The CRASH Code

NIF User Group Meeting
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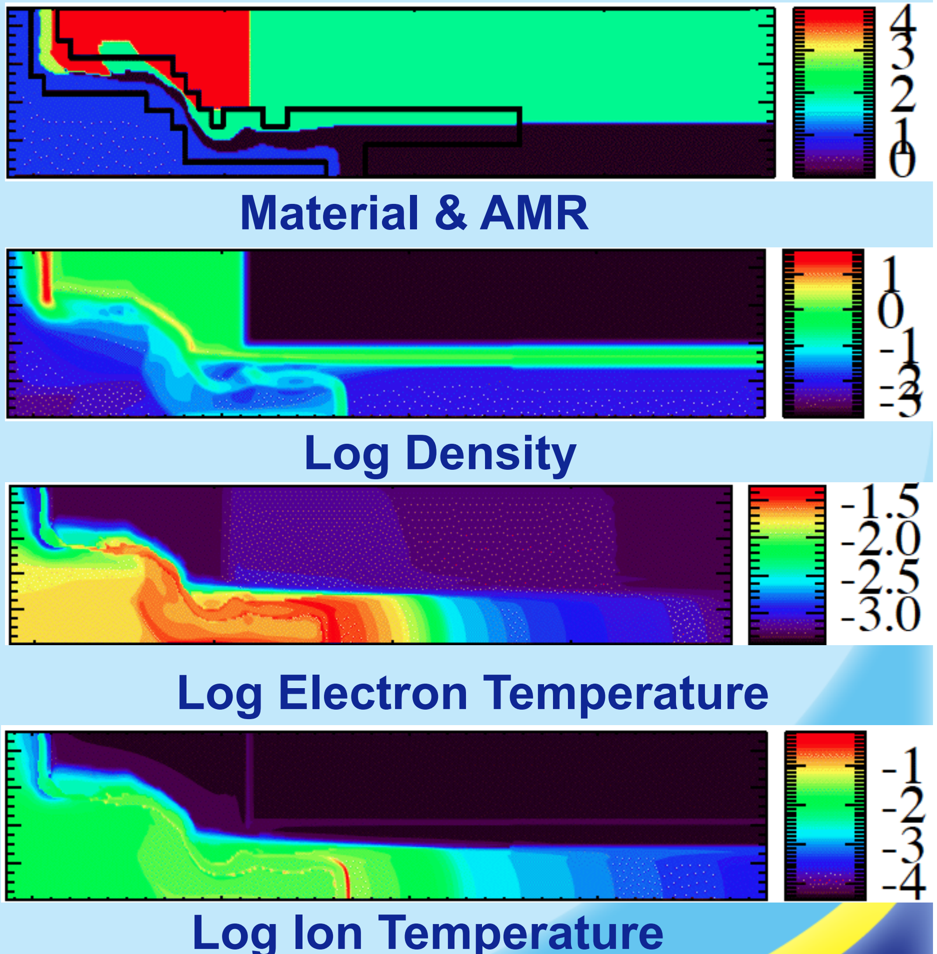
This research was supported by the DOE NNSA/ASC under the Predictive Science Academic Alliance Program by grant number DEFC52-08NA28616.

CRASH is a radiation-hydrodynamic code with a laser package

- 1D, 2D or 3D
- Dynamic adaptive AMR
- Level set interfaces
- Self-consistent EOS and opacities
- Multigroup-diffusion radiation transport
- Electron physics and flux-limited electron heat conduction
- Laser package
  - 3D ray tracing for 2D or 3D runs

3D Nozzle to Ellipse @ 13 ns



CRASH code: Van der Holst et al, Ap.J.S. 2011

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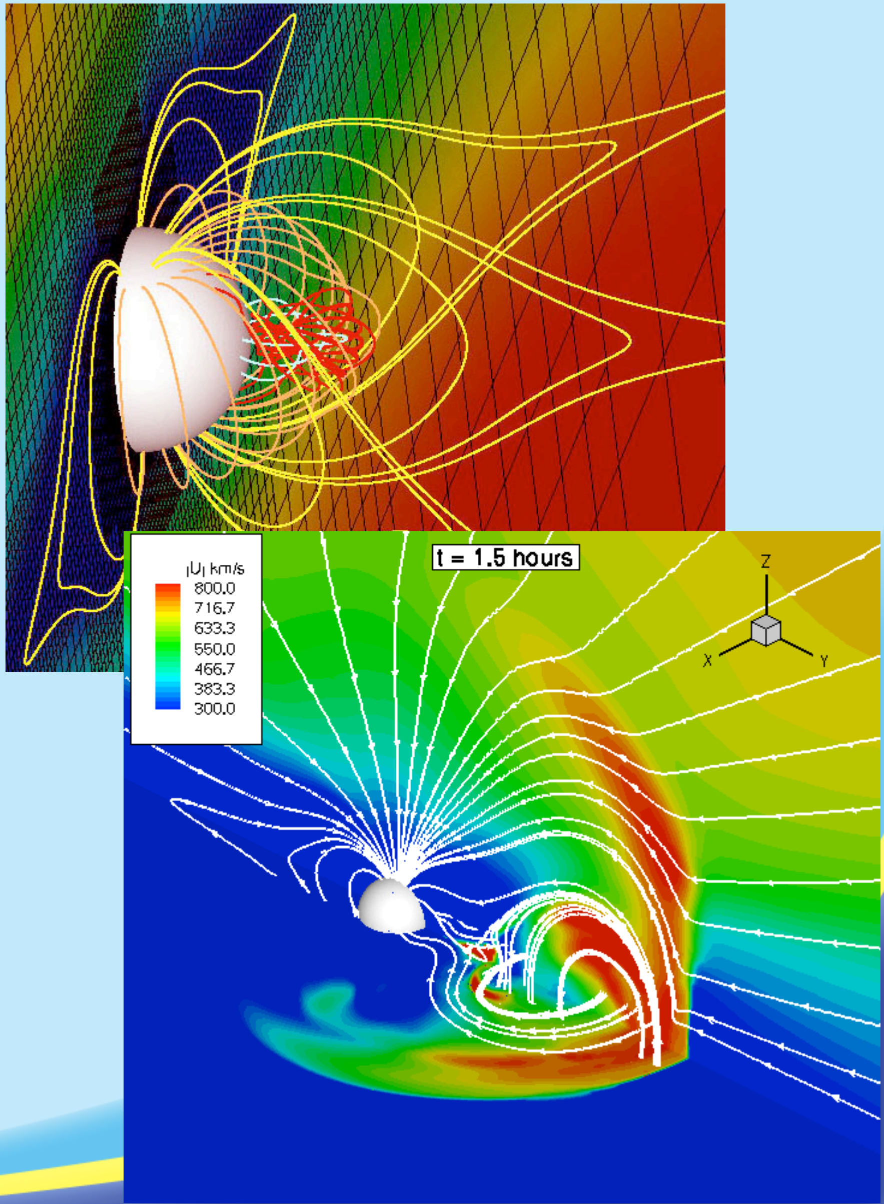
The genesis of CRASH was space-weather modeling

- We developed a practical high-resolution Godunov scheme for multi-dimensional MHD
- We built an efficient solution-adaptive parallel MHD solver (BATS-R-US)
- We tied a number of physics modules (some built on BATS-R-US) together to form the Space Weather Modeling Framework (SWMF)



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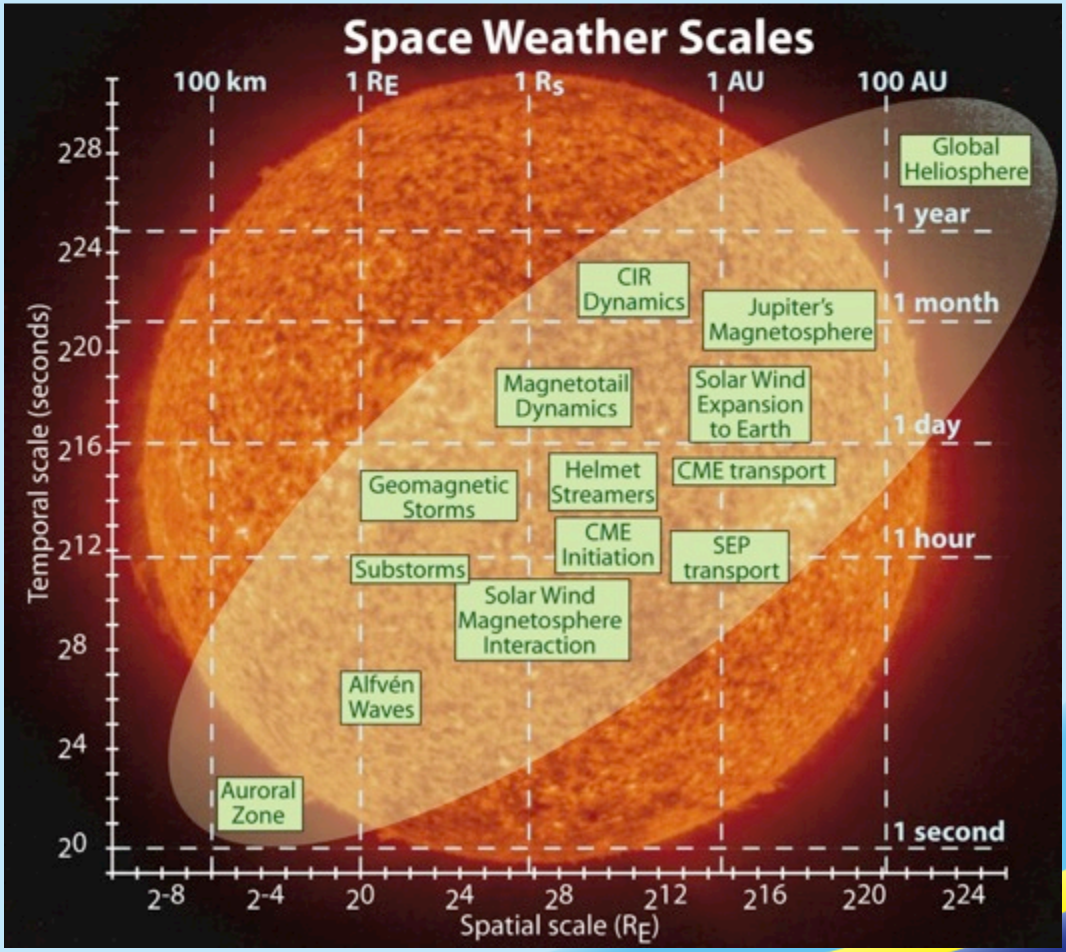
The disparate scales of space-weather drove our need for solution-adaptive parallel code

- Temporal scale range:
  - $\sim 2^{28} \approx 2.5 \times 10^8$
- Linear spatial scale range:
  - $\sim 2^{28} \approx 2.5 \times 10^8$



CSEM Talk

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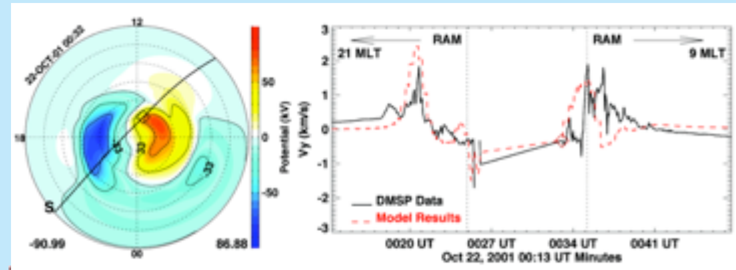
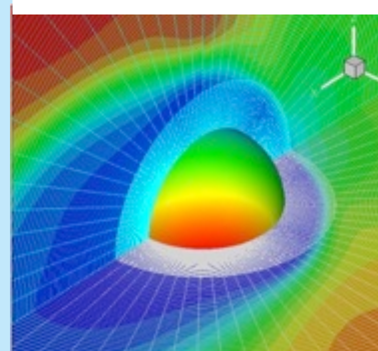
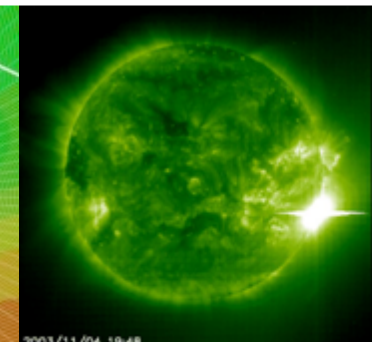
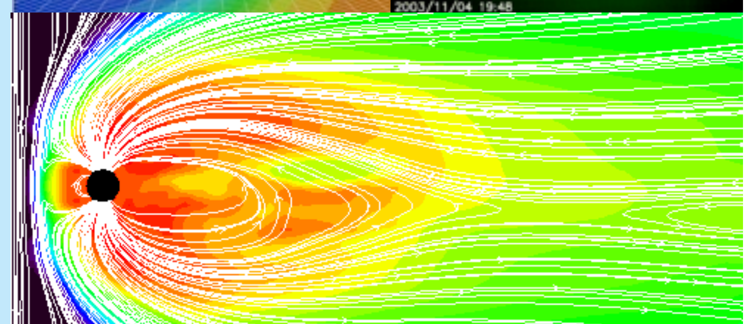
BATSRUS can model many plasma processes

- Compressible fluid dynamics
- Ideal MHD
- Resistive MHD
- Hall MHD
- Semi-relativistic MHD
- Physics-based energy transport
  - Heat conduction
  - Wave energy transport
- Multi-fluid MHD
  - Each ionic species has its own continuity, momentum and energy equation
  - Electron momentum equation is replaced by Ohm's law.









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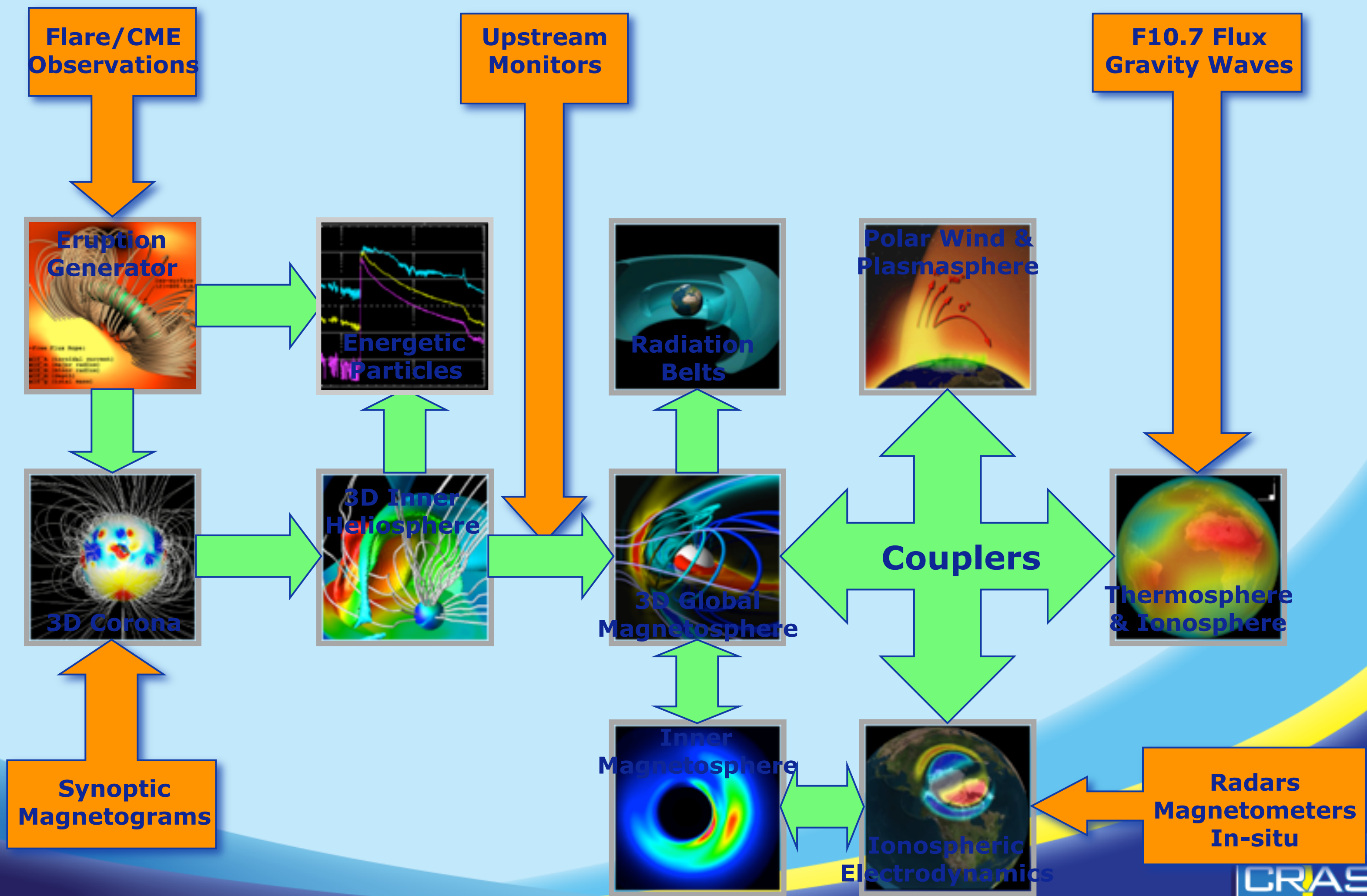
The Space-Weather Modeling Framework comprises many modules



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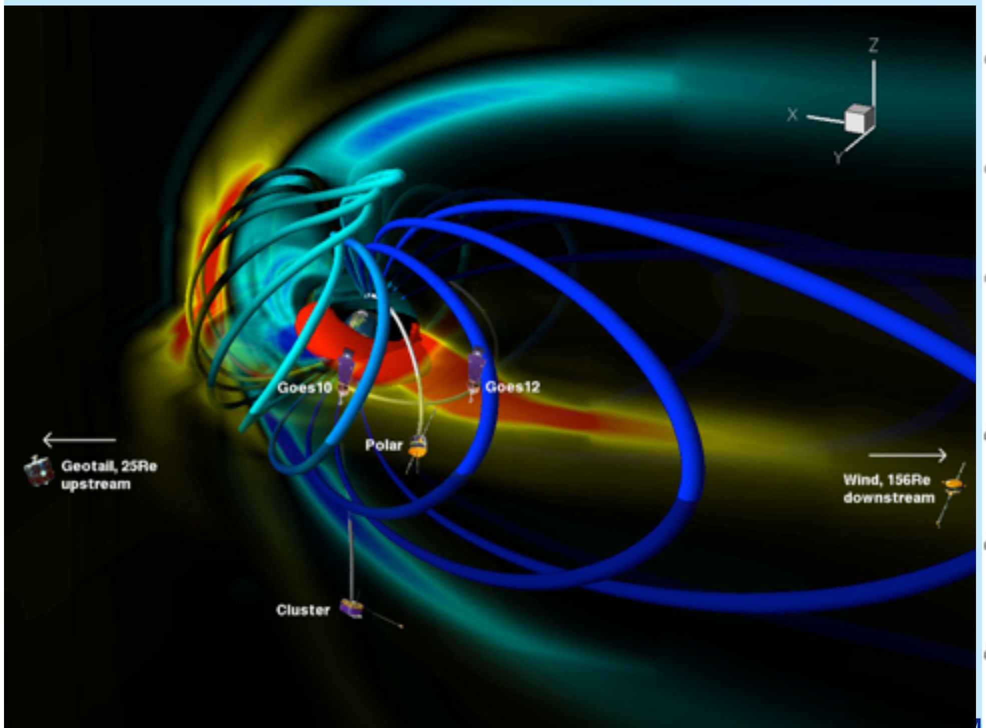
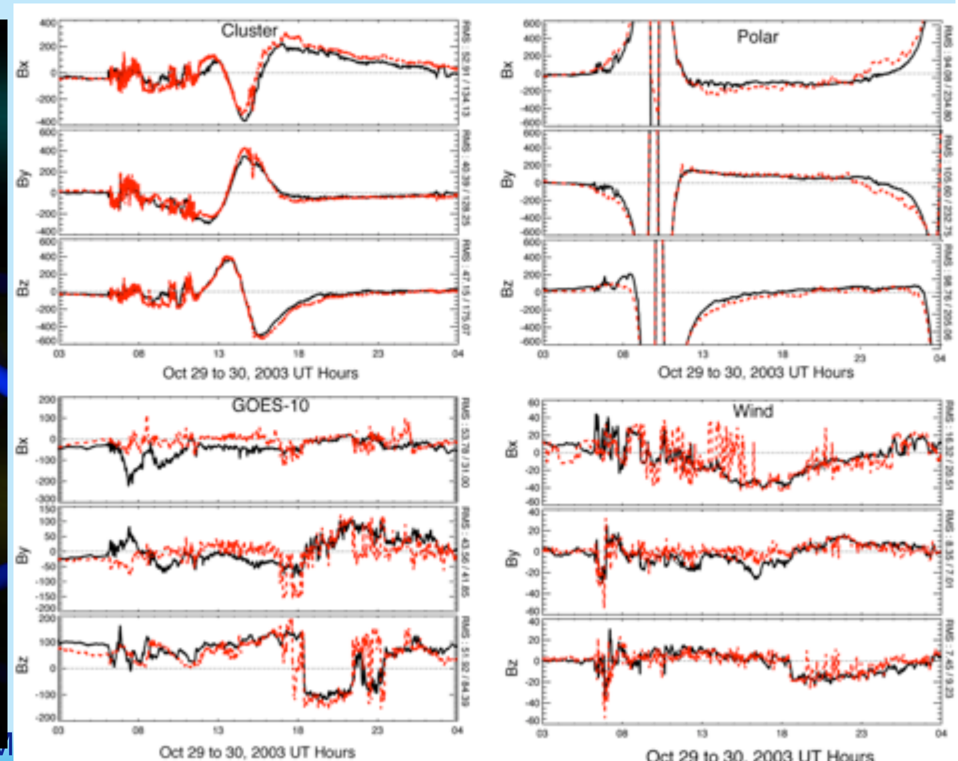
SWMF has been extensively validated

- **In late October and early November 2003 a series of some of the most powerful solar eruptions ever registered occurred.**

- **The “Halloween storm” simulation provided a unique opportunity for code/observation comparison**





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CRASH is an extension of BATS-R-US to the high-energy-density domain

- Builds on the solution-adaptive, parallel framework of BATS-R-US
- Adds new physics
  - Radiation transport
  - Electron physics and flux-limited electron heat conduction
  - Laser package
  - Tabular and self-consistent EOS and opacities
- Can tap into physics in BATS-R-US (e.g. MHD)

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We model laser energy transport using a parallel ray-tracing algorithm for AMR grids

Rays are traced by solving

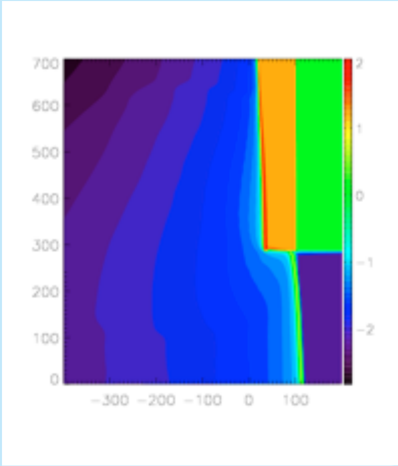
$$\frac{d\mathbf{r}^2}{ds^2} = \frac{d\mathbf{r}}{ds} \times \left(\frac{\nabla n}{n} \times \frac{d\mathbf{r}}{ds} \right)$$

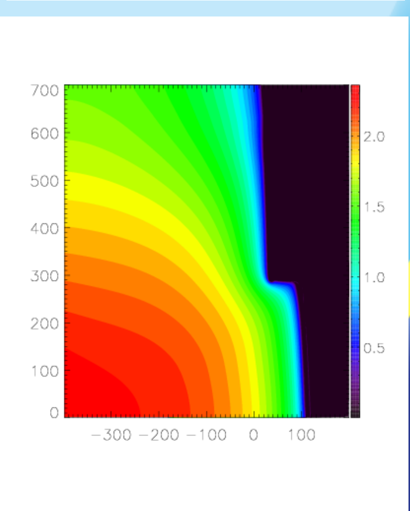
where $\mathbf{r}$ is the ray direction, s is the distance along the ray, and n is the index of refraction

∇n is determined from the plasma density distribution

Laser energy is absorbed by electron-ion collisions

The laser energy is smoothly deposited in the plasma by distributing it among the nearest cells





CRASH

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CRASH Radhydro Code: Hydro and Electron Physics

$$\frac{\partial}{\partial t}\left\{\begin{array}{c}\rho \\ \rho\mathbf{u} \\ \mathcal{E}+\frac{1}{2}\rho\mathbf{u}\cdot\mathbf{u} \\ \mathcal{E}_e\end{array}\right\}+\nabla\cdot\left\{\begin{array}{c}\rho\mathbf{u} \\ \rho\mathbf{uu}+p\mathbf{I} \\ \mathbf{u}\left(\frac{1}{2}\rho\mathbf{u}\cdot\mathbf{u}+\mathcal{E}+p\right) \\ \mathbf{u}\mathcal{E}_e\end{array}\right\}=\mathbf{S}$$

laser energy deposition

radiation/electron momentum exchange

electron heat conduction

$$\mathbf{S}=\left\{\begin{array}{c}0 \\ -\mathbf{S}_{rm} \\ \nabla\cdot C_e\nabla T_e-S_{re}+S_L \\ -p_e\nabla\cdot\mathrm{u}+\nabla\cdot C_e\nabla T_e+\frac{\rho k_B(T_i-T_e)}{M_pA\tau_{ei}}-(S_{re}-\mathbf{S}_{rm}\cdot\mathbf{u})+S_L\end{array}\right\}$$

Compression work

collisional exchange

radiation/electron energy exchange

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CRASH Radhydro Code: Multigroup diffusion

- Radiation transport equation reduces to a system of equations for spectral energy density of groups.
- Diffusion is flux-limited
- For the g^{th} group:

advection **compression work** **photon energy shift**

$$\frac{\partial E_g}{\partial t} + \nabla\cdot(E_g \mathbf{u}) - p_g \nabla\cdot\mathbf{u} - \frac{\nabla\cdot\mathbf{u}}{\Delta(log\ \varepsilon)}\Delta(p_g) = \text{diffusion + emission - absorption}$$

$$\text{diffusion} = \nabla\cdot\left(D_g \nabla E_g\right) \qquad \text{emission-absorption} = c\chi_{abs_g}\left(B_g - E_g\right)$$

$$\Delta(\cdot) = (\cdot)_{g+\frac{1}{2}} - (\cdot)_{g-\frac{1}{2}}$$

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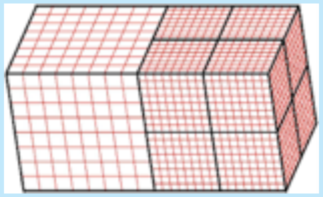
Overview of Solver Approach



- Self-similar block-based adaptive grid
- Finite-volume scheme, approximate Riemann solver for flux function, limited linear interpolation
- Level-set equations used to evolve material interfaces; each cell treated as single-material cell
- Mixed Implicit/Explicit update
  - Hydro and electron equations
    - Advection, compression and pressure force updated explicitly
    - Exchange terms and electron heat conduction treated implicitly
  - Radtran
    - Advection of radiation energy, compression work and photon shift are evaluated explicitly
    - Diffusion and emission-absorption are evaluated implicitly
  - Implicit scheme is a preconditioned Newton-Krylov-Schwarz scheme

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We extensively test our code

- New program units implemented with unit tests
  - Nightly execution of many unit tests for CRASH and its parent code
- New features implemented with verification tests
  - Daily verification & full system tests are run on a 16-core Mac.
  - Tests cover all aspects of the new feature, including restart, using grid convergence studies and model-model comparison.
- Compatibility & reproducibility checked with functionality test suite
  - Nightly runs. 9 different platforms/compilers on 1 to 4 cores: tests portability
- Parallel Scaling Tests
  - Weekly scaling test on 128 and 256 cores of hera.
  - Reveals software and hardware issues, and confirms that results are independent of the number of cores.

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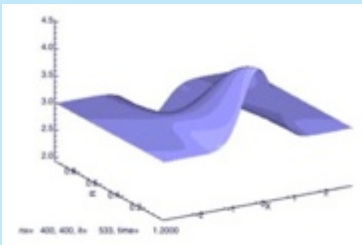
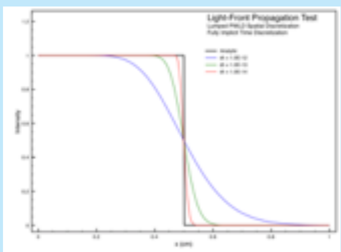
Multiple classes of tests are in our suite

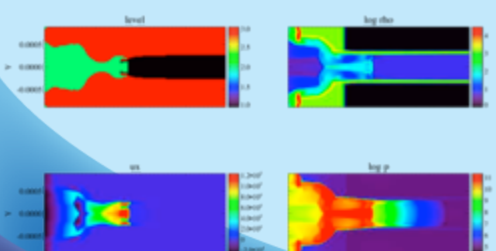
HEAT CONDUCTION



RADIATION TRANSPORT

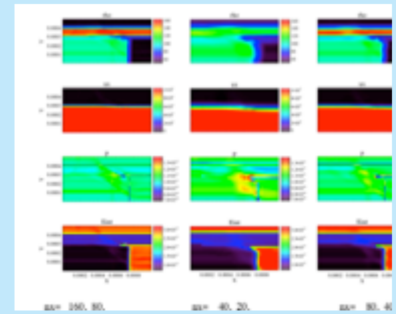


FULL SYSTEM

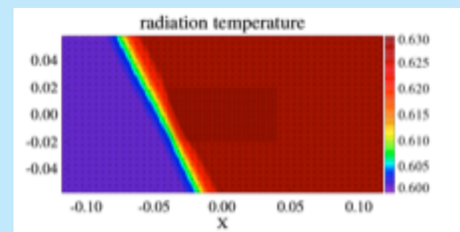


- Hydrodynamics
- Radiation transport
- Radiation hydrodynamics
- Heat conduction
- Simulated radiography
- Material properties (EOS and opacities)
- Unit tests
- Full-system tests

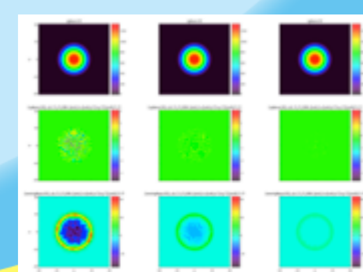
HYDRODYNAMICS



RADIATION HYDRODYNAMICS



SIMULATED RADIOGRAPHY



CRASH

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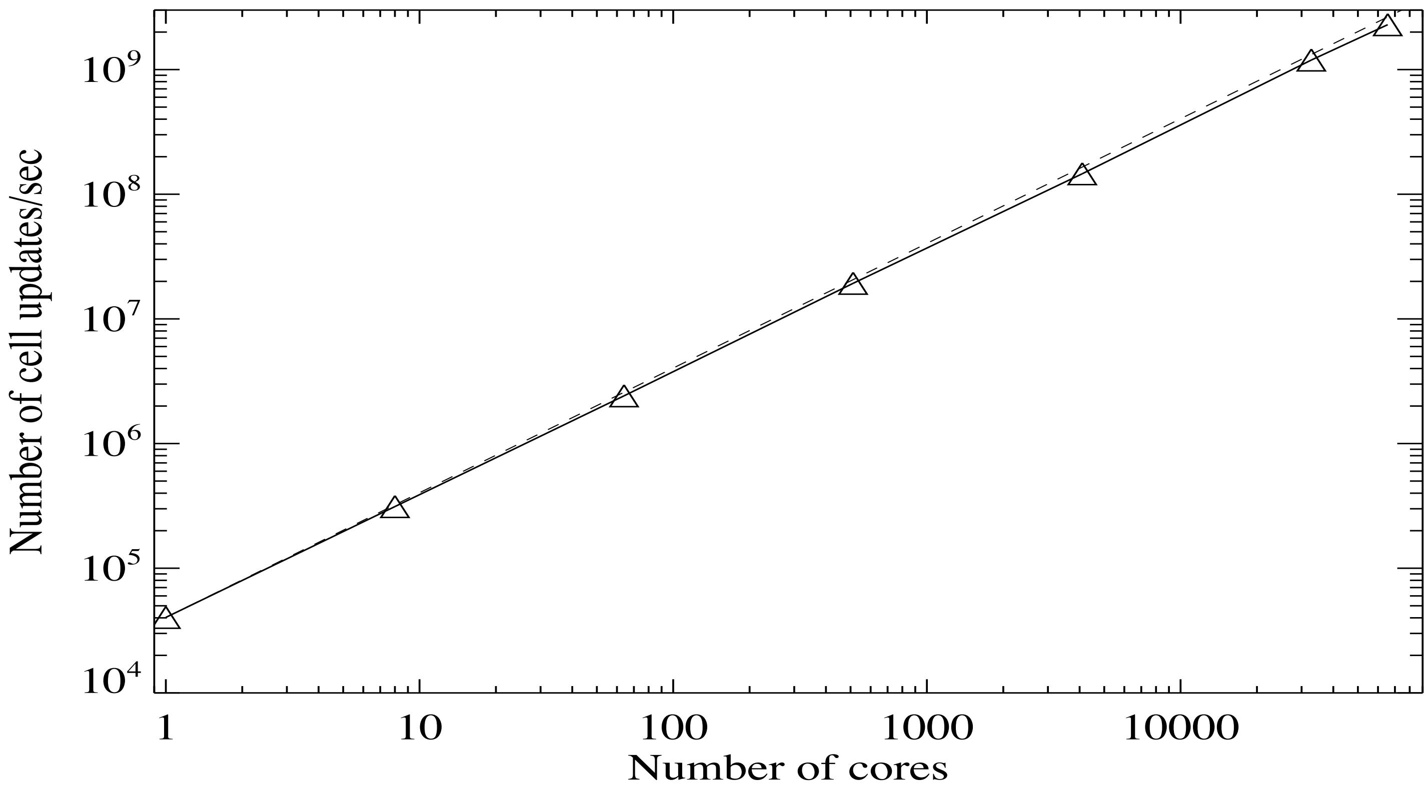
The hydro portion of the code scales well to tens of thousands of cores

(CRASH hydro Weak Scaling on BG/L)



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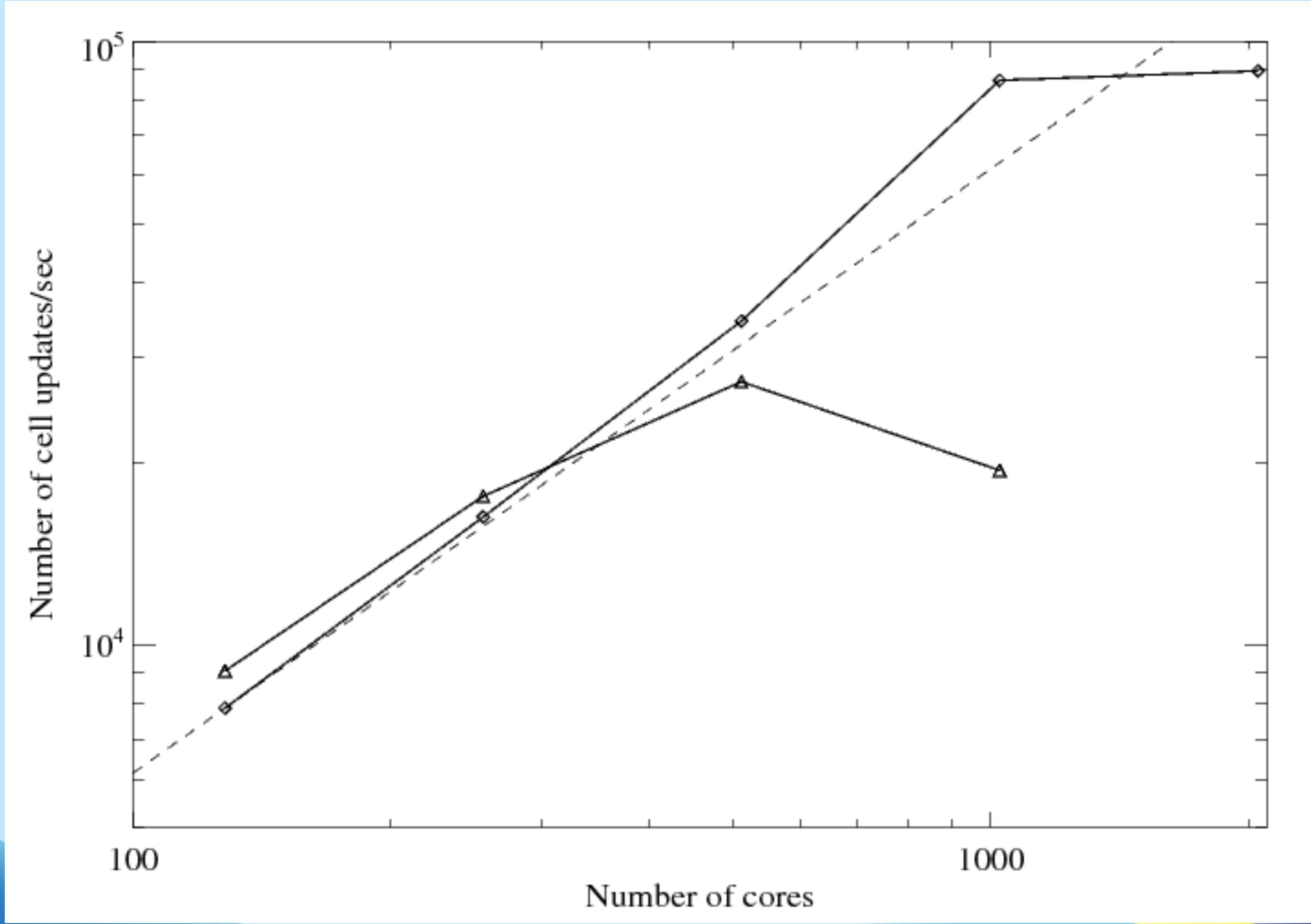
Radiation-hydrodynamics scales well to ~ 1000 cores

CRASH rad-hydro strong scaling on Hera and Pleiades



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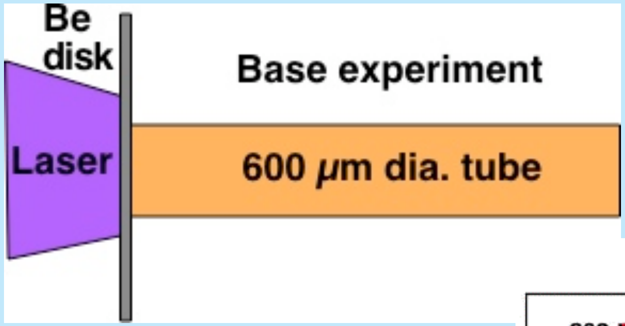
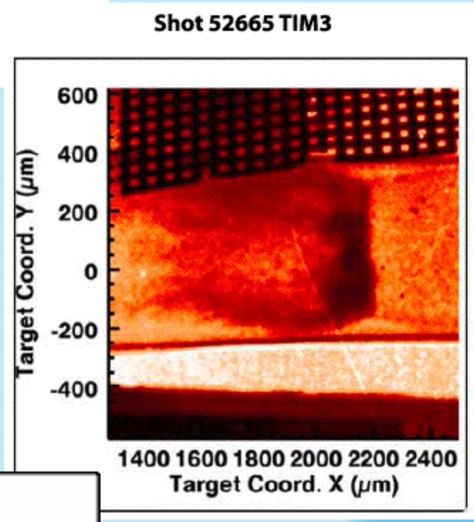
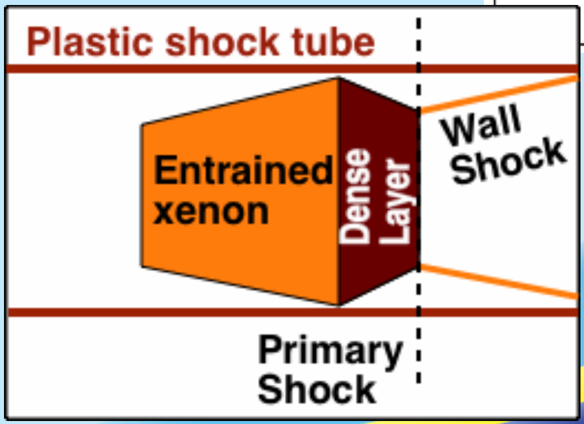
The CRASH project itself is focused on radiative shocks

- 1 ns, 4 kJ laser irradiates 20 μm Be disk
- Drives shock into Xe-filled tube at 1.1 atm.
- Radiative precursor heats wall of tube, leading to ablation
- Complex interaction among laser-driven shock, ablation-driven shock, and Xe-Be interface







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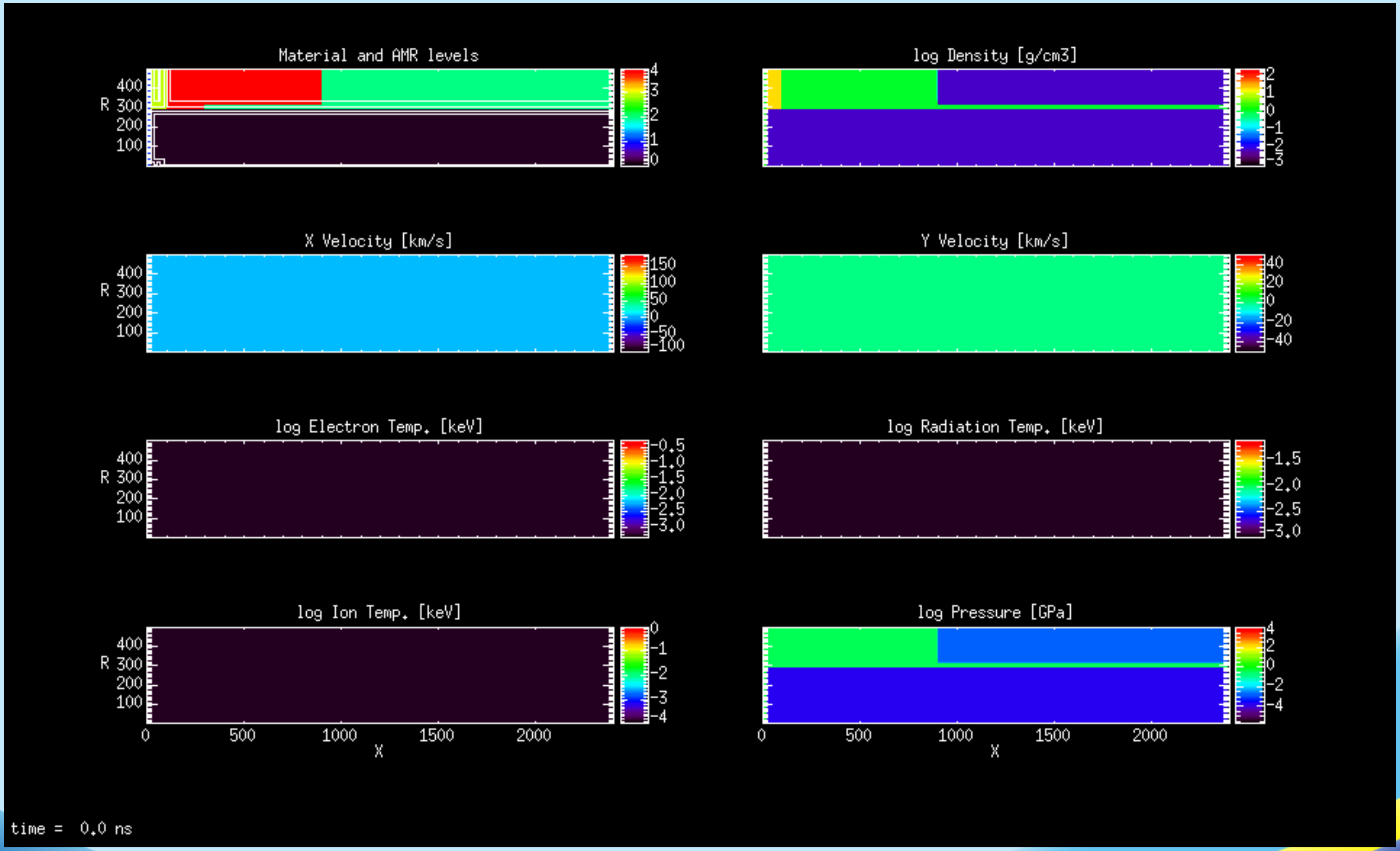
Full system with CRASH laser package



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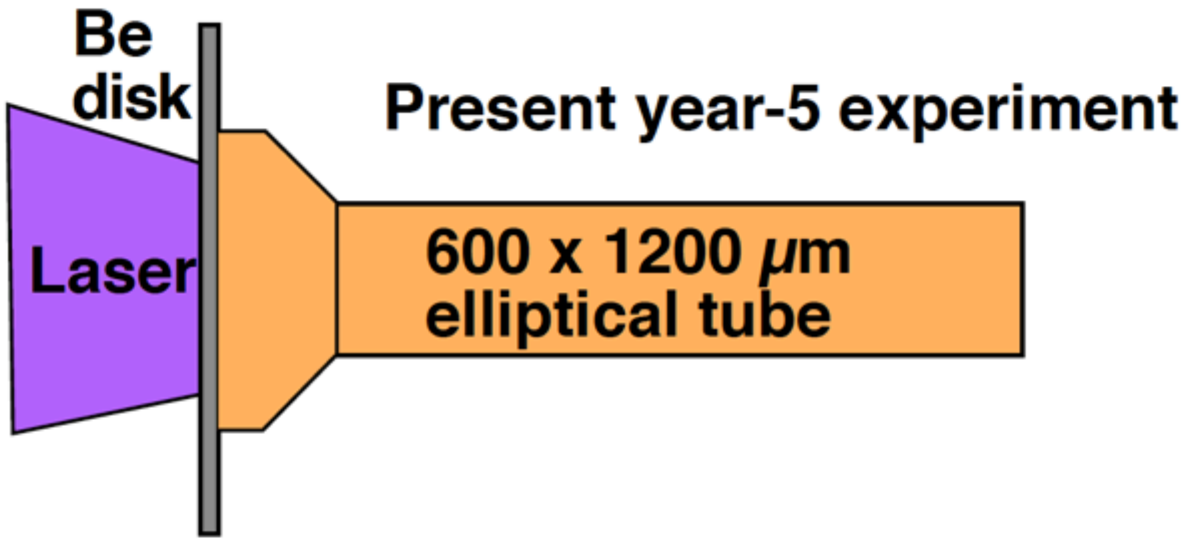
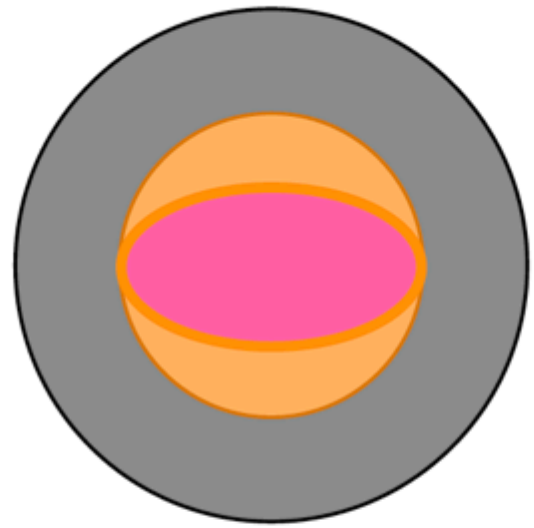
We can now simulate the Year-5 Experiment



Side Views



Rear Views

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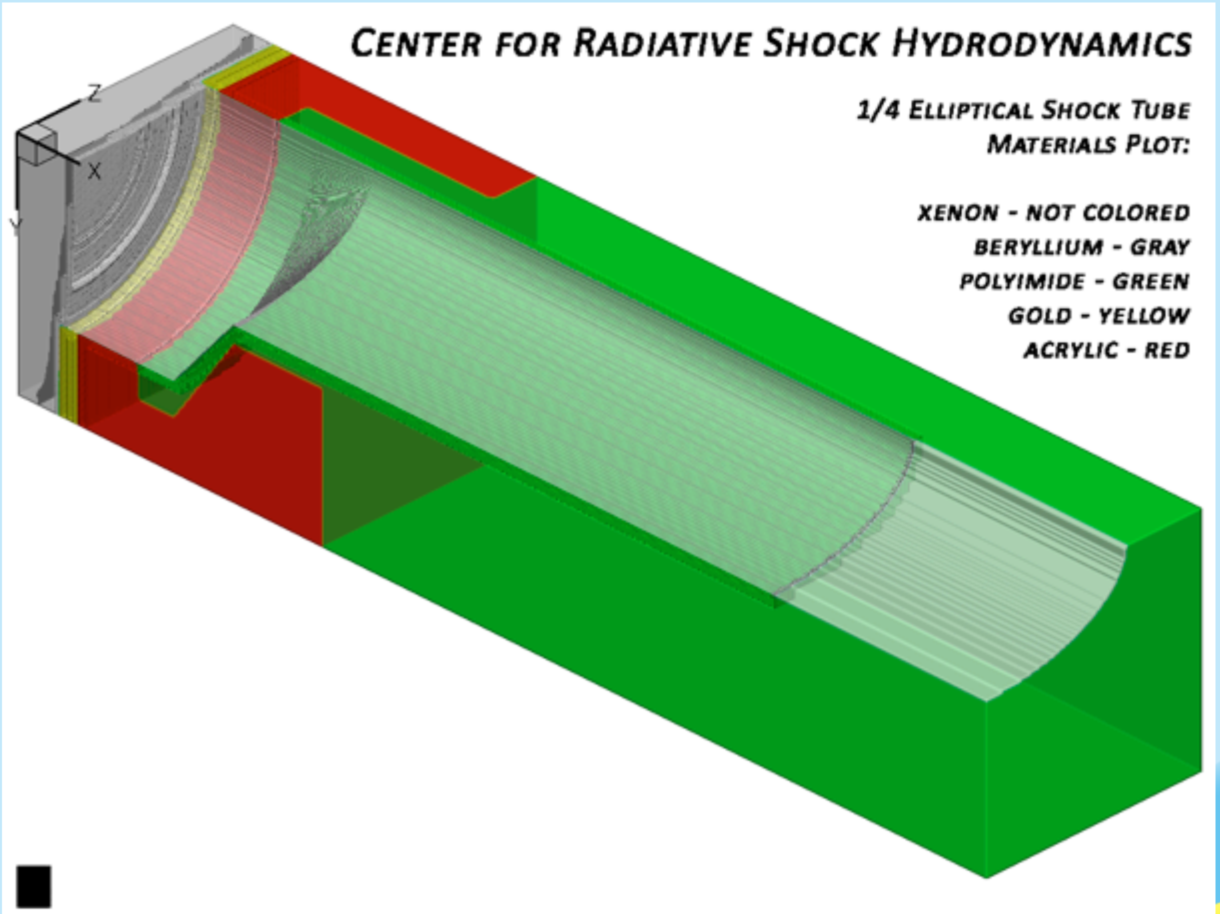
CRASH simulation of Y5 experiment



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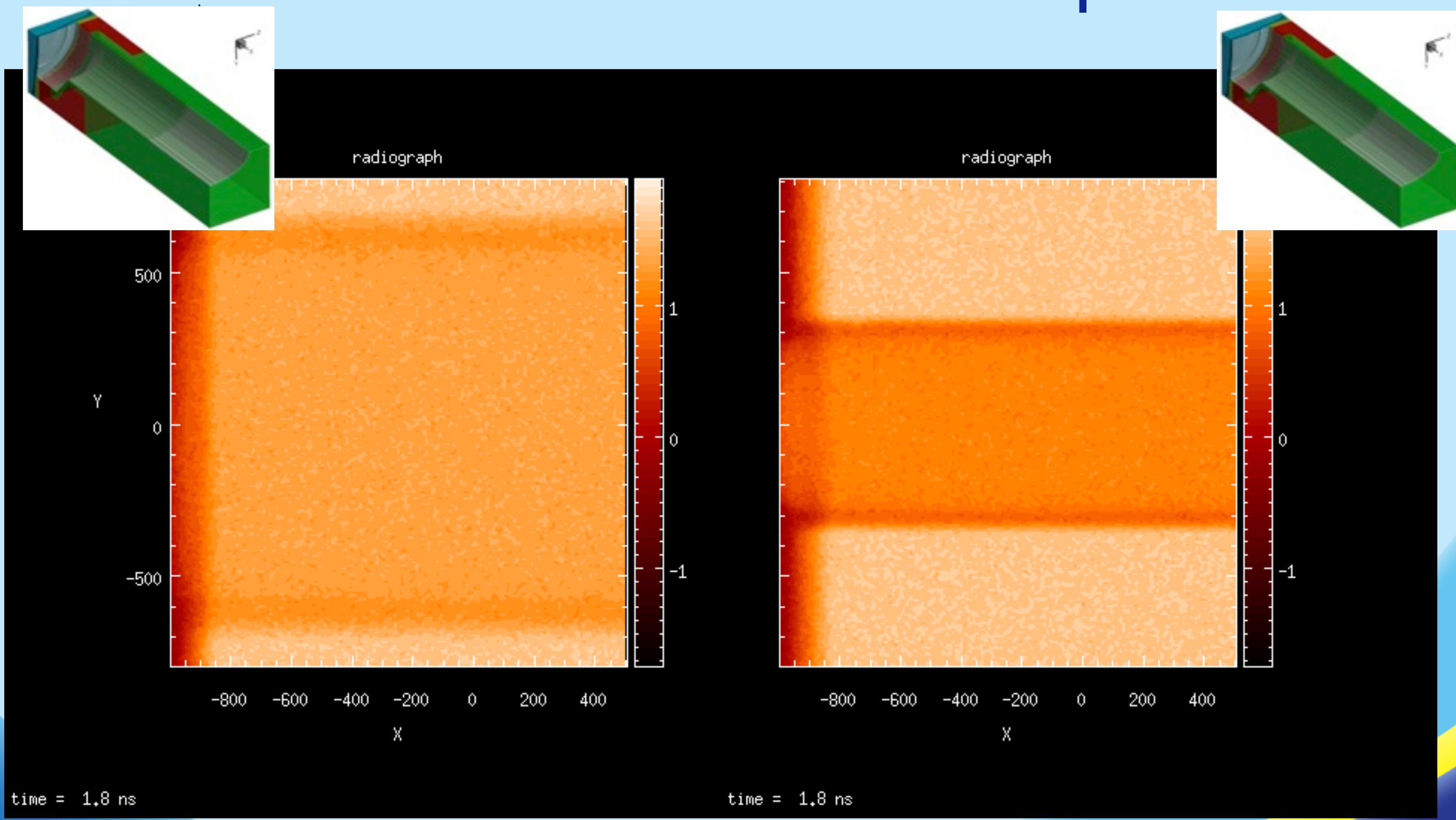
CRASH simulation of Y5 experiment



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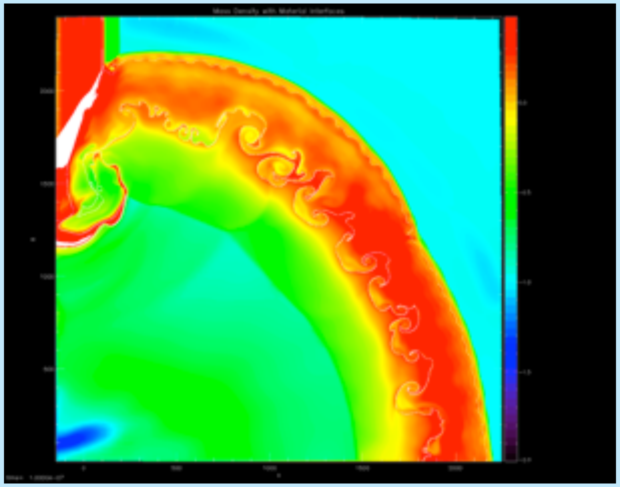
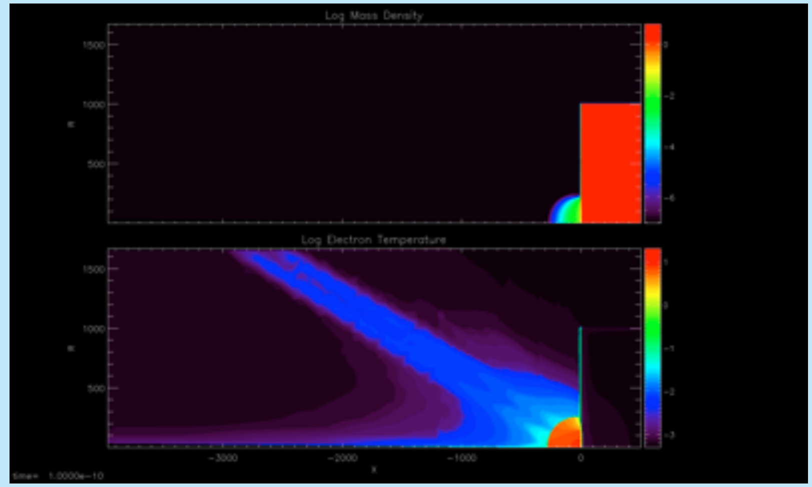
CRASH has been used to model several HED experiments



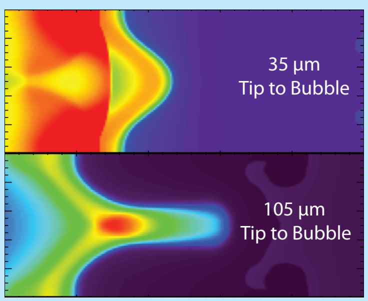
Rayleigh-Taylor growth in a diverging system



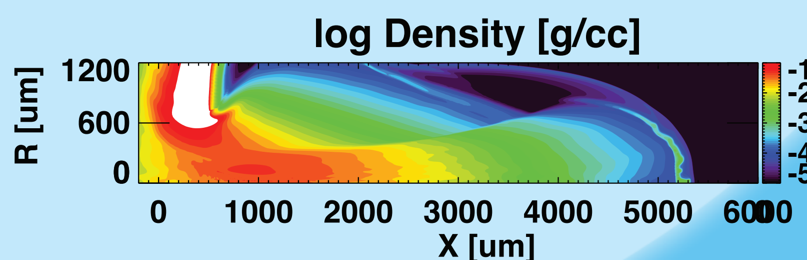
Ablative flow of laser driven foil for collisionless shock experiments

High Drive:
310 eV Tr source

Low Drive
207 eV Tr source



Rayleigh-Taylor growth in the presence of a radiative shock



Creation of plasma jets using laser irradiation of conical foils

See Poster by M J Grosskopf for more details as well as information on other applications being modeled with the CRASH code

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Concluding Remarks

- The CRASH code is now useful for applications
- We follow good practices on code development and verification
- We have simulated the experiments for the CRASH project
- We have simulated several other HED experiments
- The code is publicly available
  - But realistically requires knowledge and experience to run
  - We welcome visitors seeking these

This research was supported by the DOE NNSA/ASC under the Predictive Science Academic Alliance Program by grant number DEFC52-08NA28616.

Acknowledgments

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Related experimental work, often now using CRASH, is in the Center for Laser Experimental Astrophysics Research, funded by the NNSA-DS and SC-OFES Joint Program in High-Energy-Density Laboratory Plasmas, grant number DE-FG52-09NA29548, by the National Laser User Facility Program, grant number DE-FG52-09NA29034, and by other sponsors.