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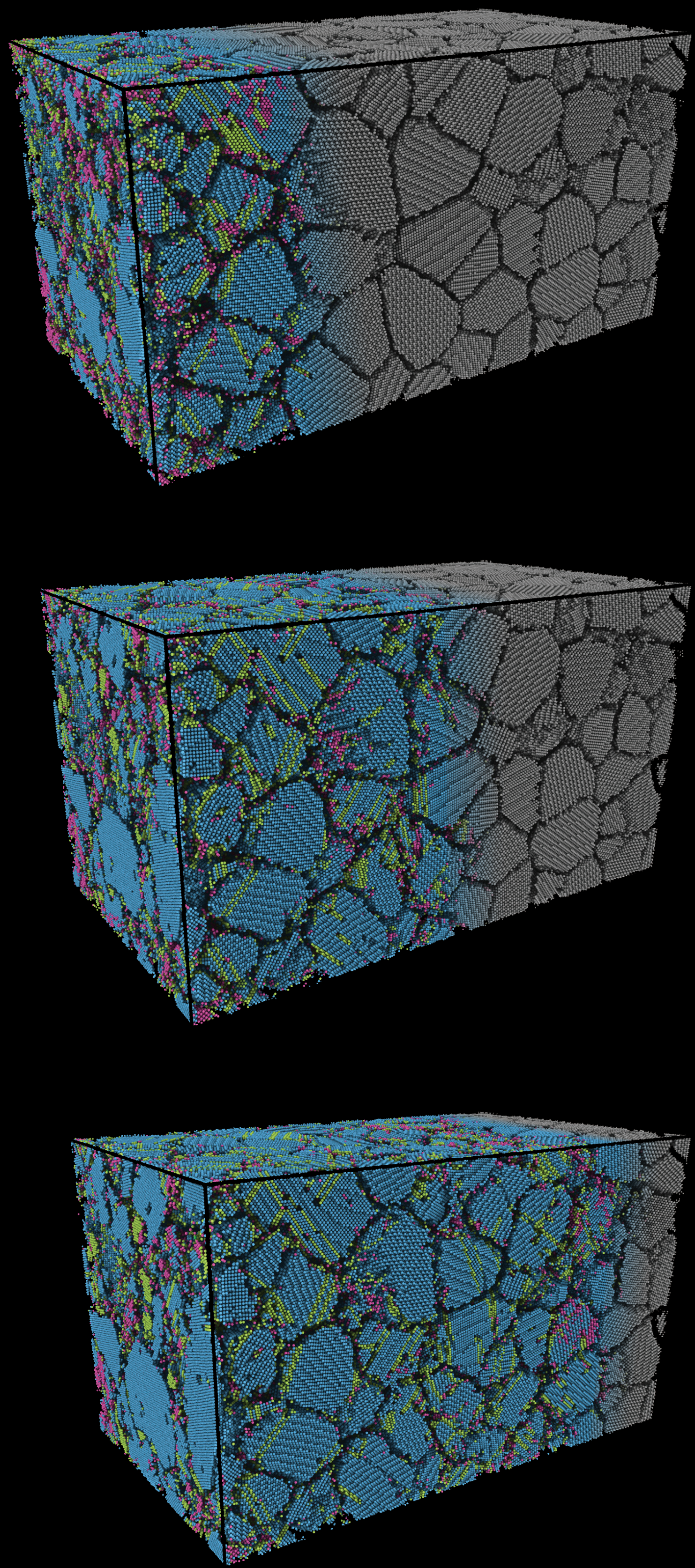


Institute of Shock Physics

Annual Review 2014

www.imperial.ac.uk/shockphysics

CONTENTS

Cover images

A 4 million atom (28.8 x 28.8 x 57.6 nm) molecular dynamics simulation in LAMMPS showing a shockwave propagating from left to right in polycrystalline copper. The shockwave is driven with a reflecting piston boundary corresponding to a particle velocity of 0.9 km/s corresponding to a pressure of over 40 GPa. Atoms are coloured according to a common neighbour analysis with blue, pink and green corresponding to FCC, BCC and HCP structures respectively. All other atoms are invisible to allow the grain structure to be visualised.

Kindly provided by
Dr Thomas White, Research Associate at the ISP, Imperial College London

Professor Steven Rose
Founding Director

Foreword – a word of thanks

The Institute of Shock Physics (ISP) would like to thank its Founding Director Professor Steven Rose for his efforts in establishing the ISP in 2008 and delivering the second phase of the contract, and for the unfaltering level of support and guidance he has given the ISP family over the last seven years. We look forward to more opportunities and successes in the years ahead, building on Steve's effective leadership.

We wish Steve well with his new pursuits awaiting him in semi-retirement, as well as with his continued AWE-funded research within the Plasma Physics group at Imperial.

The ISP team

Dr William Proud
Director

Director's overview

The past year has been one of continued growth for the Institute of Shock Physics, seeing a number of new research pathways surface. Working in close collaboration with AWE we have upgraded our 100 mm large bore gas gun. Funding from EPSRC has allowed the establishment of a miniature Hopkinson Bar system to load small samples of metals and alloys used in the aerospace and nuclear industries. Collaboration with other departments and universities has resulted in significant progress in research on biological materials. The first Institute of Physics-organised PETER 2014 Conference attracted a good number of attendees and the European Union funded an Erasmus Plus programme, bringing together a number of universities with an interest in energetic materials. The challenge in the coming year will be to build on these foundations, in doing so recognising the essential contribution made by the people within the ISP, our colleagues within Imperial and other academic institutions, and our sponsors.

Dave Chambers
Head of Hydrodynamics Technology Centre and Applied Physics

Sponsor's comment

This report demonstrates the high quality of shock physics research being undertaken at the ISP. It is great to see the ISP bringing together the people and facilities needed to tackle some of the challenges faced in this subject area. The research output from the student community has been particularly pleasing this year, and it is these people who will become future leaders in shock physics and enhance our hydrodynamics science capability for the long term. The growth of this talented community along with continued investment in research facilities will give us the ideal platform from which to build a sustainable future for shock physics research in the UK.

Professor Andrew Randewich
Chief Scientist, AWE

Chief Scientist's comment

The ISP programme goes from strength to strength, and has supported some important AWE deliverables with direct experiments on the large bore gas gun. I was particularly pleased to hear that the hydrodynamics and shock waves course has now entered the core lecture programme for undergraduate students at Imperial College London. The ISP has been very successful in nurturing scarce skills for AWE and the UK, and will provide a very valuable and enduring capability for the future.

STRATEGY AND OUTPUTS

Based at Imperial College London, the Institute of Shock Physics (ISP) is a world-class, multidisciplinary research organisation established in 2008 with major support from AWE and Imperial to provide a UK focus for shock physics research and training. From March 2013, AWE provided further, substantial funding for a second, five-year phase of the ISP at Imperial.

Shock physics focuses on the understanding of what happens to matter under extreme conditions.These conditions can occur naturally, such as during planetary impacts within the solar system, or may exist within the core of planets or other astrophysical phenomena. They may also arise as a result of man-made processes related to aeronautics, national security applications and energy futures.

In collaboration with partners from across the UK and overseas, the ISP undertakes research over multiple scales, from seconds to picoseconds and from bulk to atomistic level. Examples include investigations into the origin of dynamic material strength, studies of force protection, the behaviour of biological materials under intense loading, and the development of improved energetic materials. This work is enabled by the broad range of state-of-the-art experimental platforms, diagnostics and modelling capabilities at Imperial. The Institute also aims to educate the next generation of scientists and engineers in the science of shock waves, ultrafast material phenomena and matter at extreme conditions.

Governance and management

- William Proud » Director
- Daniel Eakins » Deputy Director
- Alice Moore » Programme Manager
- Ciara Mulholland » Institute Administrator

The ISP is currently guided by two Boards, an Operations Management Board chaired by our Director, Dr William Proud, which meets quarterly, and a Strategic Advisory Board chaired by Professor Chris Deeney (US Department of Energy), which meets annually. Day-to-day management is provided by the programme team located in the ISP headquarters at Imperial's South Kensington Campus. The ISP also runs a joint AWE/Imperial Technical Operating Group to review and agree solutions to technical issues relating to Imperial's large bore gas gun, and has recently updated the Gas Gun Governance Committee to consider external proposals to use the facility.

Figure 1: Summary of financial gearing.

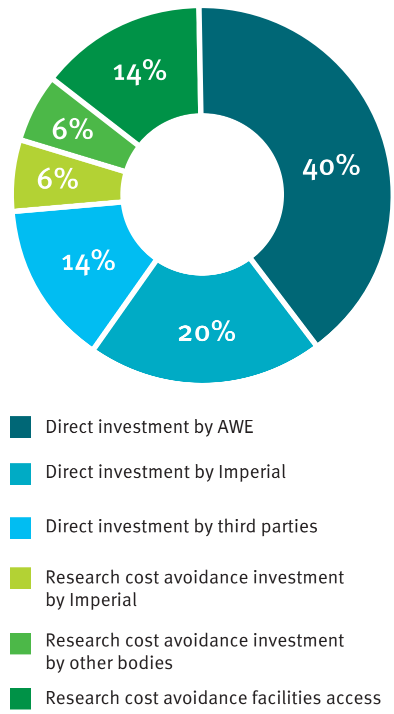
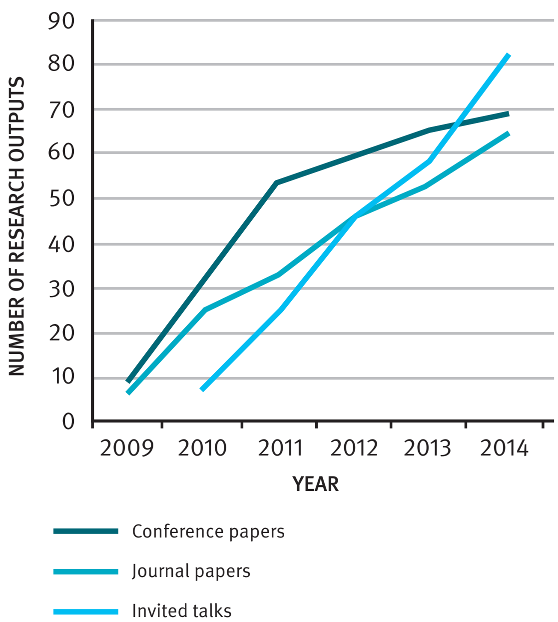


Figure 2: Cumulative total of research outputs from ISP funded staff.



Success of the Institute of Shock Physics is measured against Key Performance Indicators collected together in a Balanced Scorecard. A summary of key outputs since 2008 is as follows:

FINANCES

Following an initial investment to the ISP of around £10 million over five years spread across five institutions, AWE has provided further funding to support a second, five-year phase of the ISP at Imperial.

In order to demonstrate value for money, the ISP collects information on financial gearing across a range of categories including underpinning funding from other bodies, such as the UK Research Councils, for staff and equipment, use of other facilities including synchrotron radiation sources worldwide, equipment donation and additional resource such as visiting researchers and fellows. The financial gearing for phase two is summarised in figure 1, where gearing is AWE funding expressed as a proportion of the Full Economic Cost of the programme (all Direct Investment) plus Research Cost Avoidance.

PEOPLE DEVELOPMENT

- Twenty-eight PhD students working at five institutions. One QinetiQ funded PhD; two funded by The Royal British Legion; one funded by the Defence Ordnance Survey Group; one funded by software company Ansys; three part-funded by EPSRC
- Most PhD students who have completed their studies have been offered Research Associate positions in relevant areas of research and four have taken up a posts at AWE
- Trained 39 summer interns, some are now interested in MSc and PhD courses
- Delivered 16 successful short courses on a range of technical subjects
- Delivered the Master's in Physics with Shock Physics course to five cohorts totalling 20 students; the majority have gone on to undertake further postgraduate studies or entered relevant employment
- Delivered undergraduate course 'Shock Waves and Hydrodynamics', the most popular option on the Physics programme with an average 40% of the student body enrolling each year

INSTITUTE CAPABILITY

- Three academic staff and three Postdoctoral Research Associates (rising to four in 2015), two technicians and a programme office at Imperial
- Fifty-nine visiting academics from 14 institutions including AWE
- Current capabilities include a 100 mm bore single stage gas gun, MACH pulsed power machine for quasi-isentropic loading, several small-scale, portable impact launchers ranging in bore from 13 mm to 30 mm delivering velocities from a few 10's ms^{-1} to <1000 ms^{-1}, and a long-pulse laser-driven shock facility. These and other capabilities are described in greater detail on pages 24–26

RESEARCH OUTPUT

- **Published:** 64 journal papers, five books or chapters, 69 conference papers and delivered 82 talks or lectures at prestigious meetings and organisations
- **Recent examples of conferences:**
  - 15th International Detonation Symposium, San Francisco, July 2014,
  - TMS Pan American Materials Conference, Brazil, July 2014
  - Conference on Granular Materials, Changsha, China, 20–24 September 2014
  - PETER 2014 Conference, IOP, London April 2014
- To date, we have completed more than 170 shots using the large bore gas gun over approximately 35 experimental campaigns, of which 15 were ISP or ISP collaborations with external academics, with the remainder (20) in support of AWE research

Shock physics focus

One of the key aims of the ISP is to provide a UK focus for shock physics research and training. We do this by organising or attending international conferences, meetings and events and by raising the profile of what we do through stakeholder events. To date we have delivered five annual meetings (PETER conferences); held five successful stakeholder events to raise awareness of the Institute at AWE and Imperial; and we have hosted numerous visits from academia, industry and Government. For example, during 2014 we were delighted to host Tracy Vogler from Sandia National Laboratories who gave a well-received seminar on 'Dynamic Behaviour of Granular Materials', attracting attendees from a number of partner institutions.

Delegates at the 2014 PETER Conference.

The PETER (Pressure Energy Temperature and Extreme Rates) conference 2014 was held in the Grand Connaught Rooms, Convent Garden from 7–9 April. The ISP-led conference, this year organised by the Shock Waves and Extreme Conditions (SWEC) group of the Institute of Physics (IOP), drew 57 attendees and was sponsored by QinetiQ, AWE, Ametek, Vision Research and Speyer Photonics and the ISP. Attendees came from South Africa, France and China as well as the UK. Five invited talks were given on topics as diverse as the new Orion facility at AWE, high-speed temperature measurement, blast processes, blast injury and the high-pressure phases of diamond. Contributed talks made up the rest of the programme and there was a poster session. The venue was ideal and a high standard of science, interaction and food was maintained throughout. Thanks go to the conference team of the IOP, Amy and Vicky, who provided great support throughout.

PhD student prize

PhD student David Jones (pictured) was awarded the AWE Anne Thorne Thesis Prize for his work on 'Dynamic Fracture and Fragmentation: Studies in Ti-6Al-4V'. This prize is awarded annually for the best PhD thesis in experimental physics concerned with the development and use of new experimental instrumentation or techniques. David's work was also filmed by the *Journal of Visualised Experiments* (JoVE), and is expected to be released online in the coming months.

RESEARCH

Imperial College London

Institute of Shock Physics

- William Proud (Director)
- Dan Eakins (Deputy Director)
- Simon Bland

Over the past few years, the ISP at Imperial has established a diverse research profile, encompassing multi-scale studies extending from atmospheric to Mbar pressures, from the low to very high strain rate regimes, and from kilometres to sub-micrometre length scales. The following is a brief summary of some of the exciting work being performed by our staff, students and postgraduate researchers.

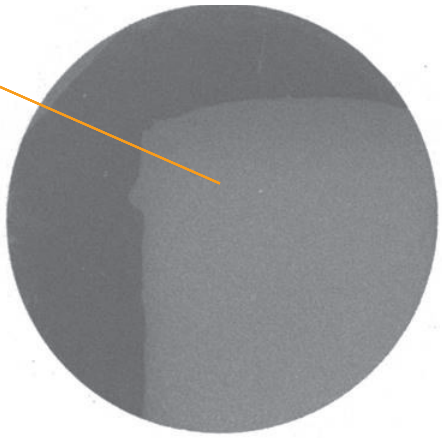


Figure 3: High magnification radiograph of a single 3x5mm HIPE foam, tungsten X-pinch, 12μm Al transmission window. Imaged with single shot at >2m from highlighting the high-flux available for multi-foam or point projection imaging.

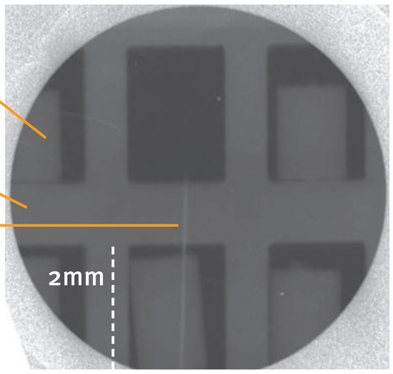


Figure 4: Radiograph of 6 foams using a 12um Ti transmission window (3-5 and above 6KeV). 300um, stainless steel needle used to provide a fiducial behind the centre foam, lower row.

X-pinch radiography

- **Simon Bland**
- **Deep Lall (summer student)**
- **Guiji Wang (Academic Visitor)**
- **Roland Smith**

Over summer 2014 Simon Bland worked on a CEMS funded project to radiograph dense foams for use in experiments on the Orion laser. Working with a UROP student, Deep Lall, and Guiji Wang, an academic visitor from the Institute of Fluid Physics (China), a small-footprint pulsed power generator 'NENE' was re-commissioned. This was then used to drive X-pinch implosions, providing a high intensity point source of X-rays.

Some 40 experiments took place to optimise X-ray generation in the wavelength range required for imaging through the ~150mg/cc HIPE foams. Some re-engineering was undertaken to allow multiple foams and X-ray diagnostics to be fielded simultaneously. The generator reliably provided ~35-40kA pulses in 50ns to the load region with very little jitter. We used time integrated pinhole cameras and slit cameras to monitor the size of the emission region formed by the X-pinches in multiple wavebands; X-ray diodes followed to examine temporal emission, and several different radiography configurations with various foams targets (some pre-diagnosed) provided by AWE.

Foams were radiographed using Fuji image plate at up to 2m from the X-pinch source, allowing for point projection magnification of images. The highest contrast results were obtained with stainless steel or tungsten X-pinch wire loads. Multiple foams were imaged simultaneously demonstrating the potential for rapid sorting of large batches of test pieces.

The X-pinch source is now being used to explore X-ray absorption spectrometry and X-ray diffraction for use in dynamic compression experiments on MACH and the miniature SHPB.

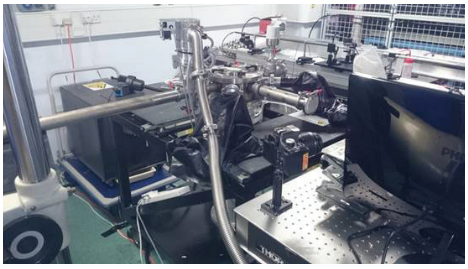


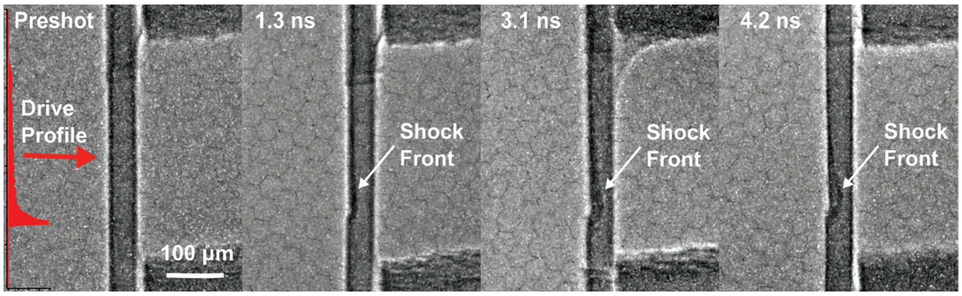
Figure 5: The NENE pulsed power driven x-pinch used for radiographing foams.

Ultrafast phase contrast imaging of laser driven shocks using betatron X-rays

- David Chapman (RA)
- Thomas White (RA)
- Michael Rutherford (PhD student)
- Daniel Eakins
- Stuart Mangles

Bright, high-energy photon sources, such as synchrotrons and more recently the new generation of X-ray free-electron lasers, offer the attractive combination of high brilliance, short pulse duration and high-energy X-rays. With their ability to probe matter on the atomic scale with unprecedented temporal and spatial resolution, they have been used in a range of applications spanning the physical, biological, and medical sciences but are particularly suitable to imaging highly transient events, such as shockwave evolution. Alternatively, betatron X-rays produced within a laser-plasma wakefield accelerator provide an exciting complementary energetic photon source to these established large scale facilities.

As a complementary research avenue to our pioneering efforts on the I12 beamline at the Diamond synchrotron, and ongoing research collaborations employing ESRF and LCLS, we recently completed proof-of-principle experiments imaging the shock-front evolution in laser driven targets using wakefield betatron X-rays. These world-first experiments were performed on the 400 TW Astra Gemini laser at the Rutherford Appleton Laboratory, UK, as part of an ongoing collaboration between the ISP and the John Adams Institute for Accelerator Science. Shock waves were driven into silicon wafers along the [100] direction, and stroboscopically imaged perpendicular to the shock propagation direction using a ≈40 fs betatron X-ray pulse generated within a laser-plasma wakefield. Figure 7 describes the experimental geometry; the uncompressed Gemini north beam (800nm, ≈2ns, 15 J) was used to directly drive a profiled shock front into the silicon wafer while the compressed Gemini south beam (800nm, ≈40 fs, 18 J) was focused in a helium gas cell, generating betatron X-rays (critical energy 34 keV, $2x10^9$ photons per pulse) with a 3-4 micron source size. The radiographs imaging the shock front evolution were captured at a magnification of 26x using a Princeton Instruments PIXIS camera (micro-columnar CsI:Tl scintillator). Figure 6 shows a time-series of radiographs indicating the evolution of the structured shock front as it transits the silicon wafer. Quantitative analysis of these ground-breaking images to reduce for example, single shot Hugoniot data, shocked density, and comparison with radiation Hydrocode simulations is ongoing. Regardless, these initial results showcase a promising, potentially table top sized X-ray source suitable for probing the response of materials under extreme conditions with micron-scale resolution.



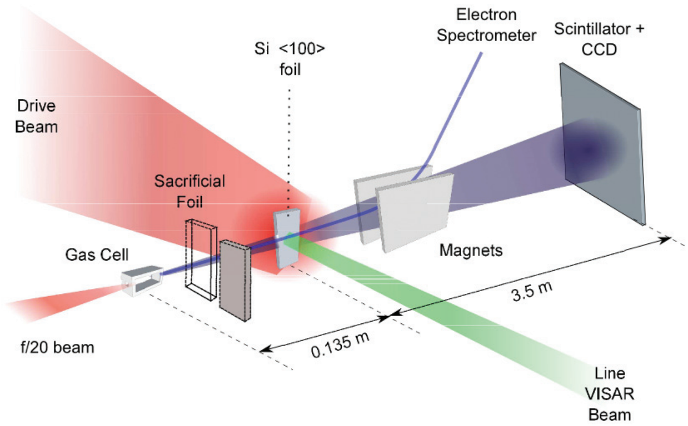


Figure 6: Time-series of radiographs showing the evolution of the shock front. The figure indicates the beam profile used to drive the structured shock waves into the silicon target, each sub figure indicates the time delay from shock drive.

Figure 7: Schematic of the experimental geometry employed at Gemini. Shock waves were driven into the silicon foil at 30 degrees off-normal using the Gemini north beam, while the compressed south beam (f/20) was focused in a helium gas cell generating betatron X-rays. The rear surface of the silicon foil was diagnosed with line-VISAR, while radiographs of the shock front evolution were captured perpendicular to the direction of shock propagation with a magnification of approximately 26x.

Large-scale molecular dynamics simulations of laser-matter interactions and dislocation generation

- **Thomas White (RA)**
- **Clément Zankoc (ERASMUS student)**
- **Daniel Eakins**

Large scale, massively parallel molecular dynamics (MD) allows the behaviour of complex many-body systems to be investigated. The ISP have recently developed the capability to simulate systems consisting of up to ten million atoms on two 48-core clusters running the open source software LAMMPS. MD is well suited to exploring the properties of extreme states of matter; that is matter with temperatures in excess of 100,000 K and pressures reaching one million atmospheres. These states of matter can be recreated here on earth during high power laser-matter interactions and represent an important step towards understanding the creation and evolution of complex systems relevant to astrophysical conditions and planetary interiors.

ERASMUS student Clément Zankoc completed a summer project investigating two separate problems. The first of these explored the behaviour of a polycrystalline copper sample consisting of four million atoms arranged in approximately 400 grains and subjected to an intense laser pulse, modelled through implementing a 900 m/s piston on one wall of the simulation. Figure 8 shows the temporal evolution of the sample, a clear wave crosses the sample ahead of the piston and stress relaxation through dislocation generation is visible within each grain. One of the fundamental difficulties with MD is selecting the best potential to represent the ion interactions within a system. With this goal, the second project examined the behaviour of a trial system consisting of a 2D layer of single crystal copper with a four Angstrom cylindrical nano-void studied under tension. Figure 9 shows the behaviour of the system as the outer most layers of atoms are systematically moved outwards. The qualitatively different response between two potentials (a-c) and (d-f) is clearly apparent.

Finally, in work recently published in PRB, the electron-phonon equilibration in laser-heated gold was determined through direct comparison with MD.[1] By irradiating a thin metal foil with an intense short-pulse laser, a uniform system far from equilibrium was created. The energy is initially deposited within the electronic subsystem, and subsequent evolution of the system governed by the electron-phonon coupling. By measuring the time evolution of the lattice parameter through multilayer Bragg diffraction and comparing to a classical MD simulation utilising a two-temperature electron-phonon system, the electron-ion coupling constant for gold was determined (figure 10).

Publication

1. TG White, P Mabey, DO Gericke, NJ Hartley, HW Doyle *et al.* *Electron-phonon equilibration in laser-heated gold films* *Physical Review B*, 90 (1), 014305, (2014)

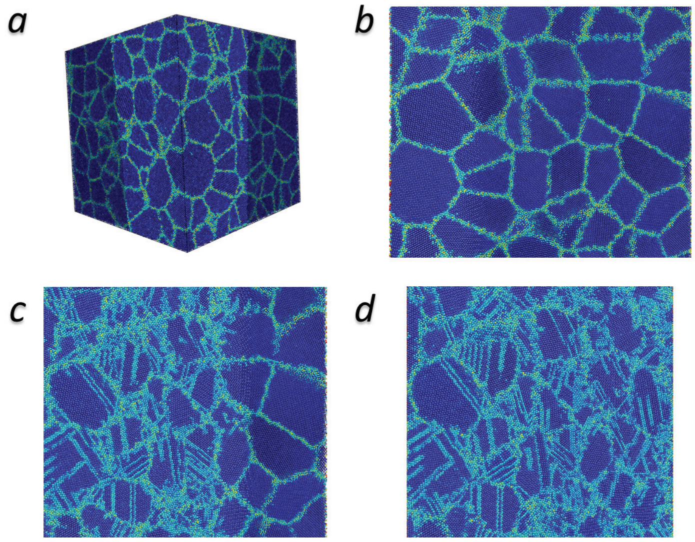


Figure 8: (a) Four million-atom polycrystalline copper containing approximately 400 grains. A shockwave is driven into the sample by implementing a 900 m/s piston. (b-d) show a 2D slice through the sample at 0 ns, 4 ns and 8 ns after the piston begins to move. Atoms are coloured according to their centrosymmetric parameter to highlight the dislocation lines forming within a grain.

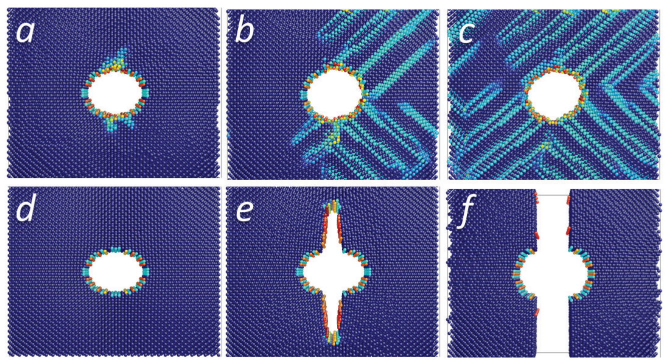


Figure 9: Dislocation generation due to a tensile force applied to a two dimensional single crystal of copper around a cylindrical nano-void defect. At each strain the simulation is relaxed to the lowest free energy surface with subsequent snapshots separated by one relaxation. The top and bottom rows show discrepancies between two common potential. The atoms have been coloured according to their centrosymmetric parameter.

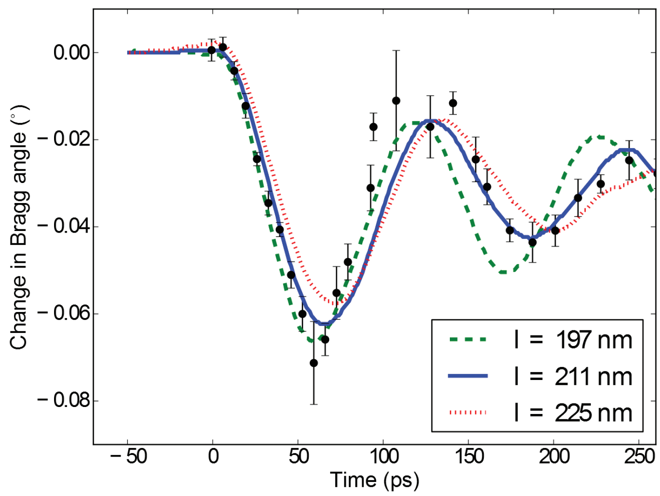


Figure 10: Change in diffraction angle from the gold nano-foil compared to results from molecular dynamics simulations where the sample thickness is varied. The solid line represents the best fit, while the dashed and dotted lines are under- and overestimates respectively.

High resolution 3D DIC for dynamic strain measurements

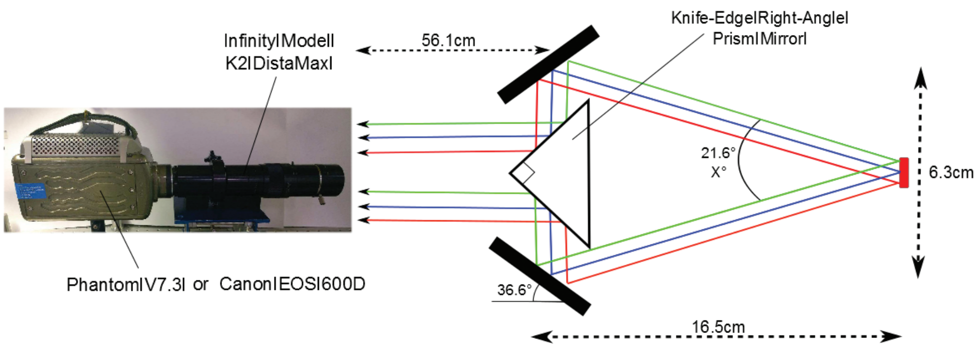
- Thomas White (RA)
- Jack Patten (PhD student)
- Gilles Tahan (ERASMUS student)
- Daniel Eakins

A high resolution digital image correlation system for use in high strain rate experiments was developed for the miniature Split Hopkinson Pressure Bar (m-SHPB) as part of the HexMat EPSRC programme grant. The system is capable of providing full 3D surface deformation with a single high frame-rate camera. Utilising open-source camera calibration and two-dimensional digital image correlation tools within the MATLAB framework sub-micron resolution is demonstrated. A displacement calibration demonstrates accuracy of beyond 1 micron matching that achievable with commercial software.

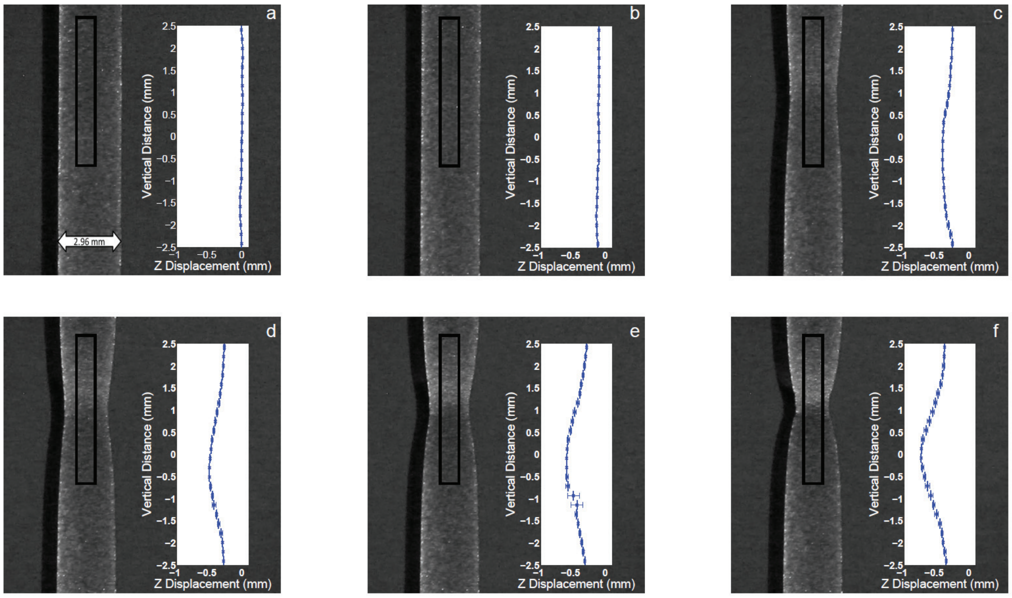
The stereoscopic system uses mirrors and a prism (see figure 11) to simultaneously view the target from two angles on a single high-speed camera, thus allowing the reconstruction of 3D surfaces. Beyond reducing the cost of the system this also overcomes synchronisation problems associated with multiple cameras; a challenging task in high strain rate experiments.

A series of tests of the imaging system, analysis code and speckle pattern application have been performed, the results of which demonstrate a sub-pixel level of precision. The imaging system is compact and mobile, allowing it to be fielded on a range of dynamic experiments, and has already been used on the m-SHPB, manually-driven deformation tests and samples subjected to uniaxial loading via an Instron machine, see figure 12. The experimental and analytical methods are robust and require only that a sample's surface displays a speckle pattern on the scale of interest.

This work was carried out in collaboration with Gilles Tahan, an ERASMUS student from ENSTA, Brest in France.



« **Figure 11:** Schematic of experimental layout demonstrating how a single high frame-rate camera can be used to perform stereoscopic imaging.



« **Figure 12:** Evolution of tensile specimen subjected to a constant velocity of 1 mm/minute. The insert shows the out-of-plain surface position averaged across the highlighted region. Data is shown for times (a) 503s (b) 675s (c) 783s (d) 795s (e) 807s (f) 819s corresponding to a global strain of (a) 24.8% (b) 33% (c) 38.6% (d) 39.2% (e) 39.8% (f) 40.4%. These times were chosen to cover the largest out-of-plane motion. Error bars represent standard deviation across the width of the sample.

Thin-plate perforation studies of Boron Carbide

- **Joao Pedro Duarte (RA)**
- **Daniel Eakins**
- **Finn Giuliani**

Boron Carbide (nominally B4C) is one of the hardest materials presently known. Its extreme strength (~45 GPa) and high Hugoniot Elastic Limit (HEL, ~20 GPa), combined with a low specific gravity, have made it a preferential ceramic material for ballistic armour for many years. In spite of such superb properties, it exhibits an anomalous drop in strength at pressures beyond the HEL. This has been correlated with the formation of amorphous shear bands thought to result from shear stresses which deform and debond the three-atom bridges connecting the icosahedral units characteristic of B4C's structure. Recent theoretical studies have nevertheless suggested that the incorporation of small amounts of Si in boron carbide could largely suppress the formation of the B4C polytype weakest to the debonding, unlocking its potential for strength >40 GPa.

A research programme in collaboration with the Department of Materials at Imperial College London investigating the dynamic behaviour of Si-incorporated boron carbide was initiated in 2014. Initial thin-plate perforation experiments have been set-up to provide an easy way to perform comparative studies using global kinematic observables such as dwell times or ballistic limit velocities. Although less clearly than with plate-impact experiments, this type of study allows drawing correlations with material strength when assisted by explicit dynamics calculations based in appropriate constitutive models. Furthermore, they require lower projectile velocities (<900 m/s) which lie within the capabilities of the ISP's meso scale launcher.

Once hypervelocity loading platforms capable of creating uniaxial stress states above 20 GPa become available at the ISP, the programme will evolve to plate-impact experiments complemented with time-resolved Raman spectroscopy to directly probe amorphous band formation.

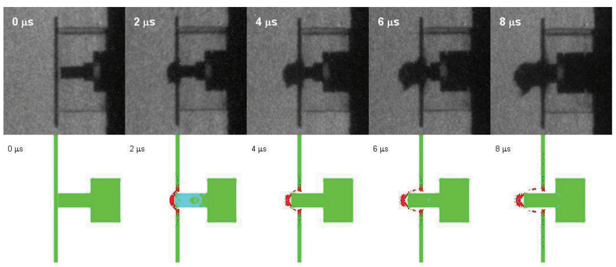


Figure 13: Image from a thin-plate perforation experiment of B_4C impacted with a steel rod penetrator and corresponding explicit dynamics simulation. Dwell time preceding interface defeat is one of the parameters which can be correlated to material strength using these simulations.

Dynamic fracture and fragmentation

- **David Jones (PhD student)**
- **David Chapman (RA)**
- **Daniel Eakins**

Materials subjected to high strain rate and dynamic loading often fail catastrophically. This terminal response of fracture and fragmentation is a complex event, governed by factors such as material properties, experimental conditions and the loading history in the sample. This makes development of accurate predictive models and simulations challenging, requiring careful design and control over experiments. There has been an ongoing theme in the ISP of developing methods of driving radial expansion in cylindrical samples using the large-bore gas gun, generating a uniform tensile state at strain rates in the order of 10^3 to 10^5 s^{-1}. Unique to our facility is the ability to perform this work with the samples at temperatures between 100K and 1000K. This allows investigation of the effect of initial sample temperature on the plastic deformation, fracture initiation and mechanism(s) occurring and the resulting fragmentation patterns.

This research has concentrated on Ti-6Al-4V cylinders at radial strain rates of 10^4 s^{-1} at initial temperatures between 150K and 800K. Experiments used a combination of high speed imaging, laser velocimetry (Het-V) and fragment recovery. While the failure strain was observed to increase with temperature, the fragmentation toughness (K_f, analogous to the quasi-static fracture toughness) showed little correlation with an average value of 101 MPa $m^{1/2}$, suggesting that strain rate is the dominant parameter. Recovered fragments were studied under optical and electron microscopy and electron backscatter diffraction. At high temperatures (>700K) the fracture mechanism observed was through void nucleation and coalescence along adiabatic shear bands, in contrast to ductile mode II tearing at lower temperatures where no signs of transformation were found.

Publication
DR Jones, DJ Chapman, DE Eakins
Gas gun driven dynamic fracture and fragmentation of Ti-6Al-4V cylinders
Journal of Physics: Conference Series, 500 (11), 112037, (2014)

Figure 14: Light microscopy image of a polished and etched fragment from a Ti-6Al-4V expanding cylinder, initial temperature 750K and a radial strain rate of 104 s^{-1}. Shown is an arrested fracture, propagating along an adiabatic shear band.

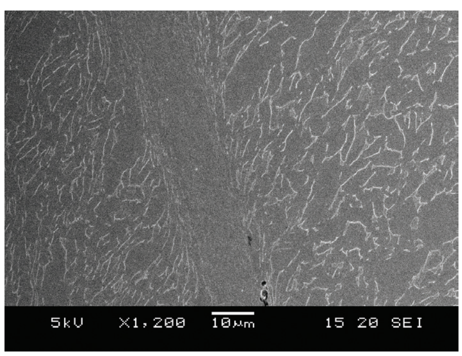
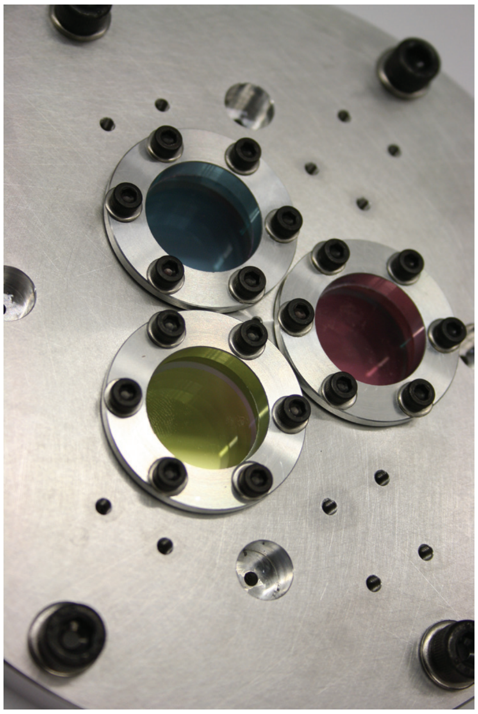


Figure 15: The same arrested fracture under a scanning electron microscope, showing the void nucleation and coalescence along the transformed band.



» **Figure 16:** A multi-liquid cell target. The cells have been filled with different coloured dye to verify vacuum sealing.

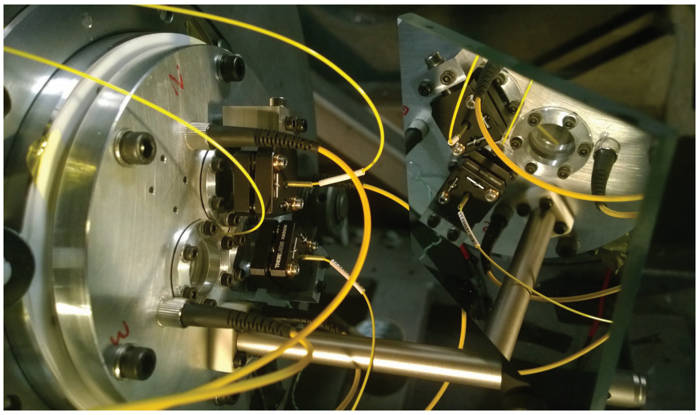


Figure 17: The same arrested fracture under a scanning electron microscope, showing the void nucleation and coalescence along the transformed band.

Freezing of water by quasi-isentropic compression

- **Sam Stafford (PhD student)**
- **David Chapman (RA)**
- **Daniel Eakins**
- **Simon Bland**

Under certain loading conditions, water may undergo a liquid-to-solid phase change during compression, freezing into one of its many phases of ice. Although the Hugoniot of water passes very close to the 'Ice VII' phase at around 3 GPa, the high associated temperatures prevent observation of this phase change under a single shock. Quasi-isentropic compression through either ramped or re-shock experiments can compress water at lower temperatures where it exhibits a slow (~100's of ns) transformation at approximately 3 GPa, identified as a discontinuity in the velocimetry measurements or through a characteristic darkening observed in high speed photography.

These quasi-isentropic compression experiments have typically used quartz/silica windows to contain the water sample. However, significantly water shows no signs of freezing with sapphire windows until 7 GPa. This suggests that sapphire does not act as the seed for nucleation of the ice. Only under isentropic compression well within the ice VII phase region will sapphire induce a rapid (<100 ns) phase change in water. It is suspected that the water is kept metastable past 3 GPa and reaches its metastable limit at 7 GPa, at which point it undergoes spontaneous volume nucleation.

Using the 100 mm large bore gas gun at Imperial, a multi-cell target containing three individual water samples was subjected to ramp and ring-up loading. These experiments have confirmed that water can undergo freezing during compression to 4 GPa when in contact with fused silica, as evidenced through high-speed imaging and velocimetry. Similar experiments utilising sapphire or silica-coated sapphire windows showed no signs of freezing until compressed past the 7 GPa limit, suggesting freezing is not governed by surface chemistry. Experiments looking into this behaviour are ongoing.

On the characterisation of shock-induced sliding along multi-material interfaces

- **Mark Collinson (PhD student)**
- **David Chapman (RA)**
- **Daniel Eakins**

The high strain rate behaviour of multi-component systems is often dominated by the characteristics of material interfaces. These characteristics include material pairing, surface roughness, regions of non-contact (gaps), and orientation of the interface with respect to loading. In order to unravel the complex interplay between these various parameters, a series of precision plate impact experiments were conducted on the Imperial meso scale gas gun. These focused on providing spatially resolved velocimetry of the early time response at aluminium – stainless steel contact interfaces of varying angle and alloy composition. Results from these demonstrate the significant role of a combination of the equilibration of pressure states and the closure of micrometre size gaps in defining the relative particle velocities of the constituent components. The results from this have enabled the successful completion of the PhD.

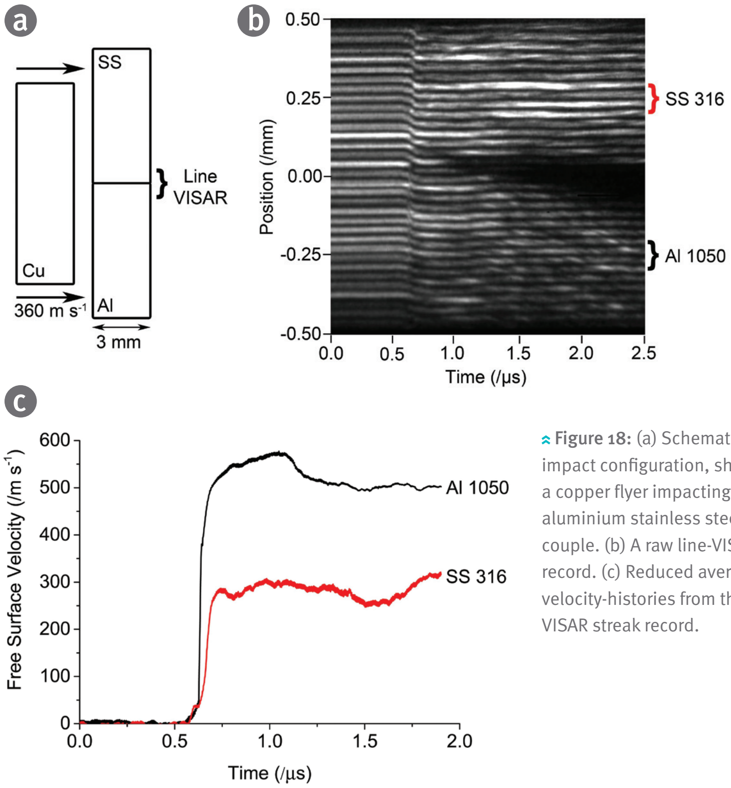


Figure 18: (a) Schematic of the impact configuration, showing a copper flyer impacting an aluminium stainless steel friction couple. (b) A raw line-VISAR streak record. (c) Reduced average velocity-histories from the line-VISAR streak record.

Shock compression of anisotropic dielectrics

- Gareth Tear (PhD student)
- David Chapman (RA)
- Daniel Eakins
- William Proud

Anisotropic materials show behaviour that is directionally dependent. This behaviour is not limited to simple variations in shock speed, and can include the generation of motion transverse to the shock wave. Optical properties are a function of this complex behaviour and optical measurements are being developed to measure this.

We have developed a combined optical ray tracing and characteristics model that offers predictive capabilities for the optical behaviour of complex anisotropic crystals under shock compression. The optical model is three dimensional and capable of resolving arbitrary orientations of biaxial materials. This has been used to generate predictive polarimeter signals for plate impact experiments on homogenous anisotropic dielectrics including calcite and sapphire.

Previous experimental work on the ISP's meso scale gas gun has demonstrated the capabilities of a high-speed polarimeter. This has been employed recently on the 100 mm bore gas gun to verify the predictive capabilities of the model.

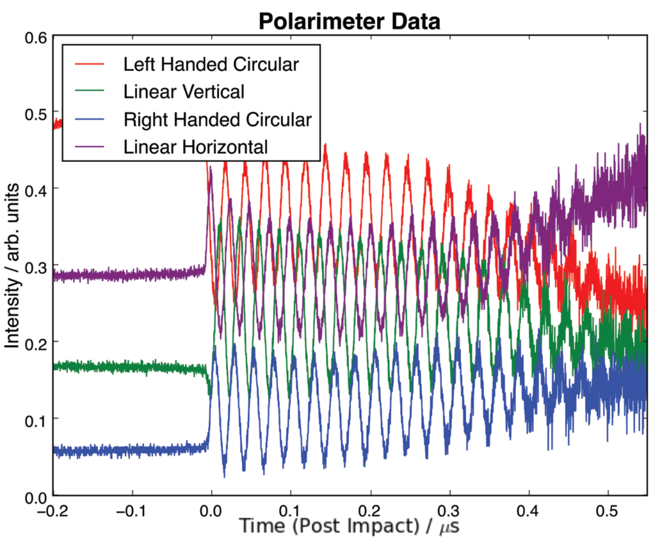


Figure 19: Polarimetery data from 206 m/s impact of magnesium and a-cut calcite. The four channels are horizontal and vertical linearly polarised light (S/P), and left and right handed circular polarised (L/RHC) light. Data was acquired for 550 ns, though shock breakout at the rear surface occurred at 1.1 microseconds. The beat frequency is caused by Fresnel reflection at the shock front.

Investigation of elastic precursor decay in thick deposited films

- John Winters (PhD student)
- Simon Bland
- Daniel Eakins
- David Chapman (RA)
- Thomas White (RA)

The phenomena of elastic precursor decay, where the threshold for the transition of elastic to plastic behaviour is observed to increase with decreasing sample thickness, has been the subject of intense study over the last few decades. However, the role of parameters such as microstructure, impurity concentrations, or defect populations remains relatively poorly understood and strongly material dependent. Over the last year significant progress has been made towards the development of laser driven shock capability within the ISP for the study of precursor decay. The Cerberus STAR (Shock Target ARea) has been readied for experiments on thinned samples, with commissioning shots on windowed thin film aluminium and tin completed in the past year. The long-pulse beam line of the Cerberus STAR is now operational, delivering in excess of 6J over 1ns onto the target at the fundamental frequency. Remote target positioning for multi-shot samples permits a 20 minute rep. rate, while maintaining a high vacuum. A Velocity Interferometer (VISAR) diagnostic has been proven, with an upgrade underway to include a Normal Displacement Interferometer (NDI) option for greater sensitivities while maintaining temporal resolution.

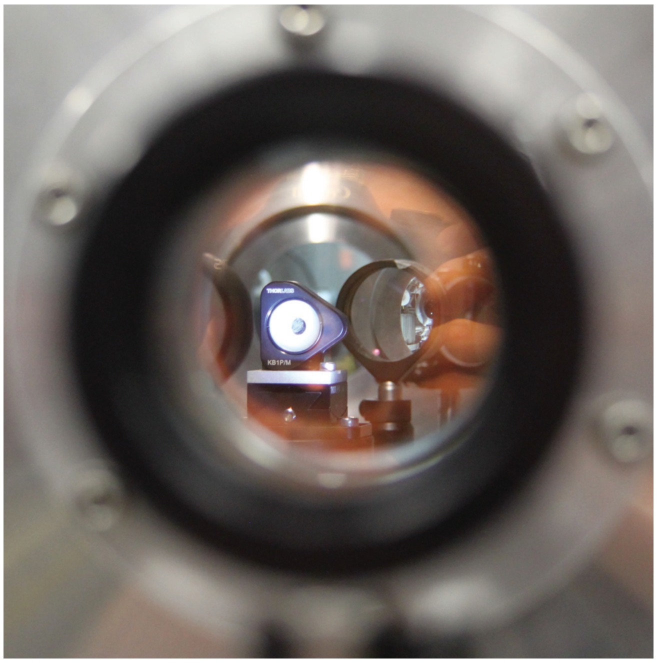


Figure 20: View down the Cerberus laser beam path towards a 17 micron thick target, where the drive beam ablates the surface to drive a shock. The line VISAR and target positioning final objective lenses can be seen either side of the target.

Porous and granular materials studies with a shock tube

- Thuy-Tien N Nguyen (PhD student)
- Theresa Davey (PhD student)
- William Proud

Porous and granular materials have been used as protective covers and filters thanks to their shock attenuation properties. In this project, the percolation of gas and attenuation of blast waves through granular beds and perforated sheets were investigated using a shock tube. This study had two purposes, firstly to understand the effect of such materials on blast waves and secondly to allow us to adapt the pressure tube to produce a wide range of pressure pulses with control of height, duration and wave shape.

To place these studies in context, the blast waves produced by the shock tube corresponded to the output seen at 9–12.6 m from 20 kg TNT. At the low pressure end of this range pressures used can cause rupture and tearing of eardrum in 50% exposed population, while 1% ending in permanent hearing loss due to severe ruptures of the ear membrane.

In the system 0.7 mm thick galvanised perforated steel sheets of different porosity were used, with 22%, 46%, 68%, and 79% of the plate surface being the holes. In addition, granular materials studied were samples of soda lime glass monospheres with diameters of 1.5, 2.0, 2.5, 3.5, 4.0, and 5.0 mm. These materials were used to form granular beds of 147, 123, 72, and 47 mm length. The beds were sealed at both ends with 46% perforated sheets. These perforated sheets and granular beds were inserted into the shock tube system as shown in figure 22.

Publication

1. T-T N Nguyen, T Davey, WG Proud
Percolation of gas and attenuation of shock waves through granular beds and perforated sheets
In proc. *New Trends in Research of Energetic Materials*, Czech Republic, 2014

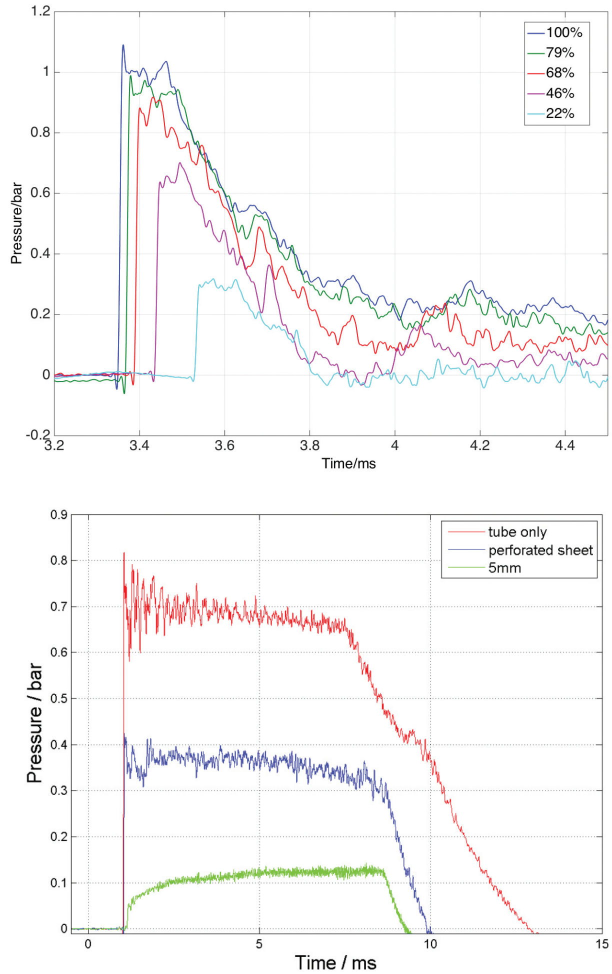


Figure 21: A – Lateral profiles of transmitted pressures behind perforated sheets with different open areas. B – Lateral profiles for 123 mm long empty bed with and without perforated seals, and when filled with 5 mm particles.[1] For the granular beds used in addition to reducing magnitude of the transmitted blast pressure also altered the shape of the waveform (figure 21b). Shock waves were transformed into a very small initial sharp rise followed by a gradual increasing a ramp wave.

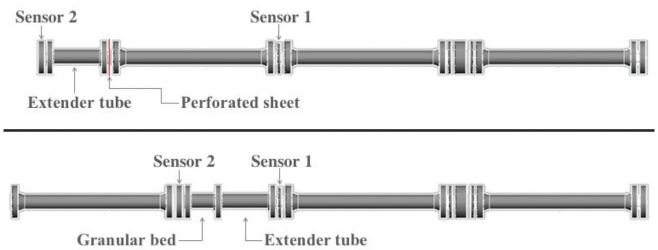


Figure 22: Shock tube schematic – full system with perforated sheet/granular bed and an extender tube inserted.[1] With their arrival at inserted materials, incident waves are transformed into transmitted and reflected waves. The amount of pressure transmitted decreases linearly with open area, reducing effects of blast exposure (figure 21A). With 22% open area, only ~30% of the incident pressure was transmitted over. A similar trend was found for shock impulse in relation to open area.

Temperature effects and strain rate effects on the piezoelectric charge production of PZT 95/5

- Amnah Khan (PhD student)
- William Proud

This research seeks to develop a better understanding of the piezoelectric ceramic lead zirconate titanate (PZT) 95/5 with varying temperatures, porosities, geometric sizes and strain rates. For this reason, a number of experiments are being carried out on both piezoelectric and non-piezoelectric materials, including epoxy resins and metals, in order to establish a good understanding of these effects on materials that are generally well understood, and to provide a comparison for the piezoelectric PZT 95/5.

Different compression rates are achieved using quasi-static loading equipment, drop-weight towers and Split Hopkinson Pressure Bars (SHPBs). Varying temperatures are achieved using purpose-built environmental chambers. Construction and characterisation of a heat exchange chamber for the SHPB is under way. The system consists of a box into which the ends of the input and output bars, sandwiching the sample, are positioned. Cold gas from a liquid nitrogen cylinder is blown in to achieve low temperatures; to achieve high temperatures helium gas is flown through a copper coil placed in oil in a pyrex beaker which is heated on a hot plate. It is hoped that this system will also be able to be used on the drop weight tower being constructed by the Centre for Blast Injury Studies (CBIS).

High rates compression of cells for blast injury studies

- David R Sory (PhD student)
- Anabela Cepa-Areias (PhD student)
- William Proud
- Darryl Overby
- Sara Rankin

This research takes forward ISP PhD graduate Dr Chiara Bo's research into using Split Hopkinson Pressure Bars (SHPB) to load biological samples. Experiments are underway to study the effects of load and strain rate on cells immobilised in a three dimensional gel culture. In the theme of Blast Force Protection a full range of testing facilities in dynamic compression experiments has been developed for the examination of different aspects of blast waves. The facilities include a drop-weight impact tower, a SHPB and a 32 mm bore light gas gun. One of the main assets of the equipment lies in the capacity to load biological samples over a large and continuous range of strain rates (from the intermediate up to the very high strain rates) producing stresses relevant to blast processes.

Initial experiments have been performed on a newly-designed biological load cell dynamically loaded in the SHPB. The biological load cell consists of cylindrical 3D-gel cell culture hermetically sealed in a polydimethylsiloxane silicone sample holder. An annotated photograph of the sample holder is shown in figure 23. Besides the benefits of fulfilling both the biological requirement of sterility and maximize transmission of the input stress to the gel sample, the polydimethylsiloxane silicone was chosen to facilitate gel recovery and post-pressurisation analysis such as cell survivability mapping and cell proliferation studies. Figure 24 shows three images taken during the compression of the new sample holder on the SHPB. The stress and strain levels experienced by the biological system in respect of the image time are presented in figure 25.

Along with the SHPB, a gas gun facility and a miniature drop-weight has been developed and brought into a calibration process in order to routinely allow material properties investigations of soft matter, and more specifically involve key experiments aiming to study the repercussions of high stress short duration pulses, and the effects of impulse delivered on biological systems.

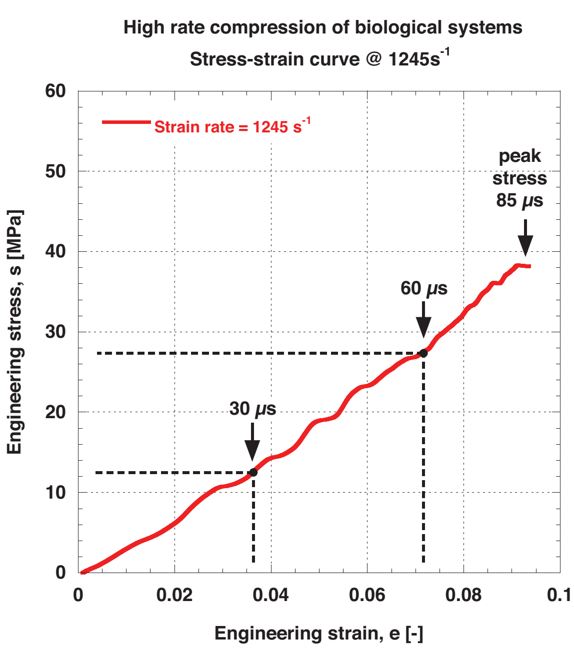


Figure 25: Stress strain curve of the biological systems. The arrows indicate the stress and strain levels experienced by the sample in respect of the images shown in figure 24.

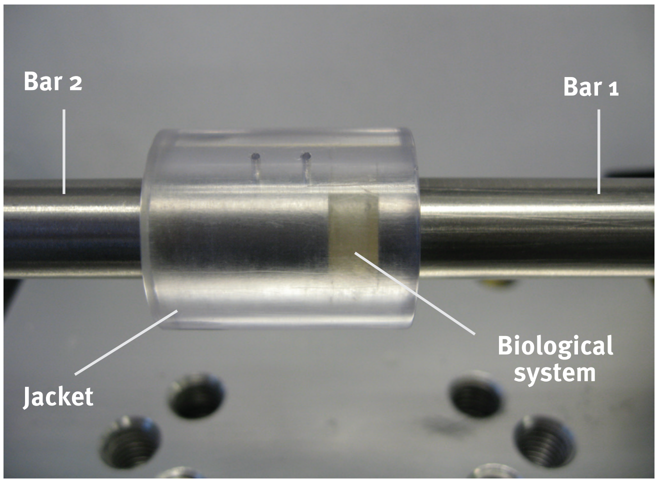


Figure 23: Loading apparatus. A jacket surrounds the sample holder to ensure uniaxial strain is achieved.

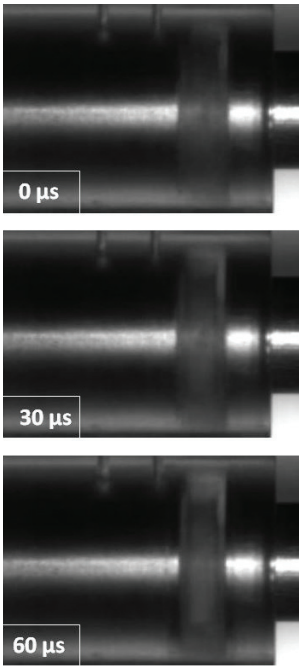
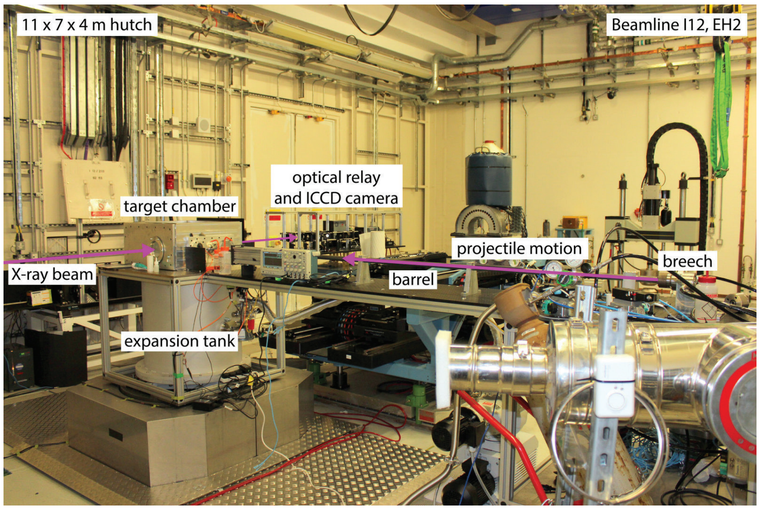


Figure 24: High speed photography of the prototype sample cell during SHPB loading.



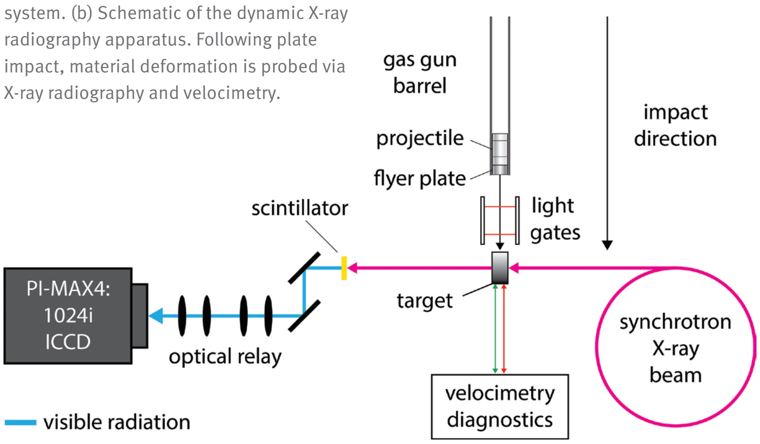


Figure 26: The apparatus at Beamline I12, showing the portable gas gun and imaging system. (b) Schematic of the dynamic X-ray radiography apparatus. Following plate impact, material deformation is probed via X-ray radiography and velocimetry.

High-energy synchrotron X-ray radiography of shock-compressed materials

- **Michael Rutherford (PhD Student)**
- **David Chapman (RA)**
- **Daniel Eakins**

Under the rapidly evolving conditions of shock-compression the interplay between sub-surface processes, such as structural phase transitions, shear localisation and void coalescence, strongly influences the bulk mechanical response of materials. Traditionally, dynamic experiments have been diagnosed with *in situ*, time-resolved surface measurements, and post-loading analysis. However, these techniques cannot provide an unobstructed view of how fundamental deformation mechanisms translate into bulk behaviour, limiting our ability to design materials with pre-defined properties from the ground up.

Unlike optical techniques, X-ray radiation offers unimpeded access to in-material quantities such as density and phase composition during dynamic loading. 2014 saw the continued development of a dynamic X-ray radiography capability at Beamline I12 at the Diamond Light Source synchrotron (Rutherford-Appleton Laboratory, UK). Shock waves are driven into materials using the ISP's portable, single stage gas gun. Following plate impact, material deformation is probed *in situ* by high-energy (50 – 250 keV) white-beam X-ray radiography and complimentary velocimetry diagnostics.[1] The high energies and large beam size (up to 95 x 30 mm) delivered by Beamline I12 allow the study of appreciable sample volumes (several cm^3) of industrially important high-Z materials, such as transition metals.

By combining traditional velocimetry diagnostics with the high-resolution *in situ* X-ray radiography possible with synchrotron radiation, a series of experiments performed in 2014 have provided new insight into the kinetics of spall fracture in Mg AZ31 (a heavily-textured aerospace alloy), the densification process in silicon carbide powder beds, and the development of interfacial structures in compressed SLM steel lattices. In addition to dynamic experiments, sample microstructures were characterised prior to loading with X-ray tomography.

With the intention of extracting quantitative information (e.g. density) from the radiographs, future work will continue to compare the high-resolution experimental radiographs with predicted images produced via 3D hydrodynamic simulations initialised from X-ray tomograms and the MCNP6 code.

Finally, a custom imaging system will permit shorter-exposure, higher-resolution imaging, which in combination with new loading platforms (SHPB and a two-stage gas gun) will increase the scope of transient physics accessible at the Diamond Light Source.

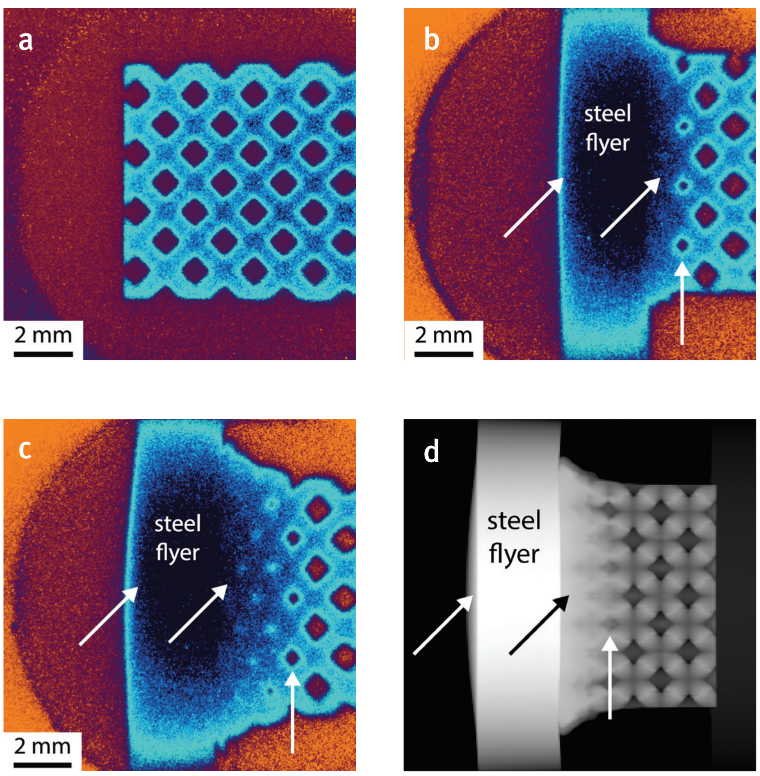


Figure 27: (a) Static, pre-shot radiograph of a SLM steel lattice. (b) and (c) Radiographs captured *in situ* 2.4 μs and 6.1 μs after impact, respectively. White arrows highlight density gradients across the flyer and the development of an interfacial structure at the flyer-lattice interface. Radiographs are shown in false colour to emphasise density contrast. (d) Output of a 3D CTH hydrodynamic simulation 6 μs after impact, shown in terms of areal density.

Cellular biomechanics of blast

- Anabela Areias (PhD student)
- Darryl Overby
- Jane Saffell
- David Sory (PhD student)
- William Proud

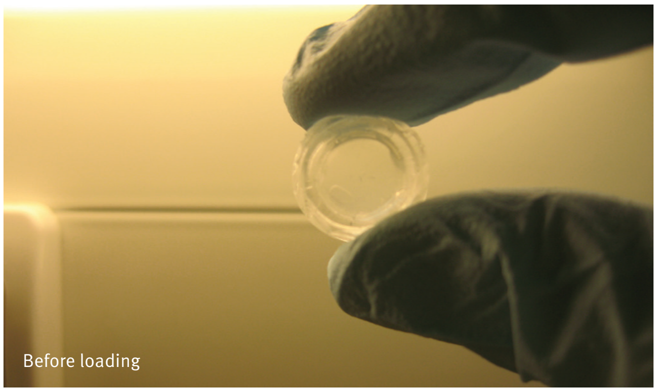
Blast injuries are the most common consequence of modern warfare in military personnel and civilians,[1] affecting the biological functions of the body. Primary blast injuries are a result of the body being exposed to a discontinuous change in pressure produced by the blast wave.[2] Living cells sense and respond to mechanical stimuli associated with the conditions of blast wave by changing their structural and functional attributes. In future work, the aim is to identify these biological changes within living cells by creating a model, which will allow us to mimic part of the real event. The intention is to use a Split Hopkinson Pressure Bar (SHPB) to produce high stress waves combined with Tissue Engineering techniques to produce a natural 3D cell environment. In this way, the current research is being focused on the design and development of a cell-seeded 3D hydrogel and (B) its holder that would interface with the SHPB allowing *in vitro* overpressure experiments with reproducible stress transmission.

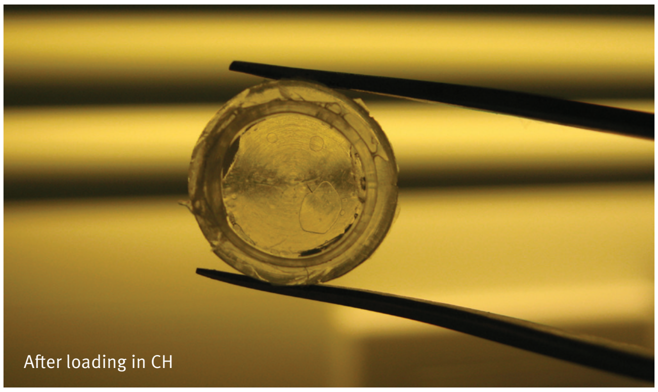
Once the system optimisation is completed, the *in vitro* system will be used to induce cellular injury or immediate cell death. In a first stage, the target is establishing a connection between cell death and mechanical stress levels. Then, the examination of the cellular viability, cytoskeletal architecture, cell adhesions and DNA will be performed in order to understand how these changes within the cell may contribute to later pathology and morbidity in survivors of primary blast injury.

Publications:

1. SD Masouros, KA Brown, J Clasper, WG Proud *et al.*
   Briefing: Blast effects on biological systems
   Proceedings of the Institution of Civil Engineers: Engineering and Computational Mechanics, 166, 113–118, (2013)

2. SJ Wolf, VS Bebarta, CJ Bonnett, PT Pons, SV Cantrill
   Blast injuries
   Lancet, 374 (9687): 405–15 (2009)





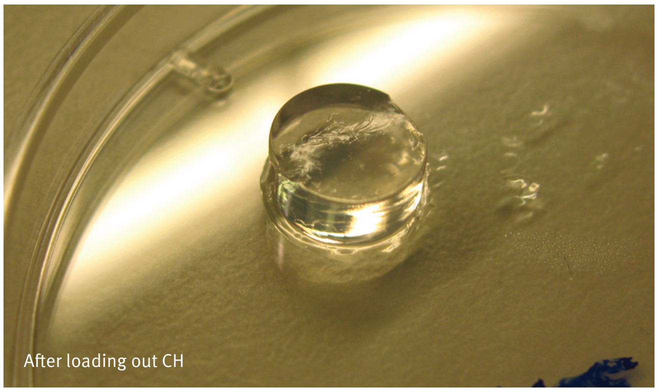


Figure 28: Hydrogel inside its correspondent holder before (A) and after (B) loading. Hydrogel outside its holder after loading (C).

Reflectance thermometry system for determination of spatial temperature variations in dynamic compression experiments

- Jasmina Music (PhD student)
- David Chapman (RA)
- Daniel Eakins

The measurement of temperature represents a long-standing challenge within the field of high-pressure science. Furthermore, in dynamic experiments where expected temperatures are below 1000 K passive diagnostic techniques such as optical pyrometry become infeasible due to the transit states that exist. Reflectance thermometry, an active diagnostic technique that has been recently reported in literature, is a promising time-resolved temperature measurement technique employing embedded optical sensors in the form of thin gold films.

Since it is known that structural imperfections of materials and the onset of dynamic phenomena cause locally non-uniform temperature distributions, in the present project a reflectance thermometry diagnostic will be adapted and its viability tested for the purpose of spatially-resolved temperature measurements.

A critical component of the reflectance thermometry technique is the optical characterisation of the embedded sensors. The reflectance measurement system will be used for reflectance spectroscopy of the gold films as a function of temperature from ambient conditions to 800 K, and as a function of pressure using a diamond anvil cell in collaboration with Simon MacLeod (AWE). The experimental data obtained at ambient pressure will be compared with commercial ellipsometry and initially be fitted to a Drude-Lorentz model for the optical properties of metals paving the way for the calibrated films to be used during future dynamic compression experiments.

Metal speciation in chloride melts

- Ken Watson (PhD student)
- Patricia Hunt
- William Proud

Storage of radioactive material for the past 60 years has led to stockpiles of spent nuclear fuel. Simply storing this material is no longer an option. The spent fuel needs to be separated into its constituent elements which can then be removed or recycled and used to generate power. One method under development is the pyroprocess. Part of the pyroprocess involves dissolving the spent fuel rods in an electrorefiner containing molten chloride salts. Different species form as the metals interact with the solvent ions, leading to changes in the chemistry of the melt. This project aims to use a combination of computational modelling and experimental work to investigate the species formed and to study how these ions interact with the molten solvent. This combination of techniques allows for experimental studies on non-radioactive elements to validate computational models which can then be used to explore the actinide elements. The knowledge gained will be used in the further development of pyroprocesses and for a more effective separation of radioactive elements.

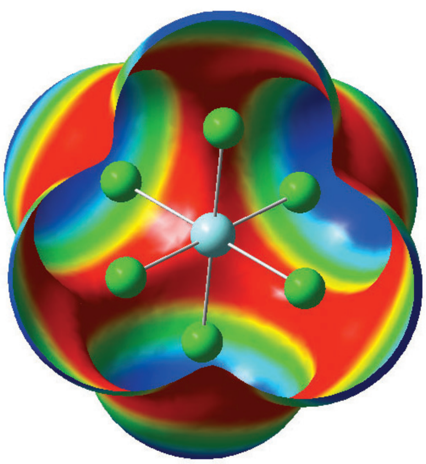


Figure 29: The computed electrostatic potential (ESP) around $[YCl_6]^{3-}$. Areas in blue show a positive potential while the red areas show a negative potential.

Optimisation of the optical imaging system and image analysis for symmetric Taylor Impact experiments

- Stefan Heufelder (MSc student)
- David Chapman (RA)
- William Proud

The Taylor impact test, involving the normal incidence impact of a cylindrical specimen on a rigid anvil was originally devised by G. I. Taylor to estimate dynamic yield strength of solids. Although rarely used for this purpose today, the Taylor impact test is still widely used as a means of validating constitutive material models used in finite element simulations as a result of the complex stress states, and range of strain rates accessed during a single experiment. The modern implementation of a Taylor impact test often involves the rod on rod geometry to reduce frictional effects and issues surrounding non-ideal anvils. In addition, modern time-resolved diagnostics such has high-speed photography or velocity-interferometry are used to monitor the damage evolution during the test for direct comparison with finite element simulations. In particular, deformation profiles captured using high-speed photography have been widely used to validate material models by direct comparison with simulated specimen profiles. However, uncertainties in the experimentally measured deformation profiles arising from imperfections in the imaging system are often not rigorously quantified. To address this shortcoming, an MSc research project which developed a robust method of characterising and correcting imaging imperfections, whilst also determining the optical resolution of a given imaging system was completed. The developed methodology involved the capture of a series of static calibration images, which were subsequently used in an automated MATLAB routine to facilitate the sub-pixel level correction of a dynamic sequence obtained using the Invisible Vision UHSi high speed-framing camera. As a demonstration, a small series of Taylor impact experiments, involving the symmetric impact of 13 mm diameter, 65 mm length copper specimens was performed on the ISP mesoscale gas gun. Figure 30 presents an example image sequence obtained using the UHSi high-speed framing camera, triggered to capture the deformation evolution in the specimen during the impact event. A novel edge detection algorithm was also developed in MATLAB to facilitate the sub-pixel identification of the specimen edge from the silhouette images for accurate specimen profile determination. The resulting specimen profile is overlaid on the dynamic image sequence in figure 30. The developed experimental methodology enabled the accurate determination of both specimen profile and quantification of experimental uncertainty, paving the way for more faithful constitutive model validation using the Taylor Impact technique.

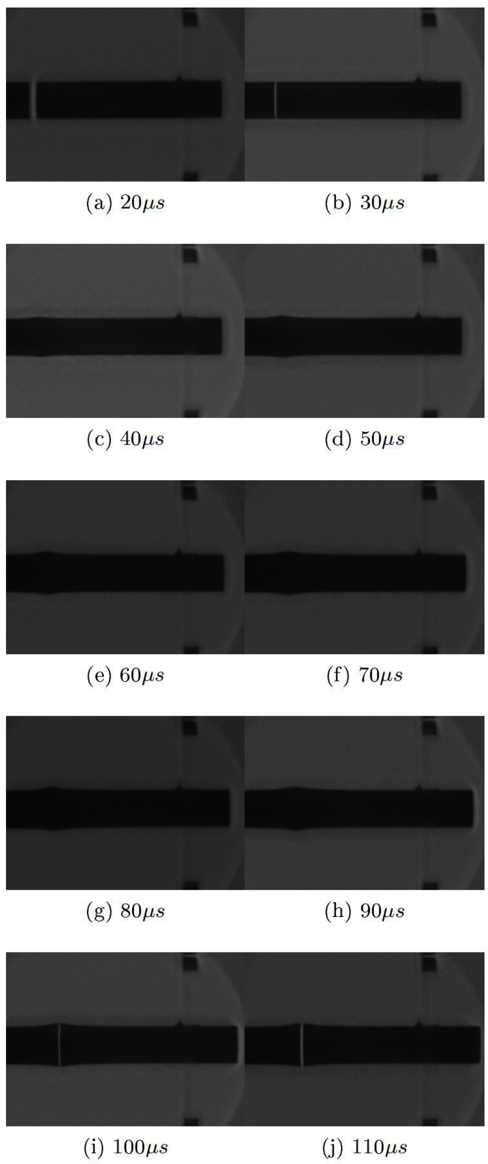


Figure 30: Corrected high-speed image sequence of a symmetric Taylor impact test using copper specimens impacted at 230 m/s. Interframe and exposure times were 10 us and 0.5 us respectively.

University of Edinburgh

Static high-pressure high-temperature (HP-HT) studies of elemental metals

- Malcolm McMahon
- Simon MacLeod (AWE)
- Graham Stinton
- Keith Munro (PhD student)

Last year we focused our attention on studying the phase properties of a number of elemental metals at HP-HT using diamond anvil cells (DACs) and synchrotron X-ray diffraction. In particular, we further refined our HP-HT capability to collect quality diffraction data utilising a stable platform, shown in figure 31.

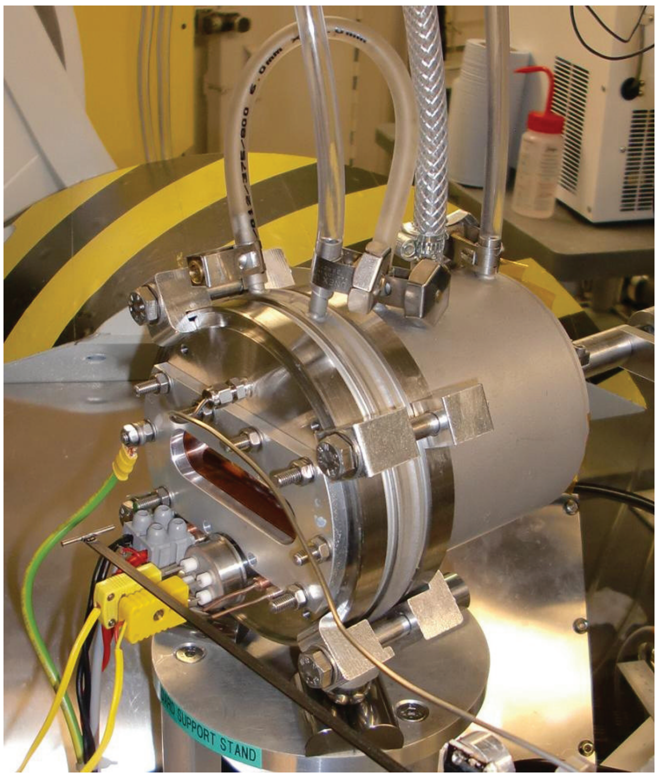


Figure 31: Dedicated DAC vacuum chamber for collecting HP-HT data. Photo taken at beamline I15 at the Diamond Light Source.

MAGNESIUM

We completed our study of the magnesium phase diagram up to a pressure of 211 GPa at 300 K and 105 GPa at 4500 K. Data were collected at the Advanced Photon Source in the US and the Diamond Light Source (DLS) in the UK. For data up to ~ 800 K we used resistive heating together with our vacuum vessels. For temperatures above 1000 K we used laser heating.

CERIUM

We investigated the thermal properties of cerium up to 20 GPa and 800 K at the DLS. Our preliminary results have revealed differences between the observed and predicted solid-solid phase boundaries. This work is currently being prepared for publication.

THALLIUM

Working in collaboration with Professor Daniel Errrandonea (University of Valencia), we are currently engaged in a study of thallium at the Alba synchrotron in Spain. We have collected diffraction patterns up to 8 GPa at 500 K and are the first to compress thallium beyond 100 GPa at 300 K, see figure 32.

Publication

GW Stinton, SG MacLeod, H Cynn, D Errandonea, WJ Evans, J Proctor, Y Meng, MI McMahon
Equation of state and high-pressure/high-temperature phase diagram of magnesium
Phys Rev B, 86, p. 134105 (2014)

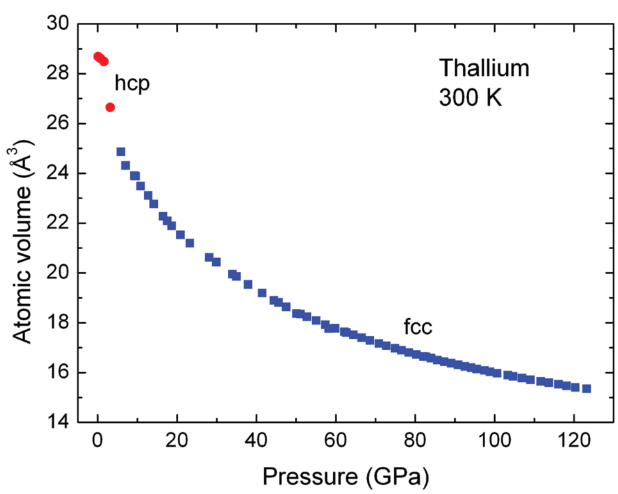


Figure 32: Volume compression of thallium up to 123 GPa.

University of Pardubice, Czech Republic

Institute of Energetic Materials

- Jiří Pachman
- Martin Künzel (PhD student)
- Jakub Šelešovský
- Vojtěch Pelikán
- Robert Matyáš

The Institute of Energetic Materials (IEM) has been part of the Faculty of Chemical Technology at University of Pardubice for over fifty years. Its research and education activities are focused on a variety of multidisciplinary areas including synthesis and characterisation of new energetic materials, computation modelling of explosive effects, detonation physics, forensics, technology of explosive processing and blasting, safety engineering and loss prevention.

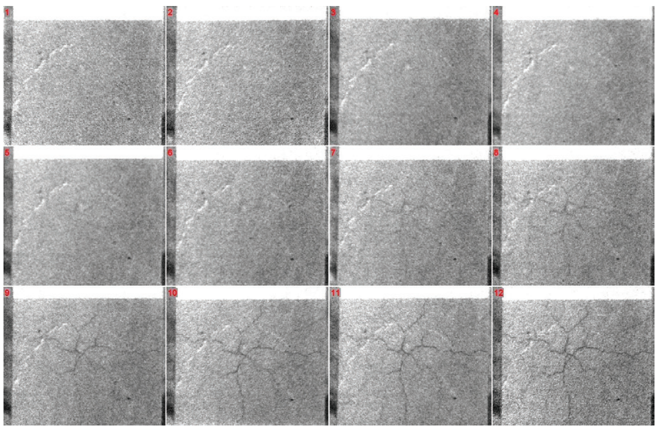
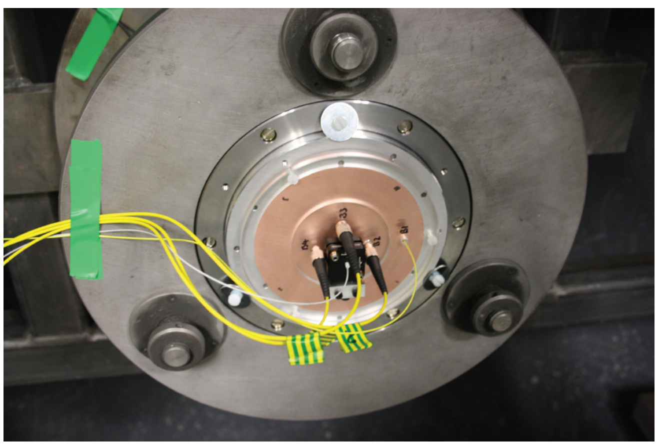


Figure 33: A sequence of high speed photographs showing crack formation on the rear side of an explosively loaded concrete slab. Cracks are first visible in frames 6 or 7, corresponding to approximately 270 – 310 microseconds after detonation. The large scale explosive tests were complemented by a series of smaller scale explosive tests at IEM and plate-impact experiments in collaboration with ISP characterising the shock response of the concrete.



The IEM, located in the university's Technological Pavilion outside of the main campus, runs the only non-military academic test site for explosives in the Czech Republic. Along with the capability for live testing in the open air it further possesses state of the art detonation chambers for testing in enclosed environments. A large variety of detonation parameters of synthesised samples may therefore be easily tested right on the campus site.

The IEM and ISP collaborate actively in a variety of ways including:

- research on concrete under shock and blast loading
- active collaboration on the NTREM seminar series
- participation of ISP students on the IEM short course on explosives

IMPACT AND BLAST LOADING OF CONCRETE

The behaviour of concrete under explosive generated shock loading represents a complex problem. Past research on concrete indicates that the behaviour of this material under low strain rates, where it is usually tested, is markedly different from its behaviour under the extreme strain rates induced by high explosive detonation. A serious interdisciplinary gap needs to be bridged in order to fully understand the options civil engineers have at their disposal to implement blast resistant designs in non-military structures. To achieve this, cooperation of explosive engineers, civil engineers, shock physicists and modellers is vital.

Pardubice's collaborative project with the ISP aims to gain insight into material behaviour of four different types of concrete including standard C-30/37 construction concrete, metal and plastic fiber concrete and ultrahigh performance concrete. Small, medium and full-scale detonation experiments were carried out on new and artificially aged specimens ranging in size from 10 cm cubes to 6 m slabs. The explosive loading was achieved by either directly placing the explosive charge in contact with the concrete surface or by the blast wave from a near field detonation. To complement the explosive loading trials a series of reverse ballistic plate-impact experiments were undertaken on the ISP large bore gas gun to characterise both the Hugoniot and ro release the isentrope of the concrete materials. The large 100 mm bore of the ISP gas gun is ideally suited to the study of heterogeneous materials, such as full-scale concrete, and promises to improve our overall understanding of this rather challenging problem.

Figure 34: The reverse ballistic copper target installed within the large bore gas gun. An array of Het-V probes were used to monitor the rear-surface velocity of the copper target impacted by the concrete flyer.

Cranfield University

The Dynamic Response Group

- Dr Gareth Appleby-Thomas
- Dr David Wood
- Andrew Roberts
- Dr Malcolm Burns (Visiting Researcher)
- Michael Goff (ISP PhD student)
- Brianna Fitzmaurice (PhD student)
- Col. Muhammad Akram (PhD student)

A founding spoke partner of the ISP, Cranfield University – via the Dynamic Response Group – takes an active role in shock-based research. The Dynamic Response Group itself has published over 30 peer-reviewed journal articles since the inauguration of the ISP. It is based within the Centre for Defence Engineering at Cranfield University's Shrivenham campus and consequently has direct access to expertise in the armour and munitions, vehicle mobility and gun barrel design spheres.

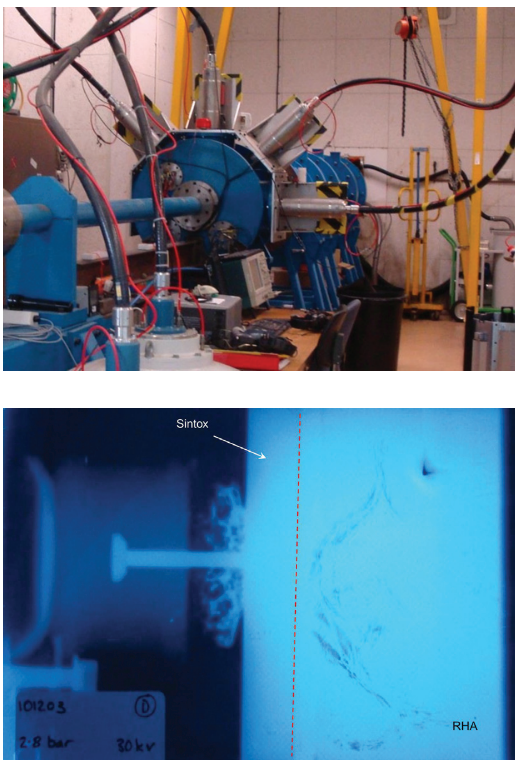


Figure 35: Investigation of dwell: (above) flash X-ray system *in situ*; (below) flash X-ray showing surface defeat of a WNi-Fe long-rod penetrator at a SintoxTM tile surface

The group has supported other members of the ISP and numerous collaborations have ensued between Imperial, University College London and AWE amongst others. Areas explored have ranged from the survivability of seeds and bacteria under shock through the spall response of HCP materials to the development of a ceramic graded areal density impact system. More recently, the group has also moved into provision of specialised courses – with courses entitled 'Armour System Design' and 'Shockwaves and Explosives' covering three to five days available.

Experimental facilities include five single stage gas guns (with bores of up to 75 mm) and one two-stage system (with an output bore of 7.62 mm); in addition, uniquely in the EU, our location and capabilities allow us to carry out experiments on explosive materials ranging from derivation of equations-of-state through run-to-detonation investigations (POP plots) and safety testing. Finally, our diagnostic capabilities are extensive, with either in-house or on-site expertise in the use of stress/strain gauges, Het-v, flash X-ray and particle-velocity (PV) gauge systems.

The group takes an active role in the support of MSc projects; a typical recent project has involved the use of the flash X-ray system, refurbished over the past year (and previously deployed in collaborative aid of ISP-centred research conducted by David Jones from Imperial) coupled with the explosives capable 50 mm bore (explosives capable) single stage gas gun. This arrangement, shown left, allowed dynamic investigation of the phenomena of dwell (surface defeat) with the aim, via careful engineering of interfaces/free surfaces of optimising ceramic armour performance under scaled long-rod penetrator attack.

Publications

GJ Appleby-Thomas, DC Wood, A Hammed, JA Leighs
On the ballistic response of an aerospace-grade composite panel to non-spheroidised fragment simulants
Compos. Struct., 119, 90–98 (2015)

GJ Appleby-Thomas, PJ Hazell, RP Sheldon, C Stennett, A Hameed, JM Wilgeroth
The high strain-rate behaviour of selected tissue analogues
J. Mech. Behav. of Biomed. Mater. 33(1), 124–135, (2014)

PJ Hazell, GJ Appleby-Thomas, E Wielewski, JP Escobedo
The shock and spall response of three industrially important HCP metals: Magnesium, Titanium and Zirconium
Phil. Trans. Of the Royal Soc. A: Mathematical, Physical & Engng. Sciences, 372(2023), 20130204, (2014)

PJ Hazell, GJ Appleby-Thomas, S Toone
Ballistic compaction of a confined ceramic powder by a non-deforming projectile: Experiments and simulations
Mater. & Des., 56, 943–952, (2014)

Centre for Blast Injury Studies

Force blast protection

- William Proud
- Kate Brown (Austin, Texas and Cambridge)
- David Sory (PhD student)
- Thuy-Tien Nguyen (PhD student)
- Andrew Jardine (Cambridge)

The Royal British Legion Centre for Blast Injury Studies (CBIS) at Imperial College London is the result of a £5 million five-year award by the Royal British Legion to promote innovative inter-disciplinary research into blast injury causation, treatment, mitigation and prevention. The Centre is a collaboration between military and civilian clinicians, scientists and engineers.

Figure 36: New underbelly blast simulation laboratory opened in 2014

Blast Force Protection, led by Dr William Proud of the ISP, is one of three research themes within the Centre. It builds on work undertaken by Dr Jens Balzer and ISP PhD graduate Dr Chiara Bo and deals with the interaction of the blast wave with the materials and structures around the human body. Much of the work is aimed at ensuring that the stress pulses applied to biological materials are representative of those experienced in the real world environment. In order to achieve this, the team will develop sensors, study the interface between materials, develop physically based models for materials used in protection and measure the load produced by the blast. This theme is being taken forward in collaboration with Dr Andrew Jardine and Dr Kate Brown.

INJURY SIMULATION LABORATORY

CBIS continued its expansion at South Kensington in 2014 with the addition of a specialised facility for underbelly blast simulation in the Department of Bioengineering. The £1.1 million laboratory, fully funded and built by Imperial College, houses AnUBIS - the Anti-Vehicle Underbelly Injury Simulator. AnUBIS is a traumatic injury simulator that replicates the response of a vehicle floor pan that has been hit with an explosive blast. Different occupant postures (seated, standing, brace, neutral and hyper extended) can be tested, highlighting the diversity in the resultant injury severities. The intention is to build upon this facility throughout 2015, allowing tests to be conducted at higher energy levels and with larger experimental specimens.

TRAINING

Industry, agencies and government increasingly require access to expert knowledge and innovative well-educated recruits in many and varied research fields. The ISP provides education across a wide spectrum of activities and target groups. A non-exhaustive list includes:

1 HOUR

Research talks

Institute staff and students give numerous talks, seminars and lectures aimed at researchers, funders and the public. These provide a good route for reporting, networking and raising awareness. For example, ISP Director Dr Bill Proud gave several invited talks in 2014 including at ICILLS 2014 (Cape Town, South Africa), and the Conference on Granular Materials (Changsha, China), and PhD student David Jones presented at the TMS Pan American Materials Conference 2014 (Sao Paolo, Brazil).

1 DAY

Continuous professional development

ISP staff deliver short consultancy projects, problem solving and short refresher-update sessions for research organisations in the public and private sectors. This enables research challenges to be resolved by consulting with experts either through focussed discussion or general overviews of a research field.

2 DAYS

Annual conference

The annual PETER (Pressure Energy Temperature and Extreme Rates) conference is aimed at ISP members and colleagues in related research areas. It provides an excellent opportunity to discuss research, report on what has been achieved and find inspiration from fellow scientists and engineers. The conference is organised by the Shock Waves and Extreme Conditions (SWEC) group of the Institute of Physics (IOP).

10 WEEKS

Undergraduate course ‘Shock Waves and Hydrodynamics’

Many university degrees allow for a degree of selection and specialisation in the latter years of the curriculum. Imperial’s Department of Physics is no exception. With the founding of the ISP, the fourth year option ‘Shock Waves and Hydrodynamics’ was entered onto the list of options. Jerry Chittenden who leads the option has found that it has great resonance amongst the undergraduates, with up to 40% of the students opting for this course. This has made it the most popular undergraduate option for all the years it has run.

3 MONTHS

BSc/short projects

Aimed at established researchers and undergraduates. The undergraduate Physics degree course leading to BSc includes a three month-long project. In the ISP these projects have included shear band formation in metals and the flow of granular materials. There is also a steady flow of visitors from academic and research institutions who spend a few months in the summer at the ISP, this provides opportunities for close networking and also for exposure to new ideas and research cultures.

6 MONTHS

MSci projects

Aimed at undergraduates and postgraduates. To obtain the award of an MSci, students need to undertake a long research project. The ISP hosts several of these every year. In 2014 Andrew Moore undertook a project investigating the response of polymers and metal foams over a range of strain rates, relevant to the mechanical response of shoes and boots under blast loading. This project was in collaboration with the Department of Aeronautics and feeds into the joint efforts of ISP and CBIS to understand the effect of dynamic load on biological tissues.

1 YEAR

MSc projects

Aimed at active researchers and postgraduate students. The ISP has established a one-year MSc course in Physics with Shock Physics (with a two-year part-time option), which gives recent graduates essential background knowledge and exposes them to current research through projects and seminars given by acknowledged experts in this field. The course is in-line with the Bologna Accord and quality is assured through internationally accepted monitoring. In addition it is not unusual for some research students to spend significant time at other research centres. In 2014, the MSc students attended the Technical University of Pardubice for blast range training.

Sustainable growth: The ISP team at the start of 2015 after a successful year of attracting new talent through our EPSRC research projects.

Short courses

The ISP delivers short courses aimed at recent recruits as well as established researchers to provide background knowledge and/or latest research findings or techniques. A short course on a general topic can provide a time-efficient opportunity to cover both these aspects through lectures by experts in the field. On average the ISP organises two of these sessions per year around topics of wide interest (e.g. energetic materials, modelling, diagnostic techniques). More specialised sessions can also be arranged.

3 DAYS

Nuffield projects

Aimed at 16–18 year olds. The Nuffield Foundation along with other Charities provides the funding for bursaries for the ‘brightest and best’ to spend part of their summer holidays in a university working on small research projects. The aim is to allow them to experience, and be enthused by real research. In the UK, physics is now amongst the top 10 most popular subjects studied at A-level; the ISP is pleased to be able to play its part in the careers of these students by hosting Nuffield projects.

6 WEEKS

Undergraduate Research Opportunity Programme (UROP) projects

Imperial operates a scheme where undergraduates can work with a research group during the summer break and obtain experience of research. This year we welcomed two students working on ISP and CBIS related projects.

8 WEEKS

ERASMUS Programmes

The ISP is a part of several Erasmus agreements with partner universities within the EU supporting undergraduate student exchange programmes, typically around four months in duration. The projects contribute to their degree awarded from the home institution. We hosted seven ERASMUS students throughout 2014.

4 MONTHS

2 YEARS

Postdoctoral contracts

For active researchers. Having staff with research experience is fundamental for both their own development and that of their group. In many ways they provide the back-bone of the research effort, often bringing knowledge from other fields.

3 YEARS

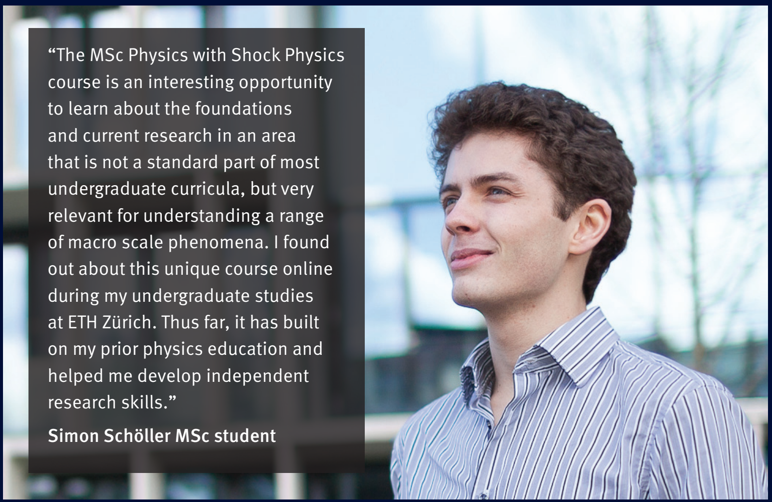
PhD studies

For graduate researchers. A doctoral degree provides the standard entry-level qualification to research. The ISP has hosted 28 PhD students so far, including one funded by EPSRC and two funded by The Royal British Legion.

6 YEARS

Part-time PhD studies

A further option is to embark on an Industry sponsored part time PhD option with the ISP. Historically these graduate research students spend the majority of their time at their Institution coming into college for meetings with their supervisor and some other group events and short courses. Dr Ruth Tunnell from QinetiQ is one example of a successful graduate who has completed in record time.



“The MSc Physics with Shock Physics course is an interesting opportunity to learn about the foundations and current research in an area that is not a standard part of most undergraduate curricula, but very relevant for understanding a range of macro scale phenomena. I found out about this unique course online during my undergraduate studies at ETH Zürich. Thus far, it has built on my prior physics education and helped me develop independent research skills.”

Simon Schöller MSc student

Imperial College London

Technical support is provided to ISP research by:

- Steve Johnson
- Dave Pitman
- Alan Finch
- Physics instrumentation workshop

The strength of the Institute of Shock Physics at Imperial College London resides in its multi-scale loading platforms and broad diagnostic suite. The application of these cutting edge diagnostics to well-established and evolving loading methods enables the determination of material properties with an unprecedented confidence, with the ability to probe short duration meso scale phenomena occurring on the nano-second timescale to the longer duration events occurring at the continuum level. These specialist facilities complement a range of standard testing platforms, and materials characterisation available to the Institute throughout Imperial enabling a holistic interrogation of material response.

Large bore gas gun

The large bore gas gun at Imperial offers the largest impact area (100 mm in diameter) and highest impact velocity (in excess of 1400 m/s) of any single stage gas gun within the UK. This unique facility can generate pressure and temperatures of up 70 GPa and nearly a thousand degrees upon impact.

Commissioned in early 2011, the ISP gas launcher is now a mature world class facility, unparalleled within the UK diagnostic capacity. The 2 m diameter experiment tank permits both bulky targets and complex diagnostic systems (e.g. heating/cooling stages, free-space optical elements), allowing a combination of elaborate experiments and precise measurements. The launcher, which can accelerate heavy (4 kg) projectiles to velocities in excess of 800 ms^{-1}, is also fitted with an extended soft-capture tube to recover targets following impact for post-shock materials characterisation.

One of the primary advantages of the large bore format is the ability to simultaneously test multiple samples in a single impact experiment. By ensuring the same loading into the target package, any differences in measured response are due exclusively to sample variations. This provides a key capability to directly compare material behaviour, and can help correlate testing performed between different platforms. Equally, a number of different materials can be shock loaded simultaneously enabling a more cost effective characterisation of the shock response of multiple materials.

A comprehensive proven diagnostic suite is available on the facility, including; a 10 channel multi-generation Het-V system (optical velocimetry), time of arrival sensors, pressure transducers, high speed imaging including; video (100k fps), framing (200 Mfps), and streak cameras. Additionally, an adjacent dedicated diagnostics table allows setup of more complex diagnostics; a line-imaging VISAR has been constructed to spatially resolve the non-uniform motion of heterogeneous surface. Future developments will include time-resolved spectroscopy and pyrometry techniques.

Although designed with the objective of performing plate-impact experiments investigating the EOS and dynamic strength of materials, the large bore launcher has also been used to investigate dynamic phenomena that are typically studied using different loading platforms. We have recently demonstrated a technique to investigate the expansion and fragmentation of cylinders, which enables studies of materials under uniform radial expansion at strain rates in the range of 10^3 to 10^5 s^{-1}. Importantly, unlike other similar gas gun driven expanding cylinder techniques, or more traditional exploding cylinder geometries, this technique enabled us to probe the role that initial sample temperature plays in the resulting failure and fragmentation.

Meso scale gas launchers

A number of small-scale impact launchers have been developed and are in regular use at the ISP, ranging in bore, from 13 mm–30 mm, and performance, from a few 10's ms^{-1} to ‹900 ms^{-1}. These facilities designed with flexibility and portability in mind are suitable for small-scale ballistics studies, materials characterisation such as Taylor impact tests or even plate-impact studies, can be used for diagnostic development, and are also readily accessible training tools for undergraduate and postgraduate students. Additionally, these meso scale facilities bridge the spatial, temporal, and pressure scales between the main experimental platforms of the laser-shock driver, MACH and the large bore gas launcher.

In 2014 the design development and commissioning of a compact two-stage light-gas gun extending the range of experimental loading platforms available to the ISP began, with operation due to start in the second quarter of 2015. Interior ballistics simulations based in a gas-dynamic model of the gun indicate velocities as high as 4 km/s can be reached using a design that combines compactness (full length under 4 m long) with a bore size and payload weight (10 mm diameter, 1 g projectiles) suitable for plate impact studies. Pressure and temperature conditions are also predicted to allow a cost-effective lifetime of critical components. Key design concepts further included an impressive turn-around time allowing up to three shots per day, inert gas based operation (with compressed Helium) for both first and second stages and, most of all, portability features which allow exploiting high brilliance beams at large-scale facilities for X-Ray and spectroscopic studies under dynamical loading conditions.

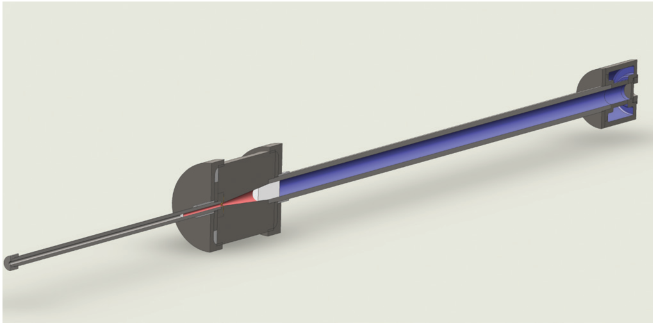


Figure 37: Schematic view of the compact two-stage light-gas gun design. Like the 13 mm single stage small bore launcher existing at the ISP, this gun was designed with portability, a fast turn-around and cost-effective operation in mind.

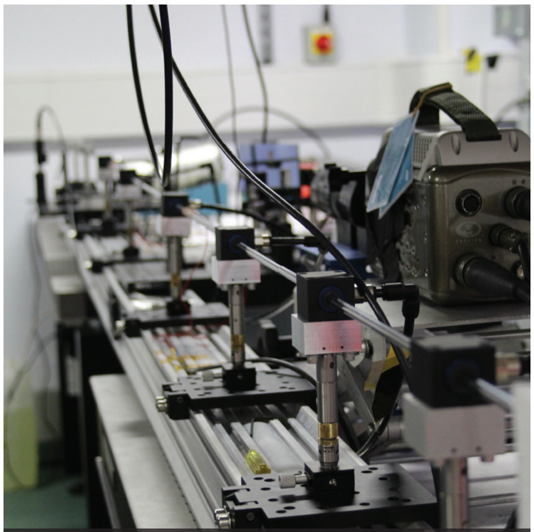


Figure 38: SHPB with 6 mm diameter bars. The bars are supported on air bearings to reduce friction. Shown in the top-right corner of the image is the Phantom 7.3 high speed camera used for digital image correlation.

Split Hopkinson Pressure Bars

We have recently completed the construction and commissioning of a new air-bearing based Split Hopkinson Pressure Bar (SHPB) as part of the HexMat EPSRC programme grant. Designed with 6 mm diameter maraging steel bars and having a 50 cm long striker it is capable of supplying a 140 µs loading pulse to millimetre sized metallic samples, see figure 38.

Designed specifically for precision measurements of low strain rate (10^2 to 10^4 s^{-1}) deformation behaviour in titanium alloys (IMI834, Ti6242, Ti6246), the long loading pulse ensures a high global strain is reached. Due to their excellent strength and lightweight properties these alloys are common throughout the aerospace industry where they have uses in blades, rings, and discs as well as in airframes and structural components.

This particular set-up allows the direct investigation into the formation of adiabatic shear bands, a widely encountered phenomenon in metals subjected to high strain rate loading and often resulting in catastrophic failure from brittle-like fracture. Adiabatic shear bands often occur during foreign-object impact, where a hard object impacts the rotating fan blades at high speed. The velocity of impact prevents thermal conduction leading to an increase in temperature. At a macroscopic level shear bands arise from local softening caused by increased temperatures in the region of plastic flow.

With the ability to test millimetre sized samples with high strength we are able to study the shear behaviour within single grains of Ti-64. By creating top-hat samples where a single grain is localised in the region of high shear the effects of heterogeneity and differing crystallographic orientations can be tested. See figure 39.

Design and construction of the new bar was completed between March and June in collaboration with ERASMUS students, Quentin de Menech and Alexandre Wirtzler from the National Engineering School of Metz (ENIM). The success of the project has led to future students from ENIM joining the ISP. The relatively compact size of the apparatus also allows transportation to large external facilities such as synchrotrons where X-ray imaging of the internal structure of the targets can be performed.

This new facility complements our previously established SHPB apparatus used by both the ISP and the CBIS. Projectile velocity is measured using a photodiode array whilst wave profiles within the (Titanium or Inconel) bars are monitored using type AFP 500-90 semiconductor gauges which are manufactured by Kulite Semiconductor Products INC. The complimentary rail and precision rail-slider design offers flexibility to the system and for bars of differing length and material composition to be interchanged with ease.

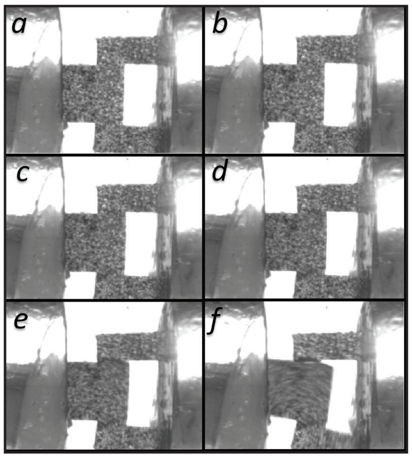


Figure 39: Top-hat sample of IMI 834 hit with a striker bar velocity of 4.8 m/s creating an average strain rate of 1.2×10^3/s and a maximum shear strain of 0.3. The speckle pattern applied to the target allows for both 2D and 3D digital image correlation.

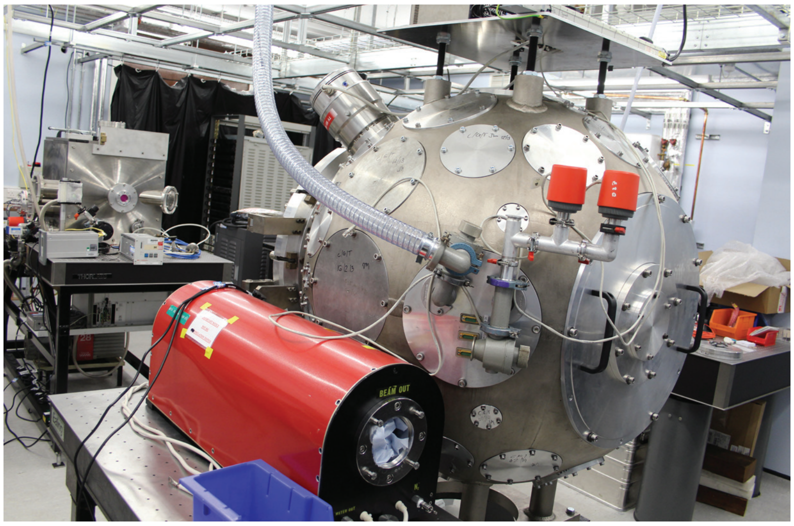


Figure 40: The long-pulse laser target area.

Long-pulse Laser Shock Driver

A long pulsed laser shock facility has been completed and is being commissioned in experiments.The former CLF TA-East chamber has been fitted with new electrics and vacuum installations, including a multi-axis target alignment system. Measurements of beam stability and pointing are in progress and beam energies ~10J have been achieved, with future upgrades planned; this will gradually be increased to a 50 Joule, 1.4 ns long-pulse focused to a uniform 1 mm^2 area, with future upgrades expected to achieve 500 J in a 4 ns shaped pulse. The system is being designed to rapidly compress very thin targets, on the order of tens of micrometres in thickness, at strain rates between 10^8-10^{10} s^{-1}, with routine diagnosis of shocked state using line VISAR.

In addition to the main drive, part of the Cerberus laser, built in collaboration with the Plasma and Quantum Optics Laser Science research groups within Imperial, a macro-pulse laser 3-15 J with a pulse shaping capability has been installed within the laboratory. This offers greater flexibility in terms of pump probe capability, and provides an alternative drive for low pressure experiments.

MACH Pulsed Power Platform

MACH is a 2MA, ~400ns risetime pulsed power facility that is being used to explore isentropic compression techniques at the ISP. Utilising new pulsed power technology, the system is designed to be compact and fast to turn around whilst requiring no noxious gases or oil to provide insulation.

Throughout Autumn and Winter 2014 commissioning experiments were performed on the MACH facility. The experiments included several new target designs to help ensure uniformity of loading and improve ease of probing; along with the use of insulating layers between the targets to prevent any break downs.

Working with Guiji Wang – an academic visitor from the Institute of Fluid Physics, China– the use of cheap mass produced targets was explored, along with 3D printed diagnostic holders. 'Core' diagnostics of 4 channels of 3rd generation Het-V were established, and mounted permanently within the laboratory. The current monitors on each bank of MACHs capacitors were also improved and calibrated, whilst connections to the capacitors and charging resistors were strengthened.

In other experiments, the use of 'long range' Het-V has been examined. Here multiple Het-V probes, each mounted in its own kinematic, are telescoped and the image relayed to target. The use of the telescope enables very close spacing of the Het-V channels (~mm separation on target) whilst maintaining ease of use and good signal recovery. The system also gives good stand-off between the probes and target – it is hoped that in future experiments only a sacrificial mirror will be destroyed by the targets, rather than multiple expensive probes.

A remote firing system based on Labview has now been established in the extreme physics laboratory, enabling all aspects of safety and charging of the MACH generator to be completed from the control and data area in the upper part of the lab. Over spring 2015 a new, advanced laser safety system will be trialled as two channels of line VISAR are added to the core diagnostics for use in further experiments.

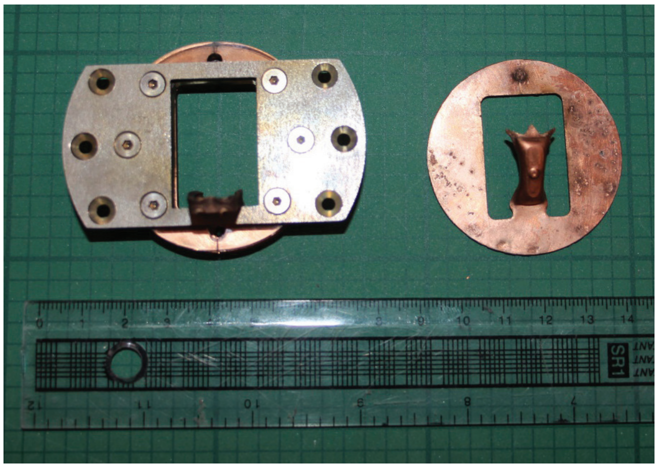


Figure 41: MACH stripline support structure (left) and target plates (right) after shot. The target plate also shows the impact point from striking the Het-V probe.

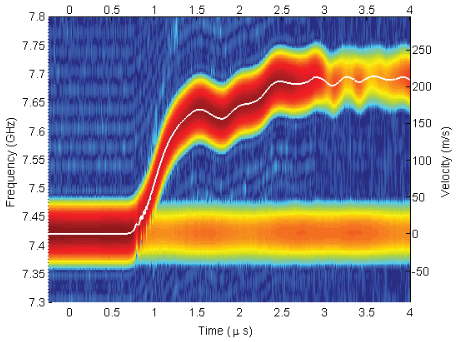
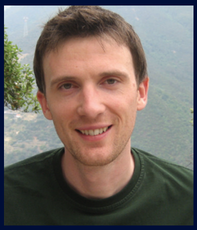


Figure 42: Velocity of mm thick copper target in MACH stripline (baseline of 5750ms^{-1}) due to 3rd generation Het-V.

ISP Associate Academic Members

To address the wider scope of material behaviour, strength and damage, in 2014 the ISP reached across faculty boundaries to key academics in Earth Sciences, Aeronautics, Mechanical Engineering, Materials Science, and Bioengineering. These academics bring both specific and complementary experimental and computational expertise to the ISP, which will benefit the overall scope of research and postgraduate teaching.



Dr Gareth Collins

READER IN PLANETARY SCIENCE, DEPARTMENT OF EARTH SCIENCE AND ENGINEERING

Impact is a fundamental solar system process: it builds planets from dust, it shapes planetary surfaces, it causes mass extinction and it threatens the survival of humankind. Gareth's research explores the many consequences of impacts in the solar system through the development and application of numerical impact models. His interests include all aspects of impact cratering and other related violent geologic processes. Gareth develops and uses numerical models to study impact processes, their consequences on Earth and in our Solar System, and related large, rapid, violent geologic processes such as large rock avalanches.

Professor John Dear

PROFESSOR OF MECHANICAL ENGINEERING, DEPARTMENT OF MECHANICAL ENGINEERING

Professor John Dear has been an academic for 26 years in the Mechanics of Materials Division of the Department of Mechanical Engineering. John has been successful in obtaining research grants worth a total of over £7 million from the UK and US government (EPSRC, ONR, MRC and DTI/TSB), European Commission, UK and overseas companies. His research expertise is structural integrity of materials including manufacturing and micro-structural effects. He has published over 200 papers; contributed to 10 books, supervised 42 PhDs and 12 RAs. Examples include: *creep life of materials in power-station plant, aerospace and automotive components, water distribution plant and high-strain rate properties of composite* and a wide range of other materials for defence applications and also for medical research.

Dr David Dye

READER IN METALLURGY, DEPARTMENT OF MATERIALS

David came to Imperial from Cambridge via the National Research Council in Chalk River, Canada. His research focuses on micromechanics and microstructural design, mostly in aero-engine materials (Ti, Ni), but also in Zr in nuclear applications, on shape memory alloys and steels. His group works on problems across the life-cycle from alloy design to processing to fatigue and failure. Much of the work involves advanced TEM techniques, complementing work at neutron and synchrotron major facilities such as ISIS, Diamond, ESRF and SNS. He has also begun to perform ps-duration X-ray experiments at LCLS within the field of shock physics.

Professor Lorenzo Iannucci

PROFESSOR OF ADVANCED STRUCTURAL DESIGN, DEPARTMENT OF AERONAUTICS

Professor Lorenzo Iannucci joined the Department of Aeronautics at Imperial in 1998 and currently holds the RAEng/DSTL chair on multi-scale composite design. Lorenzo's research interests lie in material and modelling techniques relevant to dynamic analyses, low to high velocity impact testing and modelling using LS-DYNA, ABAQUS and DYNA3D, genetic algorithms for impact optimisations, and design of UAV and morphing structures. Lorenzo has introduced the DYNA suite of codes as a tool which can be used on a range of highly non-linear design problems. He has implemented several new composite material models into the codes, which have been used on a range of projects, both in industry and within the department. He is currently involved in research funded by the CEC, EPRSC, DSTL and the TSB.

Dr Spyros Masouros

LECTURER IN TRAUMA BIOMECHANICS, CBIS

Spyros is the Biomechanics Theme Lead for The Royal British Legion Centre for Blast Injuries Studies at Imperial College London. He received his first degree in Mechanical Engineering in 2004 from the National Technical University of Athens, Greece, and his PhD in Biomechanics in 2008 from Imperial. Since then Spyros has worked in and supervised projects related to finite element (FE) modelling of human joints, material characterisation of soft tissues of joints, physical models of lower limb injury and their mitigation, design of orthopaedic devices, and engineering education. Between 2010–12 Spyros was the ABF The Soldiers' Charity Research Fellow, acting as the engineering lead within a multidisciplinary group comprising clinicians, scientists and engineers, looking primarily at lower limb injury mechanics and injury mitigation technologies. This motif has carried over since the Fellowship, only now in addition to the lower extremity his research interest is also on injury to the pelvis and the spine.

Industrial engagement

Working with corporate partners has always been part of the Imperial way of working. The 1907 Charter states that the objectives of the university shall be

> "to provide the highest specialised instruction and most advanced training, education, research and scholarship in science, technology and medicine, especially in their application to industry"

and that philosophy is very much at the heart of the strategy for the ISP. As an AWE-sponsored institute, the ISP is a very good example of how a corporate partnership with the College works in practice. Building on this relationship, we are pursuing our aim to become the UK Centre for Shock Physics by establishing links, and developing programmes with other industrial groups as well as partners in universities and other research laboratories.

In the 2014 annual report we highlight the successful partnerships and research seen via three of our translation-focussed PhD studentships funded by industry and government.

ANSYS

ANSYS develops, markets and supports engineering simulation software used to foresee how product designs will behave and how manufacturing processes will operate in real-world environments.

Improving fibre reinforced plastic material models for explicit dynamics numerical simulation

» **Jonathan Glanville (PhD student)**
» **William Proud**

Fibre reinforced plastics (FRP) are becoming an ever more common engineering material used for their high specific strength and stiffness. Material models are required by industry to use in commercially available finite element (FE) analysis software such as ANSYS Autodyn. Typical uses for modelling composite structures in explicit codes are the crash analysis of vehicle components or to assess the effectiveness of personal body armour to ballistic threat.

Improving the predictive nature of material models reduces the cost of analysis as the sometimes expensive, and time consuming calibration of FE models becomes surplus to requirements. This current work aims to improve the understanding of the dynamic behaviour of fibre reinforced plastics predominately through the use of meso–scale modelling; the impetus being to improve the predictive nature of material models. Accurate meso scale modelling requires good representation of the three main elements of an FRP: the fibre, the matrix and the interface.

The current study will restrict itself to the use of polymer fibres. These fibres are anisotropic and some exhibit strain rate dependency. Material models to represent this predictively will be required.

The matrix material could be either elastomer/rubberlike materials or stiffer epoxy materials. A host of available spring-damper material models exist in the open literature for both of these type of materials, but few relate the model parameters to defined measureable items or theories.

The third element is in understanding the fibre-matrix interface and developing numerical models to represent this. The 'breaking' of the interface will relate to the onset of a failure type in the bulk material, and then the subsequent friction contributes to the progression of damage in the bulk material. This is the area where the main focus of the study lies.

Defence Ordnance Safety Group

Defence Ordnance Safety Group (DOSG) is the MoD's focal point for Ordnance, Munitions and Explosives Safety. DOSG provides policy, advice and regulatory functions on behalf of the Secretary of State and monitors departmental performance to provide assurance to the Secretary of State through the Defence Ordnance Safety Board.

Effects of high explosive fireball on fragment flight

» **Craig Hoing (PhD student)**
» **William Proud**

Current methods for estimating the initial velocity of fragments from munitons has involved the use of data from range trials to development of free air retardation curves. This method uses measurements a significant distance from the munition which are then extrapolated back to the time and position of the weapon casing fracture. While this may give acceptable results for the modelling of long range fragment – target interactions, the neglect of any fireball-fragment interaction on the early time acceleration of the fragments could cause dramatic differences between such models and reality for targets close to the munition. This has obvious implications on the safety and stewardship of these munitions.

An extensive literature review found a variety of theoretical gas leakage models[1,2,3] used in fragment velocity predictions; however the lack of supporting experimental data was also highlighted. The limited experimental base[4,5] shows a real effect of the expanding gaseous detonation products on the velocity of the fragments generated, however, the fidelity of the available data is too coarse to allow accurate acceleration time histories to be constructed.

This doctoral research programme will concentrate on capturing high fidelity experimental data tracking the motion of explosively driven fragments within the optically dense expanding detonation product cloud using a combination of existing and novel diagnostic techniques. These experimental results will be linked to numerical modelling. This will elucidate more details of the flow mechanisms and their effects on the early time fragment motion. The results of this investigation will be incorporated into numerical predictions of fragmentation effects for use within Ministry of Defence programmes.

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Lawrence Livermore National Laboratory

Lawrence Livermore National Laboratory (LLNL) is one of three government owned national laboratories in the USA. LLNL's mission is to strengthen the USA's security through development and application of world-class science and technology to enhance the nation's defence, reduce the global threat from terrorism and weapons of mass destruction, and respond with vision, quality, integrity and technical excellence to scientific issues of national importance.

Dynamic strength as a function of temperature and microstructure

» **Laura Chen (PhD student)**
» **Daniel Eakins**
» **Joel Bernier (LLNL)**
» **Mukul Kumar (LLNL)**

A system for cooling and heating targets for laser-driven shock experiments was developed by the Institute of Shock Physics in collaboration with (LLNL) to study the temperature dependence of the dynamic strength characteristics of different microstructures.Understanding the relationship of these parameters can be applied to numerical codes in modelling empirically infeasible phenomena such as asteroid impacts. Initial experiments explored a range of metals including iron, invar ($Fe_{64}Ni_{36}$), other various iron-nickel alloys, aluminum, tantalum, and titanium to provide a foundational understanding and upcoming experiments will focus on the work pertaining to the iron-based metals to study chondritic meteorites, which are largely composed of iron.Previous experiments were performed at the Trident Laser Facility at Los Alamos National Laboratory while the next experimental run will be at the Jupiter Laser Facility at LLNL.

Studies on fcc metals aluminum and invar revealed interesting characteristics about how phonon drag affects metals during high strain rate deformation. Measurements of the stress at the peak stress of the elastic wave, σ_E, were used to study deformation behaviour.These measurements were inferred from velocimetry data taken *in situ*.

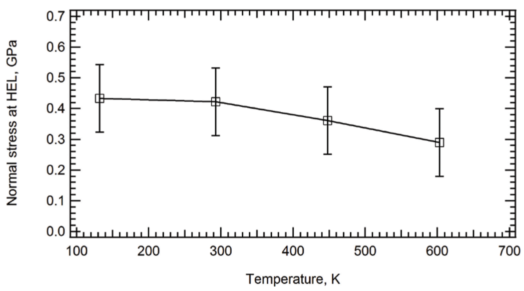
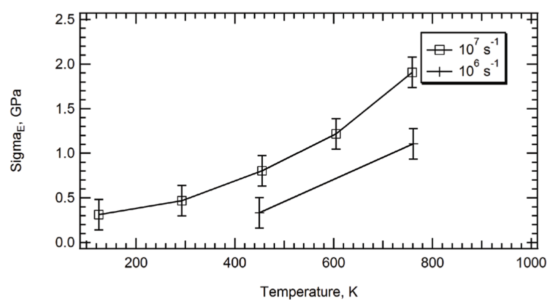


Figure 44: Invar data showing stress at HEL as a function of temperature at a strain rate comparable to the lower strain rate in the aluminum data. This has a slight decrease in HEL stress with temperature, typically seen in lower strain rate and quasi-static data. Studies on iron emphasized the dependence of yield behaviour on dislocation density and grain size. The data showed the change in temperature dependence between annealed and as-received iron with varying grain size and initial dislocation densities. The annealed iron has a higher σ_E at higher temperatures than the as-received iron. The as-received iron displayed decreasing HEL stress with temperature due to thermal activation, which is typical behaviour for a bcc metal at lower strain rates.



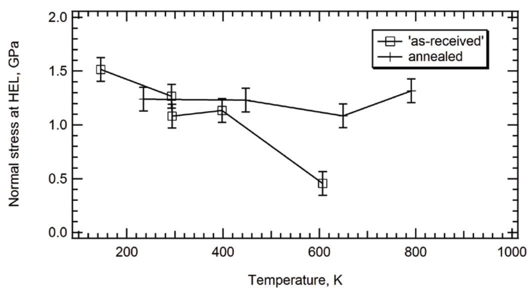


Figure 43: Aluminum data showing stress at HEL as a function of temperature for two different strain rates. There is an anomalous, marked increase of HEL stress with temperature.

Figure 45: Iron data showing that the annealed data has a higher σ_E at higher temperatures. The as-received iron shows typical behavior of decreasing σ_E with temperature due to thermal activation.

Dr Thomas White
RESEARCH ASSOCIATE

Tom joined the ISP after completing his doctorate at the University of Oxford working on the creation and diagnosis of extreme matter states with high power optical and X-ray lasers. Tom has worked on the Titan laser (LLNL, USA), the Vulcan and Gemini lasers (RAL, UK), the FLASH free electron laser (Hamburg, Germany) and the LCLS free electron laser (Stanford, USA).

He is currently working on the HexMat EPSRC programme grant looking at the performance of hexagonal alloy systems used by the Aero, Energy and Defence sectors. He has designed and built the miniature Split Hopkinson Pressure Bar and 3D digital image correlation system designed for precision measurements of shear in single grain titanium alloys subjected to moderate strain rates. In addition to this he is leading the development of a Ptycographical imaging technique at the Diamond light source, an ultra-high resolution coherent diffraction based method capable of visualising single dislocations.

Dr JP Duarte
RESEARCH ASSOCIATE

JP joined the ISP team in 2014 as the PDRA for the Boron Carbide (B4C) project. JP comes from the ancient University of Coimbra, set in the sunny margins of the Mondego river in Portugal, where he taught and did research on oxide ceramics and semiconductors using a collection of spectroscopic techniques.

JP will be upgrading ISP's meso scale launcher to a two-stage light gas gun, enabling it to accelerate masses of a few grams to velocities in excess of 2 km/s. More challengingly, he also envisages adding a novel diagnostic capability to the ISP – an *in situ* time-resolved Raman spectroscopy system able to probe structural changes during dynamic loading. Both will enable the study of B4C in order to understand how Si-doping supresses the formation of weak phases upon loading on the GPa range.

Thomas Ota
PhD STUDENT

Thomas recently joined the ISP from AWE, where he has worked on diagnostic development for nine years. His PhD research will focus on high speed optical pyrometry (temperature measurement), building on previous work at AWE. Thomas joined AWE in 2005 following completion of a Physics BSc at Nottingham. Following five years working at AWE, he enriched his shock physics background by undertaking and completing an MSc in Shock Physics within the Institute.

Thomas has experience with a wide range of diagnostics used in high strain rate experiments. These include photonic Doppler velocimetry, ejecta diagnostics and laser sheet imaging. It is hoped this experience can be used to make progress in the challenging area of high speed temperature measurement.

Jack Patten
PhD STUDENT

Jack has rejoined the ISP having completed his MSc in Shock Physics with the Institute in 2013. His Master's project within the ISP focused on a proof of concept experiment designed to show the viability of certain blasting methods for resource extraction in extra-terrestrial environments. Previously he had earned an undergraduate MSci in Physics at Imperial, during which time he published work on the adsorption of water onto graphene surfaces and the effects of substrate structure on same.

His work with the ISP will now be focusing on dynamic loading of hexagonal crystal materials, working alongside Dr Thomas White, under the supervision of Dr Daniel Eakins.

Alice Moore
PROGRAMME MANAGER

Alice joined the ISP as Programme Manager in May 2014 and oversees the day-to-day running of the Institute and manages stakeholder partnerships. She comes with several years' experience within the College in Strategic Planning, Research Services, as the REF Coordinator for the Faculty of Natural Sciences, and from her previous role working closely with the Faculty Dean as Project Manager for the Francis Crick Institute partnership. She has a degree from Imperial in Mathematics.

Imperial College London

About the Atomic Weapons Establishment (AWE)

AWE plc plays a crucial role in the defence of the United Kingdom by providing and maintaining the warheads for the country's nuclear deterrent on behalf of the Ministry of Defence. It is a centre of scientific and technological excellence, with some of the most advanced research, design and production facilities in the world.

Through its links with industry and institutions such as universities, professional bodies and government agencies, it builds upon and shares knowledge for mutual benefit.

About Imperial College London

As the only UK university to focus entirely on science, technology, engineering, medicine and business, Imperial College London offers a critical mass of international research expertise and a vibrant home for innovation and enterprise.

Sustained support for research at multidisciplinary centres like the ISP is a sound investment in the UK's economy and in developing the next generation of pioneers, researchers, innovators entrepreneurs in the field.

The ISP acknowledges support and funding from MOD/AWE plc and Imperial College London.

The Institute of Shock Physics partners

The Institute of Shock Physics has a number of partner organisations with which it has Memoranda of Understanding or legal agreements to enable joint working. We also have a number of visiting academics who spend time working in the ISP. Visit our website to join: **www.imperial.ac.uk/shockphysics**