Filtered Fast-Gate Emission Imaging of the Interaction of a Laser-Produced Plasma and an Ambient Plasma

P.V. Heuer , D.B. Schaeffer, C.G. Constantin, S. Vincena, S. Tripathi, W. Gekelman, and C. Niemann

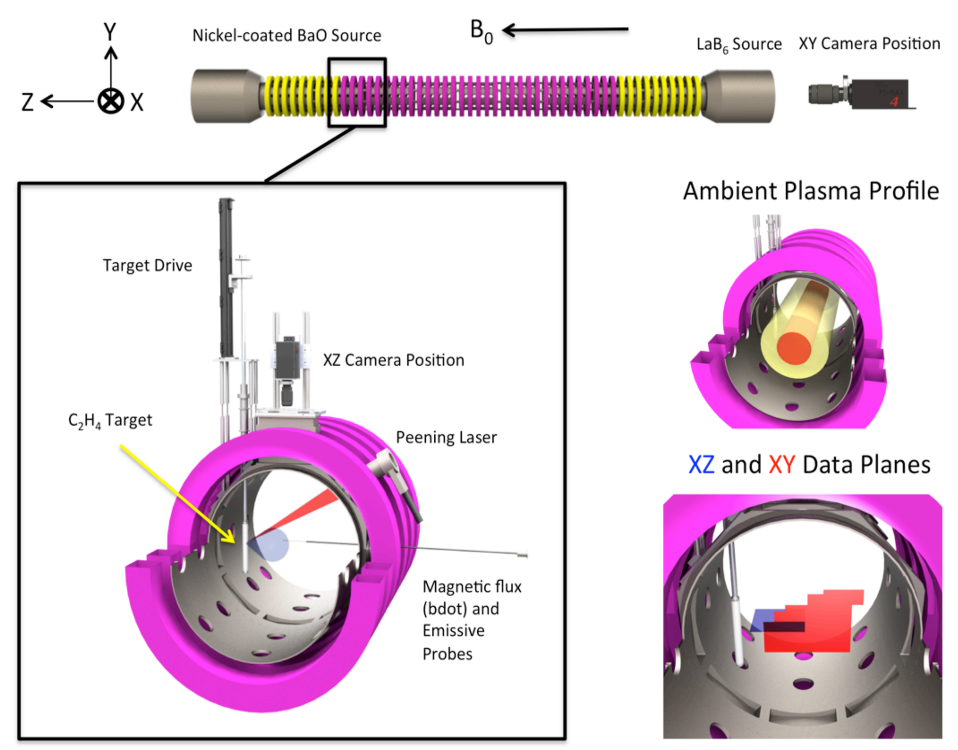
UCLA

Department of Physics & Astronomy

Abstract

Interactions between a fast, dense debris plasma and a low-density ambient plasma can lead to the formation of magnetized collisionless shocks. To study this interaction, a high-repetition rate laser (20 J, 14 ns, 1 Hz) was focused on a cylindrical plastic target embedded in the 1 Hz ambient plasma of the Large Plasma Device (LAPD) at the University of California, Los Angeles. Filtered and unfiltered emission images of the resulting debris-ambient interaction were taken both along and perpendicular to the background magnetic field using a fast-gate (ns) camera. 2D scans with a 3-axis magnetic flux probe and an emissive Langmuir probe also measured the 3D magnetic field and scalar potential, respectively, in two planes. The results show an expanding bubble of debris ions (spatially differentiated by charge state) that coincides with the formation of a diamagnetic cavity, with a ring of higher emission at the cavity edge that corresponds to a compression in the magnetic field and electrostatic potential. Imaging along the background magnetic field revealed asymmetry in the bubble structure and finger-shaped 'flute' instabilities along its edges.

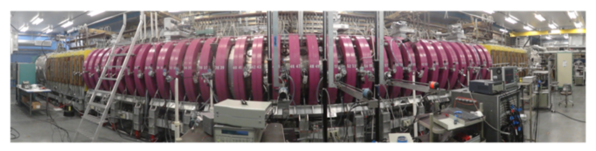
Experimental Platform



Phoenix Laboratory Peening Laser

- E = 20 J
- λ = 1053 nm
- τ = 14 ns
- 1 Hz rep

Basic Plasma Science Facility (BAPSF) Large Plasma Device (LAPD)



- 20 m long, 1 m diameter
- B_0 = 200-300 G
- $n_e \sim 10^{13}$ cm^{-3}
- $T_e \sim 5$ ev
- $T_i \sim 1$ ev
- H, He, D gas fills
- Plasma duration 5-15 ms
- 1 Hz pulsed rep

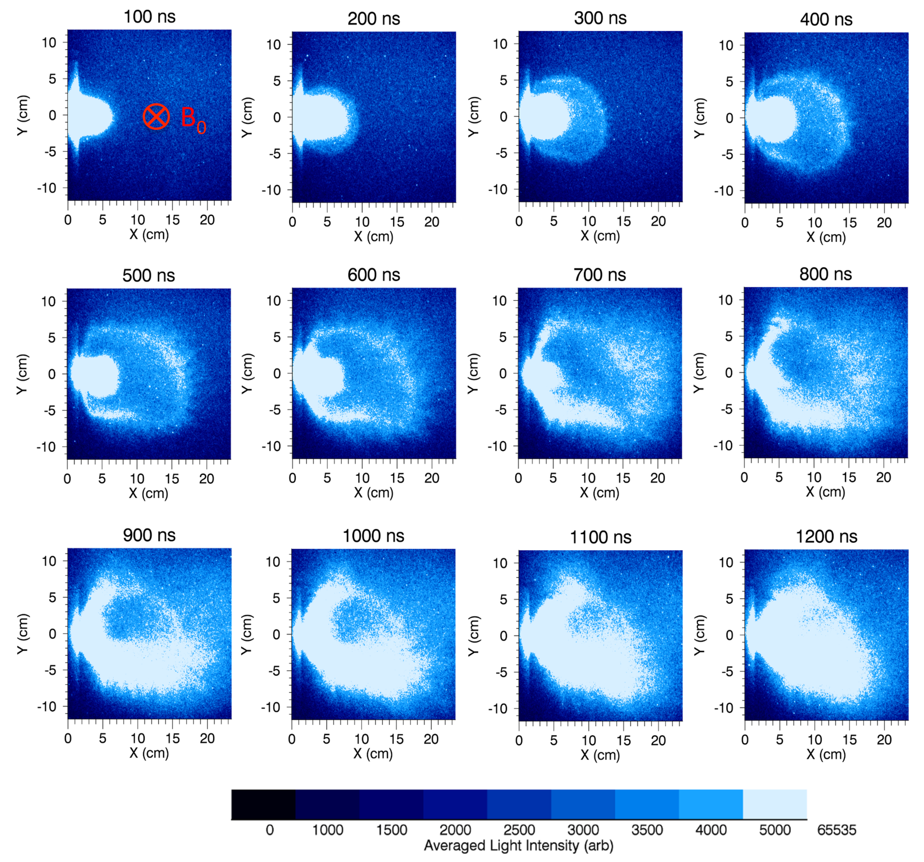
The experiments combine the moderate energy, high-repetition Peening laser with the large pre-formed, magnetized ambient plasma of the LAPD. The ambient plasma is created using a two-cathode configuration that combines a large-diameter, low-density plasma with a smaller-diameter, higher-density core plasma.

The laser strikes a plastic (high-density polyethylene) target embedded at the edge of the ambient plasma. The ablated debris plasma expands across the background magnetic field, creating a diamagnetic cavity that acts as a piston. The piston couples energy from the debris ions to the ambient ions, leading to collisionless shock formation.

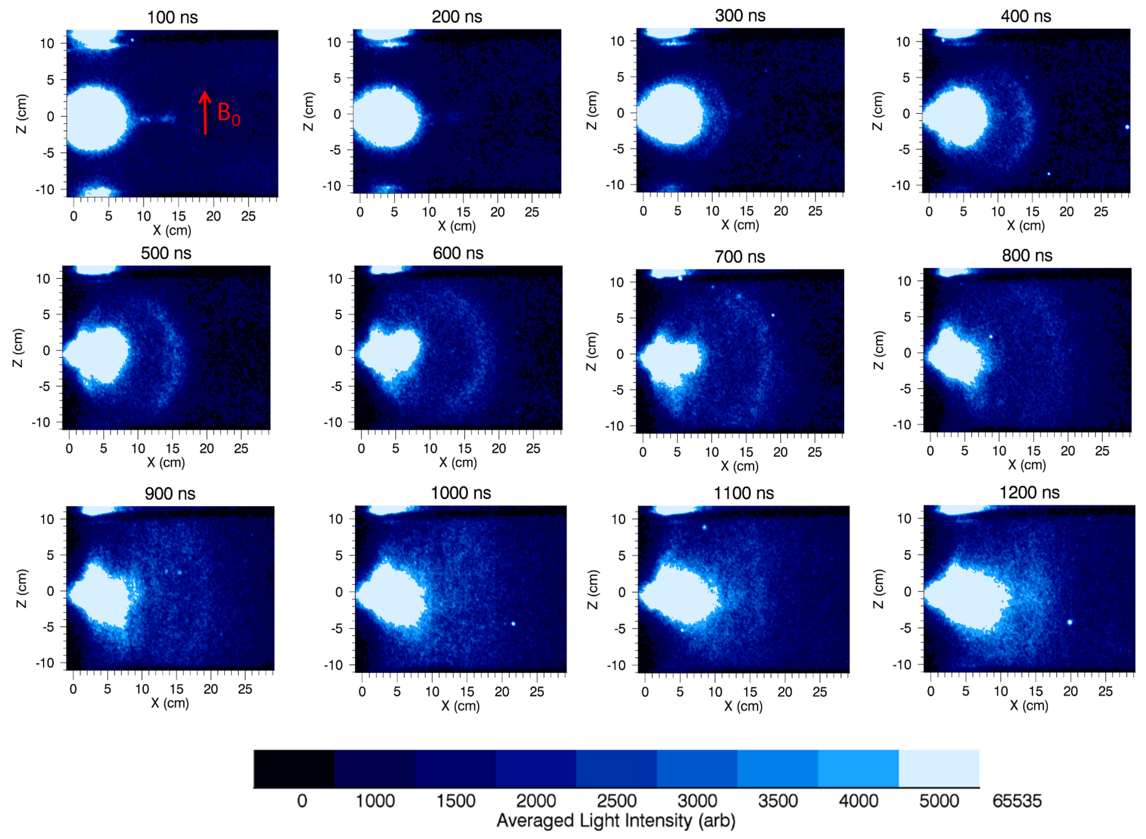
Data was taken in two orthogonal planes with magnetic flux (bdot) probes, emissive probes, and fast-gate filtered imaging. Scans were built up over thousands of shots with high reproducibility.

Fast Gate Imaging

XY Plane (Unfiltered)



XZ Plane (Unfiltered)

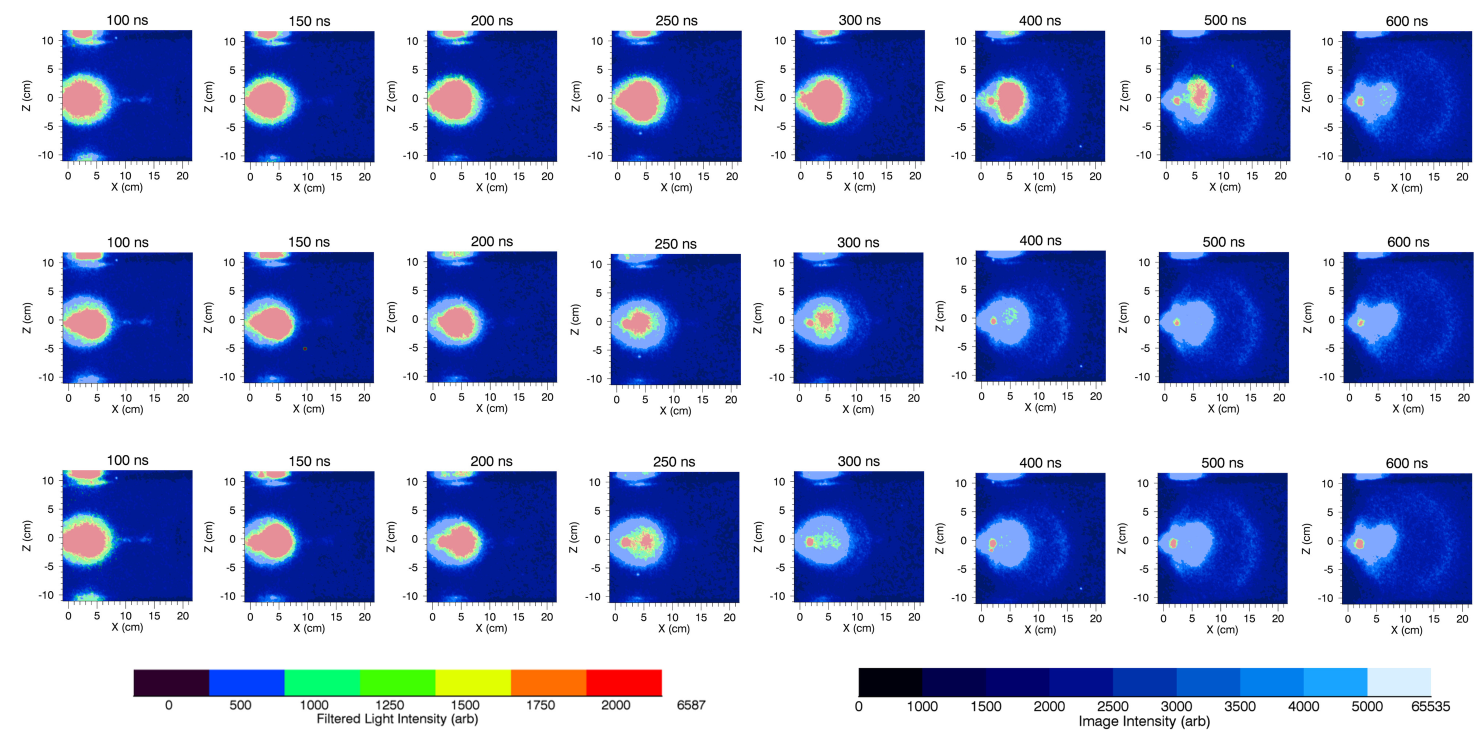


High temporal resolution images from two separate camera positions show the motion of the debris ions in the XZ and XY planes. Images were taken with an exposure time of 10 ns at different time delays, covering a range of 0-1000 ns in 10 ns steps. Multiple images were taken at each time delay and then averaged to produce the image series seen above.

In both planes, the majority of debris ions forms a cloud near the target, while a smaller number of ions are pulled out with the expanding edge of the diamagnetic bubble (forming the bright semicircle in the images above). Finger-shaped 'flute' edge instabilities are clearly observed in the XY plane.

Filtered Fast Gate Imaging

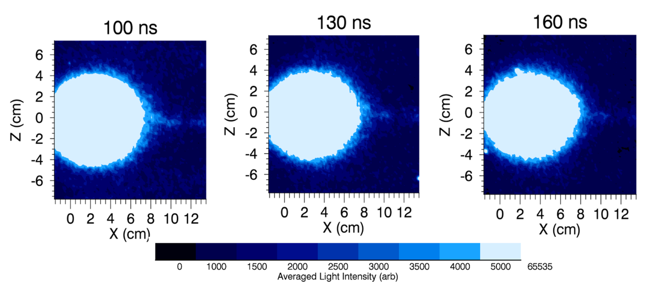
XZ Plane (Filtered)



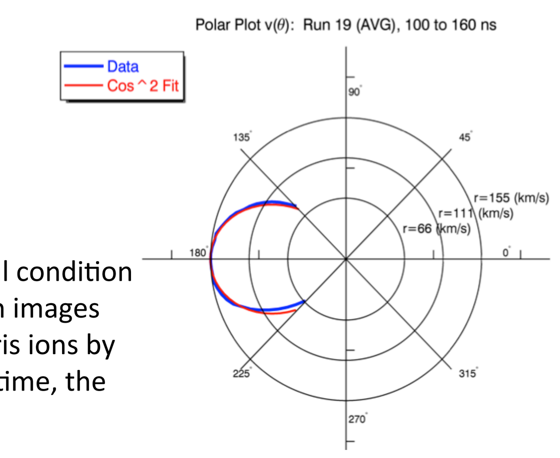
Images collected through wavelength filters show the motion of carbon ions in different charge states: CIII (C+2), CIV (C+3) and CV (C+4), in the debris cloud. The time series above overlays filtered images of each charge state (red/green) over the total unfiltered emission (blue). Ions behind the diamagnetic bubble eventually diffuse forward into the bubble as it collapses, but higher charge states respond more quickly than lower charge states. Florescence dies away as ions leak out of the cavity: higher charge states escape faster and therefore stop fluorescing earlier.

Initial Debris Velocity Distribution

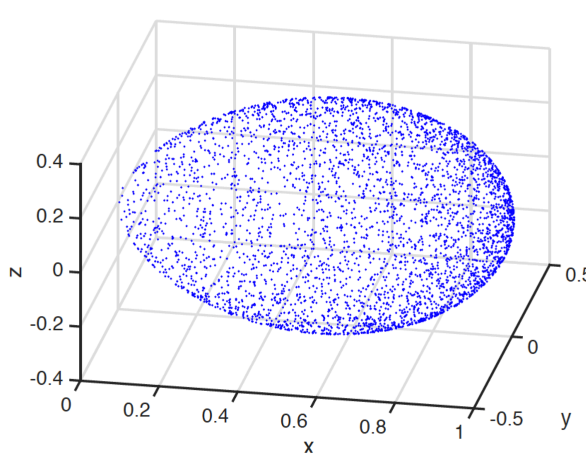
Early-time Fluorescence Images



Measured Early-time Ion Velocity Distribution



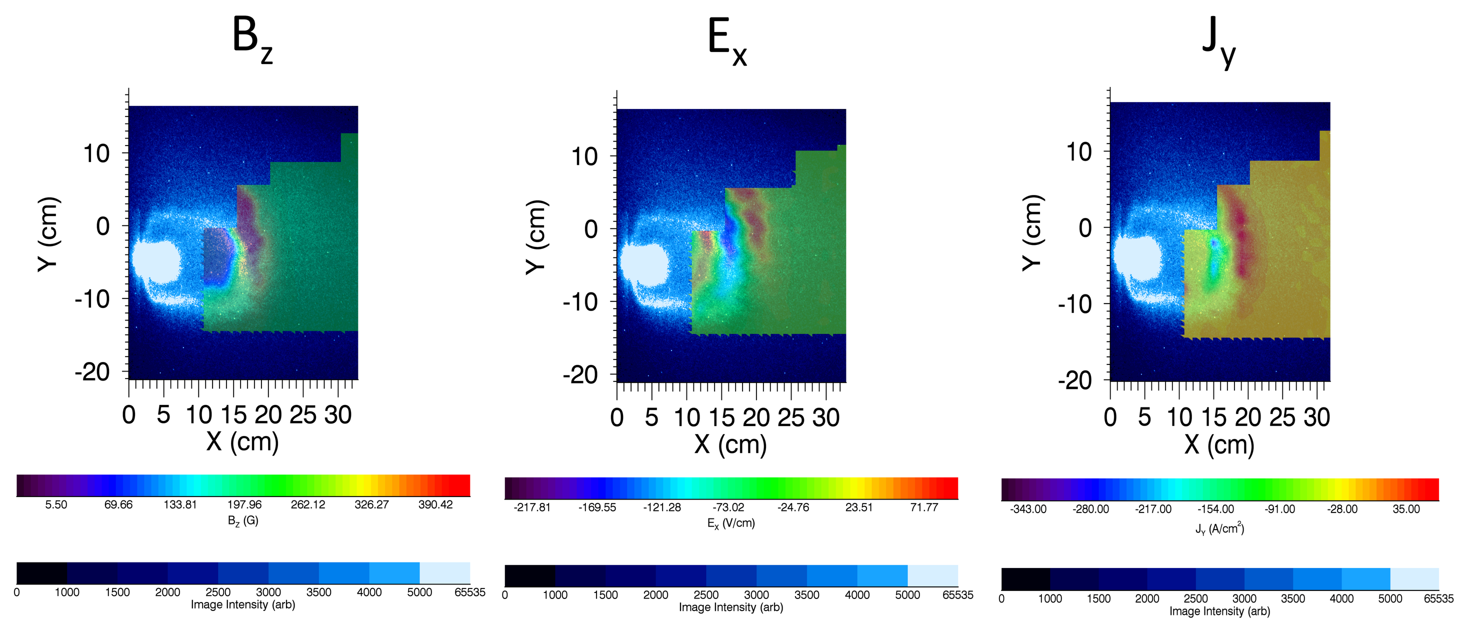
Hybrid Code Initial Ion Velocity Distribution



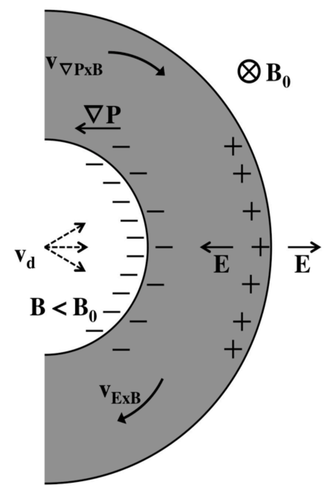
The initial velocity distribution of the debris ions is an important initial condition for hybrid simulations of collisionless shocks. High temporal resolution images were used to calculate the 2D angular velocity distribution of the debris ions by tracking the position of the intensity peak at the debris edge. Early in time, the distribution agrees well with a cosine-squared fit.

Field and Current Measurements

XY Plane at t=500ns

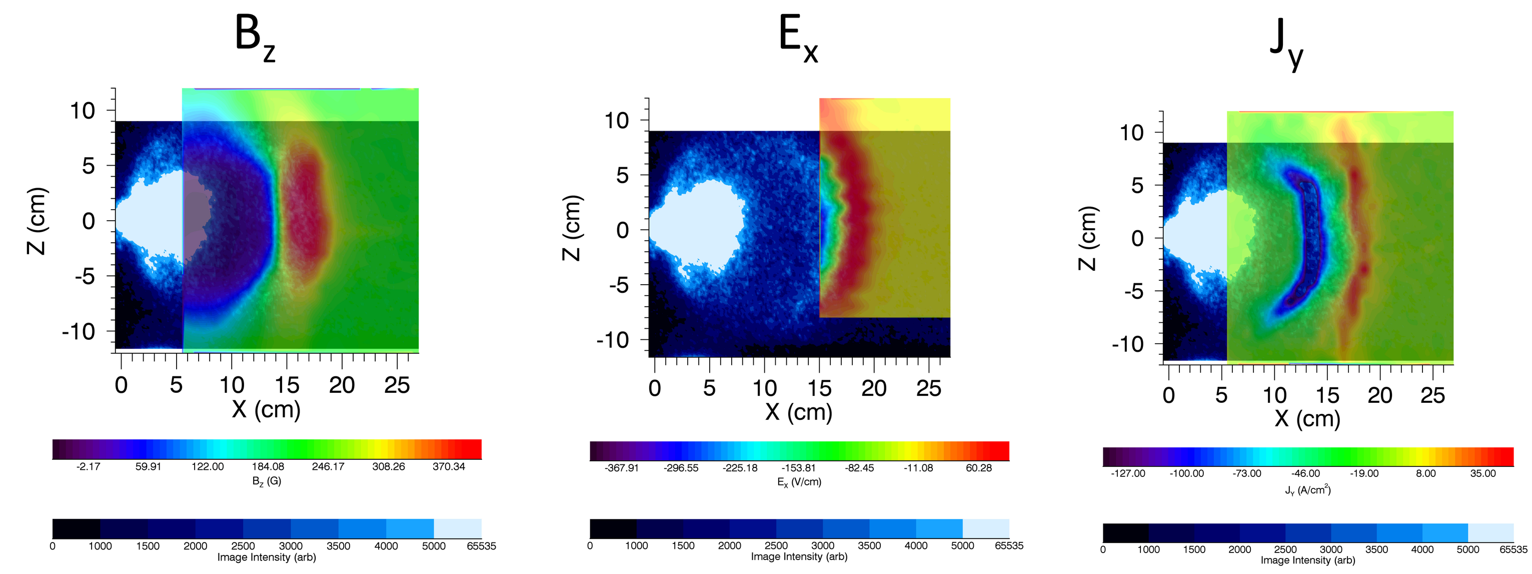


These images show directly measured magnetic field data as well as derived electric field and current density data overlaid on unfiltered fluorescence images.



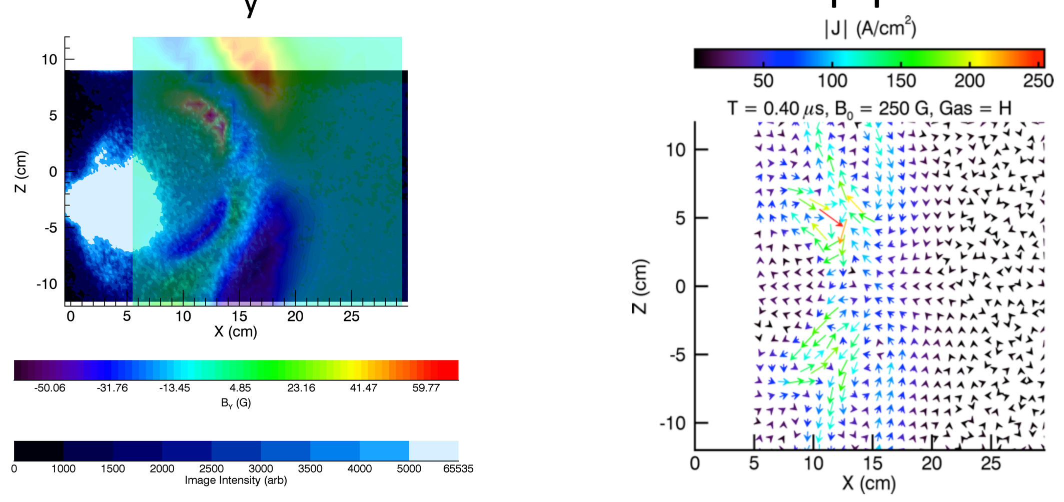
As the blowoff expands in the x-direction across the background magnetic field, it establishes a radial electric field as ions pile up at the edge of the pulse. This field drives a current in the ambient plasma which works to expel the background magnetic field from the region behind the debris. The resulting diamagnetic cavity initially expands outwards with the debris. As the debris expands, a super-Alfvénic pulse ($M_A \sim 1.6$) in both the magnetic and electric fields is formed and separates from the cavity. Late in time (~1 µs), the diamagnetic cavity collapses as the background magnetic field diffuses in from behind.

XZ Plane at t=500ns



Comparison between fast-gate images and field measurements show that the glowing 'bubble' of fluorescence corresponds to the diamagnetic cavity. The bright band of fluorescence at the edge of the cavity falls just behind the electric and magnetic pulses, but between the two opposing sheets of current, suggesting that this light is emitted by strongly heated ions at the very edge of the pulse.

Wave-like Features in the XZ Plane



In the XZ plane, wave-like features are clearly visible in the y-component of the magnetic field and current density. These appear to be launched by the cavity early in time at approximately a 45° angle.

Acknowledgements

The laser-plasma experiments are performed at the UCLA Basic Plasma Science Facility. This work was supported by the Defense Threat Reduction Agency (DTRA) under contract number HDTRA1-12-1-0024 and the DOE.

References

- Schaeffer, *et. al.*, Physics of Plasmas, 2015
- Niemann, *et. al.*, Geophysical Research Letters, 2014
- Clark, *et. al.*, Physical Review E, 2014