FLASH: A Highly Capable Open Code for the Academic High-Energy Density Physics Community

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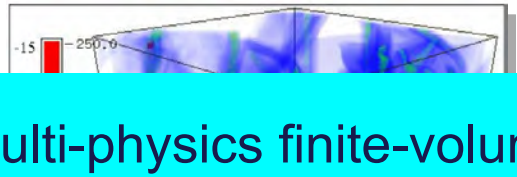
National Ignition Facility User Group Meeting
Lawrence Livermore National Laboratory
14 February 2012

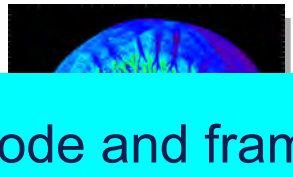
FLASH capabilities span a broad range…

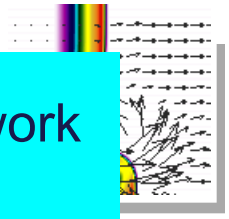
FLASH is a multi-physics finite-volume Eulerian code and framework whose capabilities include:

- Adaptive mesh refinement (AMR) on a block-structured mesh
- Multiple state-of-the-art hydrodynamic solvers (1T and 3T)
- State-of-the-art magnetohydrodynamics (currently 1T)
- Implicit solvers for diffusion using the HYPRE library (currently being used to model thermal conduction, radiation diffusion, and viscosity)
- Many physics modules relevant to astrophysics and cosmology, including gravity and nuclear burning
- Generic, highly scalable parallel particles framework (currently used for PIC simulations, laser ray tracing, dark matter, tracer particles)

Shortly: I







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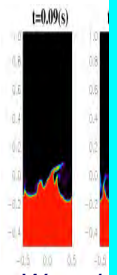
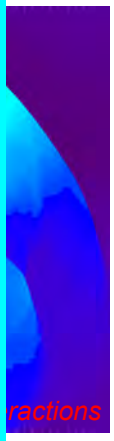


Wave b



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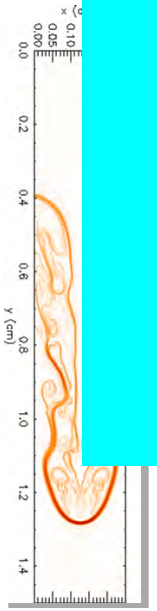
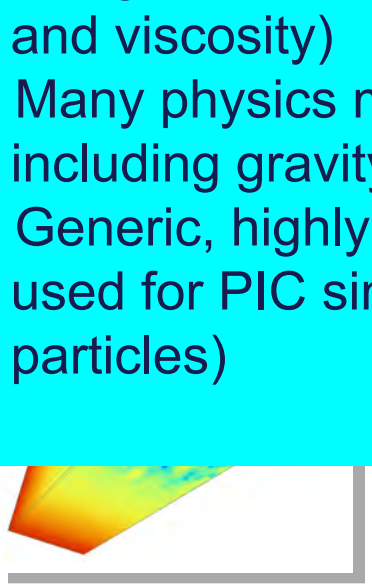
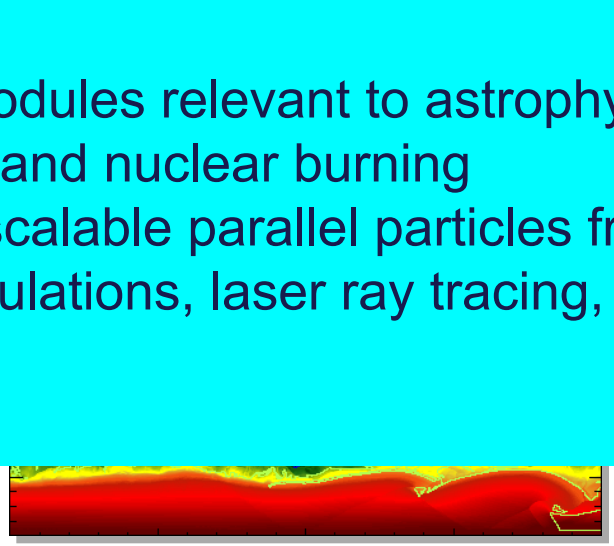


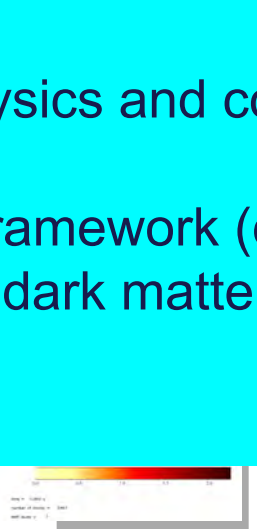
Magnetic Rayleigh-Taylor



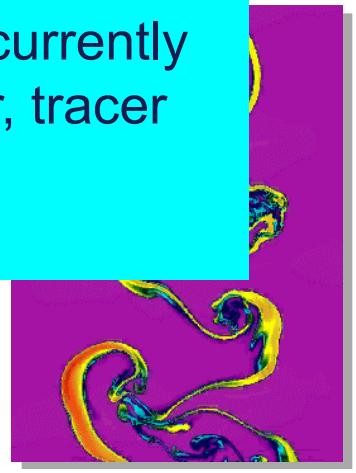
Cellular detonation



Helium burning on neutron stars



Orzag/Tang MHD vortex



Richtmyer-Meshkov instability

FLASH is being used by groups throughout the world

- FLASH scales to well over a hundred thousand processors. FLASH uses a variety of parallelization techniques including domain decomposition, mesh replication, and threading to best utilize hardware resources
- FLASH is extremely portable and can run on a variety of platforms from laptops to supercomputing systems such as the IBM BG/P and BG/Q
- FLASH is composed of interoperable units/modules; particular modules are combined to run individual simulations. Thus only the code relevant to a particular problem is included when FLASH is compiled. This also allows for important compile-time optimizations that improve performance
- FLASH is professionally managed software with daily, automated regression testing on a variety of platforms, version control, coding standards, extensive documentation, user support, and integration of code contributions from external users
- More than 700 scientists around the world have now used FLASH, and more than 400 papers have been published that directly use it.

Volume 355 Issue 3 Page 995 - December 2004
doi:10.1111/j.1365-2966.2004.08381.x

Quenching cluster cooling flows with recurrent hot plasma bubbles

Claudio Dalla Vecchia[1], Richard G. Bower[1], Tom Theuns[1,2], Michael L. Balogh[1], Pasquale Mazzotta[3] and Carlos S. Frenk[1]

FLASH has been extended to support the academic HEPD community

- Most of the codes with the physics required to study HEDP experiments are developed at national labs and their use is restricted, making it difficult for the academic HEDP community to use them
- The overarching goal of the Flash Center's HEDP initiative is to help create an active and intellectually vibrant academic HEDP community by
  - Making FLASH a highly capable open code for the academic HEDP community, and
  - Supporting the use of FLASH by the academic community to design, execute, and analyze new HEDP experiments

Current HEDP Capabilities in FLASH

- 3T Radiation Hydrodynamics
- Finite volume Eulerian hydrodynamics/MHD capabilities on an AMR mesh
- Implicit thermal conduction and multigroup radiation diffusion
- Multimaterial support with tabulated EOS and opacity
- Laser ray tracing
- Preliminary particle-in-cell capability (does not function with AMR)
- Ability to represent rigid bodies of arbitrary shape inside the hydrodynamic flow

— These capabilities are in FLASH 4.beta, which was released on February 1, 2012

See Fatenejad et al. poster and FLASH demonstrations

Planned Future Development of HEDP Capabilities in FLASH

- Extending the resistive MHD solver to simulate 3T plasmas
- Incorporating the Biermann battery mechanism source term to accurately predict magnetic field generation near shocks
- Adding 3D-in-2D laser ray trace
- Increasing the accuracy of the laser ray trace to reduce noise
- Continued improvement of the 3T hydrodynamic solver
- Addition of a fast electron capability
- Improvement of the particle-in-cell capability

The Flash Center HEDP Group

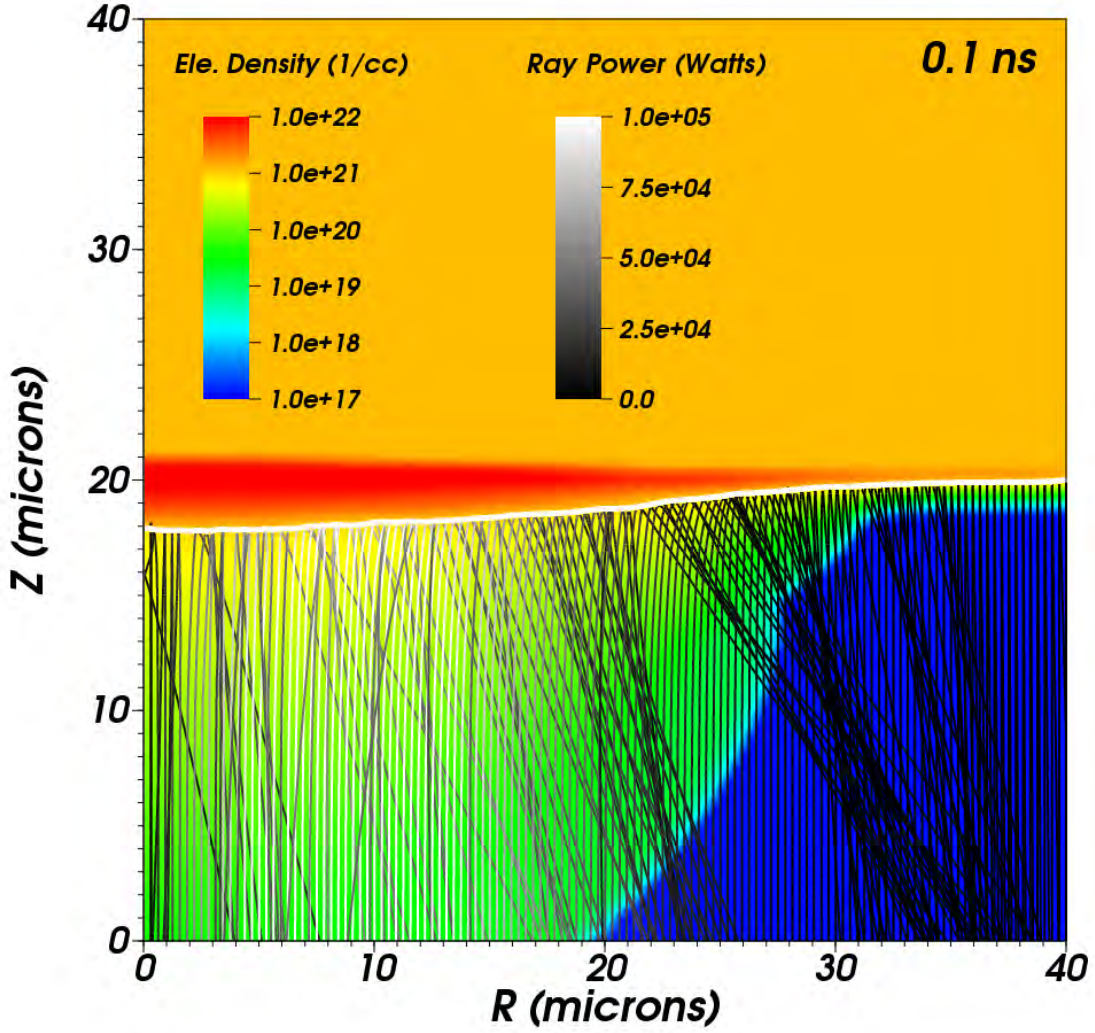
Current Members of the FLASH Center HEDP Group:

- Don Lamb (lead)
- Milad Fatenjad (deputy lead)
- Anshu Dubey
- Norbert Flocke
- Carlo Graziani
- Max Hutchison
- Dongwook Lee
- Anthony Scopatz
- Petros Tzeferacos
- Klaus Weide

Current Flash Center HEDP Collaborations with the Academic Community

- University of Michigan (Center for Radiation Shock Hydrodynamics)
- University of Oxford (High Energy Density Laboratory Astrophysics Group)
- Ohio State University (High Energy Density Physics Group)
- University of Texas (High Intensity Laser Science Group)
- University of Wisconsin (Fusion Technology Institute)
- Flash Center MoU with the UK Science Research Facilities Council (Central Laser Facility at Rutherford-Appleton Laboratory for HEDP; Computational Science and Engineering Department at Daresbury Laboratory)
- Laboratoire pour l'Utilisation de Lasers Intenses (LULI) and Universite' Paris VI Ecole Polytechnique

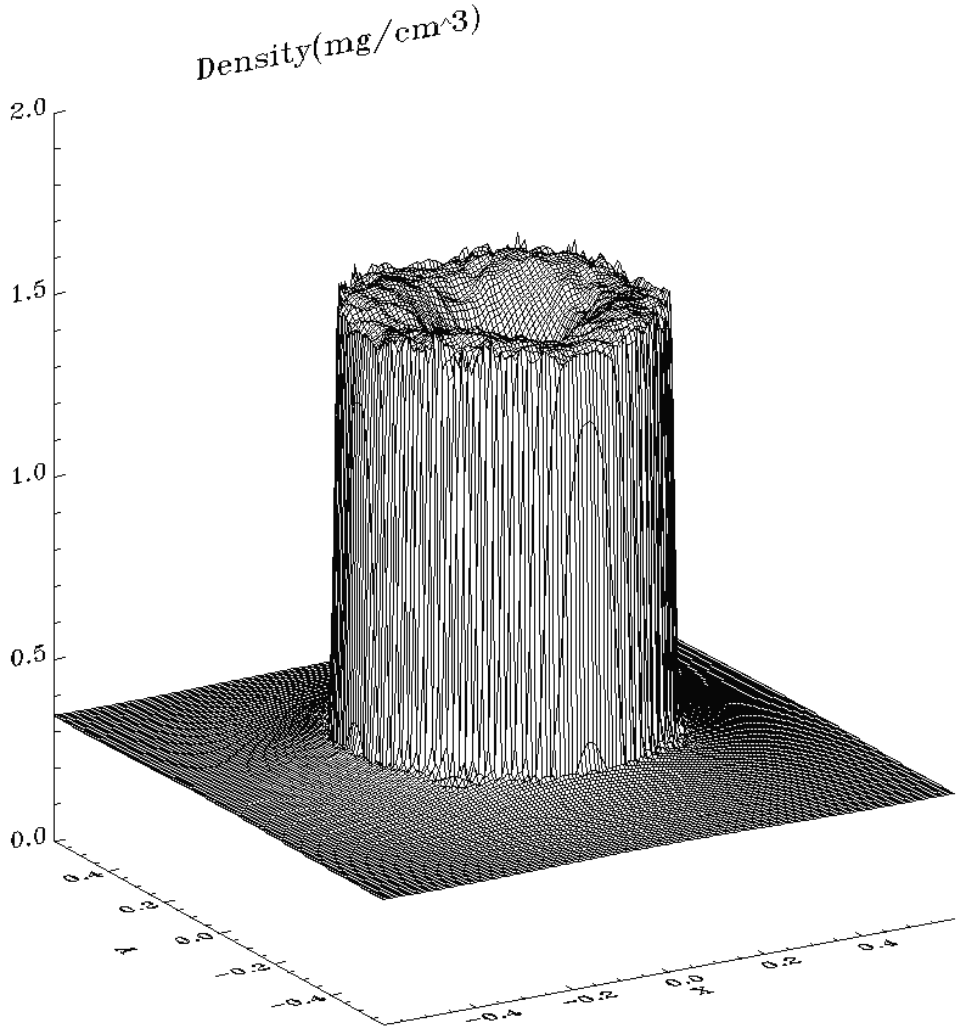
FLASH Laser Ray Tracing



FLASH uses a laser ray tracing algorithm based on the geo-Metric approximation (Kaiser, Phys. Rev. E, Vol. 61, p. 895, 2000).

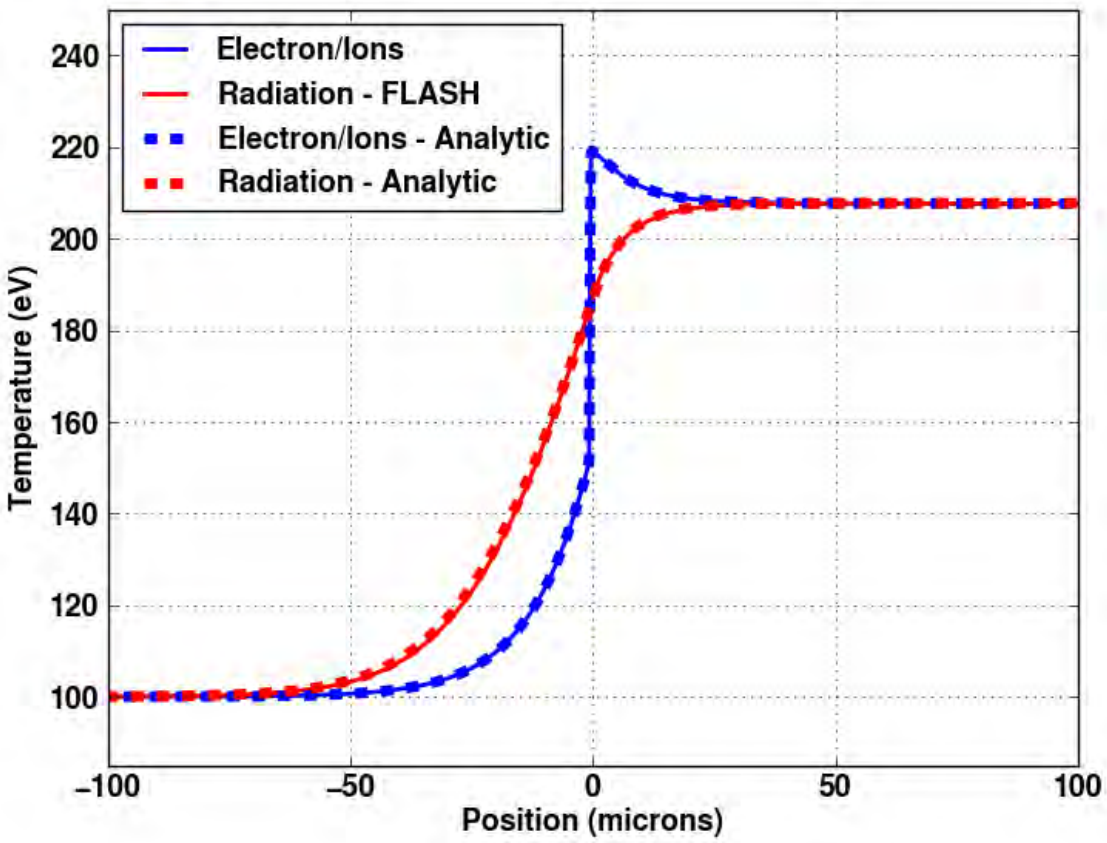
The image shows a laser heating an Aluminum slab with 6 group radiation diffusion. The rays lose power as they refract in the plasma.

FLASH Verification



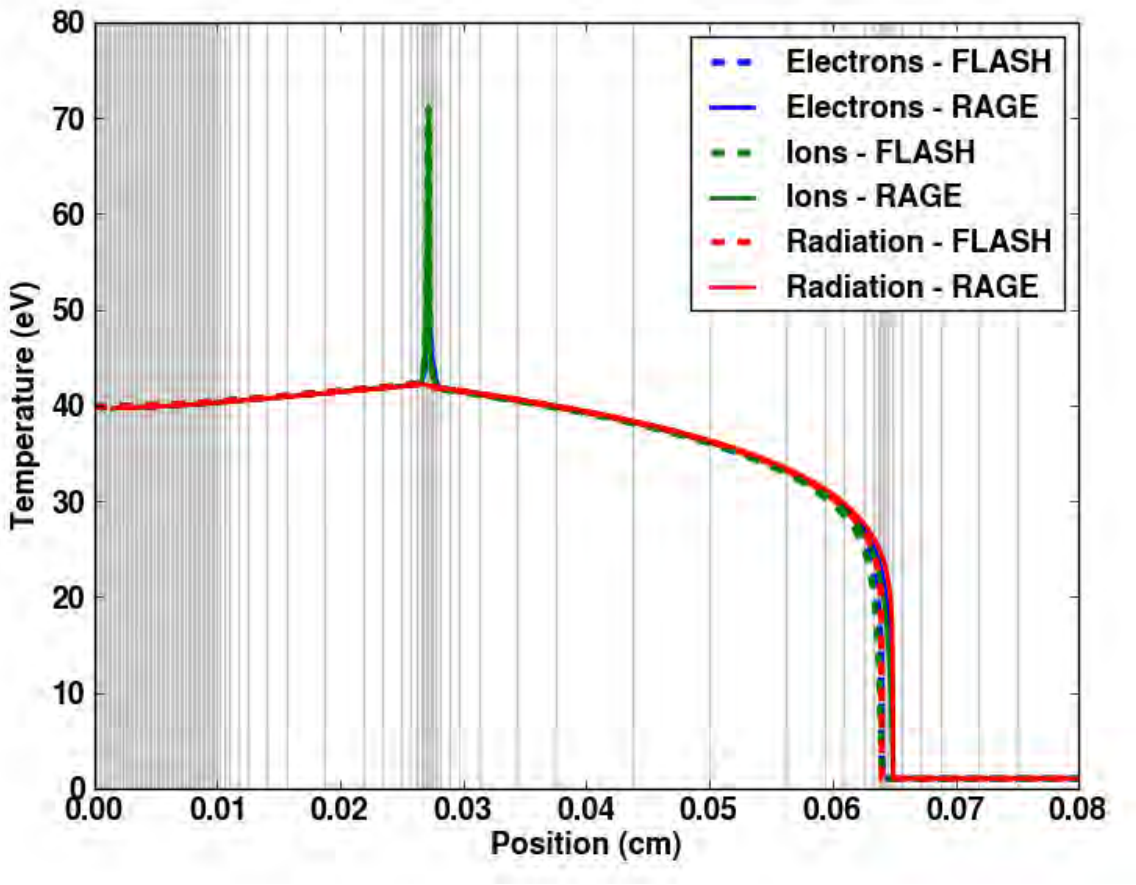
FLASH MHD simulation of the magnetic Noh problem (Velikovich et al., Phys Plasmas, Vo. 19, p. 012707, 2012)

FLASH Verification



FLASH obtains excellent Agreement with the Lowrie analytic radiative shock solution (Lowrie et al., Shock Waves, Vol. 18, p. 129, 2008)

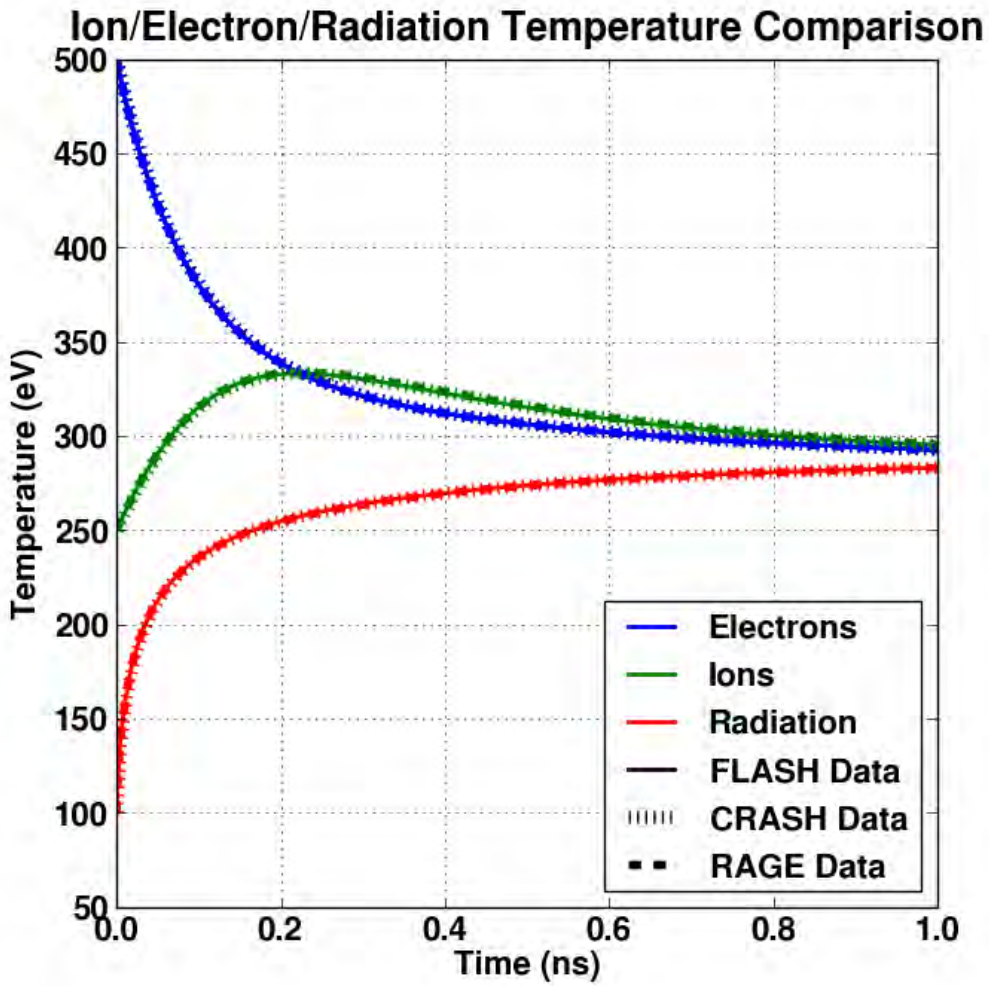
FLASH Verification



The Flash Center is leading a collaboration involving CRASH, LANL, and LLNL to perform V&V of the HEDP capabilities in several rad-hydro codes.

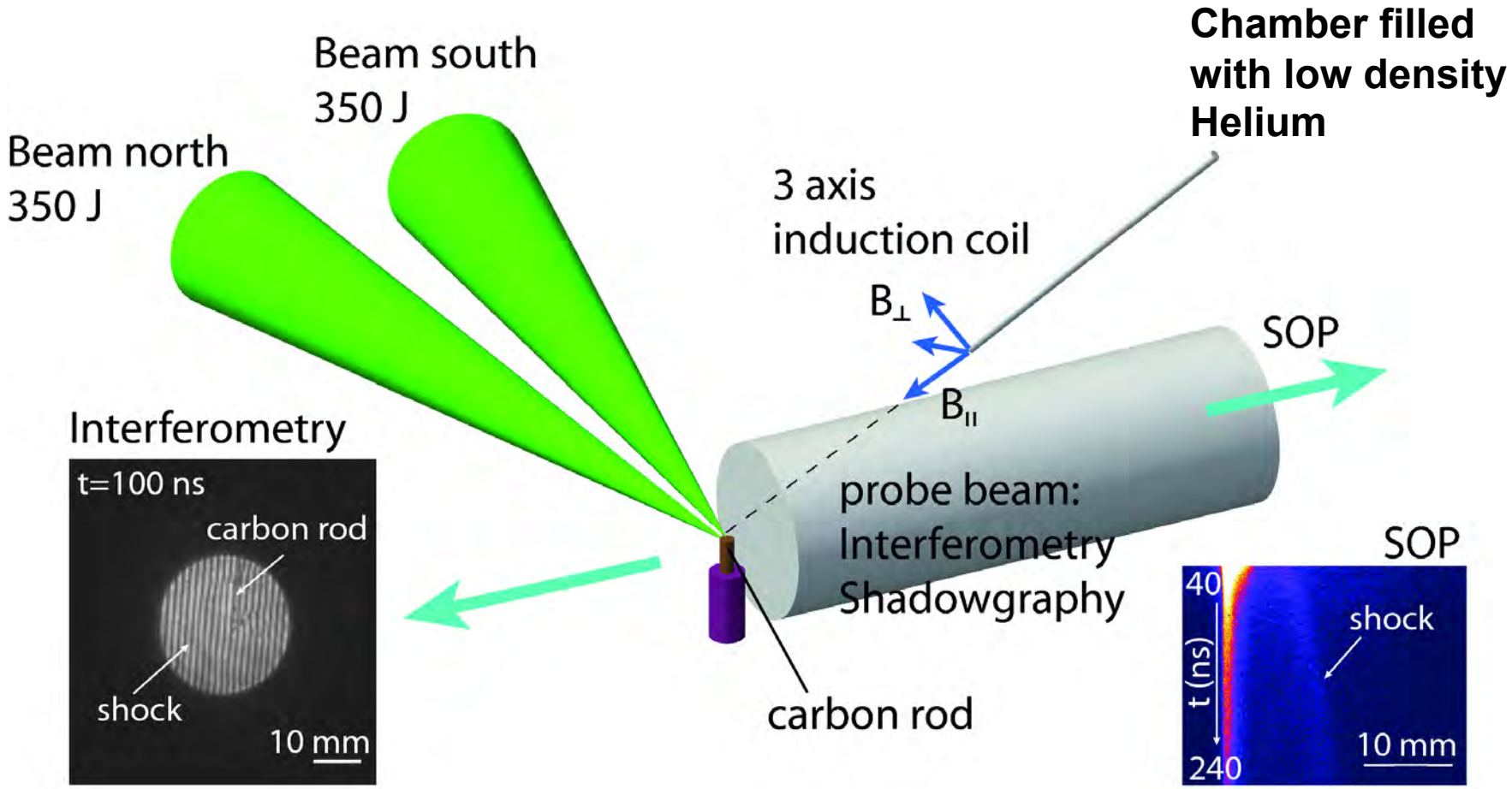
The figure compares FLASH and RAGE (Gittings et al., Comp Sci. & Disc., Vol. 1, p. 015005, 2008) for a 1D simulation of a 3T radiative shock in Xenon.

FLASH Verification



This figure compares FLASH, RAGE, and CRASH (van der Holst, et al., ApJ, Vol. 194, p. 23, 2011) for a simple infinite medium temperature relaxation test.

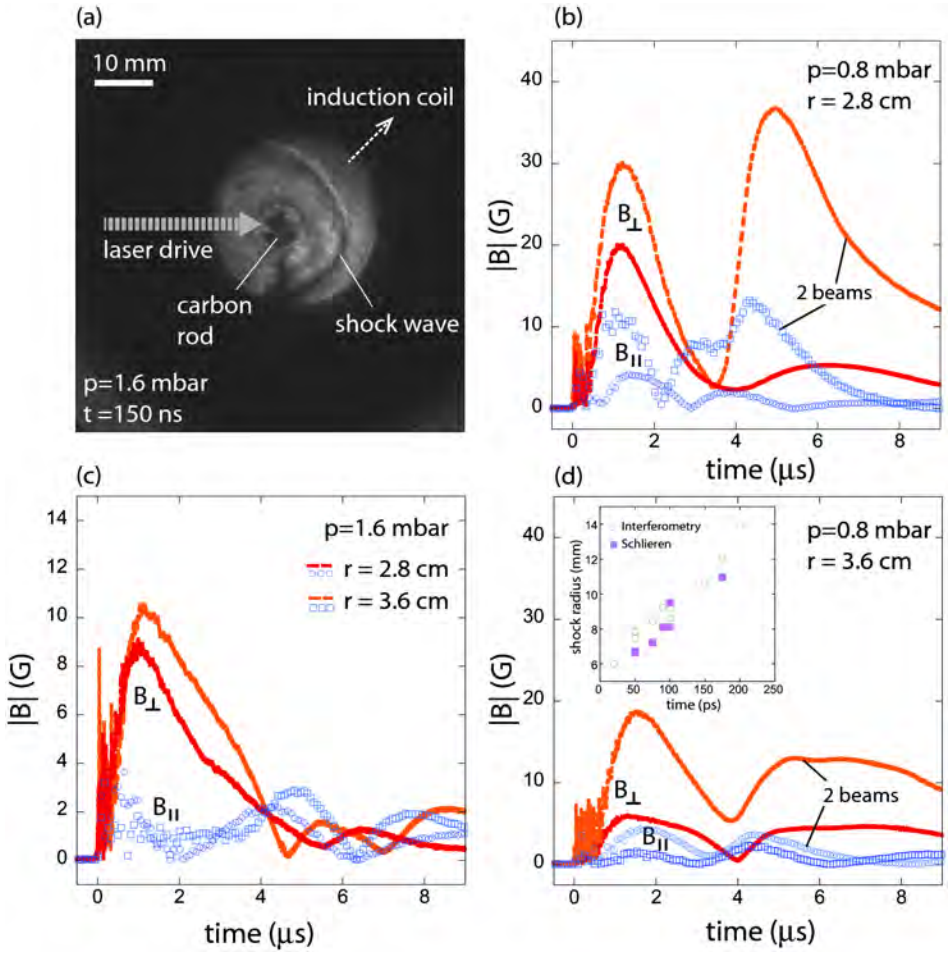
University of Oxford is conducting experiments to study the generation of magnetic fields in the IGM



Gregori et al., Nature, Vol. 481, p. 480, 2012

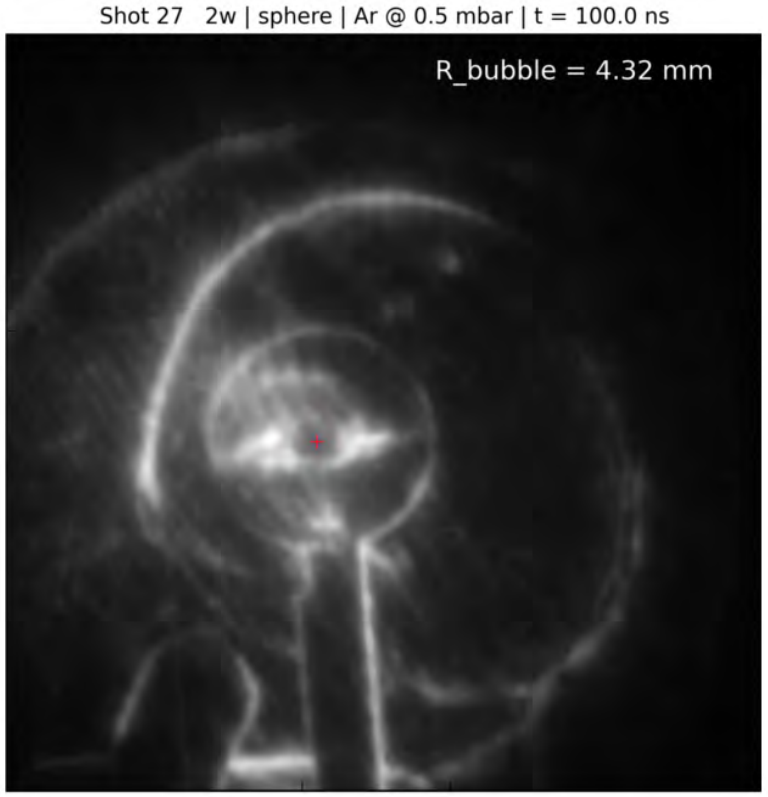
Results of the University of Oxford experiments at LULI

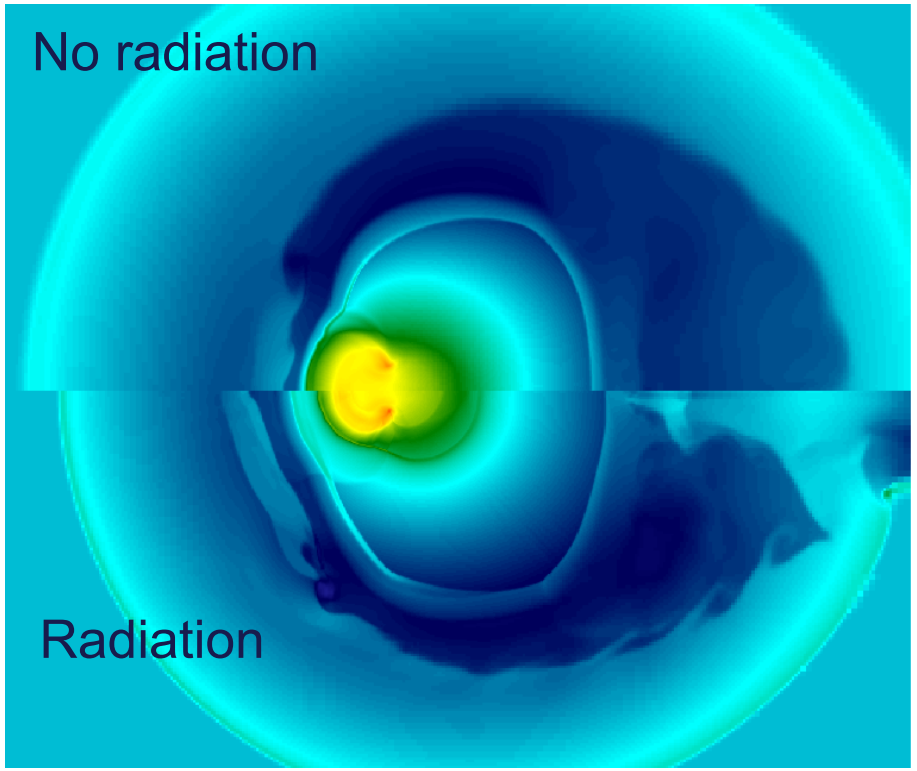
- Laser striking target from one side drives an asymmetric blast wave into the gas-filled chamber
- Three axis coils placed ~2-3 cm from target measure large-scale magnetic fields
- The strength of the B-field field peaks at the time the shock is expected to reach the coils, consistent with the generation of it by the Biermann battery mechanism
- The orientation of the B-field is also consistent with this mechanism



Gregori et al., Nature, Vol. 481, p. 480, 2012

Collaboration with University of Oxford to simulate LULI experiments using FLASH



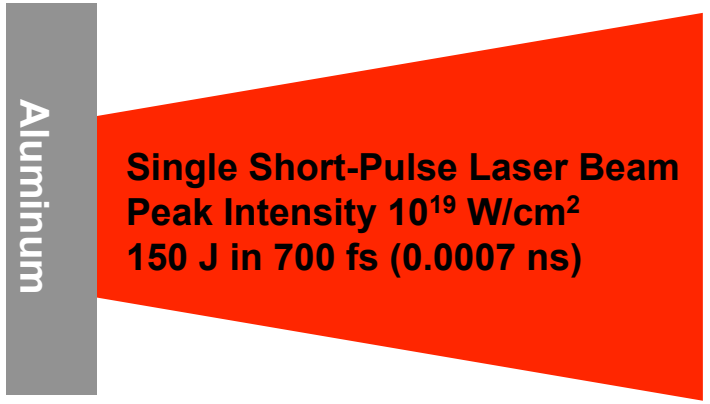


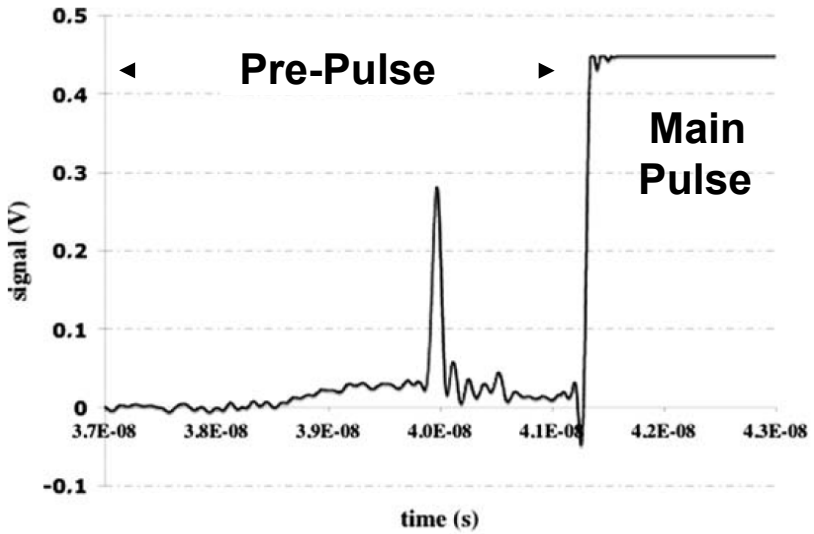
Shadowgraphy image at 100 ns shows complex shock structure.

Preliminary FLASH 2D cylindrical hydrodynamic simulations w. and w/o. radiation.

Collaboration with Ohio State University to simulate pre-plasmas using FLASH

- Short-pulse laser systems have a "pre-pulse" lasting several nano-seconds during which laser light "leaks" through the optics ahead of the main pulse and preheats the target
- The pre-pulse will create a pre-formed plasma that can affect the experiment





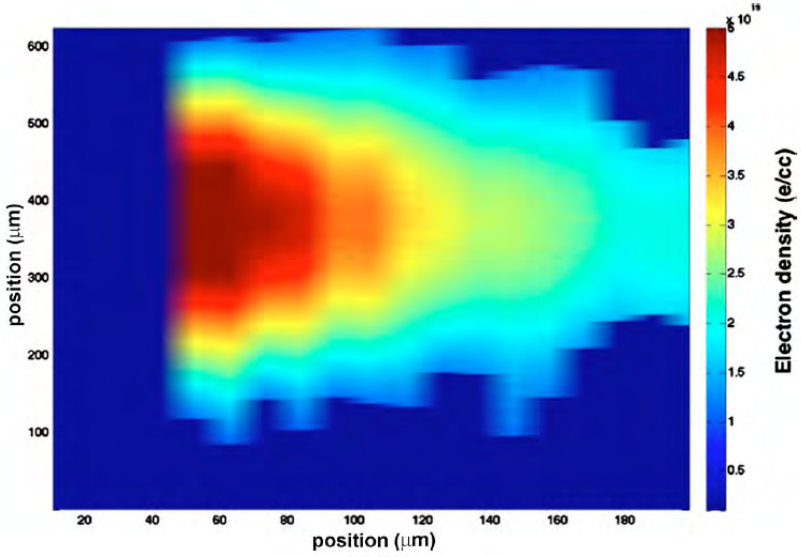
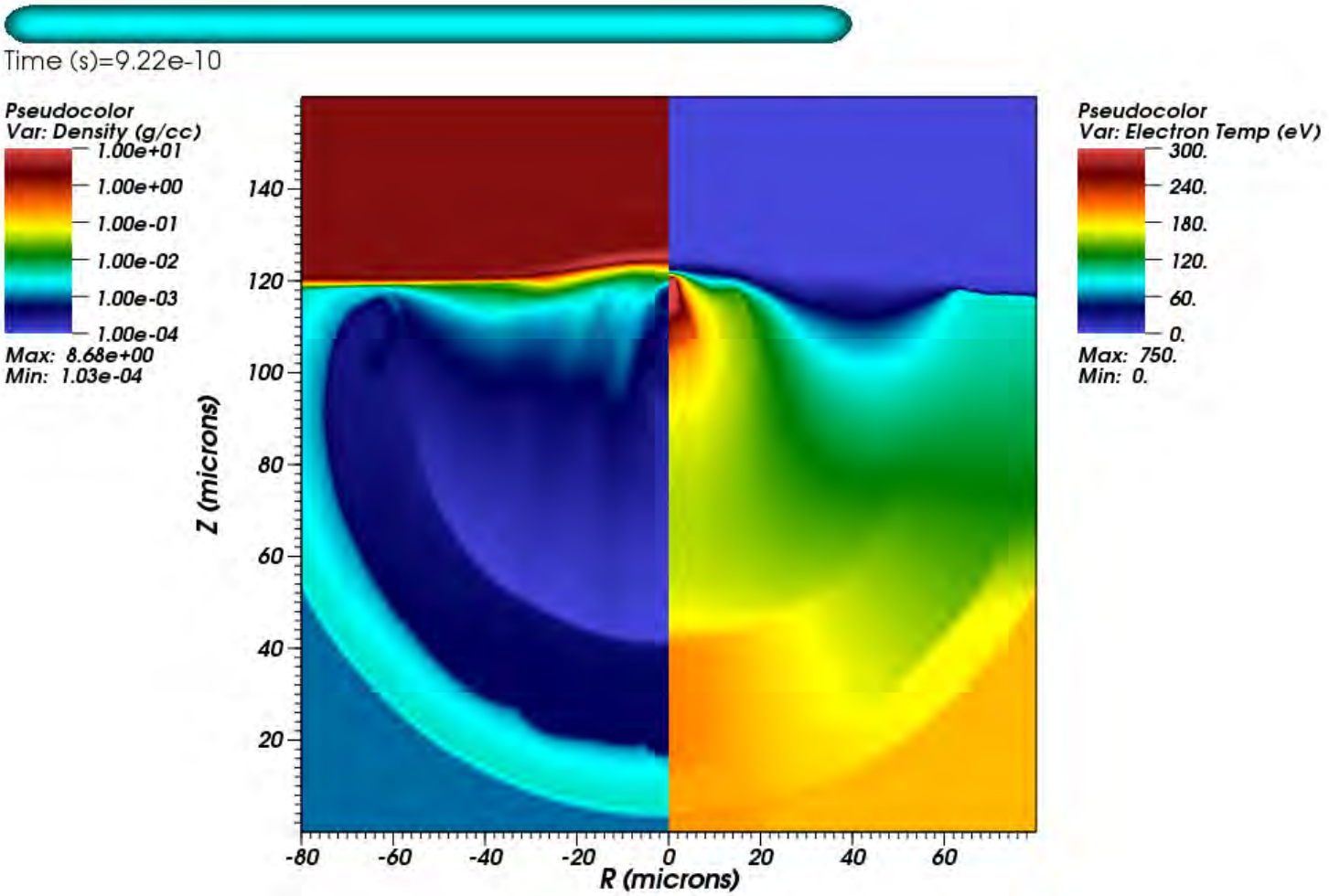


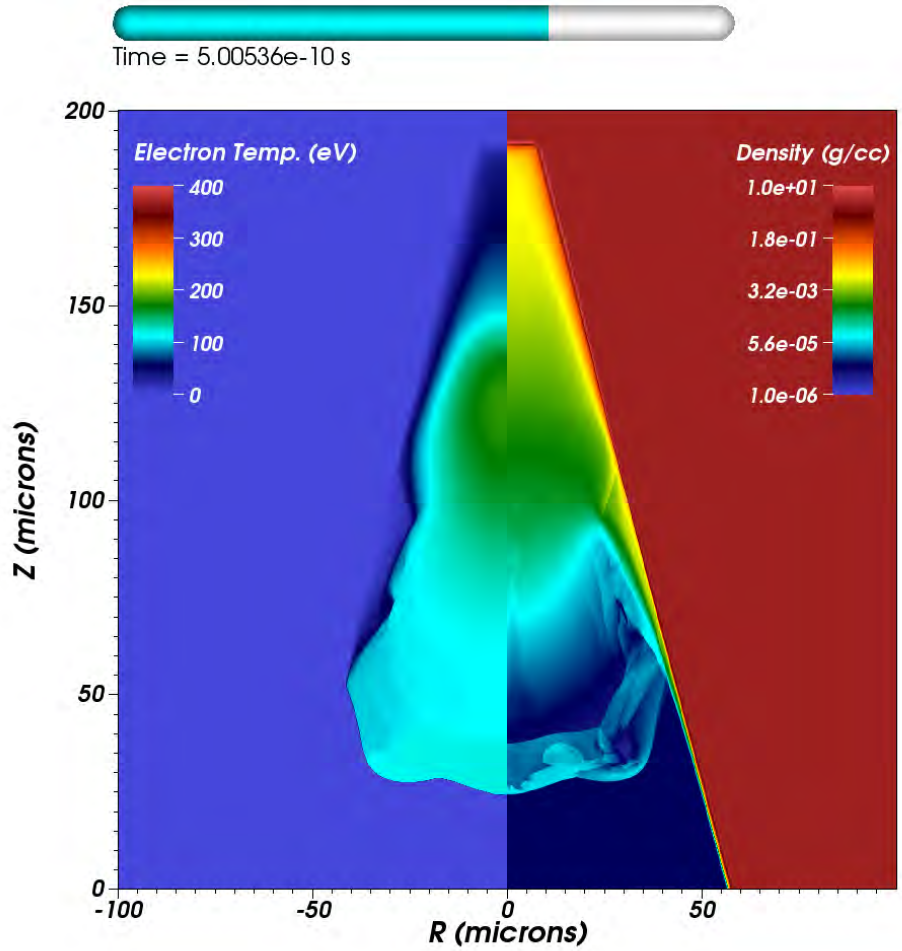
Image Source: Le Pape, et al. *Optics Letters*, 2997, 34 (2009)

Collaboration with Ohio State University to simulate pre-plasmas using FLASH



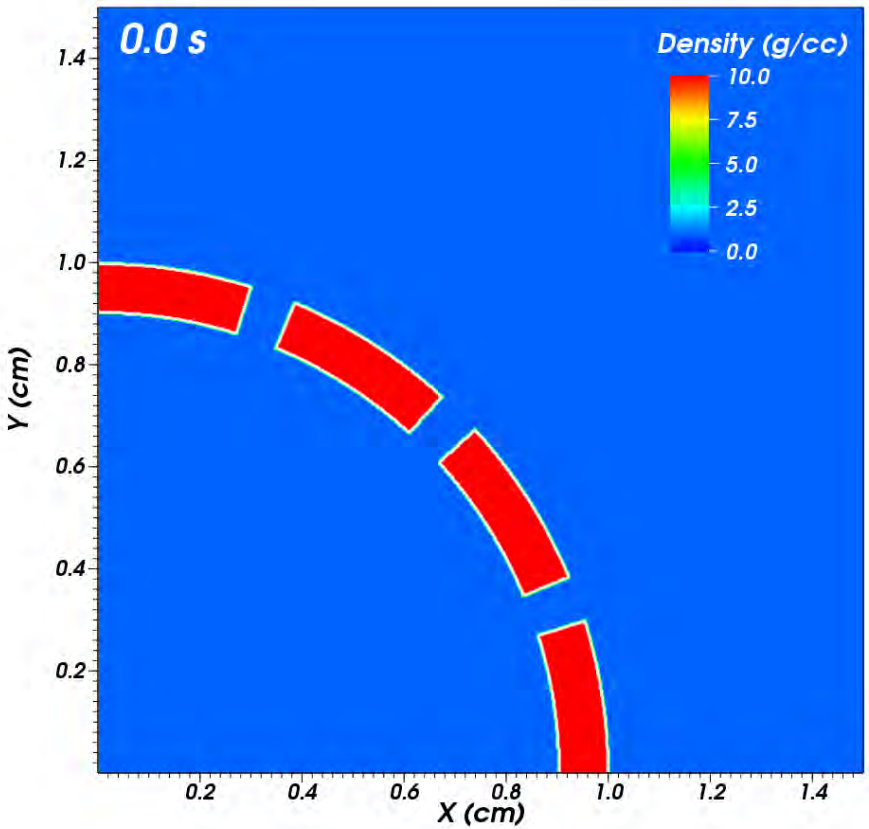
FLASH 2D simulation of a laser illuminating an Al slab target.

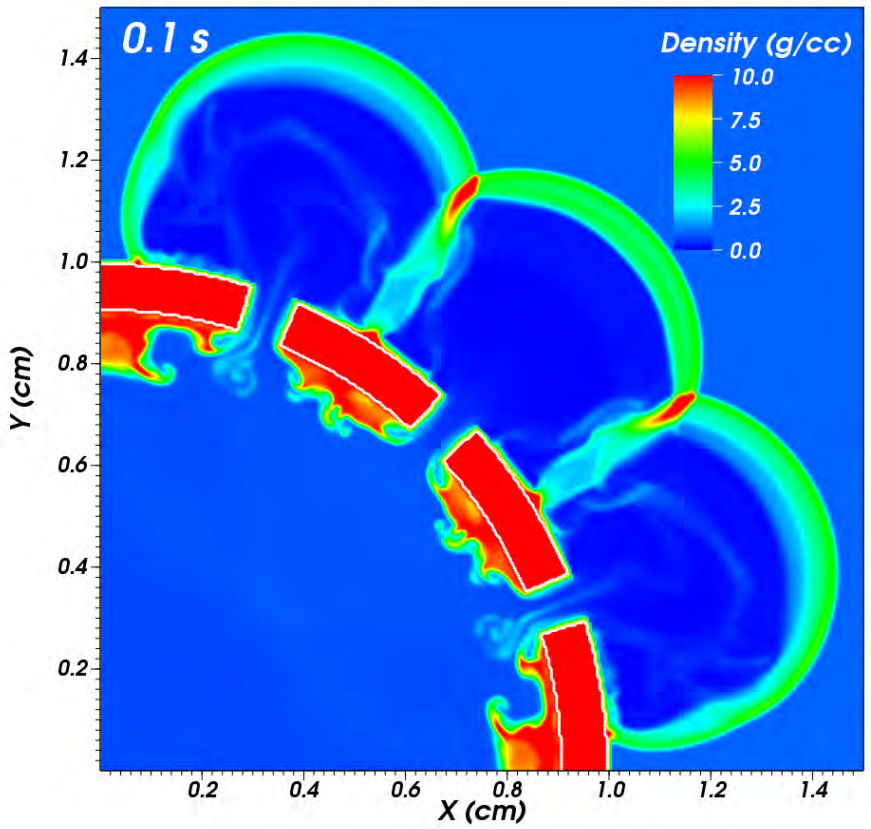
Collaboration with Ohio State University to simulate pre-plasmas using FLASH



FLASH 2D simulation of a laser illuminating an imbedded Al cone target.

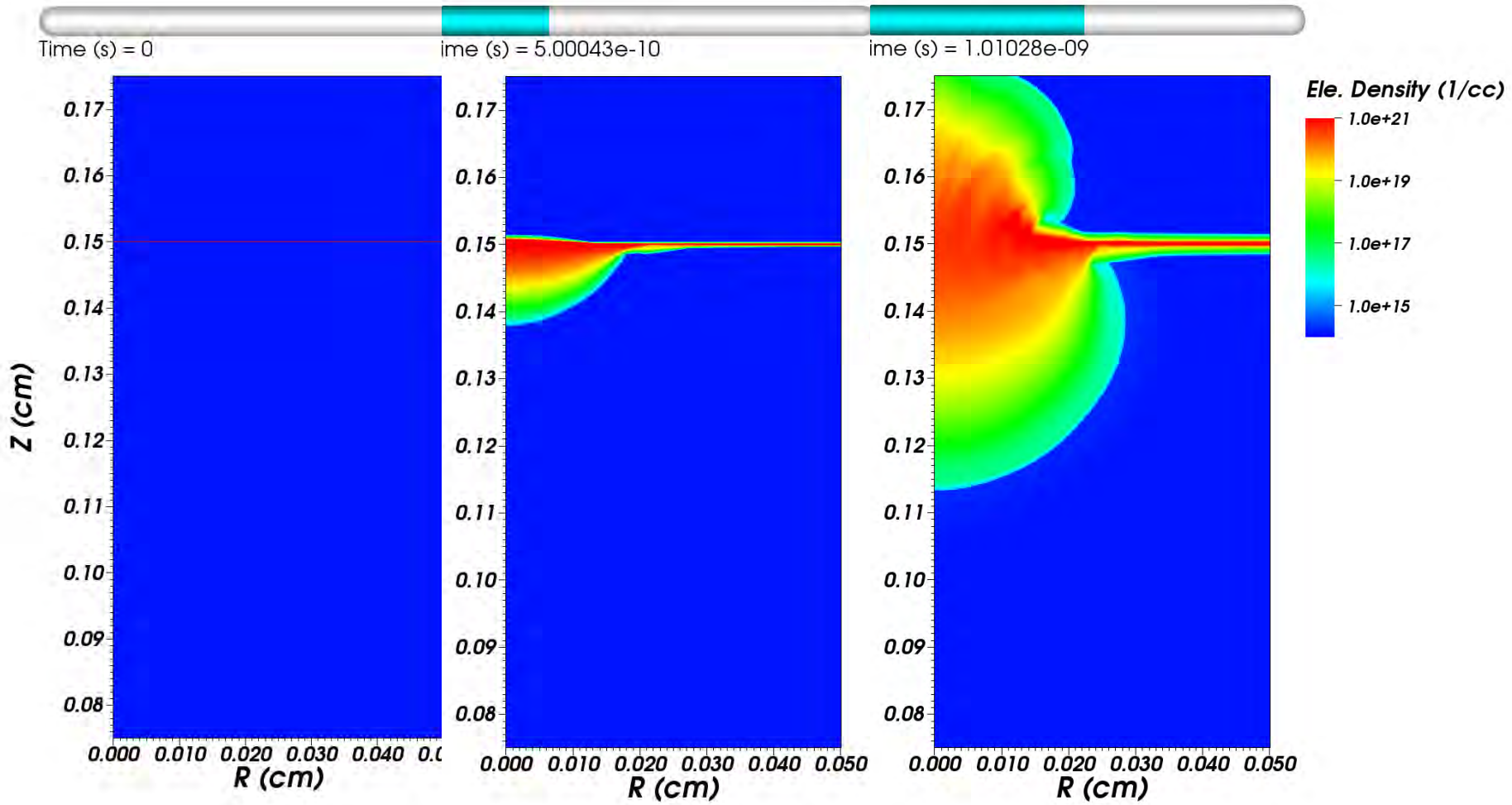
Collaboration with University of Wisconsin to simulate a blast wave in a gas-filled chamber





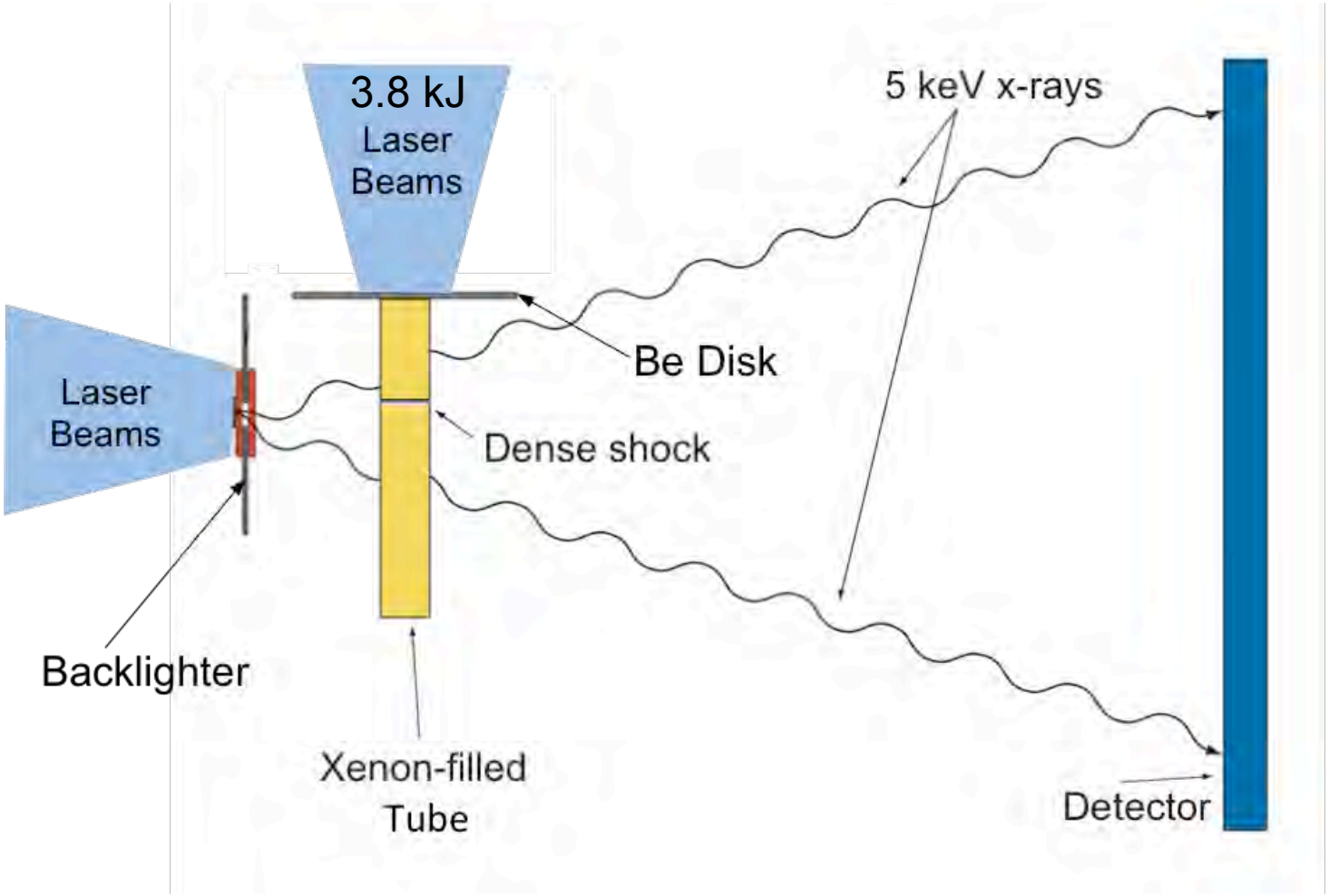
Proof of concept FLASH 2D hydrodynamic simulation including radiation of a blast wave in a circular, rigid, gas-filled chamber with ports.

Flash Center Collaboration with Ecole Polytechnic and LULI in Paris



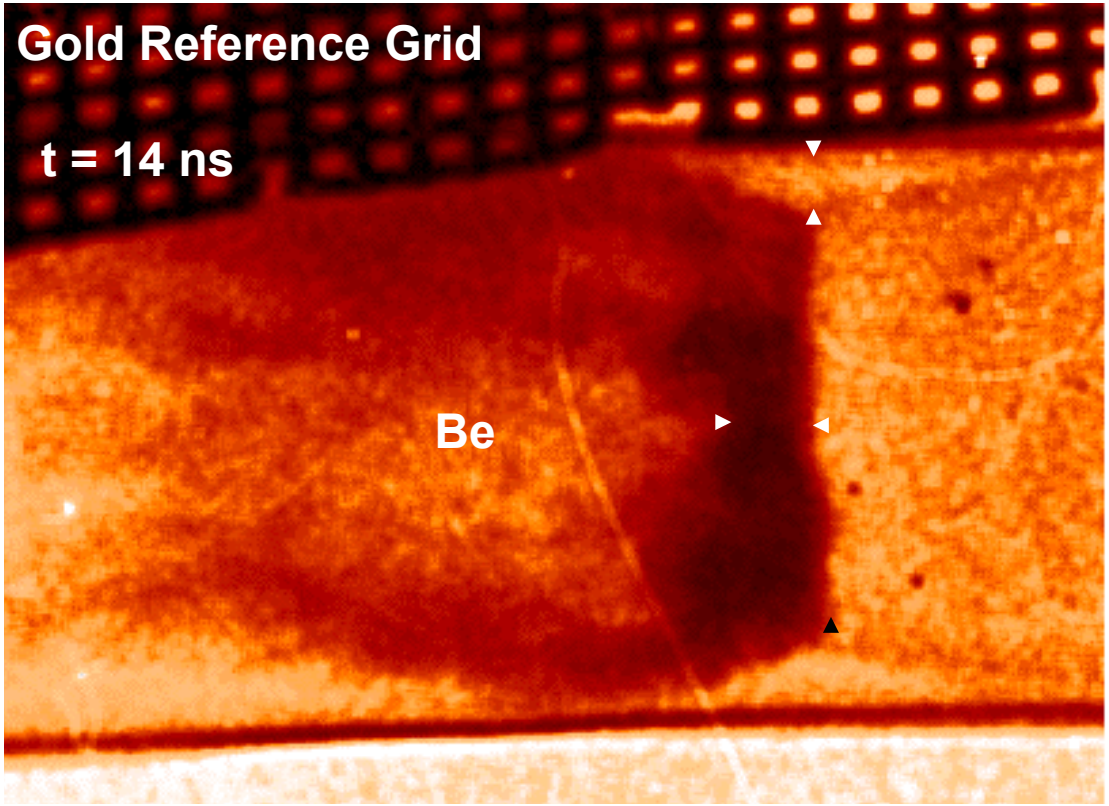
FLASH 2D simulation of a laser striking a very thin plastic target.

The CRASH experiments use 10 OMEGA beams to drive a radiative shock through Xenon



Several robust validation metrics can be extracted from the radiograph

Wall Shock Size

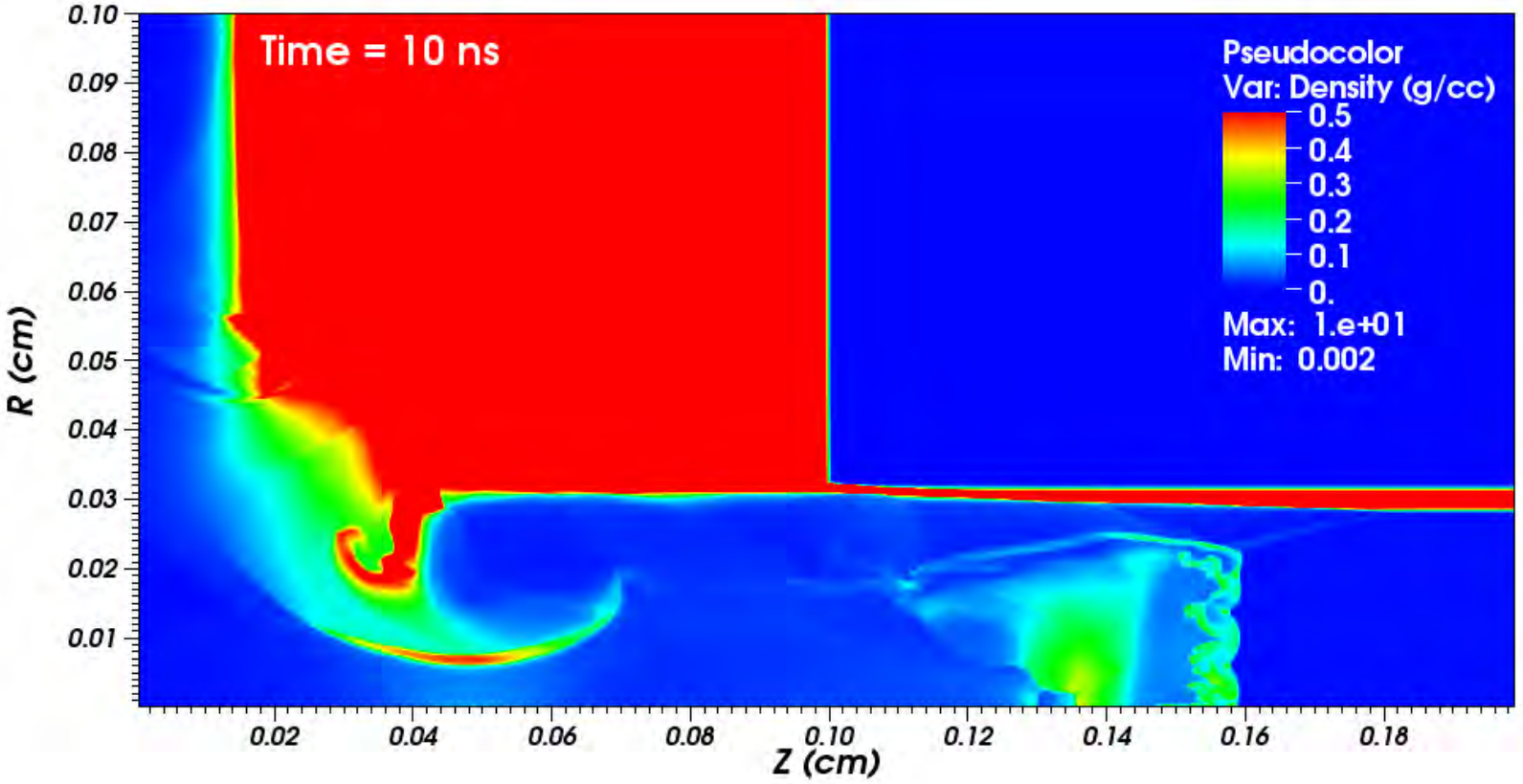


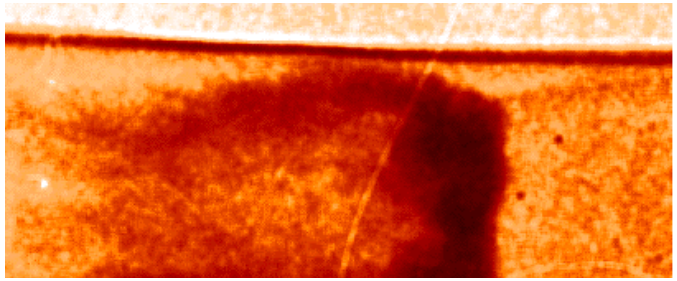
Compressed Xenon Thickness

Radiative Shock Position

Image Source: F. Doss, et al., *HEDP* 6, 157 (2010)

FLASH reduced materials simulation of CRASH radiative shock experiment





Summary

- FLASH is an open-source code being developed at the Flash Center. New capabilities have been added to FLASH to enable simulations of High Energy Density Physics (HEDP) experiments in support of the academic community.
- The Center has conducted a rigorous, systematic verification and validation of the capabilities needed to simulate radiative shocks in collaboration with U. Michigan, LANL, and LLNL.
- The Center is currently collaborating with HEDP groups at the University of Oxford, Ohio State University, the University of Wisconsin, the University of Michigan, the University of Texas, and Paris VI Ecole Polytechnique to design, analyze, and interpret experiments using FLASH.
- We encourage and support HEDP experimental groups to use FLASH.

See Fatenejad et al. poster and FLASH demonstrations