LASER RESEARCH

at Rutherford Appleton Laboratory

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LASER RESEARCH

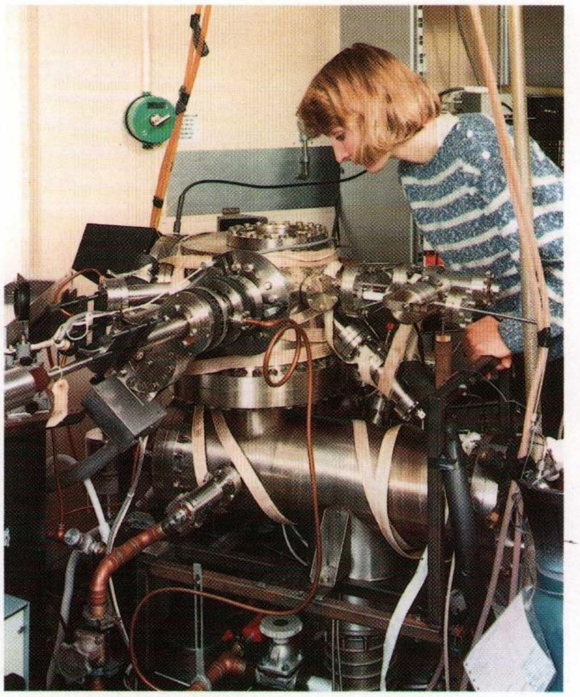
Advanced laser facilities are provided by the Central Laser Facility (CLF) for the use of scientists at UK universities and polytechnics. These facilities include high power Nd:glass (VULCAN) and KrF gas (SPRITE) lasers which can be used in many versatile configurations of pulse duration, wavelength, power and number of beams. The Laser Support Facility (LSF) provides a variety of lower power lasers supported by state of the art diagnostic equipment which are based upon commercially available systems. Researchers can either use CLF equipment for their experiments or borrow it for a limited period on a loan basis.

There continues to be a strong cross fertilisation of ideas and resources between the 150-strong user community and RAL as well as a healthy interaction between the different groups within CLF. One example of this collaboration occurred when short light pulses produced by a LSF low energy laser were transmitted by an optical fibre to the SPRITE laser in another building, where they were amplified and used to conduct plasma physics experiments of the type more usually carried out by the users of the VULCAN laser.

HIGHLIGHTS

In the collaborative effort described above, CLF achieved the notable distinction of producing in a short picosecond burst the largest concentration of energy ever produced in a light beam. This Facility development will in the coming year enable UK experimental scientists to carry out forefront research on the interaction of extremely intense electric fields with atomic, molecular and ionic species. Since the optical field strengths produced in this short pulse were of a magnitude similar to the Coulombic strength which binds electrons to atoms and molecules, new physics and chemistry will undoubtedly be discovered as this new photon-matter interaction regime begins to be explored. Currently, no satisfactory theories exist which predict what might be observed when such powerful light pulses are focused on to materials. Through CLF, the UK is in the unique position of being able to make such state of the art facilities available to researchers whose interests cover a broad range of disciplines.

4.12 Ultra high vacuum equipment of an Oxford user group studying laser desorption of gases from surfaces. (87FC5156)



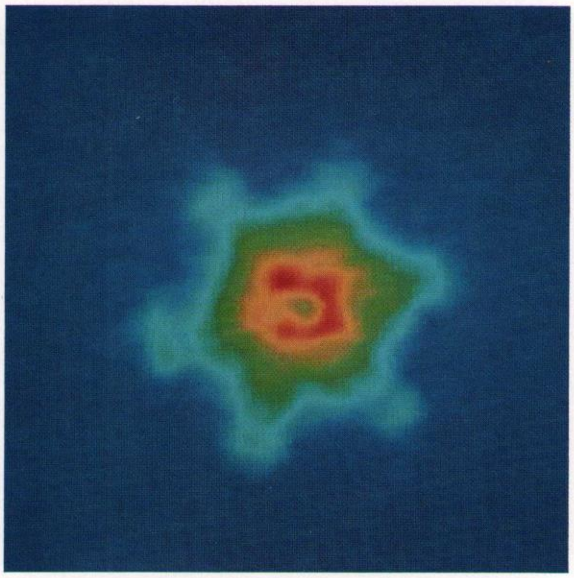
In a collaboration between UK and Japanese scientists, a major discovery was made in thermonuclear fusion research. Using thin walled high aspect ratio targets irradiated by the 12 focused beams from the VULCAN glass laser, it was found that the thermonuclear fusion neutron yield increased by a factor of 20 when the beams were focused on to the surface of the target compared with the yield obtained when the target is uniformly illuminated.

Some 50 experimental runs took place in the three laboratories at the Laser Support Facility (Fig 4.12 shows part of a typical experimental setup) and 24 laser loans were made to users in 17 institutions: from the University of Strathclyde in the north to the Universities of Essex, Sussex and Southampton in the south. More than 30 papers a year are now being published containing data obtained using LSF lasers. Research topics range from in-vivo DNA damage repair to the high field molecular physics, laser development and solid state chemistry highlighted in this Report.

THERMONUCLEAR FUSION RESEARCH

Using a new kind of fusion target pioneered in Japan, a major 20-fold improvement in the efficiency of generating thermonuclear neutrons, protons and α particles in laser driven implosions was made in a joint experiment between UK teams from Bristol, Belfast and RAL and Osaka University. Large high aspect ratio (LHART) deuterium-tritium filled glass microballoon targets with an exceptionally large ratio of radius to shell thickness (400:1) have produced a world record neutron yield with Japan's GEKKO XII laser (which has 20 times the output of the CLF VULCAN facility).

In the new joint experiment at RAL, plans were made to use smaller scale targets matched to the 0.5 kJ energy of VULCAN. New ideas were tried relating to optimisation of thermonuclear reaction yield and a surprising but exciting result was found. For the same average intensity of laser irradiation on the target, a 20-fold increase in fusion reaction yield was obtained by concentrating VULCAN's 12 beams in 12 symmetrically placed intense spots rather than defocusing them to give spherical uniformity. This non-uniform mode of implosion has been termed NUHART and is illustrated in the X-ray image of 8 keV emission shown in Fig 4.13 where the 12-fold symmetry is clearly seen. 2×10^7 D-D thermonuclear reaction events occurred in this implosion.



4.13 8 keV X – ray image of 12 beam non – uniform D – D implosion. Red regions correspond to more intense emission and more compressed matter than blue regions. The 12 beam illumination symmetry is apparent.

Uniformity of Thermal Transport on Spherical Targets

A problem of considerable practical importance in fusion research is achieving highly uniform pressure in the laser driven implosion of spherical targets. The degree of uniformity is also a major factor in fundamental physics studies of plasma energy transport in steep temperature gradients where information is often blurred when the rate of energy transport varies locally over the spherical target.

The first direct observation of the local variation of mass ablation rate from spherical targets was obtained in work by Royal Holloway and Bedford New College and RAL staff. A monochromatic X-ray image was produced by pinhole camera imaging in reflection from an XUV multilayer mirror which, by resonant Bragg reflection, selected emission at 7.5 Å. An X-ray streak camera then gave a time resolved record of this image using a slit orientated along the diameter of the sphere. The target was overcoated with a layer of Se and an outer layer of polymer. At an intensity of 10^{14} W cm^{-2}, the laser radiation burns into the target and converts solid material to hot plasma, penetrating through the 2 μm plastic layer in less than 1 nsec. As seen in the streak picture (Fig 4.14), intense X-ray line emission is observed from neon-like ions, Se^{24+}, at the time of burn through. The time delay from the fiducial UV pulse to the onset of Se^{24+} emission varies across the diameter of the target and shows directly for the first time the local variation of mass ablation rate.

X-RAY LASER RESEARCH

Laser Gain Measurements

Following last year's dramatic progress in demonstrating laser amplification at the then shortest wavelength of 8.1 nm in a rapidly recombining plasma which forms hydrogen-like F^{8+} ions, the main thrust this year was to find a more efficient laser scheme which would allow further progress towards the immediate goal of a laser wavelength in the 'water window' below 4.4 nm. There has been much supportive development of theoretical modelling using large numerical simulations on SERC computers as well as more basic analysis. An experimental collaboration between a UK consortium of research groups and a team from the University of Orsay led to tests of a different type of recombination laser in which He-like Al^{11+} ions recombine to form Li-like Al^{10+}. The French group had pioneered the initial study of this system which offers prospects of a lower pump power requirement at wavelengths similar to the hydrogenic scheme. The results indicated similar rather than better performance relative to the H-like ion results.

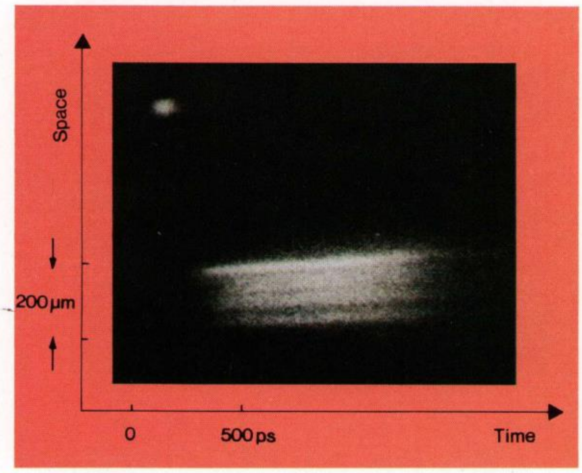
Time and Spatially Resolved Spectroscopy

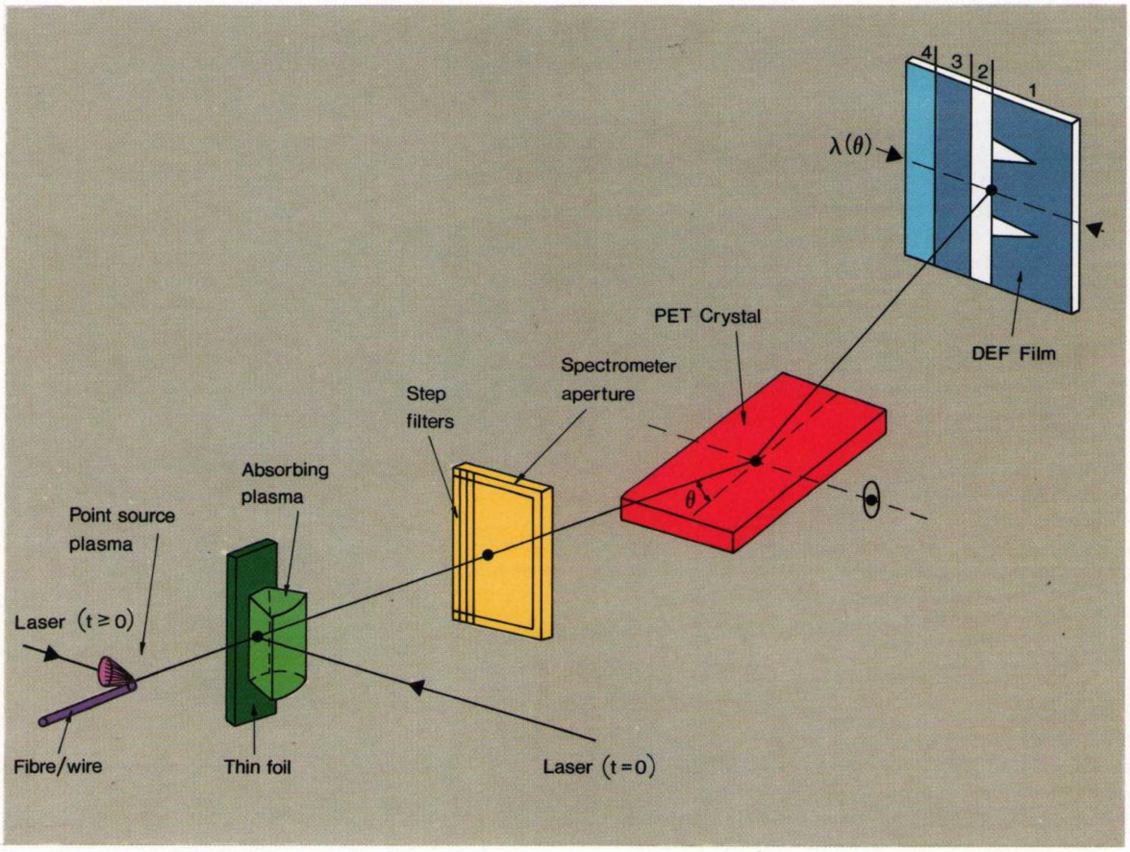
In an ingenious two-plasma CLF experiment by a group from Queen's University, Belfast, absorption spectroscopy has been used for the first time to obtain temporal and spatial resolution of ground state ion populations. A plasma of Al^{10+} and Al^{11+} ions produced by 2 nsec laser pulse irradiation is probed by intense X-ray radiation from a second plasma produced by synchronous VULCAN 70 psec pulses. With the apparatus shown in Fig 4.15, an absorption spectrum at a chosen time is displayed as a function of spatial position in the first plasma. This pioneering experiment is of considerable interest for XUV laser research where ground state populations of ions are an important factor.

LASER PRODUCED PLASMAS AS X-RAY SOURCES

Low energy commercial excimer lasers are increasingly being used in plasma physics research at CLF - particularly for the generation and application of repetitive X-ray sources. Because short laser wavelengths couple very effectively to the plasma,

4.14 Spatially and temporally resolved 7.5 Å X – ray emission arising from Se^{24+}, showing variation of burn through time across the diameter of a spherical target.





4.15 Experimental layout for time – and space – resolved spectroscopy.

excimer lasers such as KrF can efficiently convert their energy to soft X-rays in a laser produced plasma. A number of university groups are using repetitive X-ray sources generated by joule-class KrF lasers at CLF for research on topics such as X-ray microscopy, X-ray lithography and radiation damage studies in biological cells.

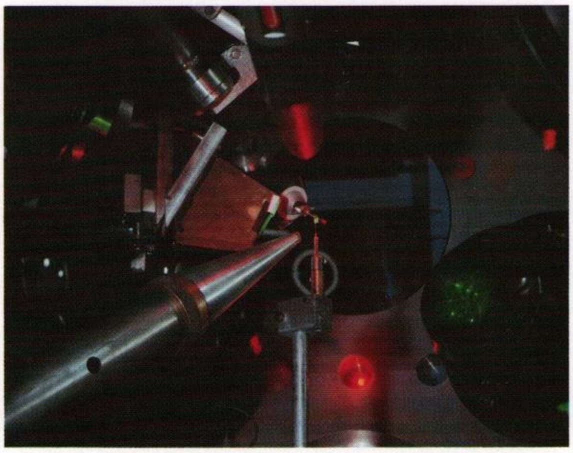
SHOCK WAVE STUDIES

EXAFS of Shock Waves in Plasmas

A new method for analysing the dense material produced in laser fusion experiments has been developed at CLF. The method uses the Extended X-ray Absorption Fine Structure (EXAFS) technique to measure the inter-atom spacing in the dense plasmas formed when two opposing laser beams are focused on to a thin foil of plastic coated aluminium. EXAFS spectra appear as a 'ripple' on the absorption spectrum of a material. The effect is caused by the electron, which is ejected from an atomic shell in the photon absorption process, being partially reflected by nearby atoms back into the shell. It is more usually employed for determining inter-atom spacings in routine solid state analysis.

The opposing shock waves which are generated collide in the centre of the foil and produce high plasma densities. The EXAFS spectrum of the foil is measured by recording the transmitted X-rays which are generated from a secondary laser-produced plasma in the setup illustrated in Fig 4.16. The EXAFS spectra obtained are the first to be recorded with exposure times as short as 10^{-10} s. Their analysis has increased understanding of the state of plasmas at densities greater than that of solid material.

4.16 Centre of target chamber configured to measure EXAFS of a plastic coated aluminium foil (illuminated green). X – rays are produced by laser irradiation of a uranium microsphere (illuminated red). (87FC5436)



Short Pulse X-ray Diffraction from Laser Shocked Crystals

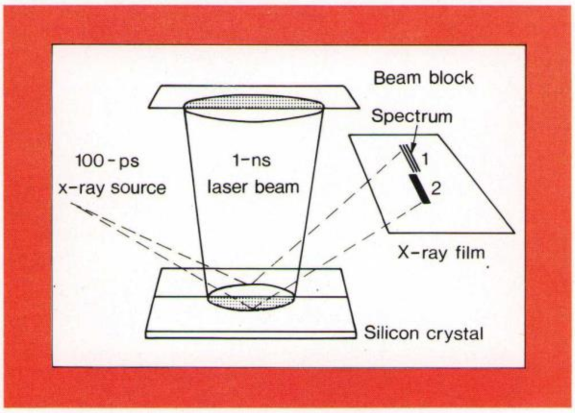
In experiments using the VULCAN laser at RAL and the JANUS laser at the Lawrence Livermore National Laboratory, short, intense pulses of X-rays from a laser-produced plasma have been used to measure directly the distance between atoms in a crystal during the passage of a laser-driven shock wave. The experiment is shown schematically in Fig 4.17. One beam from the laser (at low irradiance) impinged on the surface of a single crystal to produce ~70 kbar shock wave. The second beam, delayed with respect to the first, was focused to a 40 μm spot on a calcium target producing a subnanosecond pulse of X-rays. The X-rays were then Bragg diffracted from the surface of the shocked crystal and recorded on X-ray film. The compression of the lattice planes in the shocked crystal shifted the Bragg angle from its normal position by an amount directly related to the degree of compression. This technique promises to be a powerful tool for studying transient effects and phase changes in shocked matter.

HIGH ENERGY SHORT LIGHT PULSES

Laser Development

SPRITE, which has held many world records, was originally designed in 1979 to give a peak output power of 4 GW in a pulse lasting 50 nsec. In order to greatly increase the peak power of this laser, initial trials were carried out to investigate the short pulse amplification at 248 nm of pulses derived from a frequency-doubled mode-locked dye laser. The visible mode-locked light from a dye laser in the Laser Support Facility was transmitted to the SPRITE laser situated in an adjacent building by more than 80 m of single-mode fibre optic cable. The light from the fibre was then amplified, frequency doubled, re-amplified and sent into the SPRITE laser cell. In a pulse lasting approximately 20 psec, up to 1 J of radiation at 248 nm was obtained. Subsequently, by using a new oscillator built and installed next to the SPRITE laser, the performance was boosted to 2.5 J of ultraviolet energy in a 5 psec pulse. This is the most energetic picosecond light pulse ever produced and represents over a hundred-fold increase in power from the original SPRITE design and over seven times the energy of similar pulses produced elsewhere. Very recently, such energetic pulses have been used by a group from Imperial College and RAL to irradiate a target and study the X-ray emission so generated.

4.17 Experimental setup showing short pulse X – ray diffraction from unshocked (1) and shocked (2) silicon crystals.



MULTIPHOTON IONISATION EXPERIMENTS

When the intensity in the focal spot of a laser beam reaches ~ 10^{17} W cm^{-2}, the oscillating electric field of the light wave becomes comparable in strength to the Coulomb field which binds electrons to the nuclei of atoms and molecules. Radical alterations of the atomic and molecular dynamics are then induced by the light field. For example, it is possible for two or more electrons to be simultaneously ejected from an atom by a form of collective interaction which is induced by extremely high field strengths. To try to clarify some of these mechanisms, a group from the University of Reading and RAL carried out an experiment in which gaseous molecules were irradiated. By comparing the energy spectra of ions of different charge states it has been possible to show that both single and double electron emission can take place simultaneously when nitrogen molecules are photo-ionised with intense short pulses of light. The molecules are sequentially ionised through singly, doubly, triply, and quadruply charged states which then emit two electrons in a time much less than 2×10^{-14} s before dissociating from the sextuply charged molecular configuration.

MULTIPHOTON SPECTROSCOPY OF SOLIDS

Two photon transitions are readily excited by intense nanosecond pulsed lasers and have been widely used to study the physics and chemistry of atoms and molecules in the gaseous phase. A group from Oxford University has used Loan Pool lasers to show the great potential of the two photon technique for the analysis of molecules in crystalline solids, particularly in cases where transitions within the same shell, forbidden for one photon absorption, can be reached. Analysis of the two photon spectra uses the positions of the lines and their relative intensities which depend in a sensitive and calculable way on the polarisation of the light, the relative orientation of the crystal and symmetry class of the electronic configurations involved.

Up to 10% of all CLF time is available to industrial or other organisations. For example, British Petroleum has purchased time on a number of occasions to evaluate the powerful UV resonance Raman scattering techniques developed at the LSF by university users. It has been found that substituted anthracenes can be clearly recognised by their characteristic Raman bands at concentrations of less than 5×10^{-5} M and that it should be possible to determine the composition of mixtures. These encouraging results have led the company to set up its own Raman laboratory to pursue the work further.

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