Multi-frame radiography of shockwave interactions with clumpy material (HC-4455) - report on ESRF experiments in Feb 2022

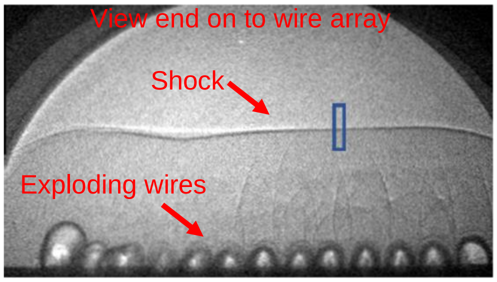
The Technion and Imperial College teams performed initial experiments on HC-4455 in February 2022. The initial aims for the experiments were to explore the interaction of intense shockwaves with clumps of dense material – simulating what may be encountered when a shockwave launched from a supernova/other event interacts with interstellar clouds, planets and asteroids. The experiments built on those performed for HC-4679 in December 2021, where it was shown that a high quality, large scale planar shockwave was able to be produced in water by exploding a planar wire array with a small, 30kA pulsed power generator.

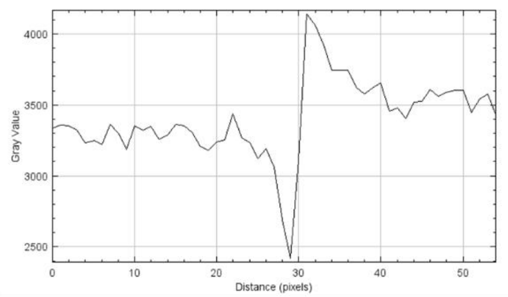
In total over ~4 days 54 experiments were performed, many requiring multiple hours to prepare by the team. With 16 bunch mode, two Shimadzu cameras were fielded to enable no missed bunches – i.e. continual radiographic 'movies' could be produced with interframe times of 176ns over almost ~50µs

Overview of results

Radiographs of the shockwaves produced by the planar arrays enabled both the density of the water behind the shockwave and the speed of the shockwave to be measured – hence all the state variables of the water behind the shock could be determined form the Rankine Hugoniot conditions:

We can calculate density of water behind shock from intensity on radiographs (assuming scintillator and camera linear)





$\rho_{shocked} = (\ln(I_{shocked}/I_{unshocked})/(-K\,l\,) + \rho_{unshocked} = (\ln(3300/3500)\,/(-3.1E\text{-}1*2.5)) + 1 = 1.08$g/cc

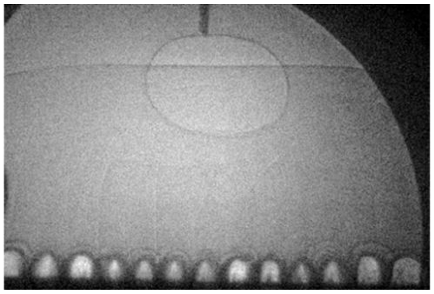
NB: Pink beam from 10-50keV – we calibrated K based on air/water calibration shots

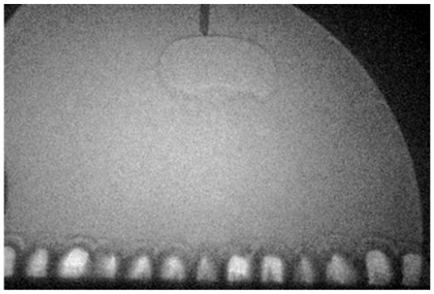
Knowing density and shock wave velocity, we can use R-H jump conditions to derive:

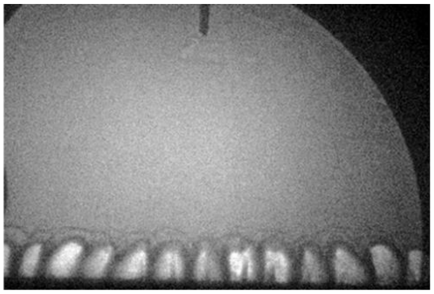
Particle velocity behind the shock = 155ms^{-1}

Pressure behind shock wave = 3.3kbar

Spherical targets of different density and strength were fielded in the area above the array. With low density polystyrene targets, the target could be seen to invert and implode along the direction of the shockwave with a speed of ~1300ms^{-1}:

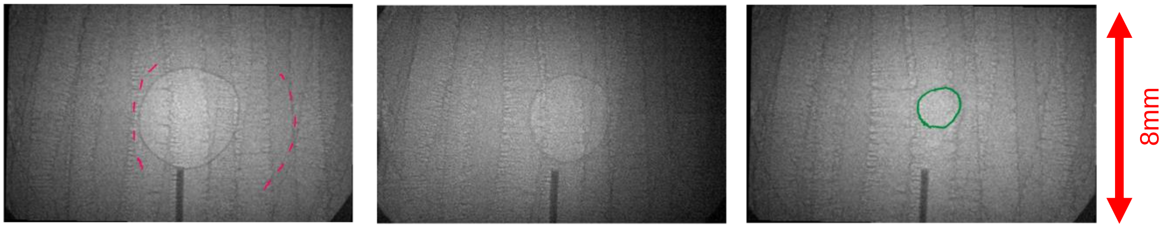

1232ns after arrival of shock


2464ns after arrival of shock


3696ns after arrival of shock

The dynamics of these and other higher density targets were presented in a **talk by Simon Bland at the IEEE ICOPS conference in 2022** and are now being analyzed further for publication. The experiments have suggested a more powerful driver would be beneficial, which we are hoping to test in experiments in December 2022; further better control of the targetry is needed, with initial aerogel experiments already being performed in August 2022.

In order to increase the available drive pressures, convergence was employed with both cylindrical and spherical configurations. Previous experiments on large scale pulsed power drivers (up to 2.5MA current) have demonstrated that high speed convergent shockwaves could be produced by exploding cylindrical arrays of wires underwater. On the large scale drivers the production of shockwaves was measured through laser imaging (though only the speed of the convergent shockwave could be measured, no densities or other properties could be inferred). Experiments with spherical arrays could not be analyzed in such a way, and the production of shockwaves in these configurations was only assumed based on limited evidence of localized damage to targets and spectrometry of light emitted from the center of the arrays. In our ESRF experiments in February we measured for the first time the production of spherical shockwaves and their interaction with low density targets on their axis:



Asymmetric and target slightly off centre due to difficulties in manufacture for 30kA

Shock arrives to left of target

+880ns shock arrives on right

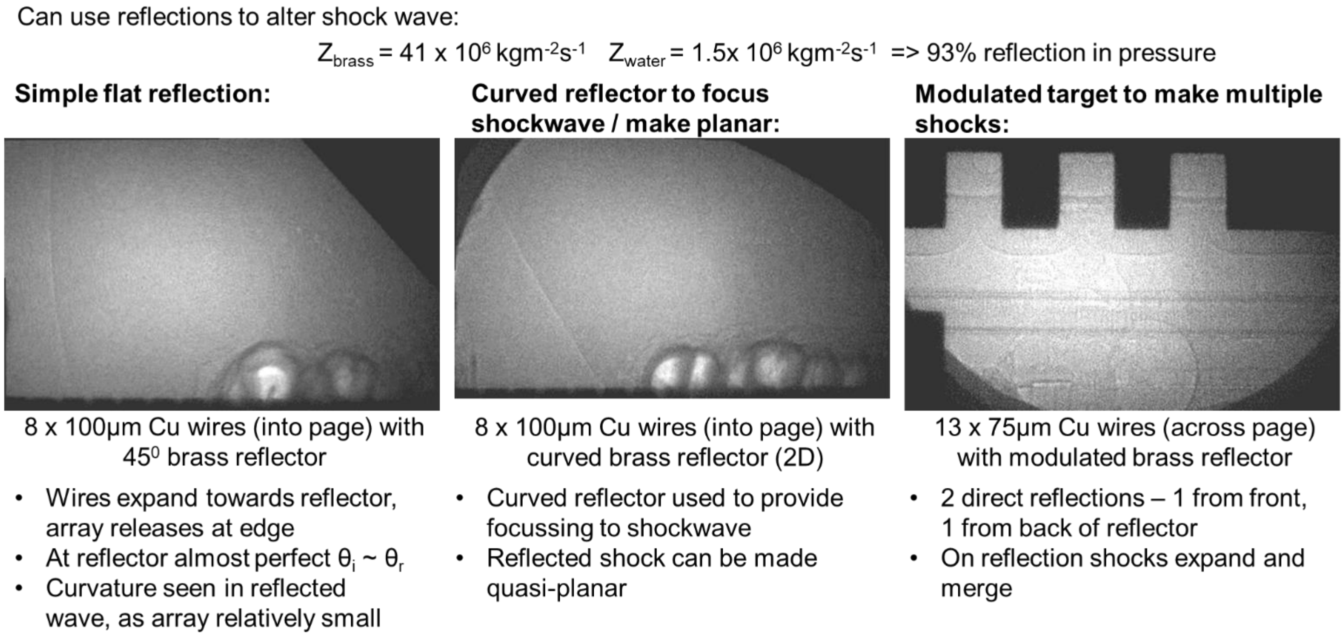
+1584ns target ~1.6mm diameter

20mm diameter spherical array made of 21x63µm Cu wires at 3.7mm polystyrene sphere

Both the position of the shockwave and the dynamics of the target as it exploded could be measured – in future experiments with a more powerful driver significantly more symmetric targets can be manufactured. These results were presented in an **invited talk by Simon Bland at the Znet US workshop.**

During the August beamtime we also explored methods to shape and manipulate the shockwaves generated by exploding wires through the use of different shaped brass reflectors. We were able to produce, flat, convergent and divergent shockwaves from a simple planar input shock, sending this shockwave into an area of undisturbed water adjacent to the wires.

We were also able to take a single input shockwave and generate a train of multiple smaller shocks through a modulated ‘comb’



Can use reflections to alter shock wave:

$Z_{brass} = 41 \times 10^6\ kgm^{-2}s^{-1}$ $Z_{water} = 1.5 \times 10^6\ kgm^{-2}s^{-1}$ => 93% reflection in pressure

Simple flat reflection:

8 x 100µm Cu wires (into page) with 45^0 brass reflector

- Wires expand towards reflector, array releases at edge
- At reflector almost perfect $\theta_i \sim \theta_r$
- Curvature seen in reflected wave, as array relatively small

Curved reflector to focus shockwave / make planar:

8 x 100µm Cu wires (into page) with curved brass reflector (2D)

- Curved reflector used to provide focussing to shockwave
- Reflected shock can be made quasi-planar

Modulated target to make multiple shocks:

13 x 75µm Cu wires (across page) with modulated brass reflector

- 2 direct reflections – 1 from front, 1 from back of reflector
- On reflection shocks expand and merge

These results were also presented in the **talk by Simon Bland at the IEEE ICOPS conference in 2022,** and will be utilized in future experiments at ESRF, enabling better separation of target materials from the driver, and smoother increases in pressure.