Tailored Blast Wave Production Pertaining to Supernova Remnants

A.S.Moore[1], D.R.Symes[2], R.A.Smith[1],

1. Blackett Laboratory, Imperial College London, London SW7 2BZ, United Kingdom
2. University of Texas at Austin, 1 University Station C1510, Austin, Texas 78712

We report on the first production of *tailored* blast waves in cluster media using a 1 ps laser pulse focused to $2x10^{16}Wcm^{-2}$. Cylindrical blast waves are produced with a strong axial modulation of variable spatial frequency, to act as a seed for instability growth. Changing the cluster density whilst keeping the atomic density of the target constant modifies energy deposition. Electron density maps confirm production of strongly modulated blast waves and show a thin shell in H at late-time. Blast waves form in H, and Ar. In Xe, a blast wave does not form on the timescale studied. Astrophysical similarity parameters suggest that the H results are hydrodynamically scalable. Further evolution would create a regime where radiative effects may be influential in Ar and Xe.

The blast wave (BW) from an 'idealized' supernova remnant (SNR) becomes adiabatic during its evolution. Analytically this is a self-similar, Sedov-Taylor (ST) solution, and is characterised by thin-shell formation behind the shock. ST analysis for a strong shock yields a power-law dependence of the shock radius in time. When the BW cannot be treated as adiabatic, two analytical, radiative solutions are obtained that assume a constant fraction of energy is lost across the shock: the pressure driven snowplow (PDS) and the momentum conserving snowplow (MCS). In the PDS regime radiative cooling only occurs in the thin-shell, whereas the MCS regime occurs later when cooling is prevalent in the thin-shell and core. In the transition to both radiative phases, modeling has predicted that instabilities can occur [1] and experiments by Grun [2] have shown some evidence of this. Overstabilities, predicted by Vishniac [3], are also of importance in these radiative situations.

In cylindrical geometry, the situation here, the BW follows a different trajectory from the spherical case. For a cylindrical ST BW the shock evolves as:

$$R(t)=\beta(\gamma)(E_l/\rho_0)^{1/4}\, t^{\alpha}$$

being dependent on E_l, the initial energy per unit length, ρ_0 the density of the unperturbed medium, γ the adiabacity, and α the deceleration parameter = 0.5. A cylindrical BW in the PDS and MCS regimes will follow a trajectory with α = 3/8 and 1/3 respectively [4].

The use of high power, sub-ps lasers to produce BWs in the laboratory is an area of growing interest [5,6,7]. Such lasers allow energy deposition to be de-coupled from the later ns hydrodynamic motion of the plasma. Used in conjunction with a target medium composed of atomic clusters [8], extremely high energy deposition efficiencies (near 100%) can be realised, compared to ≈ 1% absorption for atomic gas targets of comparable average density [9]. Resultant energy densities have been found to be as high as 10^4-10^5 Jcm^{-3} [10].

Previous work [7,4] involving BWs in high Z cluster media show strong evidence of a radiative precursor, but no instabilities were observed. We present a new method to imprint strong, variable scale length spatial modulations onto the BW to act as a seed for the growth of instabilities. In [11] a 'laser-machining' technique was used to shape the cluster medium. By destroying clusters in specific regions the average atomic density is unchanged, but the cluster density is modified. The large difference in laser absorption between clusters and monatomic gas results in a strong variation in the energy deposition of a second, high-power, heating beam, tailoring the BW radius in a controlled and repeatable fashion [12].

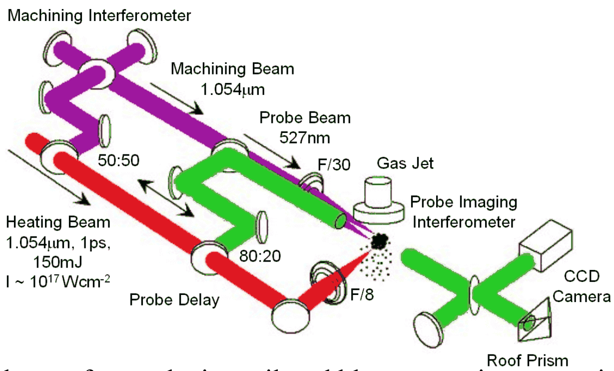

Figure 1. Experimental layout for producing tailored blast waves in an atomic cluster medium.

Our experiment used a 1 ps pulse duration, Nd:glass laser with energy of up to 1 J at 1.054 µm and is shown in Fig. 1. H_2, Ar and Xe clusters were produced with backing pressures of up to 50 bar, and temperatures between 293K and 97K (to control cluster size). The main laser beam was split into three beamlets, with half the energy focused into the cluster medium to provide a heating beam with vacuum intensity of 2×10^{16} Wcm^{-2}. The second beamlet, frequency doubled to 527 nm, interferometrically probed the plasma with a wide (>3mm) field of view, and could be delayed up to 6 ns after the heating beam. FFT processing [13] and Abel inversion of the images allowed calculation of electron density. The remaining beamlet was used to machine the cluster medium, and was split again into two synchronous but spatially separated beams that were loosely focused into the cluster medium 1.4 ns prior to, and transverse to, the heating beam, ensuring the clusters had fully disintegrated before the heating beam arrival. Each machining beam contained ≈ 100 mJ defocused to produce two low-intensity spots in the plane of the heating beam.

The interaction of the heating beam with the unmodified cluster spray formed a cylindrical plasma filament 2 mm below the gas jet nozzle, ≈ 2 mm long, with an initial radius of ≈ 50 μm. A shock developed and the electron density, initially Gaussian shaped peaked on the laser axis, typically evolved towards a more thin-shell structure.

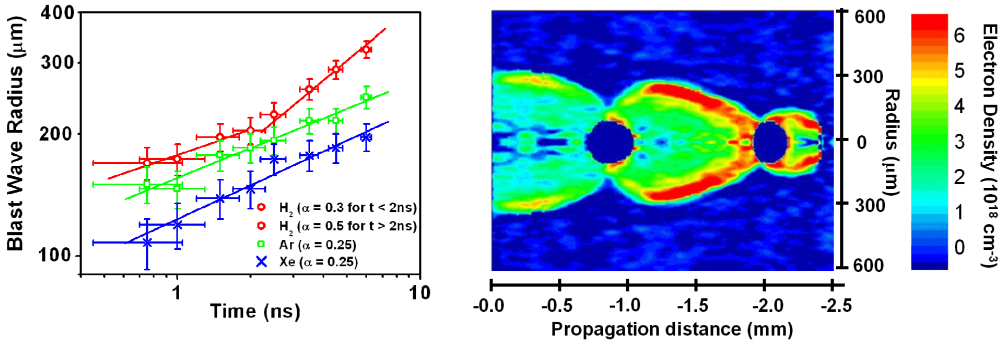

Figure 2. (a) Measured blast wave trajectories for H, Ar and Xe cluster media. Solid lines represent the best fit to the data. (b) Electron density map of a tailored blast wave in a H cluster medium after 6 ns.

With no machining beam, interferometric images show that a smooth, uniform shock parallel to the laser axis forms. No sizeable changes in the radius along the plasma filament were seen during the time-evolution. In contrast, the *tailored* BW has a maximum radius matching that of the unmachined target, but is greatly reduced where the machining beams destroyed clusters. The self-similarity denotes that the BW radius is proportional to deposited energy, so little energy is deposited in regions where clusters have previously been destroyed. A cross-section of the electron density of a machined BW is shown in Fig. 2(b).

The late-time (post 2 ns) behavior of H shows the formation of a strong shock with velocity V_{H2} = 3.0 (± 0.3) x10^6 cm/s, equivalent to Mach ≈ 45. In Ar the BW forms later at ≈ 4.5 ns, and has a slower velocity of 1.5 (± 0.3) x10^6 cm/s. In Xe it is unclear if the shock forms in the time studied. The front velocity was 1.3 (± 0.5) x10^6 cm/s. The deposited energy is the same in all three cases. For a ST trajectory, the velocity, $V \propto \rho_0^{0.25}$. The ratio of this quantity for the different gases shows that the velocities in Ar and Xe should be 0.4V_{H2} and 0.3V_{H2} respectively, in good agreement with that measured. Fig. 2(a) shows that the trajectories of the *unmodulated* BWs for each gas are initially very similar. In H the shock evolves as $t^{0.30(\pm 0.05)}$ and in Ar and Xe, α = 0.25 (± 0.07). After 2 ns, the H trajectory changes to α ≈ 0.5 corresponding to a ST situation. No change is observed in Ar or Xe.

It is clear that the BWs in each gas are at different stages of development. In H we see a thin shell and the BW radius is large compared to $r_{initial}$ ≈ 50 μm after 2 ns. At 2 ns the radius is ≈ 200 μm, corresponding to a factor of 16 change in mass from the initial interaction, sufficient to assume self-similarity. In Ar the thin-shell becomes clear later ≈ 4.5 ns, when the radius is

200 μm, but density still remains at the core, suggesting it is becoming self-similar. Most noticeably, in Xe the density is still peaked on axis, and the shock does not reach 200 μm implying that it does not propagate far enough to allow self-similar analysis.

The deceleration parameters in Ar and Xe are lower than 0.5, the ST value, which is probably due to the BW being underdeveloped, but notably different to the results of [14,4]. Energy transport at this time is due to electrons, so whilst these trajectories correspond well to an MCS or PDS, the timescales are too short compared to the e^--ion collision (≈ 10's ns), when radiation effects are expected. The likely explanation for them is electron thermal conduction that transports energy ahead of the forming shock. A radial ionization wave results from the high initial temperature ($T_e \approx 1.5$ keV), and quickly thermalises on the e^--e^- collision timescale (≈ 100's ps) forming a thermal wave [15]. On a longer timescale (up to a few ns) the ion-shock propagates into the preheated plasma, accumulating mass, until the shock merges with the electron front and the dynamics become self-similar.

Concluding, we have demonstrated a laboratory method of tailoring BWs in low and high Z gases. The BW trajectories are in good agreement with that expected during formation. Radiative effects are not observed, but calculated to occur later in the evolution. Further investigations of the BW evolution over longer timescales are in preparation. Tremendous potential exists for using this technique to create shaped BWs of relevance to astrophysics. The reproducibility of the tailored BW and the ease with which the seeded perturbation can be altered makes this desirable for studying instabilities. Early analysis indicates that the H results are hydrodynamically scalable. Extension to studying late-time evolution of BWs in high Z clusters, will probe the dynamics of radiative shocks. This work also enables the creation of spherical or custom-shaped BWs, and the study of collisions between shocks. We would like to thank J. Tisch, M. Dunne, E. Gumbrell and A. Edens for very useful discussions, and P. Ruthven and A. Gregory for technical assistance. This work was supported by EPSRC & MoD.

[1] Blondin, J.M.et al.: 1998, ApJ, 500, 342
[2] Grun, J. et al: 1991, Phys. Rev. Lett., 66, 2738
[3] Vishniac, E.T., 1983, ApJ, 274, 152
[4] Edwards, M.J. et al: 2001, Phys. Rev. Lett., 87, 085004
[5] Dunne, M. et al.: 1994, Phys. Rev. Lett., 72, 1024
[6] Remington, B.A., Arnett, D., Drake, R.P., and Takabe, H., 1999, Science, 284, 1488
[7] Ditmire, T.et al: 2000, ApJSS, 127, 299
[8] Hagena. O.F., & Obert. W., 1972, J. Chem. Phys., 56, 1793
[9] Glover, T.E. et al.: 1994, Phys. Rev. Lett., 73, 78
[10] Zweiback. J., & Ditmire. T., 2001, Phys. Plasmas, 8, 4545
[11] Symes, D.R. et al., 2002, App. Phys. Lett., 80, 4112
[12] Smith, R.A., & Ditmire, T., 2001, Mol. & Clusters in Intense Laser Fields, ed. J. Posthumus (C U Press)
[13] Takeda, M., Ina, H. & Kobayashi, S., 1982, J. Opt. Soc. Am., 72, 156
[14] Shigemori, K. et al: 2000, ApJ, 533, L159
[15] Zeldovich, Y.B., & Raizer, Y.P., 1966, Vol. 1,ed. W.D. Hayes & R.F.Probstein (New York: Academic)