Imperial College London

Multi-University Center of Excellence for Pulsed Power Driven High-Energy Density Science

Scaling of pulsed power produced convergent shockwaves in insulators – kA to MA

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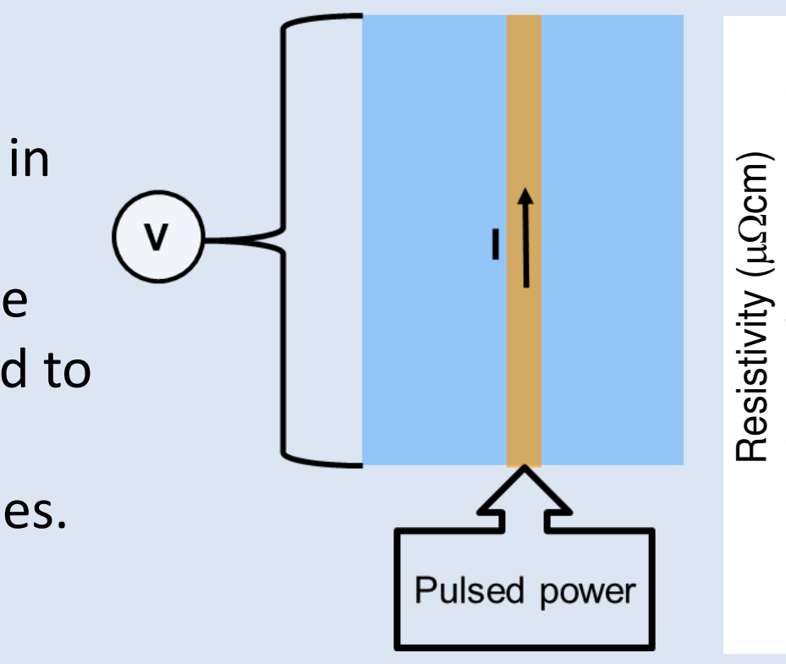
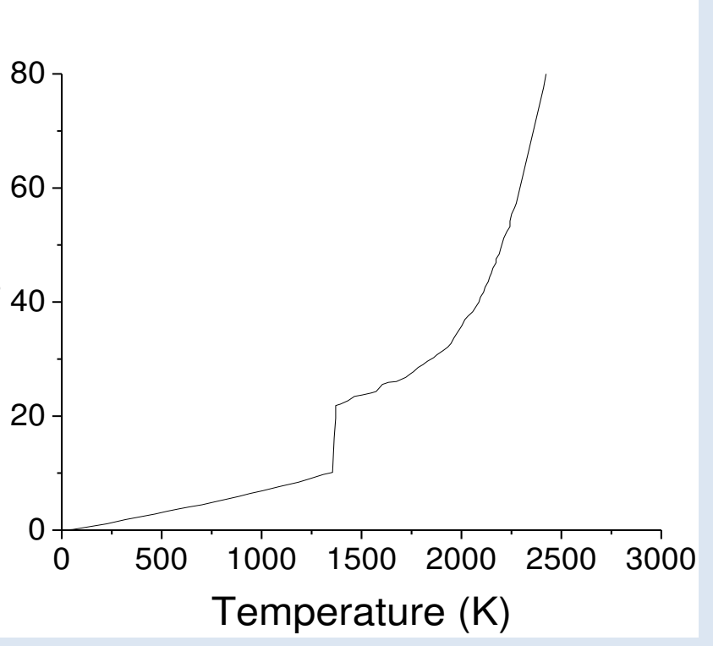
Wire in water explosions

The ability to create and diagnose Warm Dense Matter is at the forefront of High Energy Density Physics. Typically large facilities are used to produce pressures >> Mbar resulting in heating, increased density and pressure ionisation. Common techniques to create warm dense matter utilise flyer plate/isentropic compression driven by either magnetic fields (pulsed power) or via direct or indirect laser radiation. Utilising current to directly explode metallic conductors in an insulating media, and then coupling the shockwaves produced in this media to a target may produce a more efficient method of accessing these regimes suitable for universities and small scale user facilities.

Wire in water or in insulator experiments have long been utilised to provide data for conductivity tables.



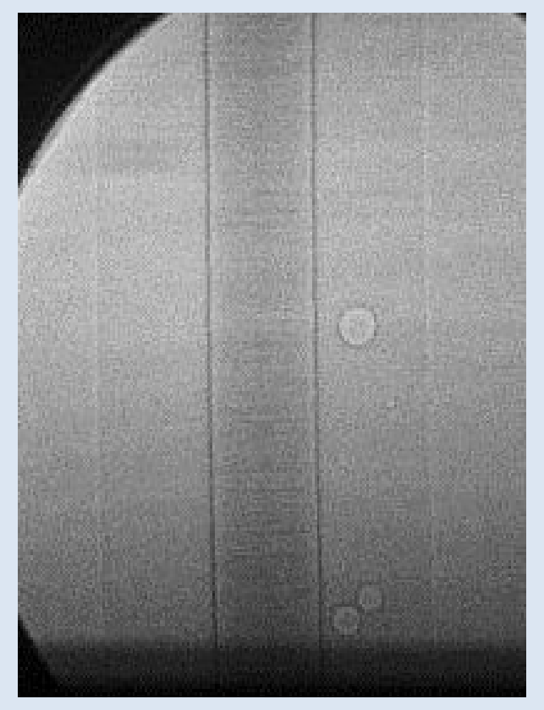


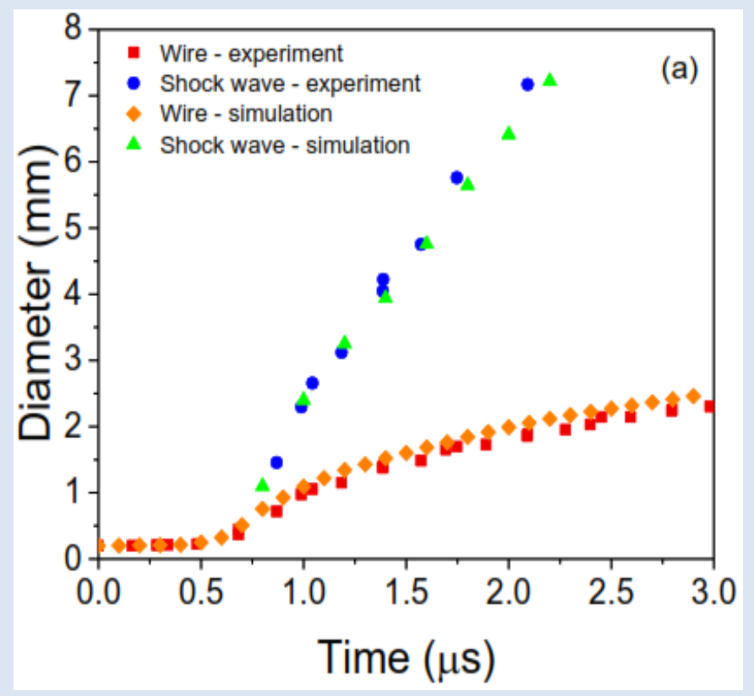
Wire in water experiments have a number of advantages over more traditional z-pinch loads performed in vacuum:

1. Water prevents surface breakdown and tamps wire expansion - significantly more energy deposition occurs into the wires than in vacuum; wires assumed to expand uniformly solid => liquid => gas => dense plasma.
2. Due to the variance of resistivity with temperature, wires remain solid for most of current pulse before phase changes occur - converts 100s of ns pulse to 10s of ns expansion of wire.
3. The wires form a resistive load – this can provide good damping to a pulsed power facility, preventing reversals from damaging generator (especially useful for newer LTD type machines which rely on smaller plastic capacitors).

When a wire explodes and expands in water it drives a strong shock into the surrounding water.

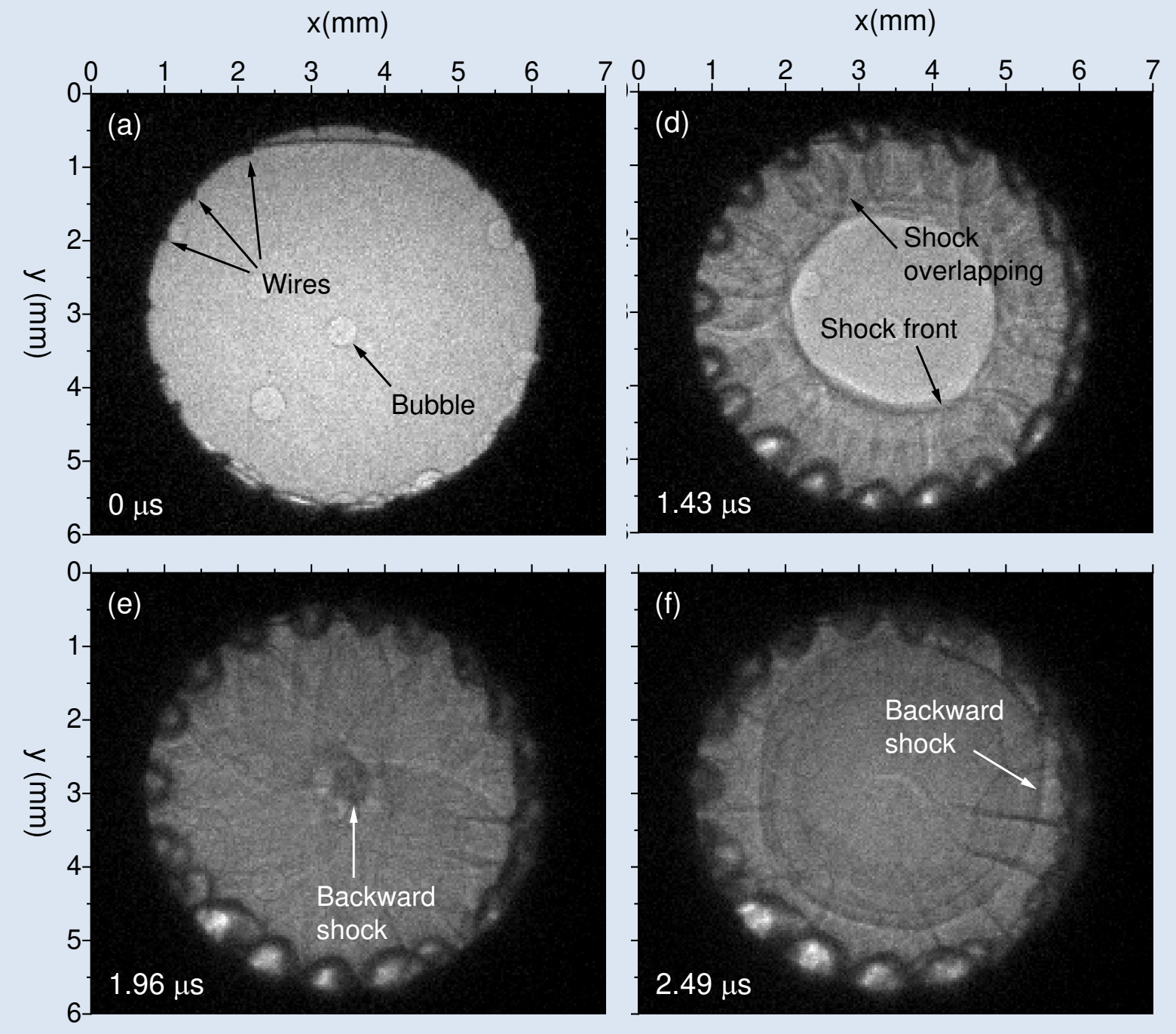
X-ray phase contrast image of 200µm copper wire driven by 30kA, 1µs current pulse explosion shows expansion of wire and details on shockwave





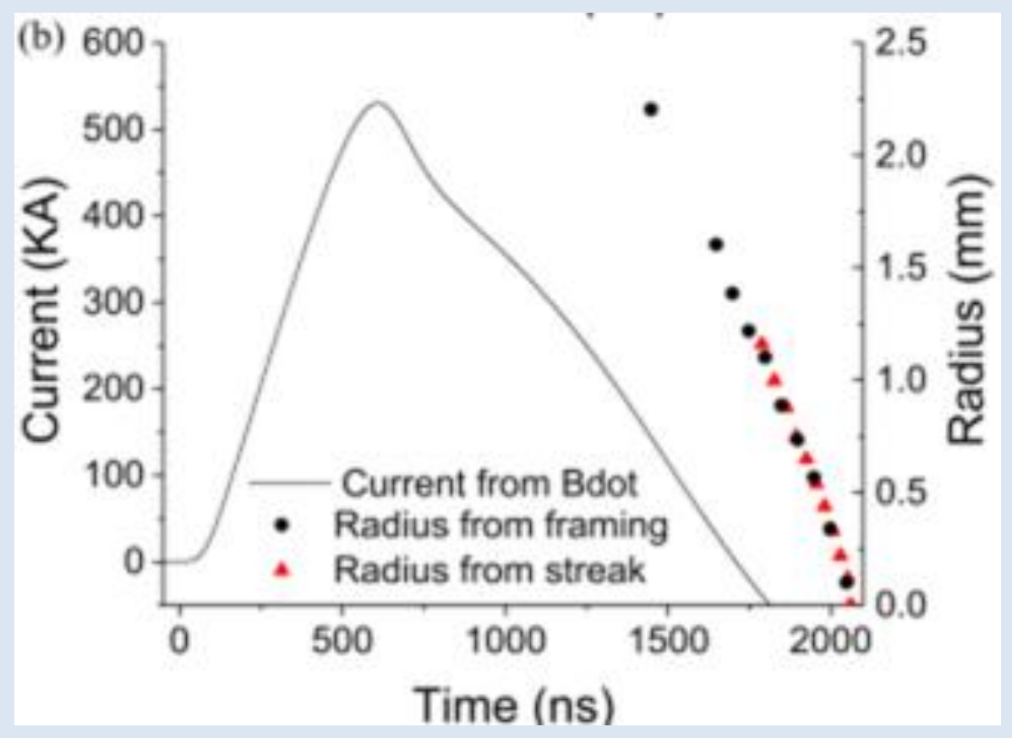
Placing wires into a cylindrical array results in merger of shockwaves and high velocity convergent shock heading towards axis.

X-ray phase contrast images of 20 x 63µm copper wire array driven by 30kA, 1µs current pulse show explosion of wires, merger of shocks and convergent shockwave heading towards the axis.



On the MACH facility at Imperial College, using arrays of 10mm diameter, I-V measurements suggested ½ to ¾ of the driver energy was coupled into the exploding wires (7-8kJ). The peak current used in experiments was 0.5MA, and the shockwave reached velocities of ~7kms^{-1} close to the axis.

Framing camera and optical streak images showing position of shockwave vs time in MACH experiments with 10mm diameter with 60x130µm wires.



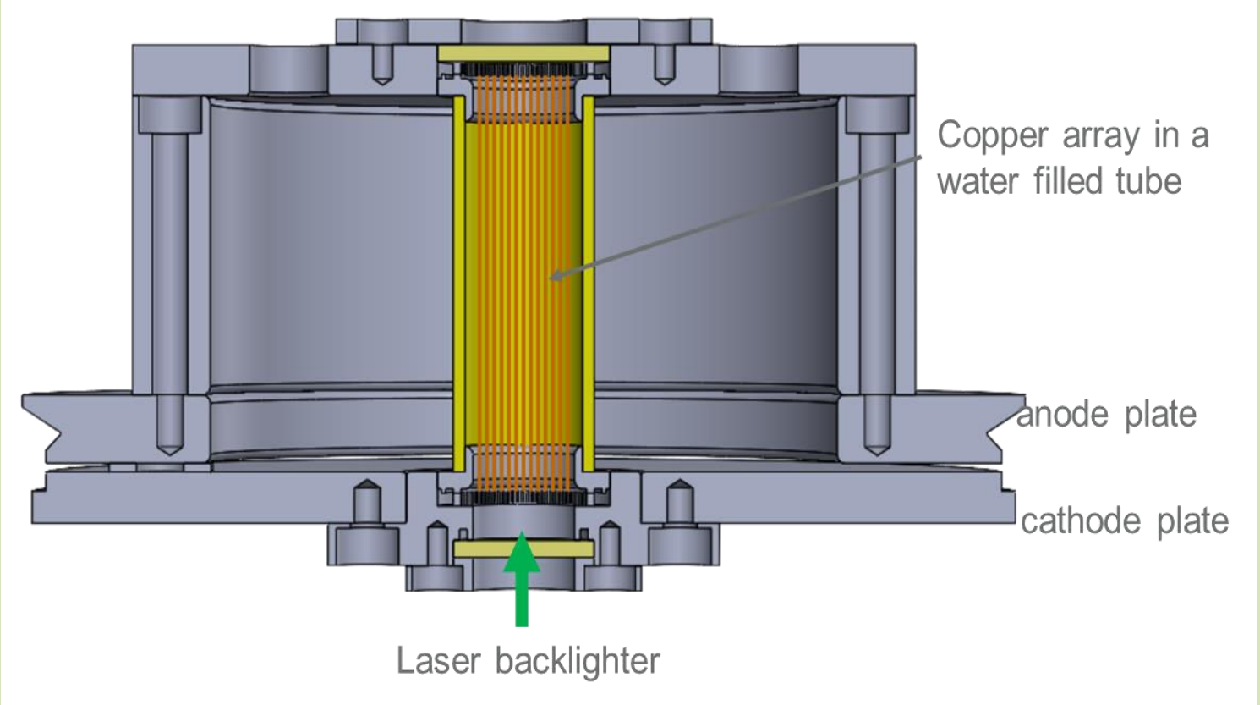
On axis pressures are predicted to be 2-3MBar and water pressures 2-3gcm^{-3}.

How does the technique scale to larger currents?

Cepage is a 3MA, 400ns pulsed power generator designed for flyer plate research at First Light Fusion. Built by ITHPP it is similar to Veloce at Sandia National Laboratories but in a very compact footprint. No oil or water is utilized, current is via direct discharge of 8 x 4µF capacitors in parallel through low inductance switches to a mylar insulated line.

Initial experiments were planned based on the loads utilised on MACH; the Cepage load was significantly higher inductance than typical flyer loads as the array had to be long enough to prevent breakdown through the expanding wire material.

Load used in experiments had a 38mm long, 13mm diameter copper wire array inside a tube of water. Silicone rubber provided insulation outside the tube.



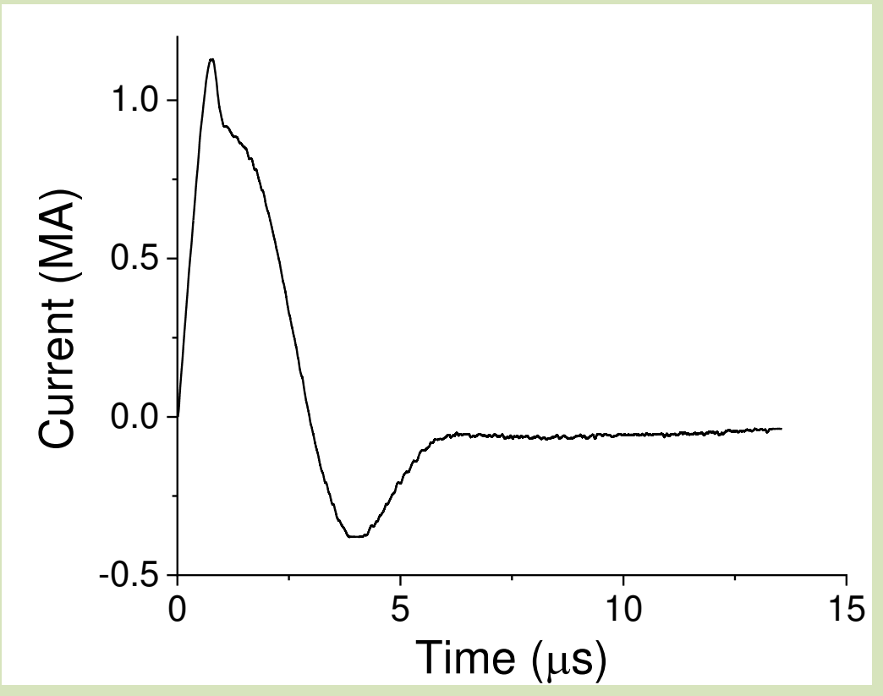
With the added inductance and 60kV charge, currents of ~1.2MA were expected through the load. The action integral was used to calculate the wires thicknesses to be used in experiments:

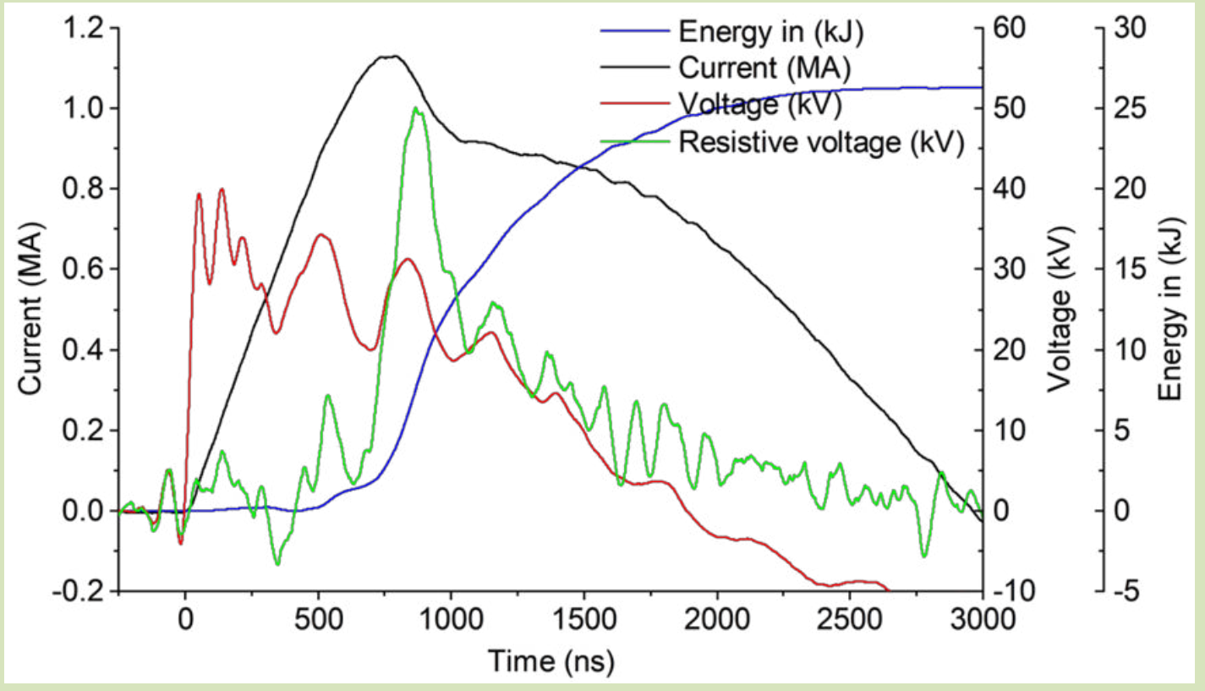
$$h = \int_0^{t_{ex}} j^2 dt \sim \frac{I_0^2 t_{ex}}{2(n\pi r_w^2)^2}$$

To obtain fast wire explosions *$h \sim 1x10^{17} A^2 s/m^4$.* With I_0, peak current ~ 1.2MA and t_{ex}, the onset of fast resistance change ~900ns, 80x160µm Cu wires was a good starting point.

The load used on initial Cepage shots. A CW laser probing @630nm through the axis of the array provided the position of the shockwave, imaging to a 16 frame SIMX camera and a radial optical Streak camera.

Wire in water explosions on the Cepage generator at First Light Fusion





Current through the load was well damped (though not critically damped).

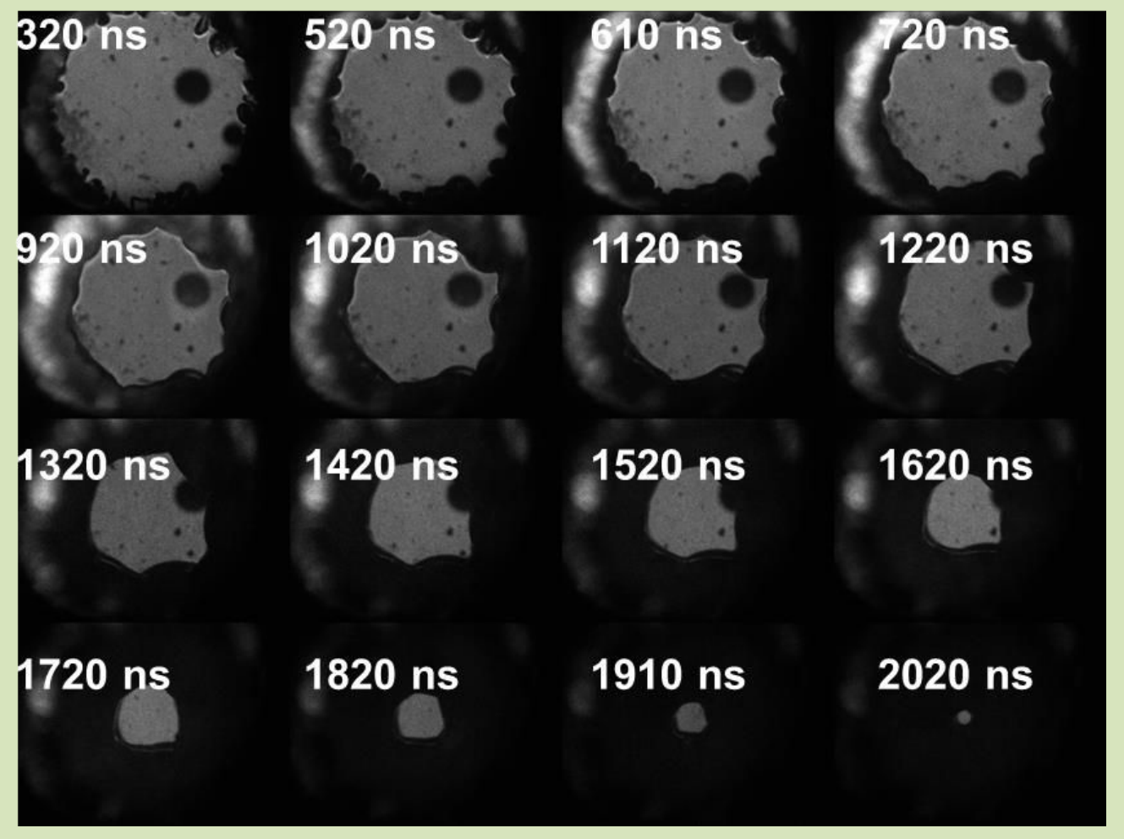
Taking into account the inductance of the load, the resistive components of the measured voltage could be found from:

$$V_{measured} = IR + L\frac{dI}{dt} + I\frac{dL}{dt}$$

This enabled the explosion of the wires to be identified on the I-V trace and the energy deposited into the wires calculated. The bulk of the energy was deposited into the wires close to peak current (~15 kJ), with a total of 26 kJ being deposited over experiment. This represents a driver to wire efficiency of ~50%.

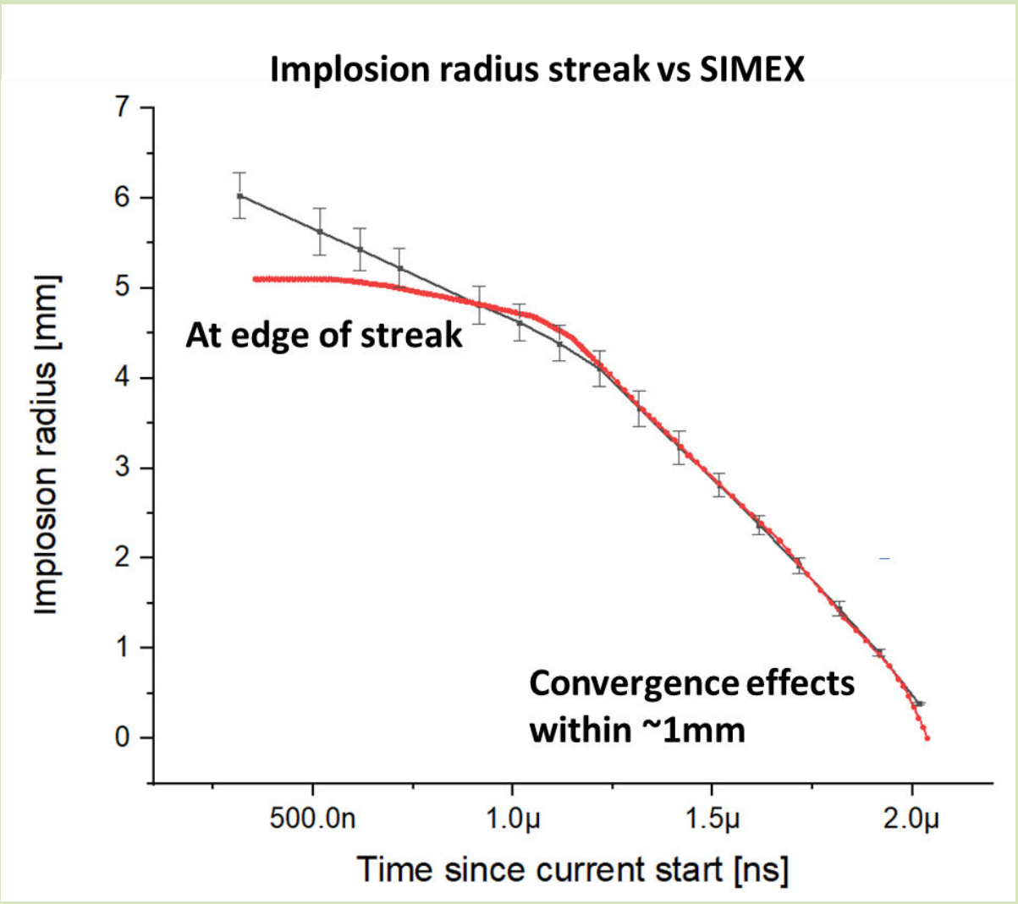
Framing images showed high speed imploding shockwave:

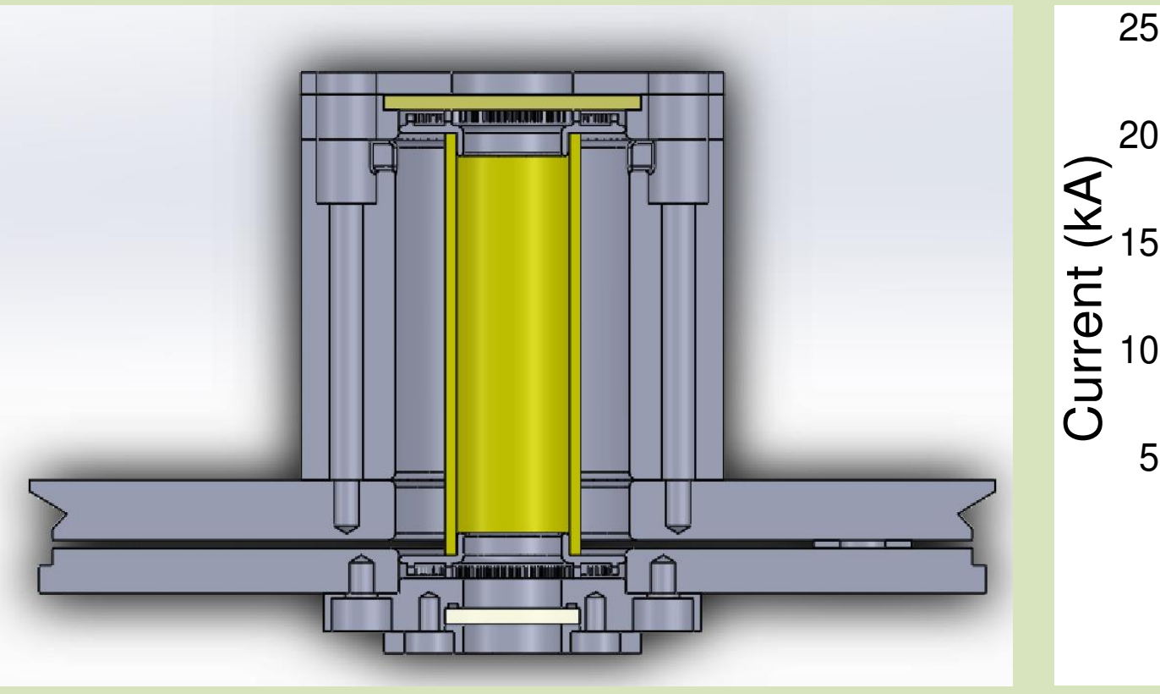
Shockwave is seen as shadow moving across diameter of the array (13mm). Initial asymmetries likely due contact issues at wires (+ bubbles!). As implosion progresses symmetry appears to increase.

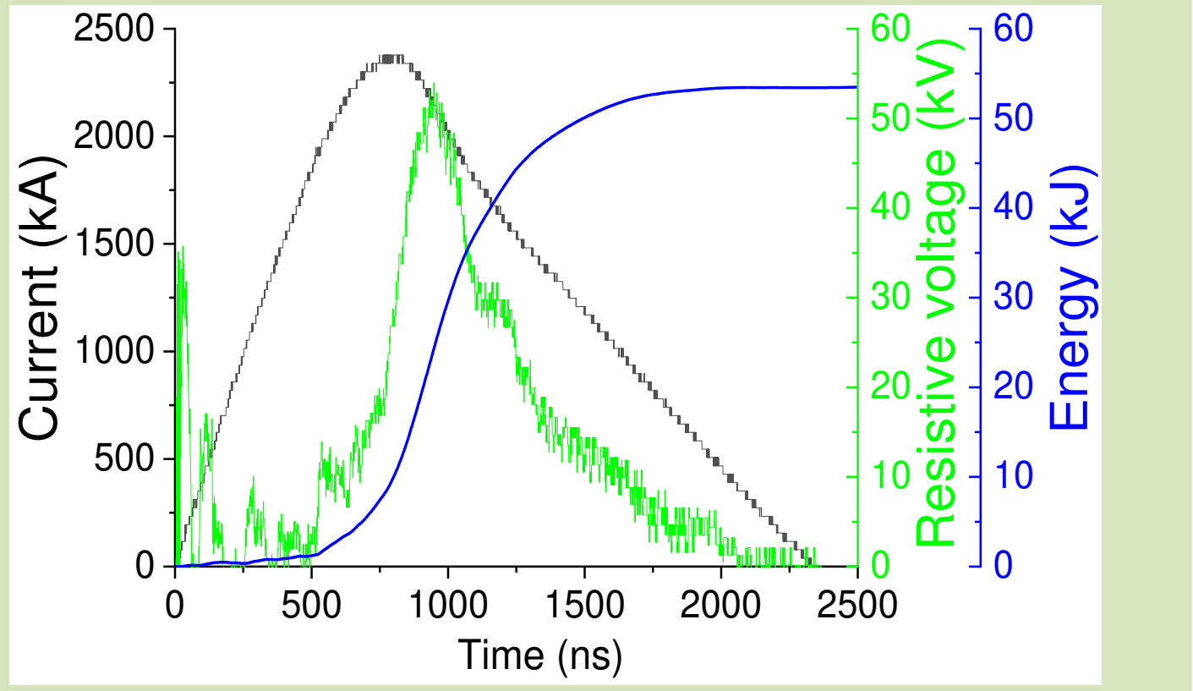


Initial Gorgon 2D simulations of implosion - synthetic streak plot from a preliminary simulation:

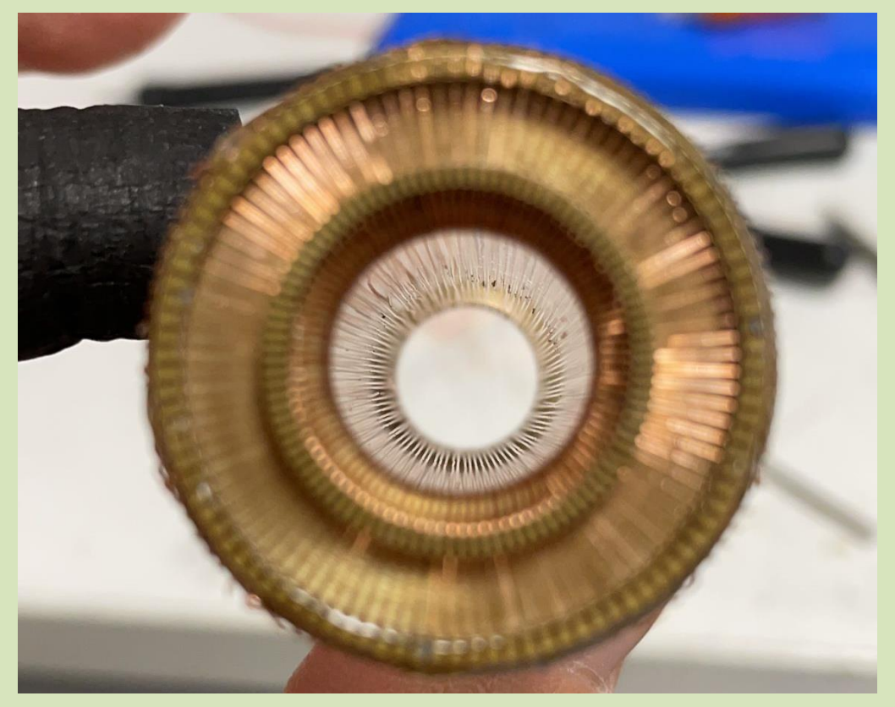
Predicted convergence speed between 1450 and 1750 ns – 4300 m/s compared to observed 4400 m/s.



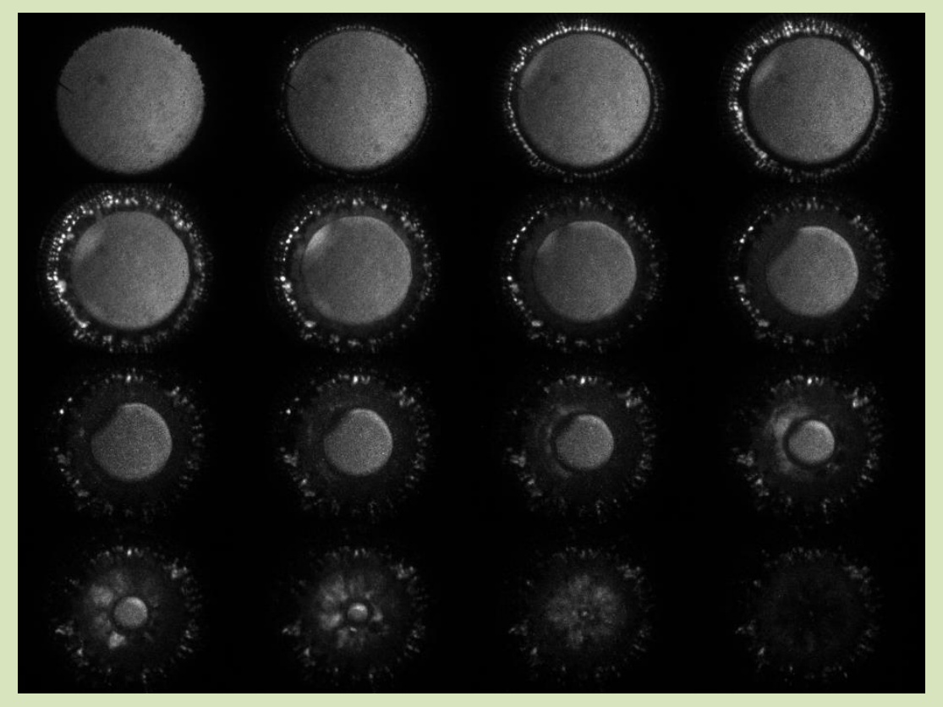




For higher current experiments a re-engineered load section was used – with much lower inductance, despite the longer array length (50mm). This and higher charging voltage enabled experiments with critically damped current up to 2.5MA, and total deposited energies of 53kJ (45kJ during explosion)



100x200µm Cu wires on a 13mm diameter were utilised for experiments

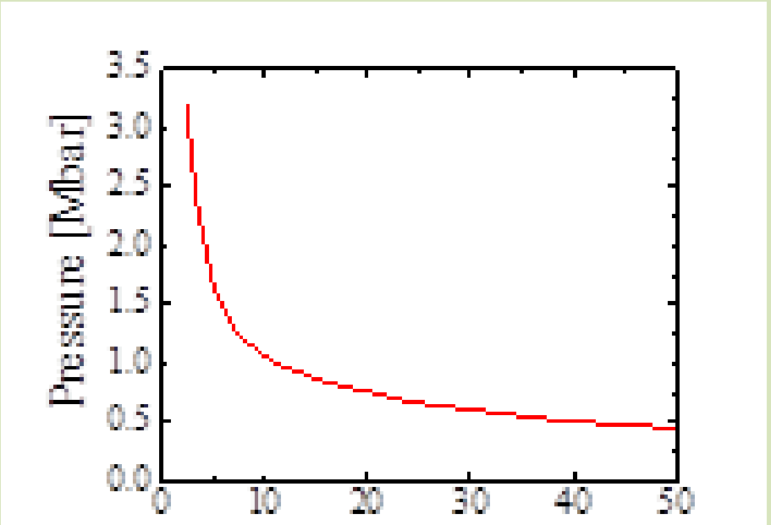


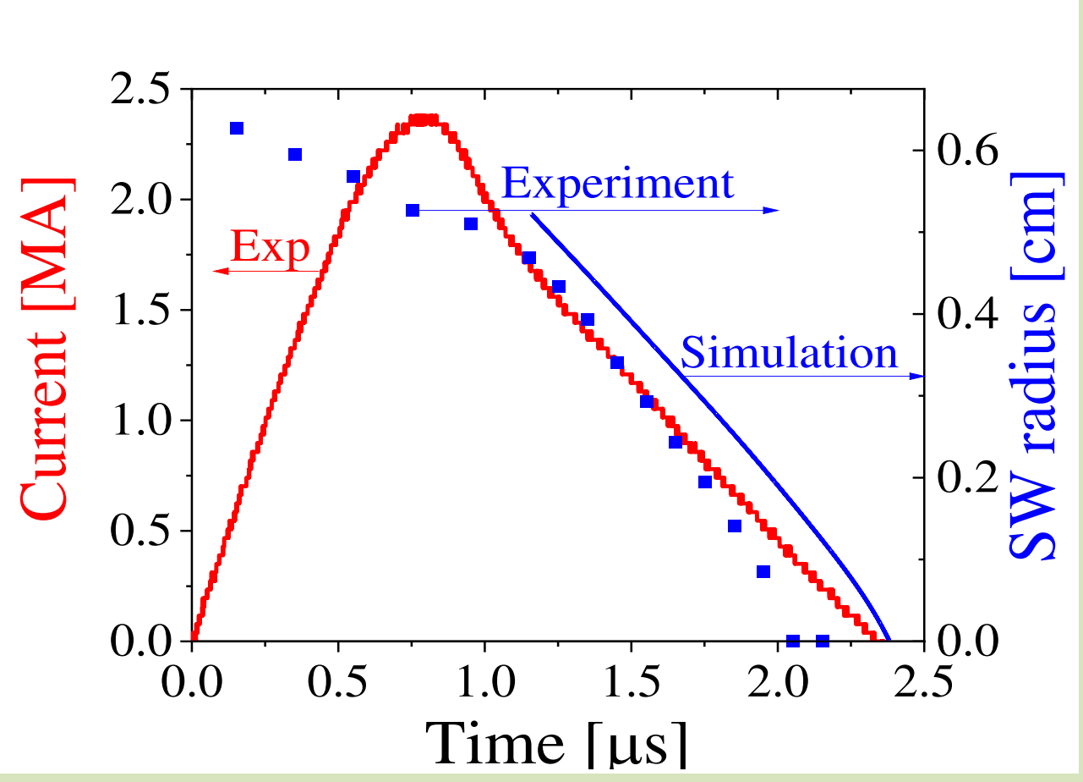
Laser backlit framing images @100ns interframe showing convergent shock

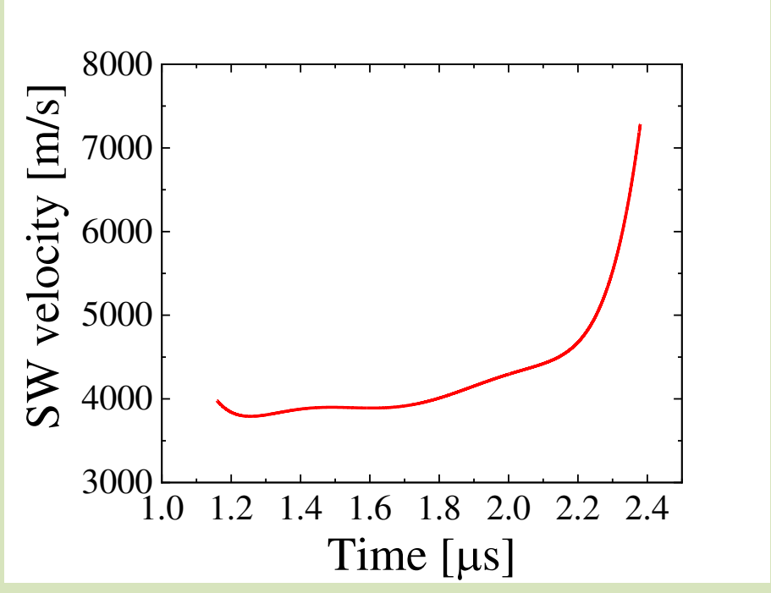
Significantly improved methods of array manufacture resulted in far high uniformity of wire explosion and launch of the convergent shock wave.

Velocity of shock from exploded wires now ~5kms^{-1} prior to convergence, and in last mm, velocity measured by streak appears to increase to 25kms^{-1}

Presently we are unable to match simulations to experimental results – but with a speed of 4.5kms^{-1} they predict 3MBar on axis.



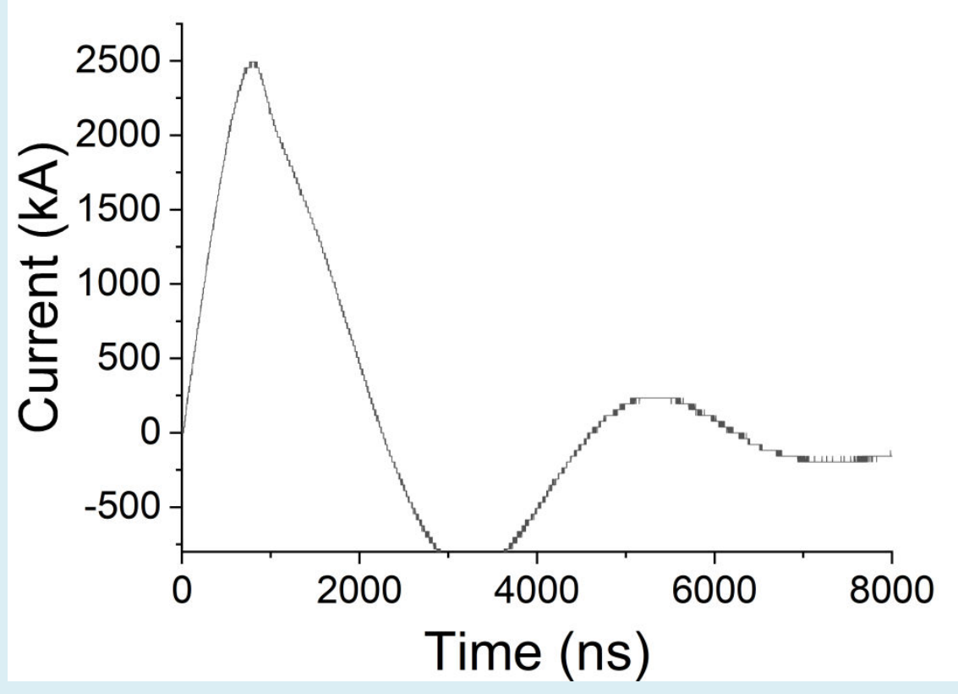




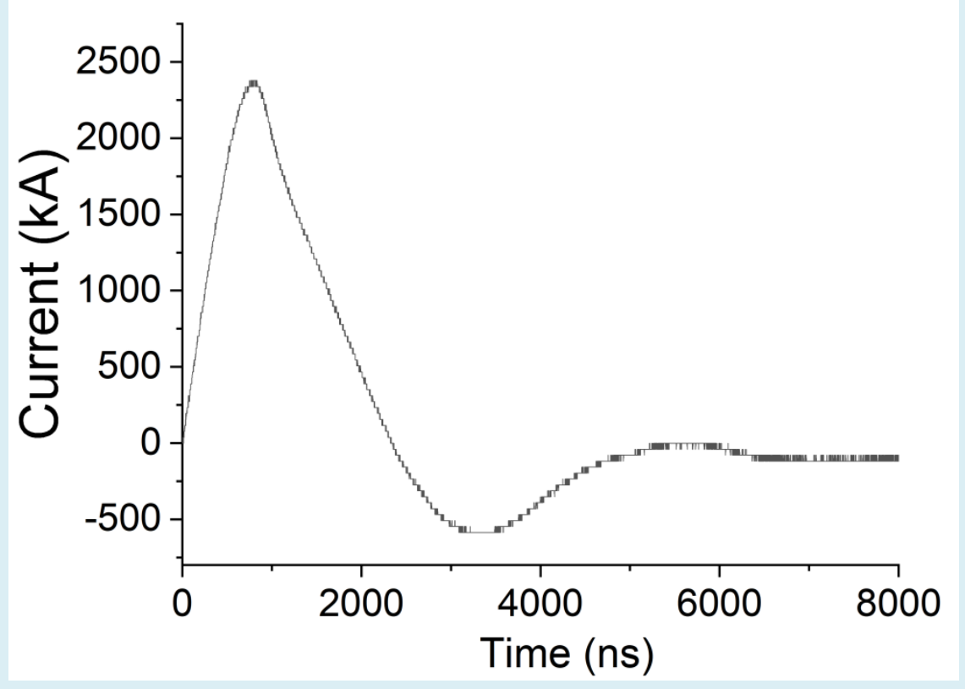
Cylindrical foil experiments

As energy in the driver increases, matching exploding wires to the current pulse becomes more difficult => so we can examine using foils instead. Foils should improve the initial symmetry of the implosion and would be simpler to prepare than wires but 2D nature could affect current paths and explosion. For higher current experiments, a 75µm Cu foil was employed, matching 100 x 200µm wires.

In all experiments (from 1 to 2.5MA) current through the foils was still damped, but not critically damped as in the case of wire arrays, despite the same mass/length being utilised – potentially this is related to the current paths available in the foil.

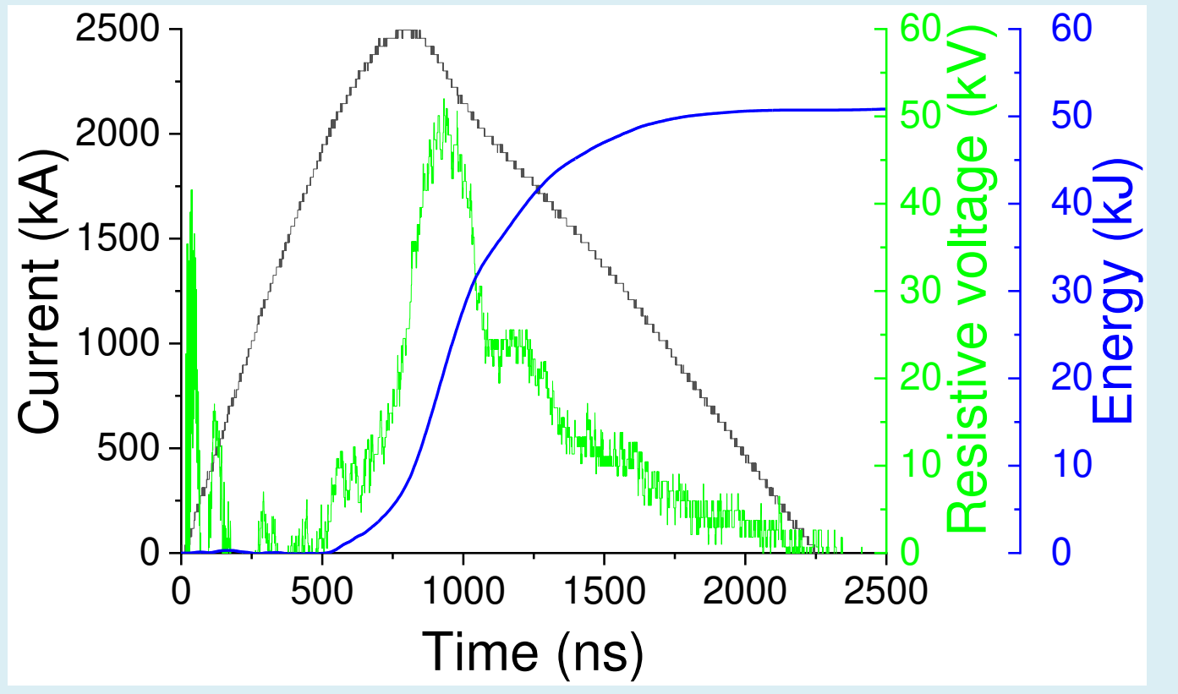


Foil - 70µm Cu foil on 13mm diameter

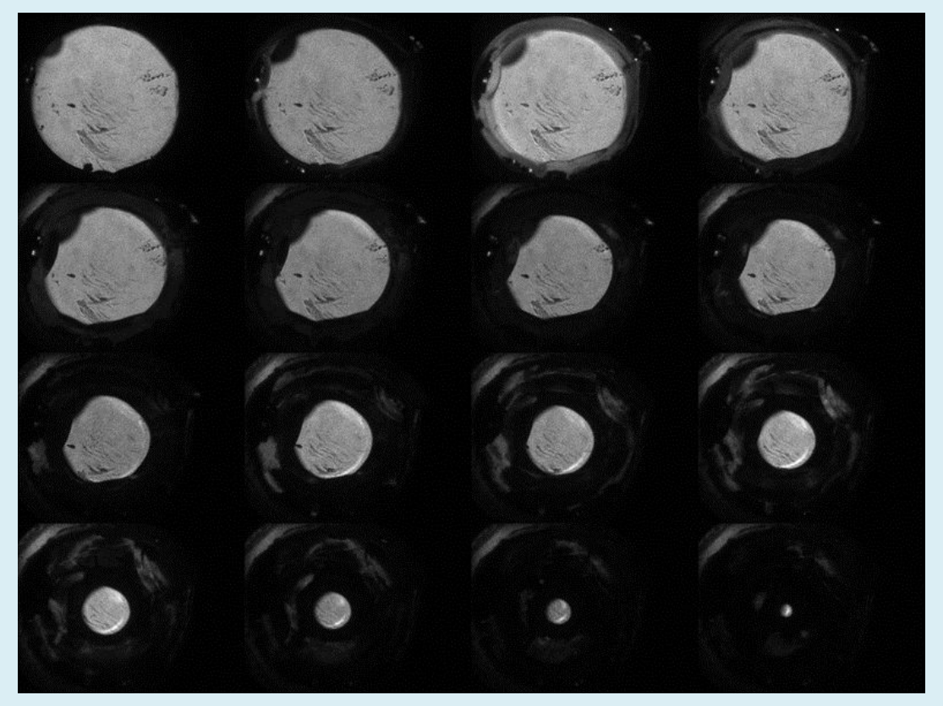


Array - 100x 200µm Cu wires on 13mm

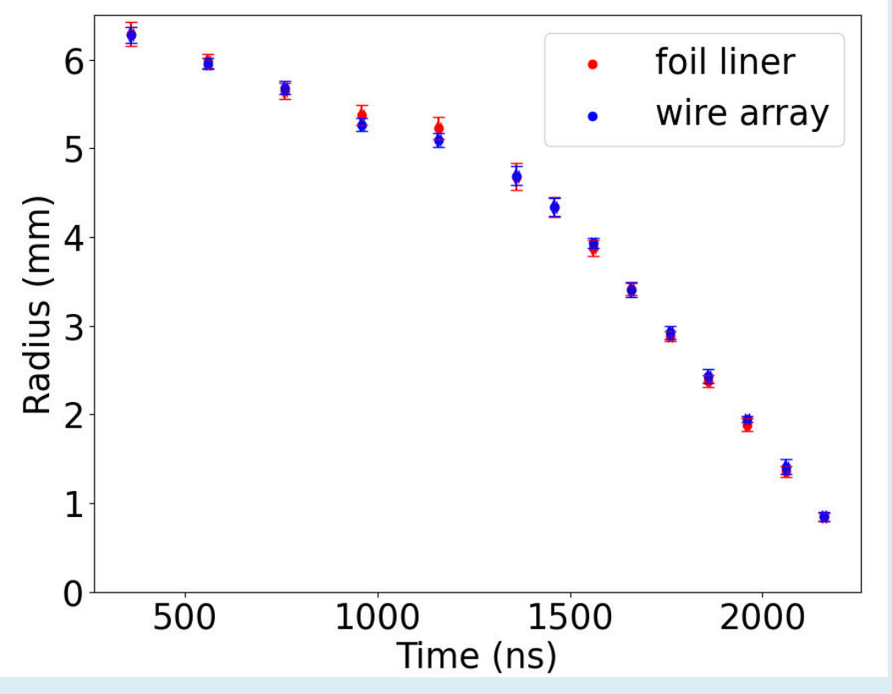
For the same load set up (length, return diameter) current through the foils was comparable to that through the arrays and energy deposited only slightly less (e.g. 51 vs 53kJ)



Optical framing images and streak camera both indicate a highly uniform, convergent shockwave heading towards the axis.



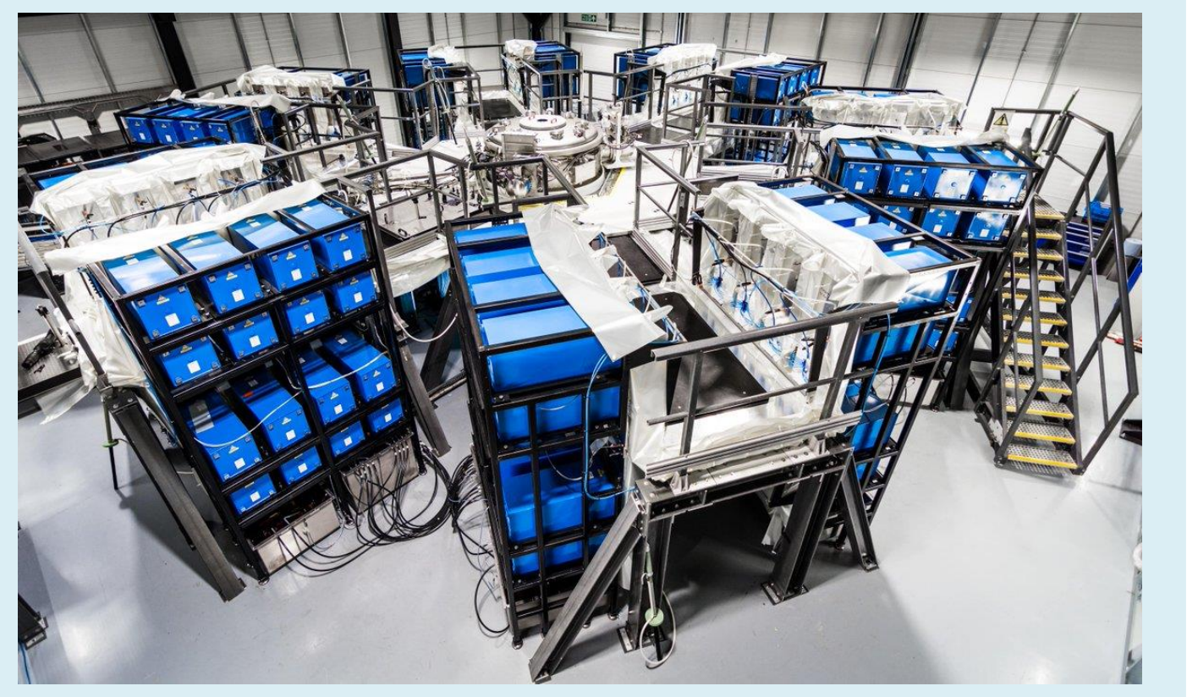
The convergent shock wave from the foil liner appears to have the same inwards velocity as the shock from a wire array – however we presently do not have measurements close to the axis.



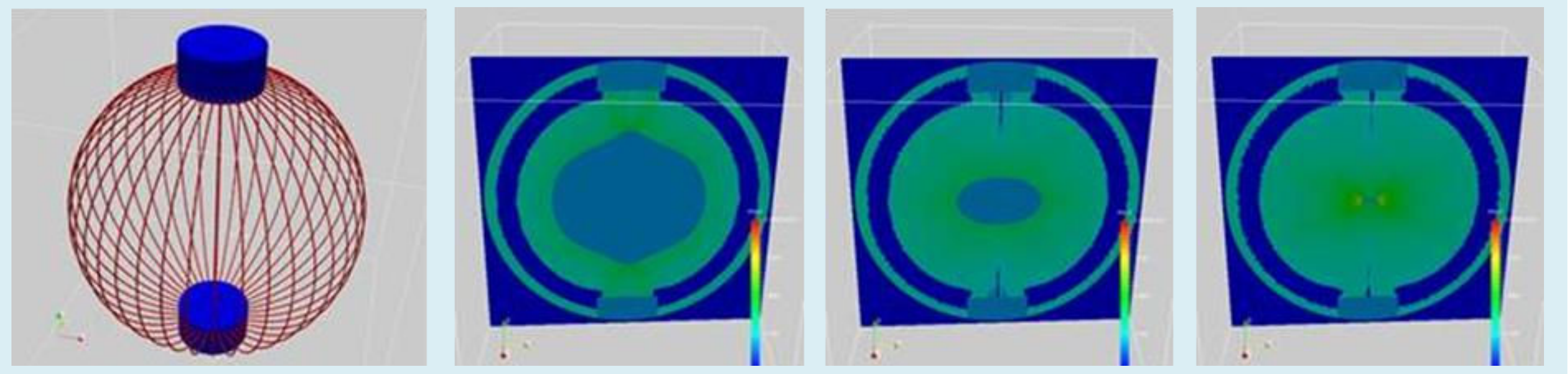
Future research directions

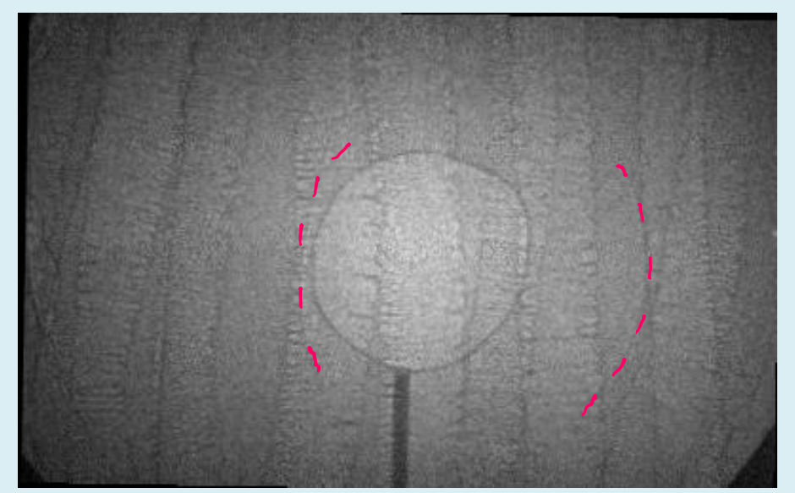
In 2023 we will expand experiments to the M3 generator at First Light Fusion. Here we expect currents of ~8MA but rise times are ~3µs.

We will also look at using much faster generators, such as Gamble II at the Naval Research Laboratories.

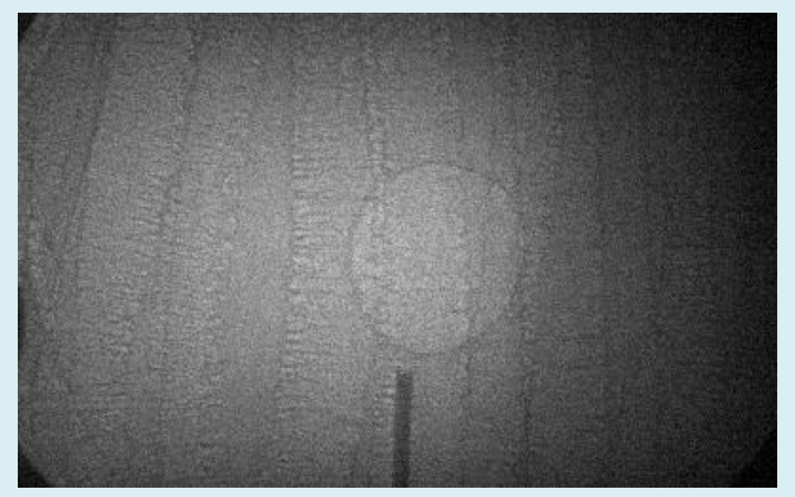


In addition to cylindrical systems we will also utilise spherical and hemispherical arrays to increase on axis pressures/densities. Recent experiments at ESRF at 30kA have demonstrated this technique:

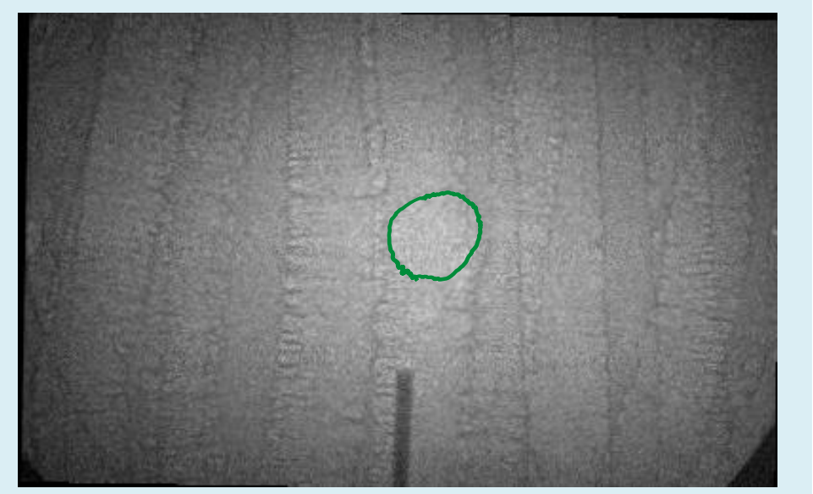




Shock arrives to left of target



+880ns shock arrives on right



+1584ns target ~1.6mm diameter

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

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