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Laboratory Studies of Colliding Blast Waves Produced in High-Intensity Laser-Cluster Interactions

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1. Introduction.

Atomic clusters are 10-100 nm-scale collections of weakly-bonded atoms with near-solid local density. An extended cluster medium produced in a low-temperature, expanding gas stream has gaseous density overall, but exhibits up to 90% absorption of sub-picosecond high intensity laser pulses [1]. This has resulted in their use in a diverse range of processes including x-ray and ion production [2, 3], "tabletop" thermonuclear fusion [4] and the production of shock and blast waves [5]. Although such experiments are typically probed on micron and nanosecond scales, hydrodynamic similarity (under certain constraints) allows the physics in these laboratory-based systems to be scaled to equivalent systems of immense size, such as supernova remnant evolution [7]. Here we discuss the extension of laser-cluster interactions to drive blast wave collisions, potentially a very attractive system for experimentally benchmarking complex astrophysical and radiation-hydrodynamics codes.

2. Creating colliding blast waves.

The absorption characteristics of a cluster target medium enable the efficient production and characterisation of shock and blast waves using high-repetition-rate, table-top CPA laser systems [5]. In order to further develop this approach to allow the creation of pairs of colliding cylindrical blast waves, a simple dual-focus system was employed (see Fig. 1). A 700fs, 800mJ, 1054nm heating beam from an Nd:Glass CPA laser system was passed through a 15° Fresnel bi-prism, creating two 'half-beams', deviating from the original laser axis by opposite angles. These were recombined using a second identical prism placed ~0.25m downstream and by tilting this about its triangular cross-section normal, phase could be added to the two recombined beams asymmetrically, resulting in a residual—and controllable—angular deviation from parallel. Subsequent F/10 focusing produced two focal spots of peak intensity ~10^{17}Wcm^{-2} with variable separation in space. These foci were used to heat two near-parallel cylindrical regions ~2mm long in a medium of 5nm hydrogen clusters, produced using a cryogenically-cooled, pulsed gas jet [7]. The subsequent blast wave evolution was interferometrically imaged perpendicularly to the heating beam axis using a frequency-doubled 500fs pulse as a backlight.

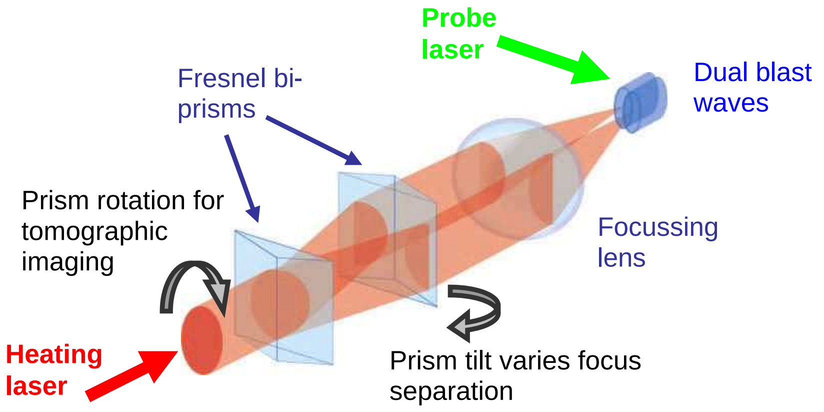


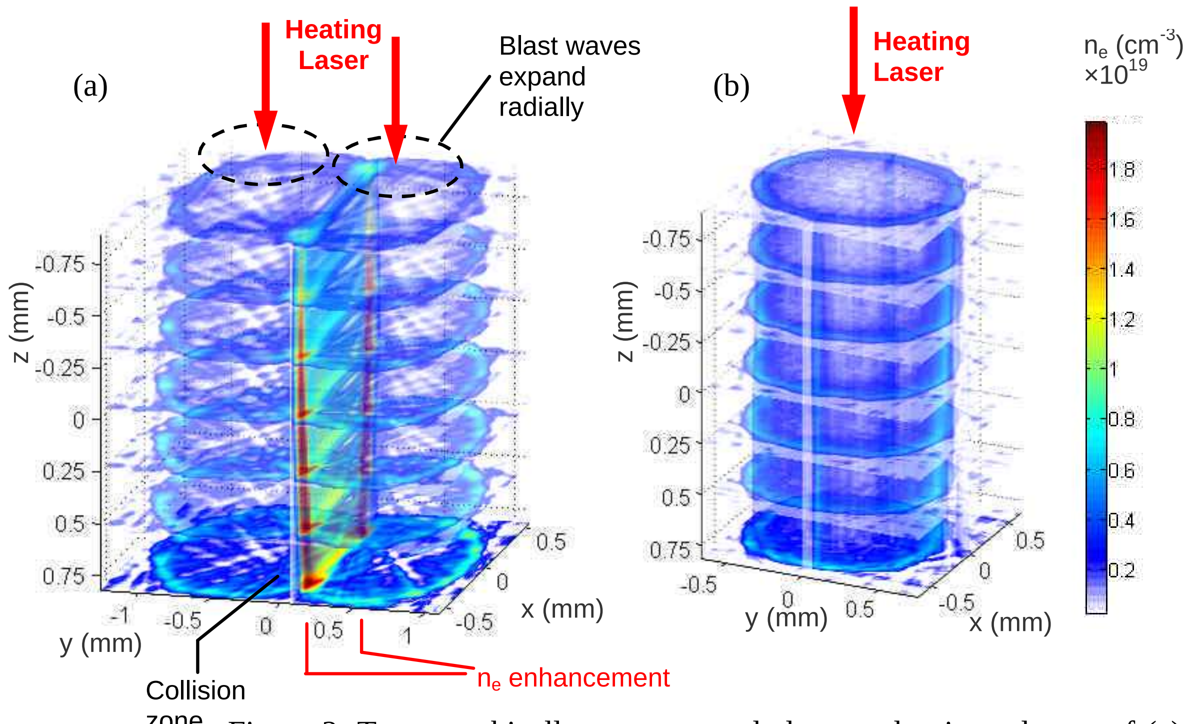
Figure 1. A bi-prism setup for launching and probing two cylindrical blast waves. The prisms can be rotated around the heating laser axis to allow optical imaging at a range of angles. The viewing angle shown is defined as 90°.

3. Image analysis.

The resulting interferogram is converted into a 2D map of the phase imparted onto the probe beam as it traverses the plasma using Fourier analysis and standard phase unwrapping techniques. This quantity takes the form of a path integral though the plasma and an inversion algorithm is required to retrieve the absolute electron density, $n_e(x,y,z)$. In the case of a rotationally-symmetric plasma this can be recovered through the inverse Abel transform. However, in the case of colliding blast waves the symmetry assumption is clearly invalid and an electron density measurement is no longer possible using this technique. Tomographic reconstruction, however, where multiple two-dimensional phase maps are combined to form a projection (or Radon transform) of the phase image, makes no inherent symmetry assumptions and is simple to implement numerically—the electron density cross section can easily be obtained using an inverse Radon transform [8]. By rotating the focus-splitting prism system about the laser axis and interferometrically probing the collision region from different angles on successive laser shots, we were able to apply this technique to dual-blast wave collision experiments. Due to symmetry considerations a reconstruction with 5° resolution was obtained using 18 individual laser shots, energy-binned to within ±10%.

4. Results.

Using the tomographic reconstruction process described above, we have measured the 3D absolute electron density volumes (depicted in Fig. 2) for both single and colliding hydrogen blast waves after 9.75ns, where $t_{collision}$=8ns. The curvature of the two blast waves at impact gives rise to both a radial and a tangential force, which induces a lateral movement of plasma outwards along the collision boundary. This is indicated by the two regions of electron density enhancement seen at the edges of the collision zone.



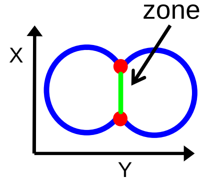


Figure 2. Tomographically-reconstructed electron density volumes of (a) two colliding blast waves and (b) a single blast wave, made up from interferometric images obtained at successive angles through the (x,y) plane. The blast wave collision results in electron density enhancements along the collision zone, which appear to vary along the laser axis, z.

The strength and separation of these features vary along the laser axis, due to the slightly-diverging focal volumes and depleting energy deposition throughout the medium [9]. Intuitively, this axis can be treated—at least qualitatively—as a post-collision time delay, due to the hydrodynamic self-similarity of the blast wave evolution prior to collision, and this is currently the subject of further analysis. Fig. 2(b) shows a tomogram volume constructed using 10% energy-binned images of a single blast wave produced in the same way, but with one focus blocked. The uniform, cylindrically-symmetric spatial profile indicates that the movement of the heating focus through the cluster distribution has negligible effect on the blast wave structure and also implies that Abel inversion is justified for this kind of interaction. In order to check the accuracy of the multi-shot reconstruction technique, longitudinal slices taken through the electron density volume at 0 and 90° were compared with Abel-inverted electron density maps calculated from the interferometric images taken at these angles (see Fig. 3). The results of the two methods are in very good agreement with each other.

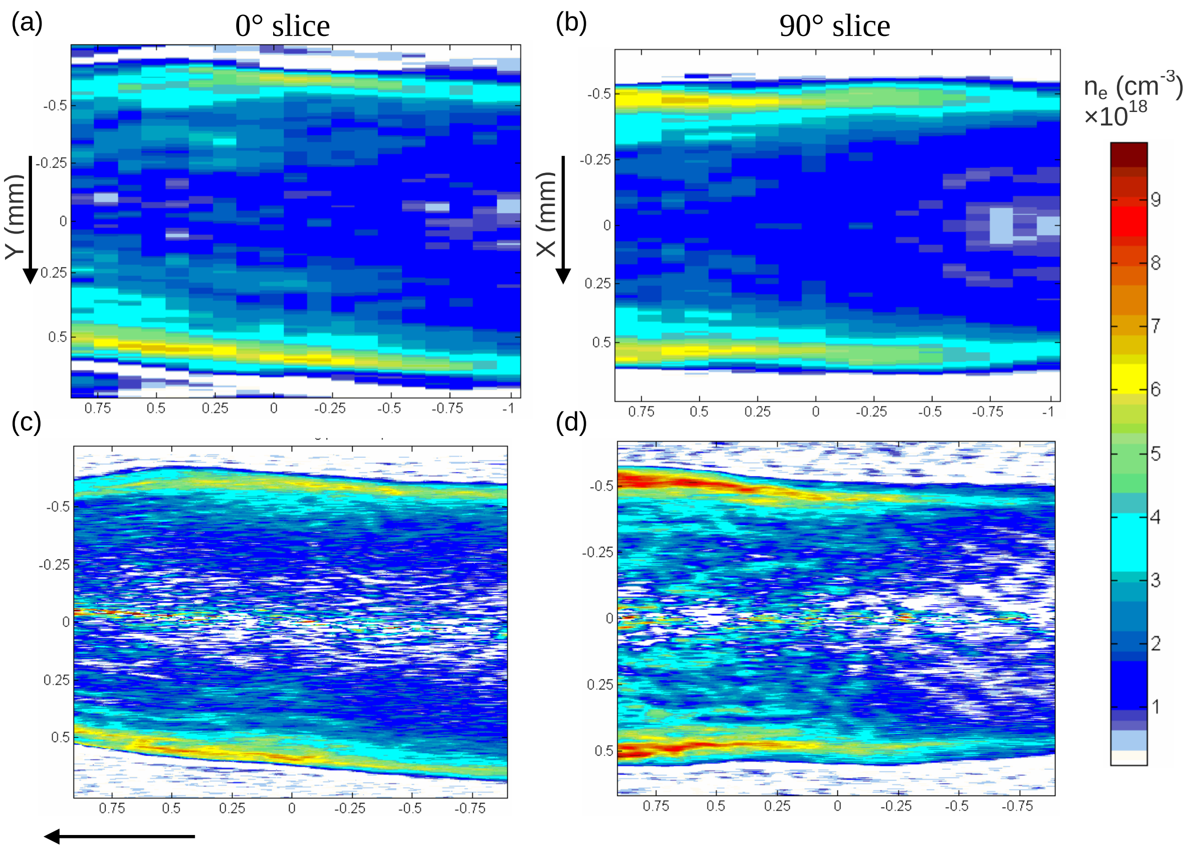


Figure 3. (a) & (b): 0° and 90° longitudinal slices taken though Tomographyically-reconstruced single blast wave electron density volumes; (c) & (d): corresponding Abel-inverted electron density maps.

5. Conclusion.

We have demonstrated a multiple-shot method for tomographic reconstruction of 3D electron density data following the collision of laser-driven blast waves and observed density enhancements at the collision site. A comparison of the reconstruction technique with single-shot Abel-inversion shows good agreement, implying that error propagation is not prohibitive. Further analysis of this work and similar experiments are currently underway with a view to comparing with astrophysical simulations of hydrodynamically-similar systems.

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