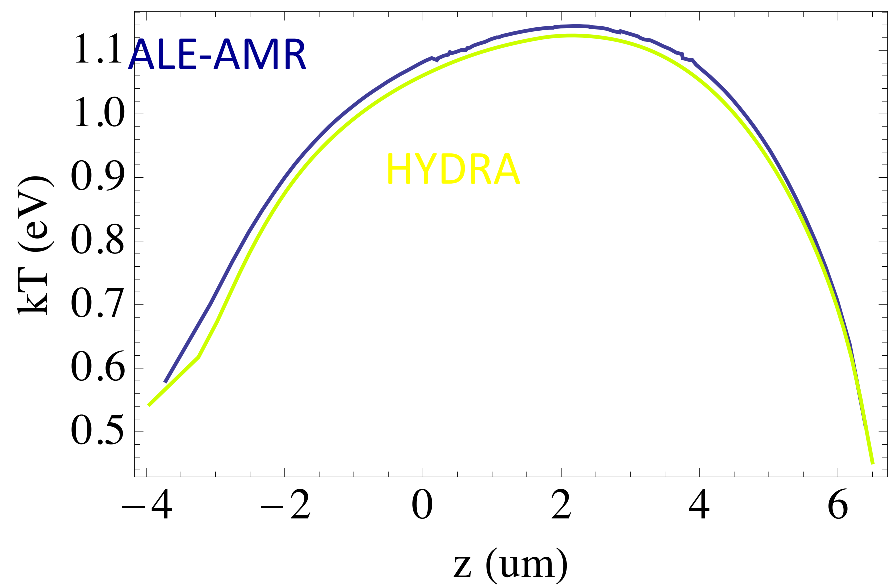

**ALE-AMR ALE mode (3 level 360x360)**



# Ion beam deposition and hydrodynamics in ALE-AMR have been benchmarked against the Hydra code

**Density and temperature profiles at the completion of the 1 ns, 2.8 MeV, Li ion heating pulse along the radial center of an Al foil. Fluence of 20 J/cm$^2$.**



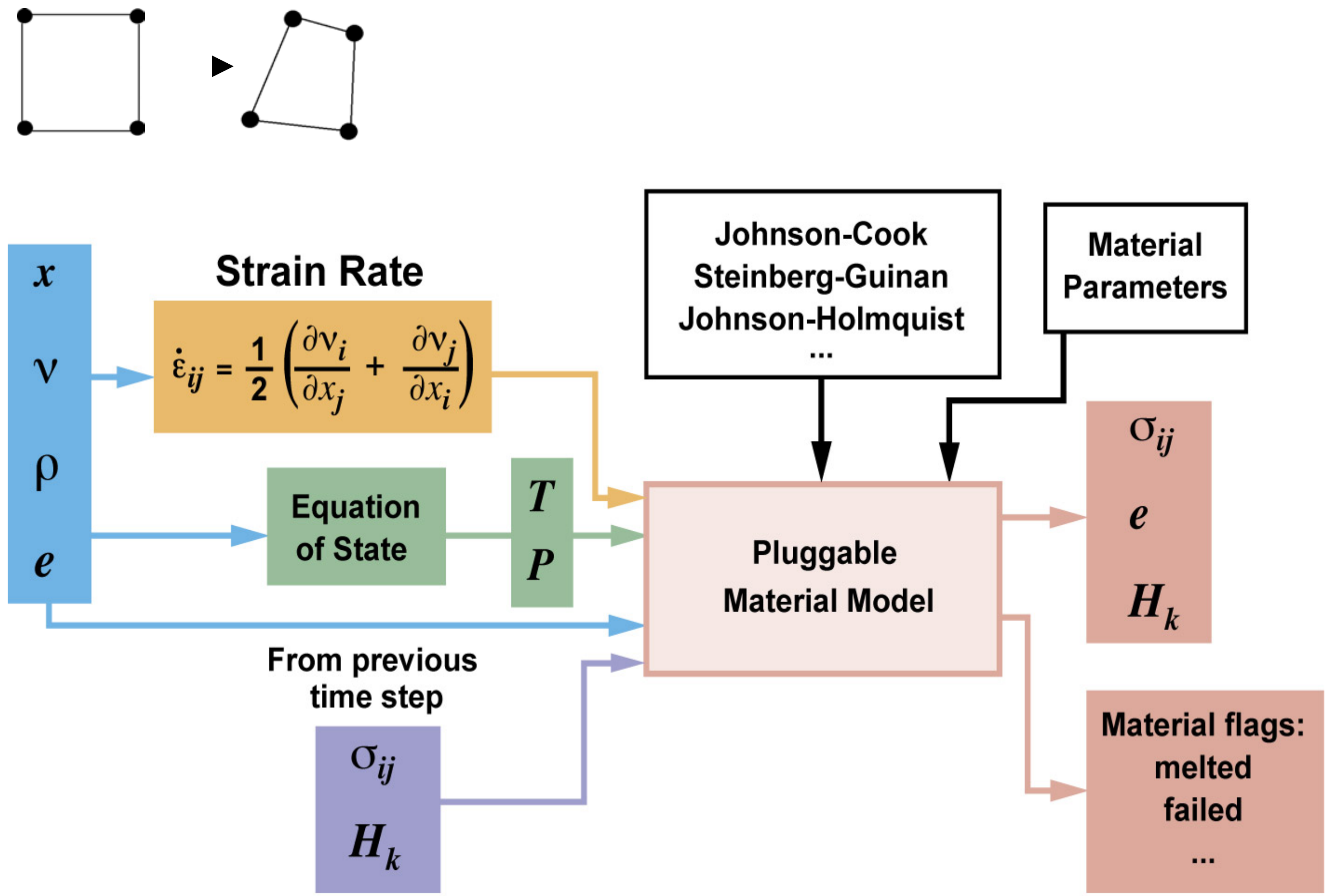



# ALE-AMR uses a flexible framework with equation of state and material material strength/failure models

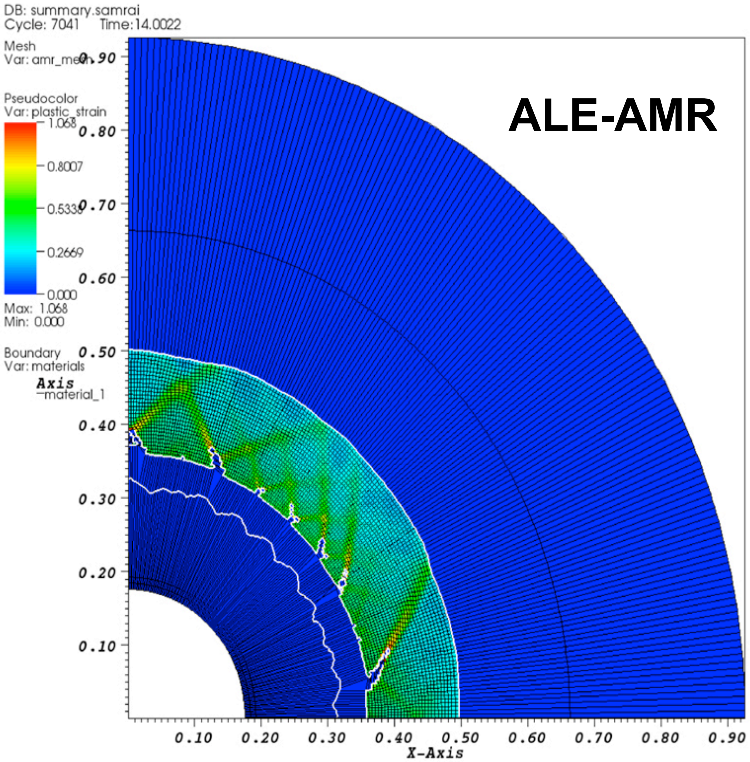
Lagrange Step

Post-Lagrange Material Update

Relax/Remap Split Physics

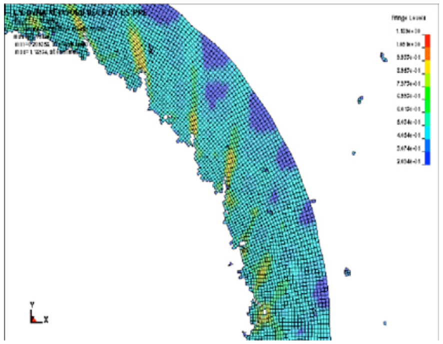


# Benchmarking against industry standard, LS-DYNA




- 4-mm ring made of Al6061 surrounded by void
- Johnson-Cook strength and damage models

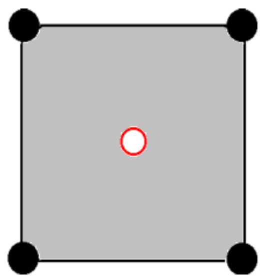
LS-DYNA



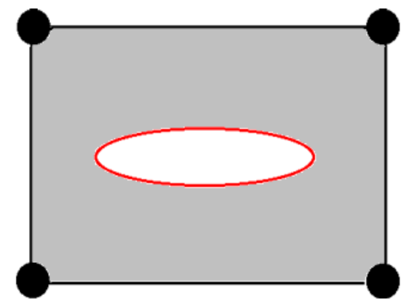
**Plastic strain comparison shows good agreement**

# Fragmentation obtained using a void insertion model plus interface reconstruction

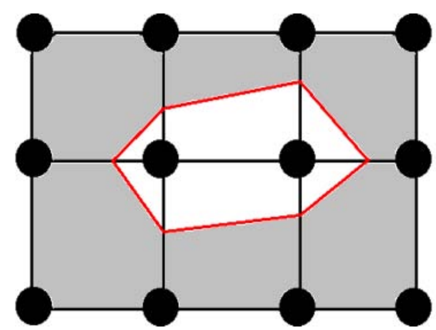
Upon failure a small volume fraction of void is introduced into the cell

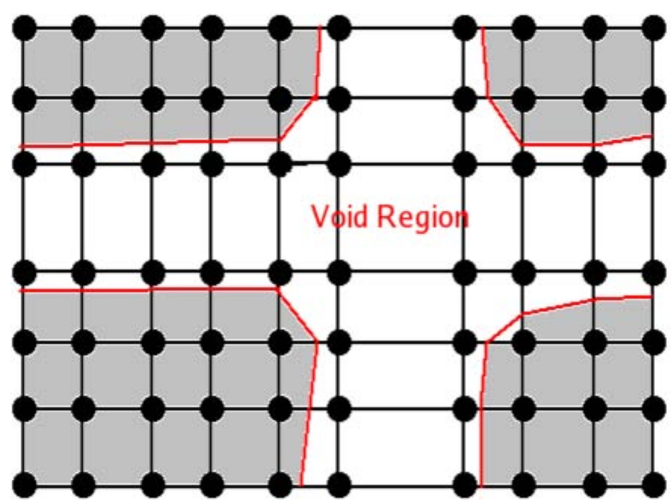


If the cell continues to grow the void enlarges to meet that growth



Volume fraction interface reconstruction allows voids to coalesce to form cracks






- **Multimaterial mixed zones treated via volume fractions**
- **Interface reconstruction used to allow complex 3D shaping of objects onto mesh**

# AMR: Coarsening is easy, refinement requires explicit interface reconstruction

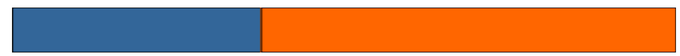
Weighted sum of volume fractions

$$V_f^c = \sum_i V_{f,i}^f V_i^f \Big/ \sum_i V_i^f$$

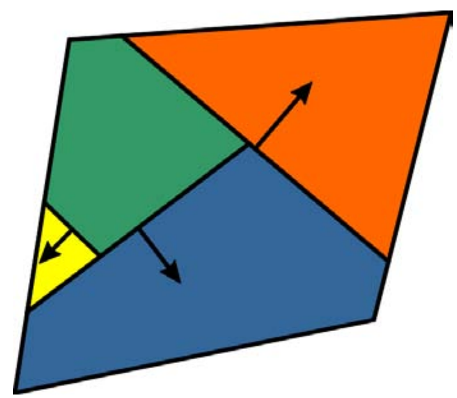
Orientation ($\boldsymbol{n}$) uses $V_f$' s of neighboring cells

Solve for location ($\rho$) of interface

Assign refined $V_f$' s

1D: 

2D: Polygons



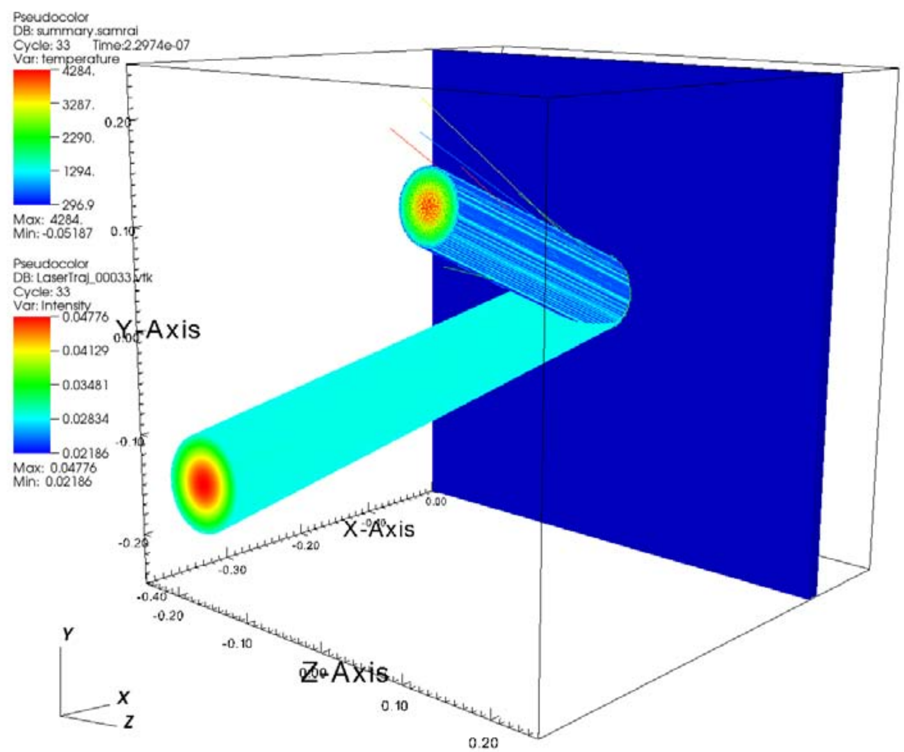
3D: Truncated Hexahedra, bounded by doubly-ruled surfaces (DRS, or hyperbolic-paroboloids)

# The 3D laser ray tracing package has inverse Bremsstrahlung and turning point deposition

- **In a linear potential field ray trajectories are parabolic**

$$\frac{d^2\boldsymbol{x}}{dt^2} = \nabla\left(-\frac{c^2}{2}\frac{n_e}{n_c}\right)$$

- **Elements are arbitrary hexahedra**
- **Intersections of parabolic curves with doubly ruled surfaces**
- **Trajectories involve solution of intersection of quadratic equations (parabola-line intersections)**
- **Test for intersections with each of the six sides**




**Kaiser, T. "Laser ray tracing and power deposition on an unstructured three-dimensional grid," Physical Review E, 61(1), 2000, pp. 895-905.**

# We model both heat conduction and radiation transport based on the diffusion approximation

**Diffusion equation**

$$\nabla \bullet \alpha \nabla u + \beta u = f$$

**Heat Conduction**

$$C_v \frac{T^{n+1} - T^n}{\Delta t} = \nabla \bullet D^n \nabla T^{n+1} - \sigma T^{n+1}$$

$$\alpha = D^n$$

$$\beta = -\sigma - \frac{C_v}{\Delta t}$$

$$f = -\frac{C_v}{\Delta t} T^n$$

**Radiation Diffusion**

$$\frac{E_R^{n+1} - E_R^n}{\Delta t} = \nabla \bullet \lambda \left( \frac{c}{\kappa_R} \right) \nabla E_R^{n+1} + \tilde{\kappa}_P (B^n - c E_R^{n+1})$$

$$C_v \frac{T^{n+1} - T^n}{\Delta t} = -\tilde{\kappa}_P (B^n - c E_R^{n+1})$$

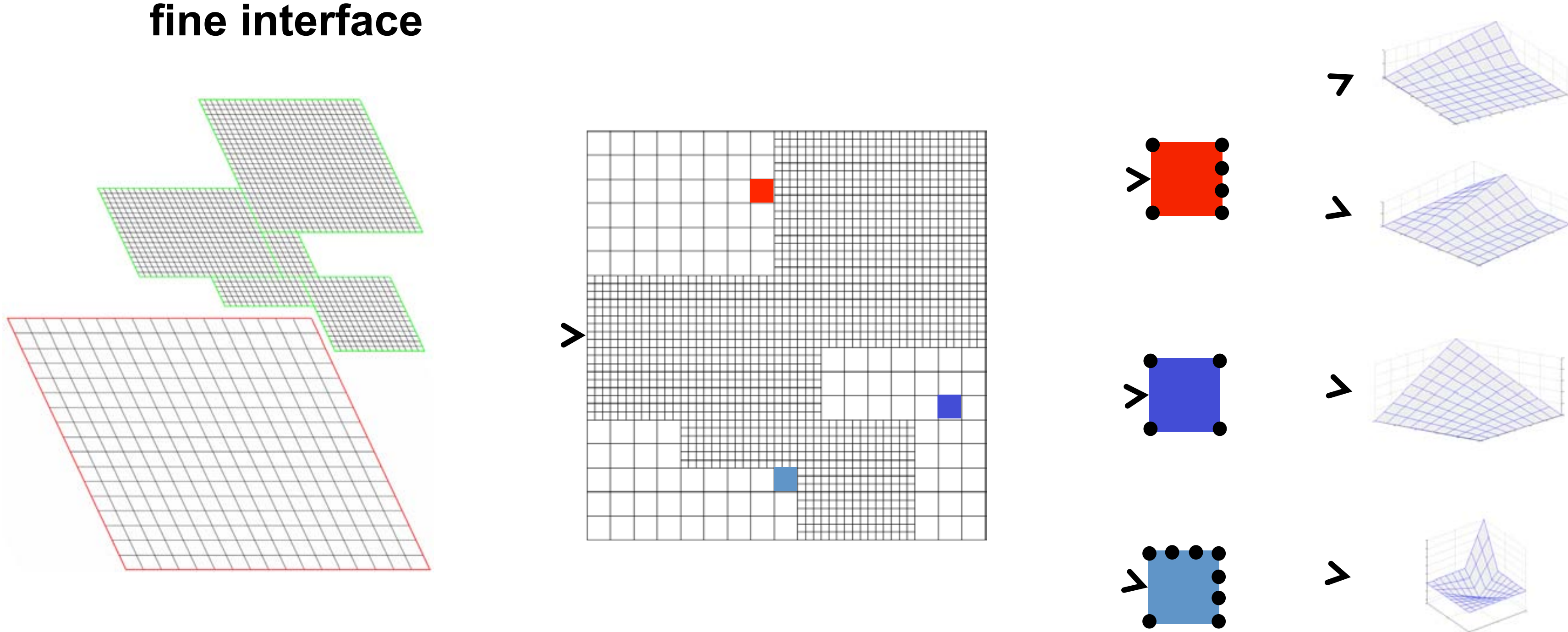
$$\alpha = \lambda \left( \frac{c}{\kappa_R} \right)$$

$$\beta = -\tilde{\kappa}_P c - \frac{1}{\Delta t}$$

$$f = -\frac{1}{\Delta t} - \tilde{\kappa}_P B^n$$

# The diffusion equations are solved using the Finite Element Approach (FEM)

- We map the level representation to an equivalent composite mesh
- Special nodal basis functions are constructed to handle the coarse-fine interface



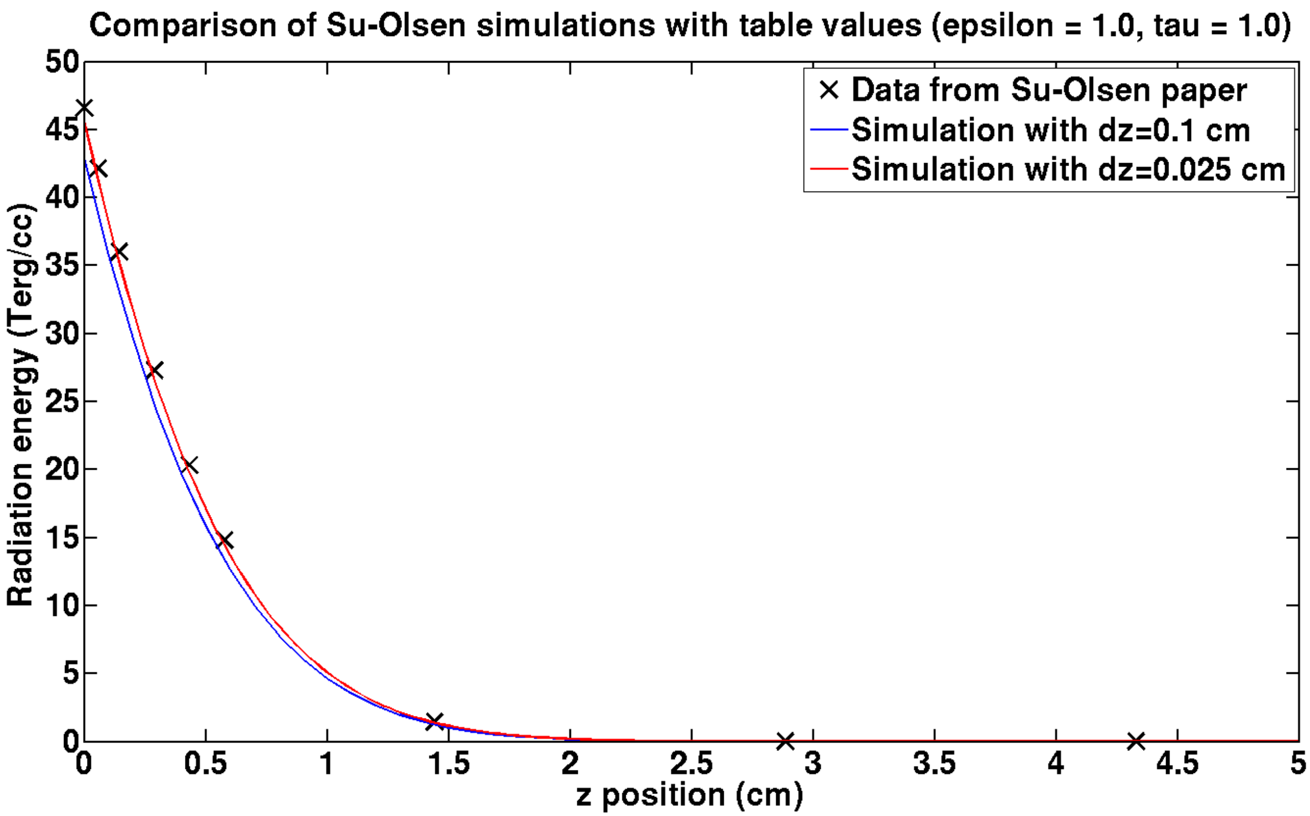
Level representation

Composite representation

Special transition elements and basis functions

# Method requires efficient coupling between cells and nodes and has been compared to analytic solutions

- **Cell centered temperatures required for hydro in ALE-AMR**
- **Nodal temperatures are required for FEM diffusion method**
- **We map the changes in cell/node temperatures ala Shestakov***



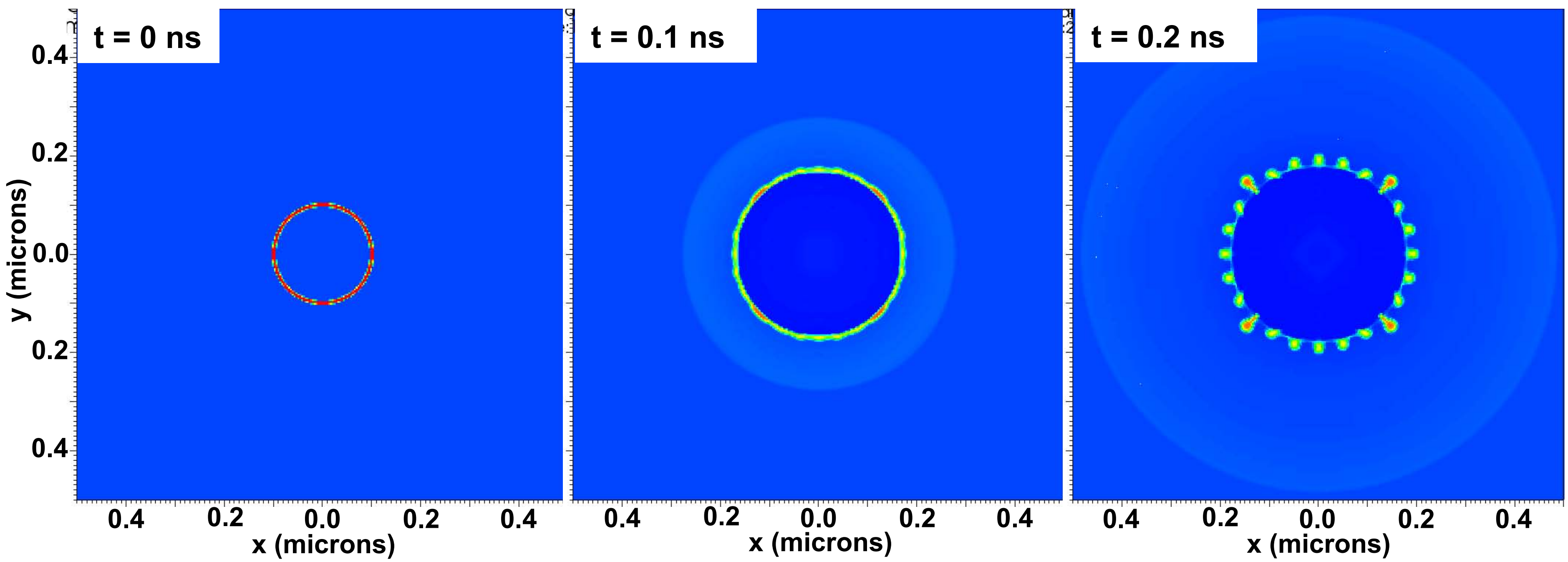

B. Su and G. L. Olson. *J. Quant. Spectrosc. Radiat. Transfer* **56** (1996), p. 337.

* "Combining Cell and Point Centered Methods in 3D Unstructured-Grid Radiation-Hydrodynamic Codes", A. I. Shestakov, J. L. Milovich, M. K. Prasad, JCP, **170**, 81-111, 2001.

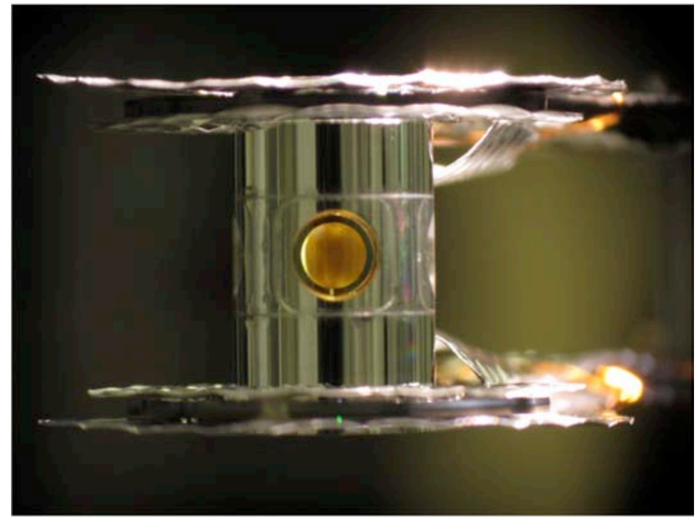
# We are testing methods to couple surface tension models to the hydrodynamics in ALE-AMR

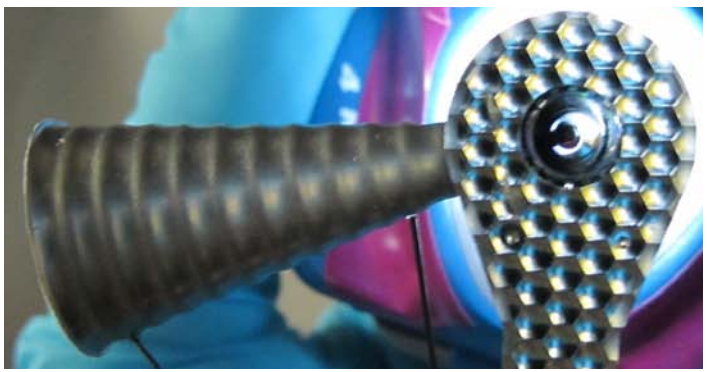
- One method uses a diffuse interface model for surface tension that couples into hydrodynamics through the stress tensor
- It allows for temperature dependent surface tension effects

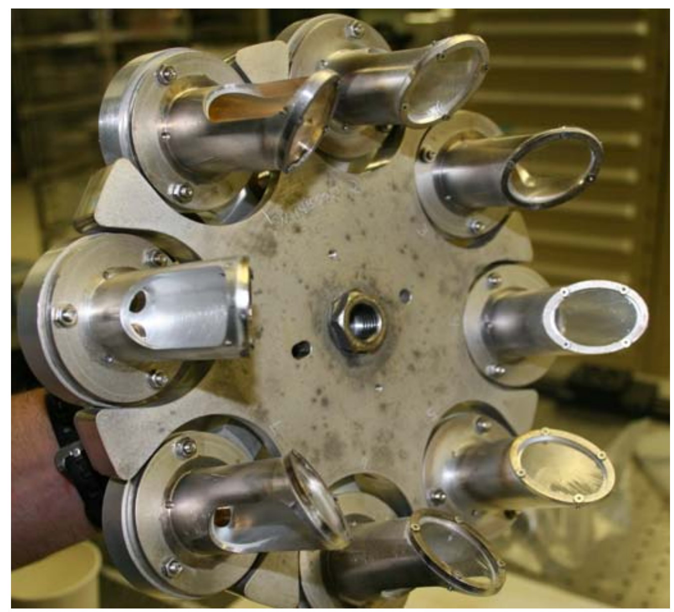
**Test Problem: Hot Al vapor inside an Al ring surround by cool Al vapor**

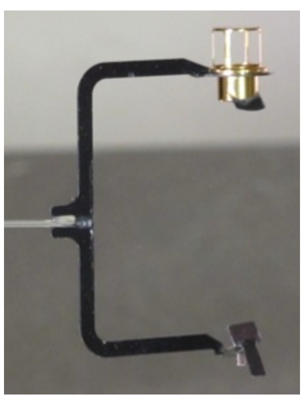


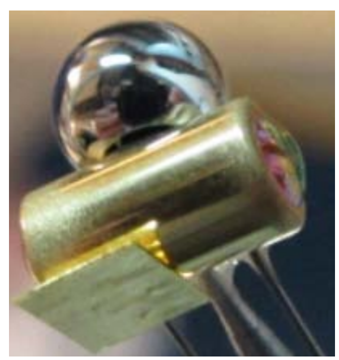
# ALE-AMR has been used to model a wide range of targets on NIF for debris/shrapnel assessment

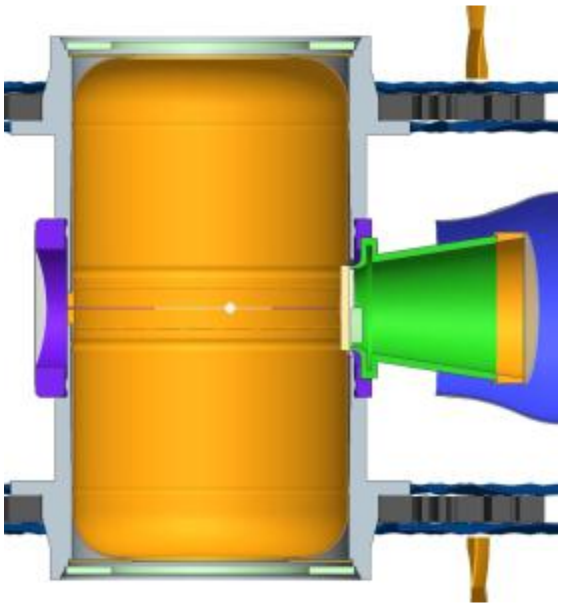




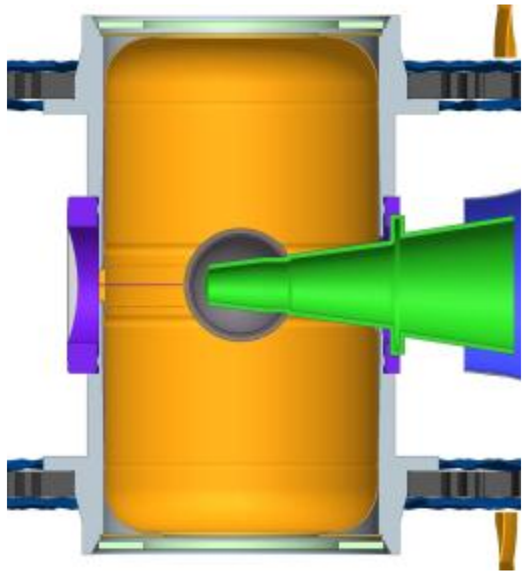




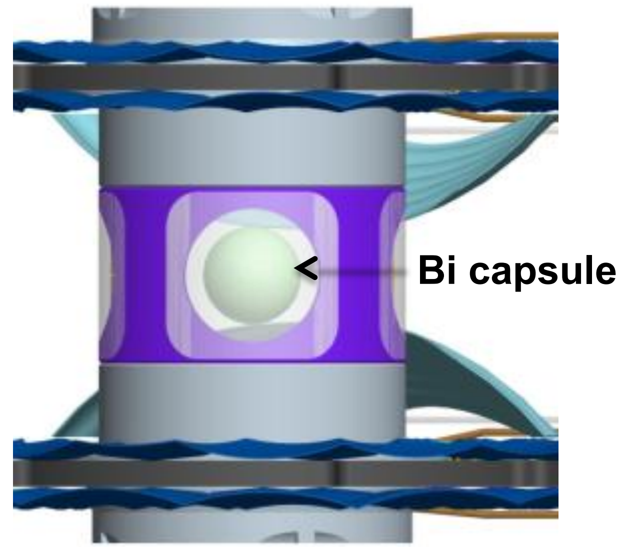
# Late-time simulations for NIC targets have focused on higher risk (lower energy) shots



ShockCom ~250 kJ



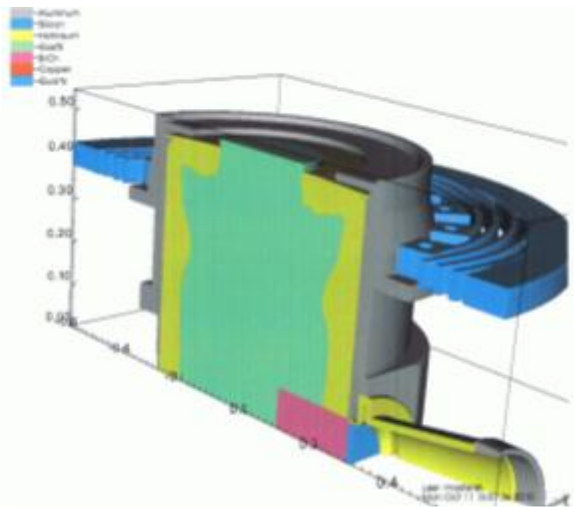
Keyhole ~150 kJ




Re-emit ~15 kJ

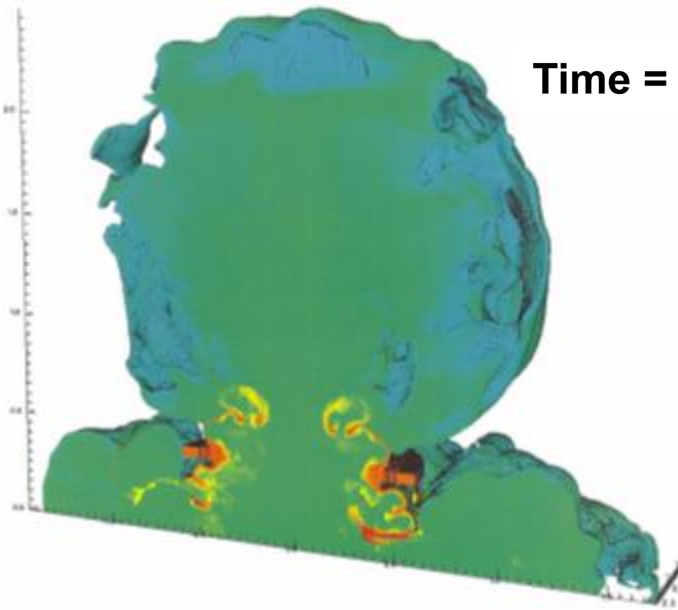
For these lower energy experiments the target is only partially vaporized and resulting shrapnel (molten and solid) can impact optics and diagnostics

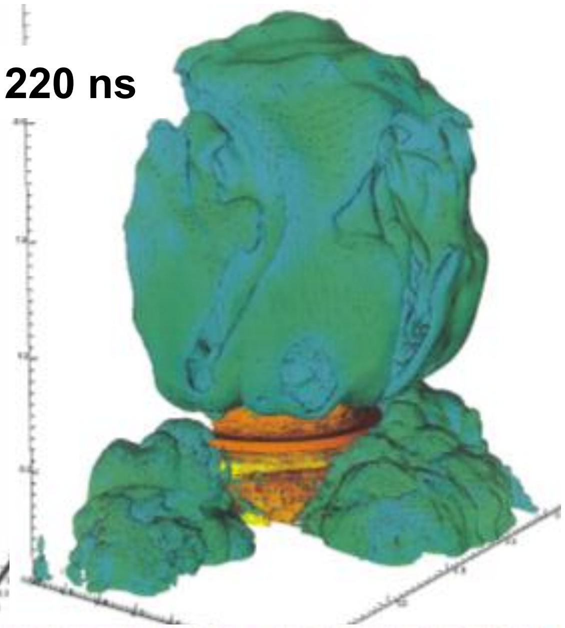
# Dynamic mesh refinement is essential to achieve high resolution on large 3D meshes

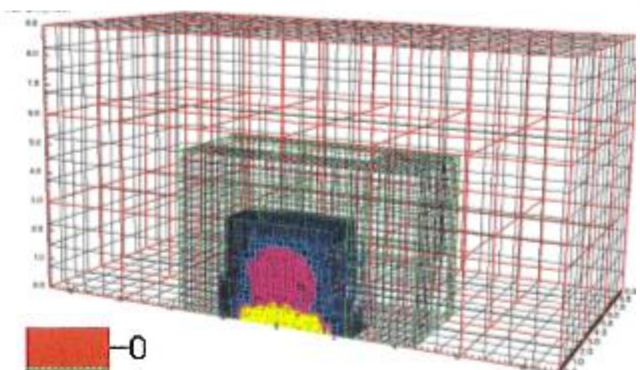


Materials at end of laser pulse

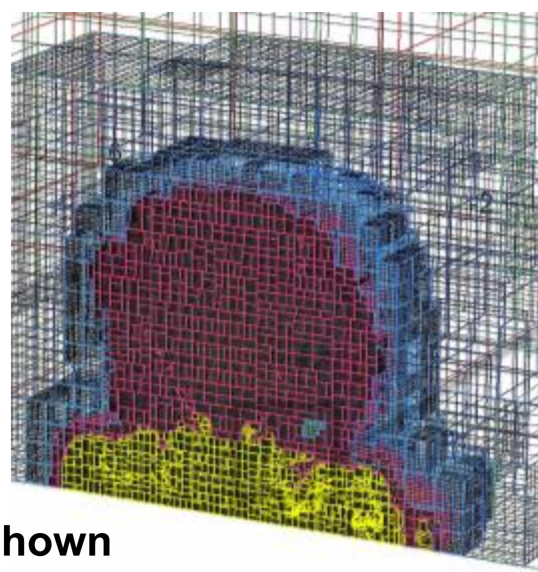
Time = 220 ns



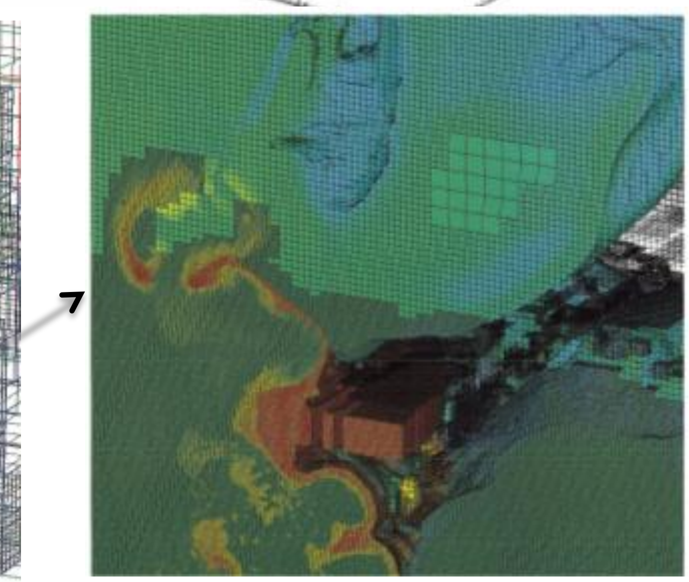




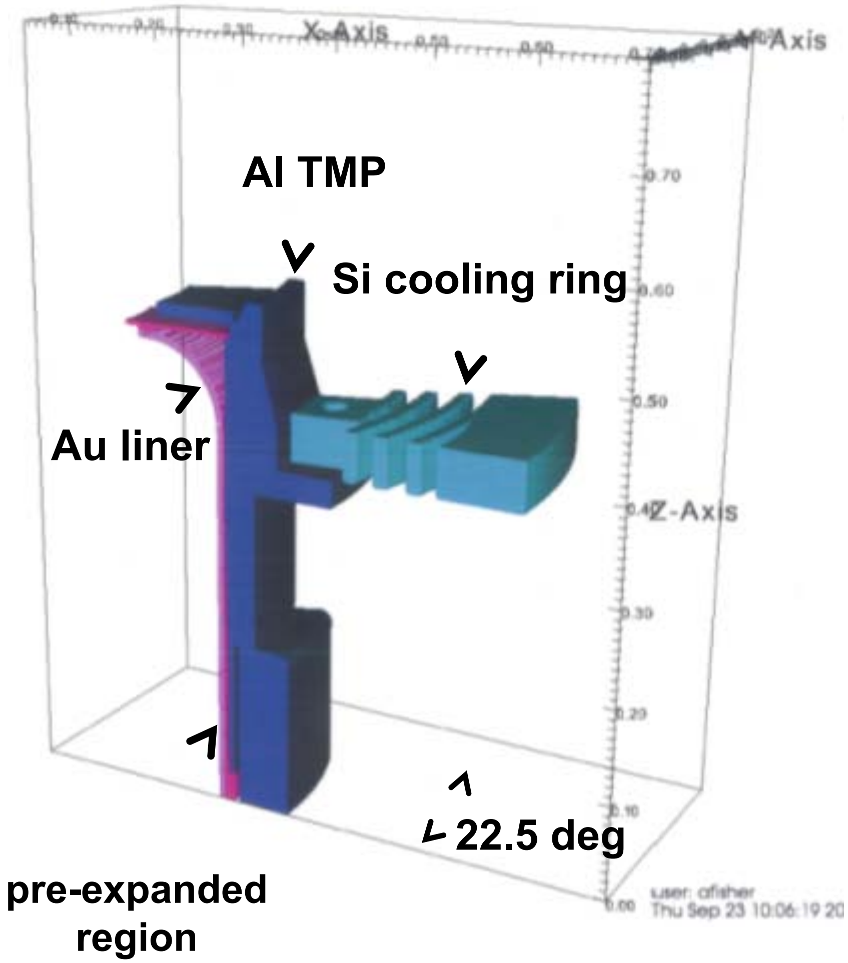

Refinement Levels



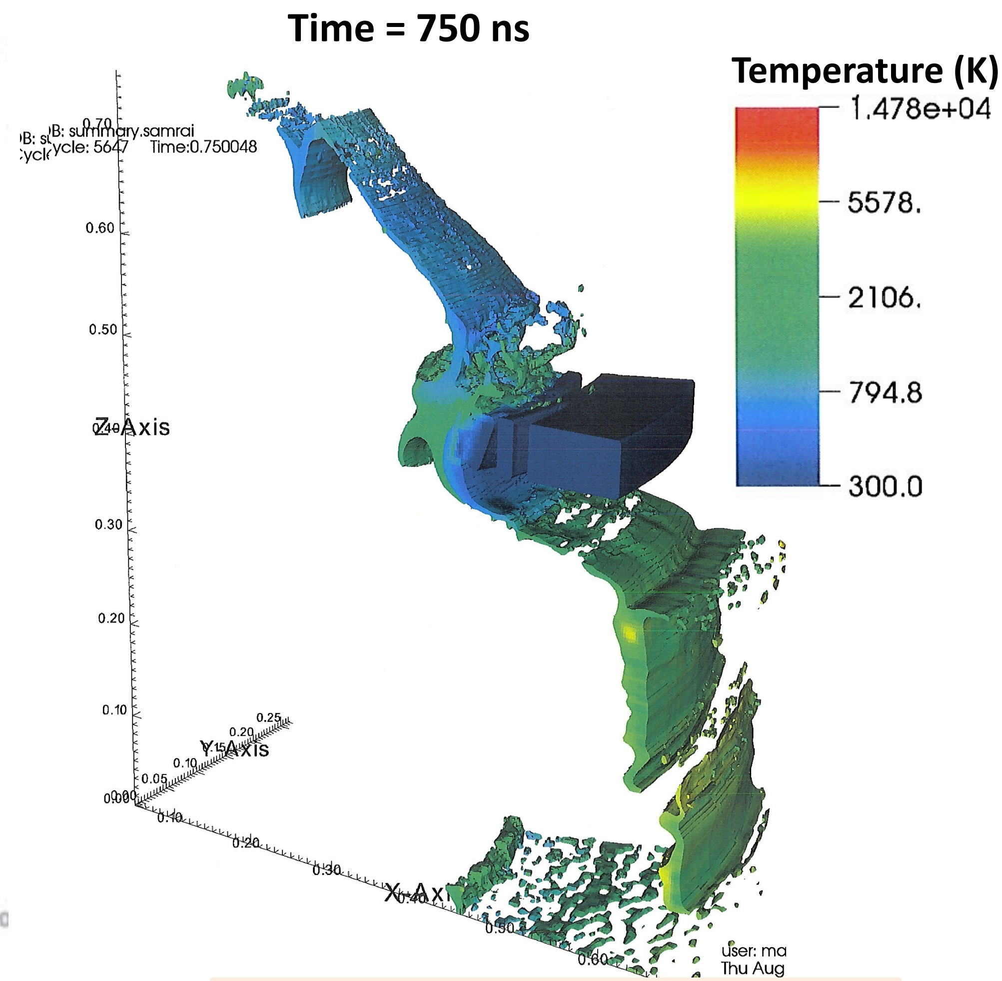
Patch boundaries shown



# The re-emit campaign studies early time symmetry and requires less than 1% of NIF's total energy




The simulation wedge is 1/32 of the entire target




A large fraction (2/3) of the target remains molten or solid

# The NIF optics that must be protected extend from 23.5° to 50° from the top (and bottom) pole of the chamber

23.5°

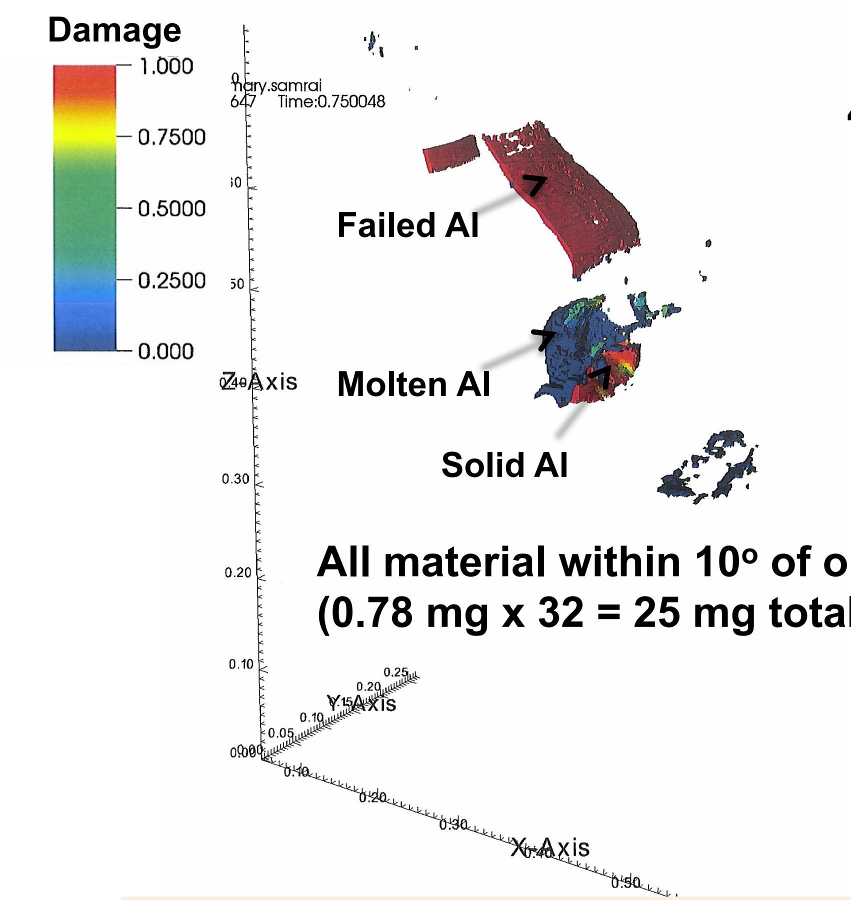
30°

Inner beams

44.5°

50°

Outer beams



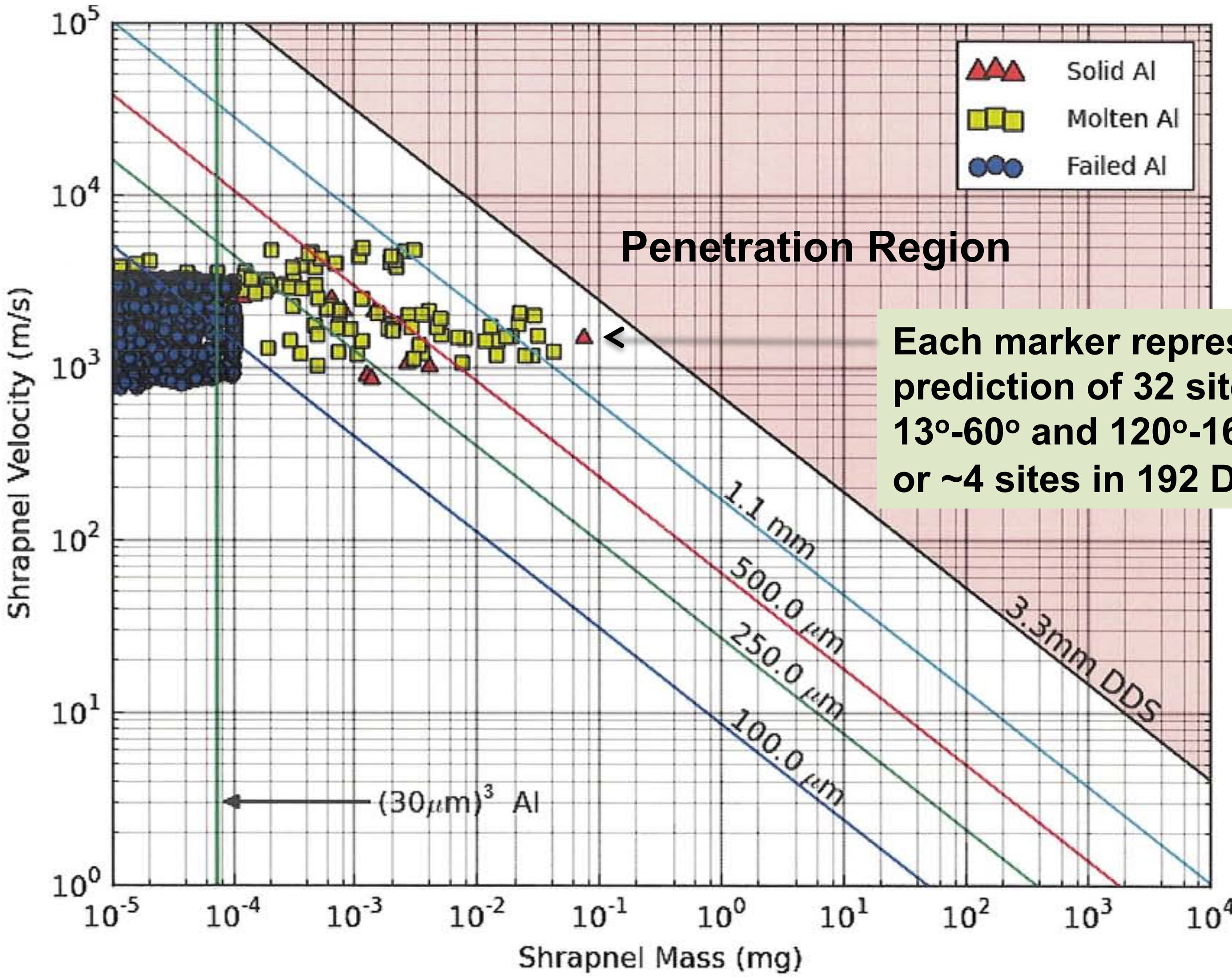

All material within 10° of optics (0.78 mg x 32 = 25 mg total)

**Assessments require mass and velocity of shrapnel**

- **Mass of failed Al shrapnel bounded by zonal mass**
- **Mass of molten Al shrapnel bounded by 300 micron droplets (~thickness of TMP - very conservative)**
- **Mass of solid Al from calculated shrapnel size**
- **Velocities averaged over shrapnel volume**

**Optimized target geometry results in 9X reduction of solid/molten material directed towards optics as compared to isotropic**

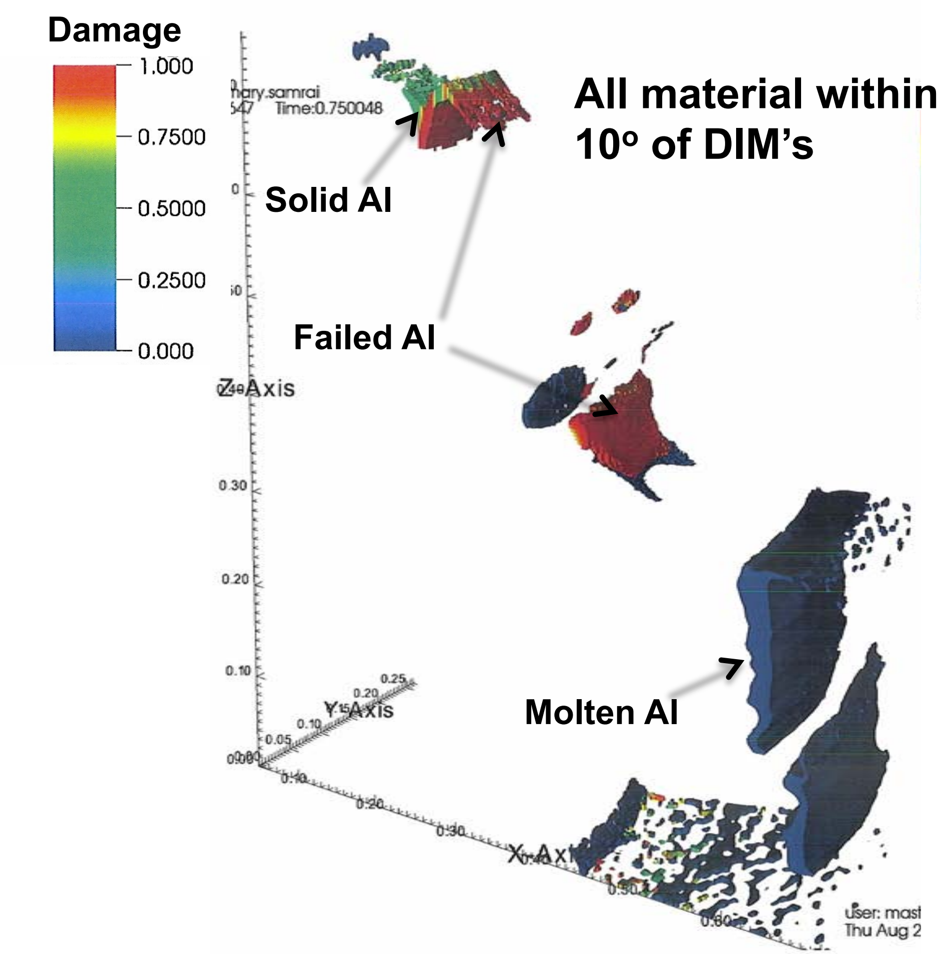
# Simulations agree with optics observations of cratering but no penetrations of the 3-mm thick DDS's



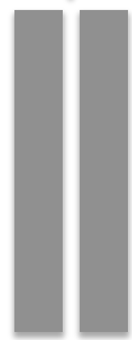

**Each marker represents a prediction of 32 sites between 13°-60° and 120°-167° degree or ~4 sites in 192 DDS's**

# Imaging diagnostics are in DIM's located at the top pole and the equator

**Polar DIM**




**DIM nosecone**

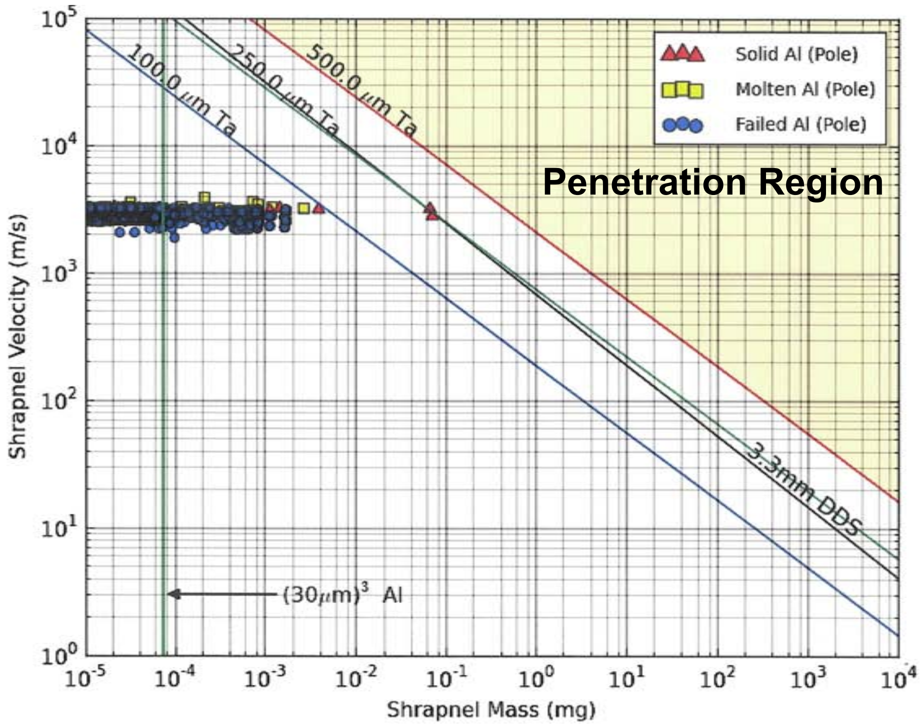


There are two 500 micron thick collimators on either side of the pinhole array

**Equatorial DIM**

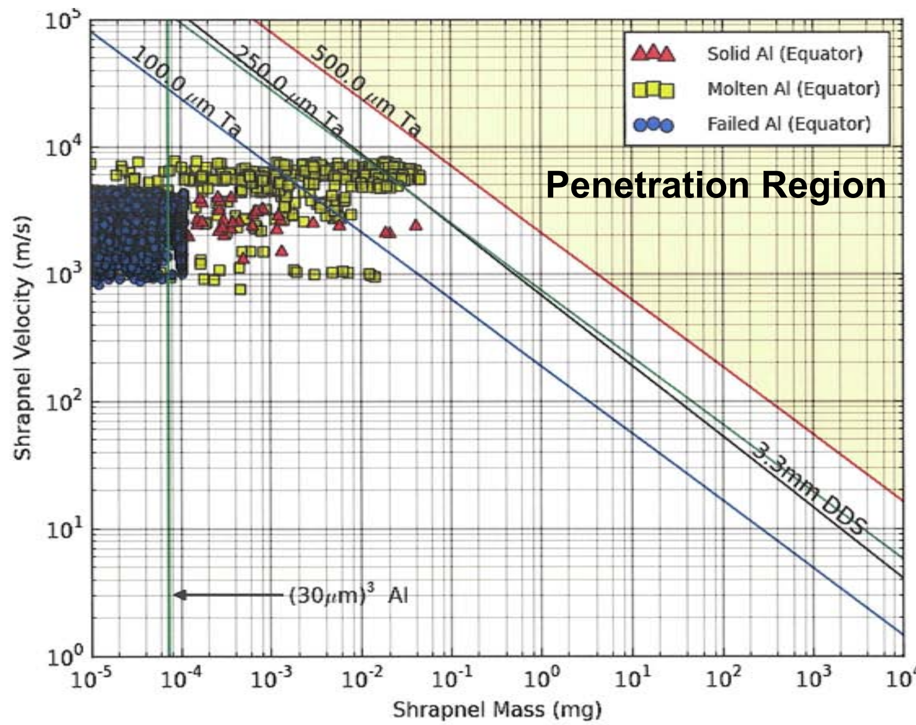
# Simulations agree with diagnostic observations of cratering but no penetrations of the 500-mm thick front Ta collimator

## Polar



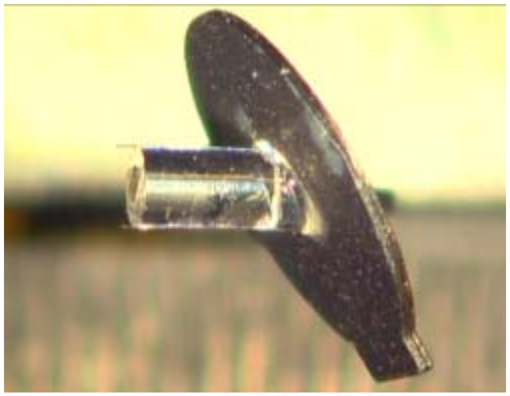

Velocities less divergent going towards pole so likely less than 16 fragments

## Equatorial

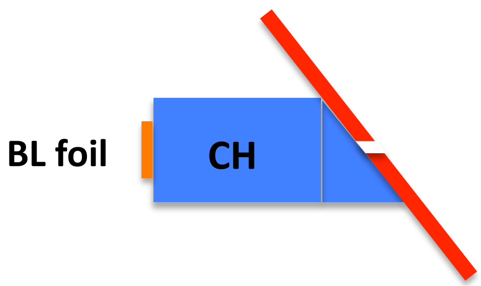



Need surface tension model to calculate mass of molten shrapnel

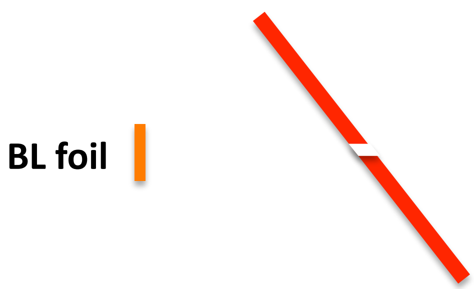
# Redesign of backlighter for radiation transport HED experiment reduces damage to diagnostic



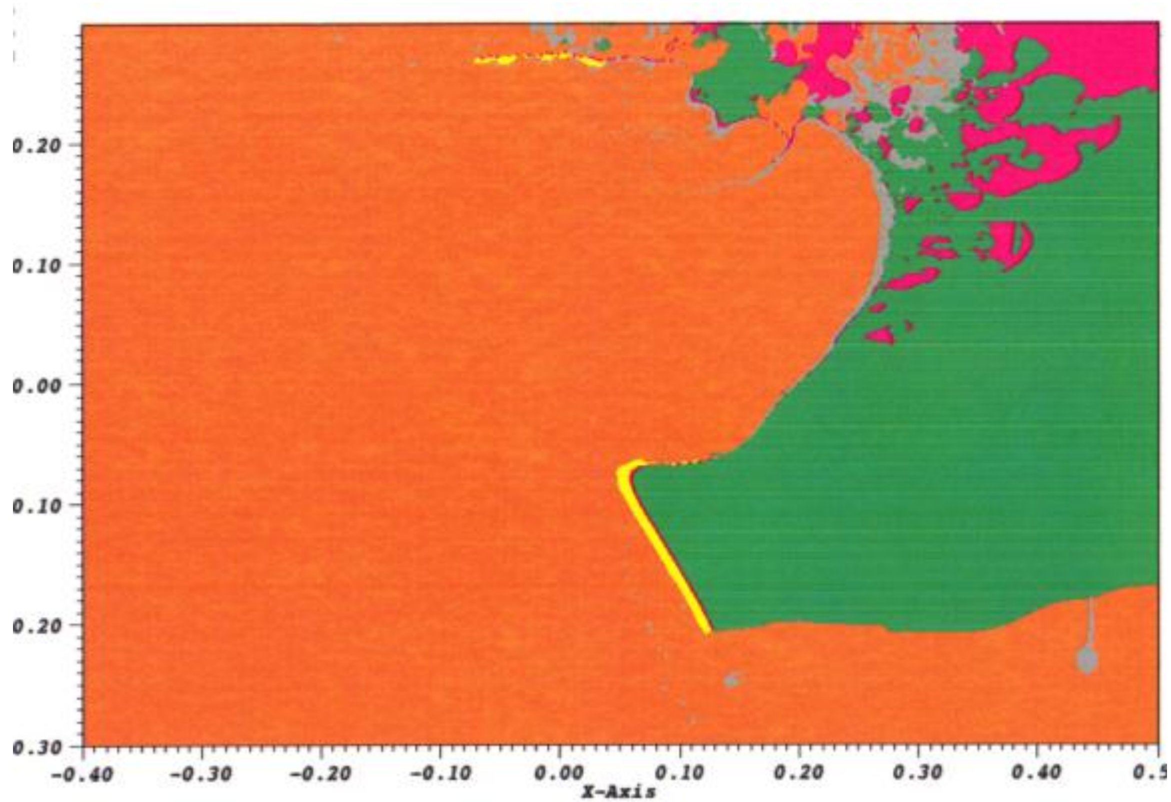
New RT backlighter target




Addition of CH has major effect



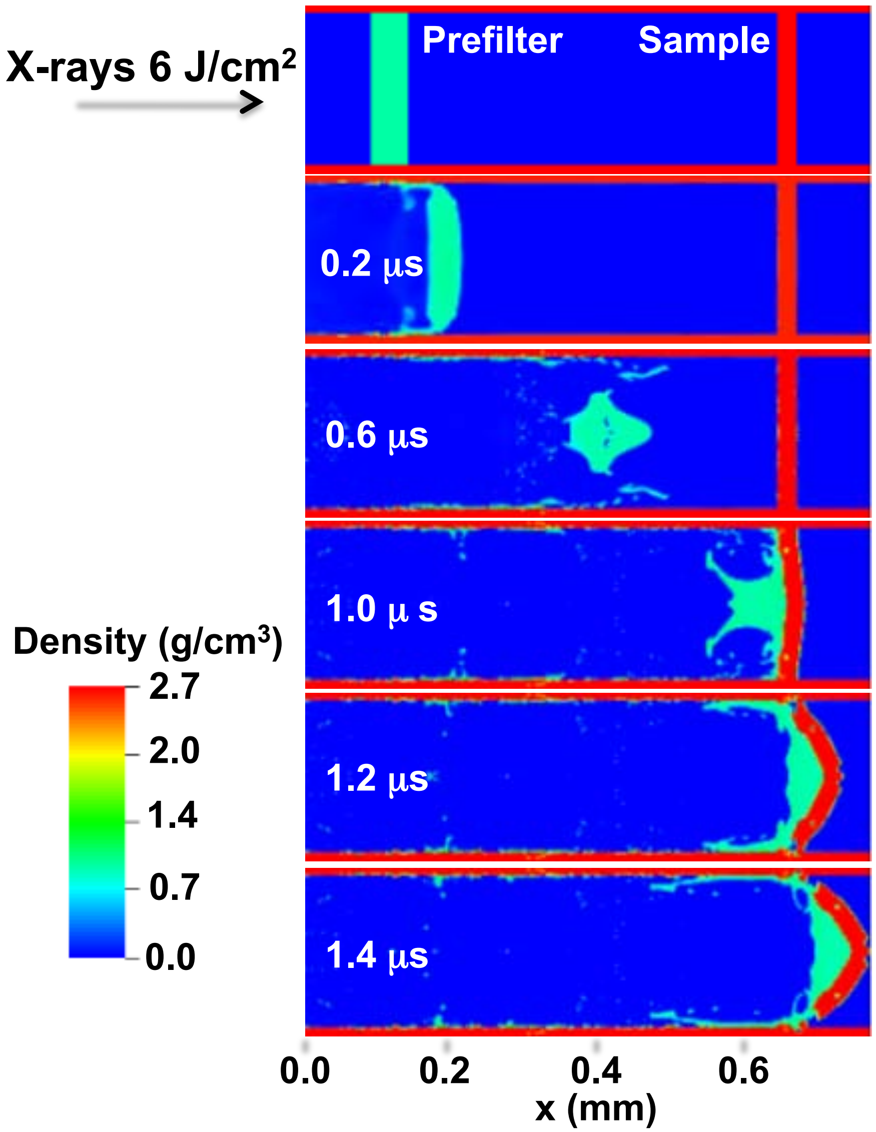

With only x-ray heating material leaves ~normal to surface



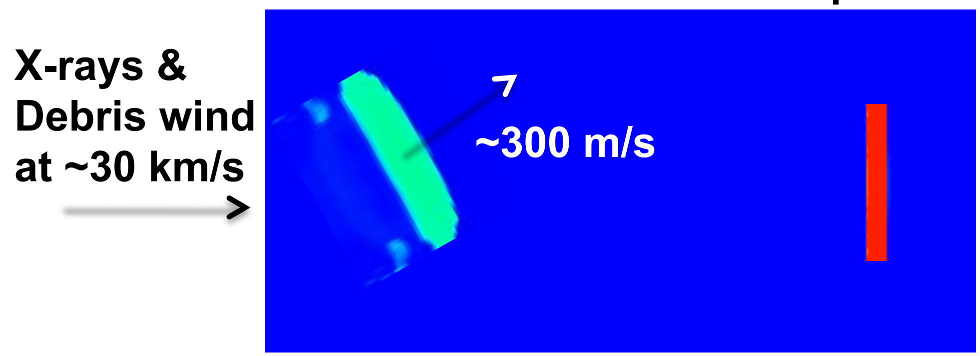

Filled boundaries of ALE-AMR simulation at 650 ns

Void
Gold
Tantalum
CH
Molten Tantalum

# Simulations show that x-ray loading in initial design damaged thin samples and tilted redesign protects samples from x-rays and fast debris wind from target

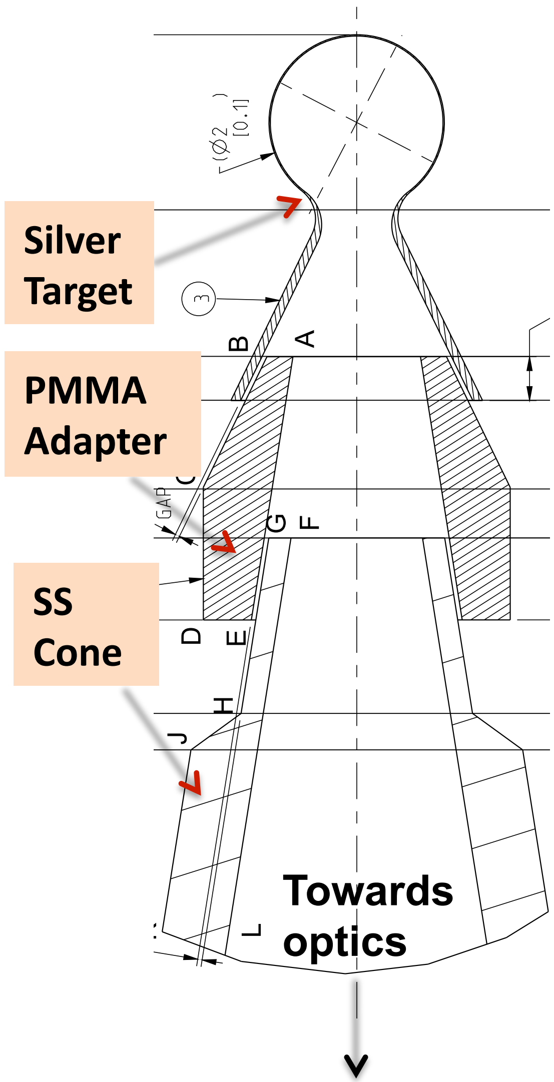


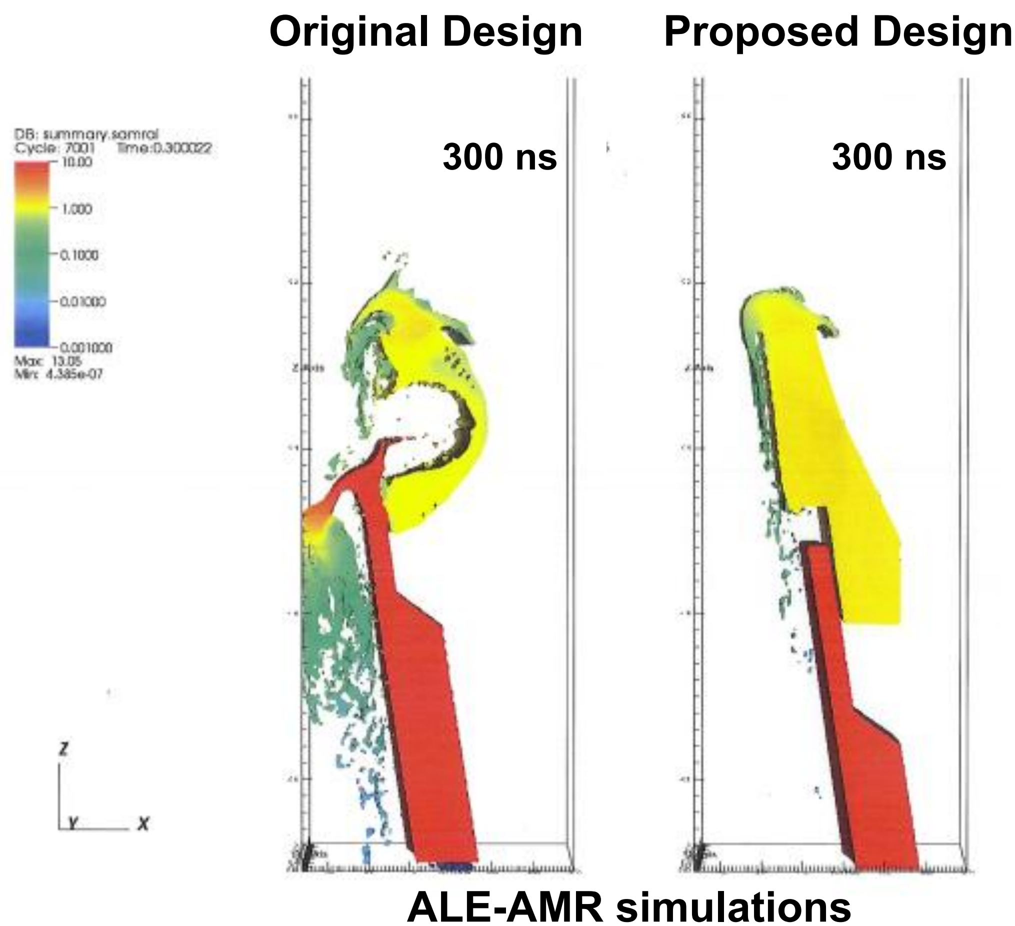

ALE-AMR simulation of tilted prefilter



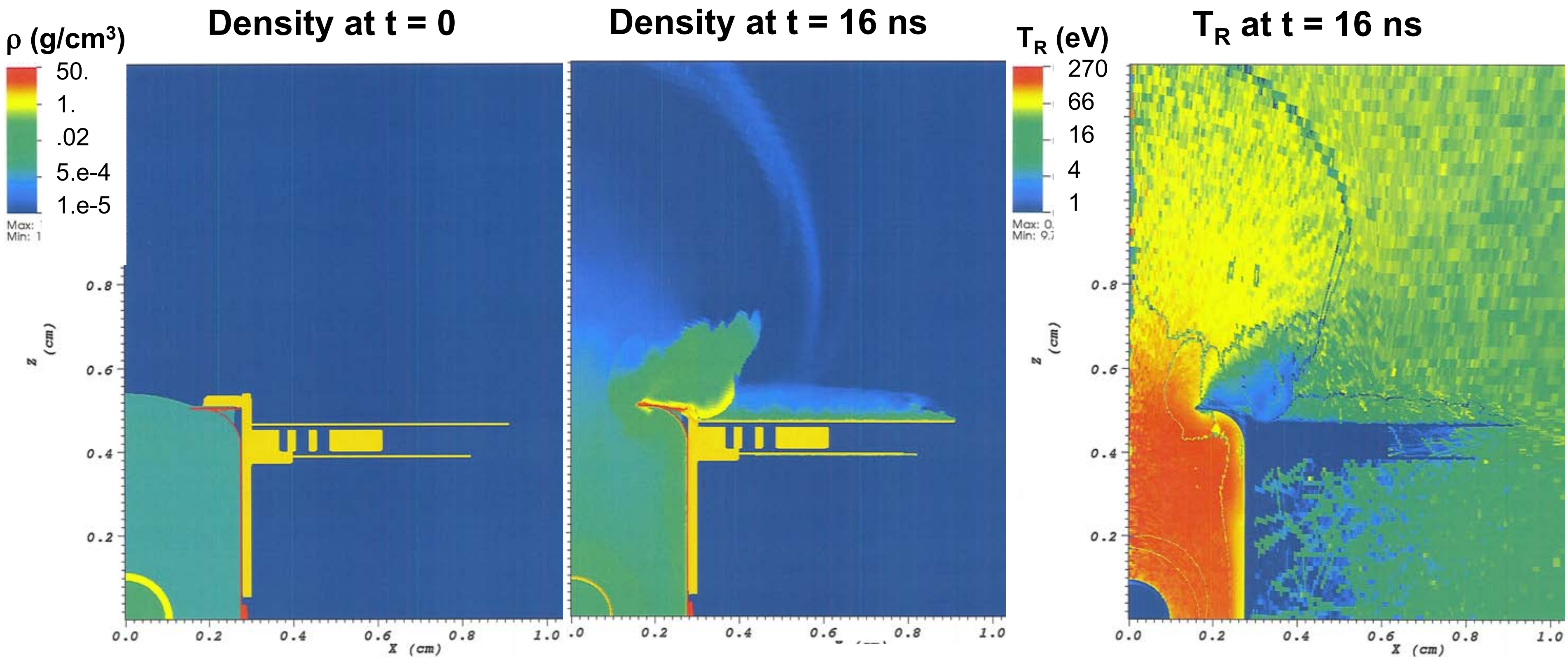

Redesigned Sample Holder

# A redesign of a single quad spherical cavity target reduces material directed towards optics



# Simulations for high energy NIC targets will provide angular dependent debris wind and x-ray loading




**Conditions at start of high-intensity portion of ignition pulse, unconverted 1ω and 2ω striking CH/Al shields covering Si cooling rings will be added in future simulations**

**Radiation, calculated here using IMC in Hydra, can significantly impact portions of the Al TMP closest to the LEH's**

# Summary

- Late-time simulations of HED targets is a new multi-physics area requiring new code development
- ALE-AMR code developed by DOE labs and UC campuses is used to model a wide range of HED targets
  - Unique in its ability to model hot radiating plasmas and cold fragmenting solids
  - Surface tension models are being developed
- ALE-AMR scales to thousands of cores at NERSC
  - Hybridization, e.g., combining OpenMP with MPI, is being studied
- Redesigns of target configurations based on simulations is critical in protecting diagnostics, optics, and obtaining data
- Collaboration in ALE-AMR code development and new application areas is invited, contact deder@llnl.gov or aekoniges@lbl.gov