Dynamic X-ray imaging of transient physical processes

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Motivation

Shock Physics concerns the study of materials at extreme strain rates, pressures and temperatures. Our understanding of mesoscopic deformation processes is typically inferred from surface-based or post-loading techniques, which inherently obscure the evolution of fundamental sub-surface phenomena. Accordingly, our appreciation of processes such as ejecta formation, heterogeneous densification and crack pattern growth lacks experimental validation. This research project focuses on high-resolution *in-situ* synchrotron X-ray imaging of macroscopic (~ 1 cm^3) dense (Z > 20) sample volumes under shock-compression with the intention of providing novel mesoscopic data to constrain predictive models.

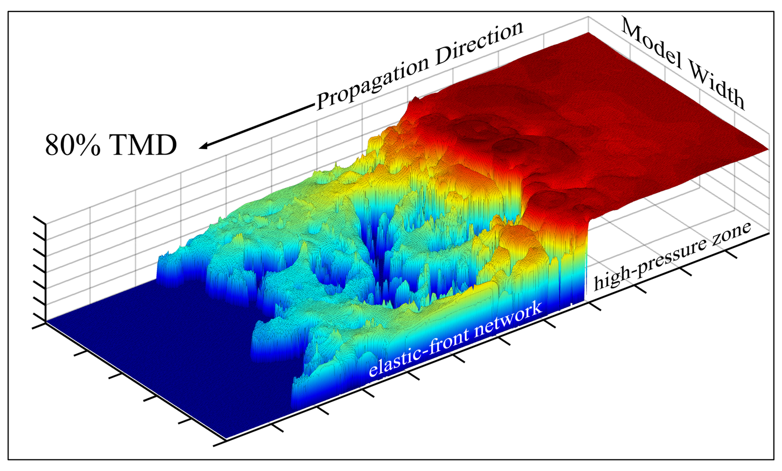


Figure 1: CTH hydrocode simulations of shocked Ni + Al powder systems reveal extended wave fronts and heterogeneous densification (Eakins, 2008).

Key challenges

1. Transmission studies of dense materials, such as transition metals and metallic composites, require high-energy X-rays for sufficient penetration. For example, 10 mm of titanium readily attenuates < 40 keV X-rays.
2. Gated, sub-μs detection of high-energy radiation is only possible with well-characterised scintillators and optical systems, and must overcome issues associated with low photon fluxes.
3. Synchronisation of an isolated loading platform with synchrotron radiation and custom X-ray pulse structures.
4. Developing and applying methods to extract quantitative information from noisy images.

Novel dynamic capabilities at the Diamond Light Source

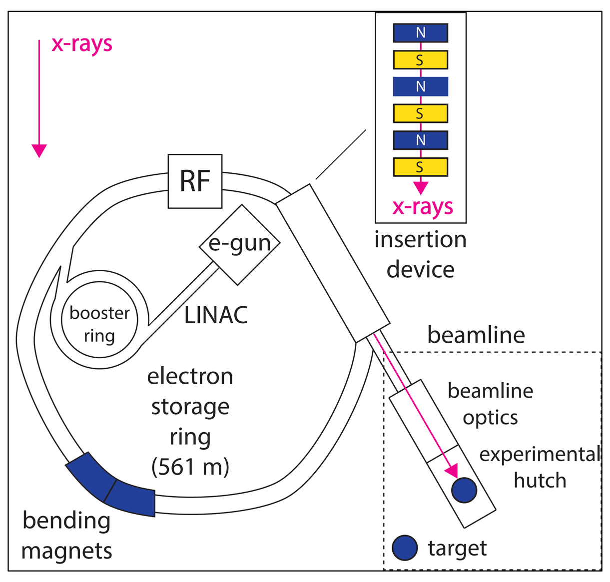


Figure 2: Illustration of a 3rd-generation synchrotron. Electron bunches orbit the storage ring and undergo betatron oscillations in insertion devices, delivering X-rays to be beamline.

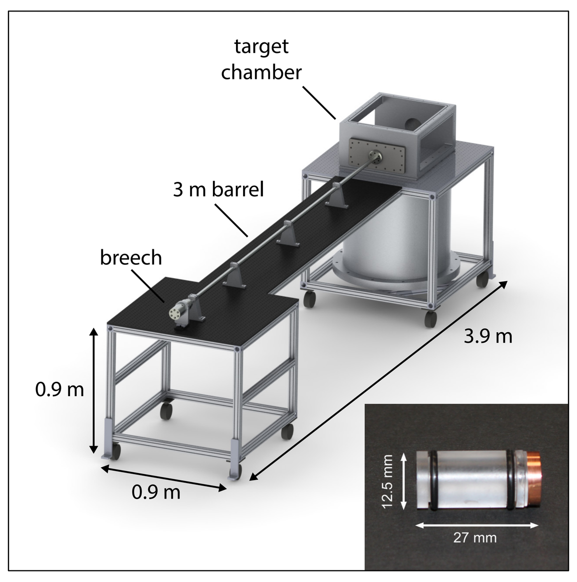


Figure 3: Schematic of the 13 mm bore portable gas-gun. **Inset:** A typical projectile comprised of a polycarbonate sabot and a 2 mm copper flyer, m ~ 7 g.

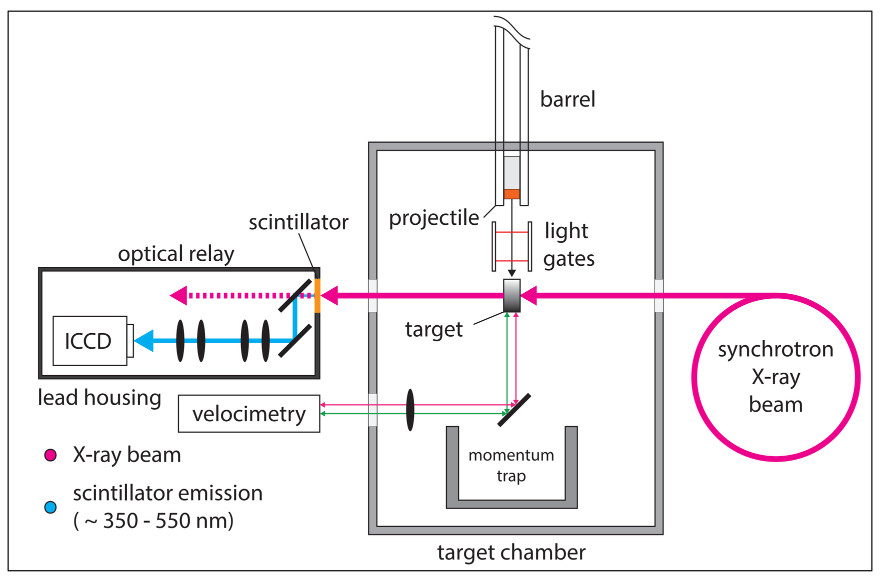


Figure 4: Illustration of the experimental apparatus. Synchrotron radiation is used to capture radiographs of shock-compressed samples perpendicular to the loading direction.

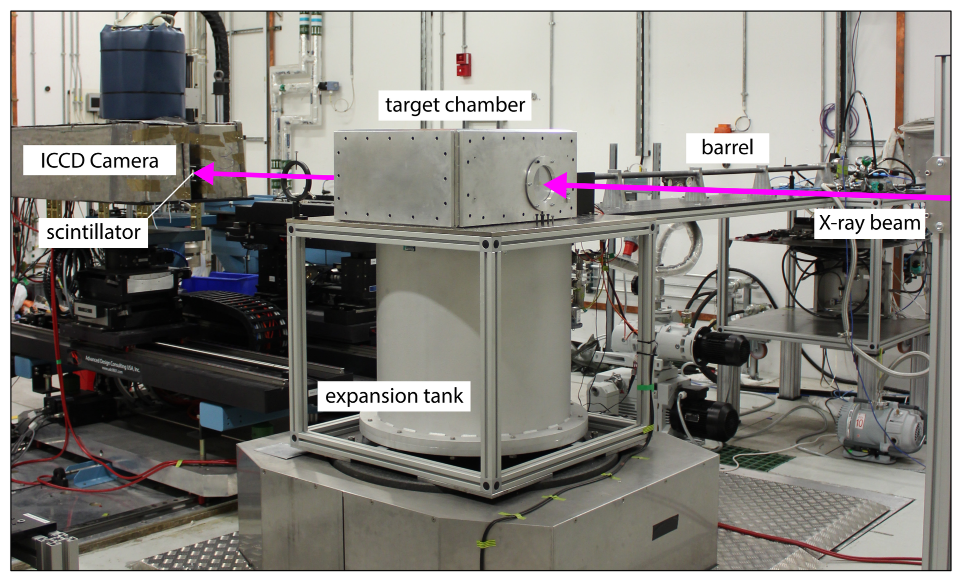


Figure 5: Annotated photograph of the apparatus at beamline I12 (March 2014). Components must be covered with 2 mm of lead to protect against the high-energy X-rays.

X-ray source:

- Beamline I12 at the Diamond Light Source Synchrotron (Harwell, UK).
- Synchrotron radiation allows high-resolution X-ray radiography, which cannot be achieved with in-house flash X-ray sources.
- X-ray energies from 50 to 250 keV permit penetration of > 10 mm of high-Z materials.
- The large experimental hutch (11 x 7 x 4 m) allows assembly and use of the portable gas-gun.
- Ultrafast X-ray pulses (33 ps) and customisable bunch structures (e.g. a 25 ns bunch) permit the *in-situ* study of highly-transient events.

Loading methods:

- Shock waves are driven into materials using a purposely-designed, portable single-stage gas-gun.
- Impact velocities up to 1 km s^{-1}.

X-ray imaging and detection:

- Customisable X-ray bunch structures allow the temporal resolution of X-ray imaging to be tailored to impact speeds and photon flux requirements.
- Triggering and synchronisation is achieved by interfacing projectile light gates with the synchrotron radio frequency bunching pulse.
- Transmission radiographs are captured via a fast-decaying single-crystal scintillator, optical relay and a gated PI-MAX 4 intensified CCD camera.
- Sample microstructures can be rigorously characterised by high-resolution (sub 5 μm) X-ray tomography prior to loading.

Materials and physics:

- To date, a range of samples including stainless steel lattices, metal alloys, and metallic and ceramic powders have been studied.
- Future work will focus on resolving heterogeneities in shocked powder systems, and high-resolution studies of ballistic penetration and ejecta formation.

Results

Figures 6 – 10 show the deformation of a selectively-laser-melted (SLM) 316-L steel lattice following copper flyer impact at 500 ms^{-1}. One radiograph was collected per shot using the full X-ray spectral flux (50 – 250 keV). Figure 8 demonstrates a temporal resolution of 16 ns where just 8 X-ray pulses were used to capture the image. However, to examine deformation of the lattice with a better signal-to-noise ratio, a series of images (including Figures 9 and 10) were captured with exposure times of 500 ns (263 X-ray pulses). The effects of photon shot noise, optical aberration, and varying through-thickness of the cylindrical flyers (observed at the top and bottom of the radiographs) make it challenging to rigorously extract spatial information from the images. Analysis, however, of the static radiographs reveals a spatial resolution of 40 μm. The addition of motion blur in Figures 9 and 10 limits spatial resolution to approximately 200 μm in images with a 500 ns exposure time.

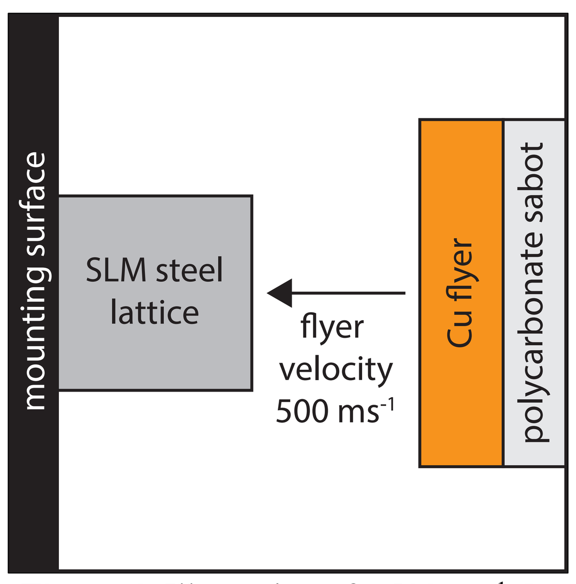


Figure 6: Illustration of a 500 ms^{-1} Cu flyer impact on a 316-L SLM stainless steel lattice.

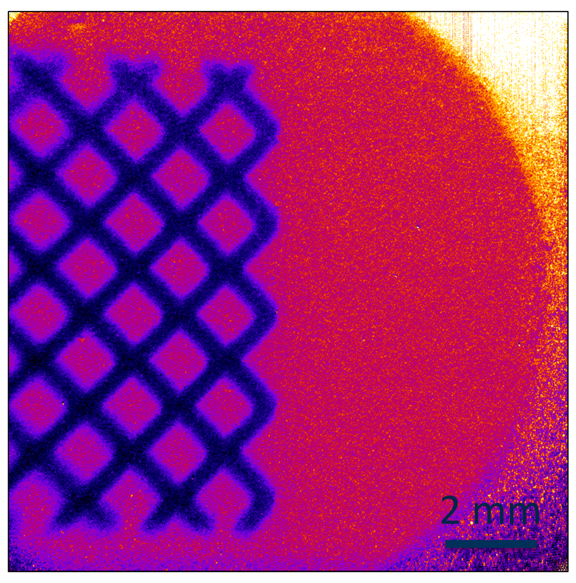


Figure 7: *In-situ,* static radiograph of a SLM steel lattice prior to impact. Acquisition time, 500 ns.

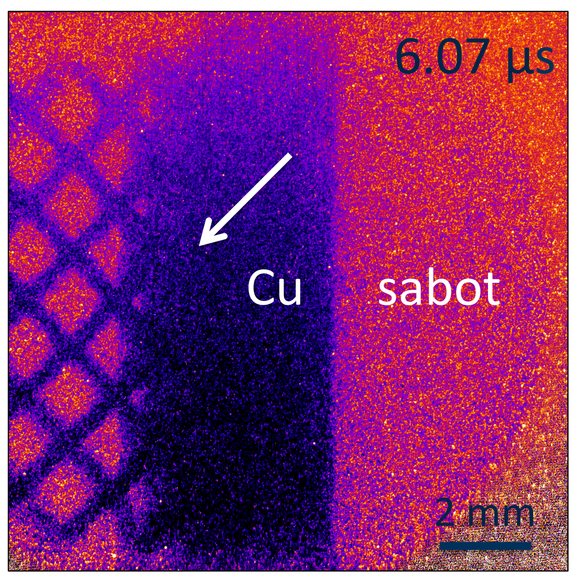


Figure 8: Dynamic, *in-situ* radiograph showing deformation in the SLM lattice 6.07 μs after impact. Acquisition time, 16 ns.

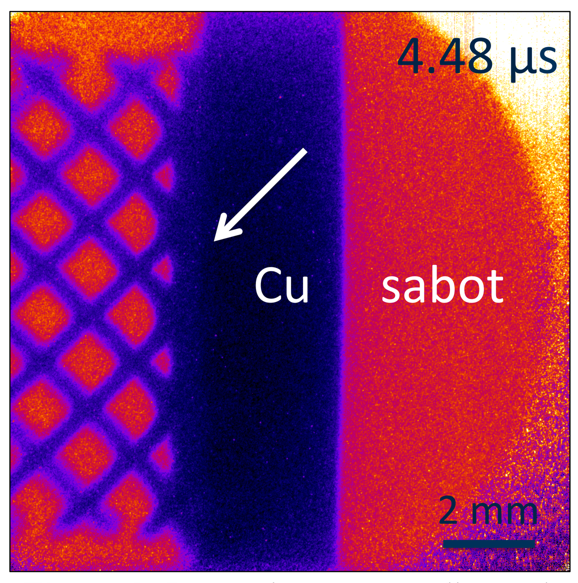


Figure 9: Dynamic, *in-situ* radiograph showing deformation in the SLM lattice 4.48 μs after impact. Acquisition time, 500 ns.

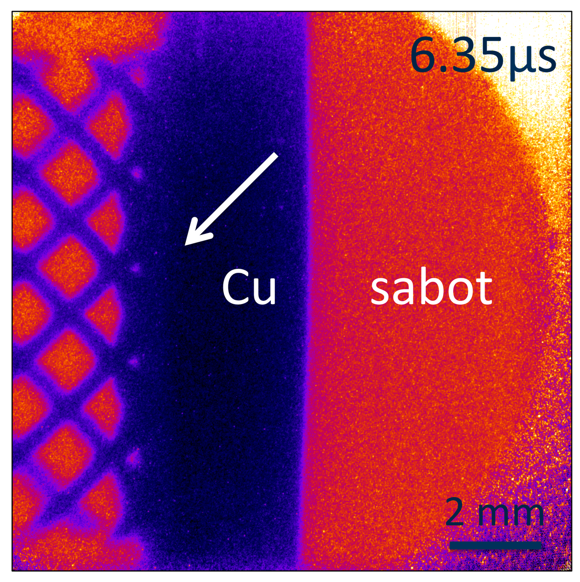
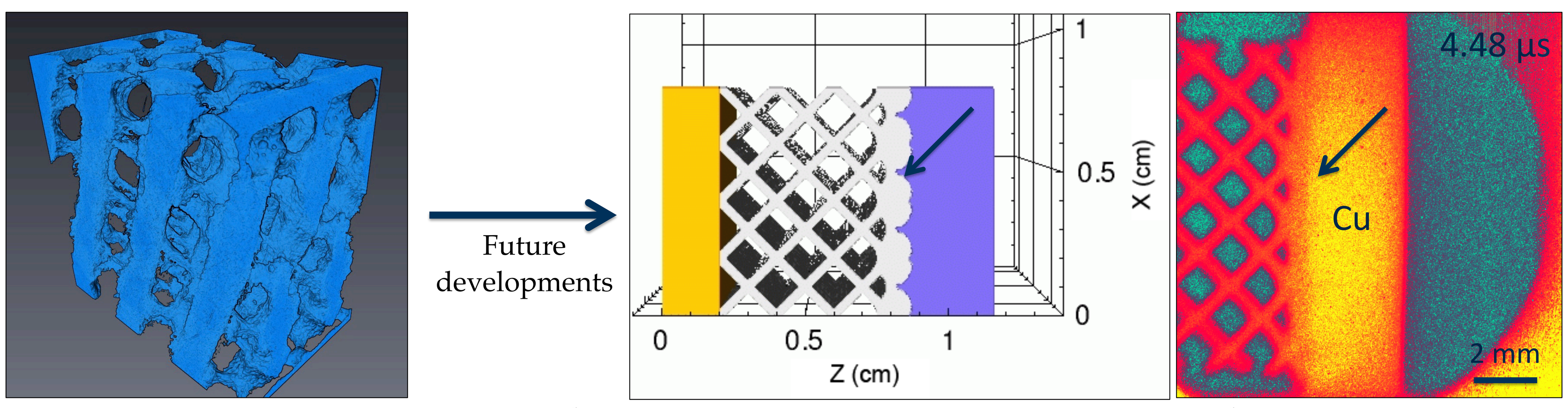


Figure 10: Dynamic, *in-situ* radiograph showing deformation in the SLM lattice 6.35 μs after impact. Acquisition time, 500 ns.

Conclusions and Future Directions

- Synchronisation of shock-induced transient events in dense materials with synchrotron X-ray pulses, and a demonstration of stroboscopic radiography.
- Acquisition of *in-situ* dynamic radiographs with temporal and spatial resolutions of 16 – 500 ns and 40 μm - 200 μm, respectively.
- An advanced understanding of high-energy radiation detection, including a rigorous characterisation of scintillator emission.
- Direct observation of sequential pore collapse, target-flyer interface densification, powder densification, and fracture.
- A new aberration-corrected optical relay will be designed to allow undistorted imaging with an improved signal-to-noise ratio.
- Multiplexed radiography will be implemented using multiple ICCD cameras and scintillators, allowing for several radiographs per shot.



Future work will use vectorised tomographic reconstructions as inputs for CTH simulations. This will allow simulations to account for true material microstructures, thereby facilitating a more rigorous comparison with experimental data.

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