The evolution of plasma shock waves on the sub-microsecond timescales.

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Introduction

High-speed plasma flows can be created in the laboratory using lasers, and are used to gain a better understanding of astrophysical objects and processes. Hydrodynamic scaling [1] allows the plasma physics occurring within large scale objects to be reproduced on much smaller scales within a laboratory environment. Several areas of particular interest to laboratory astrophysics are the magnetization of interstellar plasmas [2], by shock waves, which are common features of active galactic nuclei and young stellar objects. More recently shock wave experiments have explored how turbulent flow may amplify magnetic fields [3] and help explain the strong fields that exist within supernova remnants, such as Cassiopeia A [4].

In this report we show how using a fast multi-framing camera it is possible to track the dynamics of a laser-driven strong shock over hundreds of nanoseconds [5]. Single-shot measurements of the shock dynamics aid immediate assessment of the shot during an experimental campaign and enable more accurate understanding of the complex dynamics during data analysis.

Experimental Setup

This experiment was carried out using the Vulcan laser, Target Area West. The 6 infrared beams of 2 ns duration, with a total energy of 1.4 kJ, were clustered to a single, 300 µm focal spot on a 500 µm carbon rod. The target was enclosed in a chamber containing 0.7 mbar of argon gas. A schematic of the setup is shown in Figure 1. The evolution of the plasma from the target and propagation through the argon was imaged for 500 ns using a 16 frame camera. The plasma shock wave propagated out towards an induction (B-dot) probe, positioned to measure the magnetic field across the shock front. Other diagnostics were also used in the experiment, to extract the temperature and density of the shock wave quantitatively, although these are not discussed here

A fast multi-framing camera provides insight into the dynamics of plasmas driven by high energy laser systems, such as Vulcan. These systems are single shot and obtaining a time series to develop an understanding of the plasma dynamics can take many shots when using single frame cameras. The multiple, fast-framing camera measurements along a single line of sight are well suited to many laboratory astrophysics experiments where the phenomena of interest occur on 100's ns timescales. In this experiment, images were taken using a Specialized Imaging SIM16 camera, which uses framing speeds of up to 200,000,000 frames-per-second. The camera contains 16 CCD detectors, coupled to micro-channel plates fitted with a S25 photocathode. The minimum gate width is 5 ns. The images included in Figure 2 are taken with a 5 ns exposure, and evenly spaced at 30 ns intervals, where time t=0 ns corresponds to when the laser beams hit the target. The image is formed from the self-emission from the carbon plasma, the bright central region observed, and from the argon gas fill, primarily Ar I and Ar II emission lines, the weaker emitting regions.

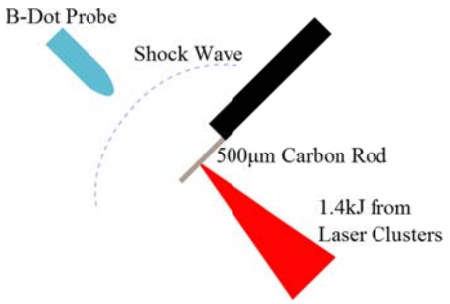

Figure 1. A schematic of the experimental setup for this experiment to measure the magnetic field across a shock wave. The 6 infrared beams were focused into a single spot on a 500 µm carbon rod. This drove a shock wave which propagated out towards a B-dot probe.

Results and Discussion

In the images shown in Figure 2 at early time, < 110 ns, the target is 'glowing' and a hemispherical shock is launched, following plasma breakout at the target rear surface. The shock wave is driven by momentum conservation, as target material ablates away from the target front surface. At ~80 ns a shock-like feature is clearly seen ahead of the globular glowing region. It is assumed that this more intensely emitting region left behind the shock is a hotter and denser area made up from the bulk ejected target material.

The shock propagates into the Ar gas, centred along the target surface normal and moves towards an induction (B-dot) probe [2] used to measure changes in the magnetic field. This probe is placed at 3 cm distance from the Al foil target. The distance moved by the shock in the images can be used to calculate the velocity. Monitoring the hemispherical shock-like front, calculations suggest that it initially expands at ~200 km/s perpendicular to the target surface and, as the shock expands and decelerates, it slows to ~65 km/s by 480 ns. These velocities are estimated to have a ~10% error associated with them. At ~450 ns the shock wave has reached and collides with the B-dot probe, which disrupts the flow and changes the magnetic fields.

As the flow starts to approach the B-dot probe it appears that the edge of the shock front nearest the probe emits more intensely, and starts to curve around the probe, as can be seen from >420 ns in Figure 2. It has also been observed from other time-sequences taken using the SIM16 [5] that the probe appears to drive other structures to manifest within the plasma as it is disturbed. Time resolved images of this type allow study of the dynamical evolution of the fluid from which growth rates and hydrodynamic instabilities can be directly inferred.

On other shots, filters were also used to observe the relative intensity of different emission lines. This could then lead to information about the local temperature of the plasma. Various different targets were also used in this experiment to see what the effect was on the field amplification. The Sim16 Camera was very useful in observing these situations and giving instantaneous feedback on what had happened.

The temporal information that can be gained from the images is instantaneously advantageous though, for noting how the laser-plasma interaction progressed, and to decide where regions of interest might be for other diagnostics to look at spatially or temporally during an experiment.

Conclusions

In conclusion, the framing camera is an effective tool for observing an interaction where shock features are created and developed over nanosecond time scales. A fast framing camera, coupled with scaled hydrodynamic simulations, could assist in understanding how a shock wave might develop and progress in astrophysical objects. [2] There are significant benefits for using such a camera on shot limited experiments, where monitoring laser-plasma interactions over larger time durations will be invaluable.

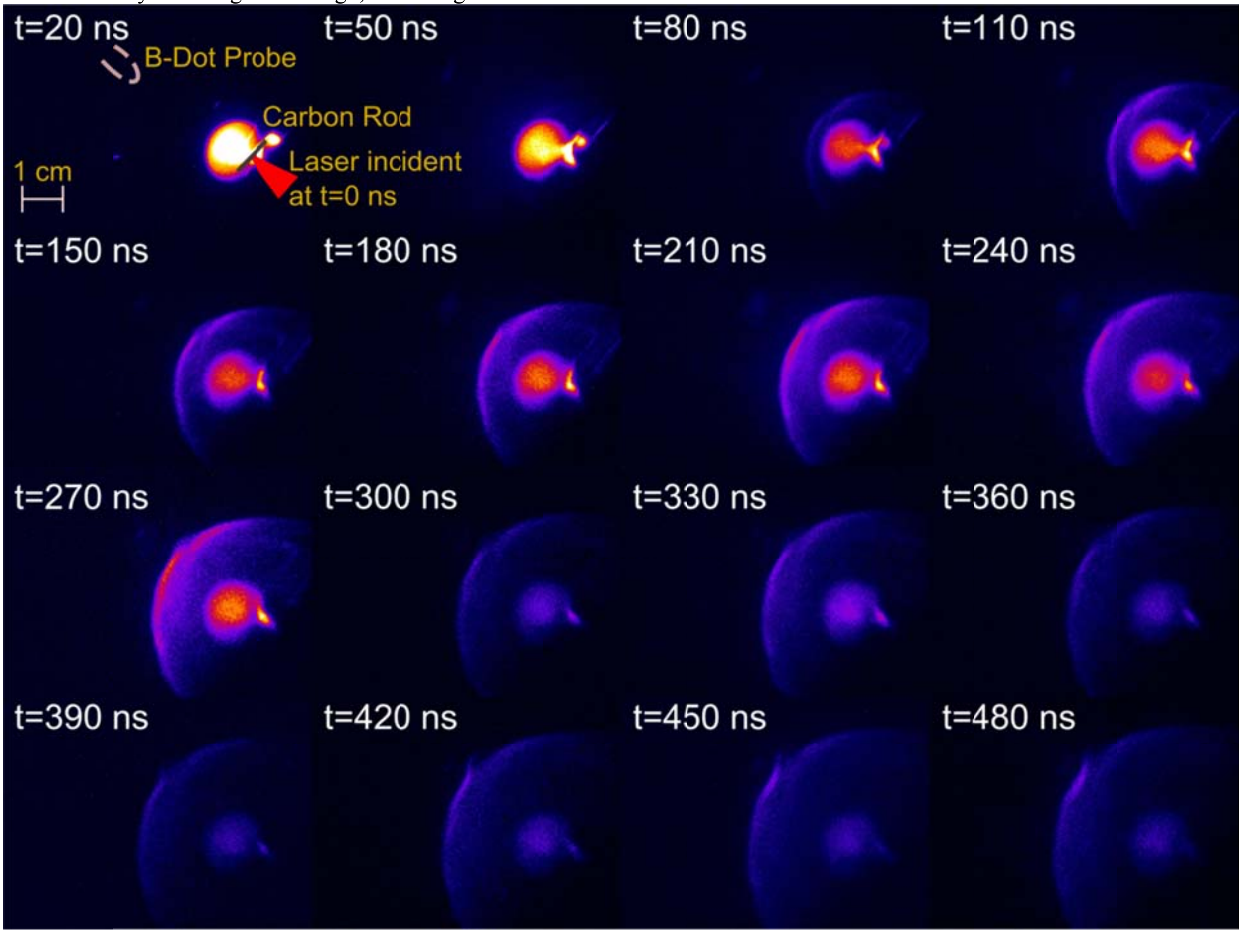

Figure 2. A set of the 16 images each with a 5 ns exposure taken by the SIM16 camera on one laser shot of the self-emission from a plasma shock wave. The shock wave expands out over time towards a B-dot probe, through an Ar background gas. The times shown are relative to when the laser cluster irradiates the carbon rod target.

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References

1. D. Ryutov et al, "Similarity criteria for the laboratory simulation of supernova hydrodynamics," *ApJ.*, vol. 518, no. 2, pp821-2, Jun. 1999.
2. G. Gregori et al, "Generation of scaled protogalactic seed magnetic fields in laser-produced shock waves," *Nature*, vol. 481, no. 7382 , pp480-483, Jan. 2012.
3. J. Meinecke et al, "Turbulent amplification of magnetic fields in laboratory laser-produced shock waves", *Nature Phys.*, June 2014.
4. M. Anderson and L. Rudnick "The deceleration powering of synchrotron emission from ejecta components in supernova remnant Cassioepeia A", *Astrophys. J.* 441, 300-306 (1995).
5. E. R. Tubman et al, "Nanosecond imaging of shock- and jet- like features", *IEEE Trans. Plasma Sci.*, July 2014.