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Solid Material and Fragmentation Modeling in NIF ALE-AMR

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Third International Workshop on High-Powered Laser Chamber Issues - Focus: Debris and Shrapnel
Livermore, CA, United States
June 2, 2008 through June 4, 2008

3rd International Workshop on High-Powered Laser Chamber Issues

Focus: Debris and Shrapnel

June 2-4, 2008

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Solid Material and Fragmentation Modeling in NIF ALE-AMR

Aaron Fisher

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Talk outline

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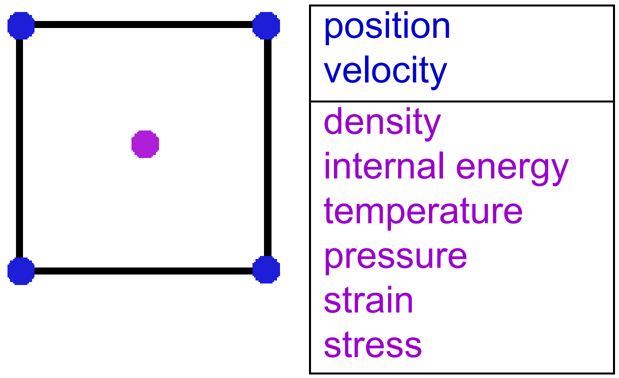
- Strength Modeling in NIF ALE-AMR
- Fragmentation Modeling in NIF ALE-AMR
- Fragmentation Validation Efforts
- Fragmentation Results
- Multi-Scale Strength Modeling
- Conclusions

Strength Modeling in NIF ALE-AMR

Stress and strain fundamental equations



Equation of motion with stress term

$$\nabla \bullet (\rho v v) + \nabla p + \nabla \Sigma' = 0$$

Constitutive stress strain relationship

$$\Sigma = \Sigma(\varepsilon, \rho, e, \ldots)$$

Debris and shrapnel studies require modeling of a wide variety of strength properties

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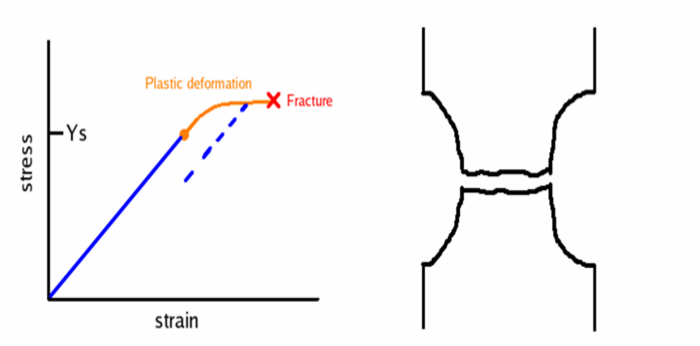
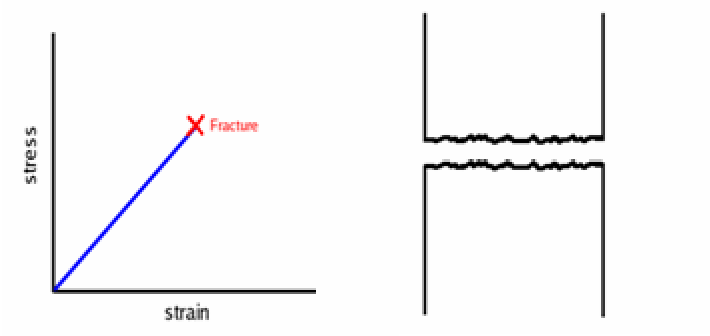
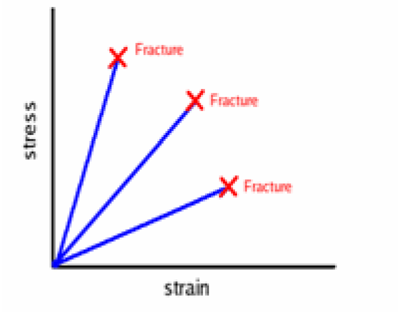
Ductile Materials and Plasticity



Brittle Materials



Anisotropy and Dependence on Material State



Flexible strength modeling framework

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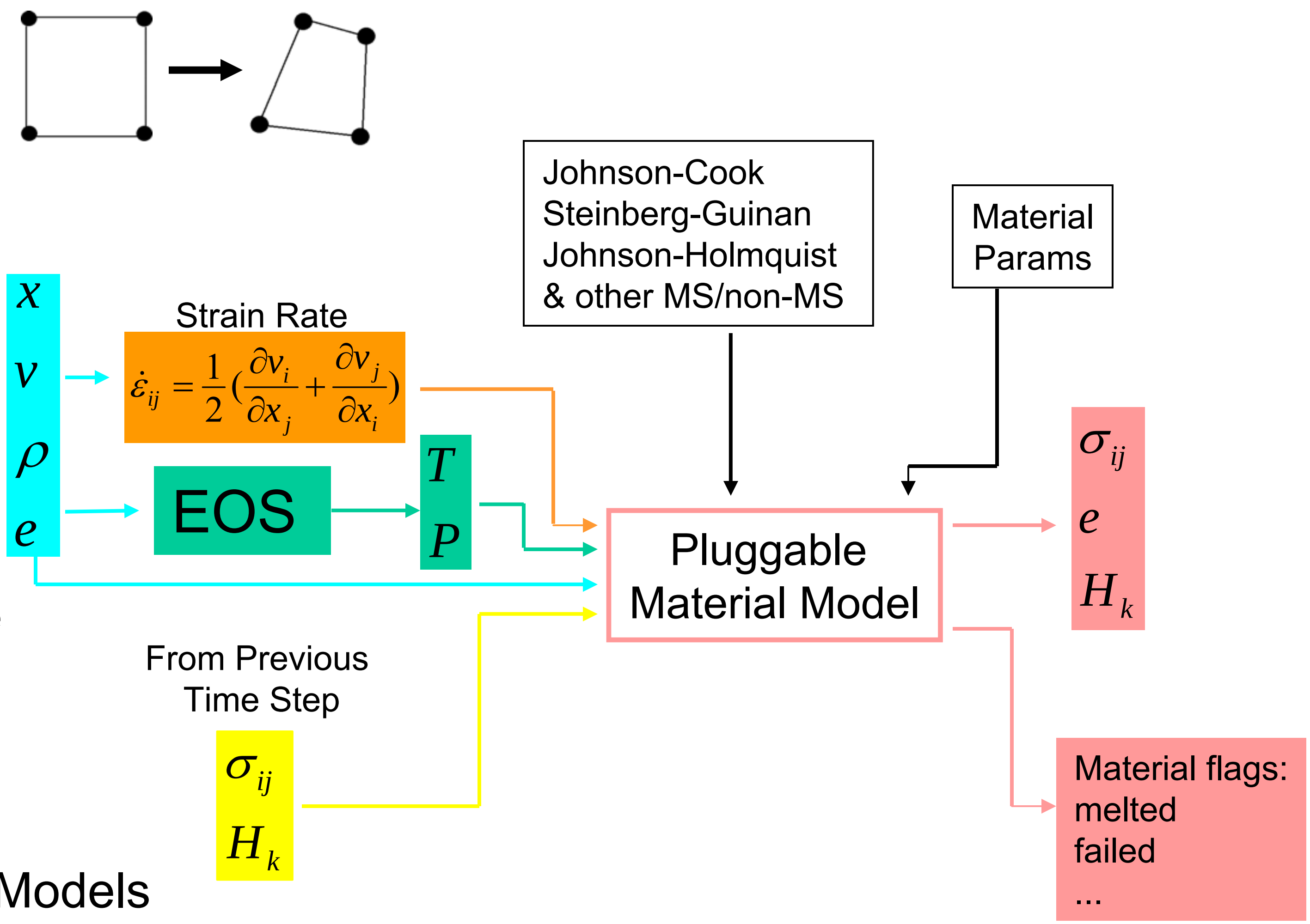
Lagrange Step



Post-Lagrange Material Update

Other Physical Models

Relax/Remap

Example: Johnson-Cook strength/fracture model plug-in

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Von Mises tensile flow stress:

$$\sigma = [A + B\varepsilon^n][1 + C\ln(\dot{\varepsilon}^*)][1 - T^{*m}]$$

Strain to fracture:

$$\varepsilon^f = [D_1 + D_2 \exp(D_3\sigma^*)][1 + D_4 \ln(\dot{\varepsilon}^*)][1 + D_5 T^*]$$

$$T^* = \frac{T - T_{room}}{T_{melt} - T_{room}}, \sigma^* = \sigma_m / \overline{\sigma}$$

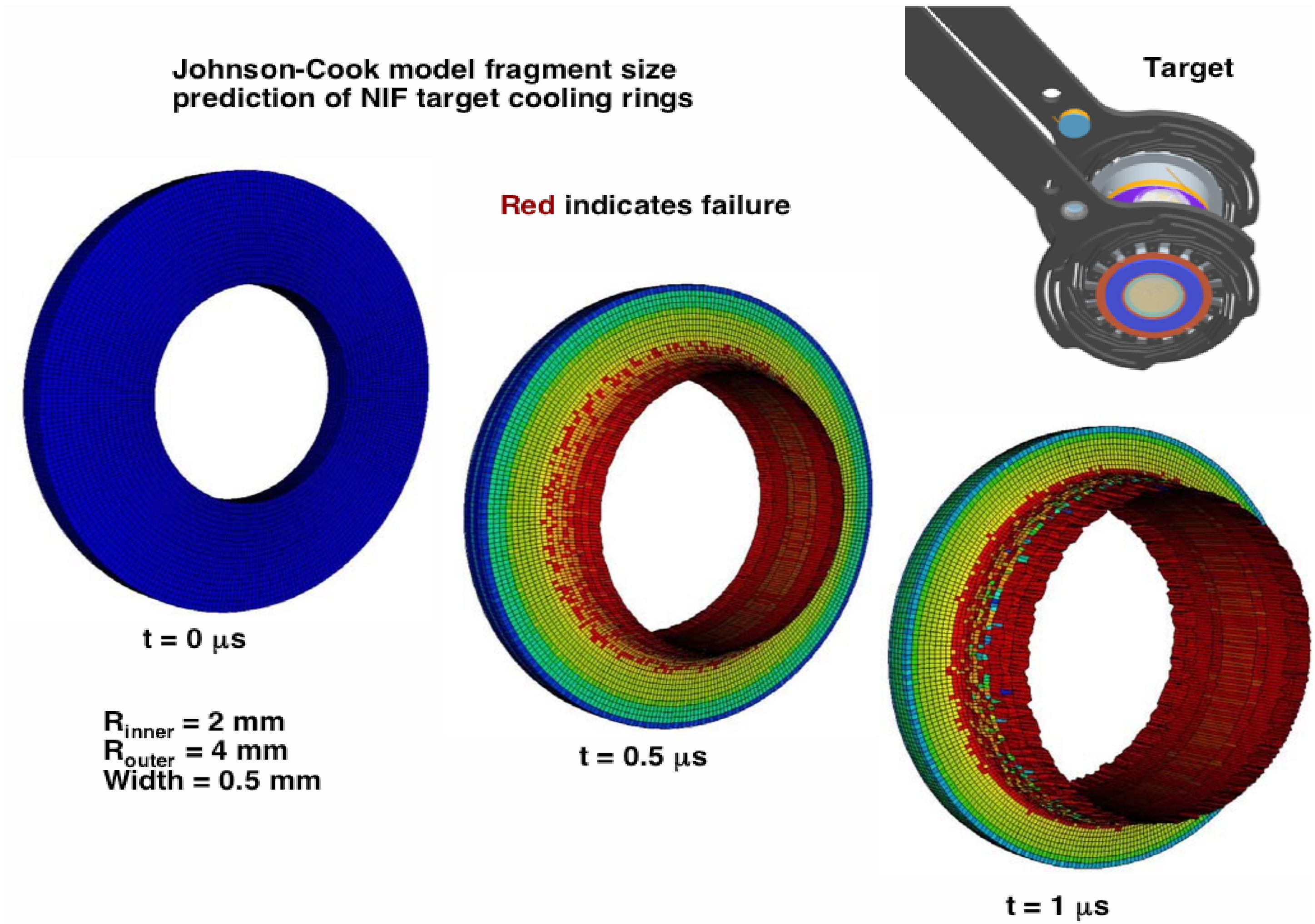
Damage:

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon^f}$$

Fracture is initiated when

$$D > 1.0$$

3D cooling ring simulation with strength (no fragmentation)



Fragmentation Modeling in NIF ALE-AMR

We are interested in results beyond fracture

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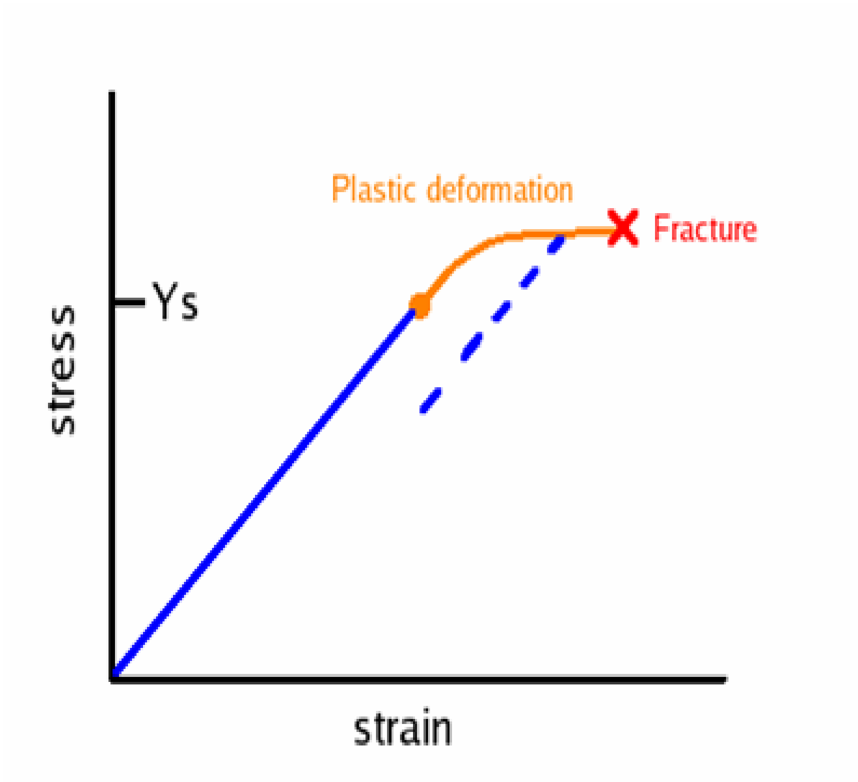
- Beyond fracture most material models give up
- At fracture we restore the cell to the previous state
- Simple fracture model is then applied



New NIF ALE-AMR model for failure, fracture, and fragmentation

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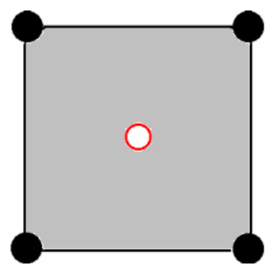
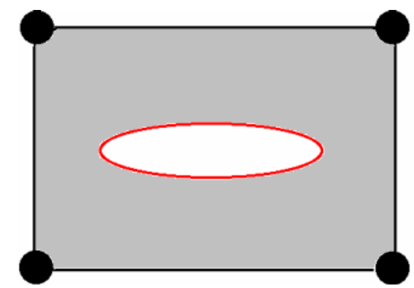
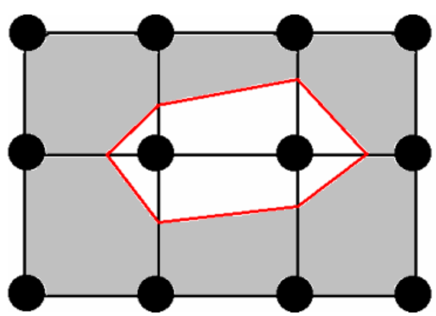
Upon failure a small volume fraction of void is introduced into the cell



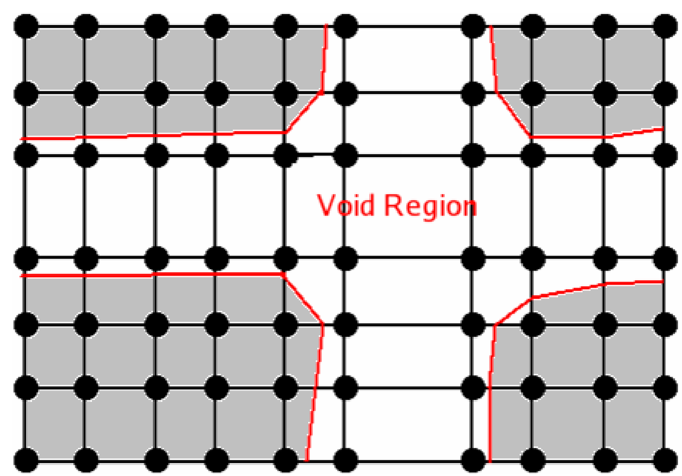
If the cell continues to grow the void enlarges to meet that growth



Volume fraction interface reconstruction allows voids to coalesce to form cracks



Cracks can grow large enough to span across cells allowing fragment formation



2D ring fragmentation simulations

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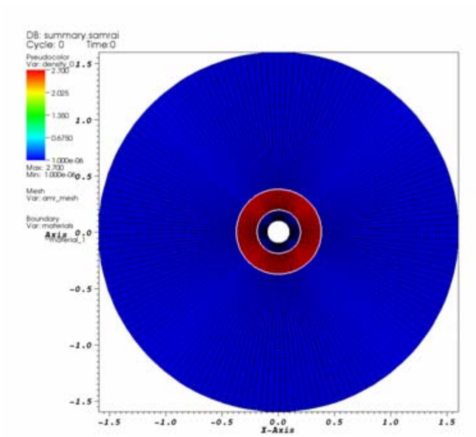
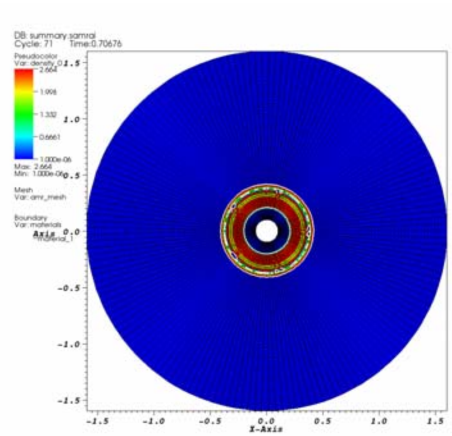
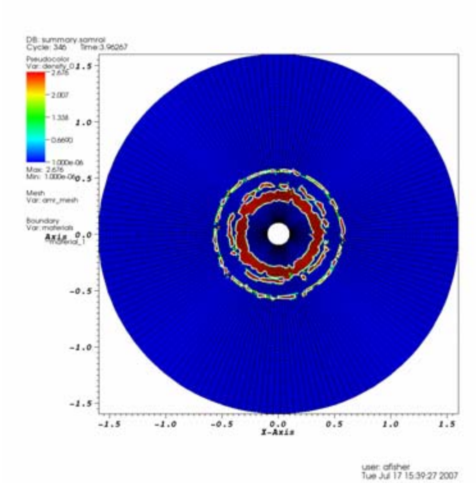
- 2mm - 4mm ring made of Al6061 surrounded by void
- Johnson-Cook strength and damage models were utilized
- Impulsively loaded with initial velocity 2000m/s on inner layer of nodes



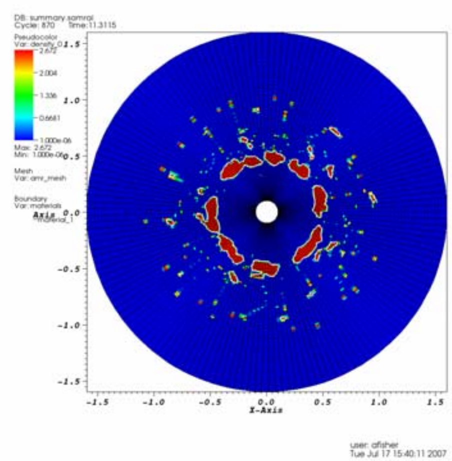
t = 0.0 us



t = 0.7 us



t = 4.0 us



t = 11.3 us

Fragmentation Validation Efforts

Ring simulation comparisons with LS-DYNA

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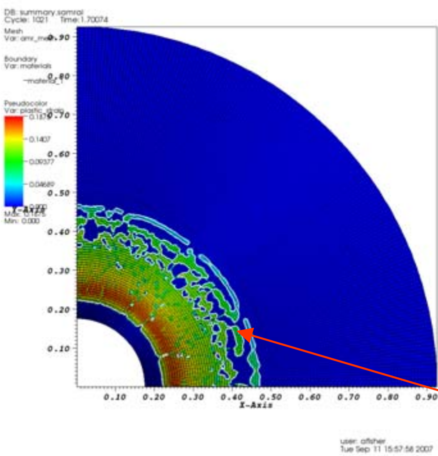
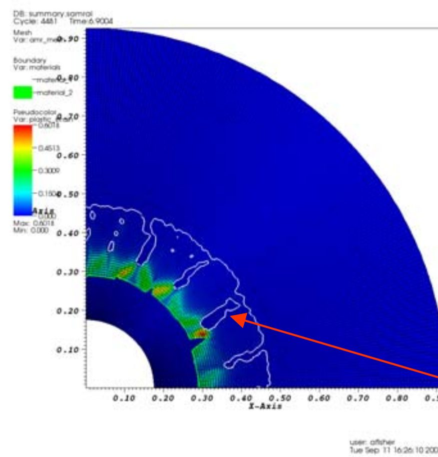
- 2mm - 4mm ring made of Al6061 surrounded by void
- Johnson-Cook strength and damage models were utilized
- Variety of loading, tensile strength options, and advection modes



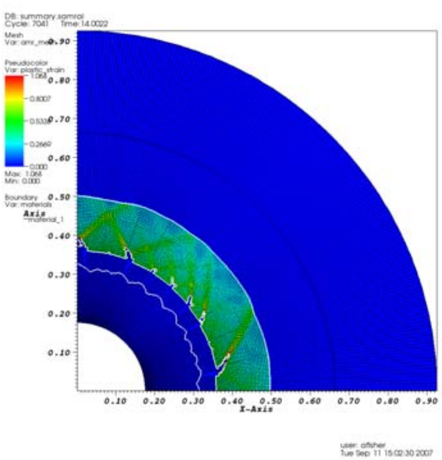
•ALE-AMR
•Eulerian
•impulsive loading
•w/ tensile failure
•mix fracture

Due to impulsive loading

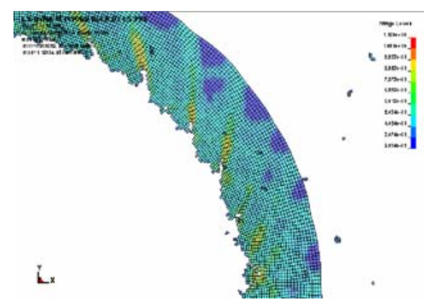


•ALE-AMR
•Eulerian
•pressure loading
•w/ tensile failure
•mix fracture

Tensile failures



•ALE-AMR
•Lagrangian
•pressure loading
•no tensile failure
•cell fracture



•LS-DYNA
•Lagrangian
•pressure loading
•no tensile failure
•cell fracture

Electromagnetic ring expansion experiment

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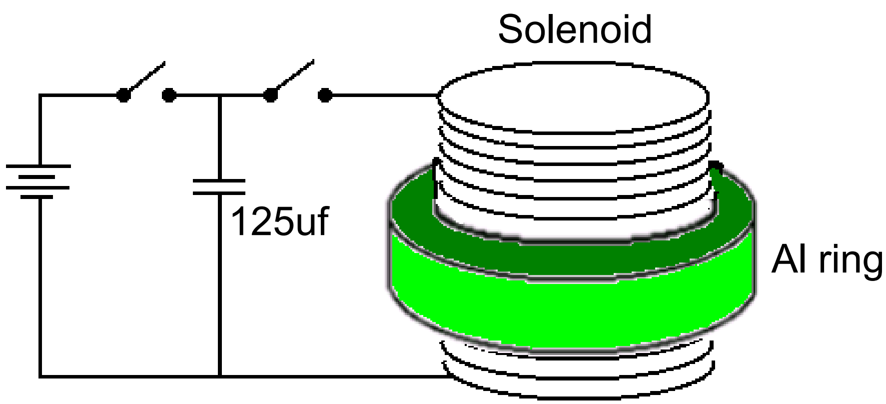
M. Altynova, X. Hu, and G. Daehn: Increased Ductility in High Velocity Electromagnetic Ring Expansion, Metall. Material Trans. A, 27A, p1837-1844, (1996)



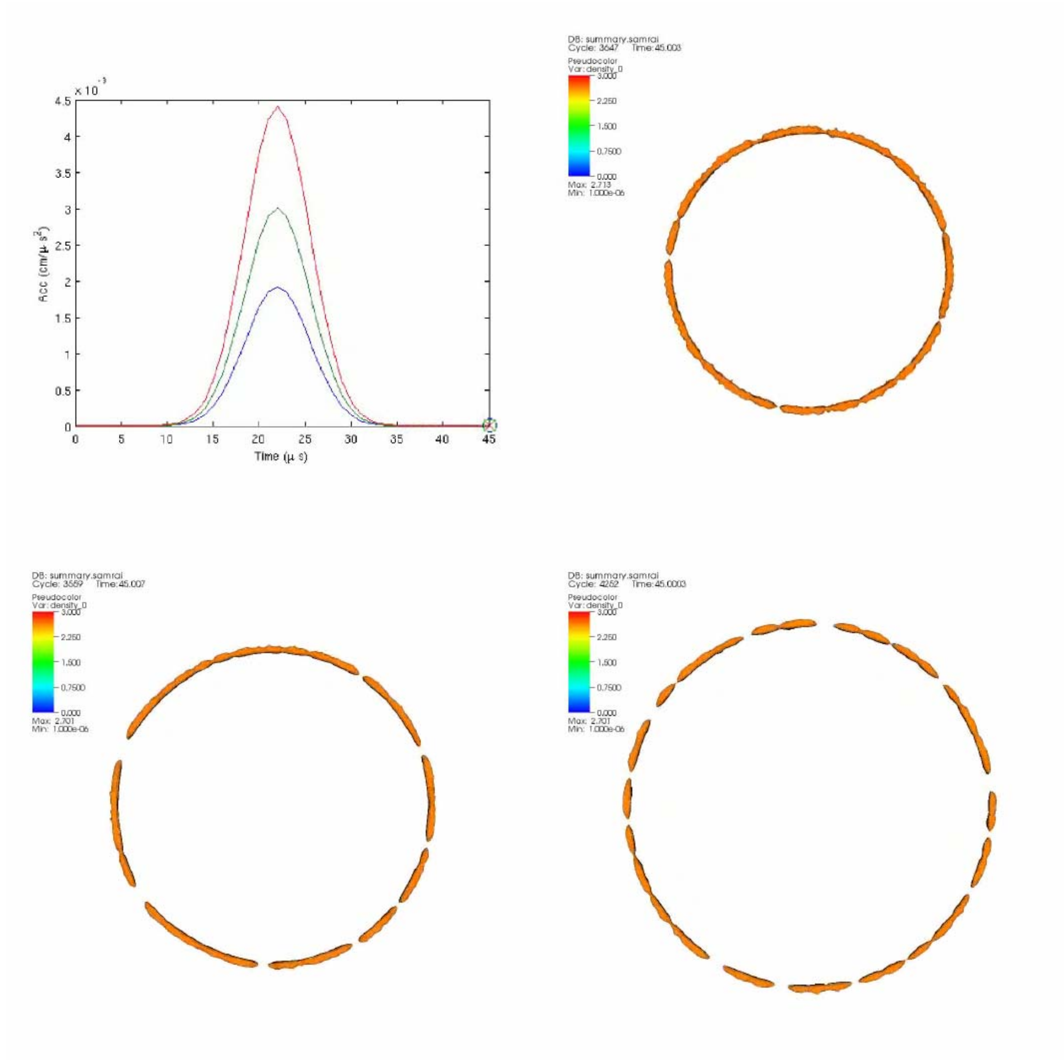
- ~15mm radius 1x1mm cross-section rings
- 0.94-3.12kJ is discharged in the solenoid
- Magnetic field induces current in the ring
- Current heats the ring and forces it outward
- Heating and expansion depend on total energy
- Fragments are collected and counted

For our simulations:

- Ring was modeled with 5x5 elements in the cross-section and 600 elements around
- Initial temperature of the ring was set to account for resistive heating
- A Gaussian pulse (11.75us FWHM) of body force was used to provide acceleration
- ~6000 time steps were taken to reach a final time of 45us
- Fragments were counted at the final time

P. Wang, An ALE Formulation with AMR for material modeling, Conference: Numerical methods for multi-material fluid flows, 5th-8th September 2005, St. Catherine's College, Oxford (invited talk)

Electromagnetic ring expansion simulations



Electromagnetic ring expansion validation results

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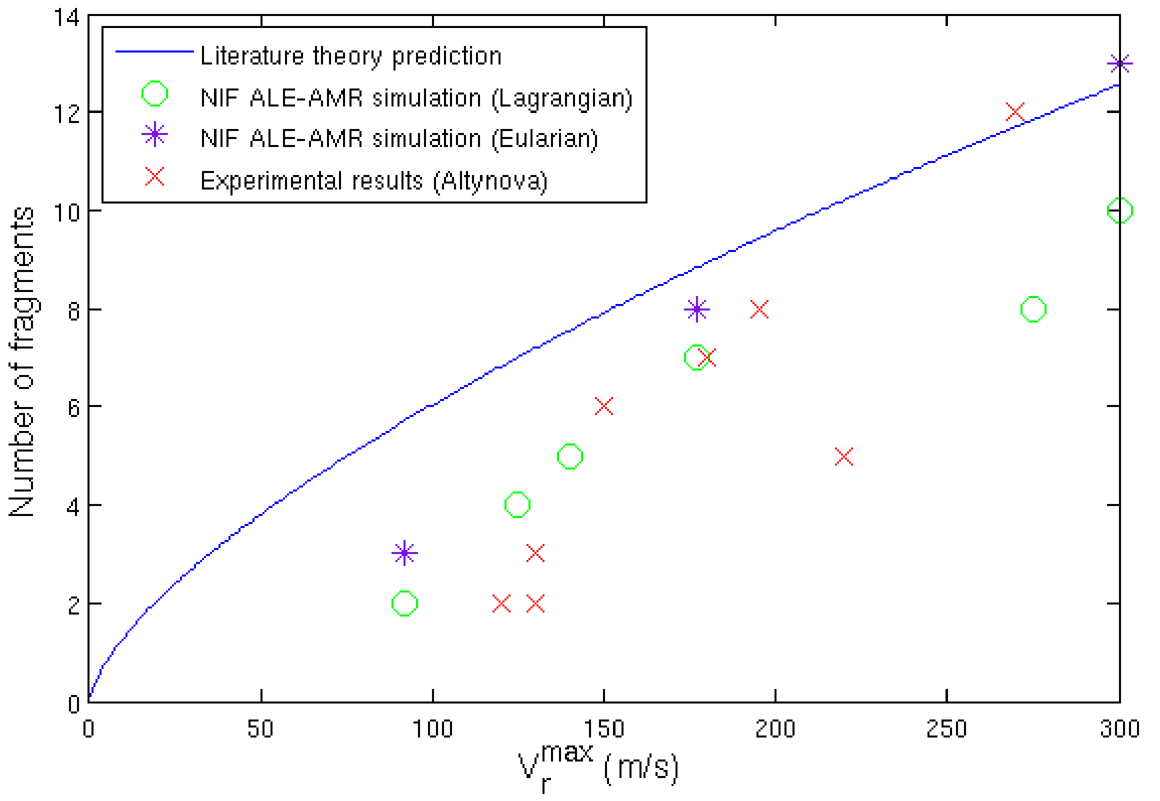
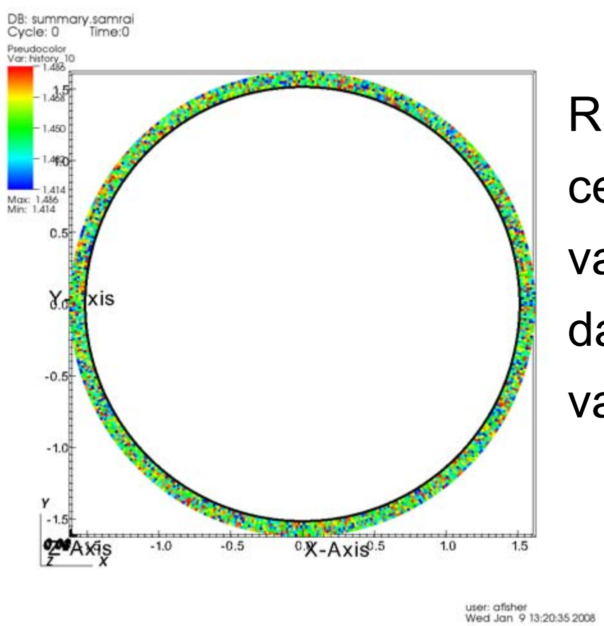


NIF ALE-AMR simulations are a good match to experimental data

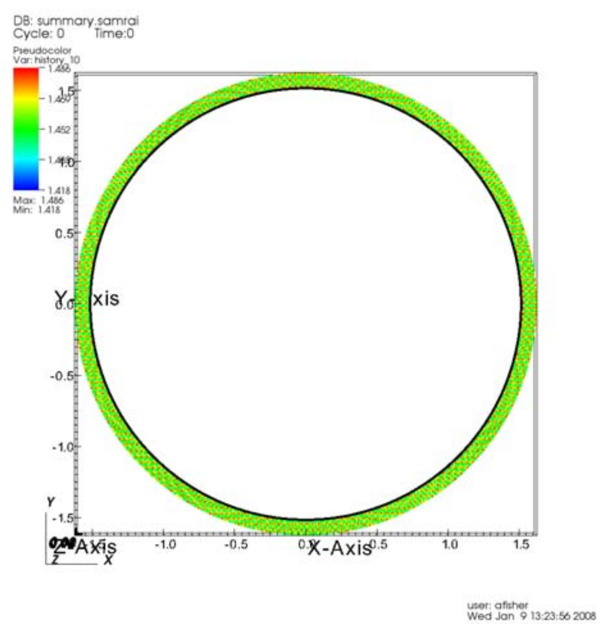
Fragmentation refinement study

- Continuum solid mechanics simulations have known issues with refinement studies
- As the mesh is refined strain is localized into smaller places causing fracture earlier

Rich Becker's "seeding" approach was used to provide some mesh independent structure



Random 5% cell to cell variation of damage variable



5% peak to peak sine variation of damage variable

Seeding with mesh independent structure enables convergence in fragment count

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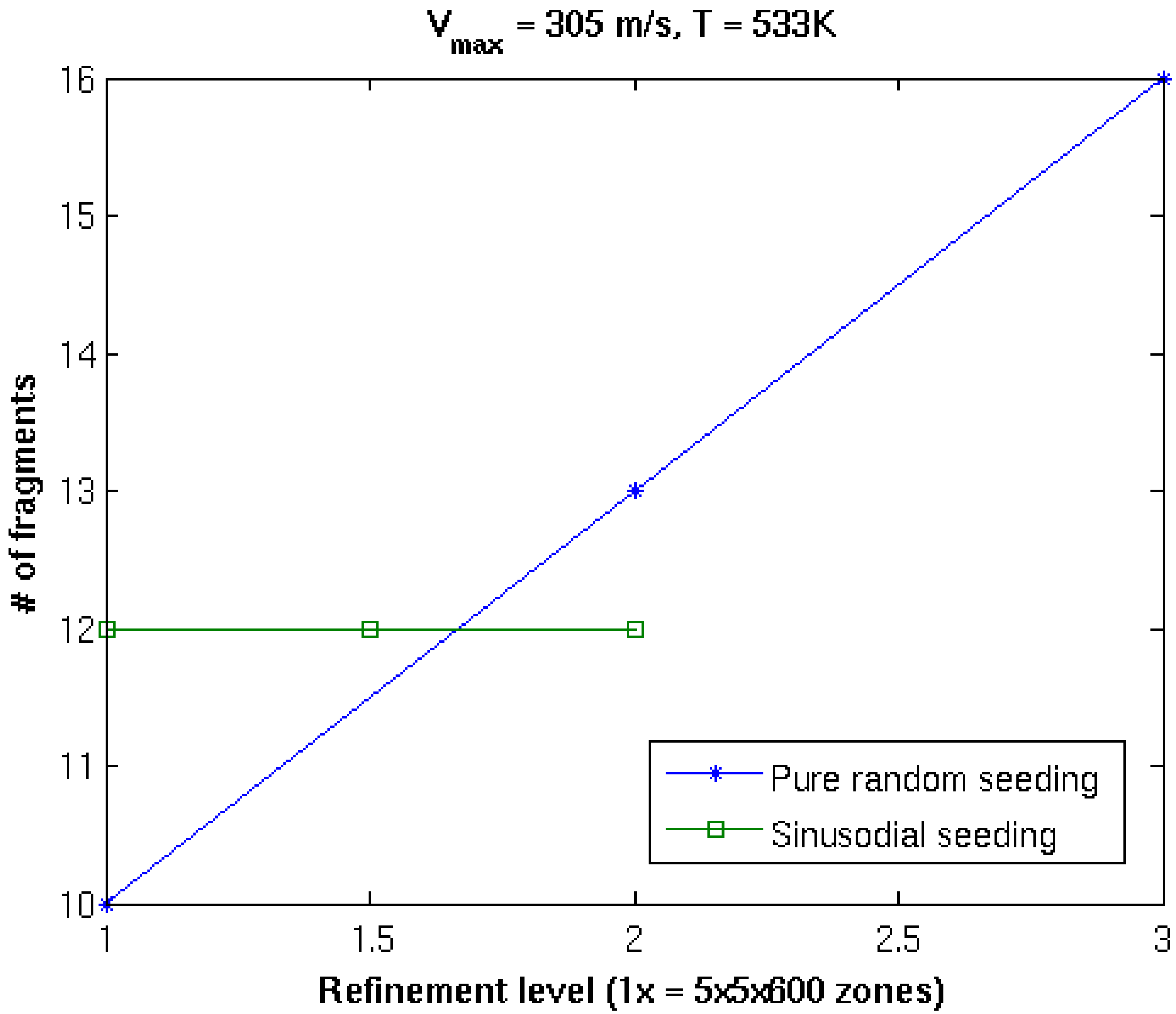

Simulations of recent laser spallation experiments are in progress

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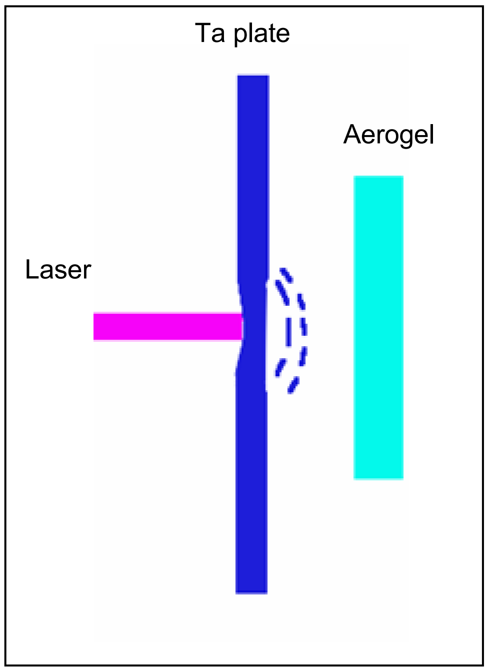
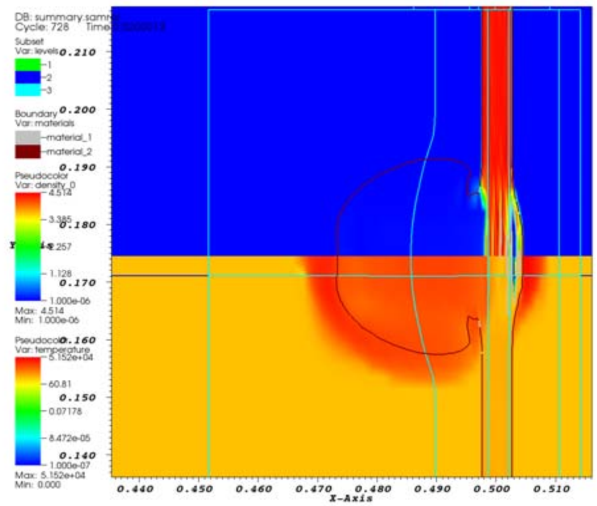
Thinplate Experiment



Aerogel sample

Initial Simulations



Laser experiments by:
Maddox, Kalantar, Eder, Koniges, Remington, Meyers*, Tobin, Andrew*

Fragmentation Results

Re-emit shrapnel study

2D Re-emit simulation @ 30J/cm^2

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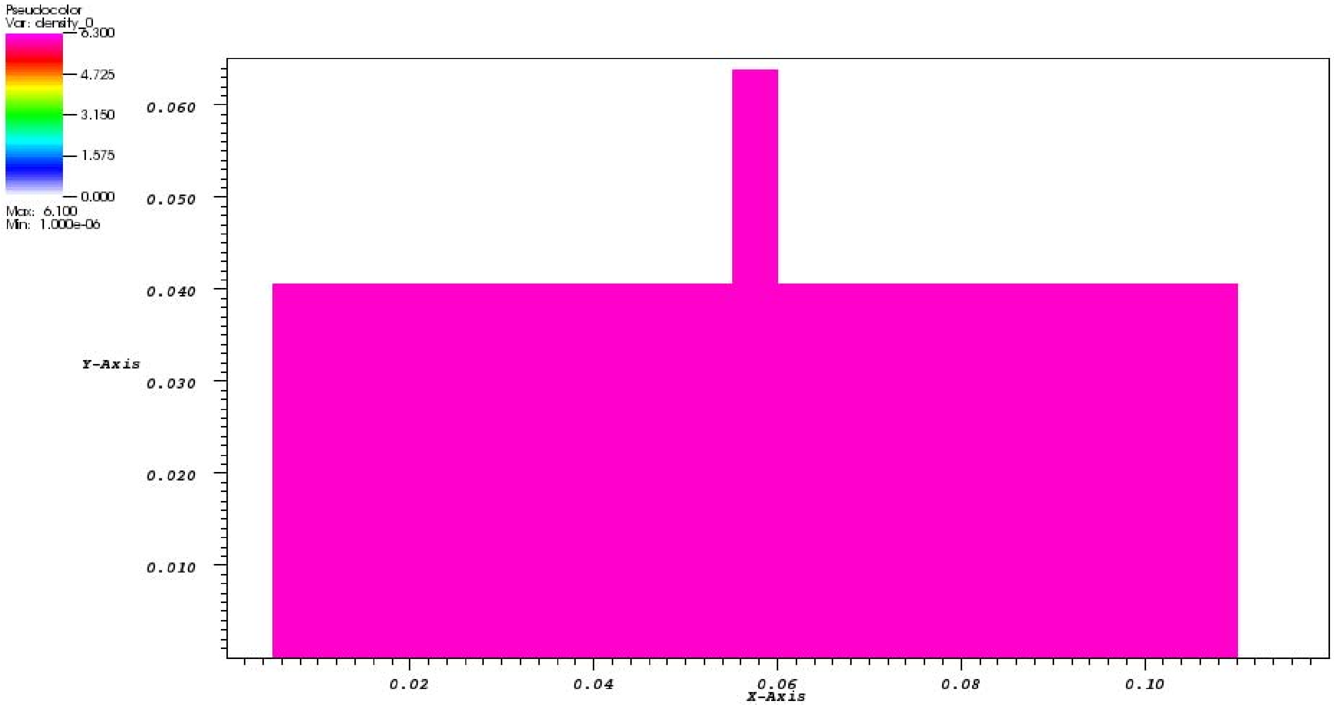
- 2D Vanadium pinhole configuration
- Vanadium modeled by Preston-Tonks-Wallace model from MS
- EOS provided by LEOS tables
- Energy fluxed into the rightmost cells of 5ns (no radiation diffusion)



2D Re-emit simulation @ 400J/cm^2

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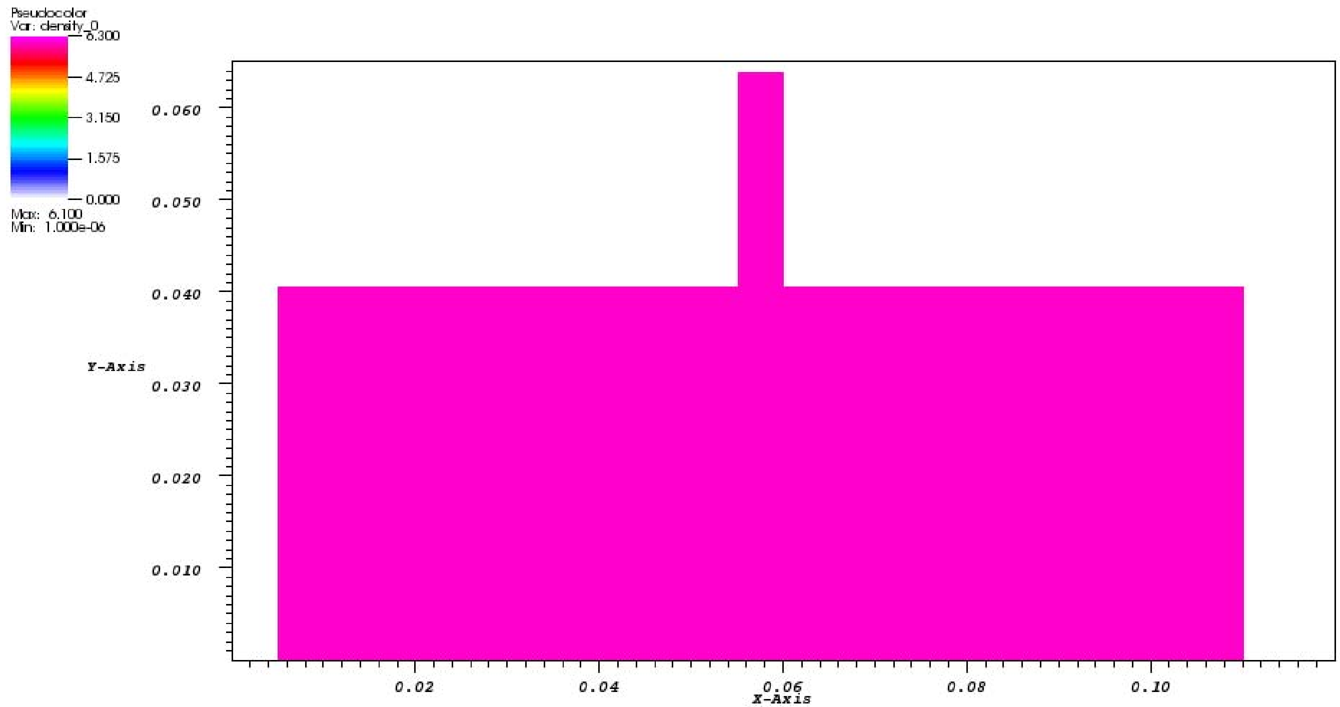

Multi-Scale Strength Modeling (in progress)

We introduce polycrystal structure with the Voronoi Tessellation Method

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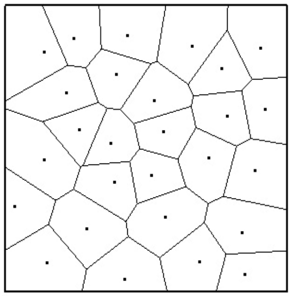
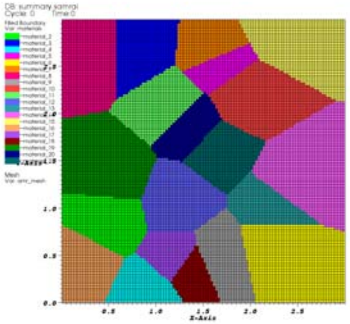
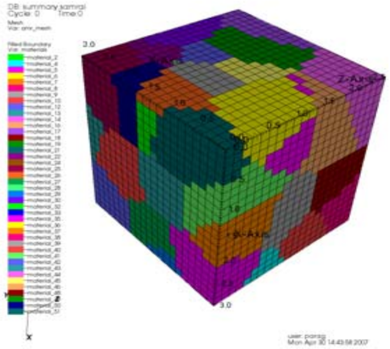
- **A Voronoi diagram decomposes a metric space based on distances from a specified discrete set of points.**
- **Polycrystals are set up at the finest scale of refinement.**
- **Large domains can be tiled with a relatively small number of Voronoi cells**



Voronoi Diagram



A 2-D Voronoi structure with 20 crystals



A 3-D Voronoi structure with 50 crystals

Multi-Material HMM framework for ALE-AMR

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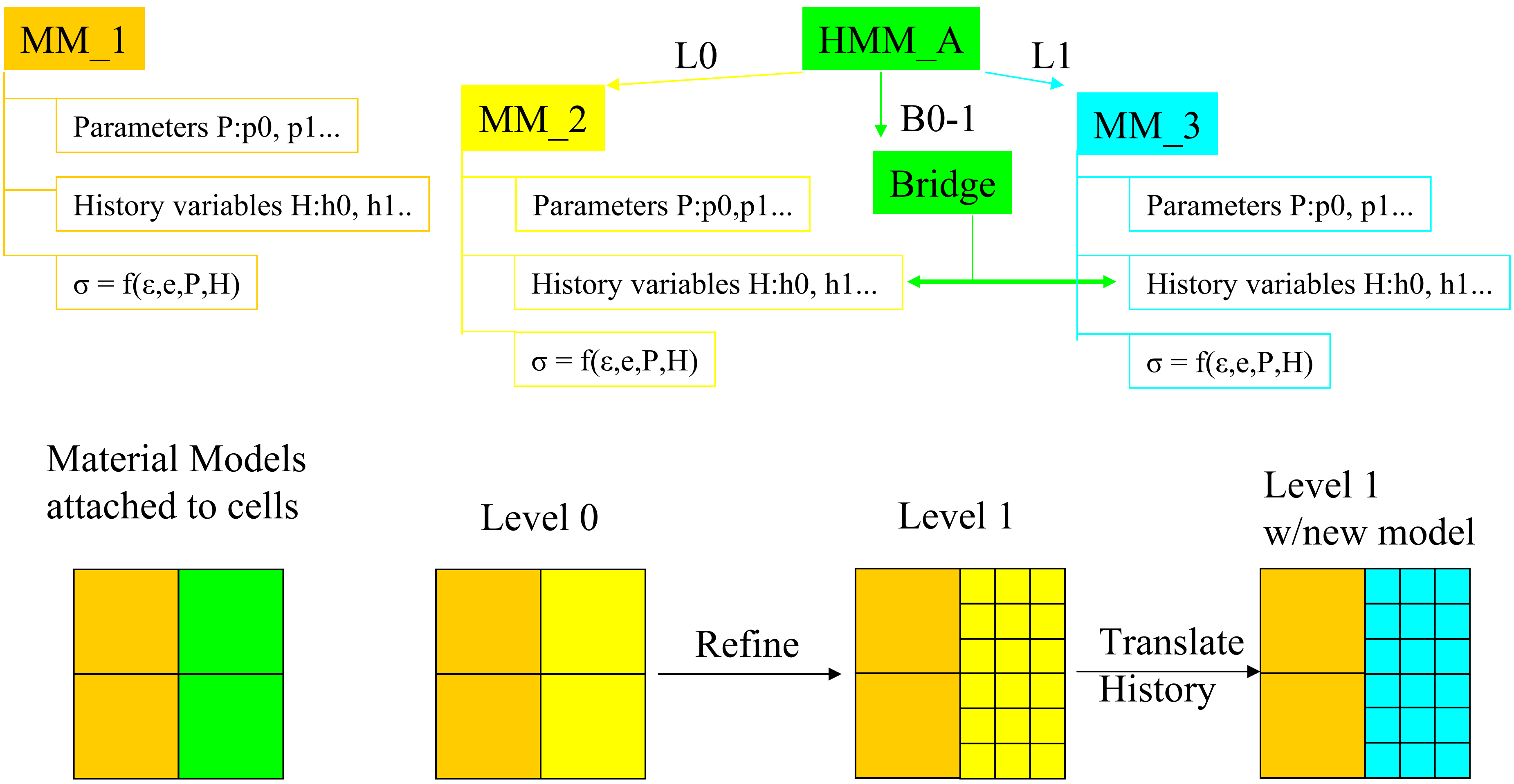

Conclusions and future work

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- **A flexible framework for material strength has been implemented**
- **Through the framework many LLNL models have been hooked in**
- **A new fragmentation model has been implemented**
- **Initial validation results are promising**
- **The code has been used in a variety of fragmentation simulations**
- **Future work includes crystal grain modeling and HMM**