Plasma Confinement via Shock-Driven Cavity Collapse

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1. Numerical Study

The resolution of the gas-liquid interface, particularly given the present large density ratio, is a well-known challenge to methods for compressible hydrodynamics. Without an explicit, low-dissipation treatment of this boundary it is very difficult to achieve sufficient accuracy. We employ a front tracking method that uses two grids: an underlying Eulerian grid on which the bulk flow away from the interface is solved and an overlaid lower-dimensional Lagrangian grid that moves with the flow in a coupled manner and is used to represent that gas-liquid interface. The methodology and comprehensive results sets have been described previously[1].

Figure 1 shows three time instances from a simulation of the problem. The shock propagates from right to left and in the first frame can be seen "wrapping around" the cavity. The first frame also shows the formation of a high-speed transverse jet, a salient feature of the problem. This jet impacts the leeward wall of the bubble, creating a strong spherically expanding shockwave, and trapping a small portion of the gas. The remains of the cavity at this stage are now toroidal. The expanding shock drives the torus to collapse further and the final frame shows the time of minimum volume. From this point on, there is no further gas compression and the remnants advect downstream within the resulting vortex ring.

2. Experimental Study

The basic experimental set up is illustrated in Figure 2. We employ a single-stage gas gun (70 mm bore, velocity up to 650 ms^{-1}) as a planar shockwave generator. A steel projectile impacts an Al striker which couples the impact into a hydrogel block. The gel is cast in two halves with a matching hemispherical inclusions in each part. The two halves are brought together to form a 50 mm cube with a 5 mm diameter spherical cavity.

A number of diagnostics have been employed. Schlieren imaging with a Specialised Imaging SIMX-16 high-speed framing camera shows the planarity of the shock front, the shock speed and the collapse timings. A fibre-optic probe hydrophone[2] provides an invasive measurement of index of refraction, yielding a time trace that can be converted via the Gladstone-Dale equation to give density. An EOS then gives conversion to pressure; the shocks produced are

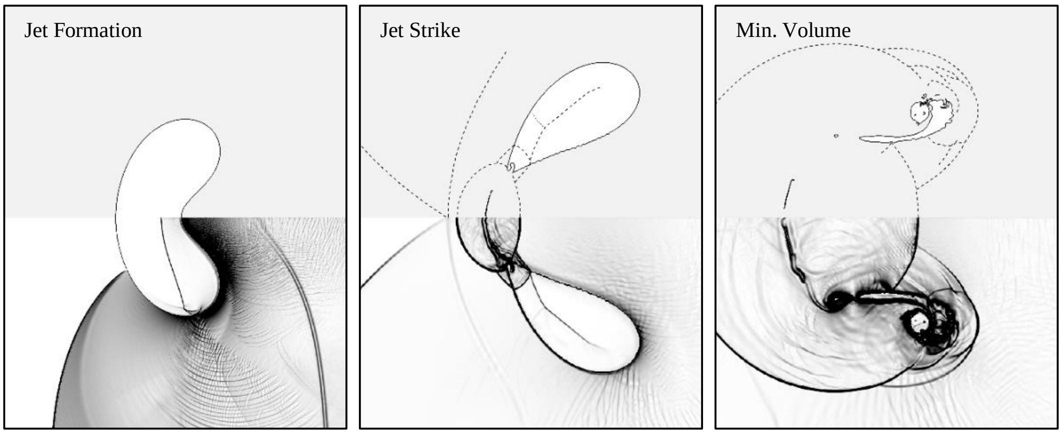

Figure 1 | Numerical simulation of shock-driven cavity collapse, showing numerical schlieren on the lower half and gas-liquid interface position (solid) and shock positions (dashed) on the upper half. The liquid is water and the gas air. The shock strength is 1 GPs and the bubble size is 1 mm.

up to 1 GPa and have a flat topped profile, i.e. the high pressure is sustained for the duration of the cavity collapse.

The focus of the results presented here is the self-emission during the cavity collapse. The numerical work predicts that an initial shock pressure of ~1 GPa will result in temperatures and densities in the gas of ~1 eV and ~1 gcc^{-1}. Previous experimental work has used cylindrical instead of spherical cavities and has observed two temporally distinct flashes of luminescence[3]. The first flash occurs at a single point and is assumed to correspond to jet impact and the second occurs in two locations, consistent with the cylinder collapsing in a planar 2D manner to form two compressed lobes.

Our first experiments aimed to reproduce this work. When viewing the cylinder collapse along the axis we observed similar results. However, when viewing transverse to the cylinder axis it was apparent that the cavity was collapsing in a complex 3D manner; regions of luminescence appearing at either end and progressing inwards. This motivated a switch to spherical cavities.

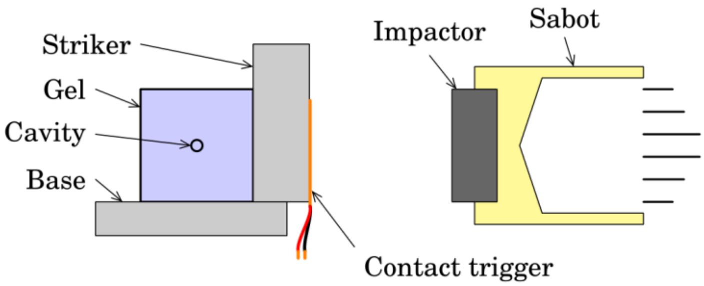

Figure 2 | Cartoon showing the basic experimental set up. A 50 mm diameter steel projectile is held in a nylon sabot and impacted into an Al striker piece. This couples the impact into a block of hydrogel (99.5% water), 50 mm on each face, within which a 5 mm cavity has been cast. The generated shock rapidly collapses the cavity.

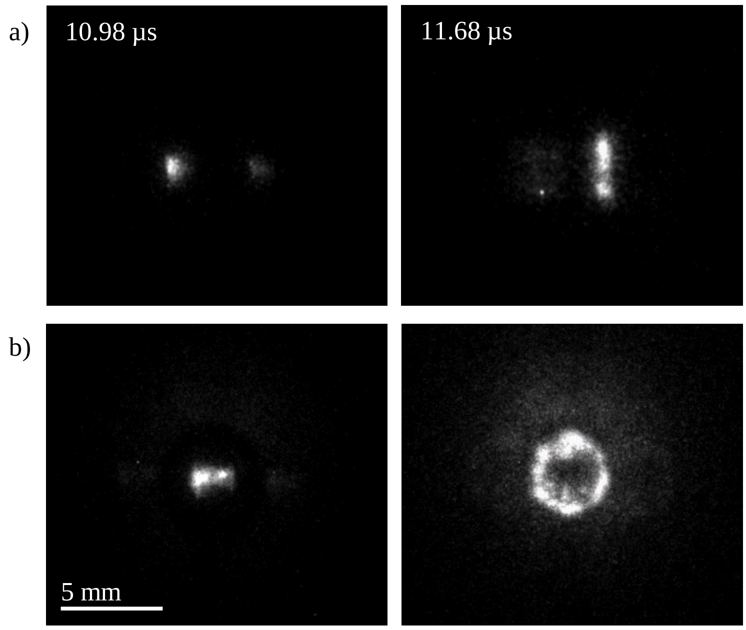

Figure 3 | images taken with a SIMX-16 with no external lighting, capturing self-emission during collapse; a) transverse to projectile axis, b) on-projectile axis, viewing from behind. The times are referenced to the initial trigger; time between jet strike and minimum volume is ~700 ns.

Figure 3 a) shows self-emission images from the spherical cavity collapse when viewed transversely to the projectile flight. The expectation was that we would see a point flash of light corresponding to jet impact, and then at later time a bar of luminescence correspond to viewing a torus of plasma from the side. This is borne out in the two images presented. The images are not perfectly clear; we believe that the surrounding gel and shock structures are refracting the emission. This is currently the subject of further study.

Figure 3 b) shows the emission imaged on the projectile axis with the projectile coming towards the camera, using a sacrificial mirror. The demonstration that luminescence is coming from the regions predicted by the simulations is very clear. The first image shows a point in the centre of the bubble back wall, corresponding to jet impact. The second shows a full, unbroken torus of plasma, albeit with smaller scale deviations from symmetry.

Figure 4 shows, for the first time, measurement of the emitted optical power over time. Two devices are used simultaneously, an avalanche photodiode (APD) and a photomultiplier tube (PMT), with 632 nm and 460 nm bandpass filters respectively. Both filters are 10 nm FWHM. The time constants of response are roughly 5 ns and 0.5 ns respectively. The differences in optic geometry and attenuation have been accounted for with calibration shots using the same filter on both devices. The calibrations have been applied such that Figure 4 shows detected optical power.

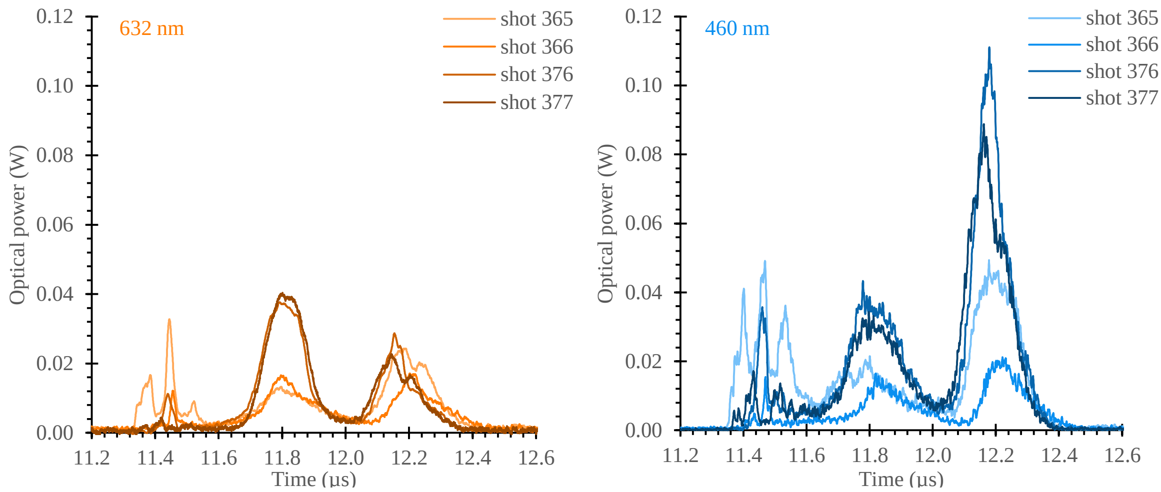

Figure 4 | Self-emission measurements made simultaneously at the frequencies indicated using 10 nm bandpass filters.

Three peaks in the signal are broadly distinguished. Comparing the timings with schlieren imaging shows a correlation between the first light flash and the emission of the shock wave from jet impact. The third flash matches the timing of the images showing the luminescing torus and is thus thought to correspond to minimum volume. The origin of the middle flash is less clear; it is likely related to the sheet jetting[1].

Comparing the traces at the two wavelengths we can get a first crude indication of the temperature of the emission. The second flash appears to have roughly equal power at both wavelengths, the first flash shows a slightly greater blue light content and the third flash substantially greater. Preliminary work with an integrating spectrometer shows a continuous spectrum of emission. In this context, the greater the blue light content the hotter the inferred temperature might be. Obviously, more rigorous work examining the spectrum is planned.

As a final comment, it is clear that shot-to-shot repeatability requires further work.

3. Conclusions and Future Work

To conclude, our experimental results demonstrate inertial confinement of a plasma via shock-driven cavity collapse. The self-emission shows three peaks, which are correlated with dynamics observed in the simulations. We intend to quantify more accurately the conditions reached within this plasma; the simulations predict temperatures of ~1 eV and densities of ~1 gcc^{-1}.

4. Bibliography

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