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Examination of scattering volume alignment in Thomson scattering off of a shock front in argon

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Thomson scattering in argon gas successfully probed the region of plasma just behind the shock front. The instantaneous shock velocity can be inferred from the duration of the signal, taking into account the size and shape of the scattering volume. Possible misalignment of the probe beam and spectrometer slits greatly affects the size and shape of the scattering volume, and therefore affects the calculation of the instantaneous shock velocity.

1. Introduction

Thomson scattering is a powerful technique for plasma diagnosis. Thomson-scattering measurements use a coherent light source with an initial wavelength and wavenumber (λ_o and k_o) to scatter light from plasma electrons with a scattering wavevector $\boldsymbol{k}$ [1],[2]. In the collective regime, where the scattered light probes many Debye lengths (λ_D) in a plasma (so $1/(k\lambda_D) = \alpha > 1$), strong signals are observed when the probed electrons have a resonant collective response (e.g. from ion-acoustic waves, when $T_i/ZT_e < \alpha$, or from electron plasma waves) [3]. Many experiments have used Thomson scattering (TS) to extract fundamental plasma properties from the scattered frequency spectrum, and TS is now widely used as a diagnostic in fusion research [4-6].

Thomson scattering was successfully implemented to measure flow velocity and electron temperature in a driven shock in argon gas [7]. Careful analysis showed that the size and shape of the scattering volume significantly affected conclusions made about other parameters in the system.

A shock velocity was calculated based on the duration of the scattered light signal. However, the following calculations show that the estimate of the shock velocity depends heavily on the alignment of the system. Without better understanding of the relative alignment of the probe beam with the collection diagnostic slits, the error bars on the shock velocity calculation will be very large.

2. Experimental Design

Figure 1 shows the setup of the experiment, the scattering vector diagram, and a three-dimensional image of the scattering volume and shock front. A more detailed description can be found in Reighard et al. [8].

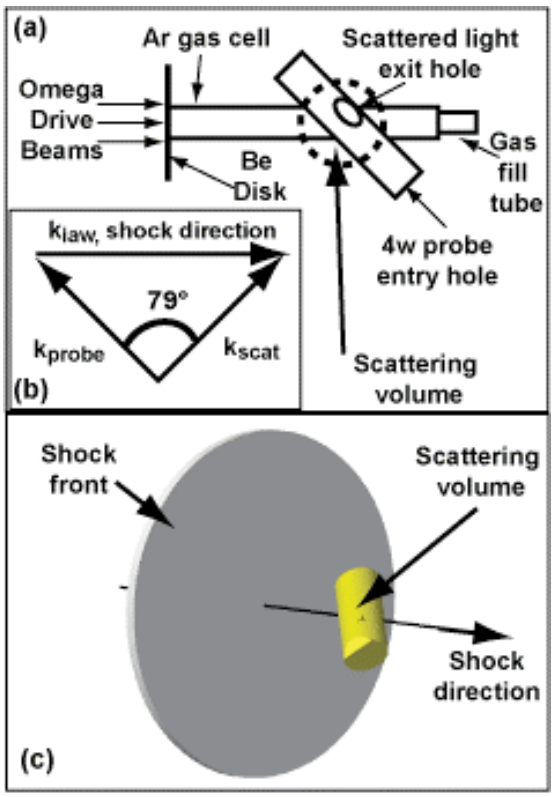

Figure 1: Target geometry and setup. a) 2D drawing of target features. This gas-tight target was filled with 1.1 ATM argon gas shortly before the shot. b) Scattering vector diagram. The probed ion-acoustic wave was parallel to the shock propagation direction. c) 3D image of scattering volume, showing the relative size and direction of the shock.

A 20 μm thick, 2 mm diameter beryllium disk was attached to the end of a 574 μm ID, 625 OD polyimide tube, 6 mm in length. This cylinder was gas tight, and filled with argon via a hypodermic tube in other end of the cylinder. A polyimide tube was mounted on this main assembly, pointed in the direction of the probe beam when the target was aligned, and had a 725 μm ID, 875 μm OD. The entrance hole of the larger tube was 2 mm from the axis of the main target assembly, was covered with 3000 Å of polyimide, and opened into a hole drilled into the main target wall at 4 mm from the beryllium disk down the cylinder's axis. The other end of this tube was filled with epoxy to keep the target gas tight. A second hole pointed in the direction of the collection spectrometer when the target was aligned, and was also covered with 3000 Å of polyimide.

These experiments were performed on the Omega laser at Rochester, NY [9]. We focused 10 smoothed laser beams with a wavelength of $\lambda = 0.35$ μm (3ω) into a 1 mm spot in a 1-ns, flat-topped, square pulse centered on the beryllium disk, with the midpoint of the rising edge defining time $t = 0$. This laser pulse shocked the disk, and then accelerated it into the argon gas cell, driving a shock. The total drive intensity on target was 5×10^{14} W/cm^2. At $t = 16$ ns a single, unsmoothed, defocused 3ω beam at an intensity of 1.5×10^{14} W/cm^2 removed the polyimide cover on the scattered light exit hole in a 2-ns square pulse. At $t = 19$ ns, a 4ω probe beam fired in a 2-ns square pulse with a wavelength of $\lambda_0 = 0.2633$ μm, an energy of 175 J, and a best focus spot size of 80 μm. The Thomson-scattered light was gathered at a scattering angle $\theta = 101°$ using a 1-m UV imaging spectrometer with a 3600 lines/mm grating and a 500 μm spectral slit width, giving a spectral resolution of 0.9 Å at FWHM. It was recorded on a UV streak camera with a sweep window duration of 5 ns centered at $t = 20$ ns, and a 500 μm temporal slit width[10]. The scattered light was collected and imaged to the spectrometer with an optical magnification of 2.

3. Scattering Volume

The scattering volume was defined by the overlap of 2 sets of orthogonal slits in the plane of the scattered light collection diagnostic and the 4-ω probe beam. The scattered light diagnostic was located at $\theta = 79.19$, $\phi = 90.0$ in the Omega chamber. The slits were both 250 μm wide. An image of a grid at target chamber center showed that the slits are rotated to a 66 degree angle from the view of the chamber port [11] in the plane of the spectrometer. This volume is shock with the shock front in Figure 1c.

The probe beam issued from port P9 in the Omega target chamber, at $\theta = 116.57$, $\phi = 18.0$. It was an f/6.67 beam with an 80 μm diameter at it's best focus. When perfectly aligned, these overlapping features produce a skew cylinder that was approximately 80 μm x 300 μm x 300 μm in size.

4. Scattered Power

Using Hyades [12], a 1D, Lagrangian radiation hydrodynamics code, we estimated the power scattered by the argon around the shock. Though the unshocked gas was preheated to a few eV, it scattered a negligible amount of light. The scattered power had a local peak at the peak of the electron temperature, just behind the shock front. Then, the scattered power continued to increase as the electron density increased, even as the shocked gas cooled radiatively. The electron density continued to rise despite cooling temperatures because of increased compression of the gas due to radiative losses [13].

This scattered power was attenuated by bremsstrahlung absorption, which was significant in the shocked argon. This absorption limited the scattered power to about 50 μm behind the shock front. Details of the absorption profile, as well as the scattered light profile, will be published elsewhere [7]. This result was convolved with the calculated signal as a function of space, resulting in a simulated instrument function.

5. Simulated instrument function

We used the above parameters to simulate the instrument function. We defined a scattering volume based on the direction and best focus size of the probe beam (80 μm diameter). Using the orientation and size of the slits, the probe beam was truncated to the volume the

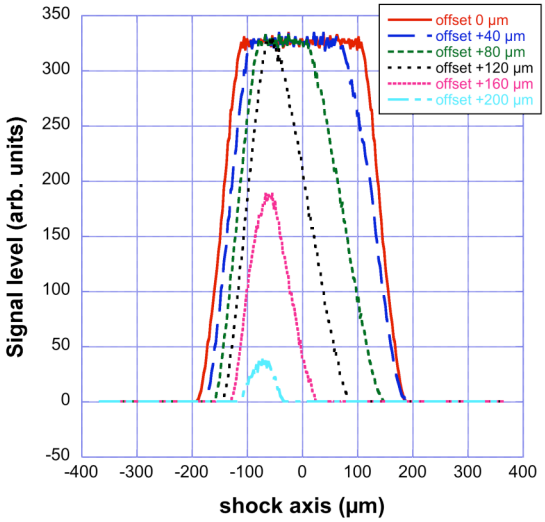

Figure 2: Calculated signal levels as a function of space. Each curve represents a different offset of the probe beam with respect to the place of the target axis and spectrometer slits. The signal is reduced to zero when the beam is offset by more than 220 µm.

collection diagnostic could detect. A delta function was then passed through the volume in the shock direction, and the signal from each step recorded. This overall response function was then convolved with the scattered-power profile. This gave the instrument function as a function of position of the shock.

Figure 2 shows the calculated signal as a function of space. Each curve shows a different offset from perfect alignment. In these cases, the probe beam was offset in a direction perpendicular to the plane made by the collection diagnostic and the probe beam.

Notice that the signal peak stays as high as the perfectly aligned case until the probe beam is misaligned by more than 120 µm. The signal did not disappear completely until the beam was offset by more than 220 µm.

Our relatively dim signal at high probe laser beam power suggests that the probe beam was significantly offset from the plane of the collection slits and the target axis. Note that other Thomson scattering experiments had stronger signal than ours using a 20 J or less probe beam [8],[10], whereas our probe beam energy was 175 J.

Assuming a constant shock velocity through the scattering volume, we then calculated how fast a shock would have to move through our calculated profile to give the same duration as the scattered light data. The duration of the collected signal in the experiment at FWHM was 350 ps.

Figure 3 shows the duration at FWHM as a function of the offset of the probe beam. Each curve assumes a different constant shock velocity through the scattering volume. The solid, horizontal line marks the duration of the collected data, at 350 ps. Note that all the curves cross this line, meaning the offset must be better characterized to use this method to determine the shock velocity through the scattering volume. As a comparison to the actual data, Figure 4 shows the velocity as a function of offset that would give a calculated duration of 350 ps, as a direct comparison to the data. From this, it is likely our experiment was offset more than 150 µm.

6. Conclusion and Acknowledgements

The orientation of the collection slits with respect to the shock volume has a large effect when correlating the observed signal duration with a constant shock velocity through the scattering volume.

Better measurements of the instantaneous shock velocity through the scattering volume would give a better

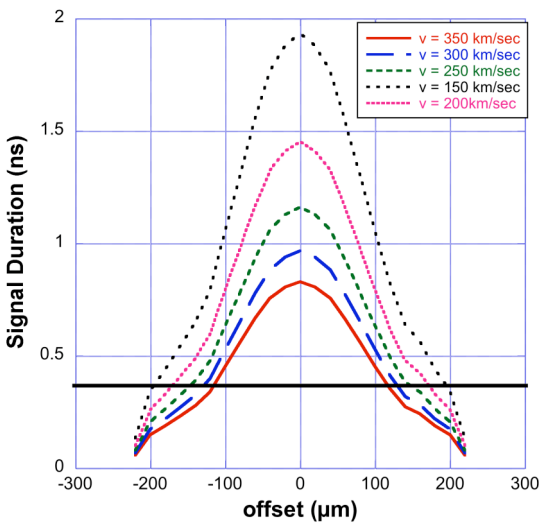

Figure 3: Signal duration as a function of probe beam offset. Each curve represents a different shock velocity through the scattering volume. The dark, horizontal line at 350 ps marks the duration of the measured signal. Each shock velocity curve crosses the horizontal line, giving a wide range of possible shock velocities, given a possible experimental misalignment.

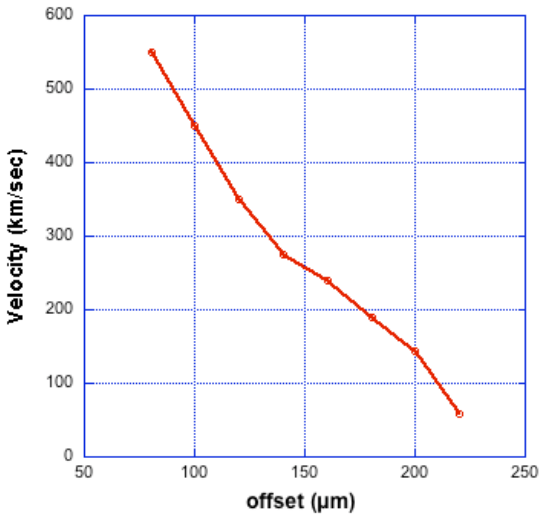

Figure 4: Calculated velocity for a given offset between the spectrometer slit and probe beam, given that the detected signal lasted 350 ps. The offset direction is perpendicular to the plane made by the slit and beam when they are perfectly aligned. Note that the signal disappears when the slit and beam are offset by more than 220 µm.

measurement of the compression of the probed gas, when measured simultaneously with the plasma flow velocity. The compression of a radiatively collapsed shock in gas has not yet been directly measured.

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