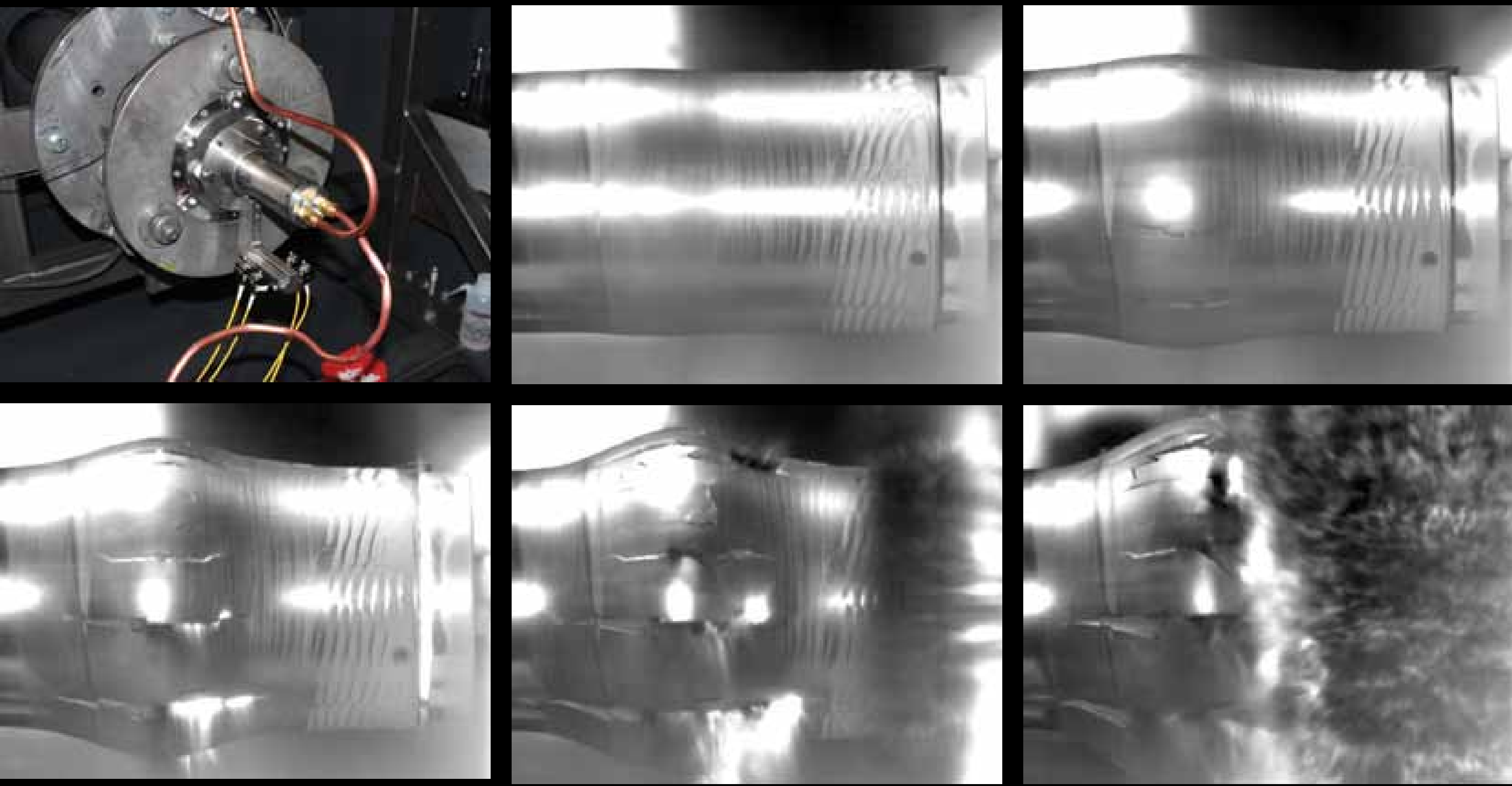
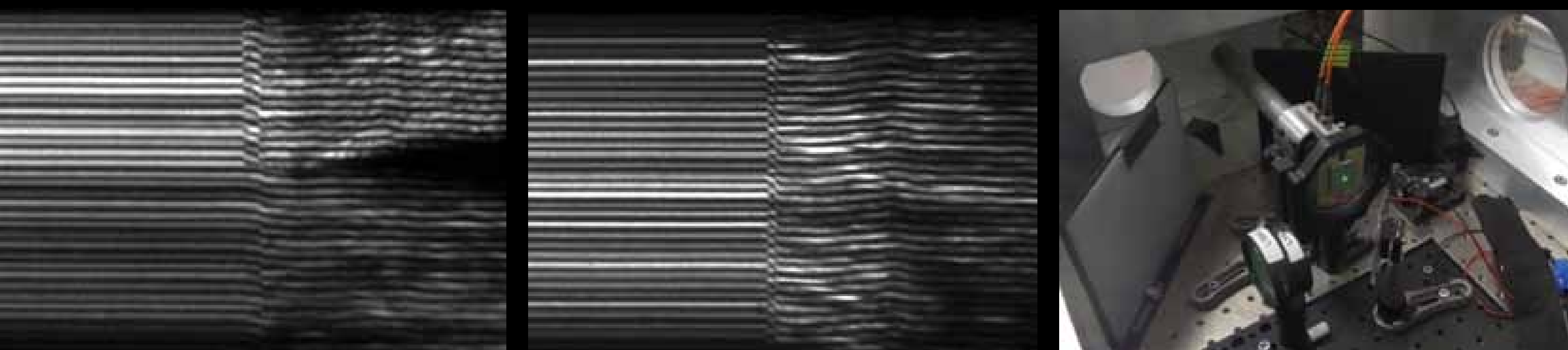
Imperial College London



Institute of Shock Physics

Annual Review 2013

www.imperial.ac.uk/shockphysics



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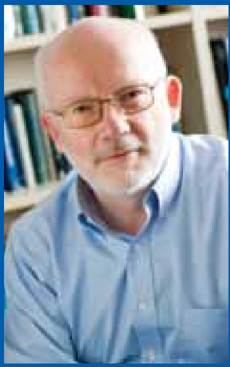

Professor Steven Rose
Founding Director

Foreword

The Institute of Shock Physics (ISP) was established in 2008 with substantial investment from AWE Aldermaston and Imperial College London. This Annual Review marks its sixth anniversary which is significant because in the last year, following review by AWE of the Institute's performance, AWE has invested in the Institute for a further five years. The Institute continues to train a new generation of shock physicists with nine PhDs having been awarded so far and many more nearing the end of their postgraduate studies.

In the future we aim to extend our work to new areas, including laser-driven shocks and diagnosing shocks using synchrotron radiation. Both areas have seen considerable attention from our staff over the last year. In this Annual Report we look back on a very successful year and forward to more opportunities in the years ahead.

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Cover images

Top: Gas gun driven expansion of a Ti-6Al-4V cylinder cooled to 150K examining the effect of temperature on dynamic fracture and fragmentation using the large bore gas gun, high speed imaging at a rate of 100,000 frames per second.

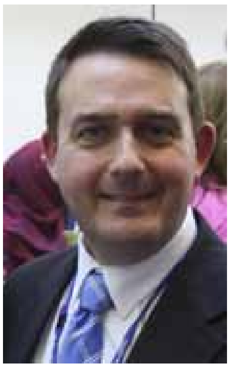
Bottom: Spatially resolved velocimetry of shock-induced sliding in the region around a planar multi-material interface. Target: Aluminium/stainless steel in the mini gun. Line VISAR streak records showing the velocity distribution around the interface (x axis = time, y axis = space).

Kindly provided by
David Jones (top) and Mark Collinson (bottom) » ISP, Imperial College London

Professor Andrew Randewich
AWE Chief Scientist

Chief Scientist's comment

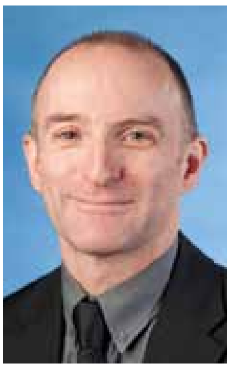
I am very pleased to introduce the 2013 Annual Review from the Institute of Shock Physics. As the reader will discover, based on a very successful initial five year phase, AWE has now agreed future funding for a second five year phase supported by a much increased contribution from other sources. That such funding is possible is a real tribute to the progress that the Institute has made, and the regard in which it is held. As well as the research output, the Institute has also delivered remarkable progress in people development, some of which AWE has directly benefitted from by recruitment. The value of the workshops and conferences has also been high in mutual knowledge exchange in the field of shock physics. I am looking forward to a continued rich relationship with the ISP over the coming period, and continuing to build on the excellent work on this and related fields, for example in laser plasma physics.



Dr William Proud
Director

Director's overview

The past year has been one of expansion and success for the ISP. The renewal of our core contract by AWE was central to our research activities and profile and, after the discussion necessary for a significant award under the steerage of our Programme Director, Dr Chris Thompson, the signatures were made at the start of March 2013. Our core funding is now secure until 2018. This has allowed us to move forward with confidence in achieving ongoing development in the Institute. Equally important is the funding of the HEXMAT (Hexagonal Materials) programme from EPSRC in which the ISP is a key centre. I was also delighted when Dr Daniel Eakins, after the success of the HEXMAT bid was also successful in obtaining substantial support from EPSRC for his research into the dynamic response of ceramics. Chiara Bo, one of my PhD students, won an AWE-sponsored award for her research into biomaterials. New students and post-doctoral researchers have arrived. The soon-to-be 'Dr' Ruth Tunnell finished her part-time PhD, funded by QinetiQ, with a rapidity normally found in only the most dedicated of full-time students; she will continue as a visitor to the ISP and also as an Industrial Research Fellow for the Royal Commission for the Great Exhibition of 1851. Finally, we have been successful in attracting funding from DOSG and ANSYS Ltd to support part-time PhDs for their employees, Craig Hoing and Jon Glanville. This is very important to me as it implies the value of training and knowledge transfer from academia into industry. Finally, Dr Chris Thompson, Programme Director for two years, is moving on to a role within one of our long-standing partner organisations, Cranfield University and we wish her well. I hope you find the contents of this Annual Review interesting and that you agree with the very positive assessment I have given.



Dave Chambers
Head of Hydrodynamics Technology Centre and Applied Physics

Sponsor's comment

I am delighted that this has been another successful year for the ISP, particularly given the challenges faced in this new contract period. It has been the first year in which the ISP has had to secure funding from new sources to be financially successful, so it is pleasing to see the ISP achieving that goal in this report. I am confident that the ISP is taking the right steps towards a sustainable future, and this is a credit to the commitment and hard work of the ISP team. It goes without saying that this has also been a year of high quality technical output from the ISP, with the first gas gun research papers being published in addition to those from plasma, blast and static high pressure research areas. This research demonstrates not only the health of the collaboration between ISP and AWE researchers, but also the growing International reputation that the ISP is achieving. And with the first graduates from the ISP now starting their careers at AWE and elsewhere, the shock physics community is becoming more vibrant than ever. It is the growth of this talented community along with the continued development of ISP research facilities that will help us enhance our hydrodynamics capability in the UK for many years to come.

Strategy and outputs

Led by 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.

Shock physics focuses on the understanding of what happens to matter under extreme conditions. The research can be applied in many ways, including analysing the effect of meteorite impacts on planets, spacecraft and satellites, understanding how tsunamis are formed and understanding the high pressure conditions that occur at the core of planets. Man-made high pressures include aeronautics and national security related applications, including studies on force protection, understanding how biological materials behave when exposed to shock waves and developing improved energetic materials.

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. It does this using a range of state-of-the-art experimental platforms, diagnostics and modelling capabilities. 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.

Our priority for the next five years will be to deliver a focused programme of research, technology development and training in the areas described above whilst diversifying our funding sources and moving to a membership model. In particular, we aim to strengthen the modelling and theoretical work linked to our experimental programmes.

Governance and management

- William Proud » Director
- Chris Thompson » Programme Director (to February 2014)
- 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, which meets annually. Day-to-day management is provided by the programme team located in the ISP headquarters at Imperial's South Kensington Campus. This team prepares quarterly progress reports for AWE and runs a joint AWE/Imperial Technical Operating Group to review and agree solutions to technical issues relating to Imperial's large bore gas gun. We have also introduced a Gas Gun Governance Committee to consider external proposals to use the facility.

Figure 1: Summary of financial gearing.

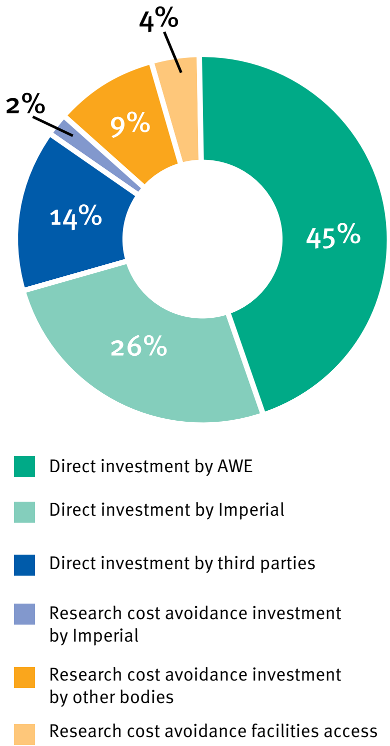
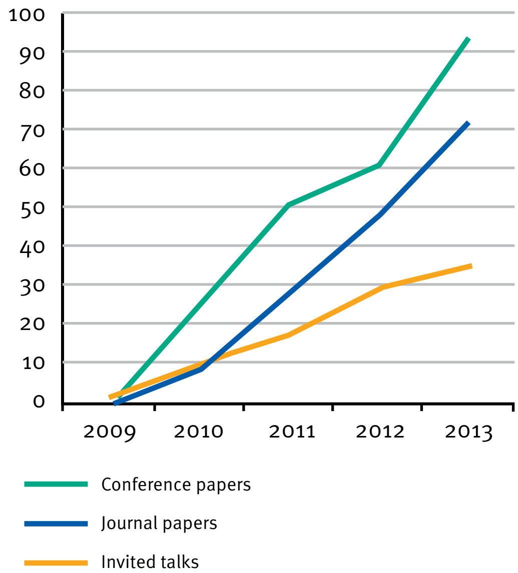


Figure 2: Cumulative total of research outputs from ISP funded staff.



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 of around £10 million over five years to the ISP 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 funders, 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-two PhD students working at five institutions; one QinetiQ funded PhD; one funded by The Royal British Legion; one funded by the Defence Ordnance Survey Group
- Most PhD students who have completed their studies have been offered Research Associate positions in relevant areas of research and one has taken up a post at AWE
- Trained 32 summer interns, some are now interested in MSc and PhD courses
- Delivered 14 very successful short courses
- Delivered taught Master's in Shock Physics to three cohorts totalling 14 students; the majority have gone on to undertake further postgraduate studies or entered relevant employment. The new Master's in Physics with Shock Physics has now been launched

INSTITUTE CAPABILITY

- Three academic staff and two Postdoctoral Research Associates (rising to four in 2014), two technical experts and a programme office at Imperial
- Forty-nine visiting academics from 14 institutions including AWE
- 100mm-bore single stage gas gun and Pulse Power MACH facilities at Imperial
- Several small-scale, portable impact launchers under development ranging in bore, from 13 mm – 30 mm, delivering velocities from a few 10's ms^{-1} to <1000 ms^{-1}

RESEARCH OUTPUT

- **Published:** 36 journal papers, 92 conference papers and delivered 71 talks or lectures at prestigious meetings and organisations
- **Recent examples of conferences:** 2013 APS SCCM/AIRAPT Joint Conference, Seattle, 40th IEEE International Conference on Plasma Science (ICOPS) 2013, San Francisco; 2013 PETER Conference, IOP, London
- Completed eight AWE campaigns on the large bore gas gun (by March 2014), undertaken several shots for ISP staff and students and re-commissioned the 30 litre breech

Key outputs are measured in terms of publications from ISP members and talks or lectures at major conferences. The cumulative total of research outputs is summarised in figure 2.

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 four annual meetings; the most recent in February 2013 with over 65 delegates attending; we have held five successful stakeholder events to raise awareness of the Institute at AWE and Imperial – in the last year a stand at the AWE-Imperial Showcase event at AWE resulted in several collaborative leads; and we hosted numerous visits from academia, industry and government. We are very pleased that Professor Naresh Thadhani of Georgia Institute of Technology and Dr Jim Gaffney from Lawrence Livermore National Laboratory also gave well-received research colloquia during 2013.

Delegates at the 2013 PETER Conference.

Established during 2012, the Institute of Physics (IOP) specialist group *Shock Wave and Extreme Conditions* (SWEC) became fully operational during 2013. This covers areas from astrophysics, climatology, construction, mining, earth sciences, static high-pressures to plasmas and the core sciences of physics and chemistry. SWEC aims to promote the science, engineering, technology and mathematical aspects of materials under rapid dynamic loading or at extreme conditions. It will do this in a number of ways, for example:

- The 2014 PETER Conference (Pressure, Energy, Temperature and Extreme Rates) – will be held at the Grand Connaught Rooms, Covent Garden
- Workshops on specific topics of interest to members
- Evening lectures
- Networking

PhD student prize

PhD student Chiara Bo (pictured with HRH Prince Harry of Wales) was awarded the AWE Thesis Prize for her work on 'Investigations of the effects of high pressure pulses on biological samples'. This prize is awarded annually for the best PhD in the field of high energy density, shock regimes and plasma physics.

Imperial College London

Research

Institute of Shock Physics

- William Proud
- Dan Eakins
- Simon Bland
- Gareth Collins

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

STRENGTH

The investigation of strength under conditions of high pressure is a core research focus of the ISP, leveraging the Institute's multi-platform multi-scale capabilities to probe the various mechanisms of stress relaxation under dynamic loading for a broad range of condensed matter systems. From studies of the behaviour of dislocations accompanying incipient relaxation, to characterization of full-field catastrophic failure and fragmentation, current research explores how strength is affected by factors such as loading-rate, temperature, microstructure, and defects.

This research theme in particular benefits from a number of local, national, and international collaborations with colleagues from:

- Departments of Physics and Materials, Imperial College London
- Diamond Light Source
- DSTL
- Atomic Weapons Establishment (AWE)
- Sandia, Los Alamos, and Lawrence Livermore National Laboratories, USA

Effects of High Explosive Fireball on Fragment Flight

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

Current methods for estimating weapon fragmentation initial speed involves the development of free air retardation curves from down range measurements which are then extrapolated back to the time and position of the weapon casing fracture. Although this may give acceptable results for the modelling of long range fragment – target interactions, neglecting any fireball-fragment interaction effects on the early time acceleration and flight of the fragments could cause dramatic differences between such models and reality for close in applications.

The research being undertaken will use explosively driven simple geometric (spherical and cube) pre-formed fragmentation to develop novel diagnostics allowing the fragments to be tracked within the optically dense expanding fireball of explosion products. Coupling the experimental observations with numerical modelling will enhance the investigation and elucidate more details within the flow mechanisms and their effects on the early time fragment motion.

The final output of the investigation will be incorporated into numerical predictions of fragmentation effects for use within Ministry of Defence programmes.

Dynamic fracture and fragmentation

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

The fracture and fragmentation of a body is a frequent terminal response in scenarios involving dynamic loading under high strain-rate and pressure conditions. The accurate simulation of fragmentation events often presents unique challenges, not the least of which is the simple population and validation of relevant models. To address this there has been an ongoing research effort at the ISP to develop an experimental technique to facilitate the study of material under uniform radial expansion at strain states of 10^3 to 10^5 s^{-1} using the large bore gas gun at Imperial. Importantly, unlike other similar gas gun driven expanding cylinder techniques, or more traditional exploding cylinder geometries, the technique developed at the ISP enables us to probe the role initial sample temperature plays in the resulting failure and fragmentation. This novel technique has been used to investigate the dynamic deformation, fracture and fragmentation behaviour in Ti-6Al-4V cylinders over a range of temperatures from 150-800K.

Initial results suggest that failure along adiabatic shear bands is the dominant failure mode at higher temperatures, while lower temperature experiments exhibit much reduced ductility and some evidence of internal damage similar to spall. Current work characterising the fragments through microscopy techniques and electron backscatter diffraction will provide more information on the fracture dynamics and the initial microstructure and texture of the widely-used but highly processing-dependent titanium alloy.

More recently, an adaptation of the gas gun cylinder technique has been used to launch rings into free expansion at a range of strain rates (from 10^3 to 10^4 s^{-1}) in the same experiment. This novel geometry has the potential to generate significant statistical data in a single experiment, which may be used to validate new material models over a range of loading conditions. It is hoped that this new experimental technique, when combined with the work examining the role of temperature in dynamic fracture and fragmentation, will provide a rich supply of statistics for the development and improvement of material understanding and failure models.

Publications

Jones DR, Chapman DJ, Eakins DE
A gas gun based technique for studying the role of temperature in dynamic fracture and fragmentation
Journal of Applied Physics 2013;114:173508. doi:10.1063/1.4828867.

Jones DR, Eakins DE, Savinykh AS, Razorenov SV
The effects of axial length on the fracture and fragmentation of expanding rings
EPJ Web of Conferences. 2012;26:01032. doi:10.1051/epjconf/20122601032.

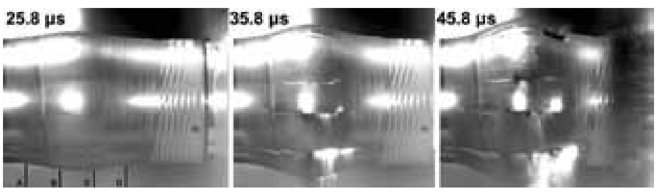


Figure 3: A series of images from a cylinder expansion experiment on the ISP gas gun, where the cylinder has been cooled to ~150K. Time is after impact, where A-D are the location of PDV probes used to measure the expansion velocity.

Dynamic strength of meteoric and Febased compositions

- **Laura Chen (PhD student)**
- **Daniel Eakins**

The ablation and breakup of meteorites upon entry into the Earth's atmosphere is an important challenge of global relevance. However, large thermal gradients, coupled with complex stoichiometry of Fe-Ni based meteorites, lead to difficulties in accurately modelling the breakup process. To address this problem, laser-driven compression experiments are being conducted with the purpose of revealing the effect of microstructure and temperature on the mechanisms of plastic relaxation in Al and Fe-based alloys. Recent experiments at Los Alamos National Laboratory's (LANL) Trident Laser Facility have focused on differentiating strength properties among a range of materials (i.e. Al, Fe, INVAR, etc.) at temperatures extending from 120 K to 600 K. Of principal interest is the ultrafast transition from elastic to plastic deformation, which has been revealed through line-imaging VISAR measurements of rear surface motion. In the future, this data will be compared to dynamic strength properties of recovered Fe-based meteorite and MD simulations, leading to improved approaches for modelling meteoritic break-up.

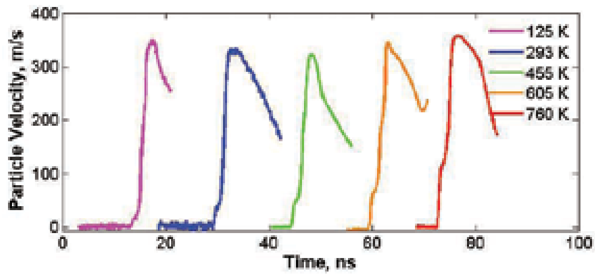


Figure 4: Average free-surface velocity histories measured using line-VISAR for aluminium specimens at a range of initial temperatures, where the profiles have been offset in time for clarity. The figure reveals the evolution of the free-surface velocity history over the range 125 – 760 K, where the HEL in particular is observed to increase with increasing temperature.

Figure 5: The Trident laser target area at Los Alamos National Laboratory, where these experiments were conducted.

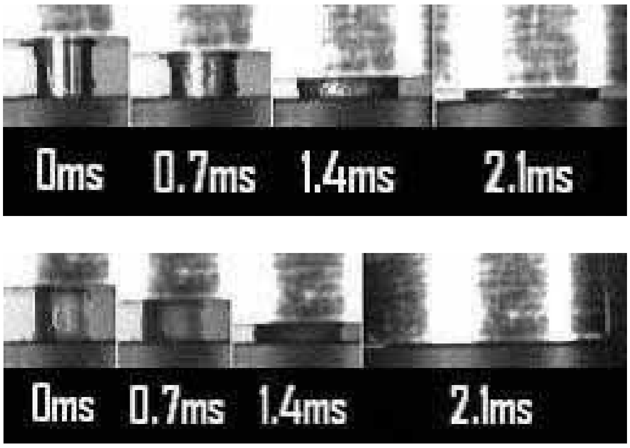


Figure 6: Drop-weight sequence for aluminium 6082 (top) and polycarbonate (above), aspect ratio = 1.

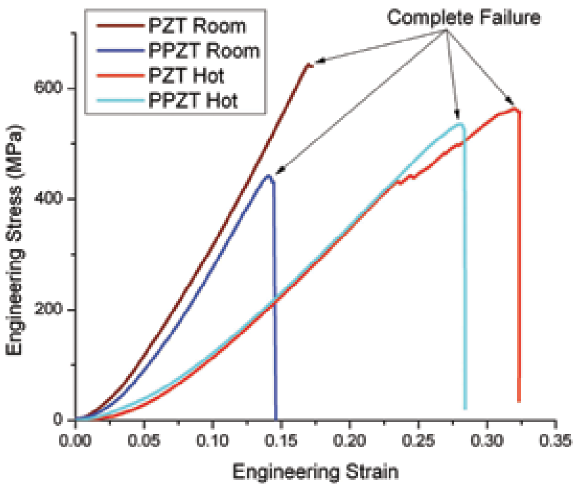


Figure 7: Engineering stress-strain data from quasi-static experiments on unpoled PZT 95/5.

High-rate behaviour of PZT at elevated temperatures

- Amnah Khan (PhD student)
- James Wilgeroth (RA)
- William Proud

This research seeks to develop a better understanding of the mechanical and piezoelectric properties of the ceramic lead zirconate titanate (PZT) 95/5. The main variables under investigation include temperature, porosity, geometric size and strain rate. Initially this project concentrated on the variation of properties of PZT and associated materials with strain rate. Different compressive strain rates were achieved using quasi-static loading, drop-weights and Split Hopkinson Pressure Bars. Temperature control is achieved using purpose-built environmental chambers.

Cylindrical polycarbonate and aluminium (6082) samples were produced, 4 mm diameter and thickness between 1 – 12 mm, giving in aspect ratios between 0.25 – 3. These samples were subjected to strain rates between $10^{-4} – 10^{3}\ s^{-1}$. The different compression rates demonstrate the similar behaviour across a wide range of aspect ratios. However, there is a wider range of consistent uniform deformation for aluminium 6082 compared to polycarbonate, before the sample fails by buckling. High-speed images from the drop-weight experiments are presented above.

The properties of square PZT samples, of varying porosity (7.75 and 7.38 g cm^{-3}), were studied with temperature. In the conditions used the low-porosity PZT was able to withstand a larger stress than the less dense, porous PZT sample. For both densities of PZT, a higher strain to failure was observed at the elevated temperature.

Elastic precursor decay in high-purity tantalum

- Daniel Eakins
- David Chapman (RA)

The decay of the elastic precursor from the loading surface with strain rate and distance contains rich information regarding the origins of yielding under intense dynamic loading. In particular, measurements of the evolution of the precursor with propagation distance can aid the development of new dislocation-based strength models. In this work we extend study of elastic precursor behaviour in tantalum foils down to 120 μm to address the role of reduced thickness and texture on the kinetics of stress relaxation. Using a multi-target impact assembly, high purity Ta foils ranging in thickness from 2 mm down to 120 μm have been simultaneously impacted using the 100 mm bore gas gun at Imperial. Multiple channels of frequency-shifted PDV were employed to measure particle velocity at each sample rear surface. Figure 9 shows the typical features observed in the breakout profiles, such as the peak elastic state and yield drop. Work is currently ongoing to relate these observations to the kinetics of incipient relaxation processes occurring during the shock loading, however the magnitude and decay of the precursor are consistent with earlier work published by Gillis. These measurements are among the first to employ frequency-shifted PDV to study elastic-precursor decay on thin foil samples, and serve to demonstrate the good temporal resolution (~1-2 ns) obtained. These results will be used to further validate the D3P code recently developed by researchers in the Theory and Simulation of Materials CDT at Imperial.

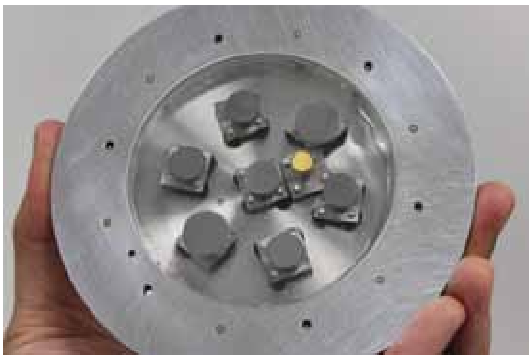


Figure 8: The impact face of the Ta multi-target, showing seven thin foil Ta targets bonded to the rear of a large sapphire buffer plate.

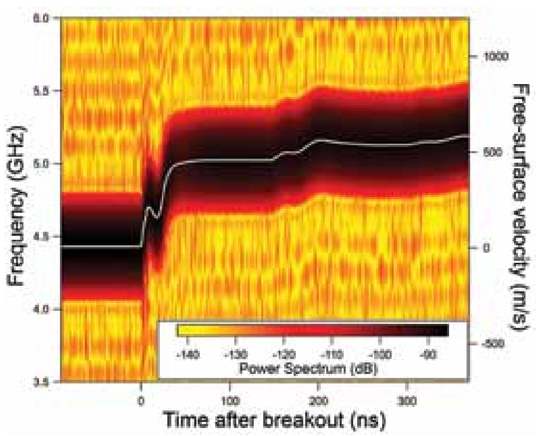


Figure 9: Typical spectrogram obtained using upshifted PDV, indicating a zero-velocity beat frequency near 4.5 GHz, and the general structure of the observed wave-profile. The reduced free-surface velocity history is superimposed over the spectrogram.

Dynamic fragmentation of an SLM steel cylinder

- Russell Amott (MSc student)
- David Chapman (RA)
- Daniel Eakins

Additive manufacture has seen a sharp rise in popularity due in part to its movement from a novel manufacturing technique allowing the creation of bespoke items into a more widely accepted manufacturing method. Understanding the behaviour of materials that have been generated using this type of manufacturing method will only become more important as it is applied to an ever increasing number of situations. Expanding cylinder experiments using gas guns allow investigations into the fracture and fragmentation mechanisms that occur within a material during failure. These experiments allow the radial strain-rate to be varied within the range 10^2 and 10^4 s^{-1}. Information is gained on not only how a material behaves during rapid tensile loading but also on the fundamental processes behind a materials eventual failure. A comparative study between additively and traditionally manufactured stainless steel cylinders is currently underway with an additional investigation into the role of deliberate macroscopic defects that have been introduced into a cylinder wall during the additive manufacturing process. Diagnostics in the form of Heterodyne Velocimetry (Het-V) measuring the surface of the cylinder and high speed imaging allowed a temporal history of the cylinder to be recorded. Comparison of these results with CTH simulations is currently ongoing with the objective of refining the modelling approach to accurately predict the dynamic failure of these potential new SLM materials.

Figure 10: The experimental set up (left) showing the mitigation that was used to reduce the chance of damaging the target tank and the entire cylinder assembly (right).

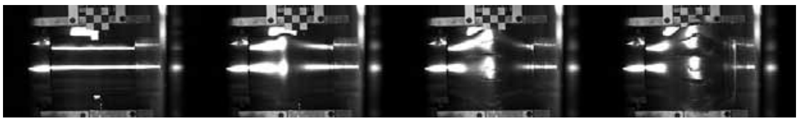


Figure 11: Shows the expansion and eventual failure (left to right) of a stainless steel cylinder that was created using additive manufacturing techniques.

Spall behaviour of HCP alloys

- Simon Finnegan (MSc student)
- David Chapman (RA)

As part of an ongoing effort to understand the response of HCP materials to dynamic loading, an investigation into the spall response of magnesium alloy AZ31 and titanium alloy Ti-6Al-4V was conducted. A series of plate-impact experiments were performed on the recently developed 13 mm bore meso-scale light gas gun employing AZ31 specimens cut both parallel and perpendicular to the extrusion direction in this highly textured alloy. The spallation process was interrogated using a cleaved fibre PDV probe monitoring the rear surface of each specimen. Generally, the spall strength for AZ31 was observed to increase for decreasing flyer width, while specimens cut perpendicular to the extrusion direction exhibited higher spall strength than those cut parallel, consistent with previous investigations. A highlight of this research were experiments on the Ti64 alloy which attempted to isolate and vary only one loading condition; strain-rate, peak shock state, and duration in the peak shock state in each experimental series. This was achieved by utilising flyer materials with different shock-impedance and sound speed and controlling the flyer widths and impact-velocities to maintain peak pulse pressure and width, and tensile strain rate. Preliminary results based on simple analytical calculations to determine the impact parameters indicated some success at isolating a given loading condition. Further work is ongoing using AUTODYN simulations to refine the impact geometry and provide a better isolation of the desired loading conditions. It is hoped that these efforts will enable us to isolate the role of strain-rate and pulse duration during the spallation process.

HIGH-PRESSURE EQUATIONS OF STATE

Knowledge of the equation of state at high pressures is critical to multiple areas of physics and industry, from the production of super hard materials, to exploring the geophysics of planets, to creating controlled nuclear fusion in the laboratory. Indeed, recent simulations have predicted that at pressures >10Mbar material structure is greatly affected by deformations in the electron orbitals, resulting in far more complicated states of matter than had previously been thought.

At the ISP we are exploring high pressure measurements at both our onsite facilities and through our many national and international collaborations. Diamond anvil cells provide static pressures to several Mbar for studying the behaviour of hydrogen, whilst quasi-isentropic drives generated by the onsite gas gun, and soon to be commissioned laser facility, are being used to explore phase changes at these pressures. Advanced diagnostic techniques, such as *in situ* X-ray diffraction and phase contrast imaging are being developed to directly explore materials on the microscopic level. Simultaneously high power molecular dynamics simulations are studying the states of matter accessed in experiment.

Exploration of structural transitions in amorphous materials

- **John Winters (PhD student)**
- **Laura Chen (PhD student)**
- **Simon Bland**
- **Daniel Eakins**

Amorphous materials offer unique properties that greatly differ from their crystalline counterparts. For example, the lack of any definitive crystal structure or long-range order grants these materials exceptional elastic strength, but typically limited toughness. Efforts to study the kinetics of various physical and deformation mechanisms under high-strain rate loading in this emerging class of materials are on going; a previous study by Laura Chen on an amorphous Ce-Al alloy at the Jupiter Laser Facility, LLNL, revealed a significant volume collapse in the region of 2 GPa, attributed to a polyamorphic transition previously reported in high-pressure static studies. The current research builds upon this earlier work; initially with the development and commissioning of the Cerberus laser facility and a long-pulse laser shock capability within the Wolfson Laboratory for Ultrafast Imaging of Extreme Physical Processes at Imperial. Once commissioned, this new facility will be used to investigate the evolution of specific polyamorphous and crystallisation transitions in Zr-based BMGs and a-Si, employing simultaneous use of line-VISAR and X-ray diffraction.

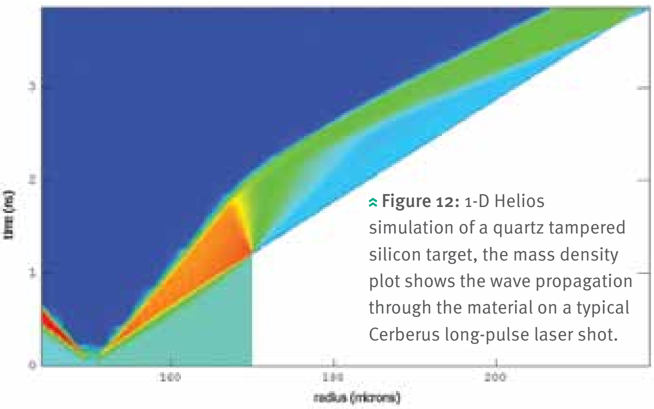


Figure 12: 1-D Helios simulation of a quartz tampered silicon target, the mass density plot shows the wave propagation through the material on a typical Cerberus long-pulse laser shot.

The effect of polarisation on the rapid freezing of water

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

Crystallisation rarely occurs under shock loading, but when observed it is accompanied by a delay due to crystal growth. The investigation of such phase change dynamics presents a dual challenge both in terms of loading (achieve a specific P,V,T path) and diagnostics (observing the transformation). Shock heating normally outpaces the drive to compress across the solidus. Water however, has been shown to freeze into the polymorph Ice VII under compression. The anomalous heat capacity and compressibility of water make it sensitive to quasi-isentropic effects at much lower pressures than metals, and the phase of Ice VII is stable at high enough temperatures that make it feasible to achieve at a gas gun facility. Using the 100 mm bore single stage gas gun and a tailored ramp loading geometry, a liquid cell has been subjected to ramp and shock loading and diagnosed using simultaneous reflectivity and velocimetry diagnostics. The onset of freezing is observed as a subtle decrease in velocity following the peak state. This suggests a long phase change on the order of 100ns but diagnosis of the frozen state needs to be improved. In future experiments, a high speed framing camera will be included to aid in visual interpretation of crystallisation behaviour. In addition, this work will build towards application of external electric fields to modify the initial polarization state, to investigate the relative rates of crystallization for validation of molecular dynamics models.

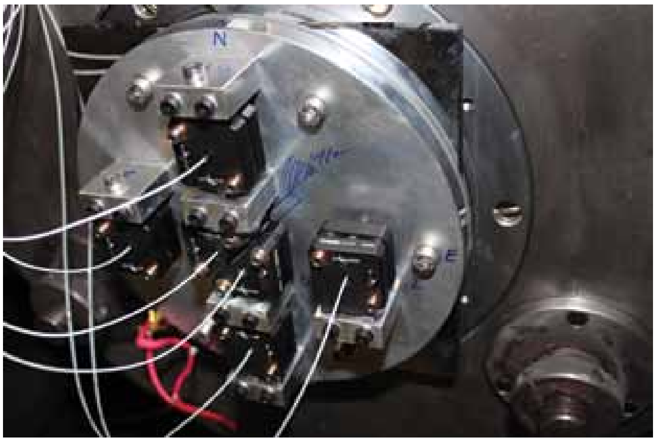


Figure 13: Water-filled target mounted in 100 mm gas gun target chamber. Het-V probes (white fibres) were used to diagnose several surfaces within the cell.

Simulations of Shock-induced Phase Transitions in Silicon

- **Gabriele Mogni (PhD student)**
- **Justin Wark (University of Oxford)**

An understanding of the fundamental mechanism behind the relief of shear stress in single-crystal silicon subject to loading by shock-waves has to this day remained elusive. What is known is that this material undergoes a first-order pressure-induced polymorphic phase transition from its ambient pressure cubic-diamond (cd) crystal structure to its first stable high-pressure phase, known as beta-tin, at a pressure of about 120 kbar under hydrostatic compression. By investigating the evolution of the transition parameters for this phase transition as a function of increasing uniaxial shear stress representative of the effects of shock-compression via ab-initio Density Functional Theory computational techniques, we predict a significant lowering of the stress at which the phase transition occurs. This raises the question as to whether the onset of plastic response at the material's Hugoniot Elastic Limit (HEL) reported in experiments corresponds in fact to the phase transition itself, a very plausible possibility which has never been considered before. Furthermore, we have performed a series of molecular dynamics simulations using a Tersoff-like potential of shock-compressed single crystals of silicon. We find an elastic response up to a critical stress, above which the shear stress is relieved by an inelastic response associated with a partial transformation to a new high-pressure mixed phase region, where both the new phase (Imma) and the original cubic diamond phase are under close to hydrostatic conditions. We note that these simulations are also consistent with shear stress relief provided directly by the shock-induced phase transition itself, without an intermediate state of plastic deformation of the cubic diamond phase.

Publication

G. Mogni *et al.*
Molecular dynamics simulations of shock-compressed single-crystal silicon
Phys Rev B, 89, 064104, 2014.

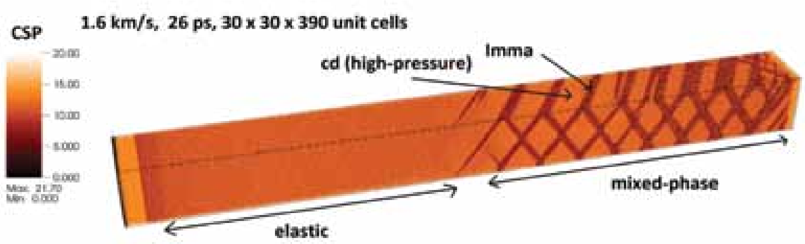


Figure 14: Example of a set I simulation of shockwave propagation (from right to left) in single-crystal Si at a particle velocity of 1.6 km s^{-1}, and 23 ps after the start of the simulation. The atoms are colour coded according to their CSP. The CSP is higher for the material in the cd phase depicted in light orange (around 11.5 Å^2) than for the remaining Imma phase shown in darker red (around 6 Å^2). The structure of intersecting parallelepipeds of Imma material that constitutes the mixed-phase region is clearly visible, together with the region of elastic compression that precedes it.

Multi-megabar pressure studies with diamond anvil cells

- **Ross Howie (PhD student)**
- **Eugene Gregoryanz (University of Edinburgh)**

Hydrogen, being the simplest and most abundant element in the universe, is of fundamental importance to condensed matter sciences. Through advances in high pressure experimental technique, hydrogen (and its isotope deuterium) has been contained and studied using *in situ* optical spectroscopy to 315 (275 GPa) at 300 K, pressure and temperature conditions previously thought to be inaccessible. At 200 GPa, hydrogen undergoes a phase transformation, attributed to phase III, previously observed only at low temperatures. This is succeeded at 220 GPa by a reversible transformation to a new phase, IV, characterised by the simultaneous appearance of the second vibrational fundamental mode, new low-frequency phonon excitations, and a dramatic softening and broadening of the first vibrational fundamental mode. To impose constraints on the P-T phase diagram, the temperature stability of phase IV is investigated through a series of low temperature experiments, where the phase IV-III transformation is observed.

Analysis of the Raman spectra suggests that phase IV is a mixture of graphene- like layers, consisting of elongated H_2 dimers experiencing large pairing fluctuations, and unbound H_2 molecules. Isotopic comparisons reveal spectral differences between the phase IV-III transition of hydrogen and deuterium, which strongly indicates the presence of proton tunnelling in phase IV.

Optical transmission spectra of phase IV reveals an overall increase of absorption and a closing band gap reaching 1.8 eV at 315 GPa. No differences between the isotopes were observed in absorption studies, resulting in identical values for the band gap. Extrapolation of the band gap yields 375 GPa as the minimum transition pressure to a metallic state of hydrogen (deuterium).

HETEROGENEOUS MATERIALS

The dynamic loading of heterogeneous materials gives rise to unique and interesting material response originating from a complex sequence of wave interactions, mixing, and relative motion occurring at the meso-scale. A clear example is the initiation of reactive materials, which is attributed to the development of thermal excursions, 'hot spots', during non-uniform deformation and flow. As the spatial and temporal resolution of diagnostics improves, we are better able to interrogate the rich compendium of phenomena occurring over a broad hierarchy of length scales. To this end, there are a series of research programs ongoing within the ISP that explore new diagnostic methods for measuring the dynamic response of this intrinsically complex class of materials.

Spatially resolved shock response at dry metallic 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 mediation by material interfaces. This is especially true of dissimilar material pairings where relative sliding and therefore frictional forces may be generated along the contact face. Of particular interest to this project has been the spatial extent of the inhomogeneous velocity response across such interfaces and its dependency on the intrinsic properties of the materials in question.

Towards this, an experimental setup consisting of stainless steel and aluminium components held in close contact along a single planar interface has been utilised. By using a gas gun driven plate impact technique, relative sliding velocities in the range 100 – 150 ms^{-1} were generated via the launching of oblique shock waves along the contact boundary. Uniquely, both spatially and time resolved velocity profiles have been recorded across the contact interface on the rear target surface using a portable line-VISAR diagnostic.

A series of over 30 experiments have been performed encompassing both varying yield strength of the paired materials and the angle of incidence of the loading wave relative to the planar contact face. Analysis of this matrix of data is in progress, however it is anticipated that material pairings of higher yield strength and subject to a greater normal force will support higher frictional forces along the sliding interface.

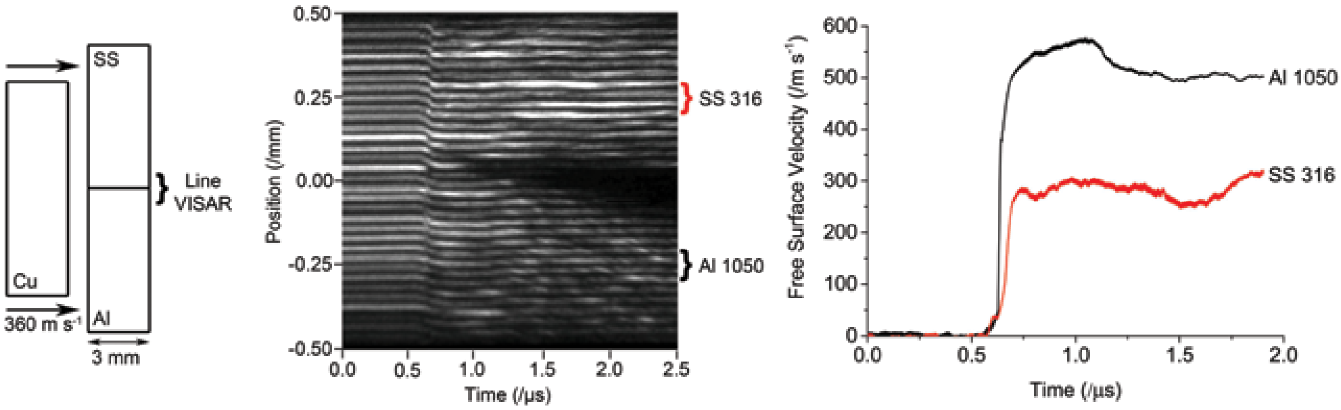


Figure 15: (a) Schematic of the impact configuration, showing a copper flyer impacting an aluminium stainless steel friction couple. (b) A raw line-VISAR streak record. (c) Reduced average velocity-histories from the line-VISAR streak record.

Modelling of multiphase flows on adaptive unstructured meshes with applications to the dynamics of volcanic ash plumes

- Christian Jacobs (PhD student; graduated February 2014)
- Gareth Collins
- Alan Dawes (AWE)

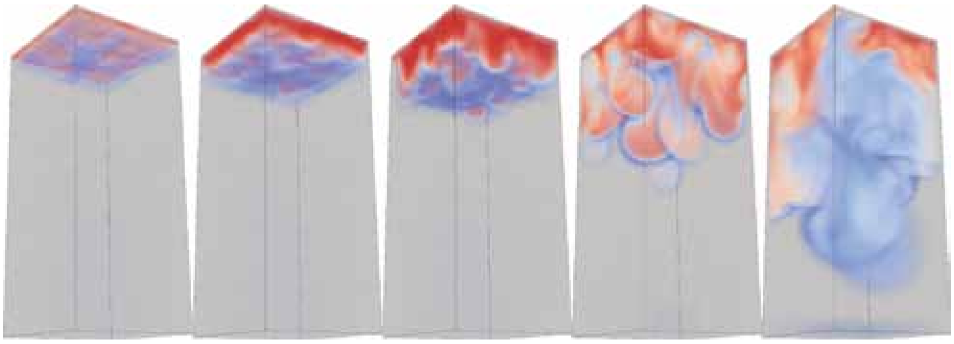
Dispersed multiphase flows, such as the motion of droplets, particles or bubbles in a surrounding fluid, are prevalent in the natural world, but their multi-scale nature makes them challenging to simulate numerically. We have extended the unstructured, adaptive mesh, finite element model Fluidity to simulate dispersed multiphase phenomena at a range of speeds.[1,2] The unstructured mesh capability of Fluidity allows for complex geometry domains, and the adaptivity library resolves the particle plumes economically by focussing resolution only where necessary. The culmination of this work has been used to establish a new criterion for the onset of collective settling of ash plumes in the ocean (figure 16) and to simulate the dispersal of volcanic particulates in an explosive Plinian-style eruption (figure 17).

We have used Fluidity to perform multi-scale simulations of volcanic ash transport in aqueous solutions[1] and in the atmosphere.[2] Simulations of ash settling in a water tank, which mimic published laboratory experiments, have been performed in two and three dimensions (figure 16). The results demonstrate that ash particles can either settle slowly and individually, or rapidly and collectively as an ash-laden cloud, referred to as a plume.[1] Our recent work has revealed that particles settling collectively in plumes are slowed by inertial drag, rather than viscous drag, and we have proposed a new criterion for predicting the tendency for plumes to form, based on particle volume fraction and particle size.[2] In addition, we have simulated two-dimensional kilometre-scale volcanic eruptions of hot gas and ash into the atmosphere. Realistic physical parameters such as particle diameter, density, and specific heat capacity were used. Both fixed (structured and unstructured) and adaptive (unstructured) meshes were employed. Our simulations are able to successfully capture the key characteristics of an eruption event (figure 17) and have been benchmarked against MFIX, a leading fixed-mesh multiphase flow code.[2]

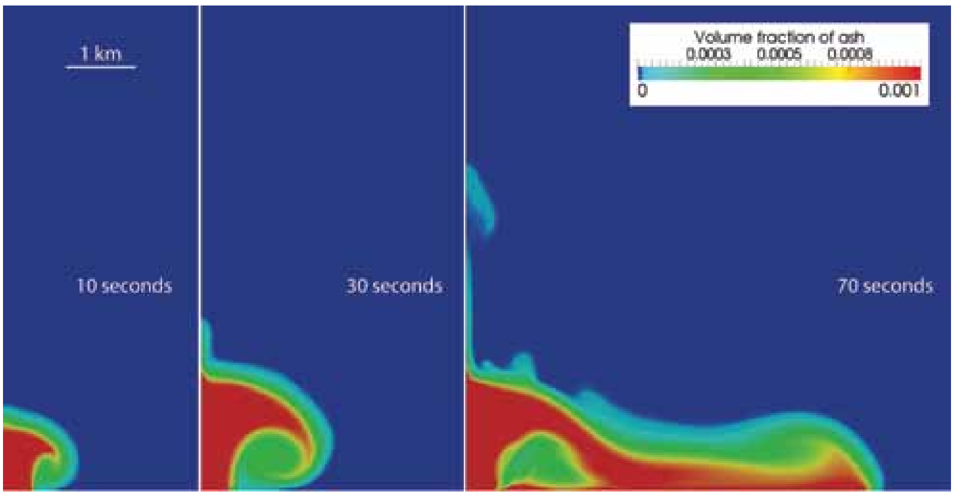
Publications

1. C. T. Jacobs, G. S. Collins, M. D. Piggott, S. C. Kramer, C. R. G. Wilson
Multiphase flow modelling of volcanic ash particle settling in water using adaptive unstructured meshes
Geophysical Journal International, 192(2), p. 647–665, 2013

2. C. T. Jacobs
Modelling of multiphase flows on adaptive unstructured meshes with applications to the dynamics of volcanic ash plumes
PhD Thesis, Imperial College London, 2014



« **Figure 16:** Volcanic ash particle settling in a water tank (0.3 x 0.3 x 0.7 metre). 48 micrometer particles initially settled at approximately 0.17 cm/s, as predicted by Stokes' law. As more particles flux in, the particle-laden layer became unstable and plumes began to form, resulting in settling velocities over 10 times greater than that of an individual particle.



« **Figure 17:** Particle distribution at three times during a simulated a volcanic eruption (10s, left; 30s, middle; 70s right). As the volcano erupts, hot ash and air at 1,100 K enter the domain at 80 m/s, forming a cloud of particles and an overhanging vortex caused by drag effects. After this buoyant fountain of ash rises until approximately 1 km above ground level, where it starts to collapse; the majority of the settling particles create a dense, high-speed, ground-hugging pyroclastic flow, while some become entrained in a dilute, buoyant convective region above the fountain. The domain is 7 km by 7 km, resolved by a mesh with a characteristic element edge length of 12.5 m.

Meso-scopic deformation in brittle granular materials

- **Will Neal (RA)**
- **Gareth Collins**

Particulate materials are ideally suited to shock absorbing applications because large amounts of energy are required to deform their inherently complex meso-structure in the process of compaction. We are using experiments and models to understand how particle-scale deformation mechanisms are affected by loading rate with a view to improving macro-scale compaction models to represent the bulk material.

In brittle particulate systems, the majority of densification is caused by particle fracture. In a preliminary study we investigated the differences in fracture behaviour between quasi-statically and shock loaded glass-microsphere beds.[1,2] Macro-scale quasi-static (20 µm s^{-1}) and dynamic compaction curves were measured that show subtle qualitative differences in stress-density space. Samples were recovered from a quasi-static and dynamic experiment at a similar order of stress. Differences in fracture behaviour were observed that may explain the differences in crush curves. Results suggest that the primary total-fracture process occurs relatively instantaneously at low stresses in the quasi-static regime. The sphere fracture process is slow relative to the stress-wave transit, causing a different fracture pattern in the shock regime.

Results from the dynamic shock compaction experiments are being used to validate meso-scale numerical simulations that replicate the experiments (figure 18). Such simulations will provide insight into grain-scale deformation and help to parameterize the compaction response in the form of a macro-scopic model.

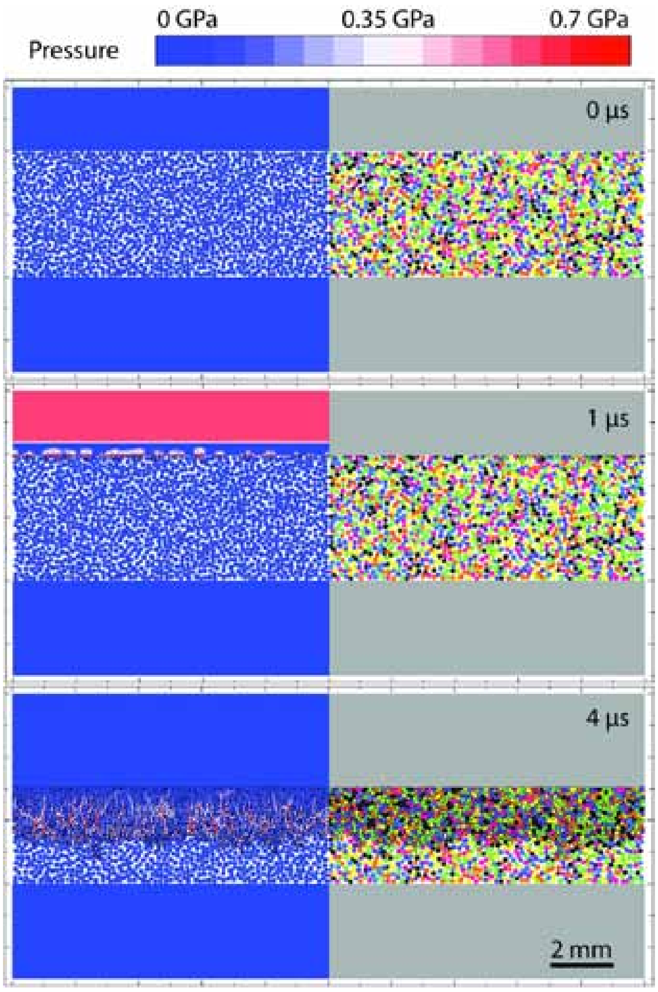


Figure 18: Three snapshots from a meso-scale numerical simulation of shock compaction of a bed of 60 µm glass beads showing pressure (left) and material (right). A 4-mm sample bed of silica beads is sandwiched between PMMA cover and buffer plates (top). A 400 m/s plate impact (not shown) sends a planar shock wave through the cover plate into the particulate bed, resulting in compaction (middle). Force chains develop in the particulate material due to the meso-scale structure of the material, resulting in heterogeneous wave propagation.

Publications

1. Neal W, Collins G. S
The Compaction of Brittle Particulates at High Strain-Rate: Experiments and Numerical Simulations
European Planetary Science Congress 2013, id. EPSC2013-1000, 2013

2. Neal W, Appleby-Thomas G, Collins G
Meso-scopic Densification in Brittle Granular Materials
Bulletin of the American Physical Society 58 (2013)

Measurements of Birefringence Change in Shocked Calcite

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

Birefringence is an optical property caused by a material's anisotropic electronic structure, which results in a directionally dependent refractive index. This effect can also be exaggerated or indeed produced under loading, as is routinely observed in polymers such as Perspex and PC. One of the principal aims of this work is to characterise the link between optical birefringence and mechanical state for a material which undergoes dynamic loading. Such an optomechanical constitutive model may be used as a non-invasive probe of strain, and ultimately to perform 2D optical mapping of strain nonuniformities in heterogeneous materials and structures (interfaces, grains, etc.).

Calcite is an excellent example of a birefringent material, having been extensively studied under dynamic loading. Initial experiments have been conducted using a free-space polarimeter to study the change in birefringence of calcite under shock compression. A change in the birefringence of 0.0029 ± 0.0001 was observed in these experiments. Since then the study has been continued, with the main aims of reducing inaccuracies and improving the quality of data. Improvements to the free space polarimeter have both extended the duration and increased the precision of data collected.

With the improvements that have been made, the optical properties on sample release have been measured. It is also possible now to distinguish more accurately the change in birefringence (difference between the ordinary and extraordinary refractive indices) compared to changes in the direction of the optical axis.

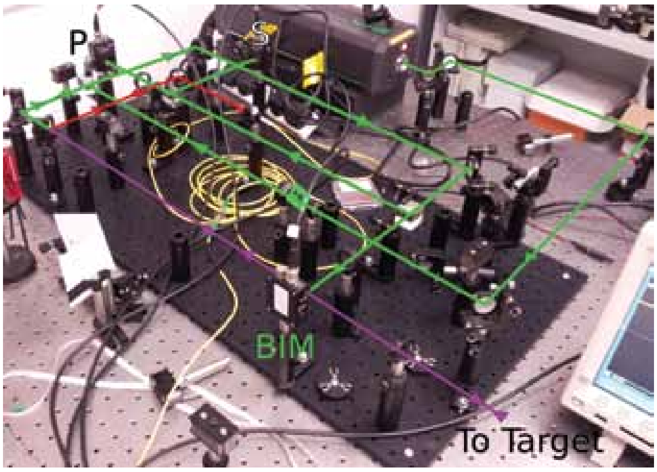


Figure 19: The optical polarimeter constructed for these experiments. The polarimeter also includes a fibre based Photon Doppler Velocimetry probe (Red Beam Path) which is combined with the polarimeter beam using a dichroic mirror. This is used for time of arrival measurements to determine shock velocity.

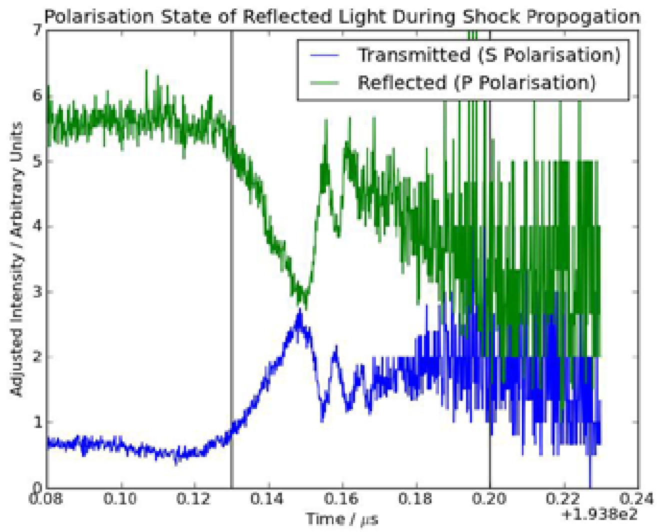


Figure 20: Change in the degree of S and P polarization in the light returned from the sample can be seen. As the shock propagates the polarization state rotates between S and P giving the out of phase oscillations. This is consistent with a change in birefringence in a material. The vertical black line marks shock arrival at the sample front surface. Transmitted and Reflected in the legend refer to the interaction with the polarizing beam splitting cube, not the sample.

TECHNIQUE DEVELOPMENT

Tailored-loading and recovery experiments with the Split Hopkinson Pressure Bar

- **James Wilgeroth (RA)**
- **William Proud**

In Split Hopkinson Pressure Bar (SHPB) experiments, the user is typically concerned with the interactions brought about by the initial compression pulse. However, the apparatus delivers successive compression pulses to the sample as the waves ring up and down the incident bar. The extent of strain imparted to the test specimen is also not limited in the typical SHPB configuration. These characteristics are undesirable when one wishes to subject the sample to a fully-determined loading history from which it may be recovered for post-test analysis. Consequently, the Centre for Blast Injury Studies (CBIS) has developed a precision wave-capture device which will allow a compression wave of predefined intensity and duration to be imparted to sample materials, e.g. human cortical bone. Furthermore, the ability to recover samples when using the system will allow the evolution of damage within materials at high rates of compression to be studied in greater detail. The device functions in three main stages (see figure 21 below). Firstly, a compression pulse is sent down the incident bar and Momentum Trap 1. The pulse is transferred through a flange to Momentum Trap 2, which then moves away and absorbs momentum from the striker. Finally, Momentum Trap 1 moves away when the reflected wave returns in the incident bar. The concentric parts of the device act sequentially to capture the waves, removing the need for the pre-set gap seen in other SHPB recovery methods.

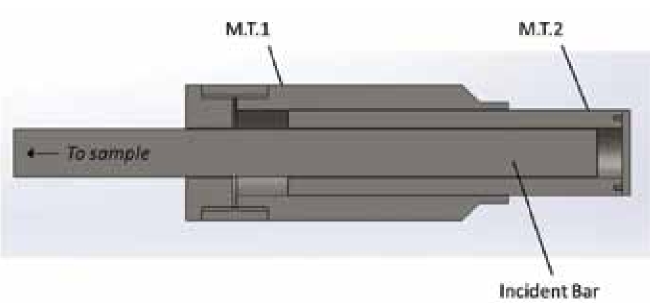


Figure 21: Schematic of the momentum-capture device designed for the SHPB, shown in open configuration.
M.T.1: Left-going capture of incident pulse.
M.T.2: Right-going capture of reflected pulse.

Shock Tube Characterisation

- **Thuy-Tien Ngoc Nguyen (PhD student)**
- **James Wilgeroth (RA)**
- **William Proud**

The shock tube is a versatile apparatus used in a wide range of scientific research fields since its invention in 1899. It is able to generate well-defined pressure pulses of various intensities and durations. The sudden rupture of the diaphragm brings the high-pressure driver gas into contact with the driven gas of low pressure (figure 22). As the expansion wave spreads out the compression wave forms a shock front that travels along the tube. Simultaneously, a rarefaction wave moves back into the driver section.

A blast wave lasts for a very short time, but can cause severe damage to surrounding objects and structures through drastic changes in pressure, flying debris and strong propulsions following the incident shock front. The ability to re-create blast effects in the laboratory environment is essential in order to study blast injuries, which is the aim of our studies using the shock tube. In this project, we are developing a shock tube system which can be used to study blast effects on biological samples representing injuries in open space as well as inside vehicles. It allows various cellular suspensions (e.g. osteoblast and Schwann cell cultures) to be exposed to shock waves of predefined intensity and duration.

Experiments were performed on an air-driven shock tube with Mylar® and aluminium diaphragms of various thicknesses, to control the output (figure 23). The evolution of shock pressure was measured and the diaphragm rupture process investigated. The arrangement was designed to enable high-speed photography and pressure measurements.

Overall, results are highly reproducible, with the double-diaphragm system shown enabling the diaphragm to be burst at a specific pressure and time, i.e. giving more control over the output shock wave. The magnitude of the shock can be manipulated with the diaphragm burst pressure which is proportional to the diaphragm thickness for the range studied. The duration of the shock pulse can be tailored without significantly affecting its magnitude, by adjusting the length of the high-pressure driver volume. Additional inserts such as granular beds and perforated plates are employed to study the attenuation of blast waves, their effects on a wide variety of materials and for understanding blast mitigation.

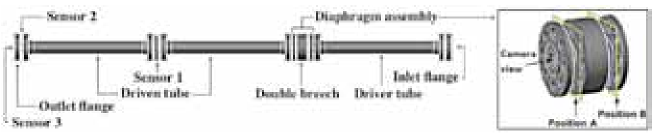


Figure 22: The full schematic of shock tube in closed configuration.

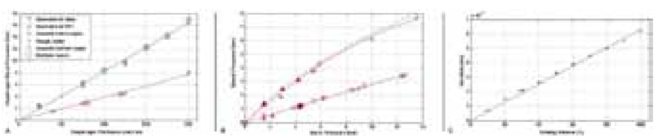


Figure 23: Overall results – A: diaphragm burst pressure versus diaphragm thickness. B: Output pressure versus burst pressure. C: Shock duration versus length of driving volume.

Replicating mild blast injuries using a shock tube

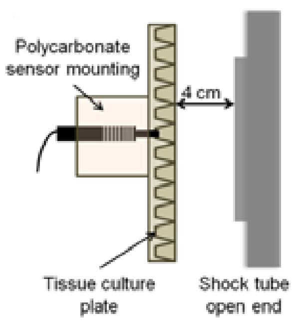
- Chiara Bo (PhD student)
- James Wilgeroth (RA)
- Spyros Masouros (CBIS)
- William Proud

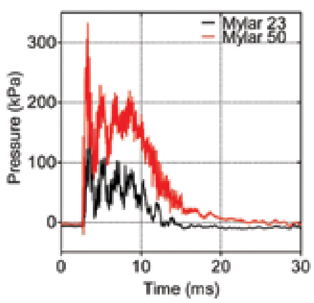
In future work, the intention is to analyse the effects of shock pulses on cells at the order of hundreds of kPa and milliseconds duration, which correspond to mild blast injuries.[1] To this end, a shock tube for *in vitro* overpressure experiments has been developed. The device consists of three stainless steel 1.22 m long tube sections. These tubes are connected by gaskets and flanges, within which pressure transducers and vents are embedded. The driver and driven sections are separated by a diaphragm. The driver section is pressurized from a standard gas cylinder of dry air to a maximum pressure of 18.2 bars. The wave evolution along the tube and at the open end is monitored using ultra high frequency piezoelectric pressure sensors (Dytran Instruments - 2300V1). For a full characterization of the system please see the accompanying paper, Nguyen et al.[2]

The *in vitro* set up consists of a tissue culture plate secured on a custom-made stainless steel support mounted at the end of the shock tube in the open configuration (figure 24). Each well of the tissue culture plate is filled with liquid medium and the entire plate is sealed with a non-permeable tape (Corning). Initial experiments have focused on the characterisation of the pressure developed within the liquid filled-wells. A custom made polycarbonate sensor mounting is attached with epoxy resin to the rear surface of the tissue culture plate, in which a hole is drilled to allow insertion of the pressure sensor (Dytran Instruments – 2300C4). As shown in figure 25, varying the diaphragm thickness corresponds to waves of increasing peak pressure generated inside the wells of the tissue culture plate. Preliminary results from overpressure experiments on a MSCs monolayer suggest that the viability of cells exposed to the shock wave is reduced depending on the orientation of the plate with respect to the open end of the shock tube.

Publication

Nguyen T-T N, Wilgeroth J M and Proud W G
Controlling blast wave generation in a shock tube for biological applications
J. Phys.: Conference Series 500 (2014) 142025





Cell-culture shock experiments

Figure 24: Pressure waves developed inside the central well of the tissue culture plate in correspondence of shock tube overpressures generated using Mylar diaphragms of 23 µm (black) and 50 µm (red) thicknesses respectively.

Figure 25: Schematic of the *in vitro* shock tube setup used for the measurement of the pressure waves generated inside the tissue culture plate.

Cylindrical Convergent Isentropic Compression

- Marcus Weinwurm (PhD student)
- Simon Bland
- Jeremy Chittenden

Cylindrical isentropic compression provides a potential mechanism for controlled compression of materials to very high density states whilst preventing excessive heating which would limit compression. By utilising the method of fictitious flow the external pressure required to generate an optimised ramp wave in the imploding material can be determined. By extending this technique to cylindrical geometry and extending the method to include magnetically driven external pressure sources, we have been able to design possible pulsed power experiments which can compress target materials to extremely high densities within imploding metallic liners. This technique can be exploited to increase the peak compression within magnetically driven inertial confinement fusion designs.

Using this technique to design methods of compressing of cryogenic hydrogen or deuterium also provides another potential application within planetary science. The 20MA current available within the ZR generator at Sandia National Laboratory, provides sufficient magnetic pressure to compress materials to TPa pressures. In order to reproduce the states of matter within gas giant planets however, this compression needs to be achieved whilst keeping the material relatively cool. Extension of the fictitious flow method has been shown to allow compression of deuterium to densities above 104 kg/m3 whilst maintaining temperatures below 1eV. For slightly smaller currents, the final compressed state can be tuned to match the conditions required for the possible production of metallic hydrogen states. The relatively large scale (cm long, mm diameter) of the compressed state with open end-on access provides significant potential for experiments to measure the conductivity of the hydrogen contained within the imploded liner.

Publication

Weinwurm M, Bland SN, Chittenden JP
Metal liner-driven quasi-isentropic compression of deuterium
Phys. Plasmas 20, p92701 (2013)

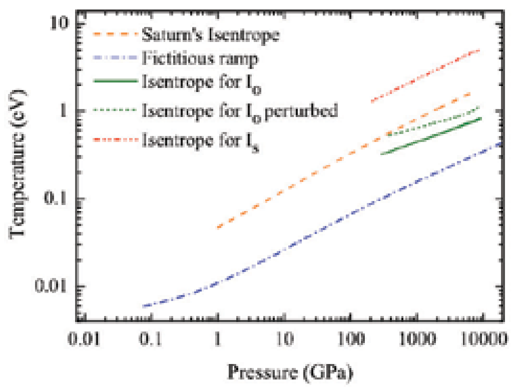


Figure 26: Comparison of calculated mass-averaged isentropes from simulations (following peak compression) to the isentrope of Saturn's planetary core. The blue dashed line is the ideal result from a perfect ramp wave represented by the fictitious flow. The green lines are from simulations of liner driven implosions with a shaped current drive. The shaped current results in a significantly lower temperature than with a straightforward sine-squared current pulse (the red line) and provides a much better approximation to the isentrope of Saturn.

Real-time, *in situ* X-ray studies of the mesoscale during dynamic loading

- Michael Rutherford (PhD student)
- David Chapman (RA)
- Daniel Eakins

A rigorous understanding of the behaviour of condensed matter under the extreme conditions induced by dynamic loading necessitates an appreciation of material behaviour across length scales spanning the mesoscale (sub-µm to mm) to the continuum. For many years though, the existence and kinetics of fundamental processes responsible for bulk material behaviour have often been inferred from either time-resolved continuum-level measurements or microstructural analysis of material recovered post-shock. Ultimately, real-time, *in vivi*, spatially and time-resolved studies of the mesoscale are required to understand the evolution of processes such as defect generation, localised plasticity, and phase transformation in compressed materials.

X-rays are ideally suited to probe transient material phenomena in real-time via non-destructive absorption and diffraction techniques. With this in mind, the ISP has recently undertaken an effort to develop an experimental X-ray capability to study mesoscale phenomena in industrially-important, dense (high-Z) materials. A key element of this project is to exploit the X-ray brilliance and sub-ns temporal resolution offered by 3rd-generation synchrotron radiation. By integrating a gas launcher on a high-energy (>50 keV) beamline this work seeks to provide direct access to intermediate time-scale processes during shock-compression, complimenting dynamic experiments at the Advanced Photon Source synchrotron (USA), which are focussed on the incipient stages of deformation.

The first campaign of the dynamic imaging project was undertaken in September 2013 at beamline I12 at the Diamond Light Source synchrotron (Harwell, UK) with the primary goal of demonstrating a dynamic X-ray imaging capability. Beamline I12 provides a broadband X-ray source (50 – 150 keV) and is therefore ideal for dynamic measurements of dense materials. Furthermore, the large experimental hutch (EH2) (11 x 7 x 4 m) facilitates assembly of the mesoscale gas-launcher alongside a host of complimentary diagnostics. Figures 27 and 28 show, respectively, the experimental apparatus in EH2, and a real-time, *in situ*, dynamic radiograph of a copper flyer impact on a stainless steel powder sample. The latter was captured over several hundred nanoseconds. Figure 28 clearly shows the sabot, copper flyer, plastic surround, and shock-compressed powder although the features appear blurred due to image ghosting on the scintillator and the long integration time. This image, along with others not shown here, are the first dynamic images captured at the Diamond Light Source and demonstrate a new real-time, *in situ* X-ray imaging capability for the ISP and UK.

Looking forward, we intend to improve light collection by implementing new optics and beam-paths, upgrading to the next-generation intensified-CCD camera, and introducing a better-performing scintillator. Together, these improvements will minimise image ghosting, thereby allowing us to approach the temporal resolutions offered by 3rd-generation synchrotron light sources. The next campaign will also see the addition of complimentary methods such as X-ray micro-tomography and velocimetry (heterodyne-velocimetry and line-VISAR). A range of mesoscale phenomena highlighted for this campaign includes: pore-collapse and jet-formation in steel lattices, grain communition and densification in ceramic powder beds, crack propagation in ceramic plates, and void coalescence in metallic alloys.

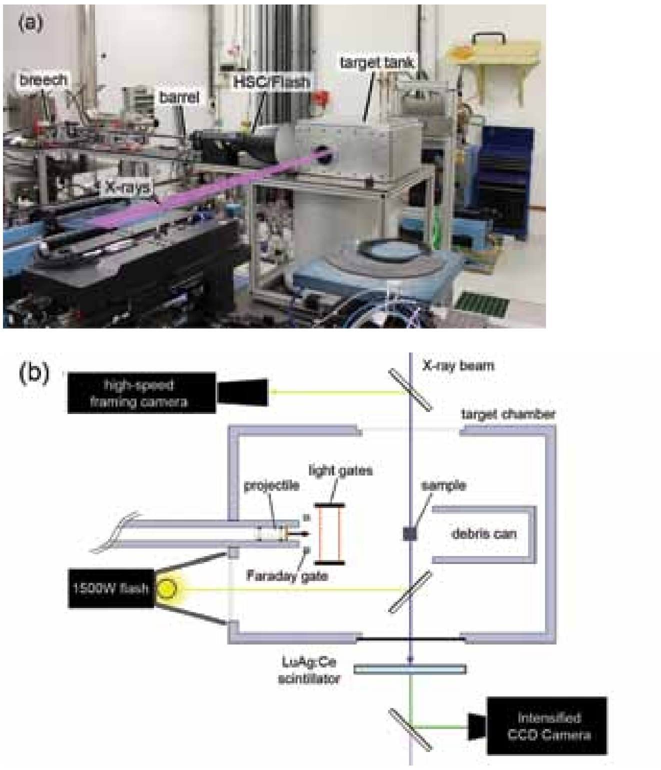


Figure 27: (a) The mesoscale gas launcher installed in EH2 of I12, and (b) schematic showing the configuration of the impact experiments with respect to the X-ray beam. Simultaneous X-ray images and backlit high-speed frames were captured in each experiment.

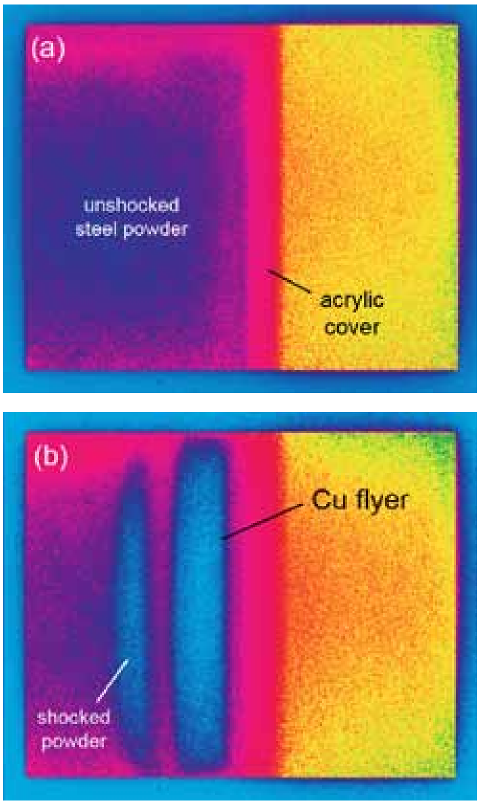


Figure 28: (a) Static, pre-shot image of a low-density stainless steel powder. (b) Dynamic X-ray image capturing the impact of the steel powder by a Cu flyer plate, and the launching of a shock wave.

Determination of spatial temperature variations in dynamically compressed materials

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

The experimental characterisation of the temperature of dynamically loaded materials is of fundamental importance and presents a long-standing issue in shock science. Difficulties lie in the short duration (<ms) of dynamic compression experiments and the fact that the onset of phenomena such as nucleation/growth of hot-spots, shear localisation and heterogeneous melting result in spatially varying temperature distributions.

Building on the principle of temperature measurement through Au reflectivity measurements, a spatially-resolved reflectometry system is being developed to measure thermal gradients in the vicinity of hot spot regions in heterogenous targets. The initial stage of this project is taking place at The Wolfson Laboratory for Ultrafast Imaging of Extreme Physical Processes at Imperial where the ISP is currently developing a long-pulse laser loading facility in collaboration with the Laser Physics Consortium and Plasma Physics Group. Once in operation, the new reflectometry diagnostic system will be transferred to other ISP loading capabilities such as the mesoscale gas gun and combined with other available diagnostics such as the dynamic high-resolution X-ray imaging.

To complement this surface measurement technique, in-material temperature measurements of shocked samples will be carried out using the neutron resonance spectroscopy (NRS) technique at the ISIS Pulsed Neutron and Muon Source at the Rutherford Appleton Laboratory. Combined with reflectivity thermometry and velocimetry interferometry, it will allow for rigorous thermo-mechanical characterisation of materials.

X-ray diffraction experiments using a portable X-pinch

- **Frederic Zucchini (CEA)**
- **Simon Bland**
- **and a whole team of friendly folk at CEA**

As part of a collaboration with Frederic Zucchini of CEA Gramat, a series of experiments examining the use of a portable X-pinch system as a source of hard X-rays for diffraction has been conducted. Measurements suggested a Mo pinch provided ~100mJ of radiation >10keV in a burst <50ns in duration. Samples of single crystal Al and Sn provided by AWE, and LiF provided by CEA were all successfully probed. In Al and LiF experiments a simple Laue camera arrangement allowed multiple reflections to be observed, which have now been analysed (figure 30).

Based on these promising results, future work will re-commission an X-pinch system at Imperial, and explore the possibility of using the X-pinch in dynamic experiments. This newly developed source will also be used to examine low density foam targets provided by AWE with phase contrast radiography.

Figure 29: The X-pinch driver used in experiments at CEA Gramat. Use of modern capacitor-switch technology, results in an extremely compact system – 0.5x0.5x1.5metres – supplying ~300kA in 450ns to the X-pinch load.

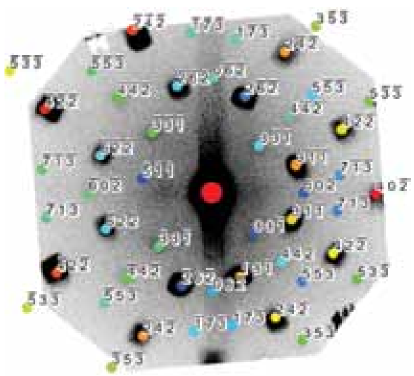


Figure 30: Laue diffraction pattern from 1mm LiF crystal, overlaid with a simulation from 'Single Crystal'. To obtain agreement between the simulation and results, incident radiation of at least 35keV must be produced by the X-pinch.

A fibre based triature interferometer for measuring low plasma densities

- James Macdonald (AWE)
- Simon Bland
- Jim Threadgold (AWE)

A novel fibre optic based interferometer incorporating triature analysis has been developed at AWE, based on original designs by Dr Bland in the ISP/Plasma Physics Group. Fibre based heterogeneous velocimetry systems have long used triature techniques to improve the accuracy of low speed measurements. Here the same method allows rapidly evolving plasma densities of ne ~ 10^{14} cm^{-3} to be measured accurately (figure 31). Such plasmas are commonly produced by the coaxial guns in plasma filled rod pinch diodes, which are used as a very hard, high yield X-ray sources in Hydrodynamics experiments. The resultant system is extremely portable, easy to field in experiments, relatively cheap to produce and – with the exception of a small open area in which the plasma is sampled – safe in operation as all laser light is enclosed. Results of the experiments will be used to help optimise the use of diodes in forthcoming research.

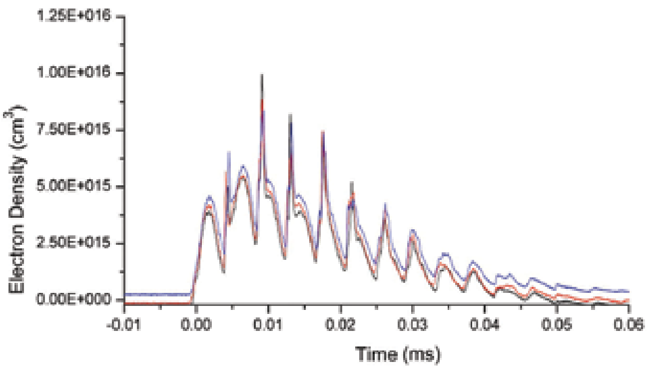


Figure 31: Time resolved electron density measurements taken across a diameter of a simple plasma gun.

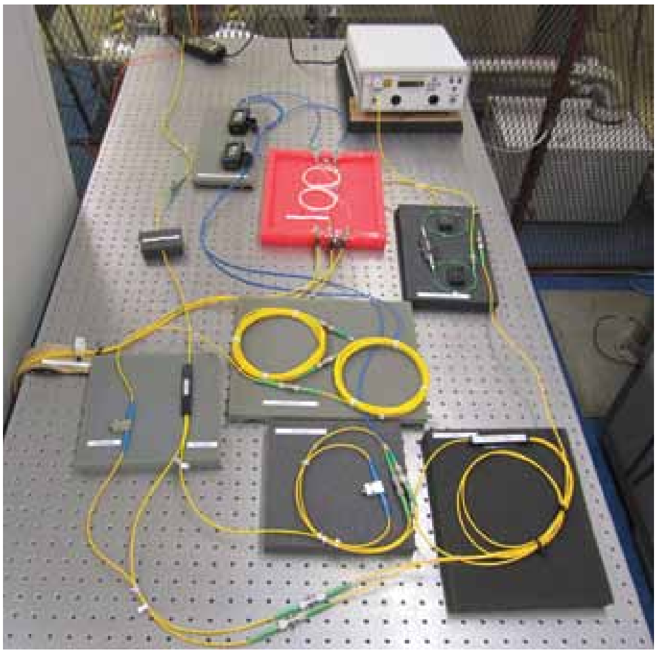


Figure 32: An initial set up of the fibre interferometer at AWE Aldermaston, prior to being encased in a 19" rack unit. The interferometer is made from simple, commercially available parts, and is highly portable.

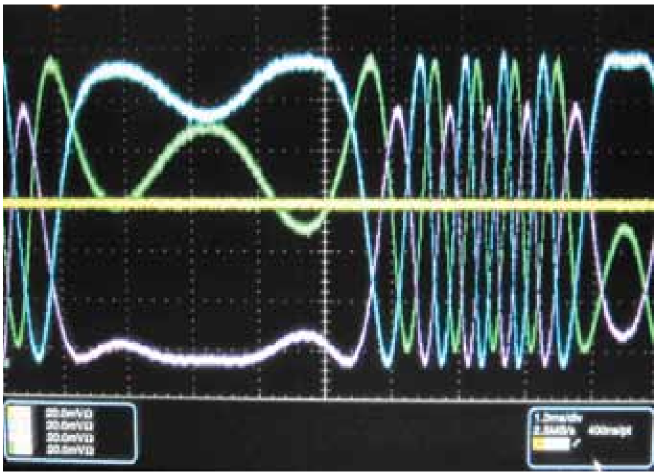


Figure 33: Results from the interferometer probing a test plasma. Three signals are recorded, with phase shifts of 1200 between the reference beam and the beam passing through the target – this allows exceptional noise reduction, enabling very low density plasmas to be probed accurately.

Sam Stafford aligning a free-space optics imaging system into the large bore gas-gun. The experiment aims to quasi-isentropical compress water, using a combination of high speed photography and velocity interferometry to investigate the kinetics of the water to ice VII phase transition.

University College London

Static High Pressure Group

- Paul McMillan
- Furio Corà
- Dominik Daisenberger (PDRA, now at Diamond Light Source)
- Richard Briggs (PhD student, now at Department of Physics and Centre for Extreme Conditions Science, University of Edinburgh)
- Melissa Cutler (PhD student)
- Ashkan Salamat (Department of Physics, Harvard University)

During the final year of our contract our group has completed several series of high-pressure, high-temperature experimental investigations in the laser-heated diamond anvil cell (LH-DAC) combined with density functional theoretical (DFT) calculations.

Unusual structural transformations and high pressure melting behaviour of tin (Sn)

This project studied crystalline transformations occurring in Sn up to 160 GPa and obtained the first melting data up to 105 GPa. Formation of the predicted hexagonal close packed (hcp) phase was recorded at 156 GPa and the unusual 'coexistence' phenomenon of body-centred tetragonal (or orthorhombic) and cubic structures was studied in the 40-70 GPa region. Current models suggest that this unexpected behaviour occurs due to domain formation in response to an underlying instability against c/a distortion within the body centred phase. That result has an influence on the melting relations that reach an apparent plateau above approximately 40 GPa. However, the melting temperature rises again beyond 70 GPa to achieve 5500 K by 105 GPa. This leads to a new numerical expression fit to the melting relations for use in materials phase and property simulations as well as permitting an extension into the multi-megabar range for comparison with shock and ramp studies.

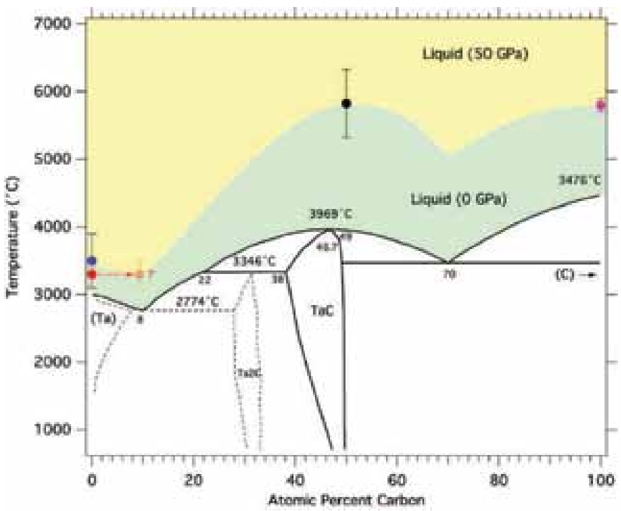


Figure 34: Melting relations in the Ta-C system at 50 GPa from LH-DAC and synchrotron X-ray data. The TaC melting point occurs at 5700 +/- 500 °C, close to that of diamond and significantly above that of pure Ta. The data previously reported for Ta melting could correspond to a eutectic or peritectic in the system due to reaction between Ta and C derived from the diamond windows (red point).

Melting Tantalum carbide (TaC) at high pressure

Recent controversies have surrounded the experimental determination of Tantalum melting with substantial differences emerging between shock data and density functional theory predictions compared with LH-DAC results. Those discrepancies were recently attributed to formation of a TaC phase during the LH-DAC experiments that could be misinterpreted as a melting event. Here, we examined the melting relations of TaC itself. This refractory phase has one of the highest melting points recorded to date, reaching 6500 K by 50 GPa. The new data will allow us to examine and complete thermodynamic phase relations in the system.

Melting Xenon (Xe) at high pressure

Melting relations of the rare gas, Xe at high pressure are likewise controversial. Theory predicts a systematic increase in Tm consistent with expectations from simple melting models. However LH-DAC studies have indicated a plateau emerging above 40 GPa that has been interpreted as hcp vs ccp domain formation within the underlying crystal. Our new results to 80 GPa find that the melting temperature increases monotonically as predicted by theory.

Publications

A. Salamat *et al.*
High pressure structural transformations of Sn up to 138 GPa
Phys Rev B, 88, 104104, 2013

R. Briggs *et al.*
Melting of Sn to 1 Mbar
J Phys: Conf Ser, 377, 012035, 2012

A. Salamat et al.
Dense close-packed phase of tin above 157 GPa observed experimentally via angle-dispersive X-ray diffraction
Phys Rev B, 84, 140104, 2011

D. Daisenberger *et al.*
Polyamorphic amorphous silicon at high pressure: Raman and spatially resolved X-ray scattering and molecular dynamics studies
J Phys Chem B, 115 (48), 14246–14255, 2011

PhD thesis
R. Briggs
In Situ Study of Polymorphism and Melting of Metals and Compounds under Extreme Conditions of High Pressure and High Temperature
UCL, Chemistry, awarded May 2013

Cranfield University

Defence Academy of the United Kingdom

Dynamic Response Group

- Dr Gareth Appleby-Thomas
- Mr David Wood
- Mr Andrew Roberts
- Dr Malcolm Burns (Visiting Researcher)
- Mr Michael Goff (PhD student)

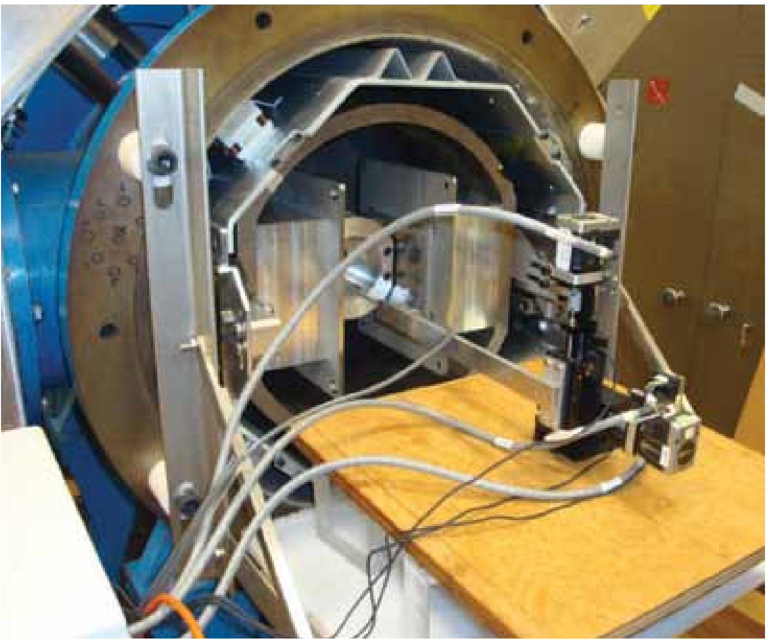


Figure 35: Three-axis defined motion system used in conjunction with a gauss meter to characterise the magnetic field of the NeFeB N50 permanent magnet system employed on the 50 mm bore single-stage 'blue gun'.

A founding partner of the ISP, Cranfield University – via the Dynamic Response Group – takes an active role in shock-based research. The group has published c.a. 30 peer-reviewed journal articles since the inauguration of the ISP. In addition, numerous collaborations have ensued between Imperial, University College London and AWE amongst others. Areas explored have ranged from survivability of seeds and bacteria to the development of a ceramic graded areal density impact system.

Our facilities include several single-stage gas guns; in addition, uniquely in the EU, our location and capabilities allow us carry out experiments on explosive materials. Since joining the ISP our diagnostic capabilities have expanded significantly and we are now able to deploy not only stress/strain gauges and multiple channels of Het-v equipment, but also flash X-ray and particle-velocity (PV) gauge systems. The latter system is the core diagnostic of an ISP funded PhD on the subject of ramp loadings of explosive targets.

The PV system (figure 34), which is used to observe run-to-detonation in shock loaded explosive targets, has been developed for use on two of our gas guns using permanent magnet systems. In this technique, wire-element gauges are embedded in explosive or inert polymer targets. When the target is shocked, the gauge packages move with the surrounding material. A planar magnetic field surrounding the target causes induced currents in these gauges that are proportional to their velocity. The use of permanent magnets as opposed to the legacy electromagnetic Helmholtz coils has the advantage of ensuring a stable and predictable field, thereby maximising data quality.

This diagnostic is being used in conjunction with a novel ceramic graded areal density impact system (colloquially referred to as 'spiky flyers') to produce ramp loadings in inert and explosive targets. This system uses a flyer with multiple raised spikes in conjunction with a buffer plate. The spikes impact the buffer and the multiple wavelets produced constructively interfere to cause a ramp loading which enters the target. This system presented several development challenges due the restrictions on material choice imposed by the PV gauge system. Currently rapid prototyped fully dense alumina ceramics are used, with laser micromachining being investigated.

Publications

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

Wielewski E., Appleby-Thomas G. J., Hazell P. J., Hameed A. (2013)
An experimental investigation into the micro-mechanics of spall initiation and propagation in Ti-6Al-4V during shock loading
Mater. Sci. & Engng., 578, 331–339

Appleby-Thomas G. J., Hazell P. J.,Sheldon R. P., Stennett C., Hameed A., Wilgeroth J. W. (2013)
The high strain-rate behaviour of selected tissue analogues
J. of Mech. Behav. Of Biomed. Mater., In-press
Hazell P. J., Appleby-Thomas G. J., Philbey D., Tolman W. (2013)*The effect of gilding jacket material on the penetration mechanics of a 7.62 mm armour-piercing projectile*
Int. J. Impact Engng., 54, 11–18

Centre for Blast Injury Studies

Force blast protection

- William Proud
- Kate Brown (Austin, Texas and Cambridge)
- Chiara Bo (PhD student)
- Thuy-Tien Nguyen (PhD student, CBIS)
- James Wilgeroth (CBIS)
- 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.

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 PhD student, 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 theme 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 from the University of Cambridge.

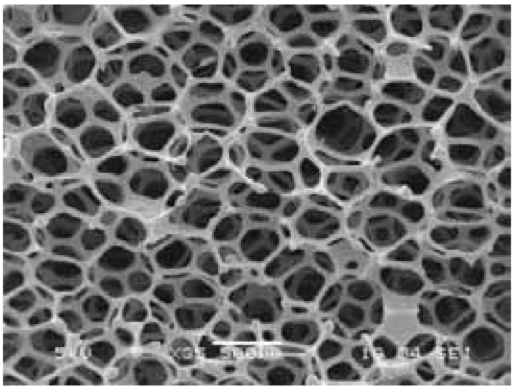


Figure 36: Scanning electron micrographs of a 79 ppi foam sample.

Blast-induced auditory injury

Injuries to the tympanic membrane (ear drum) are particularly common in individuals subjected to blast overpressure such as military personnel engaged in conflict. The interaction between blast wave and reticulated foams of varying density and thickness has been investigated using shock tube apparatus within the CBIS. The degree of mitigation afforded by the foam samples was examined in relation to an injury threshold which has been suggested for the tympanic membrane. A key focus of the research was to examine materials that may offer hearing under normal conditions but 'react' upon witnessing blast overpressure. A scanning electron micrograph of one of the tested foams (79 ppi (pores per inch) reticulated polyurethane foam) is shown below. Foams were placed ahead of a polycarbonate chamber, which was designed to mimic a 'real-world' device, and the magnitude of the transmitted shock was measured with a dynamic pressure sensor. The results from a range of foam densities and thicknesses were examined in relation to uninfluenced shock wave profiles. Results from this work showed that the shock front was indeed perturbed by the reticulated foams; however, peak overpressures were not significantly reduced. This research hence suggests that the solution to adaptive auditory protection may lie with digital technologies that are capable of detecting an incoming blast wave. Such technologies might, for example, apply an electric current to an adaptive material resulting in the closure of pore spaces.

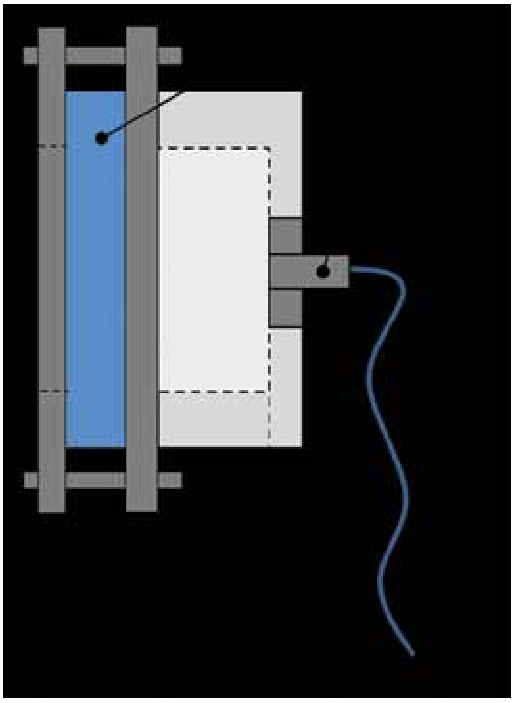


Figure 37: Experimental arrangement – polycarbonate chamber.

Figure 38: ISP/CBIS shock tube apparatus.

Performance characterisation of a shock tube system

This project seeks to characterise the performance of a shock tube system to be used in a number of research avenues within the ISP and CBIS at Imperial. The relationship between diaphragm rupture and pressure evolution within the system has been an area of key interest to date. However, methods which will allow the user to alter the pressure profile in terms of intensity, shape, and duration are in development. This will permit study of a wide range of blast conditions on biological and blast-mitigating materials within the respective centres. Materials of interest include lung tissue, cell cultures, and reticulated (open cell) foams. The shock tube system is illustrated in figure 38. The pressurised section, i.e. the driver tube, is typically separated from the ambient section of the system using either a single or double aluminium or Mylar® diaphragm arrangement. Sudden rupture of the diaphragm(s) creates a blast wave (a shock-front of compressed gas) which propagates towards the shock tube outlet and target area. Future research areas related to the performance of the shock tube apparatus include:

- The study of stress distribution and shock flow around samples of differing size and shape
- Using metallic meshes and granular materials inside the tube to alter shock flow
- Examination of shock interactions using high-speed photography with birefringence and Schlieren methods
- Development of finite-element simulations for studying shock wave formation, loading of irregular shapes (e.g. mouse lung)

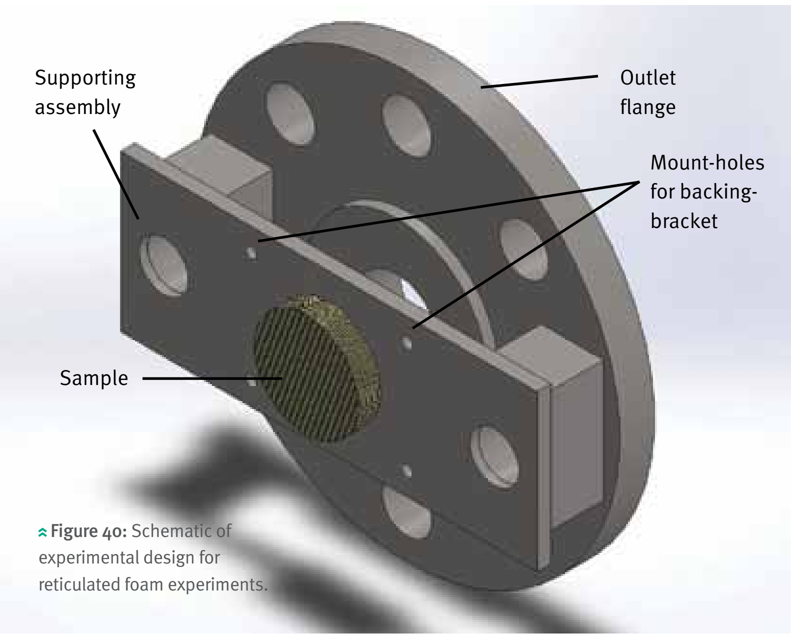


Figure 40: Schematic of experimental design for reticulated foam experiments.

Figure 39: Examples of aluminium diaphragm bulge and rupture.

The interaction of blast wave with reticulated foam

Injuries to the tympanic membrane (ear drum) and inner ear are particularly common in individuals subjected to blast overpressure, such as military personnel engaged in conflict. Consequently, there is a demand for improved auditory protection systems, which are capable of both preventing this type of injury while providing maximum situational awareness to the user. An experimental design allowing for a number of reticulated (open cell) foams to be subjected to dynamic compression using the shock tube within CBIS has been developed by James Wilgeroth. Specific effects of porosity; relative density, which is determined by the ratio of cellular material to solid material from which the foam is made; sample thickness; incident pressure; and shock pulses of varying timescale upon the evolution of peak overpressure behind foam samples are of key interest. In addition, the use of Schlieren imaging techniques will allow for detailed examination of gaseous flow at the rear surface of shocked foam samples.

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:

Research talks

1 HOUR

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, PhD student Chiara Bo has been invited to give a talk at the 2013 SCCM/APS meeting.

Continuous professional development

1 DAY

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.

Annual conference

2 DAYS

Aimed at ISP members and colleagues in related research areas. This provides an excellent opportunity to discuss research, find out what has been achieved and find inspiration from fellow scientists and engineers.

Undergraduate course 'Shock Waves and Hydrodynamics'

10 WEEKS

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.

BSc/short projects

3 MONTHS

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.

Masters projects

6 MONTHS

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 the summer of 2012 Thuy-Tien Nguyen undertook a project involving the characterisation of a shock tube for use by CBIS. She investigated the rupture of the diaphragms in the system during operation and also the propagation of the shock pulse throughout the system.

Extended projects

1 YEAR

Aimed at active researchers and postgraduate students. The ISP has established a one-year MSc course in 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 2013, the MSc students are heading out to the Technical University of Pardubice for blast range training.

A happy day. MSc graduate Sean Mongahan (AWE), Dr Will Neal and MSc graduate John Winters at the Royal Albert Hall, May 2013.

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.

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.

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 the summer at Imperial was dominated by the London Olympics and Paralympics but this did not prevent UROPs!

3 DAYS

6 WEEKS

8 WEEKS

2 YEARS

3 YEARS

6 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.

PhD studies

For graduate researchers. A doctoral degree provides the standard entry-level qualification to research. The ISP has hosted 23 PhD students so far, including one funded by QinetiQ and one funded by The Royal British Legion.

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. Ruth Tunnell is one example of a successful graduate who has completed in record time.

Dr Bill Proud with part-time industrial PhD student Ruth Tunnell as she signs a copy of her thesis for her supervisor.

Imperial College London

Facilities

Technical support is provided to ISP research:

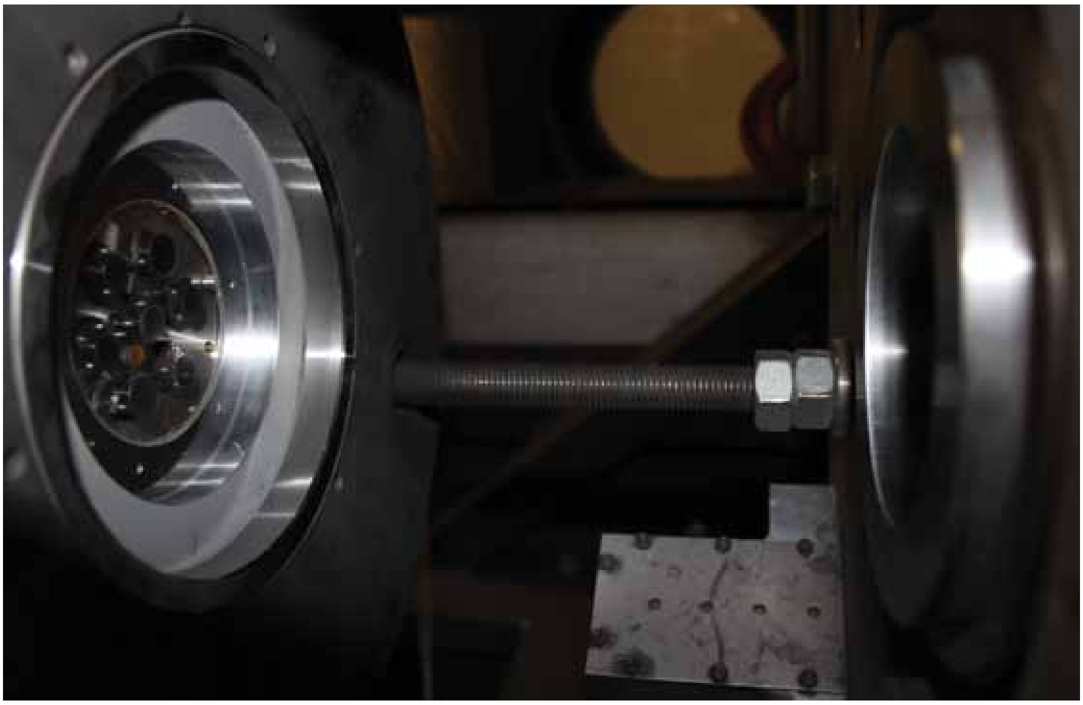
Imperial College London
- Steve Johnson
- Dave Pitman
- Alan Finch
- Physics instrumentation workshop

Cranfield University
- Andrew Roberts

University College London
- Ed Bailey
- Steve Firth

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 the wider range of standard testing platforms, and materials characterisation available to the Institute throughout the wider Imperial enabling a holistic interrogation of material response.

Figure 41: A tantalum multi-target mounted in the large bore gas gun; the sapphire buffer enables each Ta foil specimen to be viewed through the impact surface. During a plate impact experiment the 100 mm diameter projectile will exit the barrel muzzle (right of the photograph), and traverse the small distance before impact with the target (left of the photograph) shock loading the specimens.



Large bore gas gun

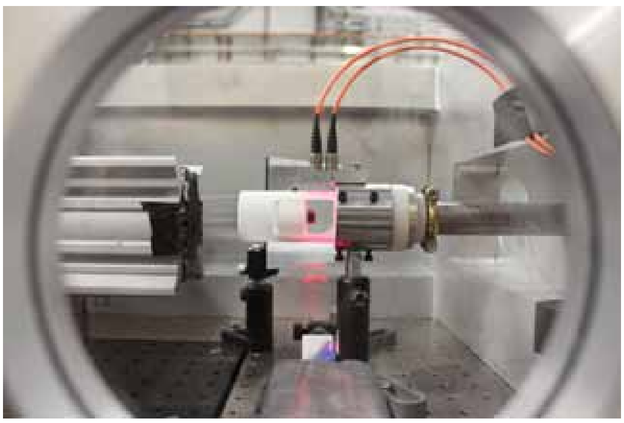
The large bore gas gun at Imperial offers the largest impact area (100 mm in diameter) and highest impact velocity (in excess of 1400 m/s) of any single-stage gas gun within the UK. This unique facility can generate pressure and temperatures of up 70 GPa and nearly a thousand degrees upon impact.

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 PDV 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 are under on going development 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.

The portability of these small scale launcher facilities also offers new and exciting opportunities in terms of the application of advanced diagnostic sources. For example, a small bore launcher (13 mm in diameter) was recently transported to, and has completed two experimental campaigns at the Diamond light source. These pioneering studies employing simultaneous application of X-ray phase-contrast imaging, line-imaging VISAR, PDV, and pre-shock tomography of the specimen are described in greater detail in the research section.

Figure 42: The mesoscale gas launcher installed on the I12 beamline at the Diamond Light Source. The gun has featured in two experimental campaigns, demonstrating the capability for X-ray imaging of dynamic processed in condensed matter.

« Figure 43: A steel lattice target just prior to impact. A combination of optical and magnetic gates were employed to trigger the visible and X-ray imaging systems.

Split Hopkinson Pressure Bar

The Split Hopkinson Pressure Bar (SHPB) apparatus used by both the ISP and CBIS is a rail-mounted system allowing for accurate alignment of both the chosen projectile and functional bars. 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.

MACH Pulsed Power Platform

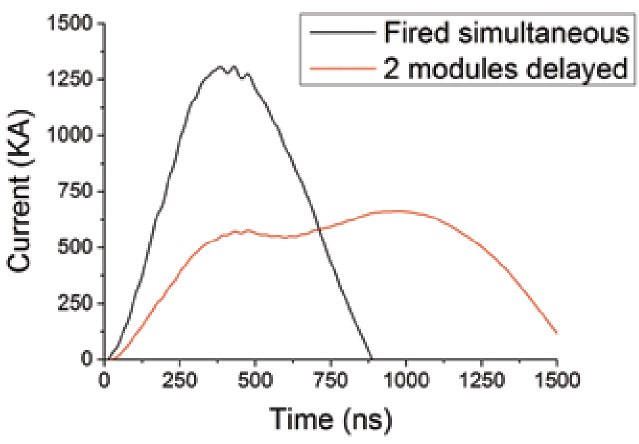
MACH is a 2MA, ~300ns risetime pulsed power facility that is being used to explore isentropic compression techniques at the ISP. Utilising new pulsed power technology, the system is designed to be compact and fast to turn around whilst requiring no noxious gases or oil to provide insulation.

2013 saw the use of MACH inside its new home – the extreme physics laboratory, a large experimental space refurbished by Imperial for collaborative experiments between the Plasma Physics Group, the ISP and the Quantum Optics and Lasers Group.

Working in collaboration with the Naval Research Laboratories the pulse shaping capabilities of MACH were demonstrated for the first time, by using multiple triggers to initiate different parts of the facility. This enabled stepped and ultra long current pulses to be attained, which could form the basis of driving novel pressure waves through targets (figure 44).

A new pulsed power feed, which transfers current from MACH to a strip line load was manufactured by the Physics Instrumentation Workshop. In test experiments this new design appeared to be significantly more reliable than previous versions, enabling strip lines designed for isentropic compression experiments – rather than simplified short circuits – to be fielded. To diagnose these targets a 2 axis orthogonal Line VISAR system was built and tested. This has been fielded in simple experiments, along with a new 3rd generation Het-V diagnostic, that is designed to resist the electrical noise generated during an experiment.

2014 will see the continued use of MACH, with a shift towards it being an experimental platform. To supplement its capabilities, we are presently constructing a large Helmholtz magnetic field system, capable of providing 10T through a large volume of material. This will provide shear based strength measurements of many metals.



« Figure 44: Demonstration of current shaping capabilities of the MACH pulse power facility. In one case all the capacitors in MACH were switched simultaneously to the load, providing a 1.3MA, ~350ns rising current pulse. In a second experiment, the discharge of half of the capacitors was delayed, producing a pulse that rose to ~500kA in 350ns then remained at a similar level for 750ns before decaying. Such currents could provide 'flat topped' pressure profiles enabling time for slower phase changes to occur.

Long-pulse Laser Shock Driver

The ISP is nearing completion of its long-pulse laser shock platform, following refurbishment and setup of a dedicated target area within the Huxley Building. 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 using a low-power beam from the adjacent Cerberus laser lab; 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 micrometers 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 Cerberus drive, 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. When complete, the result will be a new ISP experimental platform dedicated to the study of dynamic material behaviour at short length and time scales (several to 10s of micrometers, sub-ns to nanoseconds). Study at these fine scales provides a unique view to the early processes responsible for bulk behaviour.

Figure 45: The long-pulse laser target area.

Academic staff

Dr Bill Proud

Bill was appointed Director of the Institute in 2009. Bill's main research interest is into high strain rate properties of a wide range of materials, both inert and energetic. To do this a number of techniques are used: Drop-weight, Hopkinson Bar, Taylor Impact, Plate Impact. The development of novel high-speed diagnostics and analysis methods is a long-term area of interest. He is particularly interested in those materials which show a strongly non-linear behaviour in response, porous, granular, biological or composite. He has strong research links to the Royal British Legion Centre for Blast Injury Studies and is currently Chair of the Institute of Shock Physics group *Shock Wave and Extreme Conditions*.

Dr Dan Eakins

Dan joined Imperial in 2010 from Los Alamos National Laboratory. His research is directed toward the mechanisms of deformation in condensed matter at extreme strain-rates, from the bulk to sub-micron scale. Dan focuses on the transition between elastic and plastic behaviour, with specific attention to the processes of ultrafast inelastic deformation (defect generation, plasticity, localisation, fracture).

Dr Simon Bland

Simon works for both the Institute of Shock Physics and the Plasma Physics Research Group at Imperial. In 2007 he was awarded an EPSRC Advanced Research Fellowship to pursue his studies of high energy density physics experiments driven by the radiation and plasma produced by wire array z-pinches. Over the course of his career he has authored/co-authored more than 50 published journal papers, including several in PRL and MNRAS. He has spoken at multiple conferences and science festivals, and enjoys showing the public the Plasma Physics Group's work.

ISP's research associates and PhD students at the 2013 APS SCCM conference.

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. During the last year, the ISP has hosted numerous visits for potential industrial partners.

We are particularly pleased to have consolidated our very successful partnership with Thales UK over the last year.

Thales is a global technology and engineering company with a heritage in the defence sector. The missile electronics business of Thales UK provides a range of specialist fuzing and safety and arming systems for use in the latest guided weapon and missile systems. These systems cover hard target fuzing, lethal payloads, safety, arming and fuzing systems, rocket motor ignition and ordnance research activities.

In particular Thales's hard target fuzing systems provide the functionality and performance for weapon systems to penetrate very hard and deeply-buried targets such as concrete bunkers. They are specifically designed to withstand the extremely severe environments that are encountered during deployment and operation. Hydrocode modelling is used extensively in the development of system survivability.

Thales – Institute of Shock Physics collaboration

- » **Laurie Turner (Thales)**
- » **Ian Townsend (Thales)**
- » **David Chapman**
- » **James Wilgeroth**
- » **Amnah Khan (PhD student)**
- » **Dan Eakins**
- » **William Proud**

Thales routinely uses epoxy resin-based encapsulates to protect electronic components used in high-g shock environments. While the gross response of these materials has been shown to provide good shock resistance, their detailed behaviour is not fully understood, especially at extremes of temperature. For example, one of the epoxy materials appears to behave as a very high viscosity fluid rather than a solid when under high compression.

Future requirements are likely to include multiple high frequency shocks, and so it is important for Thales to improve its understanding of these materials. This is being achieved by exposing samples to controlled high-velocity impacts at different temperatures and monitoring the bulk and surface strains. This data will then be used to define parameter values for LS-Dyna material models used in simulations.

The experiments include dynamic mechanical analysis (DMA), Instron testing and SHPB experiments, each performed over a range of temperatures, and which collectively cover the required strain-rates. The experiments have been chosen to obtain data needed to populate a rate- and temperature-dependent constitutive model for polymers – for example, the Mulliken-Boyce model.

QinetiQ – The degradation behaviour of complex hybrid propellants

» **Ruth Tunnell (QinetiQ, PhD student)**
» **William Proud**

Over the past year, Ruth Tunnell's PhD has encompassed four main areas of work which are as follows:

- Understanding the fundamental ageing mechanisms of a particular complex hybrid propellant
- Looking at the effect of ammonium perchlorate with regards to ageing behaviour
- Investigating whether the chemical and mechanical properties of a particular propellant are affected by ageing in an environment where there is limited oxygen and water
- Measuring the process of Nitroglycerine migration from complex hybrid propellants

She has presented the results from all four areas of work at several conferences meetings and conferences:

- The use of Analytical Methods to Understand Complex Hybrid Propellants, presentation to the Institute of Shock Physics Annual Meeting, March 2012. Ruth was also invited to give the same presentation at a meeting at the Diamond Light Source in June 2012
- Measurement of the Vapour Pressure of Nitroglycerine above Propellants, 43rd International Conference of the ICT, Germany, June 2012

Figure 46: Vessel used for vapour pressure measurements.

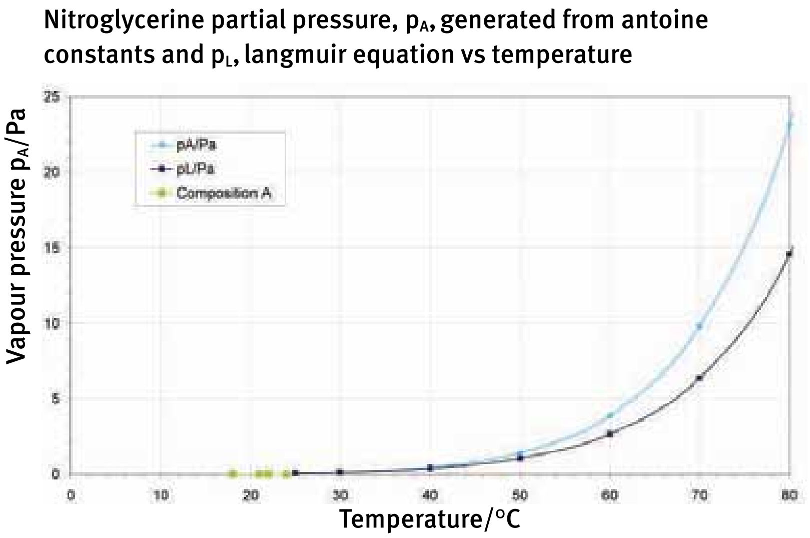


Figure 47: Comparison of initial data with literature values.

Defence Ordnance Safety Group (DOSG)

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

We are delighted that Craig Hoing has chosen to undertake his part-time PhD studies with the Institute starting in June 2013. His project description is *The effects of expanding high temperature gas flow on aeroballistic drag.*

“To be successful the group needs active members. If you are a member of the IOP – please remember to tick SWEC in the group affiliation section of your membership form.”

Dr William Proud
INAUGURAL CHAIR OF SWEC

Spatial Velocimetry Workshop

Held on Monday 9 September 2013 at the Institute of Physics, this was the first workshop organised by the *Shock Wave and Extreme Conditions* group (SWEC). It was kindly sponsored by AWE, free to attend and attracted upwards of 40 delegates—a full house. The workshop grew out of the emerging UK interest in understanding of material behaviour under extreme loading at the material grain scale. It was designed to stimulate interaction within the community and discussion topics were focused upon the theory and application of both line imaging VISAR and spatially resolved Michelson interferometry. Presentations by prominent academic and industrial researchers described some novel ideas and shared important knowledge with the attendees. In addition, informal discussion into the challenging issues of deploying and analysing spatial velocimetry proved extremely successful.

Organisers:
Dr Daniel Eakins • Imperial College London
Dr Gareth Appleby-Thomas • Cranfield University
Martin Philpott • AWE

Outreach

One of our primary aims is to educate and inspire the next generation of scientists and engineers in the science of shock waves, ultrafast material phenomena and matter at extreme conditions. We do this through open days, talks and one-to-one discussions with the emphasis very much on accessibility of our staff for open discussion. In the last year, we gave several talks at the Science Museum as part of the Museum's 'Lates' events and also hosted numerous visits. Through Exscitec, hosted a group of 17-year-olds who developed, calibrated and used a shock tube.

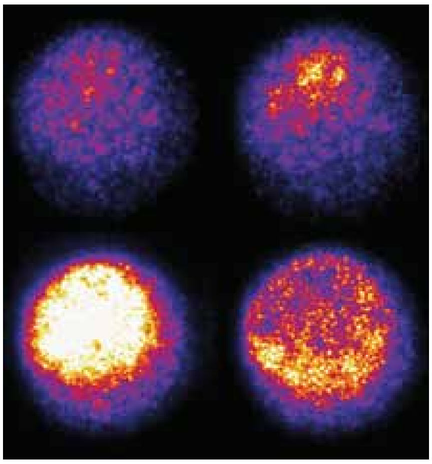
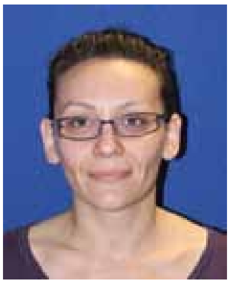


Figure 48: Bed of Ammonium Nitrate, Impact initiated 30 ns exposure time and 0 ns interframe time.



NEW STARTER

Jasmina Music

Before taking up my PhD project at ISP, I was working as an RA in Imperial's Department of Computing. I hold an MSc in Physics from Imperial and a Master of Education in Physics from the University of Zagreb. My research with Drs Dan Eakins and David Chapman on an EPSRC/AWE-supported iCASE studentship involves investigation of the development of non-uniform temperature in dynamically loaded materials. The primary focus is on the design and construction of a new, spatially resolved reflectivity thermometry system.

Short course: Key Concepts in Shock Hydrodynamics

Industry scientists Martin Bleackley and Warren Boydell from AMEC attended the ISP short course in it's fifth presentation *Key Concepts in Shock Hydrodynamics* over five days. Led by AWE scientist Dr Ron Winter the course impressed on Martin Bleackley:

“The five day continuous course was beneficial as an introduction to shock hydrodynamics in both fluid and solid materials.The course provider, Ron Winter, was very experienced and informed about the subject. The course, supported by comprehensive course notes, was well communicated by Ron and allowed for interaction with the students. The course benefited from two lectures each morning followed by supervised assignments in the afternoon to reinforce the concepts introduced during the course. Such assignment instilled both an appreciation of the Hugoniot parameters and how they are determined experimentally. As the assignment invariably used MS Excel, we found it helpful to use one's own PC during the course and to have a good appreciation beforehand of Excel, particularly relating to producing graphs.”

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 our links with industry and institutions such as universities, professional bodies and government agencies, we build upon and share 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.

ISP 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. We are now operating a membership model. Visit our website to join www.imperial.ac.uk\shockphysics

Contact

If you would like to learn more about our research and outreach activities, training programmes, or how to collaborate with our excellent researchers and technical staff, please contact:

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