FLASH SIMULATIONS OF EXPERIMENTS TO EXPLORE THE GENERATION OF COSMOLOGICAL MAGNETIC FIELDS

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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

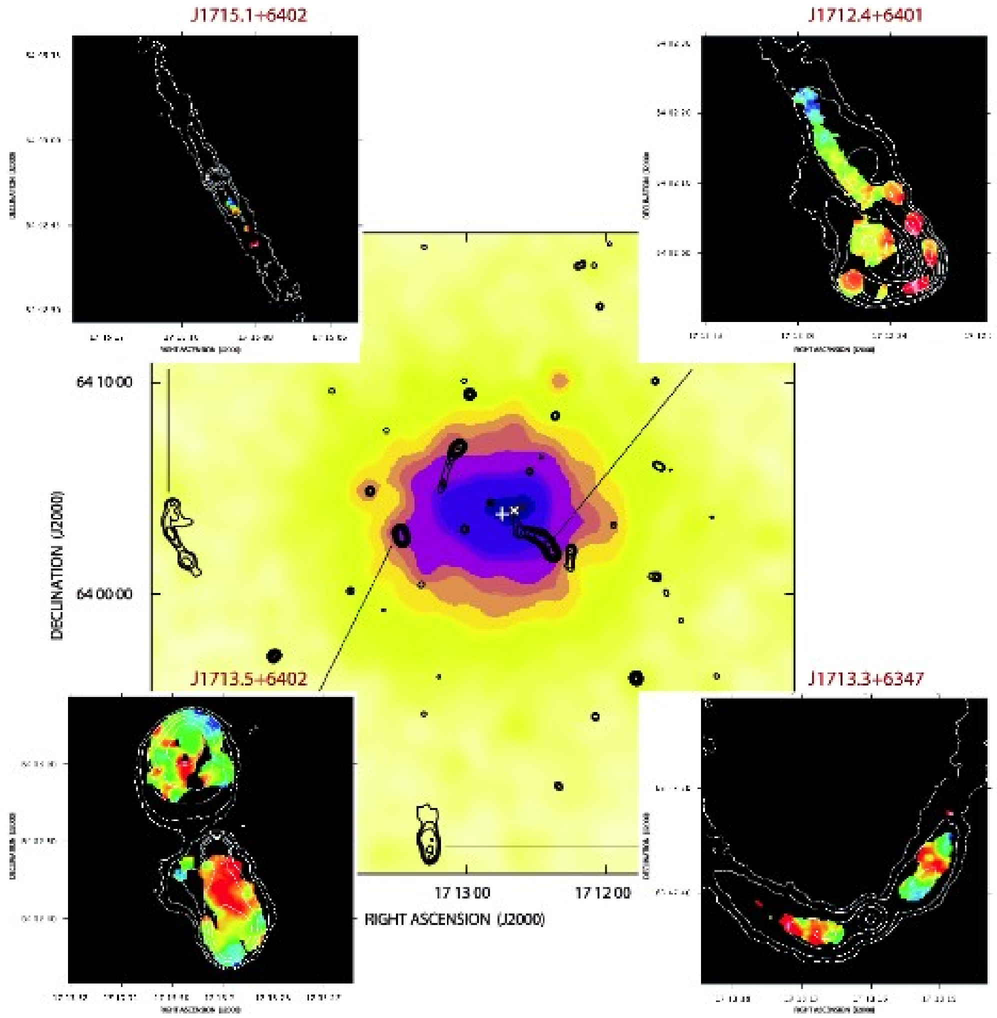


Image Source:
Govoni et al., Astronomy & Astrophysics 260, 425 (2006)

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

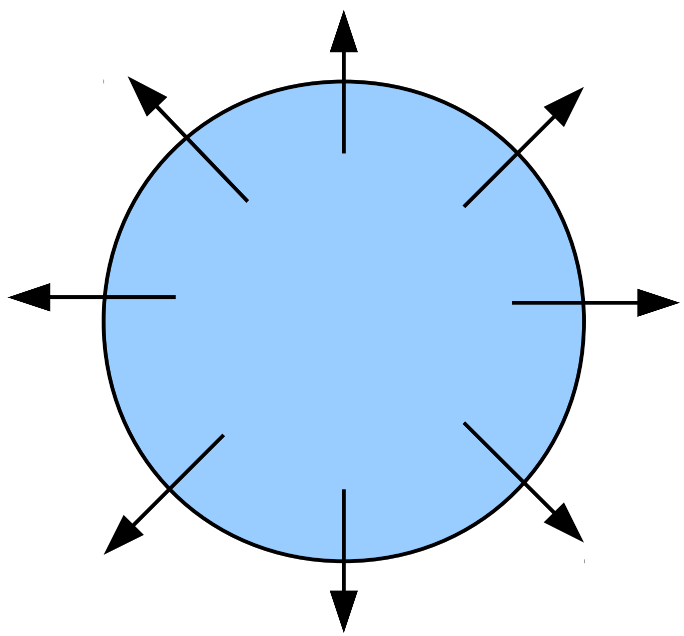
- **The generalized Ohm's law sets the strength of the electric field in the MHD approximation. Only the Battery term can produce magnetic fields from an initially unmagnetized plasma:**

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

- **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

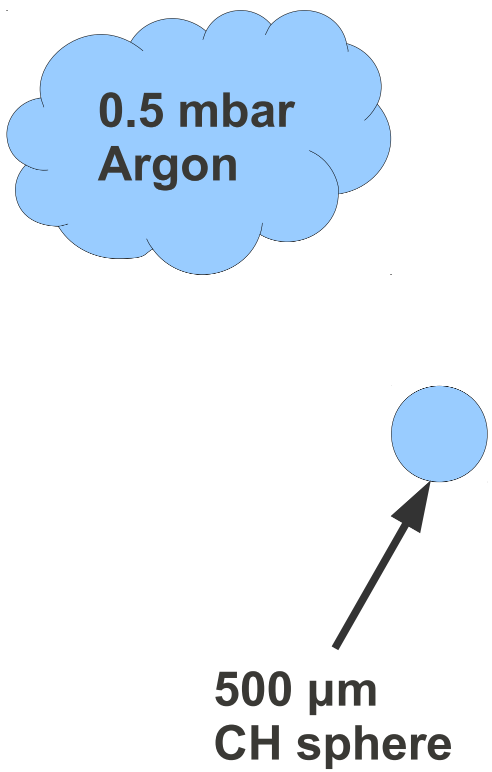


Symmetric Shock
No magnetic field

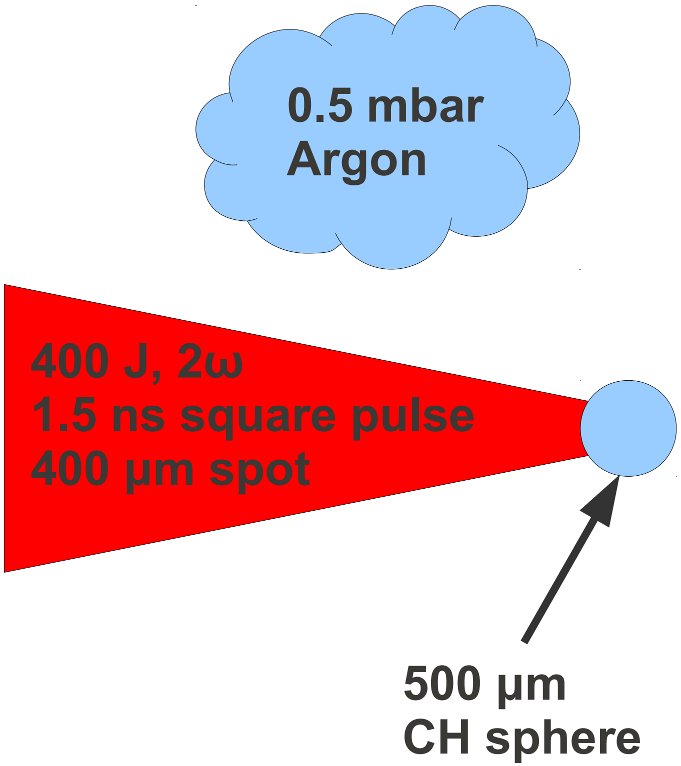
Asymmetric Shock
Magnetic field produced downstream

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

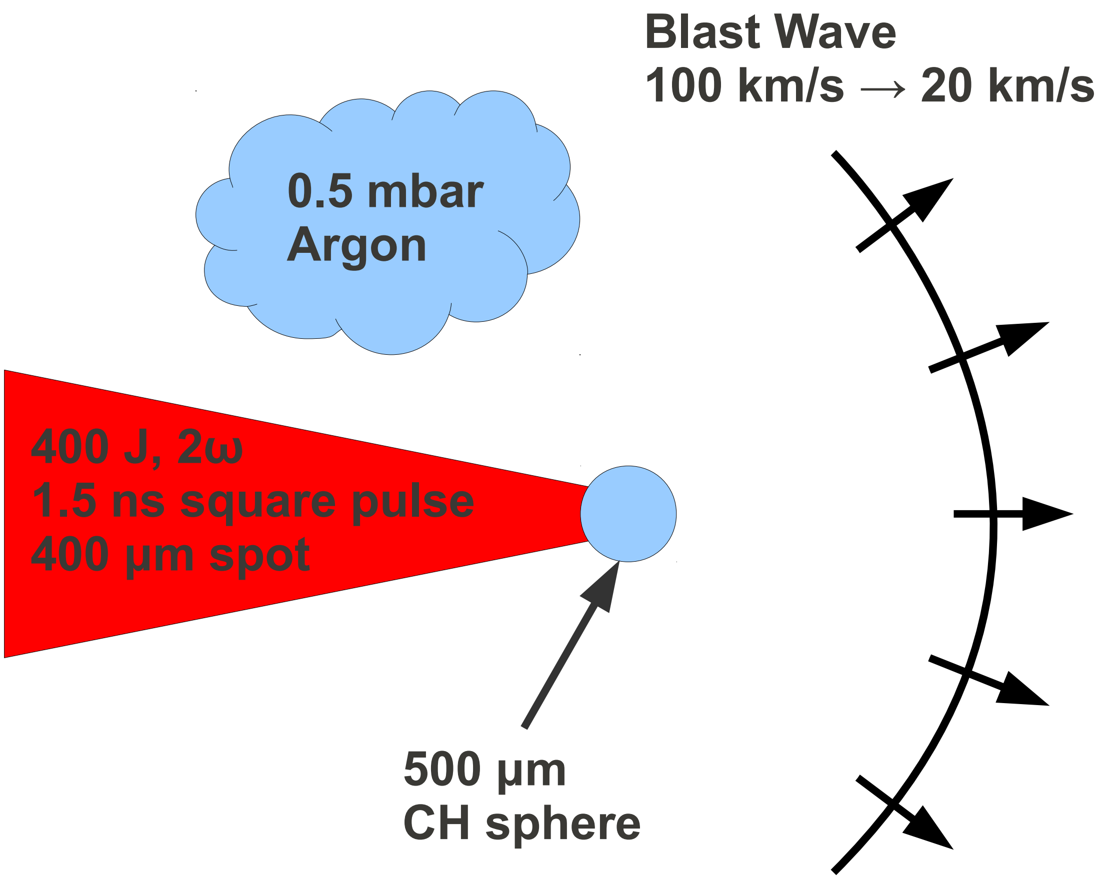
A 400 J, 1 ns square pulse illuminates a plastic sphere in an Argon filled chamber

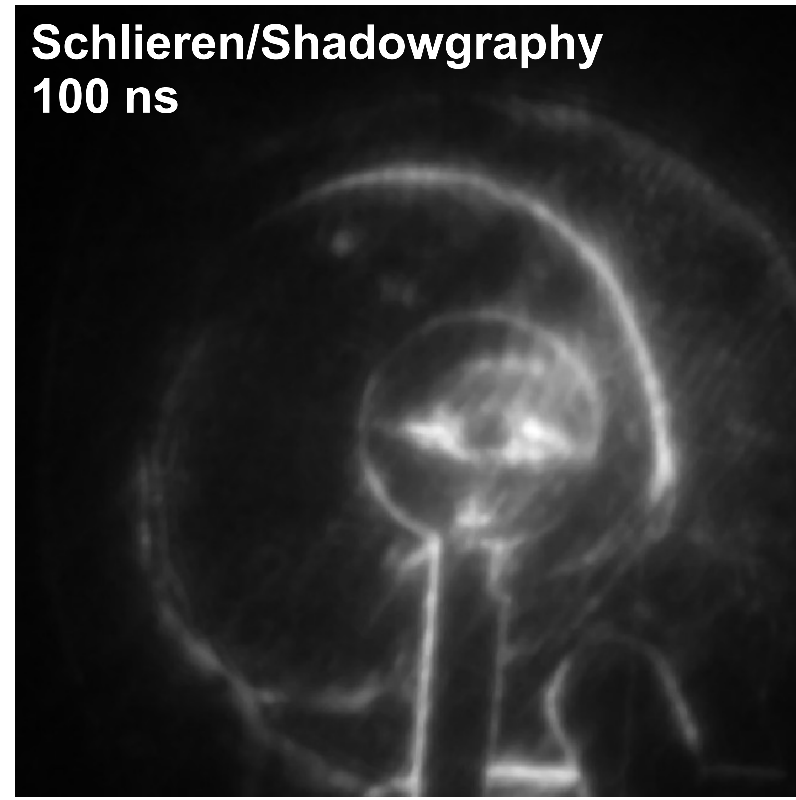


A 400 J, 1.5 ns square pulse illuminates a plastic sphere in an Argon filled chamber

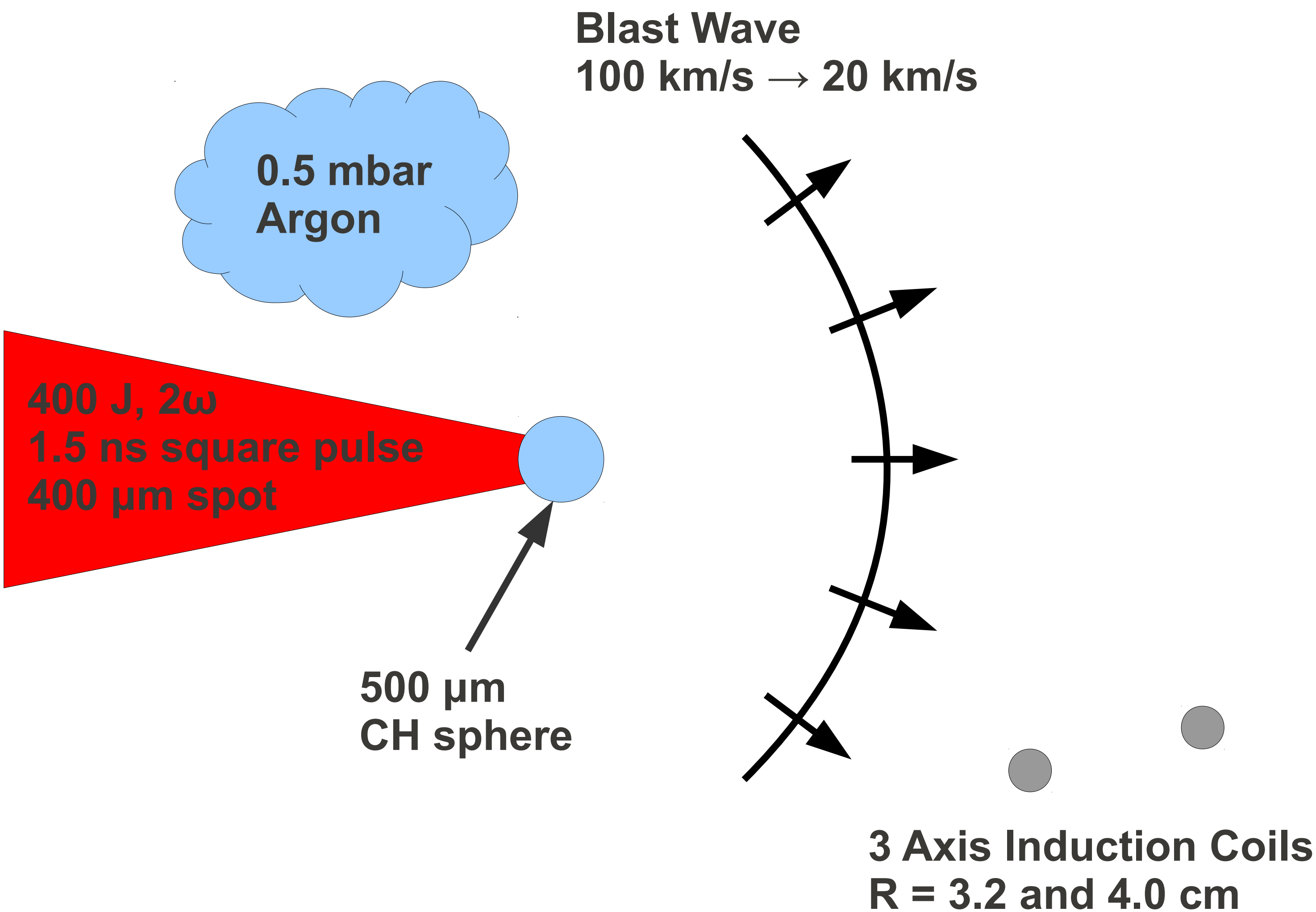


A blast wave is generated which initially travels at ~100 km/s but slows over time

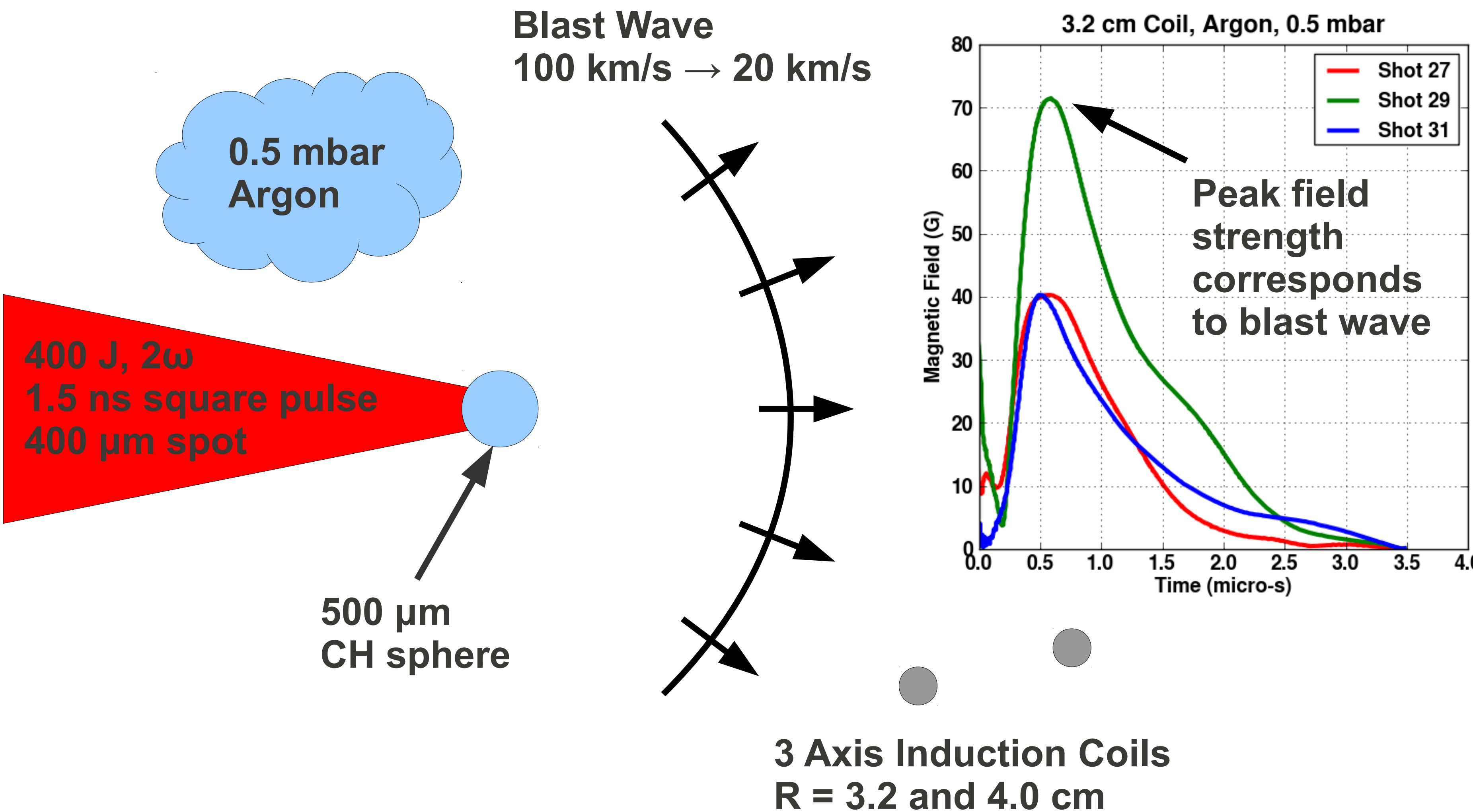




The blast wave travels past two 3-axis induction coils which measure magnetic field strength



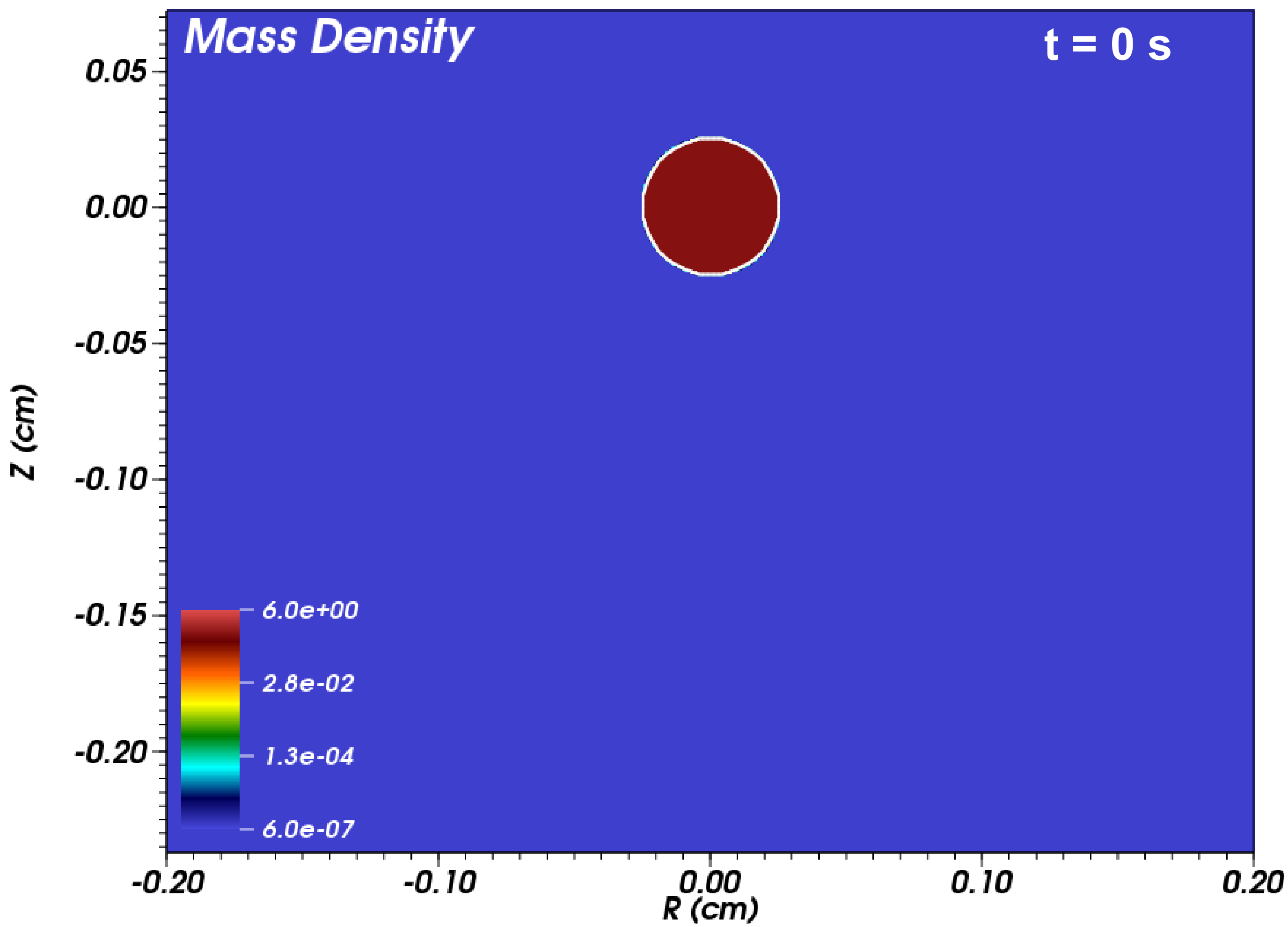
The coils provide time dependent measurements which show field strengths of 10's of Gauss



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



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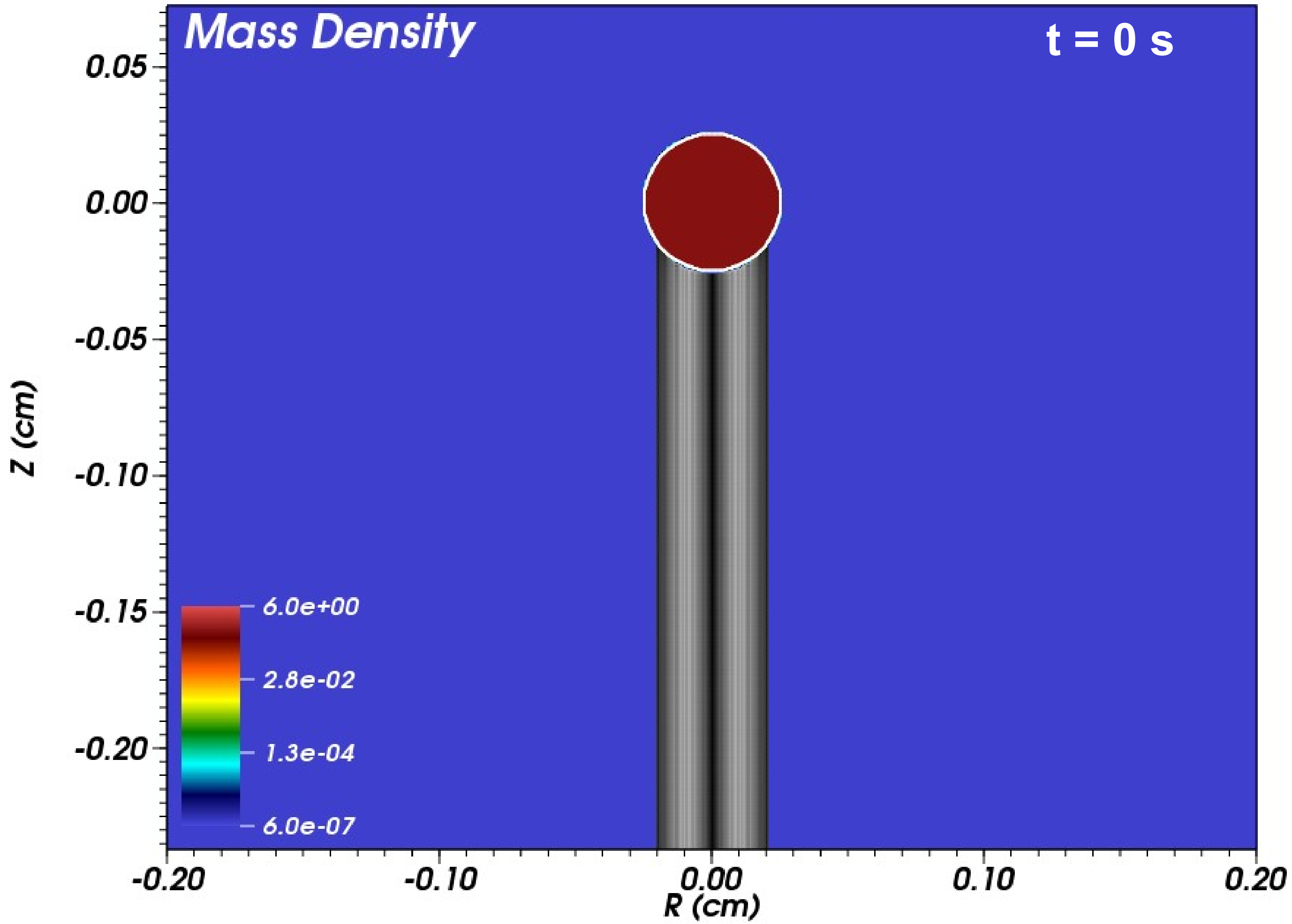

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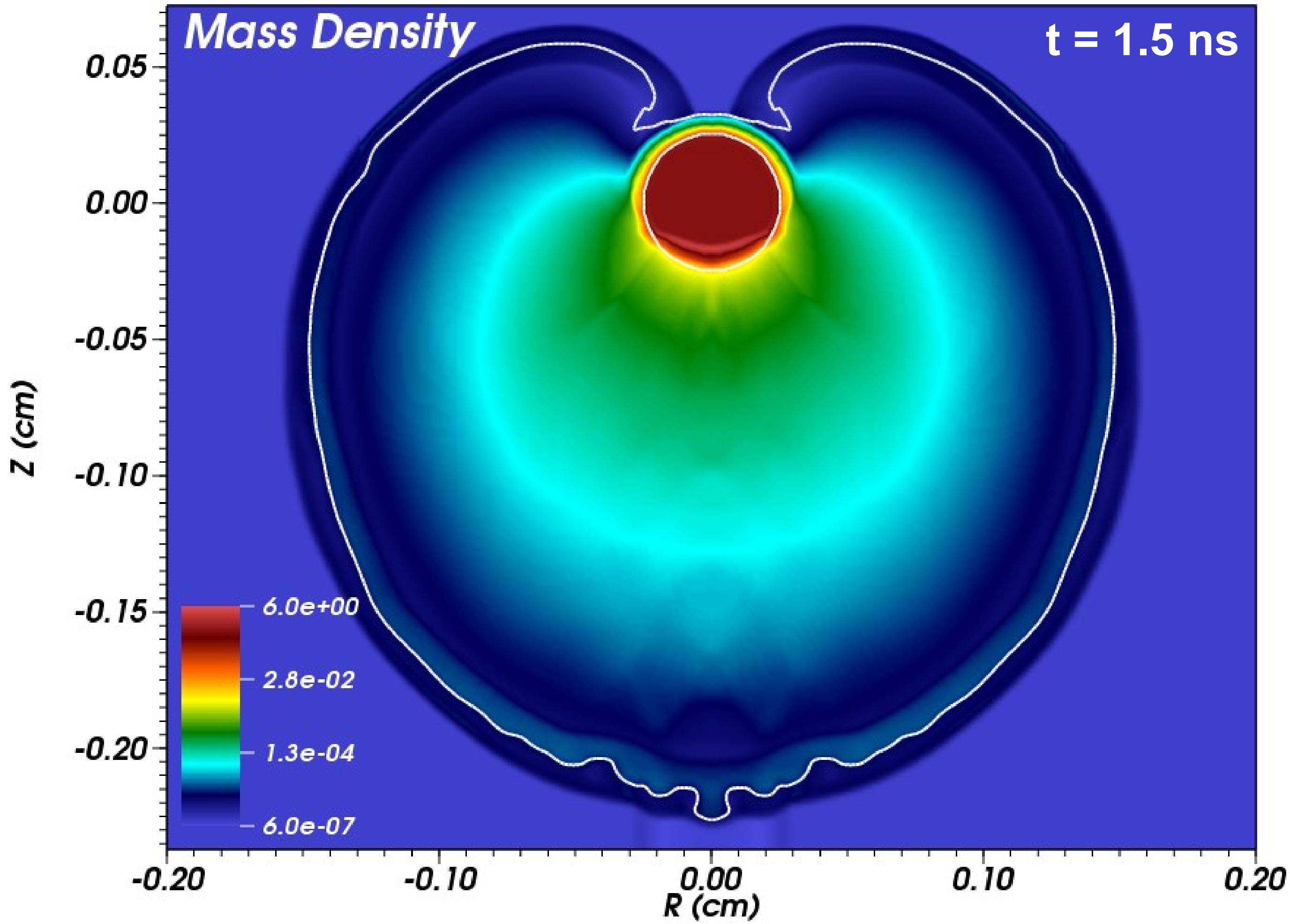
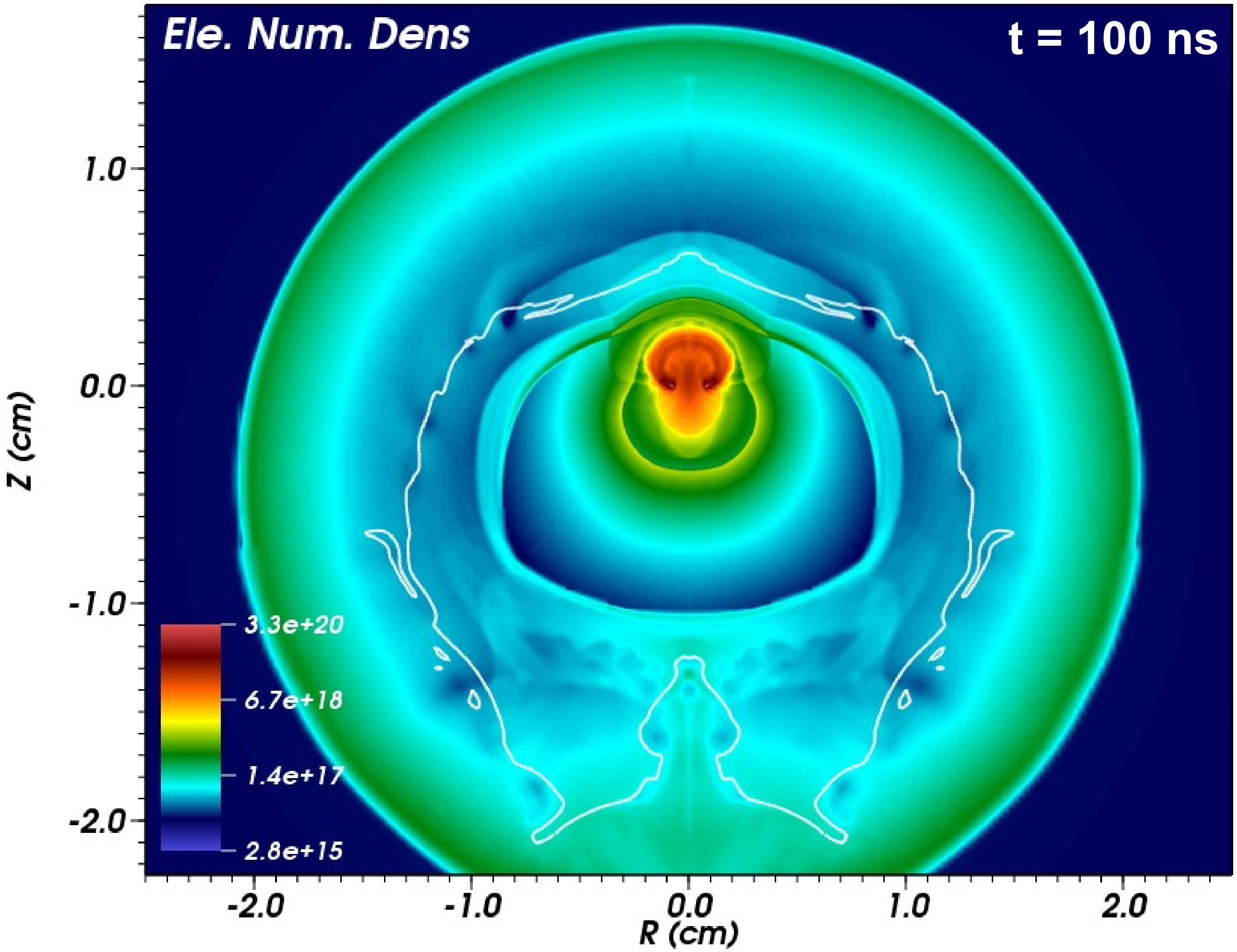
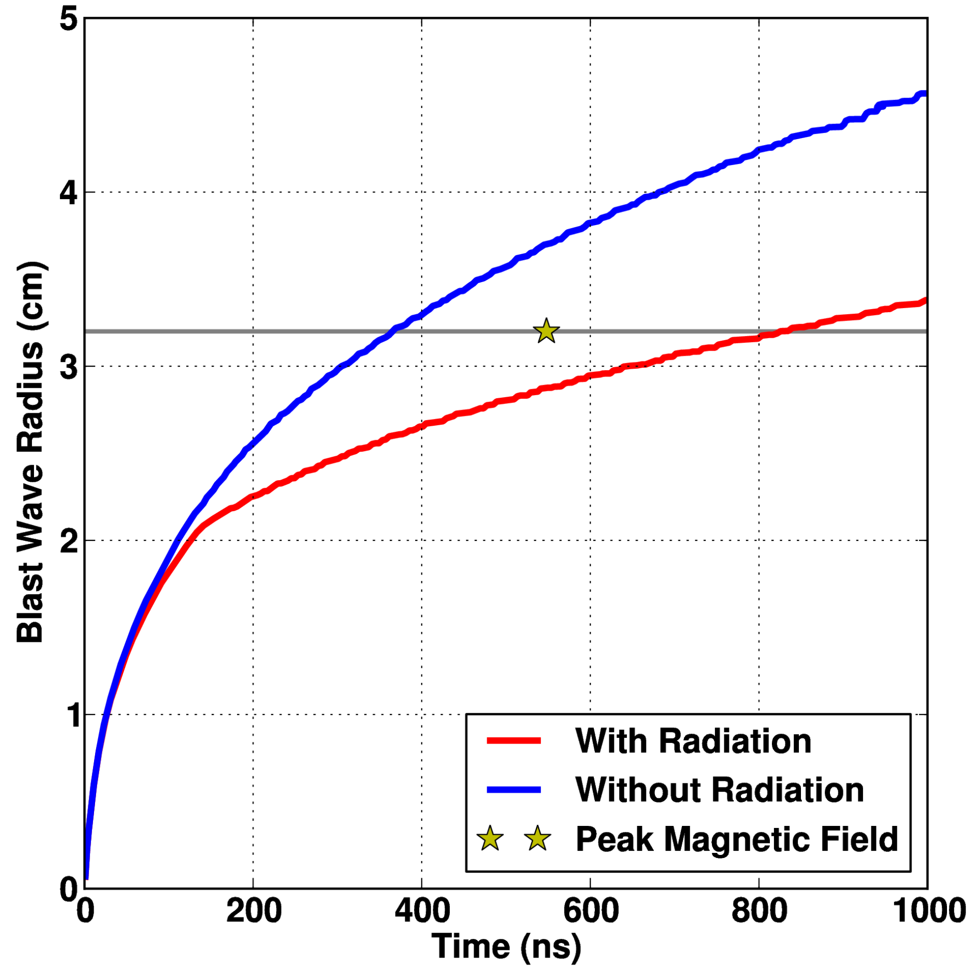


These features evolve revealing fairly complex structure at later times



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



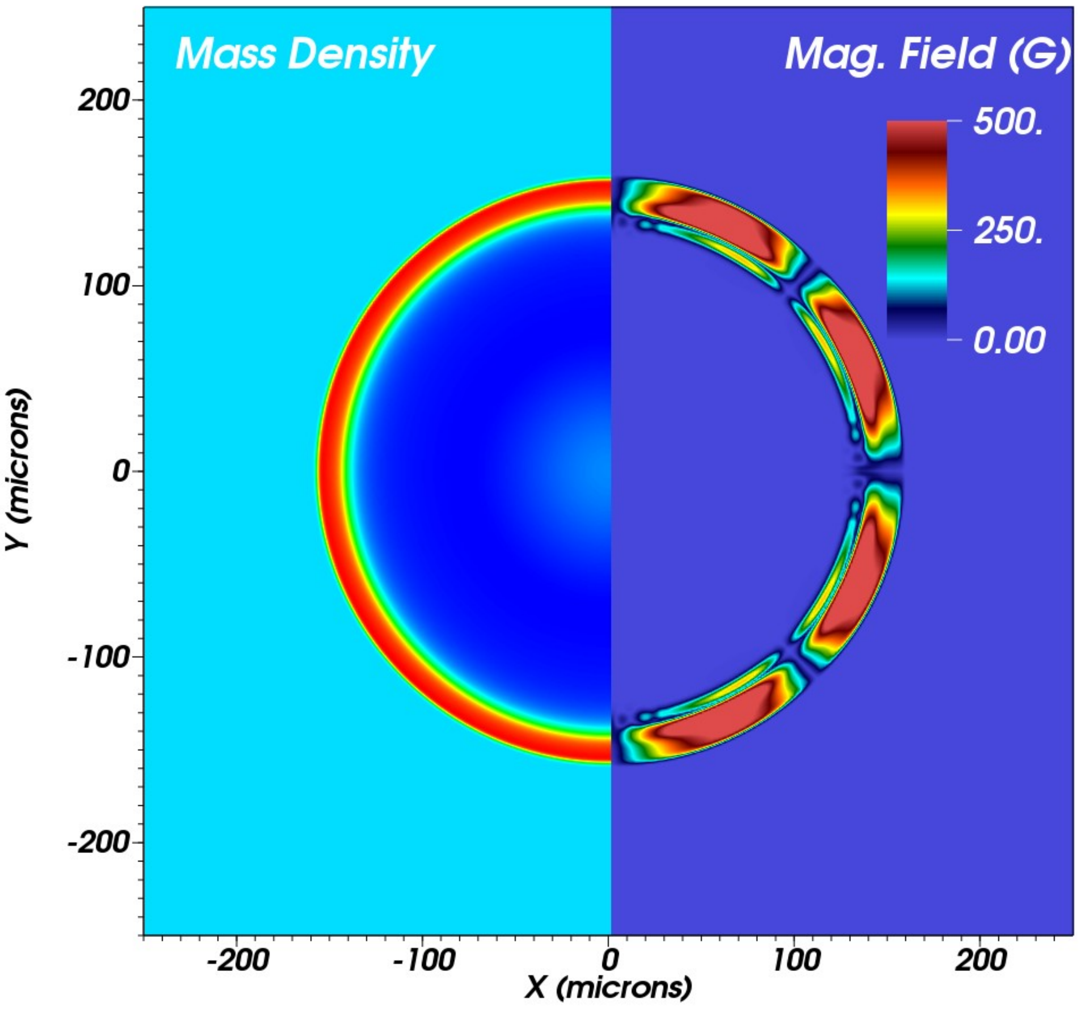
Several ongoing challenges exist in modeling the magnetic field generation experiments

- **Evaluating the Biermann Battery source term near shocks in simulation codes is challenging**
  - **At shocks, ∇P_e is discontinuous and the magnitude of the fields generated will be resolution dependent**
  - **Limiters or shock detection techniques must be used to eliminate artificial field generation at the shock front**
  - **Physically significant fields can then be generated downstream of the shock**
  - ***These experiments are particularly sensitive to these issues since the measured fields are relatively small***

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

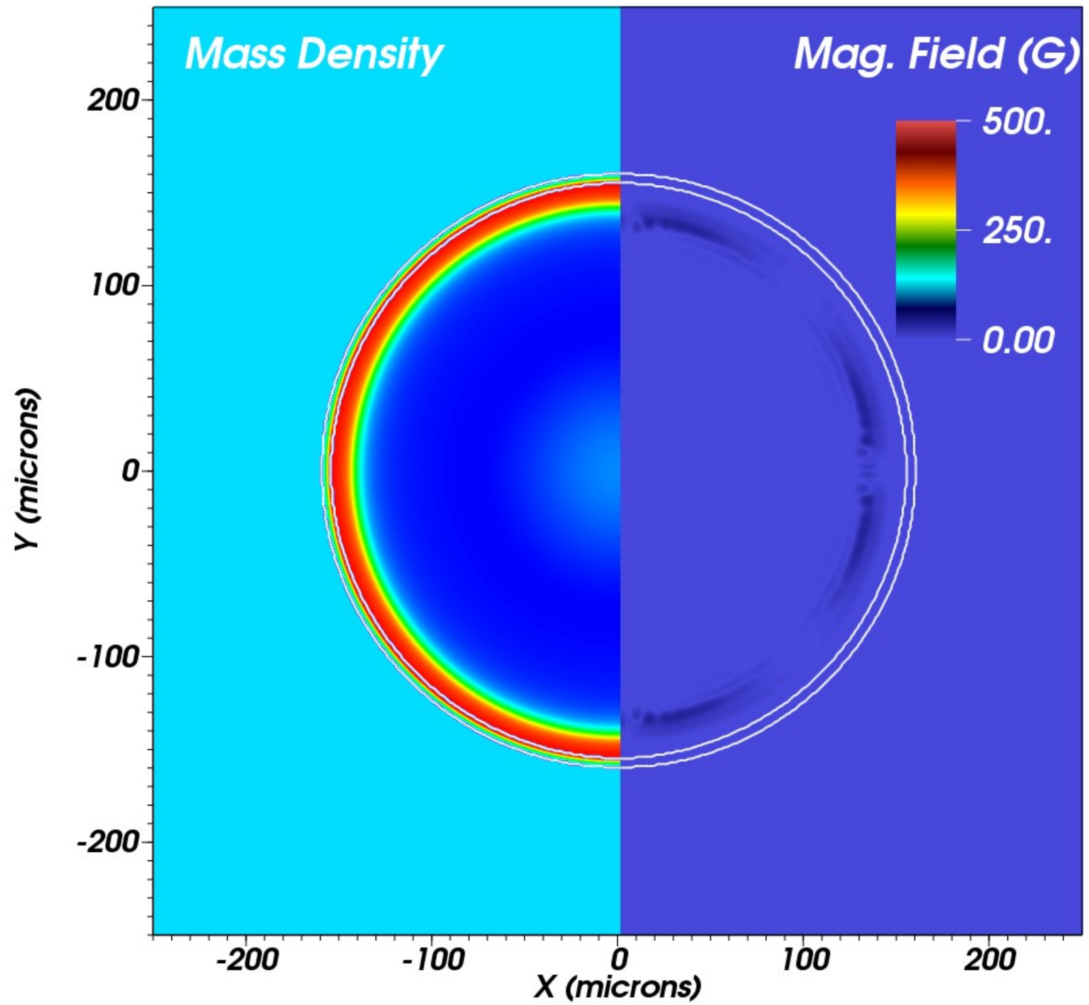
When modeling symmetric blast waves, there should be no magnetic field generation

- Evaluating the Battery source term across the blast wave results in the generation of large non-physical magnetic fields
- These artificial fields are comparable in magnitude to the physically produced magnetic fields and cannot be ignored
- Code-to-code comparisons between FLASH and three other MHD codes has demonstrated similar behavior



Use of limiters and/or shock detection is being used to avoid evaluation of Battery term across shocks

- Limiters or shock detection are being explored as a way to damp the artificial electric field across the shock
- This will leave only the field generation downstream of the shock where the hydrodynamic flow is smooth
- Similar issues will exist and must be handled near contact discontinuities



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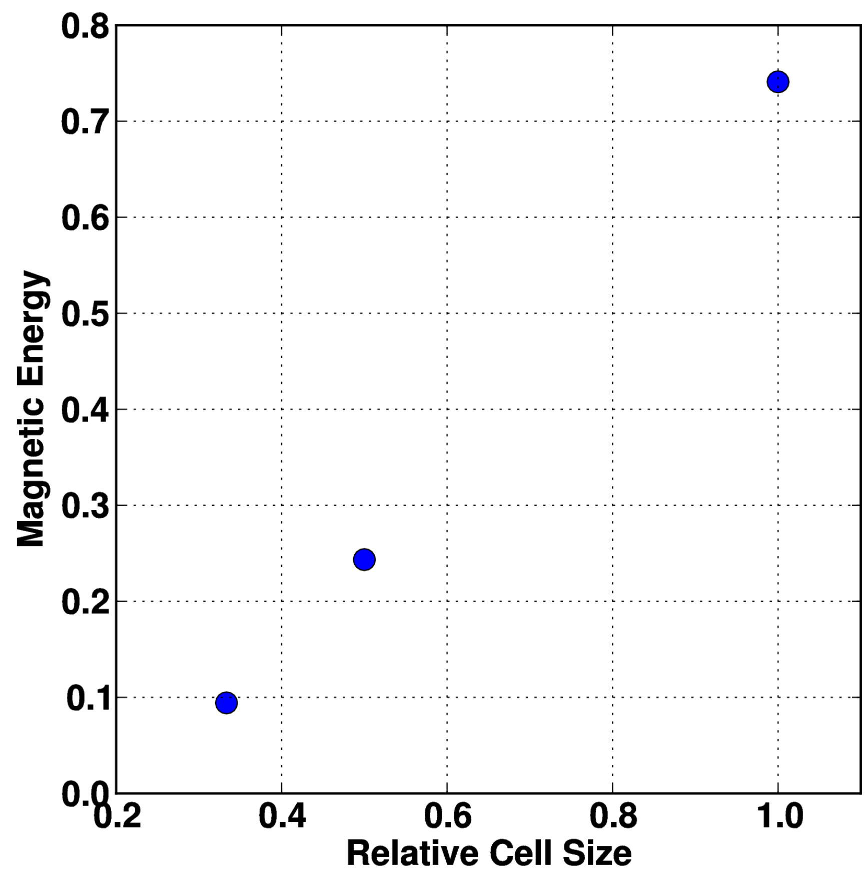
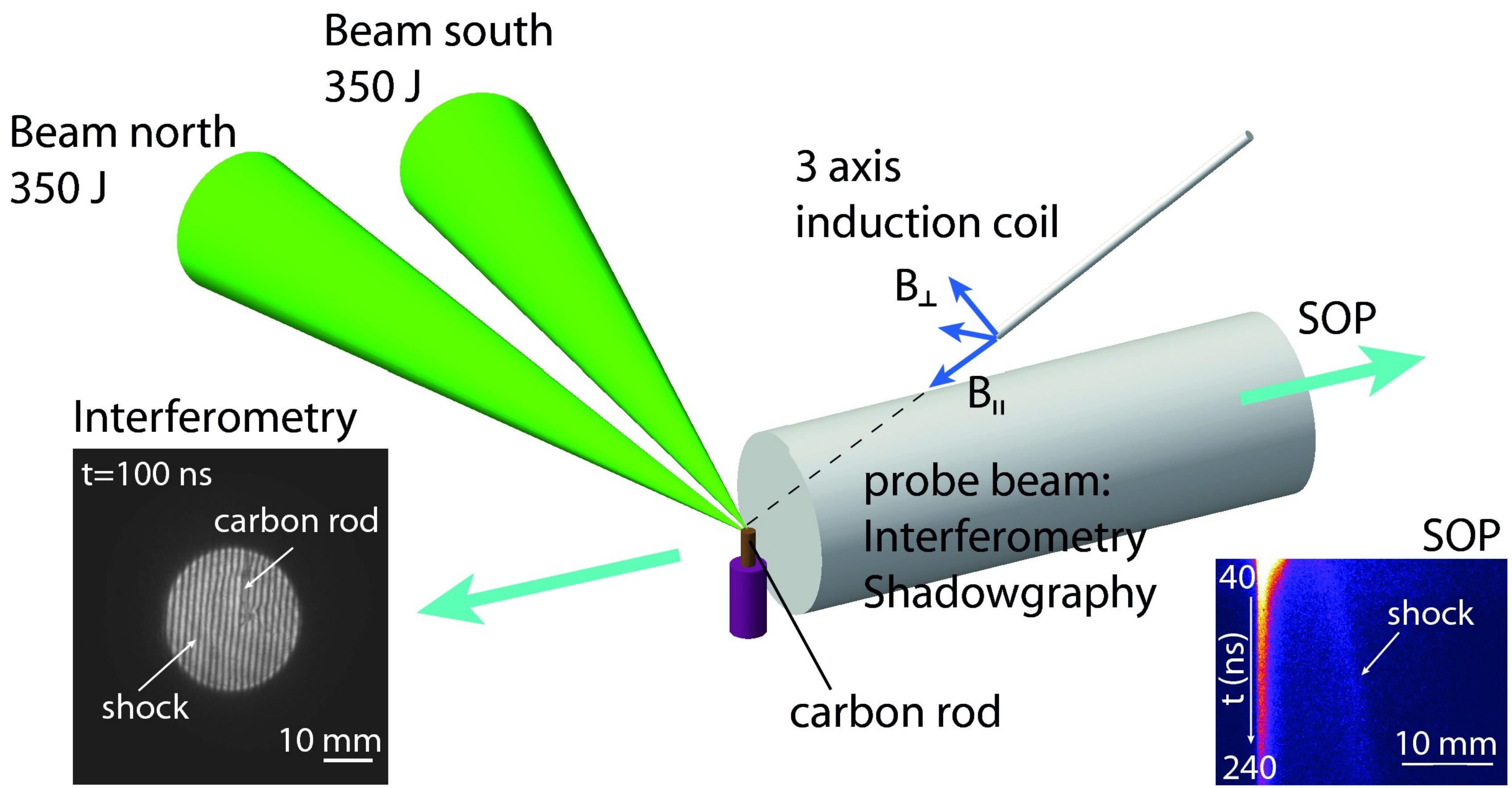


Summary

- 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)

Experiment Setup



Scaling Table

Table 1 | Similarity scaling between the laboratory and the intergalactic medium

Scaling parameters	Definition	Laboratory (LULI) value	Intergalactic medium extrapolated value
Characteristic length scale of the system	$L \approx 2r/\kappa$	18.8 cm	1 Mpc
Characteristic timescale of the system	t	1 µs	0.7 Gyr
Electron temperature	T_e	2 eV	100 eV
Electron density	n_e	5×10^{15} cm^{-3}	10^{-4} cm^{-3}
Cyclotron frequency	$\Omega_B = \dfrac{eB}{m_{ion}}$	4.8×10^4 s^{-1}	8.7×10^{-18} s^{-1}
Reynolds number	Re	7.9×10^3	3.0×10^{13}
Peclet number	Pe	69.0	7.0×10^{11}
Magnetic Reynolds number	Re_M	16.5	3.9×10^{27}

The similarity between the astrophysical and the laboratory systems breaks down owing to viscous dissipation at laboratory spatial scales $h \lesssim \lambda_{coll}$, where λ_{coll} is the collisional mean free path[9], and equally for thermal and magnetic dissipation. This implies that, for the conditions of our experiment, in which magnetic dissipation is the dominant effect, full similarity is achieved at macroscopic scales ($h \gtrsim 5$ µm), and the microphysics at the kinetic level will be different. The similarity given here roughly applies to the shocked intergalactic medium for scales of $L \gtrsim 25$ pc.