Fielding of a large gas cell for fine pressure control in collisionless shock laser plasma experiments

T. Hodge[1], H. Ahmed[1], E. Aktan[2], A. Alejo[1], B. Coleman[1], M. E. Dieckmann[3], D. Doria[1,4], J. S. Green[5], R. Heathcote[5], G. Milluzzo[1], R. Prasad[2], B. Reville[1], L. Romagnani[1,6], M. Swantusch[2], S. White[1], O. Willi[2], and M. Borghesi[1]

[1]*Centre for Plasma Physics, Queen's University Belfast, Belfast, United Kingdom*

[2]*Institute for Laser and Plasma Physics, University of Düsseldorf, Germany*

[3]*Department of Science and Technology (ITN), Linköpings University, Norrköping, Sweden*

[4]*Extreme Light Infrastructure - Nuclear Physics, Măgurele, Romania*

[5]*Central Laser Facility, Rutherford Appleton Laboratory, Oxford, United Kingdom*

[6]*École Polytechnique, CNRS, LULI, France*

Introduction

The collision of two plasmas with different properties is a scenario which has relevance to a wide range of contexts from astrophysical to laboratory plasmas. The expansion of a hot, dense plasma into a lower density background is of particular common interest as the growth of a range of nonlinear structures can be triggered including solitons and shocks as well as the formation of thin plasma shells of increased density at the interface of the two plasmas. These thin shell are prone to dynamic instabilities, such as Rayleigh-Taylor (RT), Richtmyer-Meshkov, Kelvin-Helmholtz and the thin shell instability (TSI). Previous experimental campaigns [1] [2] [3] have see indications of a number of these features forming and are of great interest for further experimental investigation. The indication from these experiments is that the formation of instabilities is highly susceptible to the experimental parameters such as laser energy and in particular, the pressure of the surrounding gas that is ionized to provide the low density background.

The laser ablation of a solid target provides a unique way to launch shocks into tenuously ionized background under a range of parameters relevant to astrophysics [4] whilst permitting the fielding of detailed plasma diagnostics to understand the phenomena.

Collisionless shocks

For a plasma to be collisionless, the mean free path between collisions must be much larger than the typical macroscopic length scale over which the plasma quantities vary and the collision

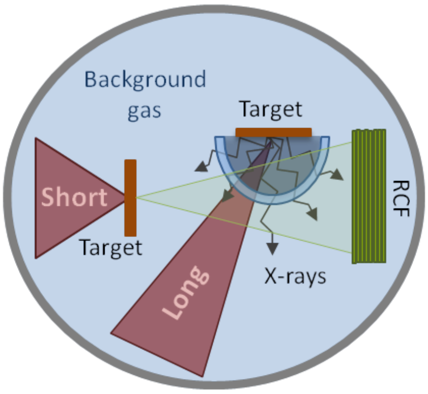

Figure 1: Typical proton probing set up for collisionless shock experiment with backfilled interaction chamber.

frequencies must be much smaller than the typical frequency at which the plasma quantities vary, for example the plasma frequency.

Common shock waves are mediated through binary collisions. Collisionless shocks are those in which the collisional mean-free path of the medium is much larger than the shock front. This means shocks are not formed by two-body Coulomb collisions since the mean free path of these is too large. The mechanism driving collisionless shocks is thought to be plasma instabilities and self generated magnetic fields, that operate on the scale of the plasma skin depth which is typically much shorter than the mean free path.

Proton radiography diagnostic

Proton radiography (Figure 1) is a relatively simple yet powerful diagnostic tool that allows "imaging" of electromagnetic fields in a plasma via the observed modulations in a proton beam on a detector. Protons are typically generated and accelerated through the interaction of an intense short pulse laser with a thin metallic target (in the work presented here, a 50 μm thick Au foil) and recorded with a stack of radiochromic films (RCF). The proton beam traverses a region of interest and is deflected due to the electric field in that region [5].

These proton beams are typically created via target normal sheath acceleration (TNSA) [6]; they have a broadband energy spectrum, resulting in different times of flight for different energies. The multi-layer configuration of the RCF stack allows for multi-frame, temporal resolution, due to different energies of protons penetrating different depths into the stack due to the Bragg peak of proton energy deposition. Adjustable delay between the proton generating laser pulse and the interaction generating laser pulse allows for temporal scanning.

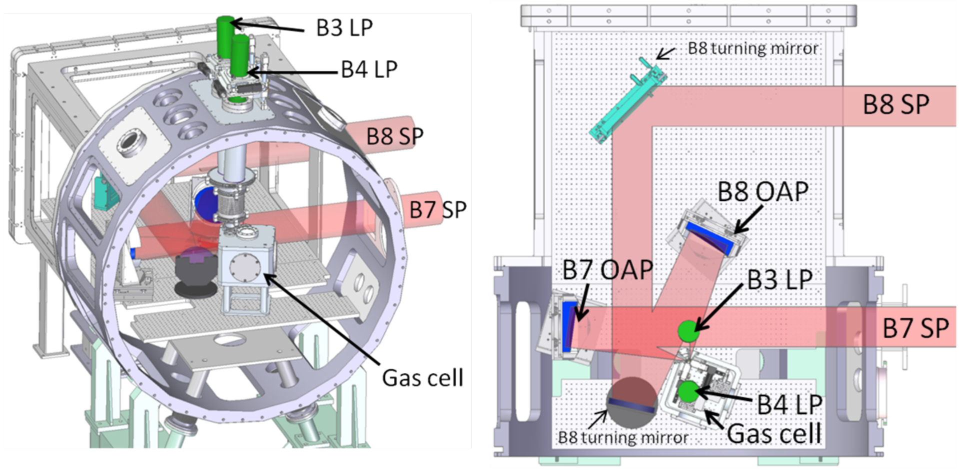

Figure 2: Left- 3D view of gas cell in the Vulcan TAW target chamber. Right- Plan view of experimental set up in target chamber including new gas cell.

General experimental setup

Experiments have been carried out using the Vulcan laser facility at the Rutherford Appleton Laboratory. A 1 ns, 150 J laser pulse (long pulse) was focused down to a focal spot of 50 μm radius, onto a 100 μm thick Au foil, resulting in a peak intensity on the order of 10^{15} W cm^{-2}. The gold foil was surrounded by nitrogen gas at a pressure ranging from 10^{-4} mbar - 10^{-1} mbar. The laser foil interaction generates a rapidly expanding warm dense plasma that collides with a more rarefied background plasma. Hydrodynamic simulations with HYADES [2] indicated that the nitrogen gas is full ionized by secondary x-ray emission from the solid target. The region of space the dense plasma expands into is probed by the proton beam for radiography.

Gas cell

The development and deployment of a large gas cell provided the ability to reach higher pressures than those reached on previous campaigns. Typically experiments were conducted by back filling the interaction chamber with the gas. This presents problems in the form of ambiguity in the measured pressure due to the small volumes of gas used and the dangers presented by focusing high intensity lasers in a low vacuum environment (self focusing). The cell allowed much higher pressures to be achieved (1 mbar), with the pressure remaining stable for several minuets. The cell was also designed to allow proton probing in two orthogonal directions. This allows for a larger temporal window to be covered in one shot, by utilizing the delay between the two short pulse lasers, reducing shot to shot variations. Other features such as configurable RCF stack position for ad hoc adjustment of magnification and unique cone and washer design for short pulse targets increased flexibility and shot rate.

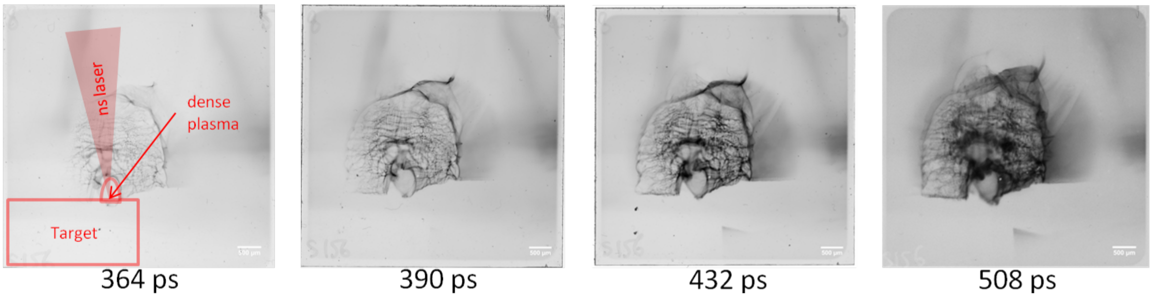

Figure 3: RCF images of a shock in a high pressure nitrogen (0.76 mbar) environment corresponding to 365 ps, 390 ps, 432 ps and 508 ps after the start of the long pulse interaction respectively. Note the modulation in the shock front.

Results

Thin shells of increased density that form at the interface of the two plasmas, are prone to dynamic instabilities. Figure 3 shows periodic spatial oscillations along the thin shell of expanding plasma. Rayleigh-Taylor instabilities are also known to form at the interface of two fluids with different densities and may affect the formation of structures observed in the experiment, which become more turbulent with time.

References

[1] L. Romagnani, S. Bulanov, M. Borghesi, P. Audebert, J. Gauthier, K. Löwenbrück, A. Mackinnon, P. Patel, G. Pretzler, T. Toncian, and O. Willi, "Observation of Collisionless Shocks in Laser-Plasma Experiments," *Phys. Rev. Lett.*, vol. 101, no. 02500, pp. 1–4, 2008.

[2] H. Ahmed, M. E. Dieckmann, L. Romagnani, D. Doria, G. Sarri, M. Cerchez, E. Ianni, I. Kourakis, A. L. Giesecke, M. Notley, R. Prasad, K. Quinn, O. Willi, and M. Borghesi, "Time-Resolved Characterization of the Formation of a Collisionless Shock," *Phys. Rev. Lett.*, vol. 110, no. 205001, pp. 1–5, 2013.

[3] H. Ahmed, D. Doria, M. E. Dieckmann, G. Sarri, L. Romagnani, A. Bret, M. Cerchez, A. L. Giesecke, E. Ianni, and S. Kar, "Experimental Observation of Thin-shell Instability in a Collisionless Plasma," *Astrophys. J. Lett.*, vol. 834, no. L21, pp. 1–5, 2017.

[4] M. E. Dieckmann, D. Doria, G. Sarri, L. Romagnani, H. Ahmed, D. Folini, R. Walder, A. Bret, and M. Borghesi, "Electrostatic shock waves in the laboratory and astrophysics: Similarities and differences," *Plasma Phys. Control. Fusion*, vol. 60, no. 014014, pp. 1–8, 2018.

[5] G. Sarri, C. A. Cecchetti, L. Romagnani, C. M. Brown, D. J. Hoarty, S. James, J. Morton, M. E. Dieckmann, R. Jung, O. Willi, S. V. Bulanov, F. Pegoraro, and M. Borghesi, "The application of laser-driven proton beams to the radiography of intense laser-hohlraum interactions," *New J. Phys.*, vol. 12, no. 045006, pp. 1–12, 2010.

[6] R. A. Snavely, M. H. Key, S. P. Hatchett, I. E. Cowan, M. Roth, T. W. Phillips, M. A. Stoyer, E. A. Henry, T. C. Sangster, M. S. Singh, S. C. Wilks, A. MacKinnon, A. Offenberger, D. M. Pennington, K. Yasuike, A. B. Langdon, B. F. Lasinski, J. Johnson, M. D. Perry, and E. M. Campbell, "Intense high-energy proton beams from petawatt-laser irradiation of solids," *Phys. Rev. Lett.*, vol. 85, no. 14, pp. 2945–2948, 2000.