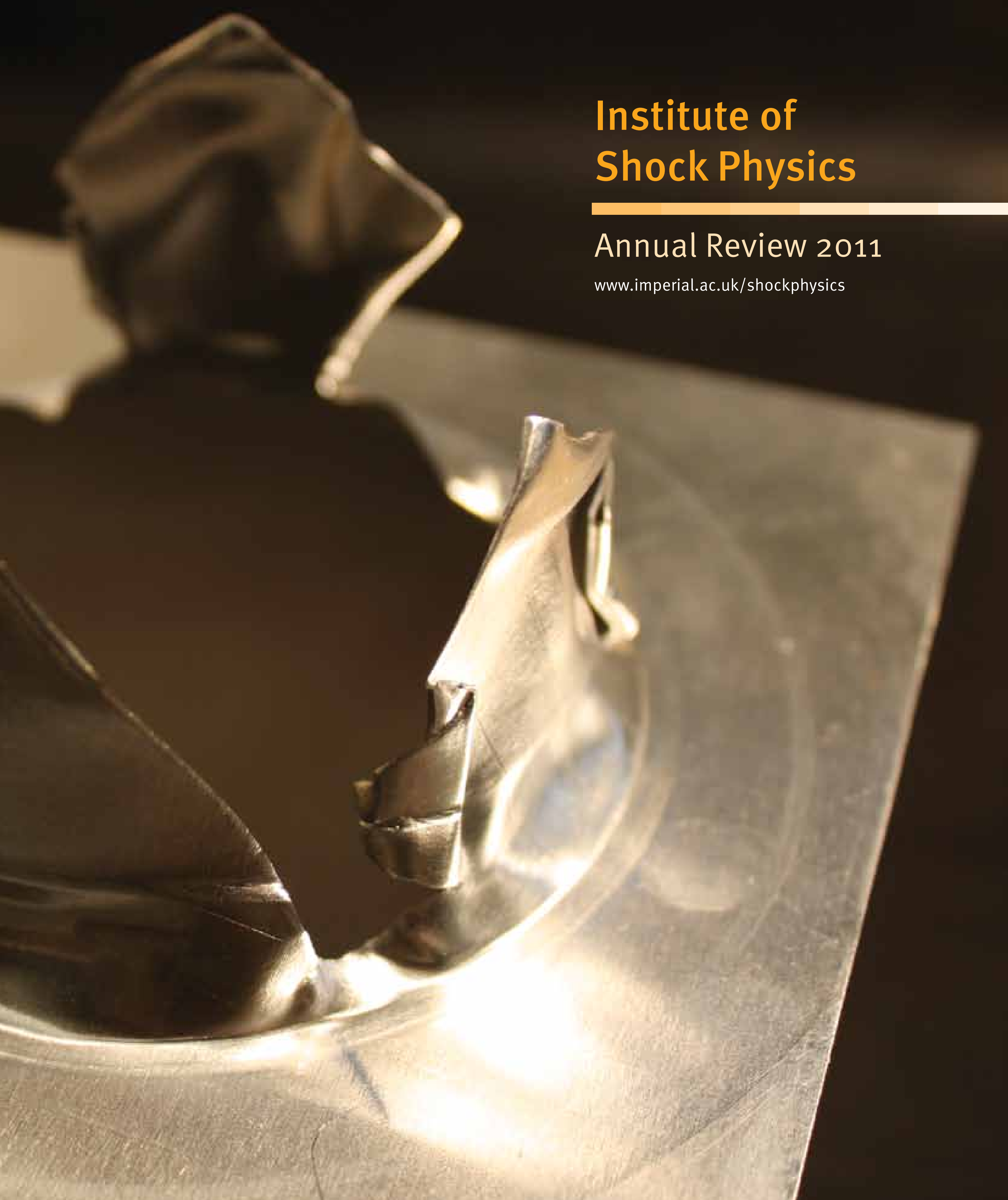
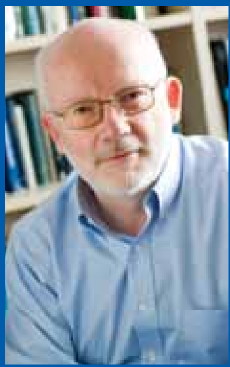
Imperial College
London

Institute of Shock Physics

Annual Review 2011

www.imperial.ac.uk/shockphysics





Professor Steve Rose
Founding Director

Foreword

The Institute of Shock Physics was established in 2008 with part-funding from AWE of £10 million. The last year has seen this research Institute move from an organisation that was being established to one in full operation and one which is making a significant contribution to the Science and Technology of AWE. Whether it is through the provision of our Masters course, through the short courses in specialist areas or through our PhD training, the Institute has certainly made an impact on the education of people from AWE and more generally in the UK. I know that the Institute is particularly proud of the achievements of its students. The community of people in the UK who work in the area of Shock Physics has grown and I am pleased that the Institute has acted as a focus for their work. I look forward to watching the ISP programme grow in the next year.

Contents

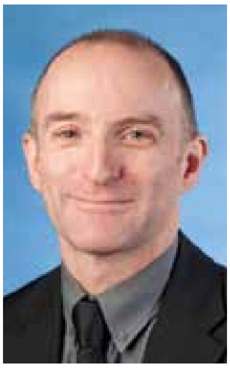
Cover image
An aluminium diaphragm which is burst by gas pressure to generate a shock wave in the NPL 1.4 MPa shock tube.

Kindly provided by
Ian Robinson » National Physical Laboratory

Dr William Proud
Director

Director's overview

When I was offered the position of Reader in the Institute of Shock Physics in July 2009, I was both honoured and delighted as I realised this would allow me to be closely involved in the formation of a new research centre in a field where I was passionate about the research and welcomed the opportunity to take a co-ordinated and interdisciplinary approach. In this Annual Review I would like to draw your attention to the fundamental research we undertake but also to the boundaries of the research presented – very transmissive and open boundaries. Within Imperial College London I have found the opportunities for cross-cutting research to literally walk up to you rather than requiring a wide-ranging search. The interaction between the various Departments at Imperial is specifically fostered and exists at all levels. I would particularly like to thank colleagues in Aeronautics, Earth Sciences and Engineering, Medicine, Bioengineering and of course Physics for their welcoming attitude and the open atmosphere for scientific discussion. In all of this, the role of AWE has been pivotal, not only in financially supporting the Institute but also in working in partnership on technical and research challenges. I would like to take this opportunity to thank all members of AWE who have provided interest and enthusiasm both for the core science relevant to AWE but also in the organisational support for areas, like biomechanics, which fall outside of traditional AWE interests. The two principal aims of the ISP have been to provide an open institute where links can be forged, research progressed and technical issues discussed in depth and resolved; and secondly to provide a stream of intelligent, motivated researchers in the field of shock and high-rate physics. In this Review you will find all of these aspects addressed and more besides. I look forward to the next five years of on-going research and interactions.



Dave Chambers
AWE Hydrodynamics Division

Sponsor's comment

The Institute of Shock Physics was originally funded by AWE with a three-fold vision in mind. As well as providing technical expertise for AWE programmes the Institute was tasked with developing the experimental capabilities and personnel required to meet the UK's needs in shock physics into the future. During its fourth year of operation, and with the installation of key experimental capabilities, that vision is now being realised. Staff and students of the Institute make significant contributions to AWE programmes and I am delighted by the extensive interactions that exist with AWE staff. It has been particularly gratifying this year to see the expertise at the Institute of Shock Physics being recognised through additional funding sources such as the recent award from The Royal British Legion. This clearly demonstrates that the Institute of Shock Physics is now established as a centre of excellence in the UK. I look forward to seeing it achieve great things in the 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.

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 such as: 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. 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 through a cohort of PhD students. Each year the ISP delivers a very popular undergraduate module in hydrodynamics and shocks, a Master's course in Shock Physics, a short course series on special topics, an annual conference and technical conferences, meetings and seminars.

Governance and management

- William Proud » Director
- Chris Thompson » Programme Director
- Ciara Mulholland » Institute Administrator
- Eva Gledhill » Administrative Assistant

The Institute of Shock Physics is guided by two Boards, the Operations Management Board and the Strategic Management Board. Day-to-day management is provided by the programme team located in the ISP headquarters at Imperial's South Kensington campus. The programme team prepares monthly reports for AWE on progress of the Institute and runs a joint AWE/Imperial Technical Operating Group to review and agree solutions to technical issues relating to the large bore light gas gun on the South Kensington campus.

Success of the Institute of Shock Physics is measured against Key Performance Indicators collected together in a Balanced Scorecard. Over the last two years, activity across the ISP has seen a significant change in emphasis, from delivery of assets and resources to generating outputs from the Institute's programme. A summary of key outputs since 2008 is as follows:

FINANCES

- » **Financial leverage:** £6.64 million plus a share of The Royal British Legion funding for a new £5 million Centre for Blast Injury Studies at Imperial

PEOPLE DEVELOPMENT

- » 18 PhD students working at five institutions; one QinetiQ funded PhD student
- » Trained 22 summer interns, some are now interested in MSc and PhD courses
- » Delivered 817 training days through eight courses
- » Established an undergraduate module in hydrodynamics and shocks
- » Established taught Masters in Shock Physics with distinguished international guest lecturers

INSTITUTE CAPABILITY

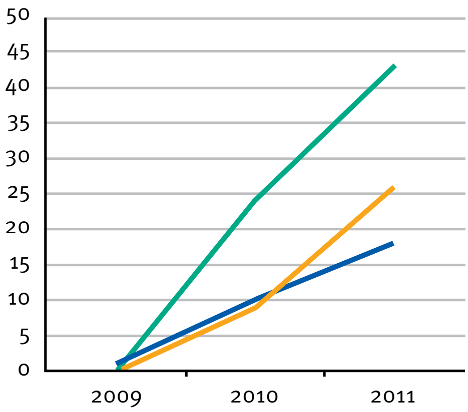
- » Six academic staff and five Postdoctoral Research Associates at three institutions, three technical experts and a programme office at Imperial
- » 43 visiting academics from 10 institutions including AWE; five affiliate members
- » 100 mm Light Gas Gun and Pulse Power MACH facilities at Imperial both formally launched in May 2011
- » First AWE shots on the Imperial Gas Gun during 2011

RESEARCH OUTPUT

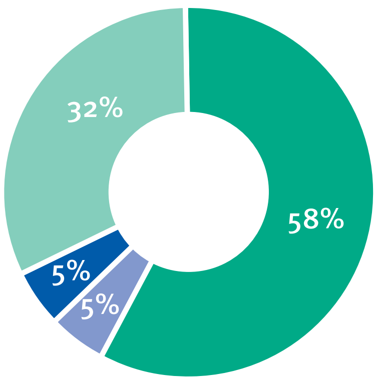
- » **Published:** 18 journal papers, 43 conference papers and delivered 26 invited talks at prestigious meetings and organisations – see Figure 1
- » **Examples of conferences:** Gordon Research Conference on Research at High Pressure, New Hampshire, 2010; High Speed Imaging Showcase, British Society for Strain Measurement, National Physical Laboratory, 2010; 17th American Physical Society Topical Group on the Shock Compression of Condensed Matter Conference, Chicago, 2011

In order to demonstrate value for money, the ISP collects information on financial leverage across a range of categories including underpinning funding from other funders such as the Engineering and Physical Sciences Research Council for staff and equipment, use of other facilities including Diamond Light Source Ltd, European Synchrotron Radiation Facility and Advance Photon Source, equipment donation and additional resource such as visiting researchers. The proportion of leveraged funding as a percentage of the whole ISP programme is summarised in Figure 2.

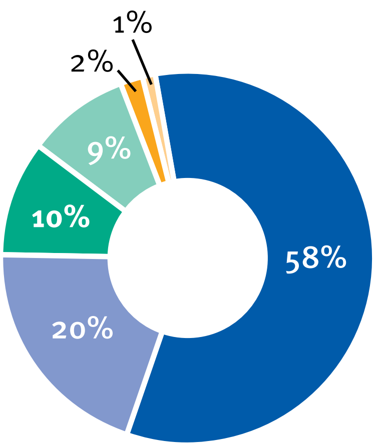
The AWE funding commitment of around £10 million over five years to the ISP is spread across five institutions, summarised in Figure 3.



« **Figure 1:** Cumulative total of research outputs from ISP-funded staff.



« **Figure 2:** Leveraged funding as a proportion of the total ISP programme.



« **Figure 3:** Proportion of £10 million AWE funding commitment to ISP by university partner.

Stakeholder engagement

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 international conferences, meetings and events and by raising the profile of what we do through stakeholder activities. In 2010, we co-hosted an International conference with the University of Cambridge on Shock and High Strain Rate Properties of Matter and spent much of the early part of 2012 planning for a major international conference, in New Models and Hydrocodes for Shock Wave Processes. We delivered three annual meetings; the third, in March 2012 was open to external collaborators; we held three successful stakeholder events to raise awareness of the Institute at AWE and Imperial; and we hosted numerous visits from academia, industry and Imperial's Physoc.

KEY STUDENT PUBLICATION

PhD student Ross Howie, working at Edinburgh University, is the first author on a Phys. Rev. Lett. paper on the first new solid phase of hydrogen discovered in more than 25 years.

SEVENTEENTH APS SCCM STUDENT POSTER PRIZE

PhD student David Jones (pictured) was awarded first place at the APS SCCM Topical Conference student poster competition.

“Just a note to say congratulations on the Shock Physics Meeting last week. It was very interesting scientifically and an incredibly good networking place. I thoroughly enjoyed the broad range of the meeting – an excellent way to run it – one of the two most successful meetings I've ever been to. Well done to all of you”.

Ranko Vrcelj
WALLOP DEFENCE SYSTEMS/UNIVERSITY OF SOUTHAMPTON KNOWLEGDGE TRANSFER SECONDMENT

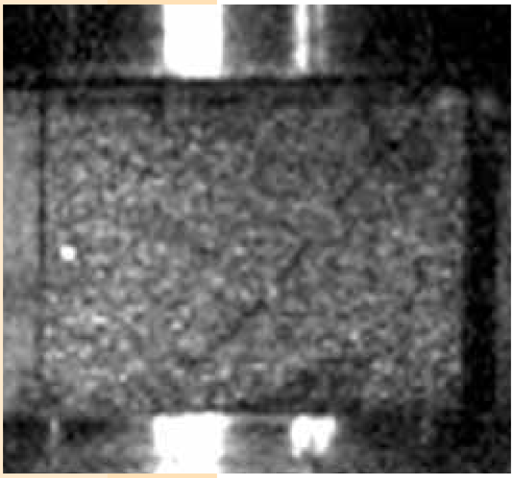
Imperial College London

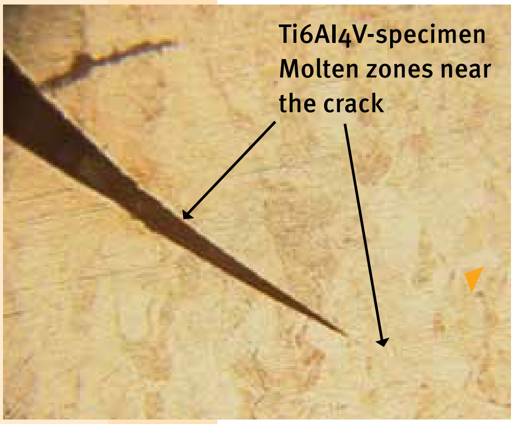
Research

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

Over the past several years, the ISP at Imperial College London has established a diverse research profile, encompassing studies across a range of scales, from MPa to Mbar, from the intermediate to very high strain-rate regimes, and from kilometers to sub-micrometer. The following is a brief summary of the exciting work being performed by the students and researchers at the ISP.

Frame from the high-speed video sequence acquired during a drop-weight test on an SLM Ti-6Al-4V sample. The failure of the material along the 45 degree maximum shear plane is evident.





Microscopy image showing the microstructure around the arrested crack tip of a tested titanium alloy specimen.

LOW STRAIN-RATE

The ISP is coupling its expertise in low and intermediate rate testing to studies involving new materials processing, new and emergent material systems, and new measurements.

Intermediate strain-rate testing of materials

- **Jens Balzer**
- **William Proud**

A new, instrumented drop-weight apparatus has been developed to investigate the deformation and failure behaviour of materials at intermediate strain-rates. This apparatus is a modular addition to drop-weight facilities already present at Imperial College London, and prevents lateral motion of the anvils and specimen during compression, ensuring a uniform dynamic load until failure.

The new drop-weight apparatus has been used to study the generation of adiabatic shear bands in Ti-6Al-4V. The novel processing technique of selective laser melting (SLM) was employed to manufacture cubic Ti-6Al-4V specimens with rectangular internal defects, providing a well-defined nucleation point for failure. In addition to the loading history, metallographic analysis of the microstructure of the recovered specimens allowed the failure mode of the specimens to be established. In addition to the SLM Ti alloy, the intermediate strain-rate behaviour of Ti, Ti alloy, and Al alloy (5083) have also been investigated using the drop-weight facility.

Biomaterials

- **Chiara Bo (PhD student)**
- **Jens Balzer**
- **Kate Brown**
- **William Proud**

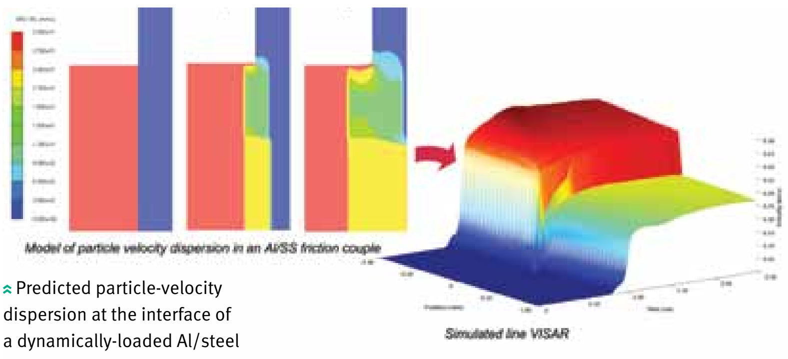
The ISP, with AWE support, and collaboration with colleagues in Bioengineering and Life Sciences has investigated the effect of short, high-intensity pressure pulses on stem cells, using a combination of Split Hopkinson Pressure Bar and modern biological assay methods. This study has found that even modest pressures (90 atmospheres for 100 microseconds) will result in significant damage to stem cell populations and also a long-term effect on cell expression. This has significant implications in the understanding of injury and recovery processes. The research was crucial in obtaining funding from the Royal British Legion Centre for Blast Injury Studies (see page 15).

Piezoelectricity under strain-rates of 10^2 - 10^3 s^{-1}

- **Amnah Khan (PhD student)**
- **William Proud**
- **Dan Eakins**

Piezoelectricity is a well-established phenomenon responsible for unique electrical behaviour during the deformation of many materials. So-called piezoelectrics have a strong correlation between crystal distortion and electrical polarisation, which allows these materials to be used as stress and time-of-arrival sensors, or generators of mechanoelectric energy. In this project, the behaviour of a novel piezoelectric material is being investigated as a function of temperature and strain-rate.

Line-imaging VISAR diagnostic constructed for experiments on the large bore gas gun.



Predicted particle-velocity dispersion at the interface of a dynamically-loaded Al/steel friction couple.

HIGH STRAIN-RATE

Resolving dynamic friction

- **Mark Collinson (PhD student)**
- **Dan Eakins**
- **Graham Ball (AWE)**
- **William Proud**

The bulk behaviour of 'real' materials and complex systems is governed partly by the defects found at the mesoscale. Of these, interfaces between grains/phases and/or material components are universally present, and influence the manner in which stress waves are communicated within a material. Our best attempts to predict the macroscopic response of such materials rely upon models that accurately represent the interaction between phases along shocked boundaries.

This need is being addressed through a study of dynamic sliding in multi-material friction couples, with focus on the role of material properties (strength, density, impedance), interface orientation, and load intensity. Their effect will be diagnosed using a newly constructed line-VISAR diagnostic, to monitor the relative motion across shocked interfaces. By coupling measurements to numerical studies incorporating models for dynamic friction, this project seeks to gain a clearer understanding of the evolution of interaction (i.e., sticking, sliding) through the loading process.

Dynamic fracture and fragmentation

- **David Jones (PhD student)**
- **Dan Eakins**
- **Sergey Razorenov (RAS*)**
- **Andrey Savinykh (RAS*)**
- **William Proud**

The manner in which materials fail and fragment under intense dynamic loading plays a large role in the performance of explosive munitions, and development of armour and protective systems. The mode of failure and therefore the conformation of fragments and fragment size distributions varies from material to material and as a function of loading, strain-rate, microstructure and temperature.

The influence of temperature and stress triaxiality on the mode of failure in Ti-6Al-4V cylinders is under study, coupling new experimental methods with recent advances in diagnostics. Novel approaches for driving pre-heated cylinders to failure in a gas gun have been developed and verified using X-ray radiography at Cranfield University (see Figure 4). In addition, the variation in failure response with changing ring geometry (and thereby stress state) is being investigated through an on-going collaboration with the Institute of Problems of Chemical Physics, Russian Academy of Sciences (see Figure 5).

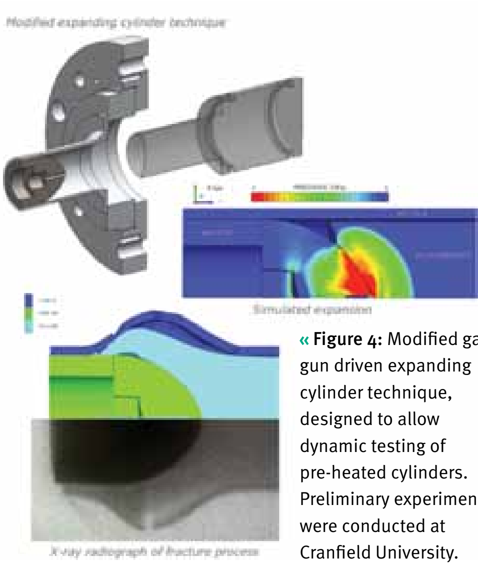


Figure 4: Modified gas gun driven expanding cylinder technique, designed to allow dynamic testing of pre-heated cylinders. Preliminary experiments were conducted at Cranfield University.

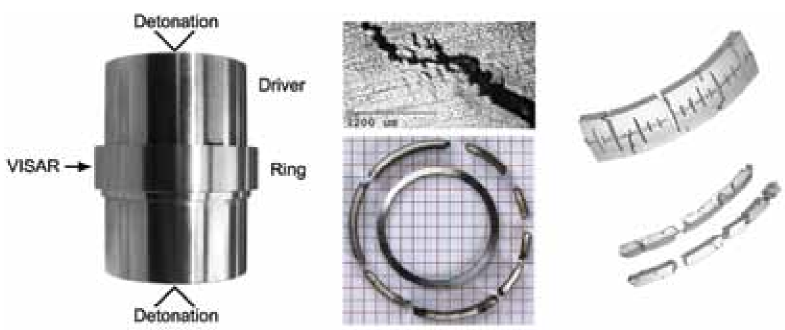
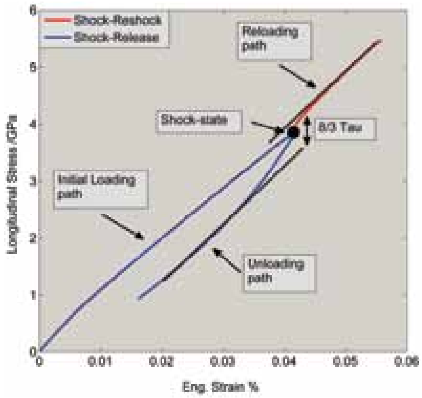


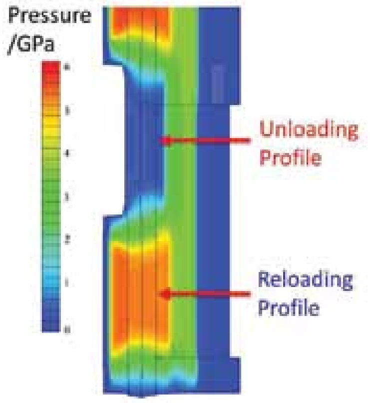
Figure 5: Explosively loaded cylinder test used to drive rings of varying aspect ratio into free expansion. Details of the failure process are deduced from a combination of velocity interferometry, recovered fragment characterisation, and numerical modelling.

* Russian Academy of Sciences



» Longitudinal stress verses strain during loading, unloading, and reloading obtained from the measured particle velocity histories. Black lines indicate the estimated tangents to the plastic portions of the loading, and unloading curves, which can be used to determine the shear stress at the shock state.

» Pressure contour plot taken from an Autodyn simulation of the shock-reshock geometry. The figure demonstrates the uniaxial strain condition at the two measurement locations several microseconds after impact.



FROM BULK TO THE MESOSCALE

Strength at high pressure

- **Laura Chen (PhD student)**
- **David Chapman**
- **Dan Eakins**

The response of materials to intense shock wave loading is often assumed to be hydrodynamic, where at high-pressures the deviatoric stresses are a small contribution to the total pressure component. However, at lower stresses, effects of material rigidity often dominate material response. The measurement of dynamic compressive strength is a core research focus of the Institute, and leverages the multi-platform multi-scale capabilities of the ISP.

The large bore gas gun has recently been used to perform the first simultaneous shock-reshock/shock-release experiment to measure the strength of Al-6061 at the shocked state. This technique removes any error introduced by performing these reshock/release experiments separately, ensuring reloading and release from an identical state. Following this proof-of-principal, further shots will be performed in which the thickness of the target material is varied in the same experiment, to study the kinetics of any further plastic deformation upon reshock. Additionally, extension of this work to the micro-scale will be performed using the forthcoming long-pulse laser shock platform, with particular emphasis on the role of temperature on the early stages of plastic relaxation.

Kinetics of high pressure phase changes

- **James De'Ath and Sam Stafford (PhD students)**
- **William Proud**
- **Simon Bland**
- **Dan Eakins**

Shock compression can result in phase changes such as melting or freezing, or a change in the microscopic crystal structure. One of the most well-known high-pressure phase changes is the change in iron from α – body centered cubic to ε – hexagonal close packed. The influence of microstructural factors (e.g., crystal orientation, precipitates) on transformation kinetics is being explored through plate-impact experiments at the ISP. In the future, the ramp-compression capabilities of MACH (see page 21) will be utilized to explore new paths through phase space, and thereby study kinetics of solid-phase or melting/refreezing transformations off the Hugoniot.

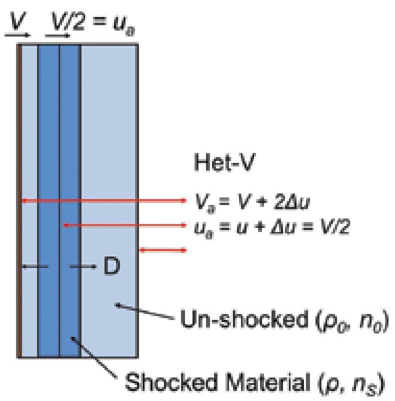
Bulk optical properties of poly(methyl methacrylate) – PMMA

- **David Chapman**
- **Dan Eakins**
- **David Williamson (Cambridge)**
- **William Proud**

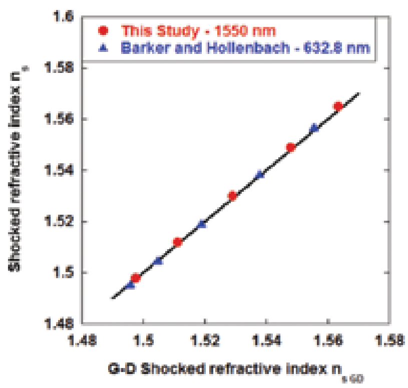
PMMA has seen widespread use as a low impedance window during dynamic loading experiments. However, the velocity correction, particularly given the rate-dependent response of the material, remains relatively under-investigated. With HetV/PDV rapidly becoming a standard diagnostic for measuring velocities in dynamic compression research, the window correction of PMMA (Perspex GS) has been measured at a wavelength of 1550 nm.

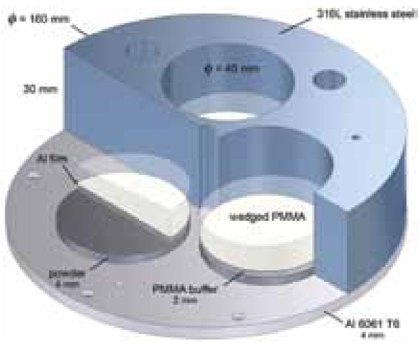
The results demonstrated that the 1550 nm window correction for PMMA was a function of particle-velocity and not constant in the investigated regime. The measured velocity corrections were of order 1%, which is consistent with results obtained by Barker and Hollenbach (1970) and with the assumption that PMMA is approximately described by a modified Gladstone-Dale relationship. Future experiments will extend measurements to lower wavelengths, to develop a rigorous optical property model for window materials.

» Experimental configuration used to measure the velocity correction indicating the various reflections which contribute to the Het-V signal a short time after impact. The figure indicates the propagation of shock waves in the flyer and target.



» Measured shocked refractive index verses shocked refractive index calculated using the Gladstone-Dale relationship for this study (wavelength 1550 nm) and data obtained by Barker and Hollenbach (wavelength 632.8 nm). The solid black line indicates perfect Gladstone-Dale behaviour.



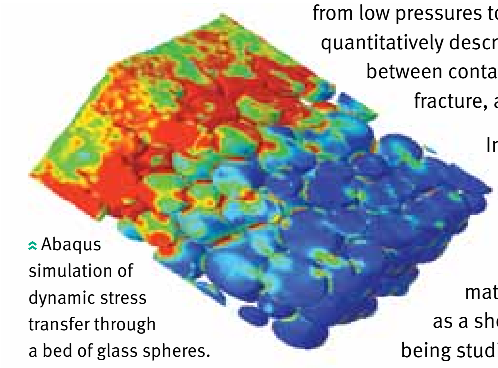


Multi-sample powder cell used to directly compare the compaction response of morphologically-distinct powder mixtures.

Granular systems

- **Will Neal (PhD student)**
- **Dan Eakins**
- **William Proud**
- **David Chapman**

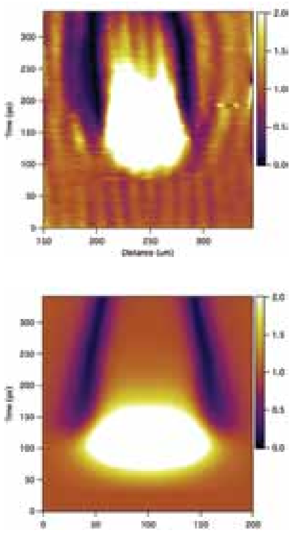
Sand, sedimentary rocks, foams, metal powders are all widely encountered in the natural and man-made world. The challenge for scientists, mathematicians and engineers is to produce an over-arching predictive method of describing the response of these materials from low pressures to intense shock pressures – quantitatively describing the time/energy-relationships between contact friction, pore collapse, grain fracture, and temperature rise.



Abaqus simulation of dynamic stress transfer through a bed of glass spheres.

In granular materials, crush-up and densification at low dynamic pressures involves numerous system-dependent multi-scale processes. For brittle granular materials, the significance of fracture as a shock compaction mechanism is being studied on sand and glass microspheres over a range of length and time scales. In the case of ductile metal powders, the role of powder morphology on subtle variations in dynamic compaction behaviour is being explored. Both of these studies take advantage of the large bore gas gun to simultaneously load multiple powder targets, yielding a sensitive study of both precursor behaviour and densification response.

Measured (top) and calculated (bottom) reflectivity maps recorded from silicon films shocked below the phase transition.



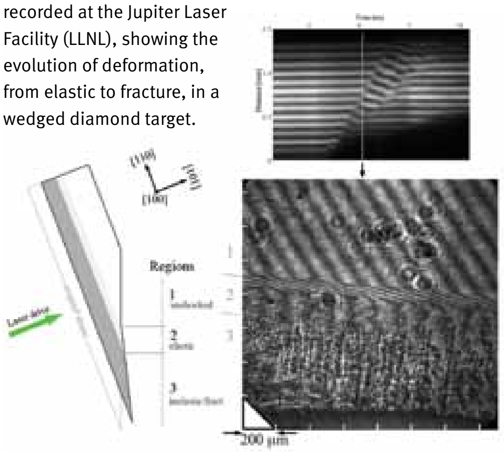
EXTREME CONDITIONS

Ultrafast compression of silicon and diamond films

- **Dan Eakins**
- **Cindy Bolme (LANL)**
- **Shawn McGrane (LANL)**
- **David Moore (LANL)**

Defect dominated deformation in covalently-bonded materials is more sluggish than in metals, with the rate of dislocation generation hampered by relatively low dislocation velocities. Measuring the kinetics of plastic flow is therefore of key importance to the development of physically-based rate-dependent dislocation dynamics models. A collaboration with Los Alamos National Laboratory (LANL) has been studying the deformation behaviour of thin silicon films at strain-rates in excess of 10^{10} s^{-1}, using the technique of ultrafast dynamic ellipsometry to infer changes in optical properties and shock wave structure. By adapting thin film optical interference models for the case of

Line and 2D interferograms recorded at the Jupiter Laser Facility (LLNL), showing the evolution of deformation, from elastic to fracture, in a wedged diamond target.



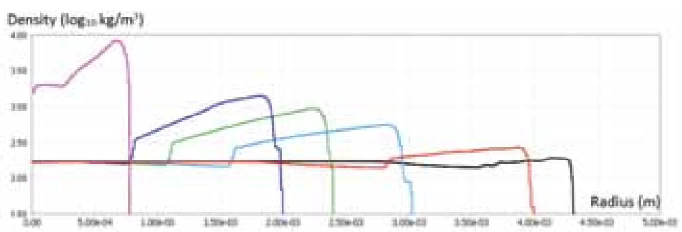
Gaussian shocks, the time-dependence of incipient plastic relaxation in crystalline films is identified, and shown to occur over several hundred picoseconds. This work has also been recently extended to study the early kinetics of elastoplasticity in diamond. Using wedged diamond targets and complementary 1D and 2D VISAR diagnostics, the onset and development of motion at the free surface during shock breakout was recorded, yielding a complete picture of the history of deformation, from elastic to fracture.

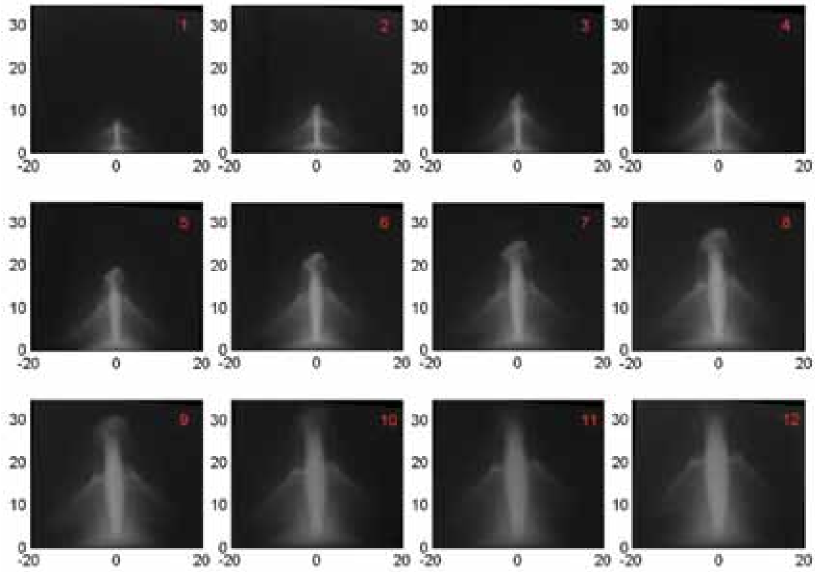
Cylindrically convergent isentropic compression

- **Marcus Weinwurm and Jon Skidmore (PhD students)**
- **Simon Bland**
- **Jerry Chittenden**

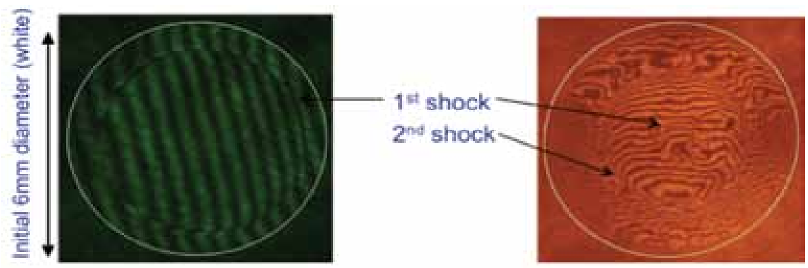
In the past 10 years, the use of pulsed power to drive isentropic compression experiments has produced extremely accurate measurements of Equations of State (EOS) at pressures up to ~5 Mbar on the world's largest pulsed power facility – the 26 Mega-Ampere Z accelerator at Sandia National Laboratories using a simple 'strip line' load. Going to high pressures using strip lines requires higher currents; however a more practical way to achieve this may be through the use of cylindrically convergent target geometries. These could potentially also allow small, university scale pulsed power facilities – such as MACH or MAGPIE – to also achieve the Mbar pressures expected, for instance, in planetary cores. The use of cylindrically convergent isentropic compression has been explored through theory and simulation. The 3D MHD Gorgon Code has been extended to incorporate Sesame and QEOS equations of state, and to use a more accurate model of material conductivity in the condensed phase. This has been used to model potential targets on MAGPIE, the CEA's SPHINX and to explore the shape of the current pulse required to produce isentropic compressions.

Density profiles for a cryogenic hydrogen cylinder being isentropically compressed on Z calculated using Gorgon.





Emission images from flat former, 20 ns interframe.



Interferograms of cylindrically convergent radiative shock waves.

Radiative shocks

- **Guy Burdiak and Jon Skidmore (PhD students)**
- **Simon Bland**
- **Sergey Lebedev**

Radiative shock waves are produced when a shock is sufficiently intense that emission by material behind the front heats and ionises material ahead of it. Such conditions are found in many astrophysical phenomena such as supernovae; whilst in the laboratory, radiative shock waves govern the implosion and heating of inertial confinement fusion experiments. Methods have been pioneered to create intense (speeds ››10 km s^{-1}) radiative shock waves in dense plasmas on the MAGPIE pulsed power facility at the cm scale over 100's of ns. Cylindrical and shaped geometries are being explored, with the launch mechanisms and physics underlying the motion of the shocks revealed through high-speed imaging. Recently, this work has successfully yielded control over wave front evolution, with both planar and spherical convergent geometries demonstrated.

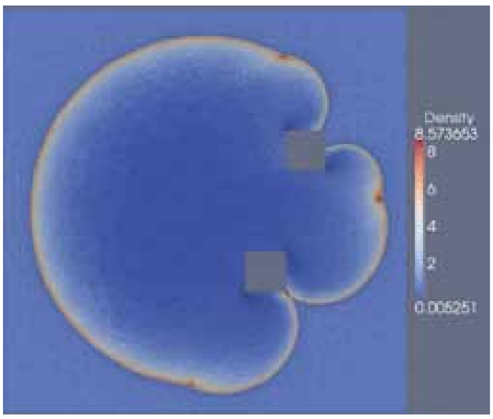
Numerical methods for modelling multi-material compressible and multi-phase flows on unstructured adaptive meshes

- **Christian Jacobs (PhD student)**
- **Gareth Collins**
- **Stephan Kramer**
- **Alan Dawes (AWE)**
- **Andy Barlow (AWE)**

Advanced numerical methods are in development for the simulation of highly dynamic multi-scale, multi-material and multi-phase flows in complex domains, based on the finite element model, Fluidity.

Fluidity has been extended to simulate dispersed multi-phase phenomena, such as the motion of droplets, particles or bubbles within a surrounding fluid. This new capability has been validated against experiments of volcanic ash particles settling through water (e.g., Figure 6) and used to establish a new criterion for the onset of collective plume settling of ash in the ocean. Fluidity has also been enhanced to simulate shock waves in gases and fluids. The unstructured mesh capability of Fluidity allows for complex geometry domains and the adaptive mesh resolves the shock wave economically, by focussing resolution only across the shock front (see Figure 7).

Figure 7: Cylindrical Sedov blast with adaptive mesh. The anisotropic, high aspect ratio elements concentrate resolution near the shock front economically by demanding closer node separation in the direction of the shock propagation than along the shock front. The obstacles in this example demonstrate the flexibility of unstructured mesh adaptivity to deal with irregular geometries.



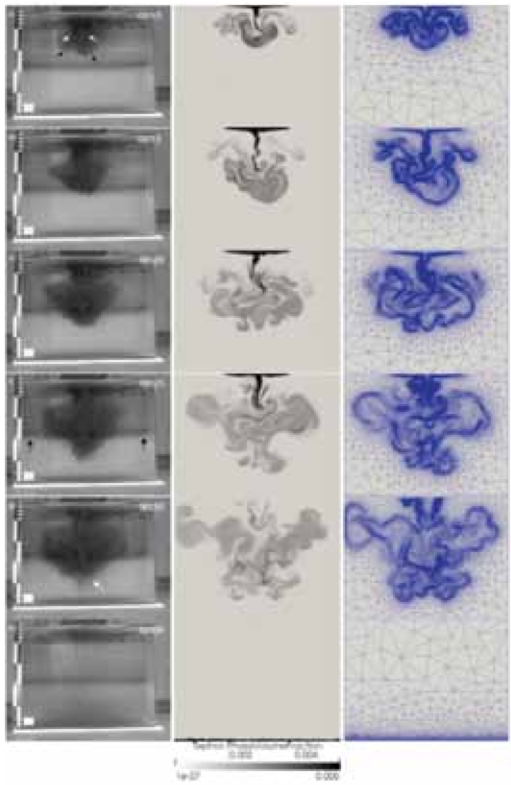


Figure 6: Particle concentration and mesh from a simulation of ash settling through a water tank, compared with video stills from the corresponding experiment. Here the adaptive mesh allows for the economical representation of fine-scale plume dynamics.

Cranfield University

Defence Academy of the United Kingdom

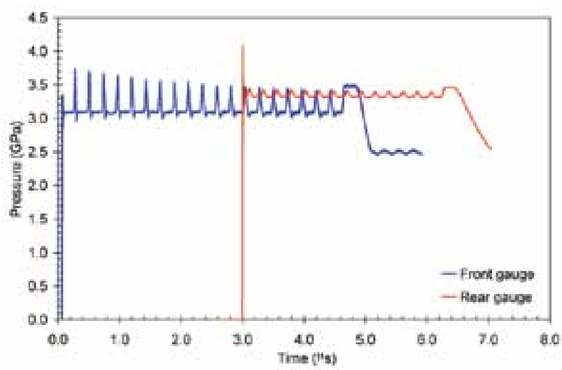
- Paul Hazell
- Gareth Appleby-Thomas
- Mike Goff (PhD)
- David Wood (PhD)

This past year, ISP funded staff at Cranfield University have been focussing on two research areas related to the shock behaviour of materials. These are: the shock behaviour of complex laminate systems and the development of techniques to probe the shock-to-detonation behaviour of polymer bonded explosives. Both projects have been directly funded by the ISP.

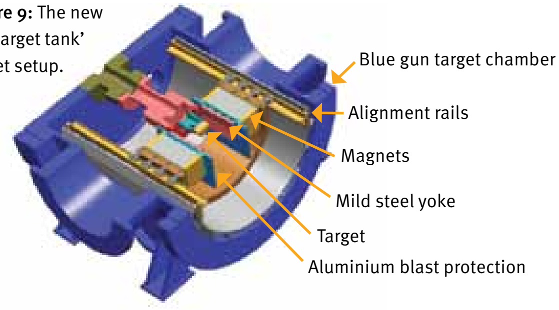
The shock behaviour of a carbon-based complex laminate system has probed the effect of laminate lay-up on the nature of shock propagation. This is particularly important as these materials are becoming increasingly used in engineering technologies that could be subjected to high velocity impact and shock. Questions remain as to how the multiple phases present within the complex laminate affect its response to shock loading and in particular how the angle of the weave changes the shock response. In this work, carried out by PhD student David Wood, Tape-Wrapped-Carbon-Phenolic (TWCP) targets have been shocked to stresses of ca. 7 GPa using the flyer-plate technique. Uniquely, wire-element manganin stress gauges have been used to track the evolution of lateral stresses within this material and provide an estimate of the material's strength behind the shock and the Hugoniot Elastic Limit where the weave is parallel to the shock front (1.5 GPa). Work has been undertaken to examine how the anisotropy in the elastic properties affects the measurement of the strength of shocked material. This has been done by changing the angle of impact loading relative to the weave orientation. Further, oscillations have been experimentally detected that have been predicted by computationally modelling the impact response of an idealised TWCP material; an example of this result is shown in Figure 8.

A PhD project which started in October 2011 has begun focussing on experimental techniques to analyse complex loading conditions on polymer-bonded-explosive (PBX) materials. Conventionally, non-conducting flyer plates have been used to track the shock-to-detonation physics in PBX materials; this work has began looking at using Sintox™FA (alumina ceramic) flyer-plates. First year PhD student, Mike Goff, has measured the Hugoniot of this material; this will allow accurate prediction of the impact stress within the PBX material prior to detonation

» Figure 8: Computational results from a shocked 'idealised' TWCP material showing oscillations due to the spacing of the weave.



» Figure 9: The new 'blue target tank' magnet setup.



and allows accurate characterisation of the impact conditions. Concurrently, a NbFeB N50 permanent magnet set-up for a 50-mm gas gun has been developed in close collaboration with AWE to enable the use of particle-velocity gauges. These magnets provide an output of 355 mT – sufficient to allow the interrogation of the particle velocities within a shocked material with only ca. 0.5 mT variation over the diagnostic region. The advantage of using permanent magnets is that they provide a stable high magnitude field surrounding the explosive. The movement of the particle velocity gauge (that is embedded in the PBX) in the magnetic field allows for the direct measurement of velocity; this allows for tracking the evolution of increasing particle velocities as the detonation proceeds.

A schematic of the magnet setup is shown in Figure 9. The permanent magnet system is located in a mild steel yoke.

Collaborations

Enjoying collaboration with colleagues from different research fields has been one of the many benefits of the ISP. Work has been underway to look at the propensity of microorganisms to survive high-pressure shock loading. To that end, a collaborative research effort involving Cranfield University, Imperial College London and University College London has focussed on developing a capsule to hold an organism-loaded broth during shock loading. Soft recovery of an intact capsule will allow for mortality rates of the organisms to be assessed. Other collaborations include work on the shock loading in Dyneema® (a material that is commonly used as part of armour systems among other things). A paper on this was published in 2011 in the *Journal of Applied Physics* that investigated evidence of shock-induced melting of the fibres.

Publications:

Hazell PJ, Appleby-Thomas GJ, Trinquant X and Chapman DJ
In-fiber shock propagation in Dyneema
Journal of Applied Physics,110, (4), 043504 (2011)
http://jap.aip.org/resource/1/japiau/v110/i4/p043504_s1

University College London

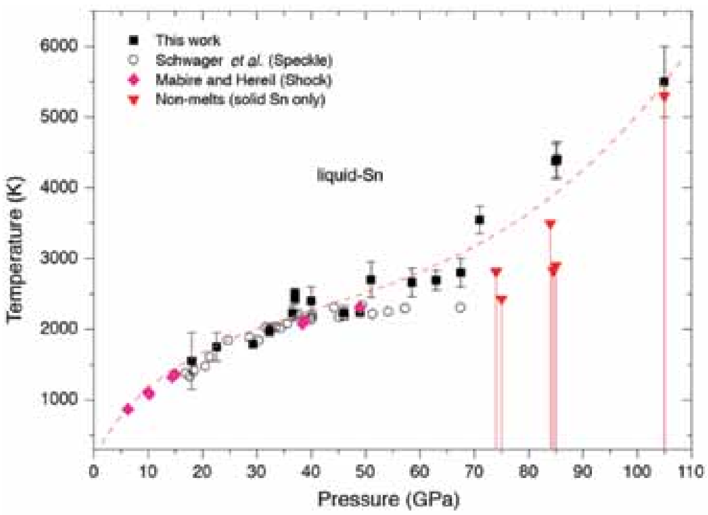
Static High Pressure Group

- Paul McMillan
- Furio Corà
- Dominik Daisenberger
- Richard Briggs (PhD)
- Melissa Cutler (PhD)

Our group has established facilities for carrying out static high-pressure, high-temperature (high-P,T) experiments on materials that are linked to dynamic high pressure (shock) studies, both to determine properties and to develop new materials syntheses.

Our laser-heated diamond anvil cell capability enables us to undertake *in situ* studies of materials under extreme high-P,T conditions. Currently, we are investigating melting relations in metals and ceramic materials to support, complement and occasionally confront shock wave results. Other projects include translating new materials syntheses from static high-P,T techniques (such as laser-heated diamond anvil cell) to dynamic high pressure experiments. The subsequent shock wave experiments, often involving novel designs (targets etc.) are then explored in collaboration with Imperial College London, Cranfield University, Shrivenham and at other facilities worldwide.

A second main aspect of our research involves developing *ab initio* and empirical molecular dynamics simulations of high-P,T behaviour of phase transitions including melting of materials. Single point calculations, full geometry optimisations and phonon calculations are performed at an *ab initio* level using density-functional theory (DFT) software packages. Large scale simulations for the study of dynamic phenomena, such as melting, are performed using classical potential based molecular dynamics.



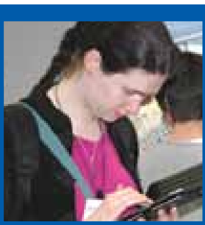
« **Figure 10:** Melt line of Sn at high pressure and high temperature.

High pressure, high temperature phase behaviour of Tin (Sn)

This project aims to study the melt line of Sn through laser heated diamond anvil cell (LHDAC) experiments with synchrotron X-ray diffraction. The data we obtained from our initial experiments showed unexpected behaviour as the melt line first flattens out and then rises again at higher pressures (Figure 10). As changes in the melt line are usually interpreted by examining the underlying solid-solid polymorphic transitions, we also focused our attention on the crystalline phases of Sn reported from room temperature compression experiments. This work led to a series of new room temperature compression experiments on Sn carried out in collaboration with the ID27 group at the European Synchrotron Radiation Facility (ESRF), as well as series of DFT calculations on Sn carried out by ISP PhD student Melissa Cutler, and detailed evaluation of high-P,T Sn diffraction data obtained both from our laser heating experiments at ESRF ID27 and from resistive heating experiments conducted at the Diamond Light Source (I15). Our high-P,T data indicate that the reported co-existence of body-centred tetragonal (BCT) and body-centred cubic (BCC) Sn extends to high temperatures and persists to the melting point. From our new results combined with DFT calculations it appears that the unusual shape of the melting line is not associated with the occurrence of solid-solid phase transitions leading to triple points in the system, but can be described by a thermodynamic mixing model between BCT and BCC Sn components.

High pressure room temperature compression studies of Sn

New room temperature compression experiments carried out in collaboration with the ID27 group at the ESRF using He as a pressure transmitting medium and angle dispersive synchrotron X-ray diffraction has demonstrated the co-existence of Sn phases over a wide pressure range. Our results also suggest that the high pressure structural polymorphism of Sn is more complicated than previously thought and supports our interpretation of the shape of the melting line.



“At AWE I am part of the Equations of State team, within the Materials Modelling Group. Our job is to develop material models that are then used in hyrdocode simulations. In the past much of that work has been done using empirical models but the mathematical models we use don't accurately capture the physics of the material. We are in the process of replacing these models with models based on the actual physics of the materials. When I return to AWE I will be applying what I have learned during my PhD at UCL about electronic structure calculations to that area. This will allow us to make predictions about materials at regions of temperature and pressure where experimental data might not be available."

Melissa Cutler
ISP PHD STUDENT AT UCL AND AWE EMPLOYEE

Theoretical investigation (DFT) of phase behaviour of Sn

During experimental investigation of the melt line of Sn it became clear that the room (or low) temperature, high pressure phase behaviour of Sn is not well understood. To investigate Sn from a theoretical point of view, we performed geometry optimisations and single point energy calculations with volumes/pressures spanning to the region of interest using accurate DFT methods. Supporting our experimental observations we calculate that BCT and BCC Sn co-exist over a wide pressure interval with energy barriers between these two structures lower than the zero point energy in the system.

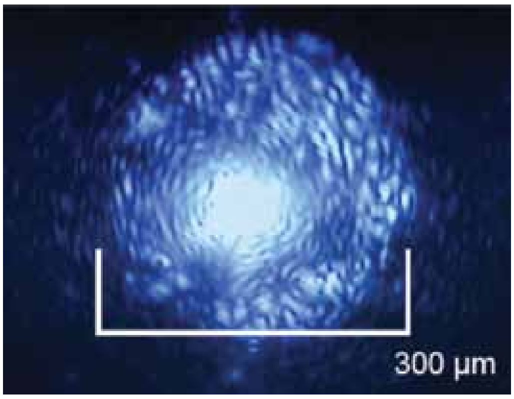
Melting in the tantalum-carbon system at high pressure

Tantalum carbide (TaC) has the highest known melting point for a binary compound (~3900° C), is of high hardness (9-10 Mohs) and is widely used for cutting tools, hard coatings and in high temperature applications. The high-P, T (melting) behaviour in this system is not only interesting in its own right but may have significance for LHDAC experiments in general. We investigated this system under combined high-P,T conditions at temperatures up to the melting point through LHDAC experiments in conjunction with synchrotron X-ray diffraction using beamline 13IDD GSECARS of the Advanced Photon Source, USA. The first experiments conducted used MgO as the pressure medium and generated oxides of Ta during laser heating. In subsequent experiments with KBr as the pressure medium no reaction occurred and we were able to obtain melting data of TaC to just above 50 GPa.

Publications

D. Daisenberger *et al*
J. Phys. Chem. B, 2011, 115 (48),14246–14255
Polyamorphic amorphous silicon at high pressure: Raman and spatially resolved X-ray scattering and molecular dynamics studies
http://pubs.acs.org/doi/abs/10.1021/jp205090s

A. Salamat *et al*
Phys. Rev. B, 2011, (84), 140104
Dense close-packed phase of tin above 157 GPa observed experimentally via angle-dispersive X-ray diffraction
http://link.aps.org/doi/10.1103/PhysRevB.84.140104



Laser hot-spot on DAC sample generated by *in situ* heating with IR laser; speckle pattern from IR laser is also visible.

Diamonds in the UCL Diamond Anvil Cell facility

University of Edinburgh

New phase of dense hydrogen: graphene-like mixed atomic molecular state

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

The search for a metallic hydrogen state is the Holy Grail of condensed matter science. Hydrogen is the most abundant element in the cosmos and metallic hydrogen is expected to show extraordinary properties such as ultra-high energy density and high-temperature superconductivity.

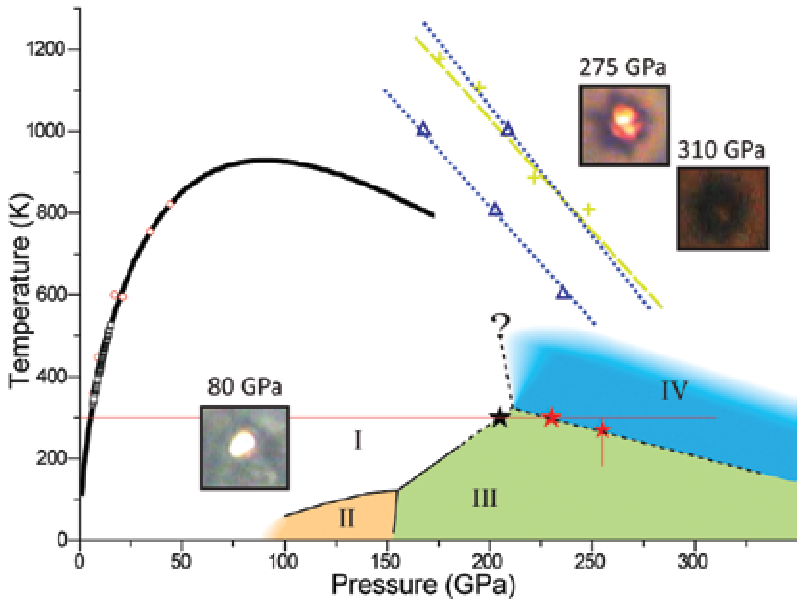
The research team of the Centre for Science at Extreme Conditions at the University of Edinburgh (CSEC) and the Geophysical Laboratory has discovered a new phase of solid hydrogen under pressures exceeding atmospheric by 2.4 million times and at room temperature. The team, which includes the PhD student Ross Howie, funded by the Institute of Shock Physics, found that at the highest pressure reached (which is 3.2 million times larger than atmospheric) some of the atoms are at least two times weaker bounded in molecules than in the ordinary molecules. The material becomes opaque at these conditions. This is only the fourth known phase of solid hydrogen, and it is perhaps the closest one to the metallic state. The further compression of this state is expected to produce two-dimensional metallic graphite-like layers along with the layers of almost unbounded molecules. Previously, hydrogen was expected to become metallic in either a monatomic or purely molecular state. As such, this discovery provides unforeseen insight into the nature of metallic hydrogen.

The great majority of hydrogen resides in high-density forms as they are gravitationally compressed in giant planets and stars. But not much is known about these states as the experiments are very challenging and the theoretical calculations are prohibitively expensive to explore all the possibilities.

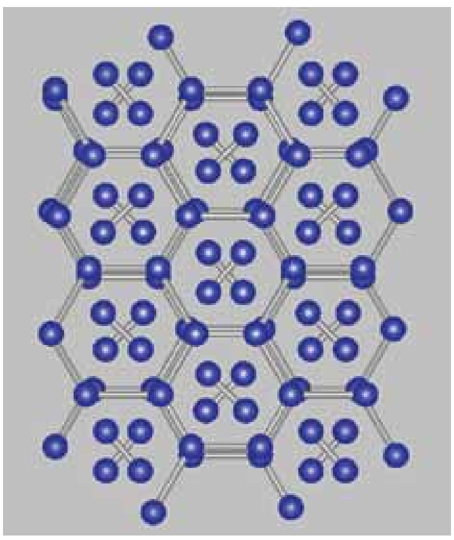
This finding has become possible because of new technological breakthroughs in the Diamond Anvil Cell technique accomplished at CSEC and also in theoretical structure predictions performed by Chris Pickard & Richard Needs in 2007. The results will stimulate further research in this area, which will give an ultimate answer to the long-standing problem. The element number one still possesses secrets. The discovery of phase IV hydrogen with atoms of two different types is a great example of complex behaviour of this putatively simple material.

Publications

R.T. Howie *et al*
Phys. Rev. Lett. 108, 125501 (2012)
http://link.aps.org/doi/10.1103/PhysRevLett.108.125501



» Proposed phase diagram of H2. The microphotographs show the appearance of deuterium in phase I and hydrogen in phase IV.



» Structure of the *Pbcn* phase of hydrogen at 300 GPa.

Centre for Blast Injury Studies

Force blast protection

- William Proud
- Kate Brown (Austin, Texas and Cambridge)
- Andrew Jardine (Cambridge)

The Royal British Legion Centre for Blast Injury Studies (CBIS) at Imperial College London is the result of a £5M 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.

The Blast Force Protection theme, led by William Proud of the ISP, is one of three research themes within the Centre. It builds on work undertaken by 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 from the University of Cambridge.

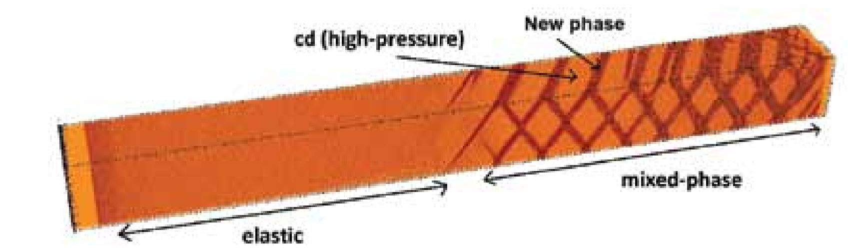
Sample on a test rig used to study the behaviour of the human skeleton under high impulse loading, such as in roadside bombs.

University of Oxford

Molecular dynamics simulations of shock-induced phase transitions in silicon

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

The aim of this project is to gain a better understanding of the mechanical response properties at the microscopic lattice level of certain crystalline solids under the effects of dynamic compression. For this purpose we rely on an interplay between *ab initio* modelling via computational simulations on one hand, and laser-based experimental investigations on the other. Of particular interest to us in recent times has been the behaviour of crystalline silicon subject to shock and ramp loading as observed in classical Molecular Dynamics simulations, especially in the context of its pressure-induced solid-solid polymorphic phase transitions. As can be observed in the figure below, multi-million atom simulations of shock-wave propagation in a single-crystal sample of silicon predict the onset of a high-pressure mixed-phase region ensuing directly after the initial elastic response, consisting on one hand of nearly-hydrostatically compressed cubic-diamond crystal structure (orange), and on the other of phase-transformed material lying in a high-pressure stable phase (red). By analysing the resulting banding structure, we are able to formulate a complete model for the relief of shear stress across the plane transverse to the shock-propagation direction which is consistent with the interatomic potential.



Multi-million atom Molecular Dynamic simulation of shock wave propagation in single crystal silicon.

Training

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

1 HOUR

Research talks

Institute staff and students give numerous talks, seminars and lectures aimed at researchers, funders and the public. These provide a good route for reporting, networking and raising awareness.

1 DAY

Continuous professional development

Institute staff deliver short consultancy projects, problem solving and short refresher-update sessions aimed at 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 to identify the opportunities and challenges.

2 DAYS

Annual conference

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.

10 WEEKS

Undergraduate course 'Shock Waves and Hydrodynamics'

Aimed at undergraduates on Physics Degree Courses. There is a constant drive to provide engagement between students and research. This can take many forms, from extended literature review 'essays' written by final year students, to the inclusion of research material in final year courses such as Shock Waves and Hydrodynamics. This has been the most popular final-year course at Imperial for three years in a row.

3 MONTHS

BSc/short projects

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

6 MONTHS

Masters projects

Aimed at undergraduates and postgraduates. To obtain the award of an MSci, students need to undertake a long research project. The ISP hosts several of these every year. A recent project involved an update and re-establishment of the dynamic breaking of wires, first studied by Professor John Hopkinson in the 1850s. The MSc project for the award of the MSc in Shock Physics is an intensive six month project, supervised by Imperial College London academics, which can be performed in any approved institution. Recent projects have included the study of the shock behaviour of tungsten alloys, the dynamic response of selective laser melted materials, the development of improved HetV systems and the improved understanding of metal-metal reactions.

1 YEAR

Extended projects

Aimed at active researchers and post-graduate 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.

Short courses

The Institute organises and provides teaching for 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, static high-pressures, diagnostic techniques etc.). More specialised sessions can also be arranged.

Training courses

Aimed at research-active scientists and engineers. These courses provide hands-on experience of research using the breadth of the IPS's facilities. Small groups of researchers can be taught from the basics up to expert level development and deployment and analysis of techniques and data. The large bore gas gun at Imperial is run as a facility and can be accessed via a simple application route.

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, singly or as part of a larger group. 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.

University research opportunity programme projects

Aimed at undergraduates. The Institute provides funding for undergraduates to spend part of their summer vacation working as part of a research group. This allows them to experience real research and get involved with current topics. It is often a good measure for the student and the research group of their suitability for more advanced research degrees.

3 DAYS · **1** WEEK · **6** WEEKS · **8** WEEKS

2 YEARS · **3** 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 19 PhD students so far, including one funded by industry, with four new students joining in 2011.

Dr David Chapman (L) and Dr Dan Eakins (R) discuss the design for a gas gun experiment.

The MSc in Shock Physics attracts internationally leading researchers as guest lecturers every year. In 2011, this included:

- Ron Winter » AWE
- Jerry Chittenden » Imperial College London
- Gareth Collins » Imperial College London
- Peter Gould » QinetiQ
- Stephen Walley » University of Cambridge
- Damien Hicks » Lawrence Livermore National Laboratory (LLNL)
- Jean-Luc Lataillade » École Nationale Supérieure d'Arts et Métiers
- Ron Armstrong » University of Maryland
- Claire Kennedy » International Dynamics Ltd, Cambridge
- Rip Collins » LLNL
- Kate Brown » University of Austin, Texas
- Bradley Dodd » Imperial College London
- Steve Rose » Imperial College London

Translation

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 Institute of Shock Physics. 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 visits by a number of potential industrial partners and is following-up on discussions around: PhD and MSc sponsorship, short research projects, short course provision and teaching, shared facilities, and consultancy.

We are particularly pleased to host a PhD student funded by QinetiQ, Ruth Tunnell. In 2011, Ruth was awarded a prestigious Royal Commission for the Exhibition of 1851 Industrial Fellowship for her PhD work on the degradation of complex hybrid propellant systems.

QinetiQ – Degradation Behaviour in Complex Hybrid Propellant Systems

- **Ruth Tunnell (PhD student)**
- **William Proud**

High energy propellant compositions are required to meet the demanding performance requirements of many current and proposed future weapons systems such as mass, weight and acceleration. In addition, such materials have a number of functions in the civilian arena including distress rockets for ships and ferries, space applications such as commercial satellite launching and uses in the automotive industry which incorporates items like airbags and seat belt pretensioners.

However, high performance alone is not the only aspect that must be considered when a new composition is formulated as the safety, environmental impact, vulnerability and cost of the system must also be fully understood.

Complex hybrid propellants are replacing older compositions as they combine the advantageous characteristics of composite materials – high energy, thermal stability, mechanical properties – with those of colloidal propellants, for example, the ability to make smoke free compositions.

Conversely, these complex materials can display the relative disadvantages of composite (e.g., toxicity, smoke) and colloidal propellants (e.g., lower energy, less thermal stability). Furthermore, there is now evidence that such hybrid propellant systems can show different modes of failure than those exhibited in either predecessor type of propellant. It has also been found that traditional analytical techniques and test methods have not always warned of the consequences of such behaviour.

It is therefore becoming increasingly important to understand the degradation behaviours of such complex hybrid propellant systems.

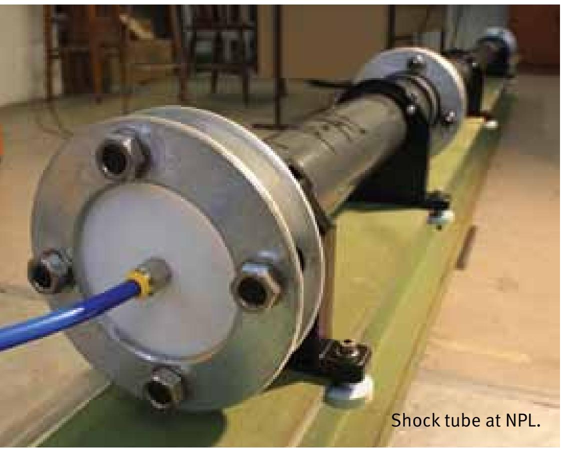
This research will enable these failure mechanisms to be understood so that they can be eliminated or solutions developed to overcome them. This will be achieved through the application of modern thermal, mechanical and related analytical techniques such as heat flow calorimetry, accelerating rate calorimetry, advanced optical analysis and mechanical loading techniques.

> "The gas gun was extremely impressive; we were all surprised that such a large piece of equipment was hidden away in the centre of the campus. The tour gave us an opportunity to speak first-hand to the physicists in an informal setting, and gave us an insight into the research being conducted in the group. It was the first time that many of us on the tour were able to get up close to a modern physics experiment, and we were all very grateful for the opportunity."
>
> **David Govier**
> TOURS OFFICER FOR THE PHYSICS SOCIETY AT IMPERIAL

National Physical Laboratory – Knowledge Transfer Secondment project funded by the Engineering and Physics Sciences Research Council

- **Ian Robinson (NPL)**
- **Andy Knott (NPL)**
- **Stephen Downes (NPL)**
- **Stephen Johnson**
- **William Proud**

High speed pressure sensors are used in science and industry to monitor rapid changes in pressure, such as those found in turbines and internal combustion engines. As the search for increasingly efficient engines continues, there is a requirement to ensure that these dynamic measurements are giving true real-time pressure values. To measure the dynamic response of such sensors, the National Physical Laboratory (NPL) has a need to develop a source of pressure steps with the pressure change across the step traceable to the SI. The step should have a rise-time much less than 1 µs followed by a few milliseconds of constant pressure. Such pressure pulses can be produced using a shock tube where the rapid bursting of a metal diaphragm, exposed to high pressure on one side, generates a shock wave which, under ideal circumstances, provides a well-defined pressure step whose height can be calculated from measurements readily traceable to the SI. However the quality of the step generated by a shock tube depends on the suppression of unwanted wave phenomena in the tube, some of which may arise from the way in which the diaphragm bursts. To support its work on this technique, NPL wishes to understand how metal diaphragms burst under high gas pressures and the subsequent effect of this on the quality and intensity of the shock wave and the pressure step that it produces.



Shock tube at NPL.

These effects are being investigated in collaboration with the ISP who provide experience in the production of the diaphragms along with diagnostic equipment (high-speed cameras, velocity probes, deformation metrology) and help with the analysis of the data. The objective of the work is for NPL to be able to produce pressure pulses suitable for the calibration of high speed pressure sensors using bursting diaphragms in a shock tube. The prime interest is in understanding the fracture process of the diaphragm material and then controlling that process to produce well defined pressure pulses. This will involve understanding of the materials, the fracture process and the production parameters which control this process and will give ISP/Imperial enhanced knowledge of the characteristics of the bursting diaphragms currently used in devices in ISP, Physics and Aeronautics at Imperial College London.

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 organised a very successful show case and also hosted a visit by Imperial's Physics Society. The students were very impressed with what they saw and we hope that at least some of them will be inspired to take up a career in this area.

ISP in the media

David Chapman assisted the research team for the design and development of the 1000 mph Bloodhound Car. Specifically, he was involved in research to identify the best alloy for the wheels, which involved firing pieces of grit at samples of metal using a gas gun at Cavendish Laboratory, Cambridge. See further details via: **www.bbc.co.uk/news/science-environment-11742606**

A close-up view of a small crater in an alloy sample plate struck by a piece of rock travelling at 450-500m/s.

Informing the public

ISP PhD student Chiara Bo was chosen to present a poster of her work on how cells in the human body respond to high intensity-compression waves that cause blast injuries at SET for Britain in March 2012. Chiara found the experience really rewarding and was particularly pleased that the MPs she had invited came along to find about more about her work.

Facilities

Imperial College London

Technical support is provided to ISP research:

- **Imperial College London**
  Steve Johnson
  Mike Lennon
  Mark Grant
  Alan Finch
- **Cranfield Univesity**
  Andrew Roberts
- **Univesity 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.

Large bore single stage gas gun

Delivered and commissioned in February of 2011, the single-stage gas gun at Imperial is the largest precision impact system in the UK. Using highly compressed helium, the gas gun can launch 100 mm diameter projectiles at velocities in excess of 1000 m/s which, upon impact, produce pressures up to 70 GPa, and temperatures greater than a few thousand degrees. It is at these extreme conditions that materials exhibit a new range of behaviour which is the focus of much of the ISP research programme.

The gun features a two metre diameter experiment tank which permits both bulky targets and complex diagnostic systems (e.g., heating/cooling stages, free-space optical elements). Simultaneous testing of multiple samples in a single impact experiment is also possible. This provides a key capability to directly compare the behaviour of materials, and can help correlate testing performed between different platforms.

New diagnostics developed for the gun include an 8-channel, multi-generation HetV system, used routinely to measure the velocity of a surface in response to intense loading. In addition, new light-gate and shorting-pin diagnostics have been constructed to increase timing sensitivity and diagnostic flexibility.

Installation of the large bore gas gun at Imperial (right), completed in February 2011 (above).

Laser-driven shock system (in development)

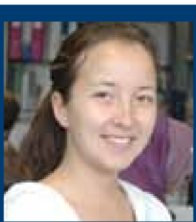
The ISP is working with the Blackett Laser Consortium to construct a new laser-based experimental platform for studying the ultrafast response of materials at Mbar pressures.

Using components from Rutherford Appleton Laboratory and the former (AWE) Helen laser, the Imperial Cerebus laser will be upgraded to deliver a 50 Joule, 2 ns long-pulse in a uniform 1 mm^2 area, with future upgrades expected to achieve 500 J in a 4 ns pulse. The system is being designed to rapidly compress very thin targets, of the order of tens of micrometers in thickness, at strain-rates between 10^8-10^{10} s^{-1}. The result will be a new ISP experimental platform dedicated to the study of dynamic material behaviour at short length and time scales. Study at these fine scales provides a unique view to the early processes responsible for bulk behaviour.

The laser driver is a complementary loading platform for the ISP, allowing the seamless investigation of various phenomena from their origins (laser) through to their mesoscale (MACH) and bulk conclusions (gas gun).

Extreme Physics Laboratory

In the latter part of 2011, the Plasma Physics Group, Quantum Optics and Laser Science and the Institute of Shock Physics obtained ~£1 million strategic funding from Imperial to create new, high quality laboratory space for 'Extreme Physics' research. The funding sees the high power, high energy Cerberus laser being routed through the physics building to reach the laboratory that houses MACH, which will enable a multitude of new diagnostic techniques to be developed – including X-ray radiography and diffraction. The laboratory itself will be refurbished, with MACH gaining a significant amount of space for its research program; whilst a new floor added over the other part of the laboratory will be used to house additional laser amplifiers. Eventually, this will enable experiments coupling ultra-intense laser interactions with the dense plasmas and high magnetic fields created by pulsed power.



Laura Chen, a PhD student at Imperial spends time at Lawrence Livermore National Laboratory (LLNL) each year.

Q What benefit do you get from spending time at LLNL?

A By spending time at LLNL, I get hands-on experience with industry leaders, that instils me with knowledge and skills I can take back to Imperial to carry on work with my PhD. I am able to aid in the collaboration between Livermore and Imperial, which enables me to take part in new, interesting, innovative research, and allows me to have access to the advanced facilities at both institutions.

» 2 MA pulsed power Mega Ampere Compression and Hydrodynamics Facility, MACH

MACH pulsed power platform

MACH is a newly installed 2 MA, ~300 ns rise time pulsed power facility based on Linear Transformer Driver technology. Unusually for a Mega-Ampere generator, MACH incorporates no oil, no water and no SF6 insulation gases; this allows for an extremely low maintenance, 'fast turnaround' system. During 2011, commissioning experiments took place with MACH firing into a resistive load with charge voltages up to 90 kV – near the peak operating voltage of 95 kV. MACH will be performing its first physics experiments during 2012.

To measure the P-V characteristics of the targets used on MACH a new 8 channel HetV system has been assembled. Testing of the HetV system, along with a light gate velocimetry system for the gas gun, is being made on a small electro-thermal launcher. This apparatus uses a 30 kJ capacitor bank to explode a wire load inside a plastic breech. Expansion of gases from the wire accelerates a 16 mm diameter 80 gram flyer down a 1m barrel, at speeds up to ~200 ms^{-1}.

Cranfield University

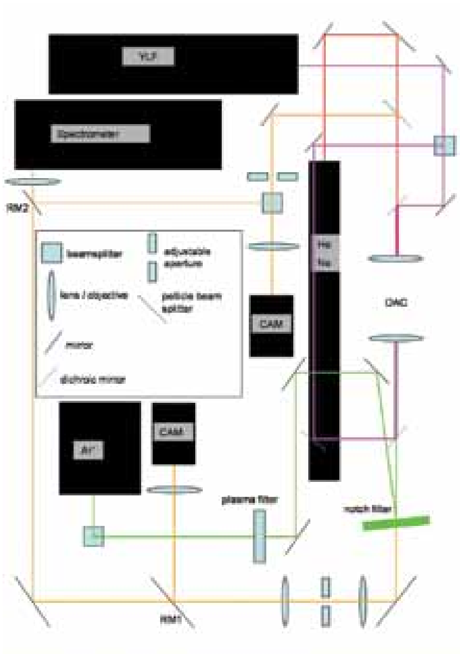
The lab at Cranfield University (Shrivenham) is furnished with several gas guns ranging in calibre from 22 mm to 75 mm. Much of the core work is carried out using 50 mm gas guns; one gas gun is dedicated for working on explosives; and one gas gun is reserved for inert materials. Diagnostics include piezo-resistive gauges; heterodyne velocimeter and high-speed imaging. Split Hopkinson Pressure Bars and drop-weight towers are also installed to interrogate the dynamic behaviour of materials at lower strain-rates. In particular, the ISP has access to a 4-channel Flash X-Ray 300 kV system that allows interrogation of dynamic in-material events at micro-second time resolution. The figure below shows this system fitted to one of the 50 mm bore gas guns.

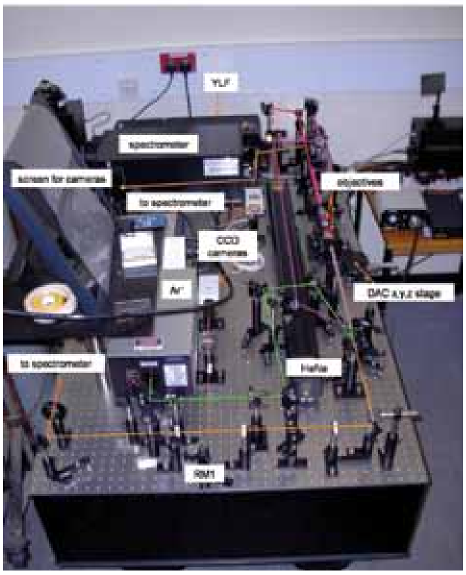
Flash X-ray on the blue target chamber

University College London

Diamond anvil cell and laser facility

The argon ion laser is used as the excitation source for Raman scattering experiments. A notch filter and back-scattering geometry are employed to record the Raman scattered signal. Double sided YLF (neodymium-doped yttrium lithium fluoride) laser heating is employed to heat samples in DACs, dichroic mirrors on either side of the DAC make the YLF radiation coincident with the visible lasers. Laser speckle experiments can be carried out on both sides of the sample with either the Ar ion or HeNe lines. Thermal emission spectra can also be recorded from both sides. Variable apertures are used to select a sub-region of the sample for Raman scattering and speckle/thermal emission measurements.





» Schematic (top right) and photograph (bottom right) of ISP Diamond Anvil Cell and laser facility. Green lines represent 514.5 nm line of argon ion laser, red lines represent 633 nm line of HeNe laser, magenta lines represent 1053 nm radiation from YLF laser and orange lines represent scattered radiation/thermal emission/imaging pathways (dashed and dotted lines on the photograph represent vertical laser paths and laser paths below main optical axis respectively).

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. 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 end entrepreneurs in the field.

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

ISP partners

The Institute of Shock Physics has two primary 'spoke' partners – University College London and Cranfield University, Shrivenham – plus a number of other 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. Over the next year, we will be moving to a membership model that will welcome many more organisations into our network.

The ISP also collaborates with the Russian Academy of Sciences.

Contact

If you are interested in working with us by carrying out research or providing teaching, funding us, accessing our training programmes or collaborating with our excellent researhers and technical staff, please contact:

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