FLASH SIMULATIONS OF EXPERIMENTS TO EXPLORE THE GENERATION OF COSMOLOGICAL MAGNETIC FIELDS AT LABORATOIRE d'UTILISATION DES LASERS INTENSES (LULI)

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RAL Tutorial
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Summary

- Magnetic fields are ubiquitous in the intergalactic medium
- The Biermann Battery effect has been proposed as the mechanism by which intergalactic magnetic fields were originally produced[1]
- Recently, experiments[2] have demonstrated that astrophysically relevant magnetic fields are produced near asymmetric shock fronts through the Biermann Battery mechanism
- The results of 2D rad-hydro simulations, performed using the FLASH code, will be presented which demonstrate the complex hydrodynamic evolution of the experiments
- Significant challenges exist in directly modeling the Biermann Battery source term near shock fronts in MHD simulations

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[1]*Kulsrud and Zweibel, Rep Prog Phys, 71, 046901 (2008)*

[2]*Gregori, et al., Nature, 481, 480 (2012)*

Magnetic fields are ubiquitous in the intergalactic medium

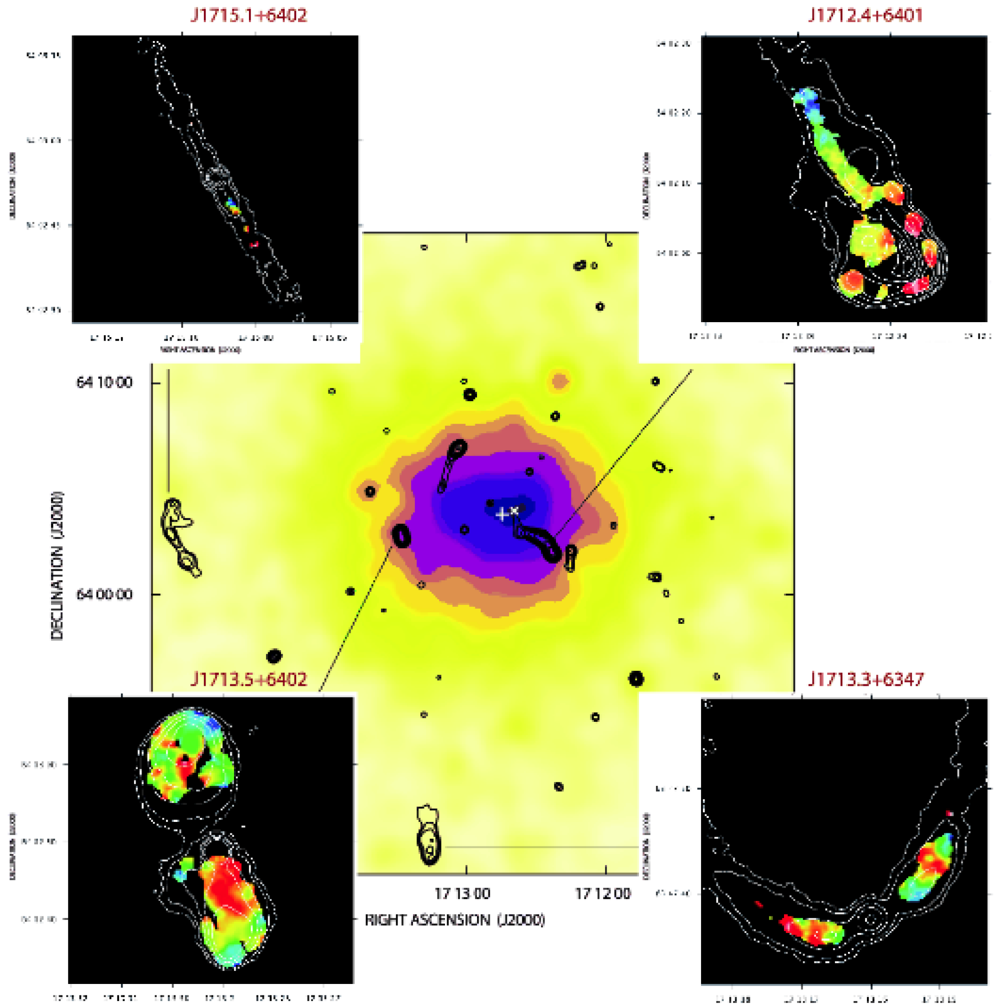


Image Source:
Govoni et al., Astronomy & Astrophysics 260, 425 (2006)

Magnetic fields are generated through the Biermann Battery mechanism when pressure/density gradients are not aligned

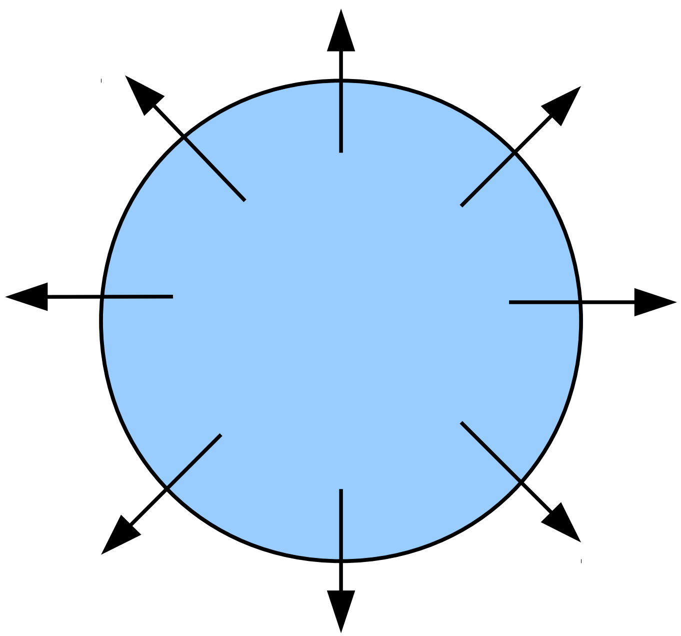
- **The generalized Ohm's law sets the strength of the electric field in the MHD approximation. Only the Battery term can produce magnetic fields from an initially unmagnetized plasma:**

$$\boldsymbol{E} = \boldsymbol{u} \times \boldsymbol{B} + \eta \boldsymbol{j} + \frac{1}{n_e e} \boldsymbol{j} \times \boldsymbol{B} - \frac{\nabla P_e}{e n_e}$$

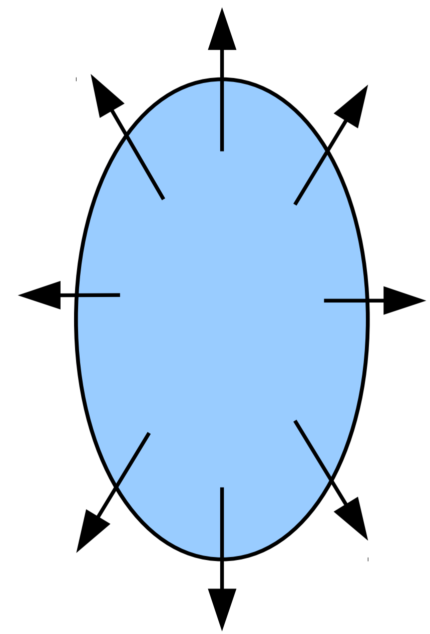
- **Faraday's law relates the electric field to the rate of change of the magnetic field:**

$$\left(\frac{\partial \boldsymbol{B}}{\partial t} \right)_{Biermann} = c \nabla \times \left(\frac{\nabla P_e}{e n_e} \right) = c \frac{\nabla P_e \times \nabla n_e}{e n_e^2}$$

Asymmetric shocks generate vorticity[1] and will generate magnetic fields through the Biermann Battery mechanism



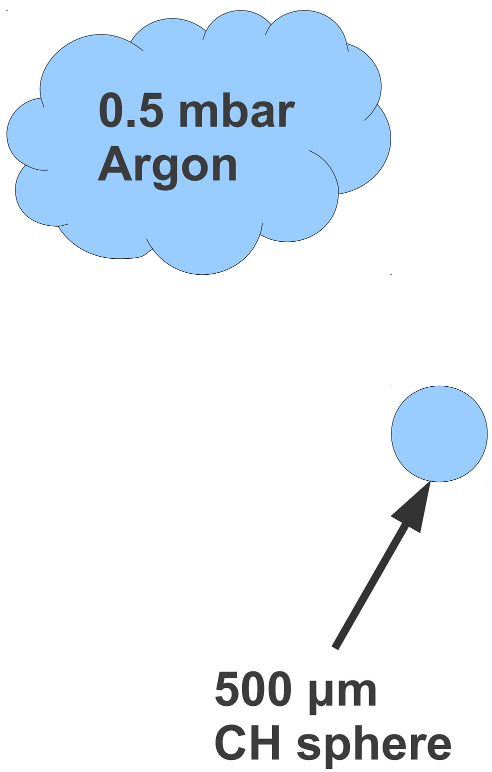
Symmetric Shock
No magnetic field



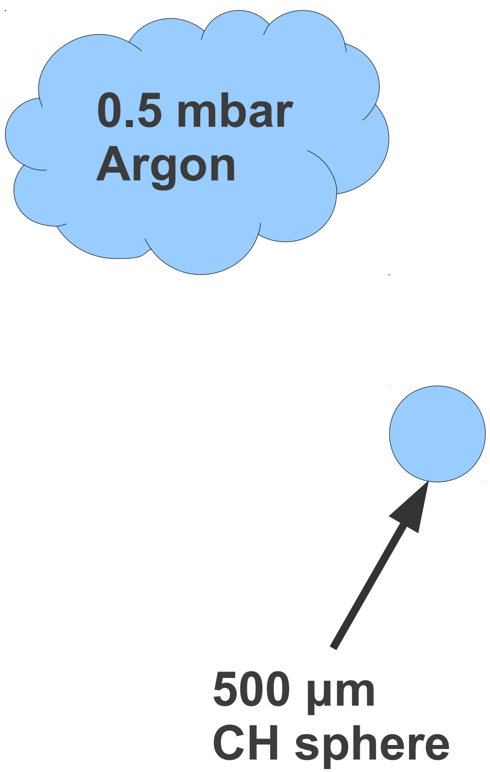
Asymmetric Shock
Magnetic field produced downstream

[1]*Hayes, J Fluid Mech, 2, 595 (1957)*

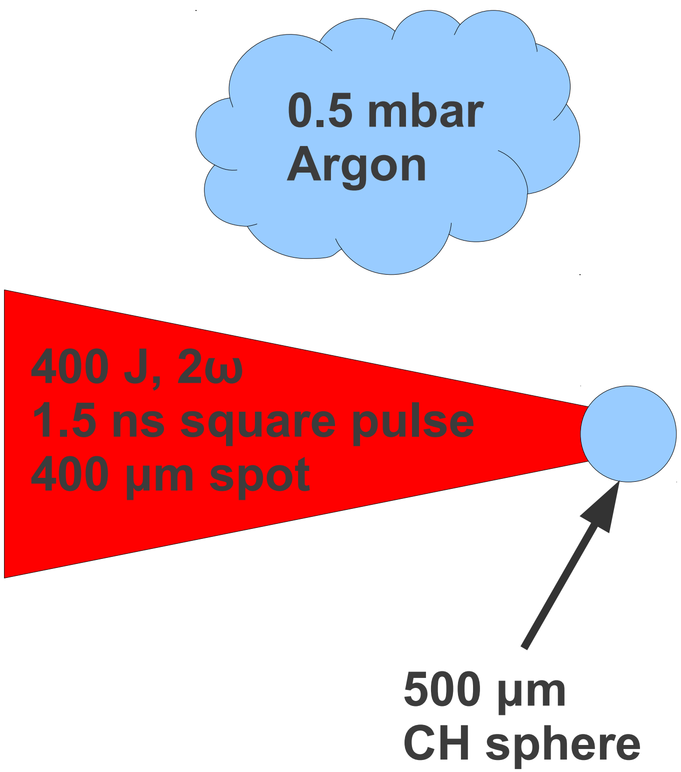
A 400 J, 1 ns square pulse illuminates a plastic sphere in an Argon filled chamber



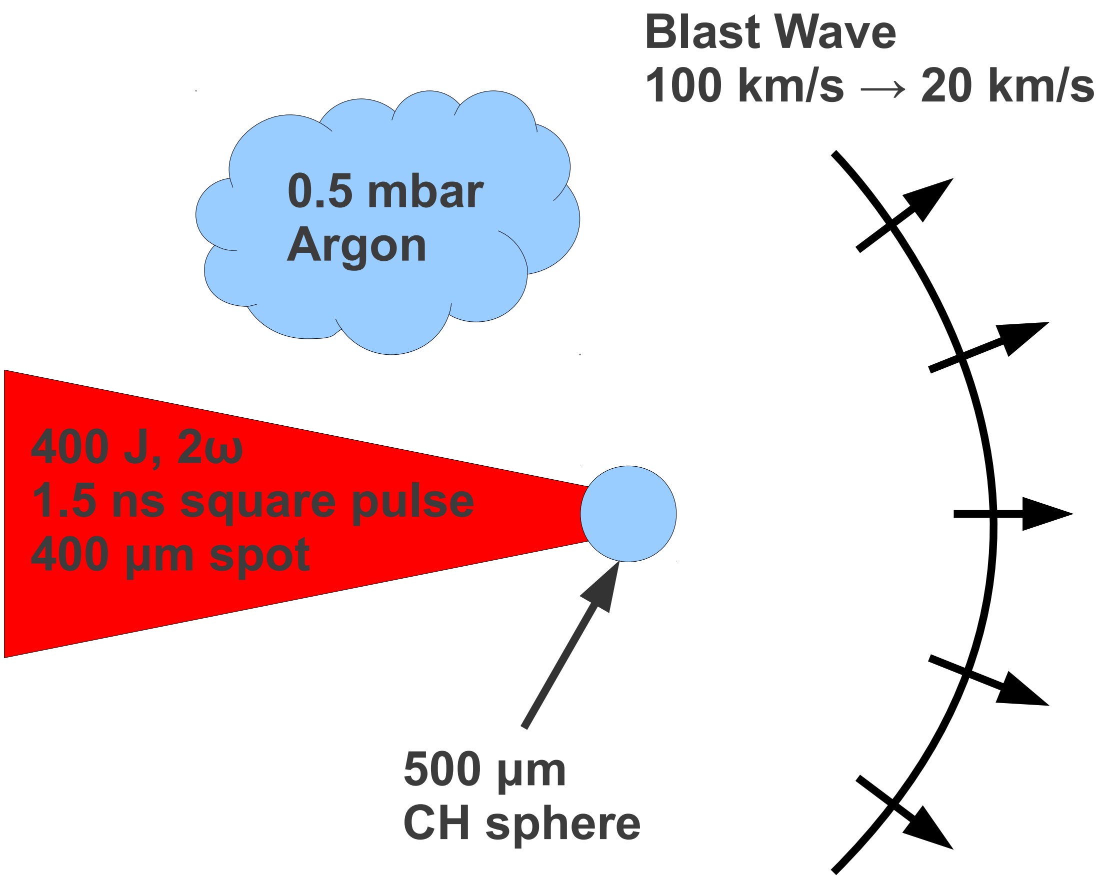
A 400 J, 1 ns square pulse illuminates a plastic sphere in an Argon filled chamber

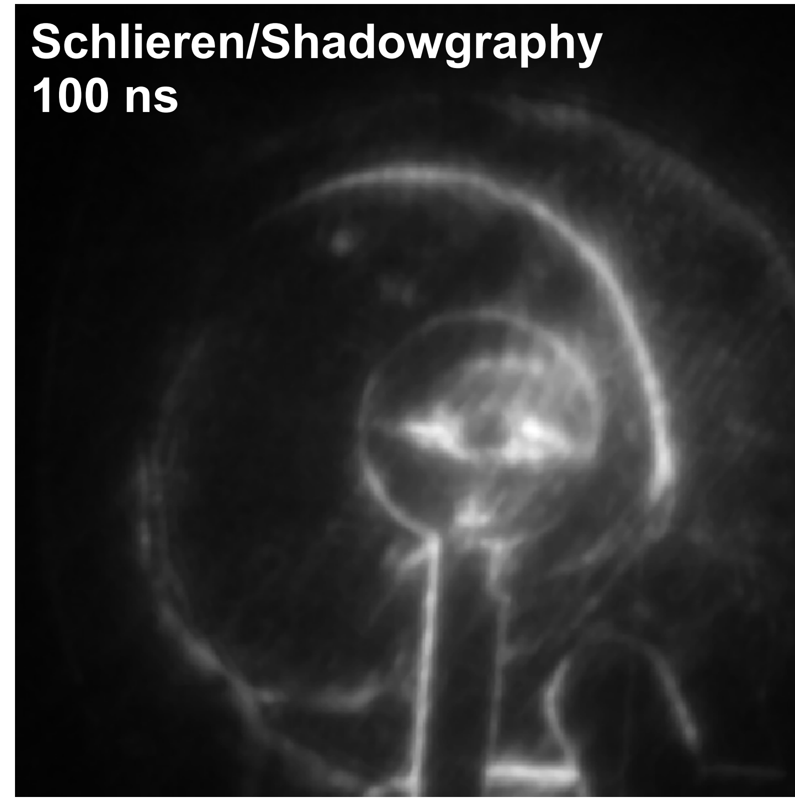


A 400 J, 1.5 ns square pulse illuminates a plastic sphere in an Argon filled chamber

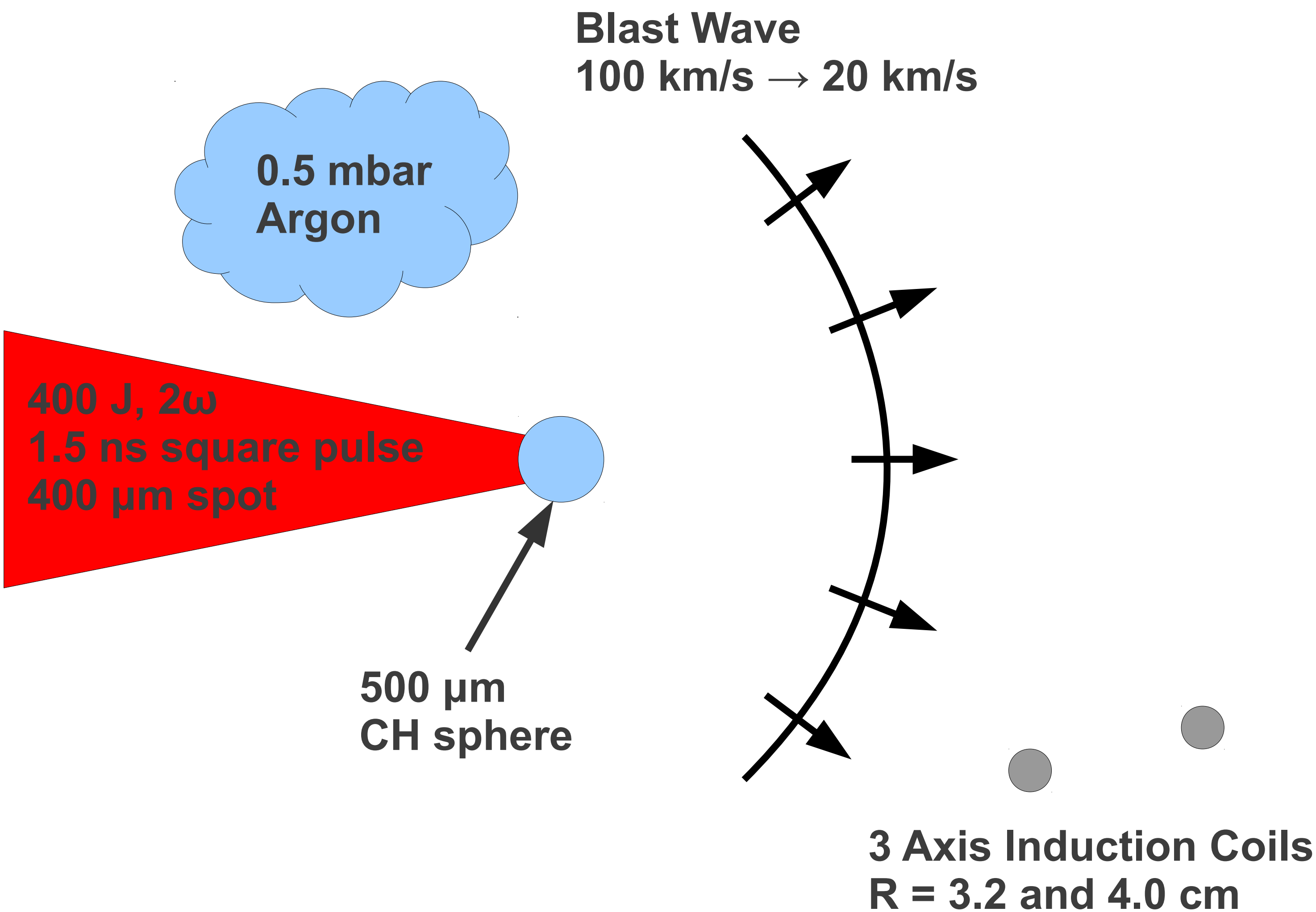


A blast wave is generated which initially travels at ~100 km/s but slows over time

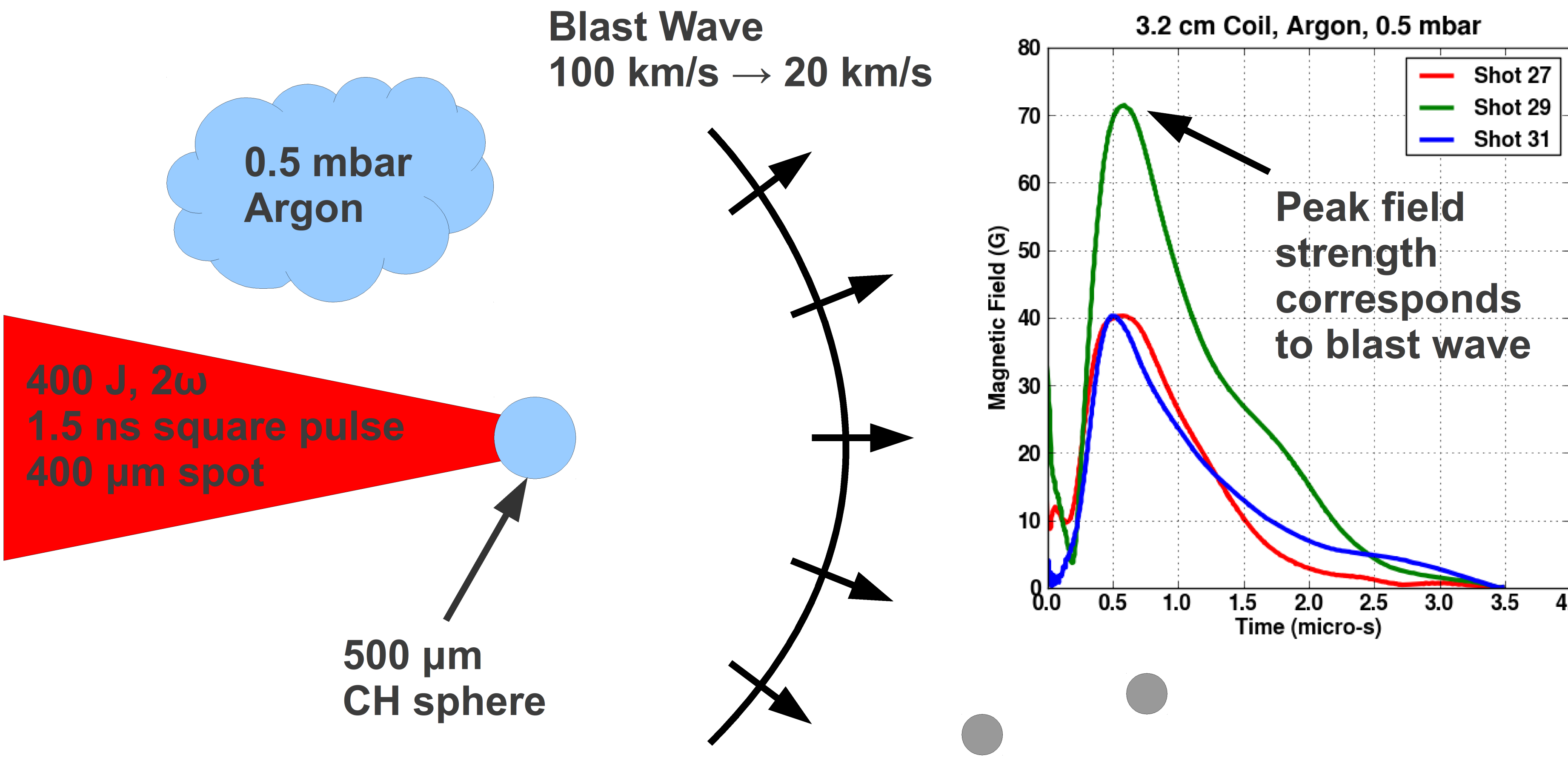




The blast wave travels past two 3-axis induction coils which measure magnetic field strength

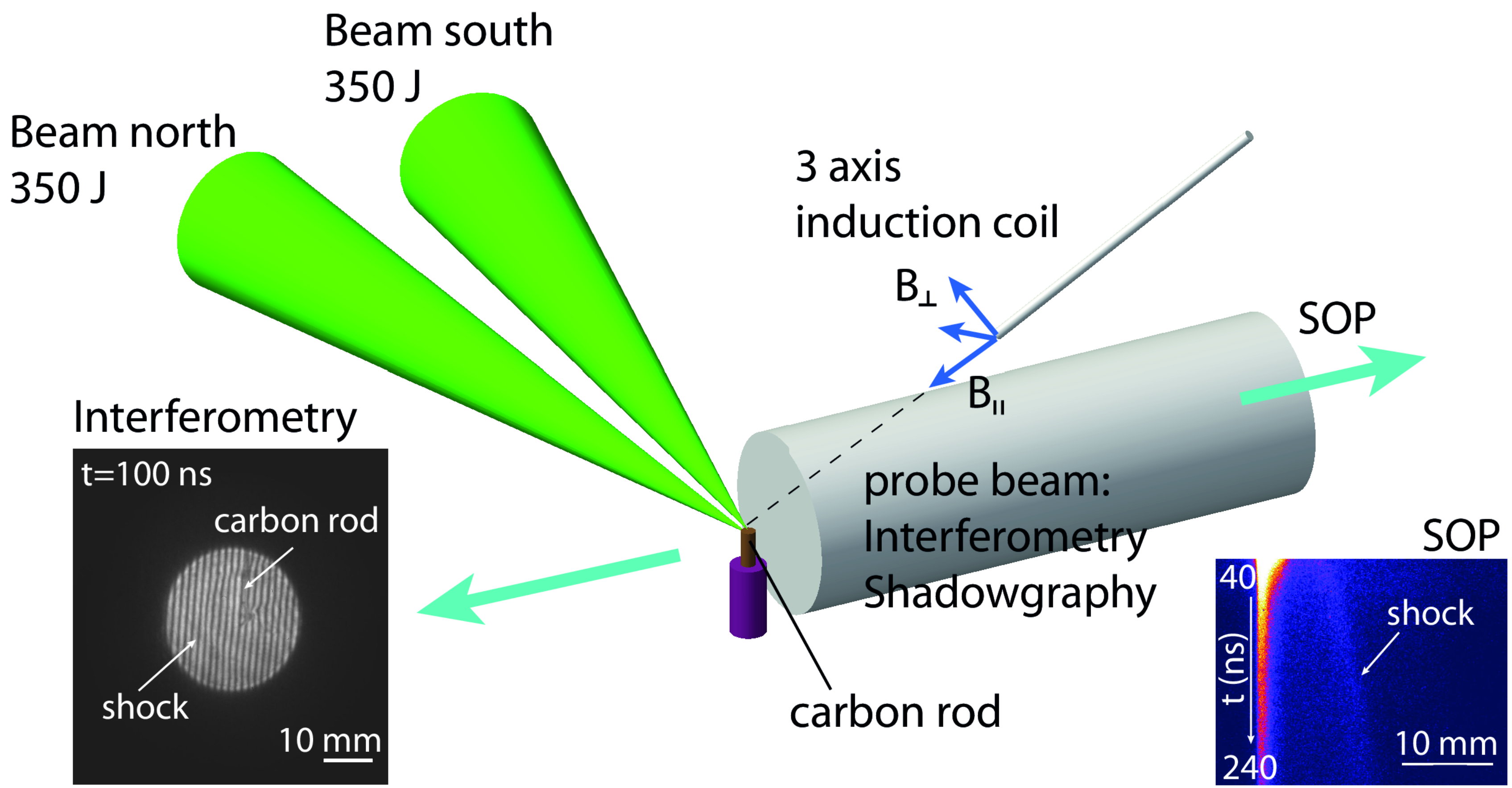


The coils provide time dependent measurements which show field strengths of 10's of Gauss



3 Axis Induction Coils
R = 3.2 and 4.0 cm

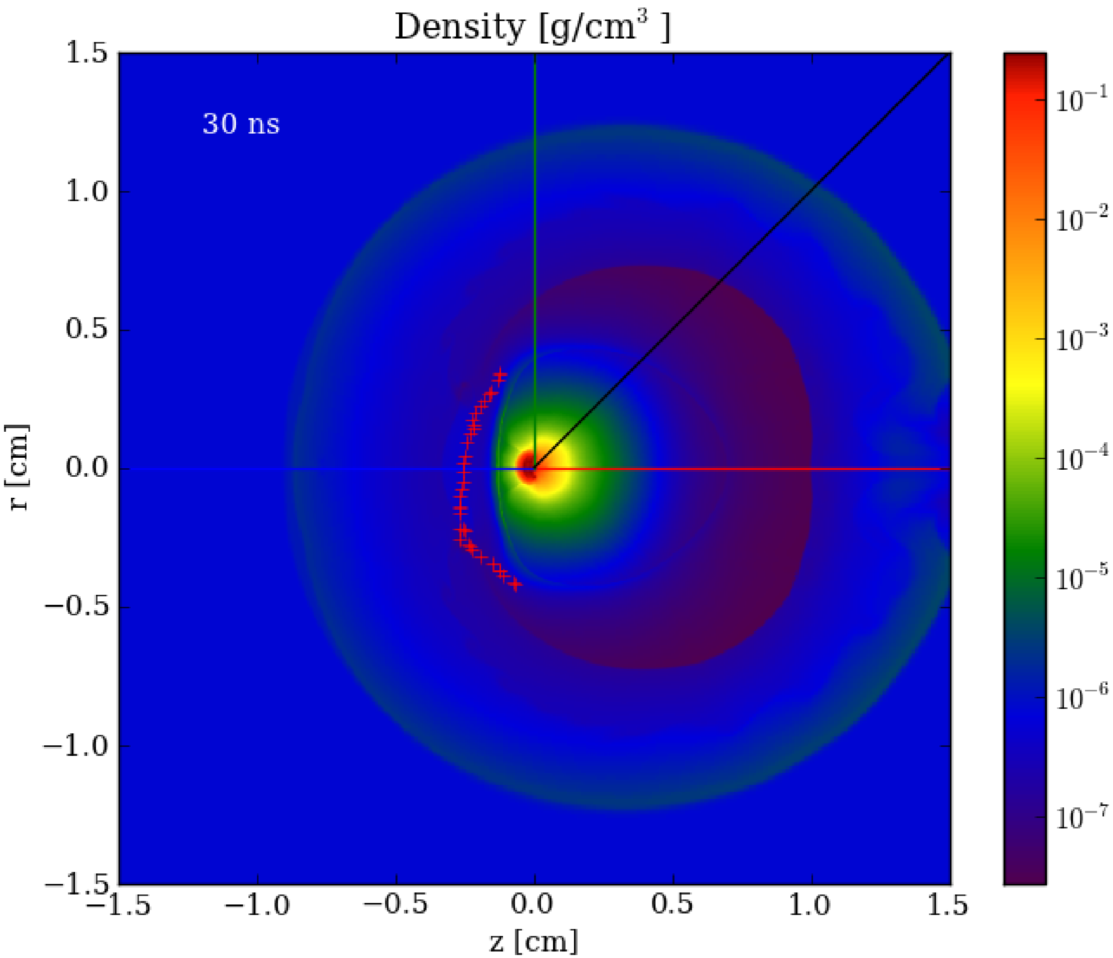
Experimental Setup

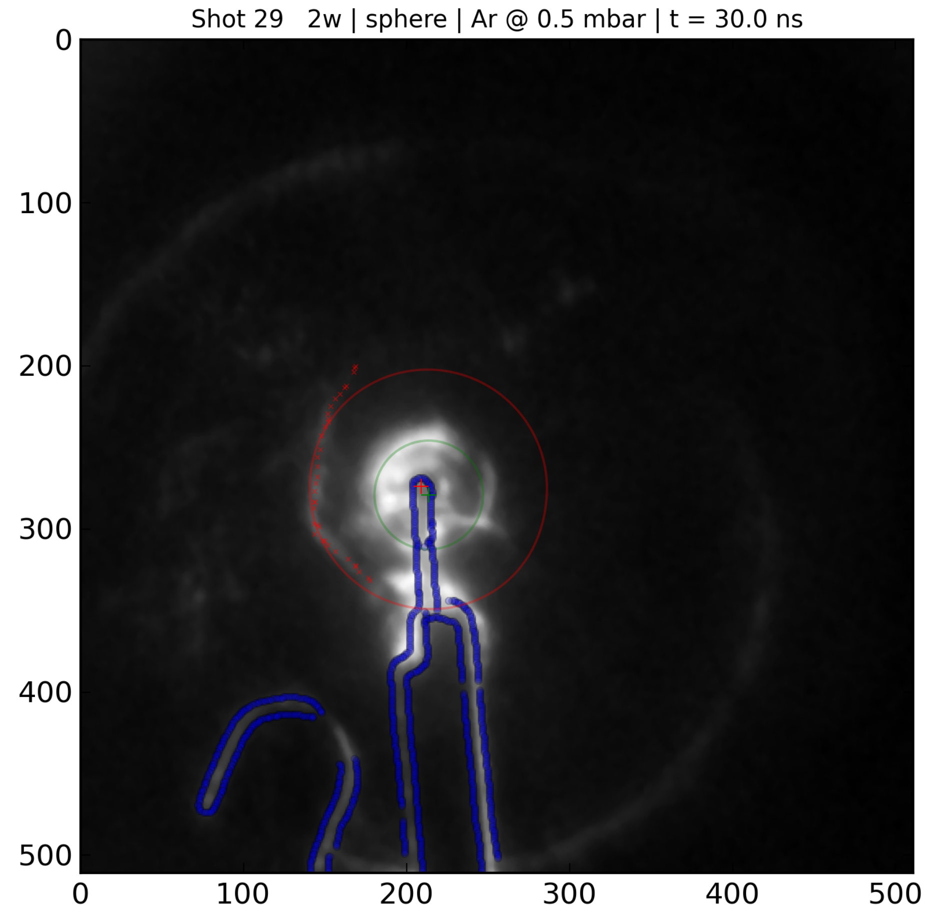


FLASH simulations have been performed to help interpret the results of the experiment

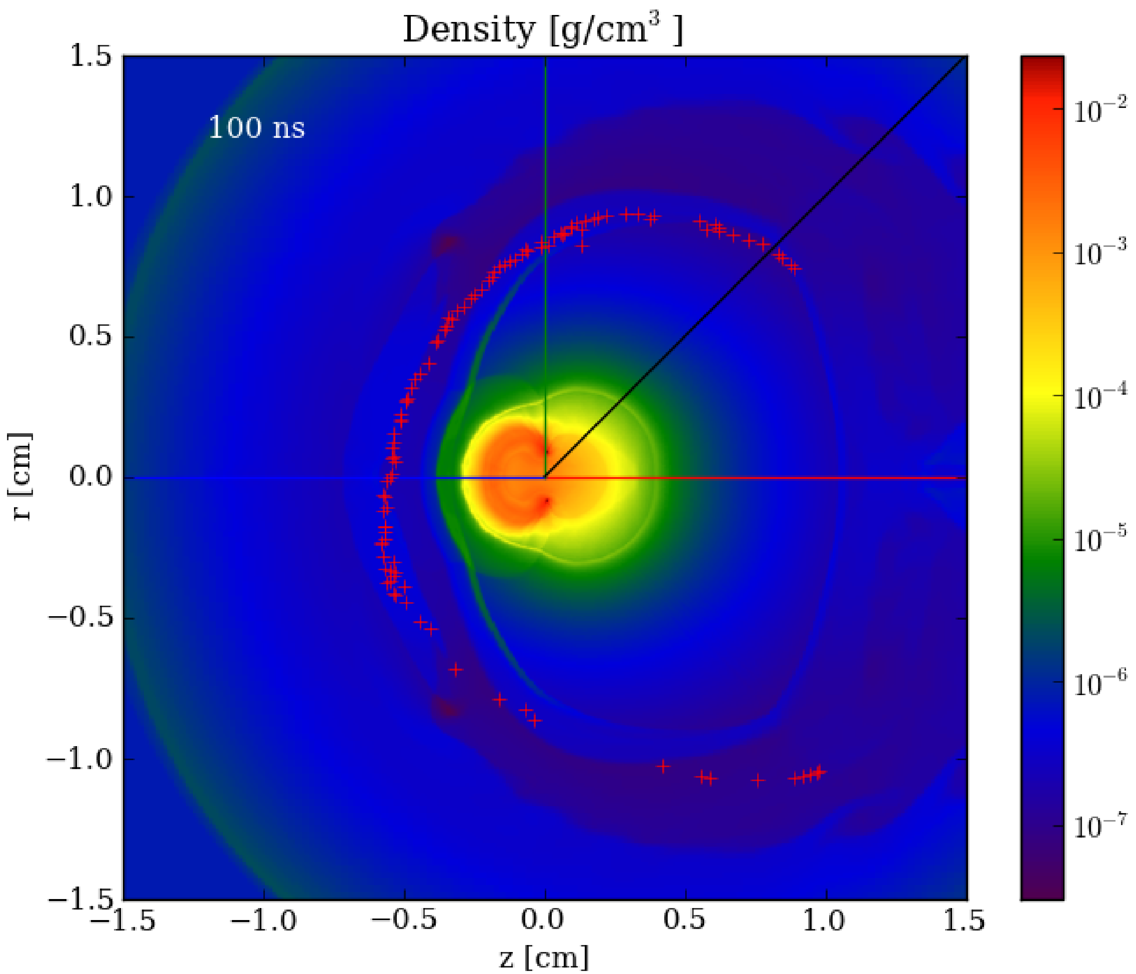
- Measured fields do not significantly affect the hydrodynamic flow
- 2D cylindrical FLASH radiation hydrodynamics experiments have revealed complex behavior
  - 3T Eulerian Hydrodynamics on AMR mesh
  - Laser Energy Deposition via ray tracing
  - Flux-limited multigroup radiation diffusion
  - Thermal conduction
  - Tabulated EOS/opacity with treatment of mixed material cells
    - Argon is relatively cool ($T_e < 1$ eV), at late times. Accurately modeling the EOS and opacity of Argon and CH at remains challenging
- End-to-end simulations have been performed which model the laser energy deposition ($t < 1.5$ ns) and are carried to late times ($t = 10$ μs)

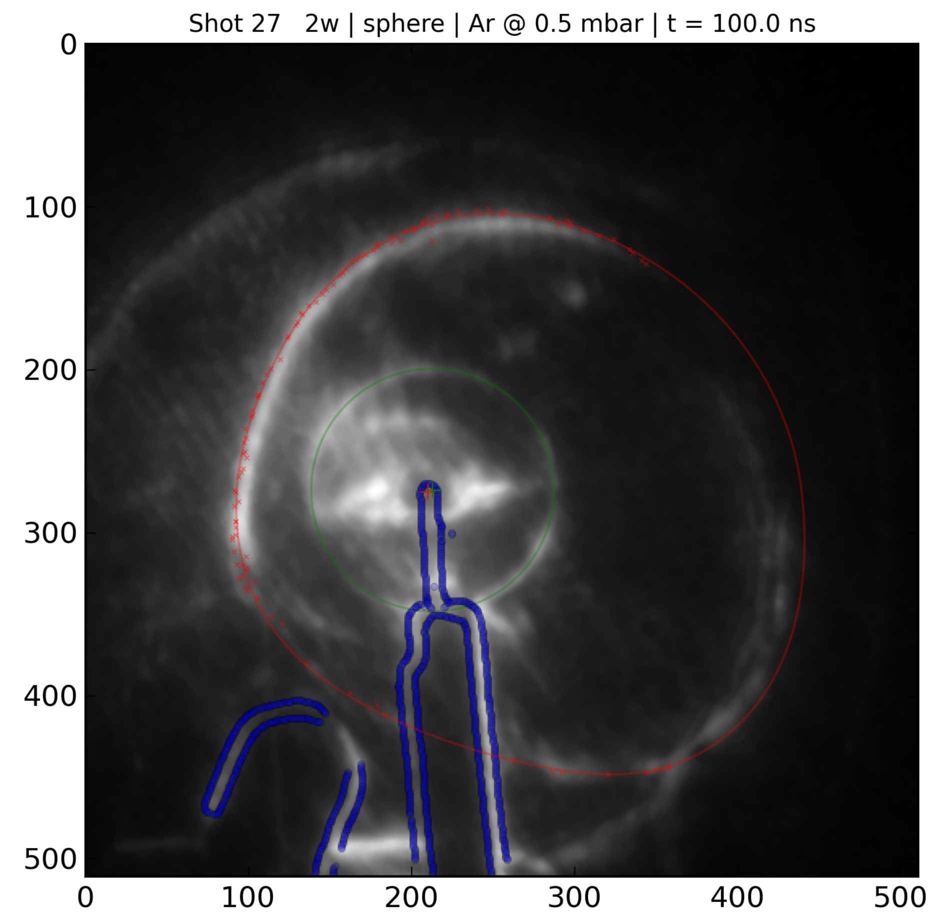
Laser ablates a small fraction of the plastic sphere and launches a shock into the Argon gas and the target



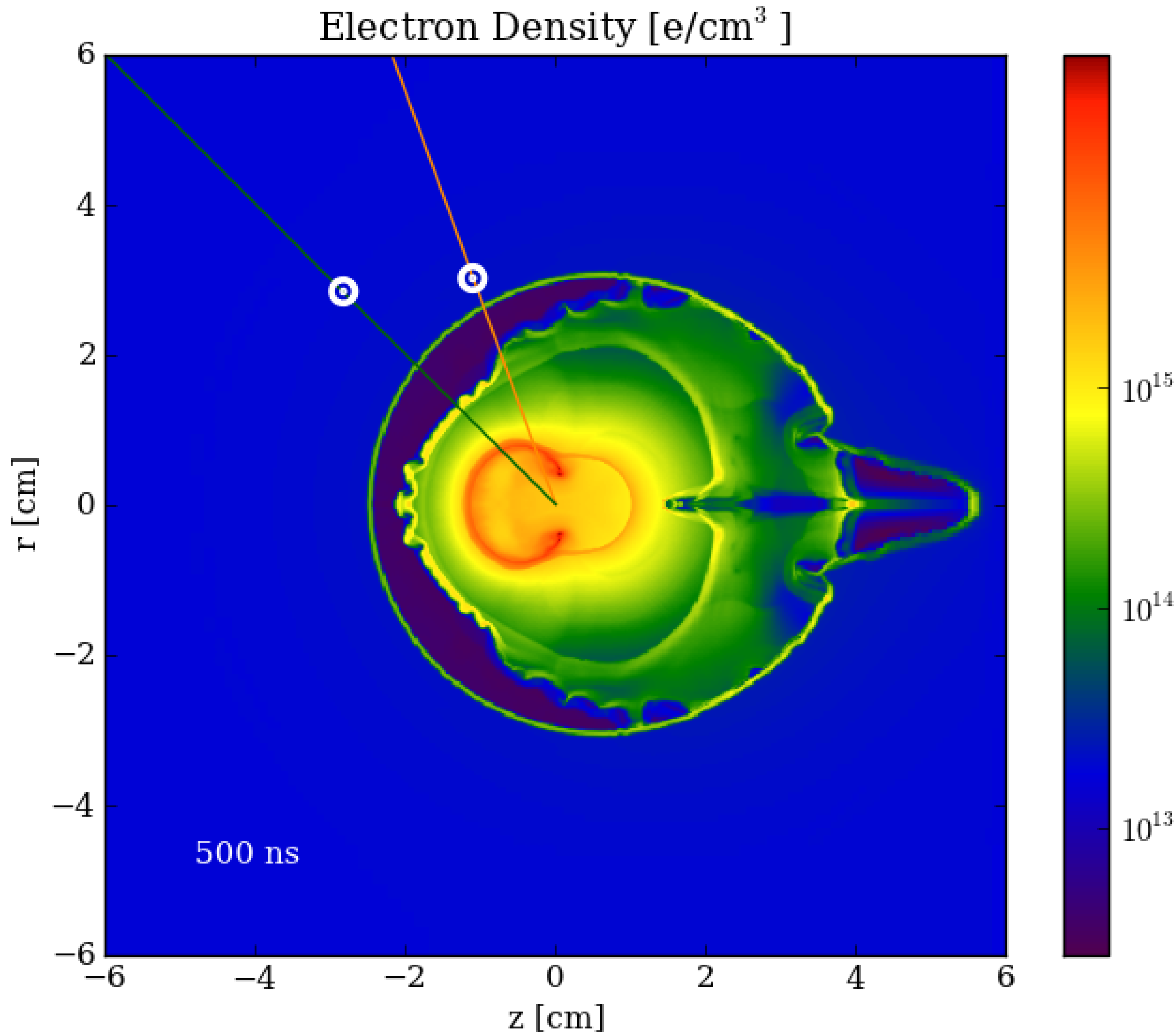


These features evolve revealing fairly complex structure at later times

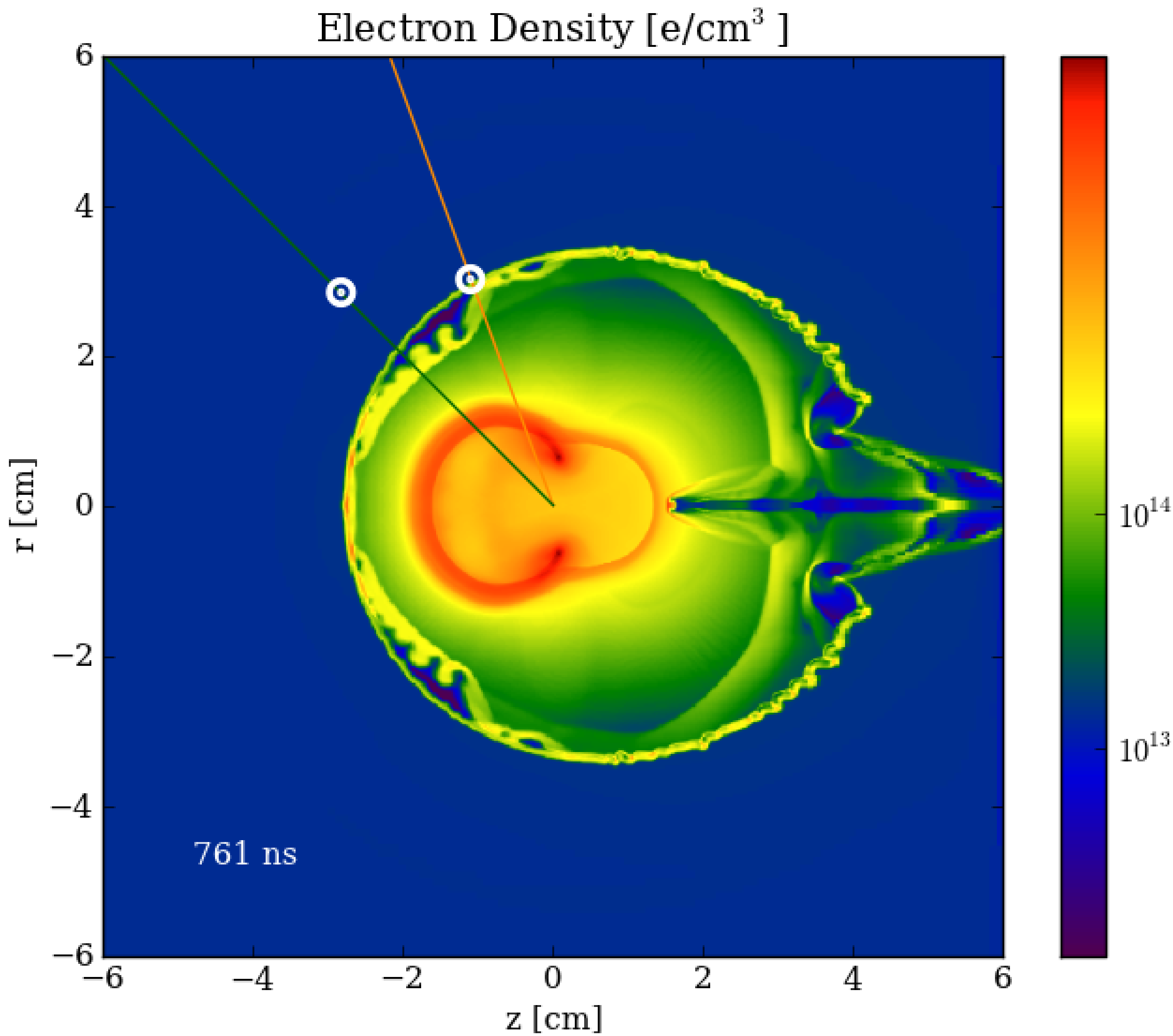




At the time the shock crosses the near probe in the experiment



At the time the shock crosses the far probe in the experiment



This may be better seen in a movie

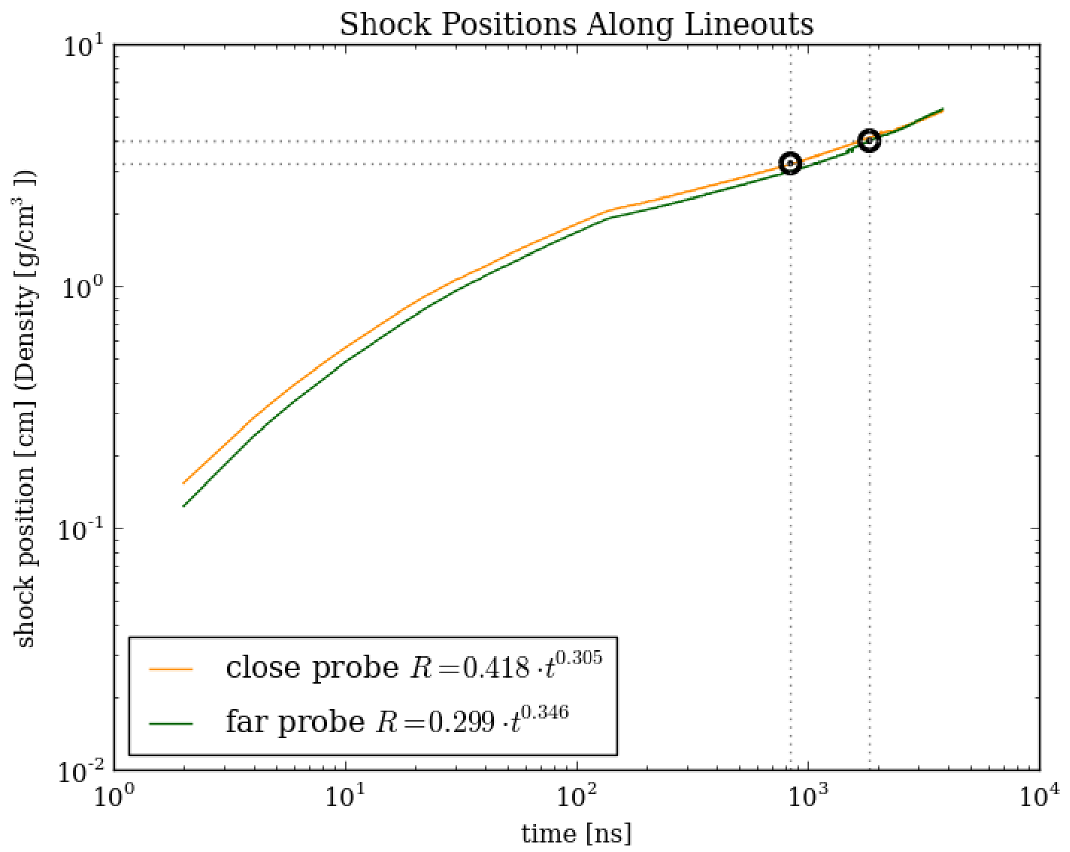
See luli-400J-big_edens.mpg

Shock position changes with angle from r-axis

- **One method of calibrating the simulation to the experiment is when the shock hits the coils.**
- **The shock position follows a standard power law before slowing down.**

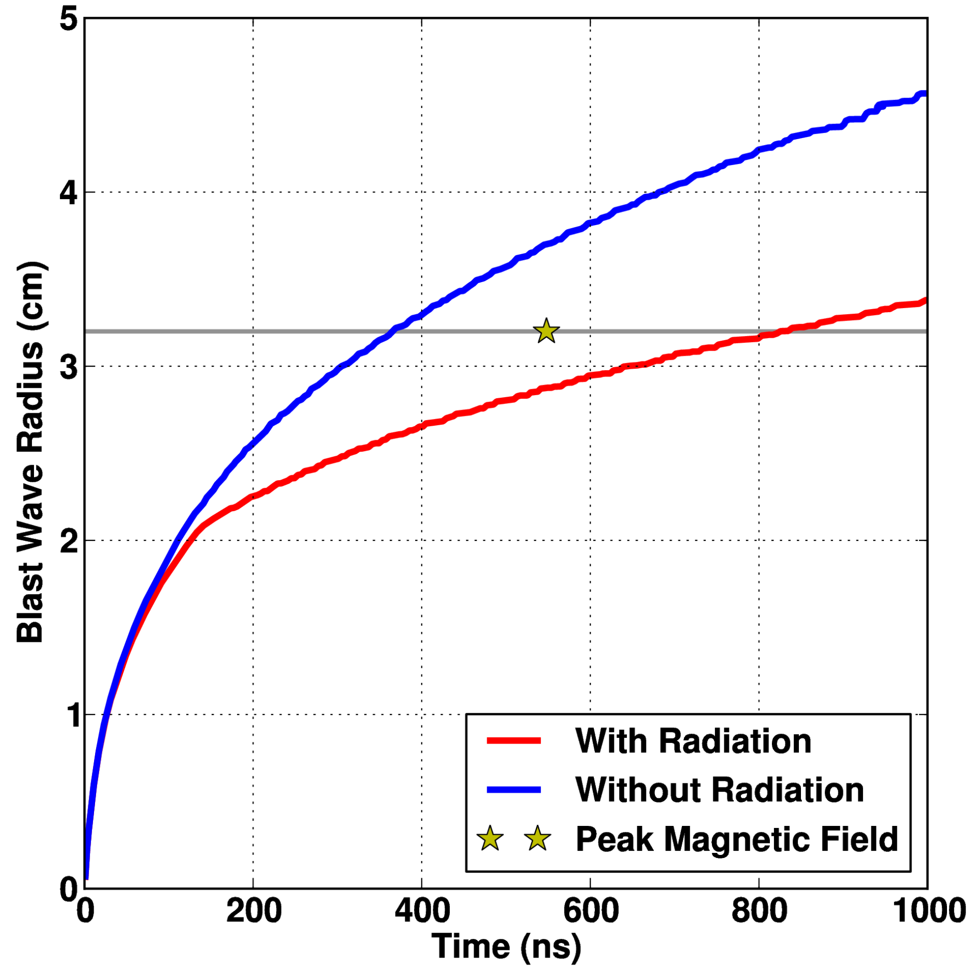
$$R = R_0 \cdot t^{\alpha}$$

- **Neither of the shocks hits its target at the appropriate time.**



Simulations with and without radiation bracket the experimental shock position measured using 3-axis coils

- Radiation preheats the Argon, affecting the shock speed
- Simulations without radiation produce too fast a shock, while preliminary radiation diffusion simulations produce too slow a shock
- Future simulations will explore the accuracy of EOS and opacity at low temperatures ($T_e < 1$ eV)
- We will also generate simulated diagnostic responses with FLASH to directly compare to experimental results



We may also compare the rad/no-rad domains

See luli-rad_no-rad_compare_edens.mpg

Summary

- The Biermann Battery effect has been proposed as the mechanism by which galactic magnetic fields were originally produced
- Recently, experiments[1] have demonstrated that astrophysically relevant magnetic fields are produced near shock fronts through the Biermann Battery mechanism
- The results of 2D rad-hydro simulations, performed using the FLASH code, will be presented which demonstrate the complex hydrodynamic evolution of the experiments
  - Simulated responses will be used to compare directly to diagnostics
  - Use more accurate opacity/EOS tables
- Significant challenges exist in directly modeling the Biermann Battery source term near shock fronts in MHD simulations

Gregori, et al., Nature, 481, 480 (2012)