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Summary of Two Applications of ALEGRA:

CN-III Flux Compression Generator
and
Pegasus Stabilized Liner

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National Nuclear Security Administration

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ALEGRA Simulations of the CN-III Flux Compression Generator

- **Simulations are part of a feasibility study for a Fragment-Producing Chemical-Electrical Laucher (FP-CEL).**
- **This is a Work-for-Others project for Washington State University.**
- **The purpose is to investigate the use of explosively driven magnetic loading techniques to launch controlled fragments is a predictable manner.**
- **The first phase established the feasibility of the concept.**
- **The second (and present) phase is to determine the actual efficiency of such a concept.**

FP-CEL Feasibility Study

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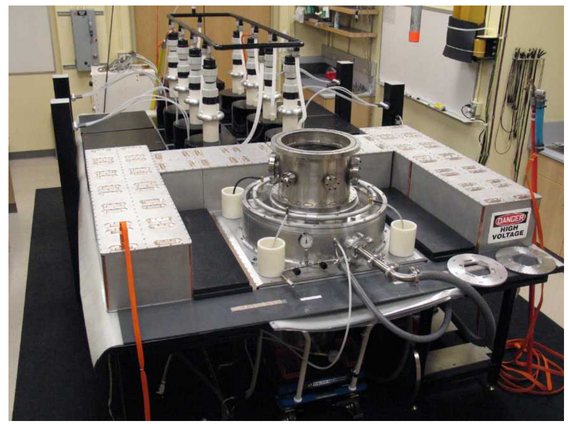
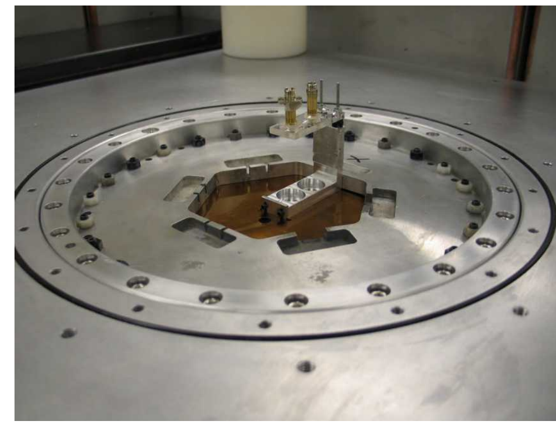
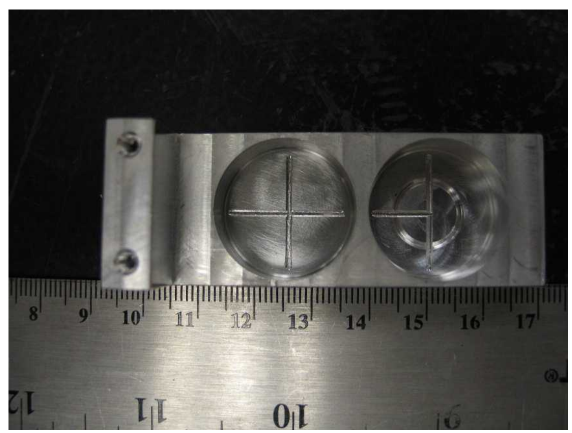
Consisted of:

- Experiments on 3 MA WSU pulser
- Al flyer plates
- Composite flyer plates (Al backed with Lexan)
- Scored flyer plates with various patterns
- 3D and 1D ALEGRA simulations
- Scaling study to 90 MA
- Results were presented at the PPPS 2007 conference in June.







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Comparison of Currents on WSU Pulser

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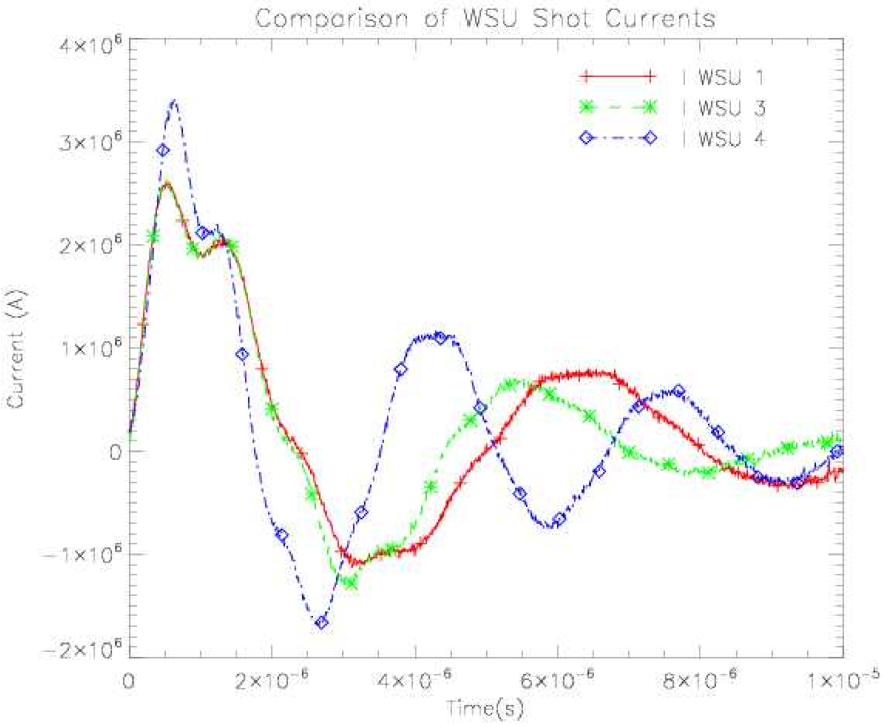

- Simulations based on data from 3 WSU shots
  - WSU shot #1
  - WSU shot #3
  - WSU shot #4
- 2.5 to 3.5 MA total current
- 3.0 to 4.0 μs total period
- 0.7 to 1.0 mm thick Al flyers

Physics Models in ALEGRA - a 3D/2D Radiation Magneto-Hydrodyanmics code

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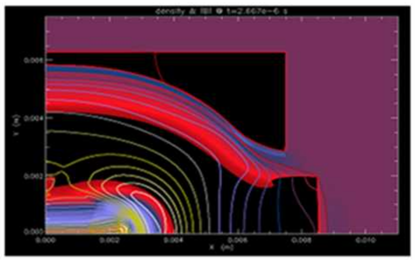

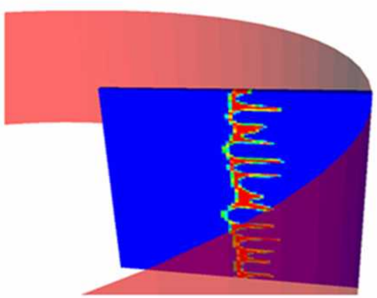

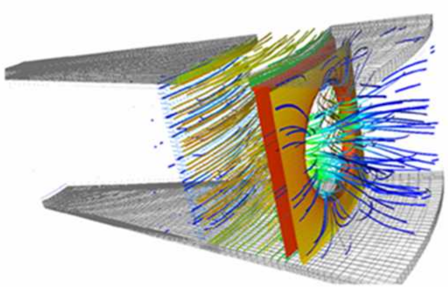

- 2D (RZ & XY) and 3D (XYZ)
- Unstructured Finite-Element Based
- Eulerian/Lagrangian/ALE
- Object Oriented
- Massively Parallel
- Multi-Material
- Coupled Physics
  - Hydrodynamics
  - Magnetics
  - Thermal Conduction
  - Radiation (Multi-Group Diffusion & IMC)
- Material Models
  - LANL Sesame & other EOS
  - Lee-More-Desjarlais (LMD) Conductivity
  - XSN & Propaceos Opacities

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The HEDP Equations

Hydrodynamics

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0$$

$$\rho\left(\frac{\partial \vec{V}}{\partial t} + \left(\vec{V} \cdot \nabla\right)\vec{V}\right) = -\nabla \cdot \tilde{T} + \left[\rho_q \vec{E}\right] + \vec{J} \times \vec{B}$$

$$\rho\left(\frac{\partial e}{\partial t} + \left(\vec{V} \cdot \nabla\right)e\right) = -\tilde{T} : \nabla \vec{V} + \eta\left(\vec{J} \cdot \vec{J}\right) - \nabla \cdot \vec{Q} - \int \kappa\left(4\pi B_\nu - cE_\nu\right) d\nu$$

Magnetics

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{H} = \vec{J} + \left[\frac{\partial \vec{D}}{\partial t}\right]$$

$$\nabla \cdot \vec{B} = 0$$

$$\left[\nabla \cdot \vec{D} = \rho_q\right]$$

$$\eta \vec{J} = \vec{E} + \vec{V} \times \vec{B}$$

$$\vec{B} = \mu \vec{H} \qquad \left[\vec{D} = \varepsilon \vec{E}\right]$$

Conduction

$$\vec{Q} = -k \nabla T$$

$$\rho C_V \frac{\partial T}{\partial t} = \nabla \cdot (\vec{Q}) = -\nabla \cdot (k \nabla T)$$

Radiation

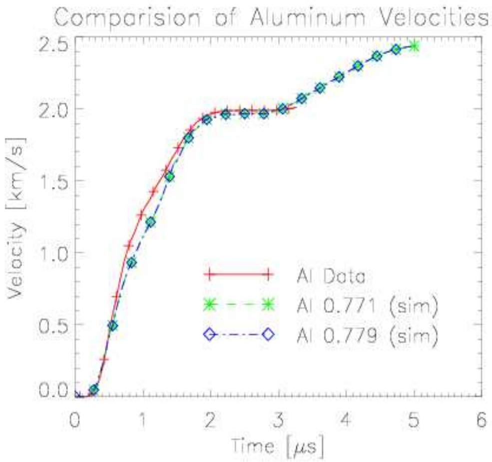
$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} = -\hat{n} \cdot \nabla I_\nu + \kappa\left(B_\nu - I_\nu\right)$$

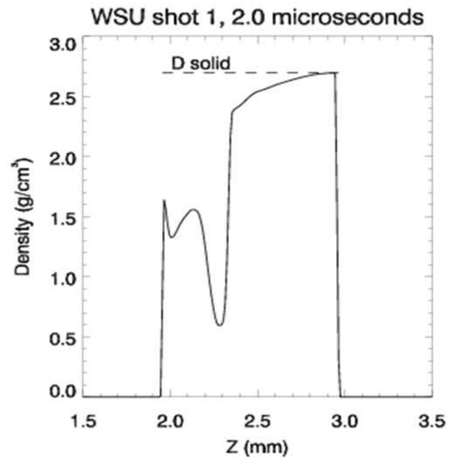
$$cE_\nu = \int_{4\pi} I_\nu \, d\Omega$$

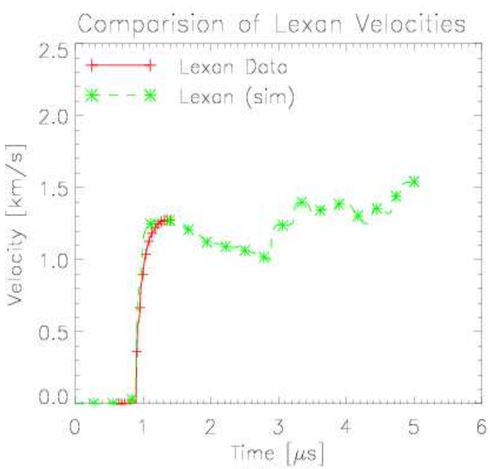
ALEGRA Material Models

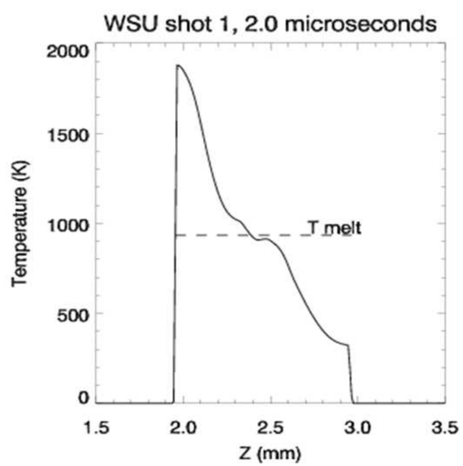
- Equation of State
  - Tabular EOS
    - Kerley Sesame
    - LANL Sesame
  - Mie-Gruneisen EOS
  - Us-Up EOS
- Strength
  - Steinberg-Guinan-Lund
  - Elastic-Plastic
- Fracture
  - Pressure Dependent
- Electrical/Thermal Conductivity
  - LMD
  - Spitzer
- Opacity
  - XSN
  - PrOpacEos
  - Planck & Rosseland

1D Simulation of WSU shot #1









- Flyers
  - Al only
    - 0.771 or 0.779 mm thick
  - Al and Lexan
    - 0.771 and 1.532 mm thick
- Scaled B field at gap
  - 0.75 times nominal value
- Peak current
  - 2.6 MA
- Corresponding velocity
  - 2.0 km/s
- About 12% of Al flyer solid
- About 25% of Al flyer melted
- About 63% in between

1D Simulation of WSU shot #3

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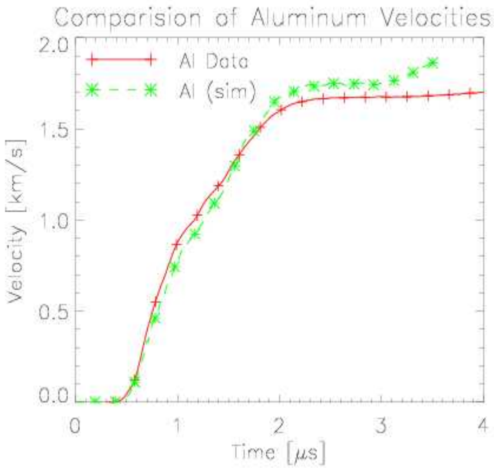

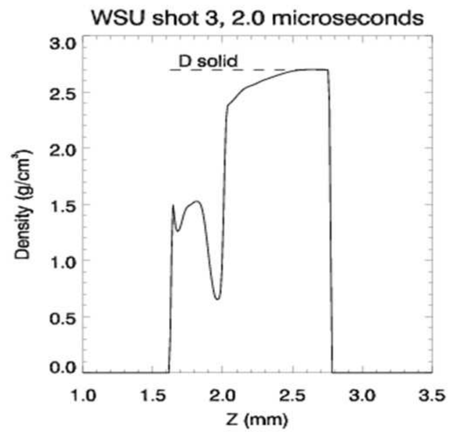

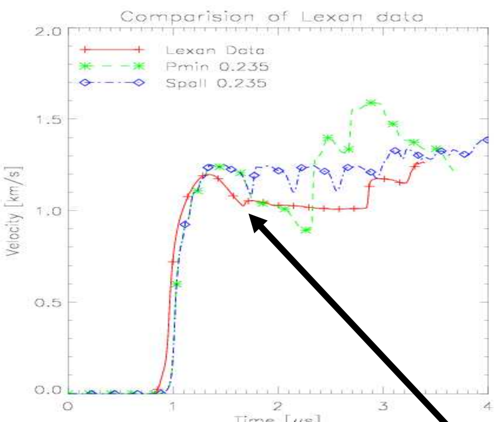

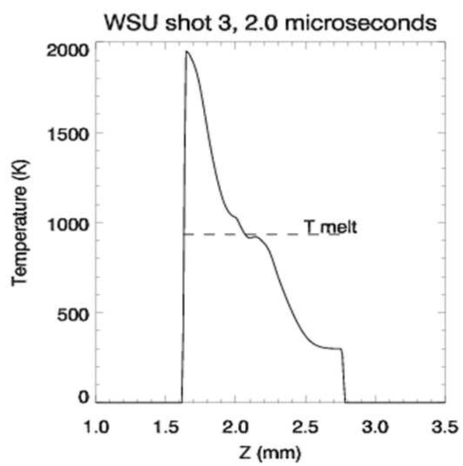

- **Flyers**
  - **Al**
    - **0.919 mm thick**
  - **Al and Lexan**
    - **0.923 and 0.944 mm thick**
- **Scaled B field at gap**
  - **0.75 times nominal value**
- **Peak current**
  - **2.6 MA**
- **Corresponding velocity**
  - **1.7 km/s**
- **About 25% of Al flyer solid**
- **About 25% of Al flyer melted**
- **About 50% in between**

- **Pullback in Lexan data**
  - $\rho_0 = 1.196$ g/cm^3
  - $C_l = 2.18$ km/s
  - $\Delta V = 0.18$ km/s

$$P_{spall} = -0.5 \cdot \rho_0 \cdot C_l \cdot \Delta V = -0.235 \quad kbar$$

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1D Simulation of WSU shot #4

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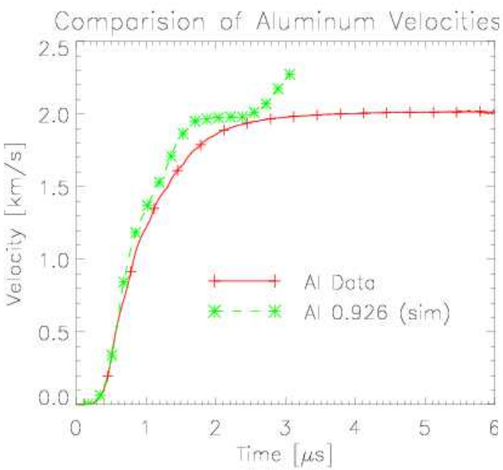

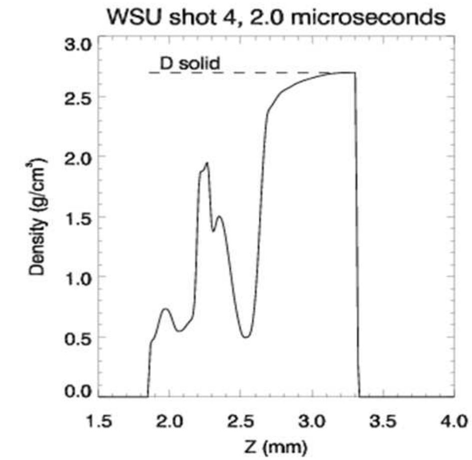

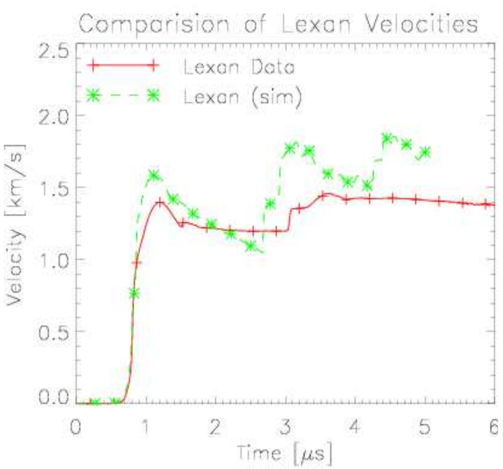

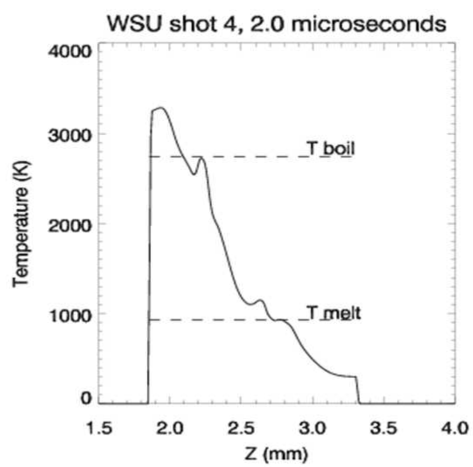

- Flyers
  - Al
    - 0.926 mm thick
  - Al and Lexan
    - 0.920 and 0.946 mm thick
- Scaled B field at gap
  - 0.75 times nominal value
- Peak current
  - 3.4 MA
- Corresponding velocity
  - 2.0 km/s
- About 25% of Al flyer solid
- About 33% of Al flyer melted
- About 42% is in between

- Pullback in Lexan data
  - P_{min} model used

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Scaling to 90 MA

- The magnetic field scales according to:

$$B = f\,\frac{\mu_0 I}{w}$$

- The magnetic force per area acting upon the panel is:

$$\frac{F}{A} = \frac{B^2}{2\mu_0} = f^2\,\frac{\mu_0 I^2}{2w^2}$$

- Applying Newton's Law, we have:

$$F = \rho A d\,\frac{V_{scaled}}{\tau}$$

- Combining these expressions, the velocity could scale according to:

$$V_{scaled} = \frac{1}{2} f^2\,\frac{\mu_0 I^2}{w^2}\,\frac{\tau}{\rho d}$$

- Averaging over a half-period results in an additional factor of ½:

$$V_{scaled} = \frac{1}{4} f^2\,\frac{\mu_0 I^2}{w^2}\,\frac{\tau}{\rho d}$$

Scaling Study to 90 MA

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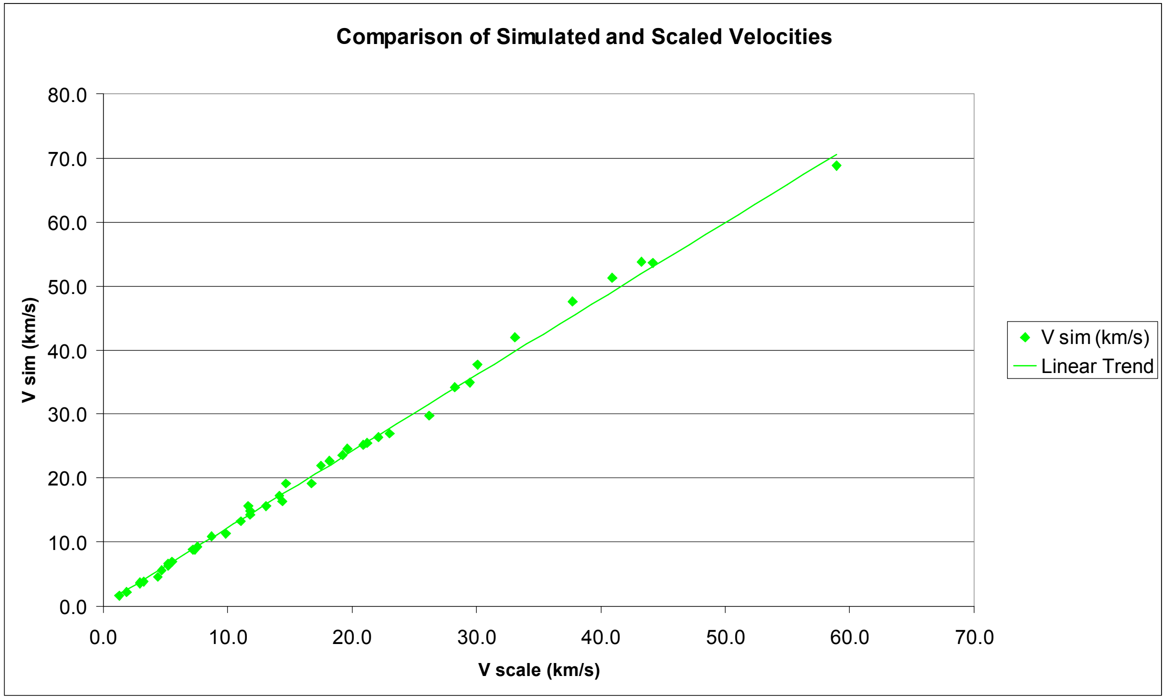


- **The scaled and simulated velocities are proportional, indicating the scaling formula is valid for the range of parameters chosen.**

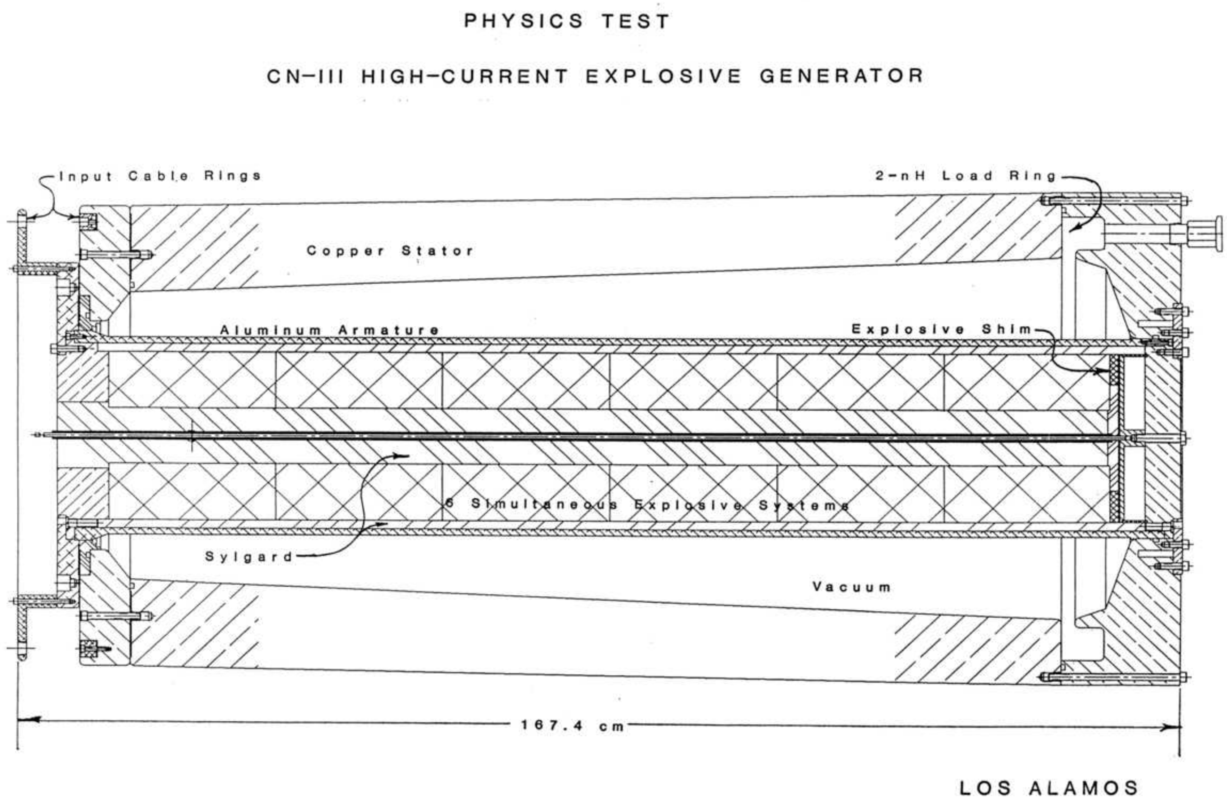
At this stage of the project we can make a number reasonable conclusions regarding overall feasibility.

- **Small-scale experiments demonstrate the feasibility of magnetically launching and fragmenting flyers in a controlled and predictable manner.**
- **Fully coupled, multi-dimensional, magneto-hydrodynamic calculations help to guide the experiments, and demonstrate the capabilities of numerical modeling for simulating the relevant phenomena, both at small scale, and potentially at full scale.**
- **Preliminary estimates of overall energy-scaling efficiencies suggest the an FP-CEL system is comparable with other advanced concepts that are under active investigation else where.**
- **The consensus seems to be that coaxial FCGs (for efficiency and Δt requirements) will be the best choice for FP-CEL systems. The most significant issues are:**
  - **pulse conditioning for FP-CEL applications**
  - **generation of the appropriate seed current.**

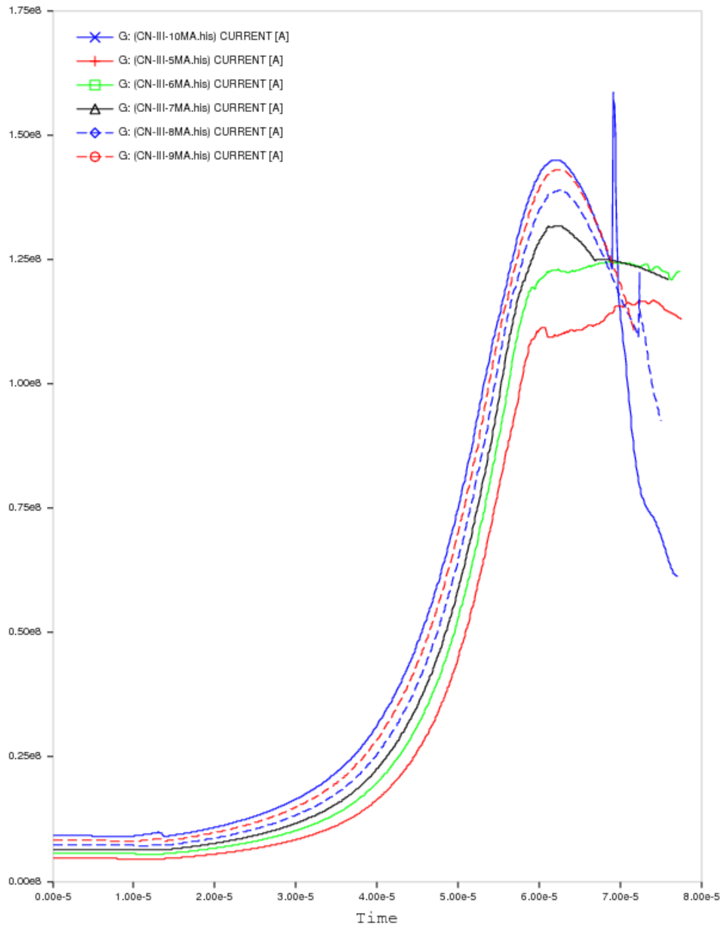
Future Goals of a Comprehensive Efficiency Study

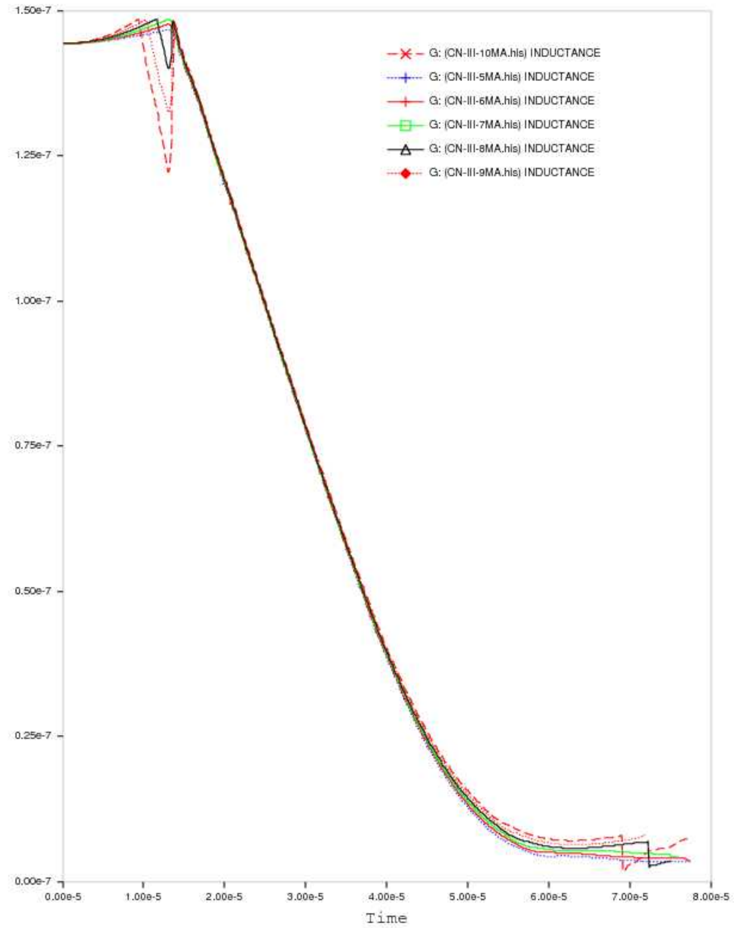
- Model Ranchero or other FCG with ALEGRA
  - Benchmark code against existing data
- Develop FCG model consistent with load
  - Determine efficiency
    - Output magnetic energy / input chemical energy
    - Output load current / input seed current
    - Compare to non-FCG systems
- Develop prototype FP-CEL load
  - Power using current from Ranchero generator
  - Ensure launched fragments meet requirements
  - Determine efficiency
    - Fragment kinetic energy / input magnetic energy
    - Compare to non-FCG systems
- Consider merits of other FCG configurations
  - Disk explosive magnetic generator (DEMG)
  - Compare to efficiency for Ranchero

Preliminary results of CN-III simulations

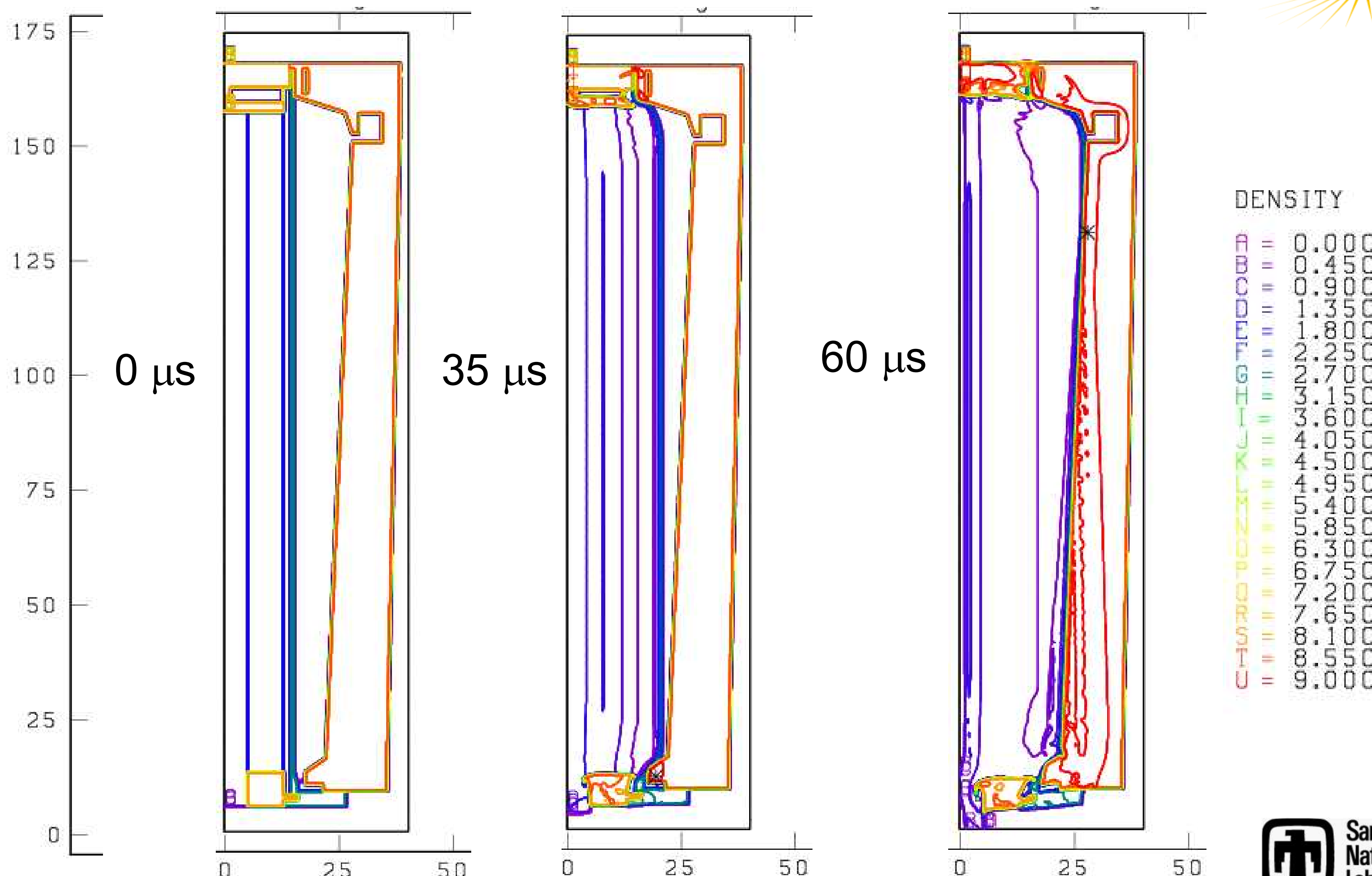


Current and Inductance changes of CN-III





Evolution of CN-III Density Contours



ALEGRA Simulations of the Pegasus Stabilized Liner Implosion

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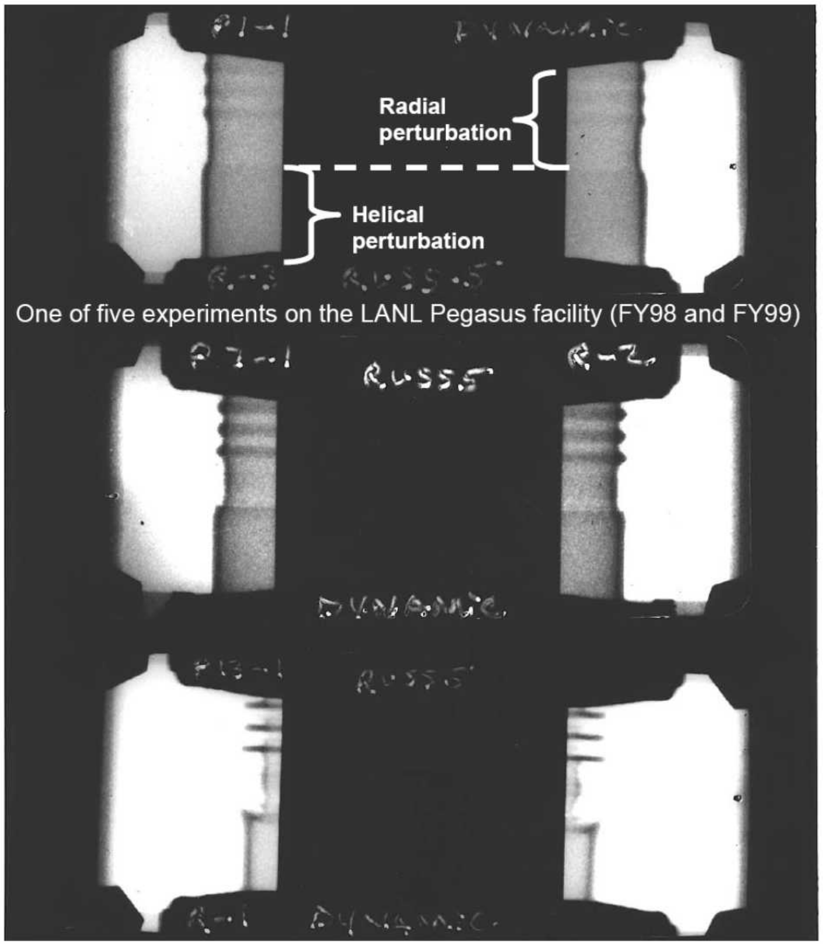
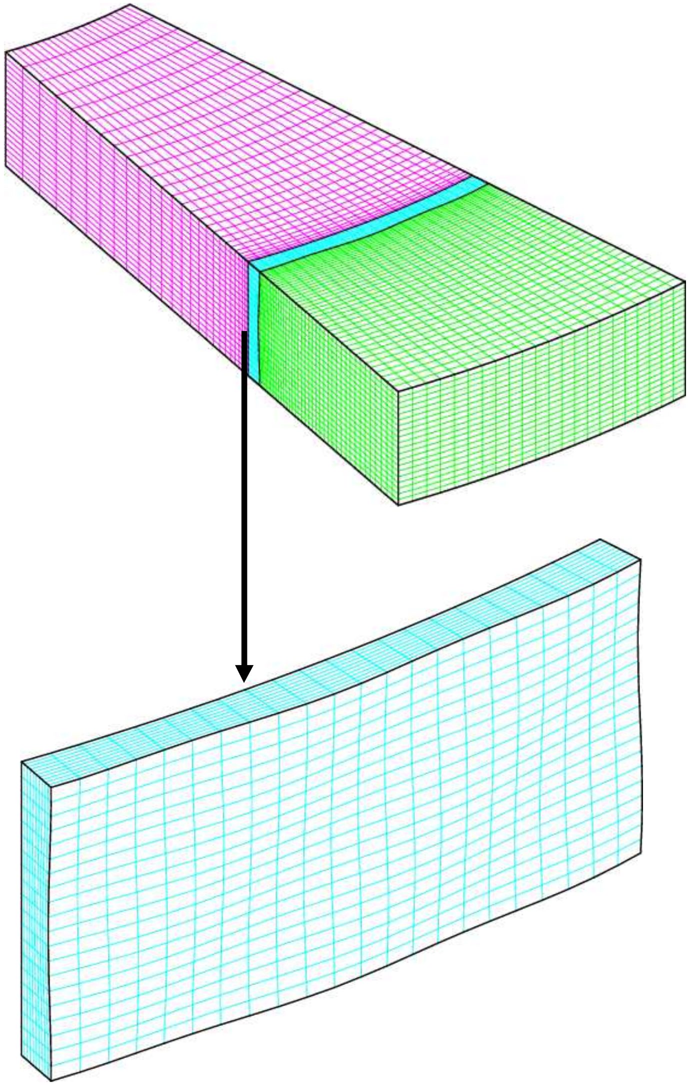


Courtesy of R. Reinovsky, LANL

- **Joint LANL-VNIIEF liner implosions on Pegasus demonstrated helical perturbation supression of RT instability.**
- **Two perturbations were machined into a common sample, with a nearly uniform section inbetween.**
- **Radiographs showed the growth of the parallel (azimuthally symmetric) perturbation, but showed no discernable growth for the imposed helical perturbation.**
- **Reference:**
  - **E.G. Harris, Phys. Fluids, v. 5, no. 9, p. 1057 (1962)**

Initial and boundary conditions



- Full 360° simulation
  - Run on 24 processors
  - 1/24 of mesh shown to left
  - Periodic top to bottom
- Pertubation on outer liner surface
  - 47 mm diameter
  - 0.5 mm thick
  - λ = 2 mm wavelength
  - δ = 0.05 mm amplitude
  - α = 45° perturbation pitch
- Simulation driven by measured Pegasus current profile
- ~ 72 hours on Linux cluster

Time evolution of helical perturbation shows no significant growth

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