# Femtosecond Pulse Physics

## An assessment of the reproducibility of the Gemini retro focusing system

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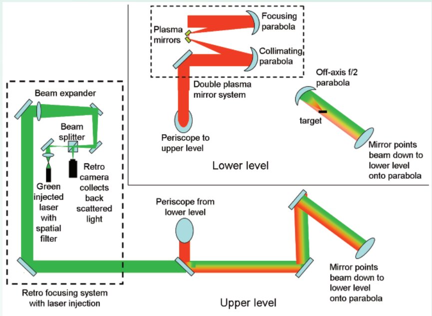
The retro-focus system in the Astra Gemini laser area is used in experiments to position solid targets relative to the tight focus of the laser focused by the off-axis parabolic mirror.

The consistency of positioning a target relative to tight focus was tested. Multiple attempts of positioning the target using the retro-focus system were measured for multiple operators.

It was found that any individual attempt at placing a target at tight focus was not sufficiently consistent to ensure that the target position was within the Rayleigh range. It was found that taking the average of multiple attempts at positioning the target was considerably more consistent such that for all operators their average was either close or within the Rayleigh range.




*Astra Gemini beam path with retro system layout. It also shows how the beam path is split between an upper and a lower level in the chamber.*

## Coherent control of high harmonic generation from relativistically oscillating plasmas via elliptically polarized laser pulses

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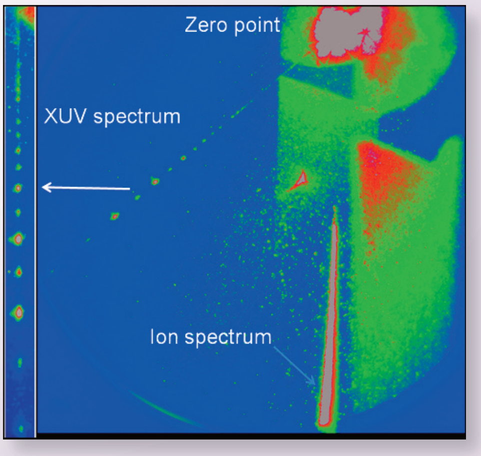
Coherent control of high harmonic generation in transmission from relativistically oscillating plasmas generated on ultrathin (nm scale) foils is examined for the first time using the Gemini laser system. Clear suppression of the generation process using circularly polarised laser pulses is verified in near 1-D interaction geometry for the first time.

*Typical ion and X-ray spectra recorded on the MCP detector at the end of the detector. In this shot the voltage on the Thompson parabola plates is reduced for clarity of the XUV spectrum.*



# TLD measurements of electron and x-ray emission from different materials irradiated by the Gemini laser

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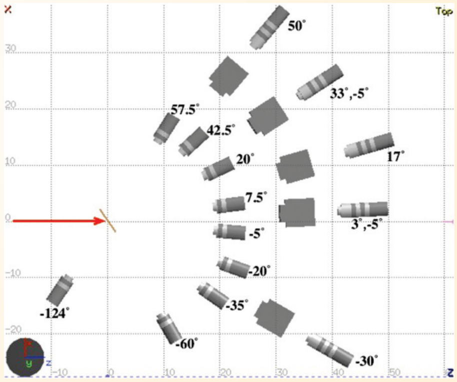
In the experiment we used Thermo Luminescent Dosimeter (TLD-700) chips to record the dose released by electrons and photons produced by the interaction of the Astra Gemini laser and solid targets (Ta, Cu, PMMA and $SiO_2$). The TLD chips were inserted between absorbers to form a stack. Each stack was positioned around the target as shown.

Through the dose absorbed by the TLD chips we studied specific properties of the electron and photon beams, such as the energy and the angular distribution. In addition, a system of magnets was deployed in front of some TLD stacks to enable us to separately obtain the contribution to the dose of the electrons and photons beams.

The dependence of the beams' characteristics on the material and thickness of the irradiated targets is reported.




*Experimental set-up showing the stack disposition around the target on ZX plane.*

# The Petatron: A high-rep rate combination diagnostic for laser-plasma experiments

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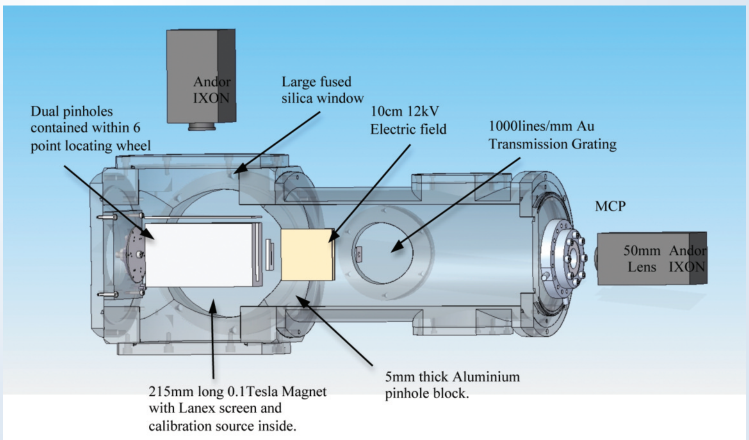
We demonstrate the design and operation of a new combined diagnostic for the characterisation of high intensity laser-matter interactions. Traditionally ion, electron and x-ray spectra have been measured either on different shots (assuming shot-to shot reproducibility) or at the same time but from different direction (assuming smooth, wide angle and angularly uniform trends). These various assumptions have been accepted in a wide range of experiments however here we have developed a diagnostic which simultaneously measures Ion spectra (Proton range: 4MeV-20MeV).




*Experimental schematic. Multi-TW relativistic-irradiance femtosecond laser pulse irradiating He gas jet generates high-order harmonics recorded with the grazing-incidence flat-field soft X-ray spectrograph. The magnet deflects accelerated electrons.*

## Measurement of laser-generated electron slope temperature using electron stopping

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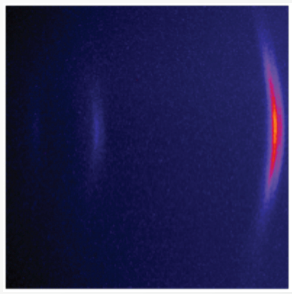
Measurements of *Kα* fluorescence from buried layers of Ni and Cu have been used to investigate the energy of laser-generated hot electrons by characterizing their transport range. The x-ray emissions were recorded using a cylindrically bent crystal HOPG spectrometer. The approximate slope temperature of the hot electrons, $T_e$, and its variation with laser intensity, $I_L$, are inferred from the relative fluorescence intensities of the buried layers at different depths. The Monte Carlo code MCNP is used to model the transport of the hot electrons and infer $T_e$. Simulations using non-relativistic calculations of the electron source and the hybrid PIC code LSP will be necessary to properly simulate the experimental results. Extensions of this experimental work combined with modeling have the potential to further reveal the basic physics of how hot electrons transport solid materials.



*X-ray fluorescence from (right to left) Ni-Kα, Cu-Kα, Ni-Kβ (very faint).*

## Relativistic high-order harmonics from gas jets and their power scaling

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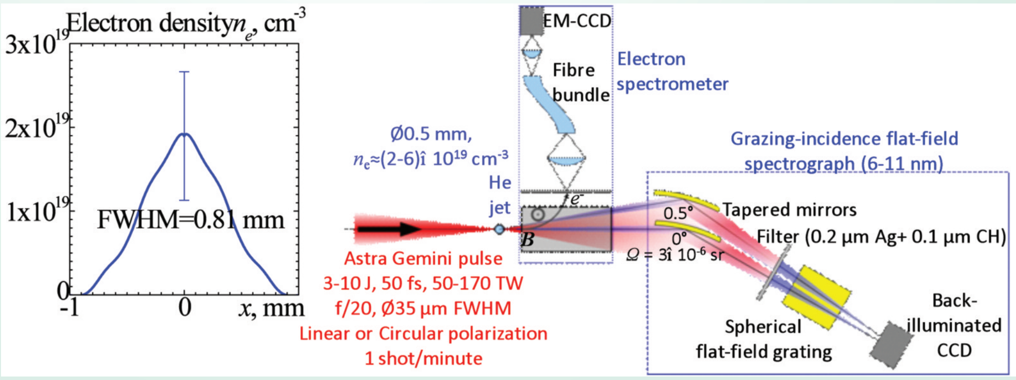
We demonstrate generation of soft X-ray high-order harmonics in experiments with multi-TW relativistic-irradiance femtosecond lasers focusing into Helium gas jet targets. Both odd and even harmonic orders with down-shifted base frequency are emitted in the forward direction while the driving laser polarization can be linear or circular. The harmonics have the angular distribution width of a few degrees and the photon yield is scalable with laser power, increasing by ~2 orders of magnitude as the power increases from 9 to 120 TW. The observed harmonics cannot be explained by previously suggested mechanisms. We introduced a new harmonic generation mechanism where harmonics are collectively emitted by an oscillating electron spike formed at the joint of boundaries of a cavity and bow wave created by a relativistically self-focusing laser in underdense plasma. The spike sharpness and stability are explained by catastrophe theory. The mechanism is corroborated by particle-in-cell simulations.

*Experimental schematic. Multi-TW relativistic-irradiance femtosecond laser pulse irradiating He gas jet generates high-order harmonics recorded with the grazing-incidence flat-field soft X-ray spectrograph. The magnet deflects accelerated electrons.*



# Characterisation of temporal contrast following a double plasma mirror system

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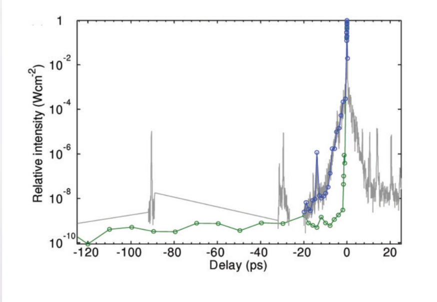
Many experiments performed using short pulse lasers generating intensities approaching $10^{22}$ $Wcm^{-2}$ require an exceptionally high level of pulse contrast. On Astra-Gemini we improve the final contrast using a double plasma mirror system so that the peak of the pulse interacts with an undisturbed target. We have measured the temporal profile of the laser pulse after the plasma mirrors to verify that prepulses are not transmitted and to investigate their effectiveness in eliminating the coherent pedestal which rises before the main pulse on a ~10ps timescale. We find a contrast of $>10^9$ up to 2 ps and $10^6$ at 1.1 ps before the peak intensity. The onset of plasma mirror reflectivity occurs earlier than expected and suggests a lower threshold intensity, possibly caused by a degradation of the optic through irradiation with low level prepulses. Further investigations of this effect should lead to improvements in plasma mirror performance.




*Astra-Gemini pulse contrast measured using the 10Hz beam (grey) and with full power shots (blue). The green data was measured after passage through the double plasma mirror system.*

# High Energy Laser Interactions

## Characterisation of collisionless shocks in tenuous plasma

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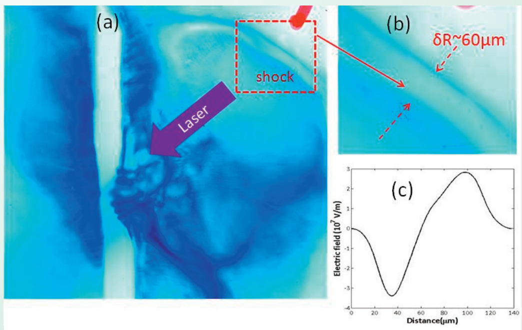
The observation and characterisation of collisionless shock waves generated in laser plasma interactions is presented. The shock waves are generated by long pulse (~1ns), intense ($10^{15}$ W/cm$^2$) laser irradiation of solid targets and are observed to propagate in a tenuous ($10^{13}$-$10^{16}$ cm$^{-3}$), non magnetized background plasma. These nonlinear entities are detected and characterized by employing a proton imaging technique, which allows the simultaneous detection of propagation velocity, width of the shock front and electrostatic field associated with the shock, with high spatial and temporal resolution. Ion Acoustic Solitons (IAS) were observed under certain conditions and as inferred from reconstructed associated electric field profile. The variation of IAS velocity and width as a function of the ambient parameters was characterized. The data show an increase in velocity and decrease in width as the density of the background plasma (generated via photo ionization of controlled, low density gas in a gas cell) is increased.




*(a) Proton image of the interaction of nanosecond pulse with 50µm thick Au stripe, showing shock structure created by the expansion of laser-ablating plasma into tenuous plasma at 350ps after the interaction. (b) zoom of observed structure and (c) reconstructed electric field associated with shock structure.*

## The effect of using multiple laser pulses on the angular distribution of laser accelerated proton beams

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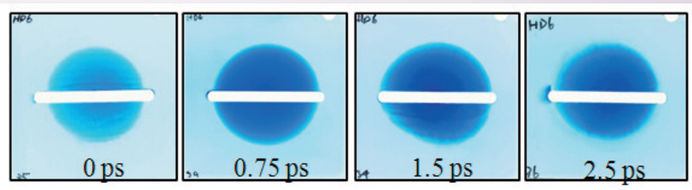
Presented in this report are the results of a laser proton acceleration campaign in which two, relativistically intense laser pulses are incident on a solid foil with a very fine temporal separation of a few picoseconds. We report here on how, along with enhancement of the laser-to-proton conversion efficiency (as first reported by Markey et al [1]), the double-pulse acceleration technique can also be used to improve and change the angular distribution of the proton beam dose in the detector plane.

1. K. Markey et al., Physical Review Letters 105, 195008 (2010).

*Example pieces of RCF irradiated with a proton beam produced by using (left to right) the single pulse and the double pulse technique with temporal separation of 0.75 ps, 1.5 ps and 2.5 ps respectively, with a 100 µm thick Au foil target. The proton energy that this piece represents is 7.3 ± 0.2 MeV.*



# Implications of primary and secondary sources of debris for ultrathin targets on Vulcan Petawatt

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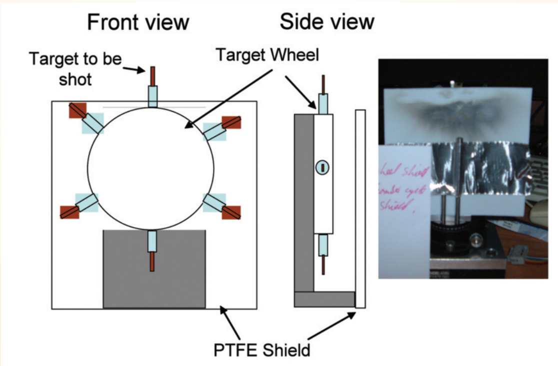
Ultrathin targets (nm) are irradiated with ultrahigh intensity laser pulses. Debris from the target and the frame supporting the ultrathin target foil was found to be generating secondary debris from nearby surfaces. This debris resulted in the loss of ultrathin foils in the vacuum chamber that were intended for subsequent shots. A simple debris shield solution was implemented and found to be successful in protecting the ultrathin foil targets in the hostile environment near the laser interaction.




*The left side shows a schematic of the debris shield put in place to protect the targets. Note that the top edge of the shield should be low enough to avoid target debris hitting it and bouncing back as otherwise this defeats the purpose of the shield. The right side shows the debris shield after a single pump down. The debris deposited coming back towards the target wheel can clearly be seen on the white debris shield.*

# Effects of laser pulse parameters on TNSA proton acceleration

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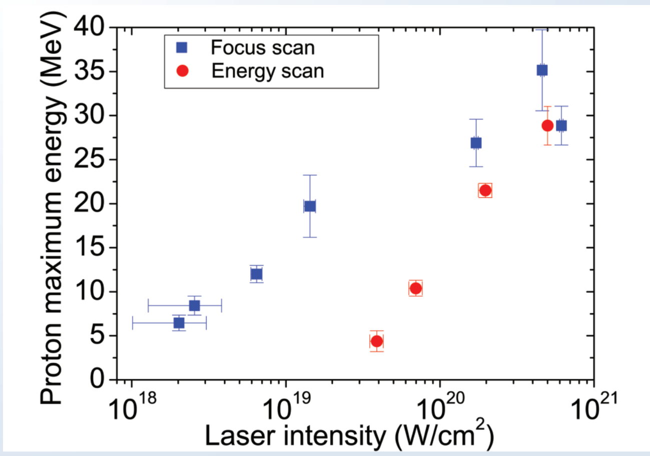
Relativistic electron beams, generated during high power laser-solid interactions, drive multi-MeV ion acceleration. Laser energy coupling to relativistic electrons and the accelerated MeV protons are experimentally investigated for laser intensities from $1\times10^{18}$ W/cm$^2$ to $6\times10^{20}$ W/cm$^2$, by variation of the laser pulse energy for a fixed laser spot size, and by variation of the laser focal spot at fixed laser energy.

Higher proton energies are measured, at a given laser intensity, for large laser energy and focal spot compared to lower energy and smaller focal spot case.

This work highlights the importance of the laser energy coupling to fast electrons, in a defocused geometry, on the maximum proton energy.




*Experimental proton maximum energy as a function of laser intensity.*

## Features of ion acceleration from ultra-thin foils on Vulcan Petawatt

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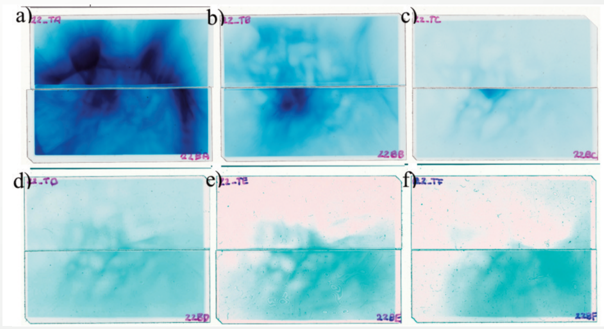
The acceleration of protons and ions from the interaction of the Vulcan Petawatt laser pulse with ultra-thin, nanometre scale diamond-like-carbon foils has been investigated experimentally. A preliminary analysis presented here shows a variety of different structures in the proton beam, indicating a number of different acceleration mechanisms. Observed features include 1) low energy ring structures, due to channel formation as the target becomes underdense; 2) filamentation for 5 and 10 nm targets due to the Rayleigh-Taylor instability; 3) central non-thermal peaked proton beams due to 'self cleaning' of the lower charge density proton species; 4) a smooth off-axis proton beam going to higher energies with a characteristic low flux, possibly related to post-acceleration in the relativistic transparency regime. By gaining a deeper understanding of the acceleration mechanisms, further experiments should be better positioned to optimise the experimental parameters needed to reach high proton and carbon energies with higher efficiencies.




*Example of radiochromic film scans showing proton energy deposition from the interaction of the Vulcan Petawatt pulse with a 5 nm DLC target. From a) to f), the energy corresponding to each layer is 4, 8, 14, and 20, 24 and 30 MeV respectively, where d-f) have been individually contrast enhanced to see detail. There was a gap of 7 mm between the top and bottom pieces.*

## Effects of density scale length on critical surface morphology via measurements of laser specular reflectivity

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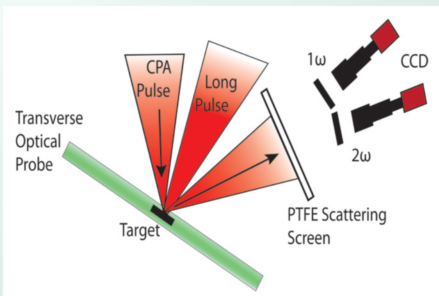
Developing applications of intense laser-solid interactions requires not only a thorough understanding of the bulk transport physics but also a detailed knowledge of the laser interaction with the target front surface.

High power lasers often have some level of ASE/pre-pulse which generates plasma on the front surface of the target prior to the arrival of the main pulse. The density profile of this plasma has significant implications for the laser energy absorption and laser-electron coupling.

In this report we demonstrate a novel diagnostic of the preplasma density profile by measuring the divergence of the laser beam reflected from the relativistic critical surface. In contrast with the commonly used technique of transverse optical probe interferometry, which is restricted to densities much less than critical, this technique has the potential to measure the density profile of the preplasma up to the relativistic critical density surface.




*Top view of experimental setup.*

## Scaling of ion spectral peaks in a hybrid RPA-TNSA regime

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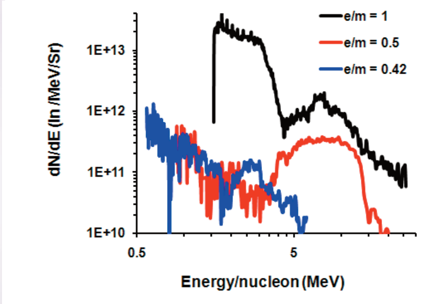
Employing the Vulcan Petawatt laser of the Rutherford Appleton Laboratory, UK, the effect of Radiation Pressure on the spectra of ions accelerated from thin foils has been investigated. For sufficiently thin targets, the data shows features consistent with onset of the Light Sail regime of RPA (narrow band ion spectra with energy up to 20 MeV/nucleon), in competition with the TNSA mechanism. The ion energy scaling obtained from parametric scans agrees well with theoretical estimations and particle in cell simulations.




*Ion spectra of different ion species from irradiation of 100 nm thick Cu foil by the Vulcan Petawatt laser at an intensity $3\times10^{20}$W/cm$^2$*

## Reflectivity measurements in ultraintense laser-plasma interactions

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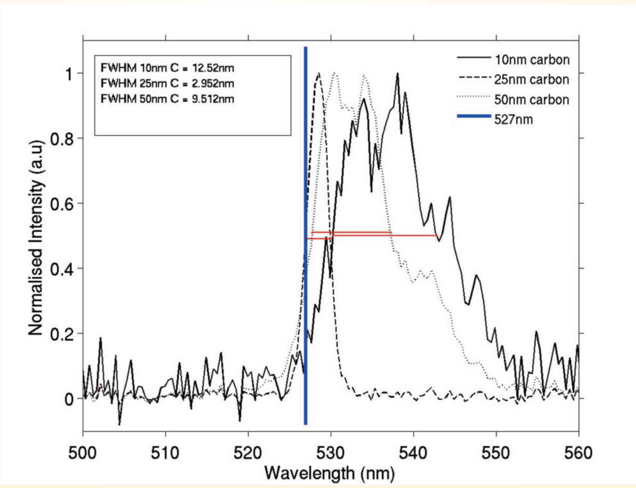
The interaction of an ultraintense laser pulse with a solid density target is of fundamental importance to a number of applications, such as the Fast Ignition approach to Inertial Confinement Fusion and laser-driven ion acceleration. Key to this interaction is the role of critical density surface dynamics on coupling the laser pulse energy into the plasma. The absorption and transport of this energy is therefore of critical importance .
In this report, we describe spectral measurements of backreflected light from laser-plasma interactions at intensities >$10^{20}$ Wcm$^{-2}$. We show that these measurements can give an indication of the critical surface dynamics under intense laser drive. Preliminary examination of the underlying physics is given, as well as potential future directions for this research.




*Reflected second harmonic spectra from carbon of thickness 10nm, 25nm and 50nm. The blue line denotes the second harmonic of the fundamental wavelength. Strong spectral modulations, line shifting and linewidth broadening are shown which correspond to movement of the critical density surface.*

# Lattice structure effects on energetic electron transport in solids

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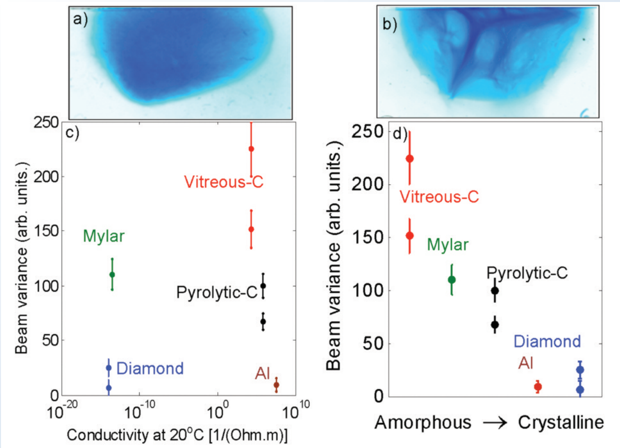
The effect of lattice structure on the transport of energetic (MeV) electrons in solids irradiated by ultraintense laser pulses is investigated. Various allotropes of carbon are used to investigate lattice effects independent of target element. Smooth electron transport in diamond and beam filamentation in less ordered forms of carbon is observed. The highly ordered lattice structure of diamond is shown to result in a transient state of warm dense carbon with metallic-like conductivity, in the temperatures range of 1–100 eV, leading to suppression of electron beam filamentation.




*Spatial-intensity profile measurements (lower half) of the proton beam, at energy 10 MeV, for a) diamond and b) vitreous carbon.*
*c) Variance in the proton signal near the centre of the proton beam, for given target materials with increasing room temperature conductivity left to right.*
*d) Variance in the proton signal with increasing atomic ordering from left to right.*
*Error bars correspond to statistical variations over the multiple samples.*

# High-energy proton acceleration using an innovative plasma-based fast (f/0.6) focusing optic

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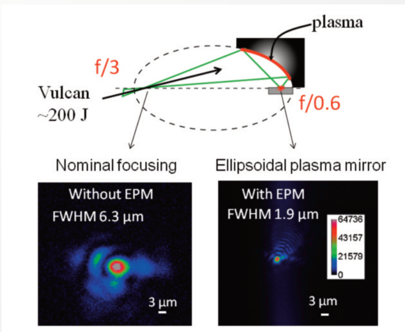
Achieving ever-higher irradiance for lasers holds great promise as it opens access to applications ranging from extreme nonlinear physics to the generation of bright sources of coherent radiation and particles, fast ignition of fusion targets, or hadron therapy. Further enhancement of irradiance is planned through laser energy increase and pulse-duration reduction. An alternate route would be to decrease the focused spot size, but this is limited by the impracticality of extremely low f-number (high NA) focusing optics for conventional parabolic reflectors. We demonstrated an f/# = 0.6 optic that is a plasma-based, compact (~ 1 cm$^3$), ellipsoidal reflector. It reduces the spot size multiple-fold compared to standard focusing, leading to substantial enhancement to both the laser intensity and the maximum energy of the resultant proton beam. We applied this novel plasma optic at the Vulcan PetaWatt facility to accelerate the laser-generated protons to a much higher energy than previously observed.




*Experimental setup for tight focusing of ultrahigh intensity Vulcan PetaWatt laser pulses by low f/# confocal ellipsoid plasma mirrors (EPM). Direct measurement of the focal spot shows that the focal spot size is reduced by a factor of ~3.*

# Measurement of Rayleigh-Taylor instability growth in a layered target heated by a high power short pulse laser

18

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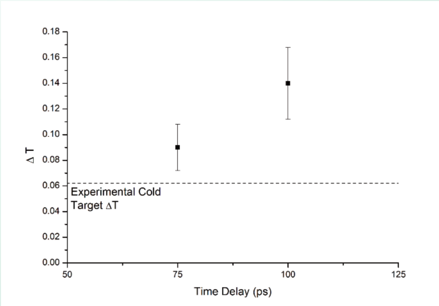
The Rayleigh-Taylor (RT) instability, as observed in inertial confinement fusion and astrophysics, occurs when a lighter fluid accelerates a heavier fluid, causing instability between two immiscible fluids. Slight irregularities between otherwise planar layers increase rapidly in time creating 'finger-like' ridges of dense material moving around bubbles of the less dense fluid.

The work presented here uses a 300J, 3ps pulse from the Vulcan laser to volumetrically heat a two layer target of copper and CH plastic with an approximately sinusoidal perturbation at the interface between the two materials. Upon radiative cooling of the Cu this creates an RT unstable plasma. The evolution of this plasma is investigated by performing back-lit radiography at different times using Kα x-rays from a Ti foil illuminated separately by a 2ps, 100J laser pulse. These Kα x-rays are imaged using a spherically bent $SiO_2$ crystal.

A CH/Cu target, seeded with an initial perturbation of amplitude 300nm at the interface between the two materials, demonstrated RT growth in the first 100ps after the laser interaction with a growth rate of $\gamma = 10 \pm 2$ ns$^{-1}$.




*The total change in transmission, ΔT, from peak to trough of the target perturbation as a function of time delay between the heating pulse and the pulse generating the titanium Kα back-lighter. The dashed line represents the experimentally measured value of ΔT for the cold RT target.*

# Proton beam steering from ultra-thin foils irradiated by intense laser pulses

19

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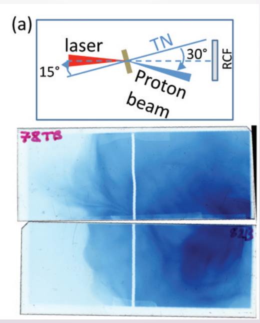
While ion beams accelerated from thin foils via Target Normal Sheath Acceleration are typically directed (as the name implies) along the normal to the irradiated target, in a number of experiments [1,2] a beam deflection from target normal has been observed and attributed to the effect of target rear deformation induced by shock waves launched into the target by the ASE prepulse. A similar effect has been recently observed on the VulcanPetawatt laser when irradiating sub-micron Cu foils at intensities exceeding $10^{20}$ W/cm$^2$ and employing a plasma mirror (PM) to enhance the laser contrast. Even for normal incidence a substantial deviation, from the target normal was observed, and the deflection angle showed a correlation with the incidence angle. The phenomenology of the results, and particularly the comparison with shots at lower contrast, shows clear differences from the previous observations described above. It appears likely that these results are related to non-ideal PM operation due to a strongly uneven near field profile. Further analysis and modelling is required in order to clarify how this can affect the ion acceleration dynamics.




*Deviation of proton beam from target normal direction observed for 15° (clockwise rotation from the top) laser incidence on a 100nm Cu foil target. In (a) schematic of the experimental measurement is drawn. In (b) The corresponding beam profile and its position imprinted on a RCF layer is shown. The vertical line is shadow of wire attached to the stack in order to define laser axis. For this case beam deviation about 30° is observed.*

1. F. Lindau et. al., Phys. Rev. Lett. 95, 175002 (2005)
2. K Zeil et. al., New Journal Phys. 12, 045015 (2010)

## Formation of plasma channel with long pulse interaction

20

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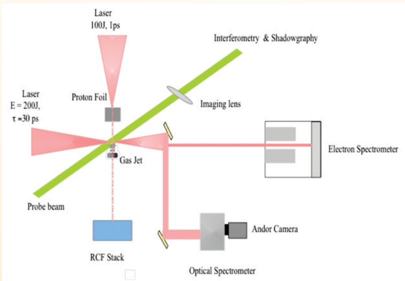
The propagation of an intense laser pulse through fully ionised plasma has been investigated extensively in the last decade [1]. There are a number of applications that require the formation of a stable channel in underdense plasma. The aim of the experiment was to study laser channelling in underdense plasma by laser pulses of comparatively long duration, emulating the one proposed by Li et al. [1], focused into a supersonic deuterium gas jet at various densities. It is shown that even when the laser power is below the threshold for relativistic self-focusing the ponderomotive force is able to create a longitudinally smooth channel. We report here on the experimental observation of plasma channels created by focusing a high intense long pulse laser (30 ps) into a deuterium gas jet. The size of the plasma channel was measured to be ~ 2 mm in length and the diameter of the plasma channel was ~300 µm for higher densities.

1.G. Li et al., Laser Channeling in Millimeter-Scale Underdense Plasmas of Fast-Ignition Targets. Physical Review Letters. 100:125002 (2008).




*Sketch of experimental setup.*

## Characterisation of debris emission from PW laser solid interactions

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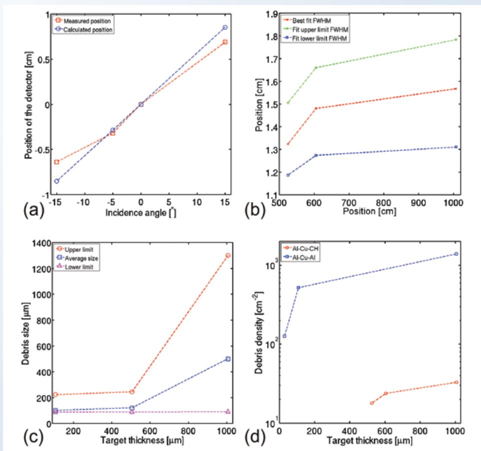
We report on the characterisation of particulate debris produced by PW laser pulse interactions with solid targets. It is shown that the debris emission is mostly directed along the target normal direction, for both the emission coming from the front and rear surface. The size and density of the debris increase with increasing target thickness. It is found that liquid debris is emitted in a ring like distribution centered on the target normal direction with a radius found to increase approximately linearly with target thickness. This observation indicates a constant divergence of the debris corresponding to the divergence of the shock wave inside the target. The divergence half angle of the rear surface debris emission is found to be ~16°. It is also found that in the case of layered targets, large portions of the buried layer can survive the laser interaction and be ejected in the target normal direction.




*(a) Measured and calculated front surface debris emission direction for varying laser incidence angle. (b) Radius of the rear debris emission distribution as a function of target thickness. (c) Variations of the size of the debris particulate with increasing target thickness. (d) Variations of the rear debris emission density as a function of the target thickness for different target types.*

# Exotic x-ray spectra from ultra-intense laser driven hollow atom transitions

22

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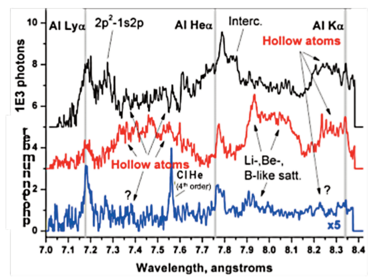
The fundamental science of high intensity interaction with atoms and molecules is a large and rich area of study with the relativistic regime ($I\lambda^2 > 10^{19}$ W cm$^{-2}$ μm$^2$) remaining relatively unexplored. Hollow atoms are atoms or ions with an empty inner shell and occupied outer shell [1], and K-shell hollow atoms have an empty principal quantum number n = 1, innermost, shell. These exotic ions are short-lived and are created by K-shell double ionization with photon, electron or ion collisions, and in nuclear α, β, electron capture (EC) decays. Hollow atom states are of fundamental interest and an example of systems far from equilibrium. Double photo-ionisation is of great interest as the advent of intense, tunable free-electron lasers in the soft x-ray region offers the possibility of creating large populations of hollow atoms.

1. J. P. Briand et al., Phys. Rev. Lett. 65, 159 (1990)




*Aluminium K-shell spectra recorded using the FSSR spectrometer from the front (laser irradiated) surface.*

# Theory and Computation

## Super-Gaussian transport theory and field generating instability in laser-plasmas

23

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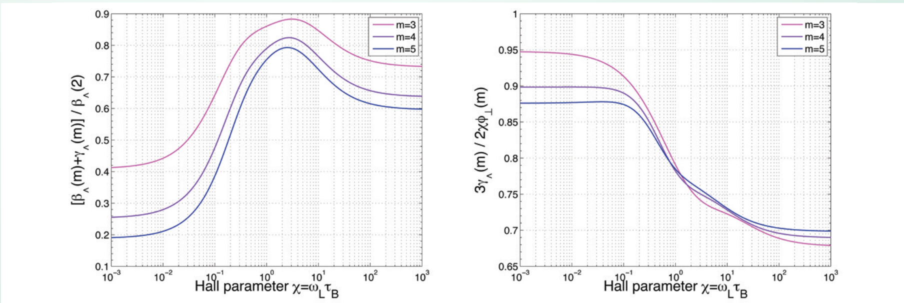
Inverse bremsstrahlung (I.B.), which is a key heating mechanism in long-pulse laser systems and distorts the electron distribution function towards a super-Gaussian, impacts on thermal transport by modifying the equations of classical transport theory (C. P. Ridgers et al., Phys Plas. 15, 092311 [2008]). In this report we examine these modified equations, and show that super-Gaussian effects both suppress traditional phenomena and introduce a new magnetic field advection effect in the direction of increasing density. Suppression of traditional effects is shown to be most pronounced in the limit of low Hall-Parameter $\chi$, in which case the Nernst effect is reduced by a factor of five, the $\nabla T_e \times \nabla n_e$ field generation mechanism by ~30%, and the diffusive and Righi-Leduc heat-flows by ~80% and ~90% respectively.

Given such strong inhibition of transport effects at low $\chi$, we explore the impact of I.B. on the seeding and evolution of magnetic fields in un-magnetized conditions by re-deriving the well-known field-generating thermal instability (D. A. Tidman and R.A. Shanny, Phys Fluids 17, p. 1207 [1974]) in the light of super-Gaussian transport theory. Calculations based on conditions in an inertial confinement (I.C.F.) hohlraum demonstrate that super-Gaussian effects reduce the growth-rate of the instability by more than ~70%. This may be important for I.C.F. fusion experiments, since by increasing the strength of I.B. heating, it would appear possible to inhibit the spontaneous generation of large magnetic fields.




*Suppression of the Nernst effect (left-hand plot) visualised by plotting $[\beta_\wedge(m)+\gamma_\wedge(m)]/\beta_\wedge(2)$ as a function of $\chi$ for different values of super-Gaussian power m.*

## High-field electrodynamics in plasmas

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Non-linear theories of electrodynamics have received much attention over many decades. In particular, recent years have seen a resurgence of interest in Born-Infeld electrodynamics following its rediscovery during the first superstring revolution in the mid-1980s. In particular, it has been suggested that pathologies in the dynamical behaviour of a radiating point charge, such as those described by solutions to the Lorentz-Dirac equation, may be avoided by appealing to Born-Infeld, rather than Maxwellian, electrodynamics. Motivated by the above considerations, we summarize our recent exploration of Born-Infeld electrodynamics within the context of plasma physics. We examine the behaviour of linear waves in a magnetized Born-Infeld plasma, and summarize the properties of non-linear waves near breaking.

## 2D hydrodynamic code development and simulations relevant to fast ignition fusion targets

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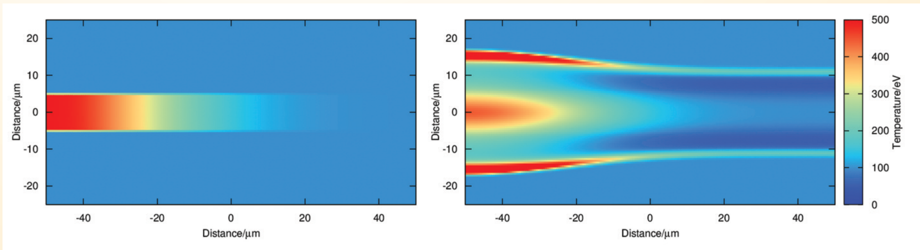
Details of the development of a 2D hydrocode are presented, along with some initial results. The hydrocode includes separate temperatures for ions and electrons, as well as ion-electron equilibration and thermal conduction.

The hydrodynamic response of a plasma subjected to strong Ohmic heating, via relativistic electron beams used in fast-ignition fusion, is an important concept.

If the target used to get the relativistic electron beams into the centre of the fuel does not stay intact for long enough it will prevent the compressed fuel from being heated. A test simulation is presented here, with simulations relevant to fast-ignition fusion to be preformed in the future.

*Electron temperature at 0 and 20 ps, for an aluminium plasma starting at solid density, with an initial uniform ion temperature of 100 eV.*




## Evolution of a short pulse via ray tracing

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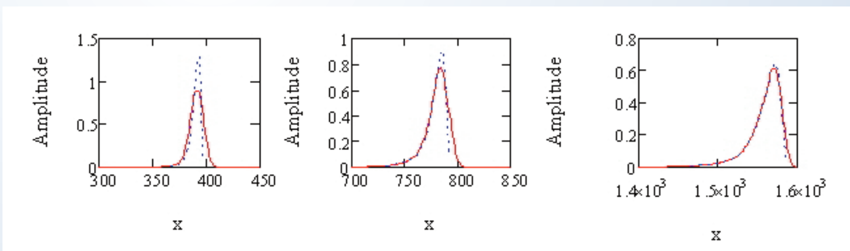
A recent paper (Cairns and Fuchs, Nucl. Fusion 50, 095001, 2010) describes how ray-tracing may be used to reproduce the wave pattern produced by a small antenna launching a wave into a plasma. The present work uses the same ideas to look at propagation of a short pulse in a plasma with arbitrary space and time dependence of the density. It involves launching a multiple set of rays each corresponding to a different Fourier component of the initial pulse.

The exact wave profile sufficiently far from the launch point can then be reconstructed from an algorithm using only the information contained in the rays. Enough rays to give good resolution of the pulse can be followed over a long time scale with much less computational effort than is needed for solution of the exact wave equations. This may be a useful tool in some laser-plasma problems.




*Evolution of a pulse with a Gaussian envelope launched into a constant density plasma. The exact solution (red) can be calculated and compared with the approximation (blue). After a sufficient propagation distance the solutions are essentially indistinguishable.*

## Calculation of Siegert states of molecules in electric field : an $H_2^+$ study

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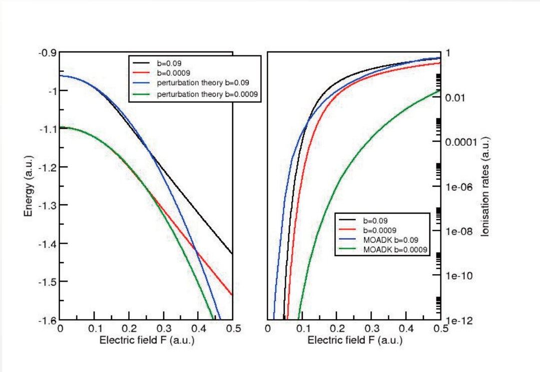
The ionization of atoms and molecules by an intense laser field has been investigated extensively in the last few decades, both theoretically and experimentally. While the MO-ADK model [1] based on the semi classical asymptotic theory has been widely used to estimate the ionization rates for various molecular systems, it is known to work well only for relatively weak fields in the tunnelling regime. A new more reliable theory for strong field ionization of molecules is hence necessary. We use a soft Coulomb model potential to study $H_2^+$ molecular ion in electric field up to 0.5 a.u. We obtained energies and ionisation rates for the ground state $\sigma$. The energies are compared with energies obtained from perturbation theory and the ionisation rates are compared with data obtained from MOADK. We can observe a good agreement below the limit of accuracy of the method used for comparison.

1. A. J. F. Siegert, Phys. Rev. 56, 750 (1939)




*Electric field dependent energies and ionisation rates obtained with two soft Coulomb potential model with softening parameter bb=0.09 and bb=0.0009 compared with energies obtained from perturbation theory calculation and ionisation rates obtained from MOADK.*

## Radiation reaction in ultra-intense laser fields

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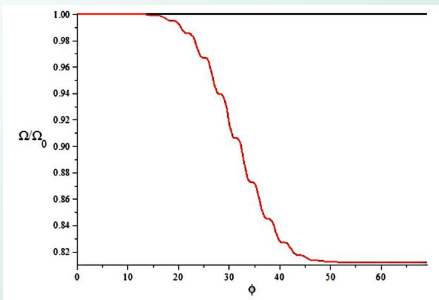
With lasers reaching higher and higher intensities (such that the dimensionless laser amplitude $a_0 >> 1$) effects of radiation reaction can no longer be neglected. As long as the Lorentz force remains larger than the reaction force, radiation loss effects on moving charges are consistently described by the Landau-Lifshitz equation of motion. Both for infinite and pulsed a plane wave fields this equation can be solved analytically. Radiation reaction can then be quantified in terms of a symmetry breaking parameter associated with the violation of null translation invariance in the direction opposite to the laser beam. In more physical terms, for a plane wave with wave 4-vector k, this parameter is just the laser frequency, $\Omega = k \cdot u$, 'seen' by the electron in its instantaneous rest frame co-moving with 4-velocity u. Hence, $\Omega$ ceases to be conserved in the presence of radiation reaction.




*Laser frequency $\Omega$ in units of its initial value $\Omega_0$ as 'seen' by the electron during the passing of a 10-cycle pulse as a function of invariant phase, $\varphi = k \cdot x$. Black line: Constant result without radiative reaction. Red line: Solution of the Landau-Lifshitz equation.*

## Time-dependent R-matrix theory for ultra-fast processes

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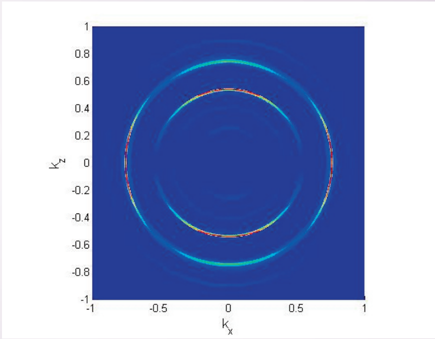
Recent developments in laser technology may offer opportunities to observe, and possibly alter, how electrons move within atoms and molecules. We have developed a new theory, time-dependent R-matrix theory, to investigate how the repulsion between electrons affects the movement of several electrons simultaneously.

As a first application of this theory we have shown how the correlated dynamics of several electrons can be visualised through momentum distributions of the ejected electrons in a pump-probe scheme. These distributions change depending on the delay between the two laser pulses. In a second application of this theory we study the role of electron-electron repulsion on harmonic spectra.

At present, our research is focused on dynamics which is fully driven by the repulsion between the electrons.

The next challenge is to understand how the full multi-electron dynamics is built from dynamics arising from each of the individual forces in the atom.




*Typical ejected-electron momentum distribution obtained for singly charged carbon ions excited by a six-cycle laser pulse with 10.9 eV photons and subsequently ionized by a six-cycle laser pulse with 16.3 eV photons.*

## Molecular dynamics simulations for the viscosity of non-ideal plasmas

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J. Daligault
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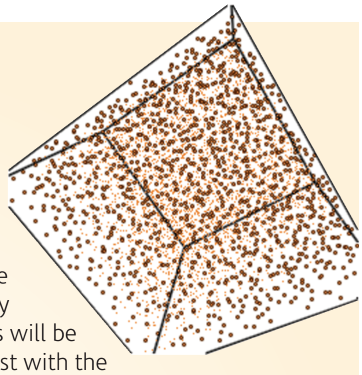
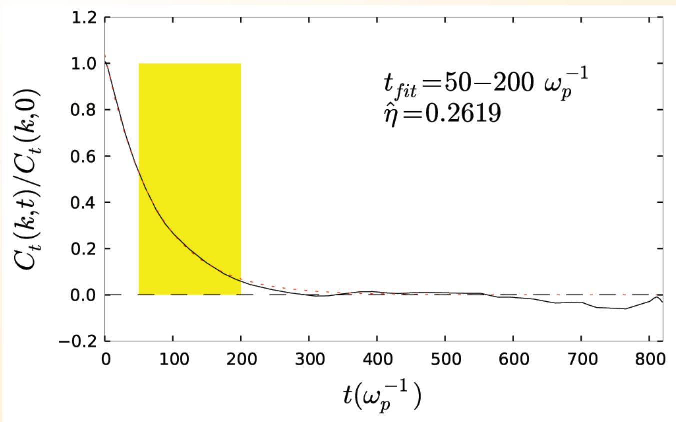


Viscosity is a fundamental characteristic property of all liquids. Recently, it was shown that the viscosity of non-ideal plasmas - which have liquidlike properties - could in principle be measured in x-ray scattering experiments on laser produced plasmas. With this in mind, it is desirable to have theoretical estimates of the viscosity of non-ideal plasmas. In this contribution, we discuss two methods for computing the viscosity and present our numerical results. We expect that in the future our viscosity calculations will be used to assist with the interpretation and analysis of x-ray scattering experiments, which could in principle measure this fundamental quantity.




*Transverse current correlation function of the Yukawa one-component plasma and its decay which, in the hydrodynamic regime, is governed by the shear viscosity.*

## Kinetic theory of radiation reaction 31

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D. Burton, J. Gratus
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The development of ultra-high intensity laser facilities requires a detailed understanding of how accelerating charged particles interact with their own radiation fields. The Abraham-Lorentz-Dirac (ALD) equation - the standard description of radiation reaction - is beset with difficulties, but when handled with care can provide useful information.

A kinetic theory has been developed, based on the exact ALD equation. Although the unphysical solutions of the ALD equation obstruct the reduction of this theory to the usual Vlasov-Maxwell system in the appropriate limit, its moments give rise to a fluid theory which does have the correct limiting behaviour.

As a simple illustration of the theory, the radiative damping of Langmuir waves gives rise to a modified dispersion relation. A new unphysical instability is found, originating from the runaway solutions of the ALD equation, which must be rejected, leaving the physical solutions which display the correct slow damping.

## Simulating prolific pair-production in 10PW laser-plasma interactions 32

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J. G. Kirk
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With the next generation of high intensity lasers it will be possible to access the regime in which Quantum Electrodynamics (QED) plays an important role. Specifically, the laser-fields may be sufficiently strong to generate electron-positron pairs. The controlling parameter determining the rate of pair production is

$$\eta = \gamma \left| \frac{\mathbf{E}_\perp}{\mathbf{E}_s} + \mathbf{v} \times \frac{\mathbf{B}}{\mathbf{B}_s} \right| \qquad (1)$$

Here $E_\perp$ is the electric field perpendicular to the direction of motion of the electron $E_s$ (= cBs =1.3x10$^{18}$Vm$^{-1}$) is the Schwinger field. Pair production becomes important when η becomes of the order of 0.1. For an intensity of 10$^{23}$Wcm$^{-2}$ the electric field of the laser is of the order of 10$^{15}$Vm$^{-1}$. From equation (1) one can see that when the Lorentz factor of the electrons (γ) is of the order of 100 then pairs should be produced in significant quantities. Electrons are accelerated to this energy by a 10PW laser.

## The magnetic switchyard: Guiding fast electrons for fast ignition ICF 33

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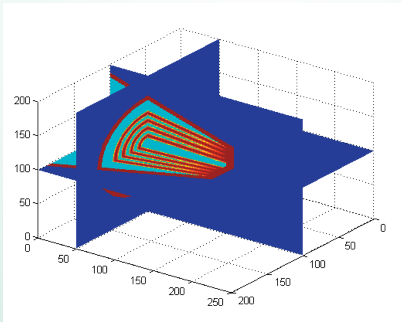
We propose a new scheme for guiding fast electrons for Fast Ignition ICF. The principal concern being that typical fast electron divergence angles are too large to provide sufficiently efficient coupling into hot spots that are of similar size to the laser spot. In our new scheme we use an insert that sits inside the re-entrant cone, the insert is a solid mass of guiding elements that are embedded in a lower-Z substrate. The scheme exploits the growth of magnetic fields at the interfaces as the fast electrons flow through the structure. The magnetic fields that grow can then effectively guide the fast electron. The scheme does not require any structures that sit outside the re-entrant cone. Numerical simulations of the concept show that fast electron-hot spot coupling efficiencies of 27% can be achieved even when the fast electron divergence half-angle is 70 degrees.




*Slice Plot of Z for a Magnetic Switchyard insert into a cone. Red regions are higher Z than blue regions. This shows the concentric, axisymmetric shells embedded in the lower-Z material.*

# Production of high energy protons with hole-boring radiation pressure acceleration

34

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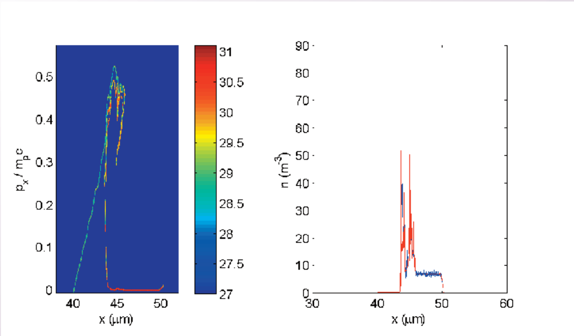
The utility of “Hole-Boring” Radiation Pressure Acceleration for producing very high energy (> 100MeV) protons has been seen as rather limited. This is because HB-RPA scales as 1/n, and n, the plasma density, is thought to be limited to $a_0 n_c$. In fact this limit, which comes from linear theory, is not a rigid limit and penetration can be limited to much less than this due to non-linear processes. We have checked the analytic theory with numerical simulations and we find that this reduction in the minimum density might relax the intensity requirement to reach 100-200MeV by a factor of 4.




*(Left) px-x phase space for protons. (Right) Number densities of protons (red) and electrons (blue). Data is taken from the $n = 7 \times 10^{27} m^{-3}$ simulation.*

# The effect of density scalelength on the fast electron beam generated by ultra-intence laser-solid interactions

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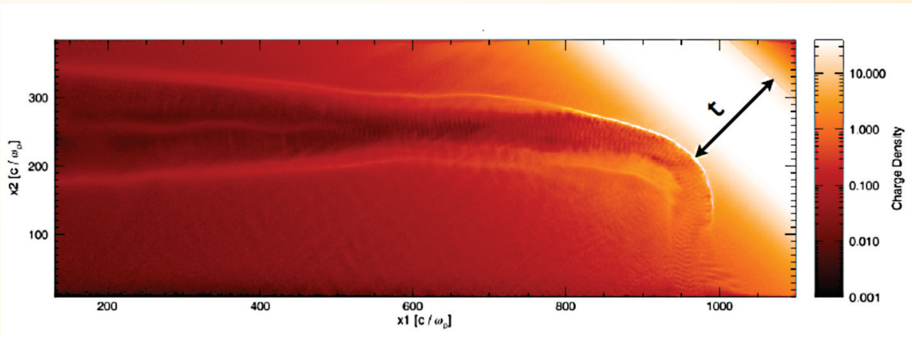
A systematic experimental and computational investigation of the effects of density scalelength on ultra-intense laser-solid interactions is described. When the density scalelength is sufficiently large, the fast electron beam resulting from the laser-solid interaction is best described by two distinct populations: those accelerated within the sub-solid density plasma - the fast electron pre-beam, and those accelerated nearer the target front surface - the fast electron main-beam. The pre-beam has considerably lower divergence than that of the main-beam with a half-angle of 20°, under the conditions investigated it contains up to 30% of the total fast electron energy absorbed into the target. The number, kinetic energy, and total energy of the fast electrons in the pre-beam is increased by an increase in density scalelength. It is shown that with a large density scalelength the fast electrons heat a smaller cross sectional area of the target, causing the thinnest targets to reach significantly higher rear surface temperatures. This is ascribed to the enhanced fast electron pre-beam which generates a magnetic field within the target of sufficient magnitude to partially collimate the subsequent, more divergent, fast electron main-beam.




*Channelling by, and subsequent refraction of the laser beam in the large density scalelength underdense plasma as it approaches the 45° p-polarised 40$n_c$ target*

## An analytical model for the energy of relativistic electrons escaping a plasma

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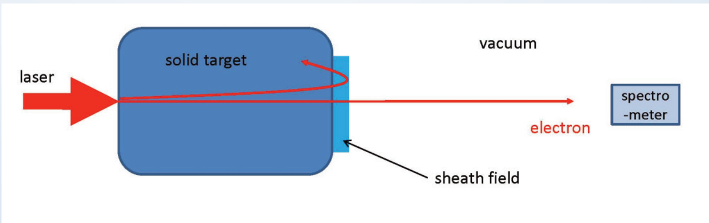
In relativistic laser-plasma interactions, highly energetic electrons are produced which stream through the target plasma. Once these electrons reach the target's rear surface they can in principle leave the target and propagate through the vacuum, where they may be detected by a spectrometer. The energy of the electrons once they reach the spectrometer is not representative of their energy just prior to exiting the target, because the electrons generate an electric field which attempts to pull them back toward the target. It might be argued that the energy of electrons that reach far into the vacuum is less than their energy as they leave, because the field is decelerating. On the other hand it could be argued that only the very highest energy electrons are able to reach far into the vacuum because they are the only ones with sufficient energy to overcome the decelerating fields.

We will show with a simple analytical model that the energy distribution function for electrons that reach far into the vacuum is such that their energy is lower by a factor of about 2. This result is independent of geometry (and hence is valid in 3-dimensions).




*The idealised experimental setup.*

## Numerical simulation of plasma-based laser pulse compression to petawatt powers via Raman amplification

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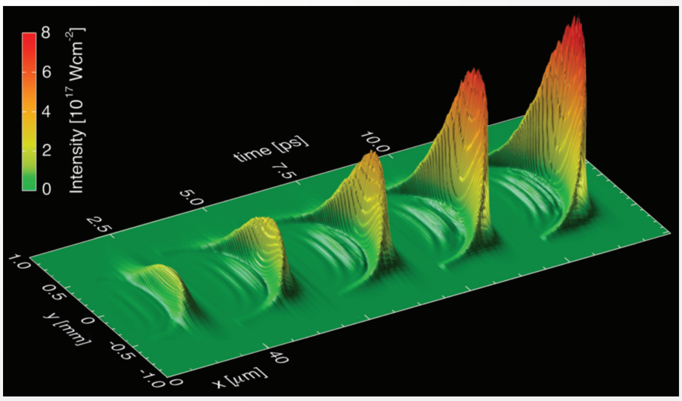
Contemporary high-power laser systems make use of solid-state laser technology to reach petawatt pulse powers. The breakdown threshold for optical components in these systems, however, demands beam diameters up to 1 metre. Raman amplification of laser beams promises a breakthrough by the use of much smaller amplifying media, i.e. millimetre diameter wide plasmas. Through the first large scale multi-dimensional particle-in-cell simulations of this process, we have identified the parameter regime where multi-petawatt peak laser powers can be reached, while the influence of damaging laser-plasma instabilities is only minor. Such powerful laser pulses have many applications in e.g. plasma-based particle acceleration, laser-driven nuclear fusion and laboratory astrophysics.




*Raman compression of a 4 TW, 25 ps pulse to 1.5 PW in 25 fs for $\omega_0/\omega_p = 20$. Shown are five snapshots of the growing probe at 2.5 ps intervals. The x and y scales refer to the local coordinates of the probe pulse itself, and the 'time' scale refers to the probe propagation time. The amplified probe has a mostly smooth intensity envelope, enabling it to be focused tightly.*

## Use of the Debye-Waller factor as a temperature diagnostic in strongly coupled non-equilibrium plasmas

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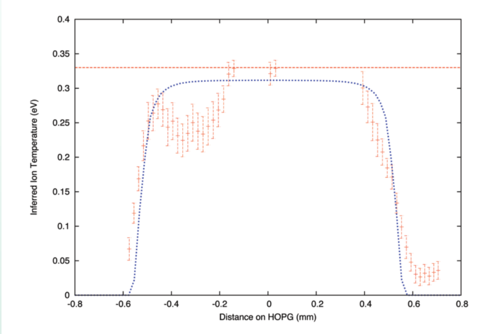
The Debye-Waller (DW) technique has been used in solid-state physics as a way to characterize the displacement of atoms in a crystal from equilibrium. This method utilises the drop in intensity of coherent elastically scattered radiation with reduction in periodicity. Here we examine the applicability of this technique to infer ion dynamics and temperature within the warm dense matter (WDM) regime. An understanding of WDM plays an important role in describing many physical phenomena ranging from phase transitions within the interior of large astrophysical objects to the internal processes of inertial confinement fusion.

Through a combination of the DW theory and large-scale molecular dynamics the temperature dependent reduction in x-ray scattering is determined. Using this method we infer the ion temperature in warm dense graphite and have shown that the results obtained from the DW theory compare favourably with an approximate proton spectrum and known energy deposition in graphite.




*Inferred ion temperature from the Debye-Waller theory (red lines) and expected temperature from the theoretical proton spectrum (blue lines) for 50 μm of graphite behind 15 μm of PP. The red dashed line indicates the equilibrium melt temperature of graphite ~0.33 eV.*

## A new VFP-PIC hybrid code to model fast electron transport with hydrodynamic response

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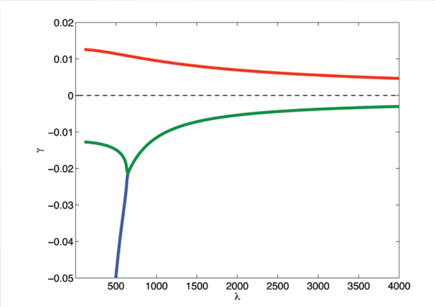
The interaction of a high-intensity laser beam with a solid target generates a large number of fast-electrons with long mean free paths. The study of these fast-electrons is still the subject of active research, given their relevance to Tabak's proposed fast-ignition (FI) approach to inertial confinement fusion [1]. Modelling of these electrons from the region in which they are generated to the dense fuel core is not a trivial task given the range of plasma conditions experienced by the electrons.




*Real part of roots of the dispersion relation. Wavelength is normalized to the thermal electron mean free path, and the growth rate is normalized to the collision frequency for a thermal electron.*

We present a new approach to modeling fast-electrons propagating through a background plasma. This novel VFP-PIC hybrid code provides a good description of the fast-electrons (Particle in Cell), and an improved description of the background (Vlasov Fokker-Planck) compared to conventional hybrid codes. As it is a hybrid code, several picosecond timescales are easily achievable. This makes the code well suited to study the effects of hydrodynamics on fast-electron transport. The code has been tested against a relevant beam-plasma instability. This short article provides a prescription for calculating the theoretical growth rate of the filamentation instability in the beam-background system. The theoretical dispersion relation is shown to be in good agreement with the results of the hybrid code.

[1] Tabak M et al, Phys. Plasmas 1 1626A (1994)

# Ultrafast and XUV Science

## Time-domain dual pulse coherent control with few-cycle strong-field laser pulses

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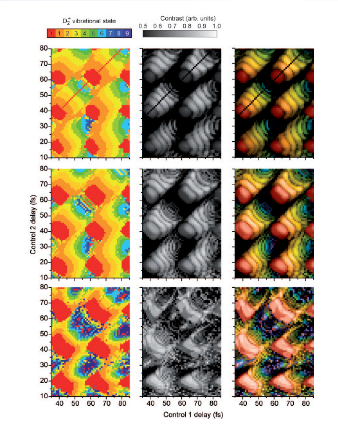
We use a recently developed quasi-classical model of the interaction of a strong-field (i.e. intensities in excess of $10^{13}$ Wcm$^{-2}$) few-cycle ultrafast (durations of 10 femtoseconds or less) laser pulse with a simple diatomic molecule to predict the creation, manipulation and imaging of vibrational wavepackets. Temporal and spectral pulse shaping with genetic algorithms is routinely employed to coherently control the outcome of light-matter interactions in chemical systems, however the best-fit outcome is often extremely complex and difficult or impossible to interpret. In the present work, we predict how a $D_2$ molecule exposed to a series of identical few-cycle laser pulses will evolve, where the coupling between the bound electron orbital and the nuclear motion allows an intuitive understanding.

As indicated in figure, our dual-control pulse scheme allows the population of a single vibrational states with high fidelity, and the populated state defined by varying the arrival time of the two control pulses. The relevance of such strong-field coherent control methods to the manipulation of electron localization and attosecond science is discussed.




*Section of the dual control pulse landscape as the pump:control ratio is varied from 3:1 (top), 2:1 (middle) and 1:1 (bottom). The pump intensity = $10^{14}$ Wcm$^{-2}$ and the duration of pump, control and probe = 6 fs. The most populated vibrational state, contrast and final state fidelity are observed to vary with delay and intensity.*

## Redistribution of vibrational population with few-cycle strong-field laser pulses

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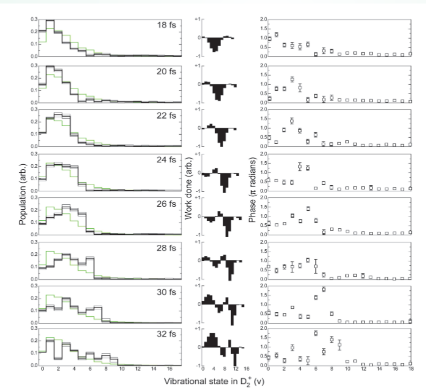
Molecules can be launched into quantum superpositions whereby a range of rotational, vibrational or electronic states are simultaneously populated, producing a wavepacket. The interaction of an intense ultrashort laser pulse with the bound electrons of a molecule readily initiates such a wavepacket, and can also be used to image the evolution of the system by collapsing the wavepacket some time after its creation.

We present an experimental demonstration of the manipulation of a vibrational wavepacket in a molecule by an intense ultrashort laser pulse. Applying an intense control pulse distorts the electronic environment of the nuclei, transferring vibrational population. Comparing the measured fragmentation yield with a quasi-classical trajectory model allows us to determine the redistribution of vibrational population caused by the control pulse. The results of this manipulation are shown in the figure whereby the population, work done and phase are all observed to be modified. Such observations will open new routes for coherently controlling chemical and biological processes with light via the coupling of the electronic and nuclear dynamics.




*Modified vibrational population, work done and wavepacket phase as a function of pump-control delay and vibrational state. The initial distribution created by the pump pulse is given by the green line and modified distribution is the dark black line. The positive and negative work done indicates the motion of the wavepacket components can be accelerated or decelerated by the laser field.*

## KEIRA-CHIMERA: a new method in high resolution femtosecond laser mass spectrometry

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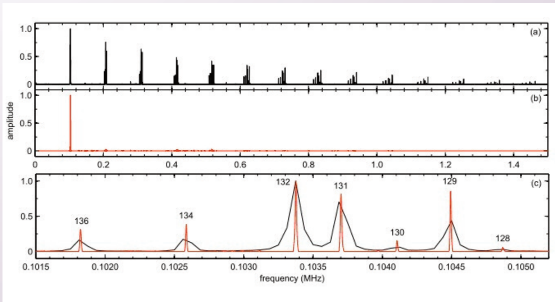
We introduce a new mass spectrometry technique; KEIRA-CHIMERA. We utilise a femtosecond laser for efficient ionisation, an electrostatic device for mass independent ion trapping (KEIRA), and a new frequency analysis algorithm for analysing ion oscillation frequencies (CHIMERA). Ion bunches generated by femtosecond laser ionisation, are confined in the KEIRA device by two mirrors which operate as an electrostatic optics equivalent of a laser cavity. The motion of the ions is detected non-destructively via the image-charge induced on pick-up rings. Since the ions oscillate at frequencies dependent on their mass to charge ratio, a mass spectrum can be extracted from this data.

Fourier analysis is commonly used to extract such frequency information. However, as the signals from KEIRA are non-sinusoidal, a Fourier transform generates many harmonics for each ion species making conversion to mass spectra non-trivial. In this article, we present a new frequency analysis technique, CHIMERA, which uses comb-functions to sample data taken from multiple pick-up rings. As the comb-functions are a much better match to the time signal, mass spectra with better resolution can be readily generated, as shown below.




*Frequency analysis of trapped Xe+ isotopes using (a) Fourier transform (b) CHIMERA comb-sampling Plot (c) shows a comparison of each for the fundamental frequency*

## Fragmentation of allene by intense femtosecond lasers

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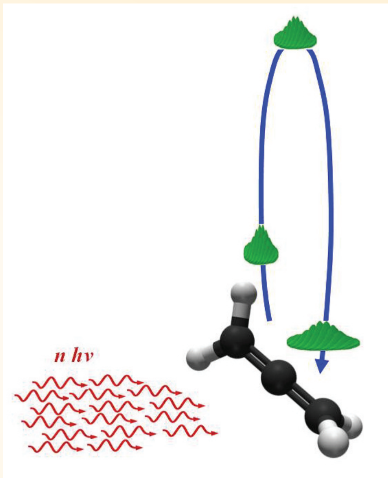
In the work presented here, fs-ionisation is coupled with KEIRA, a linear electrostatic trap, to produce high resolution mass spectra of the small organic molecule, allene ($H_2CCCH_2$). The tuneability of femtosecond laser systems is exploited to look at the ionisation and fragmentation of allene in intense light. By changing the characteristics of the incident laser pulse, such as changing the polarisation from linear to circular, it is possible to extract information on the ultrafast dynamics that leads to bond breakages in this small molecule.

Understanding the behaviour of species like allene in intense fields will promote the applicability of fs lasers as a universal, reliable and tuneable ionisation source in mass spectrometry, both for chemical or trace analysis and structural analysis of complex systems.




*Schematic of the interaction of a laser pulse with high photon density with an allene molecule resulting in emission of an electron wavepacket which oscillates in the laser field and subsequently re-colliding with the molecule.*

## Beam-transport diffraction in near-infrared few-cycle strong-field experiments

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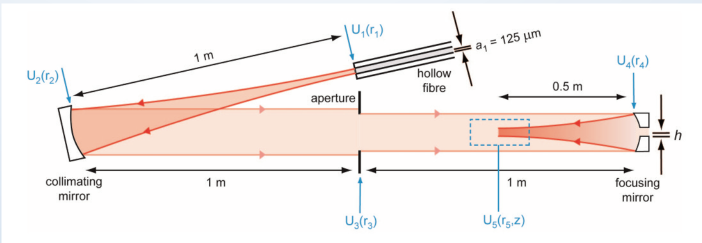
Ultrashort pulses of near-infrared (NIR) laser radiation have led to the production of attosecond pulses, either as pulse trains or in isolation. The generation of such coherent bursts of radiation requires an ultrabroadband laser oscillator producing sub-10 fs pulses, chirped pulse amplification to a peak power in excess of 1 GW and a self-referencing phase measurement allowing the relative phase of the carrier and envelope to be locked with respect to each other, referred to as carrier-envelope-phase (CEP) stabilization. Modern titanium-sapphire oscillators and amplifiers generate near-transform-limited high power CEP-stable pulses with a duration of around 20 fs, which when focused into a Noble gas jet, initiates high harmonic generation (HHG) of XUV photons. This photon energy upconversion is the result of the strong-field initiating tunnel ionization of the Noble gas atom, propagation of the ejected electron in the time-varying field, followed by the release of additional odd-quanta of the fundamental photon energy as a single high energy photon upon recombination with the parent ion.




*Schematic of the optical system considered: a Bessel EH11 spatial mode propagates from the input plane at the exit of the hollow fibre via a spherical collimating mirror through an intensity-controlling aperture of variable radius $a_3$ and focused into the interaction region by a spherical mirror. The annulus is modified by increasing the radius h of the central hole from 0 to 2 mm.*

## Dissecting charge and lattice order in 1T–$TaS_2$ with ultrafast XUV ARPES

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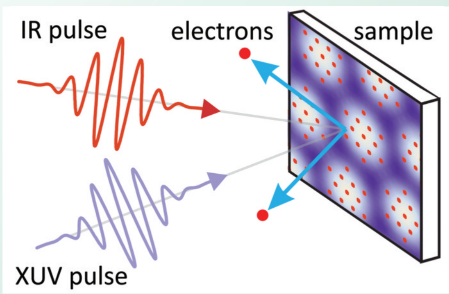
Charge density waves (CDWs) underpin the electronic properties of many complex materials. The canonical source of CDW order is Fermi-surface nesting, driven by electron-phonon coupling via the Peierls mechanism. In many systems there are also pronounced electron-electron correlations, and multiple orderings may coexist or compete. Characterizing the interplay between different interaction mechanisms, and the associated hierarchy of energy scales and timescales, is crucial to understanding CDW physics in real materials.

We use time- and angle-resolved photoemission spectroscopy with sub-30-fs XUV pulses to map the time- and momentum-dependent electronic structure of photoexcited 1T–$TaS_2$, a two-dimensional Mott insulator with CDW ordering. Charge order, which splits occupied sub-bands at finite momentum, melts along with the Mott gap – both well before the lattice responds. This challenges the view of a CDW caused by electron-phonon coupling and Fermi-surface nesting alone, and suggests that electronic correlations originate charge order.

*In the technique of time-resolved ARPES, an ultrashort laser pulse creates a transient phase in a material. A subsequent XUV pulse generates photoelectrons, which are collected and analysed to reveal the momentum- and energy-dependent electronic structure as it evolves on femtosecond time scales.*



## Double slit interferometry to measure the EUV refractive indices of solids using high harmonics

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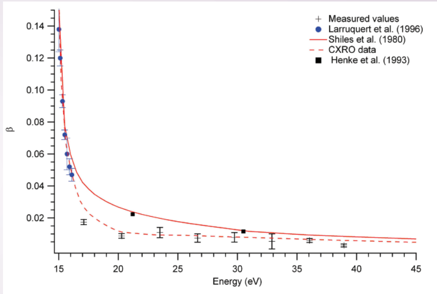
Accurate values of the extreme ultraviolet (EUV) optical properties of materials are required to make EUV optics. The optical properties of aluminium studied in this report are required, in particular, as aluminium is used as an EUV filter material. The complex refractive index of solid aluminium and the imaginary part of the refractive index of solid iron between 17 eV – 39 eV have been measured using Artemis EUV harmonics impinging on a double slit interferometer. The technique may have future applicability in measuring the optical properties of warm and hot plasmas.




*Measurements of the imaginary component of the refractive index of Al compared to the CXRO database, Henke et al. (1993), Shiles et al. (1980) and previous experimental work by Larruquert et al. (1996).*

## Probing the microscopic origin of laser-induced ultrafast spin dynamics using time resolved photoemission/MOKE

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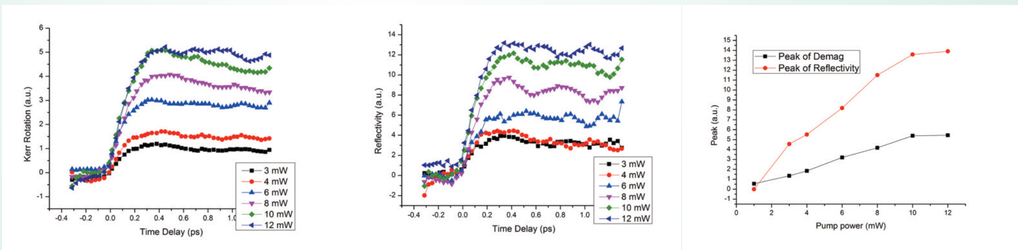
This paper reports the experimental results from our first beam time at the STFC's Artemis facility where time-resolved photoemission spectroscopy and time-resolved magneto optical Kerr effect (TR-MOKE) measurements were conducted on single-crystal Fe thin-films. The electron temperature of the Fe thin films reaches its maximum around 200fs after laser excitation, which leads to a demagnetisation maximum in 100 fs later.




*Kerr rotation and reflectivity versus time delay between probe and pump. - Observed from a 56 ML Fe on GaAs sample. Right: Peak signals versus pump power for the same thin film.*