LASER RESEARCH

at Rutherford Appleton Laboratory

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Laser Research

Advanced high-power laser research facilities are provided at the Central Laser Facility (CLF) for use by UK university research workers in physics, chemistry, biology and microelectronics and also by Industry. 76 scheduled experiments by university groups were carried out during the year. The facilities include: VULCAN, Europe's most powerful laser, now equipped with a variable geometry target area designed for X-ray laser research; SPRITE, the world's most powerful UV laser available for research use; and the Laser Support Facility which provides tunable radiation at wavelengths from 121nm in the VUV to beyond 1500nm in the infra-red and now includes a picosecond laboratory. The Laser Loan Pool makes advanced laser equipment available for experiments in the user's home laboratory.

Highlights

The most important scientific and technical achievement of the year was the observation of gain at 18.2nm in a laser-produced plasma during the commissioning of a novel purpose-built X-ray laser research facility equipped with powerful diagnostic instruments. The VULCAN laser was focused by an optical system of original design which can irradiate a carbon fibre uniformly over a 2cm length. X-rays are emitted from the expanding cylindrical plasma formed from the irradiated fibre. Large gain was observed for X-rays emitted parallel to the fibre and detected in a time-resolving spectrometer. The results confirm and extend observations of gain at 18.2nm first made at the University of Hull. This is a most encouraging start to the expansion of the X-ray laser research programme at the Laboratory, despite the delay in the completion of the new facility brought about by earlier funding cuts.

The unique CLF facilities continue to attract international collaborators. Definitive measurements of heat flow in spherical geometry were made by a joint British-American team working in the 12-beam target area. Preliminary results agree with recent Fokker-Planck theories which CLF staff have developed. This is a significant step forward in the understanding of an important process in laser fusion.

Links with European laboratories are also being strengthened and the Bristol group was invited to participate in laser fusion experiments at Ecole Polytechnique in Paris. The value of Bristol particle spectroscopic methods for the analysis of laser-driven implosions has been shown in numerous experiments at the CLF.

An experimental and theoretical study of the beat wave accelerator concept is being made in conjunction with CERN. The first experimental stage was successfully completed with the demonstration that simultaneous pulses of light at two wavelengths could be amplified in a specially adapted VULCAN amplifier chain containing both phosphate and silicate glass components.

Following last year's very successful trial of laser-induced flash X-ray microscopy, scientists from ten laboratories in the UK and three in the USA exposed more than 300 specimens in a survey experiment. Both VULCAN and SPRITE were used to generate intense bursts of X-rays to record high-resolution images of biological material in its natural state without any drying, fixing or staining. Internal structure not revealed by conventional techniques has been seen in the epidermal hairs of the foxglove. An image of human fibroblasts is shown in Plate XIV.

The research phase of the gas laser R&D programme was brought to a successful conclusion with the first demonstration that a Raman amplifier with a gain of 500 could be made to operate with an efficiency of up to 65%. This opens the route to high peak power as well as high energy for the SPRITE laser.

The new Laser Support Facility (LSF) consists of a laboratory-based user programme of multidisciplinary research with a strong emphasis on photochemistry and photobiology, and a Laser Loan Pool. In the laboratory-based programme, very successful trials of a novel method for the study of cell development have been made by a Birmingham-Sussex-MRC collaboration. A pulsed laser is used to activate previously inert reagents already loaded into the cells so that a rapidly-occurring biological process such as the repair of radiation damage in DNA can be arrested at a chosen instant of time.

The Loan Pool began operations with two tuneable dye laser systems and has made seven loans to UK universities in the first eight months of its operation, six of which resulted in successful experiments.

X-ray Laser Research

The New Facilities

At the culmination of a year's intensive design and engineering work, a novel variable-geometry target irradiation laboratory for the VULCAN laser was brought into operation. It is designed particularly for X-ray laser research and complements the facility for 12-beam symmetric irradiation of spherical targets completed in 1984 (Plate XIII). A new computer-controlled beam switchyard equipped with devices to insert harmonic conversion crystals and vary beam timing and power enables the new facility to operate in parallel with the 12-beam target area on alternate shots of the laser.

The new target area caters for an exceptionally wide

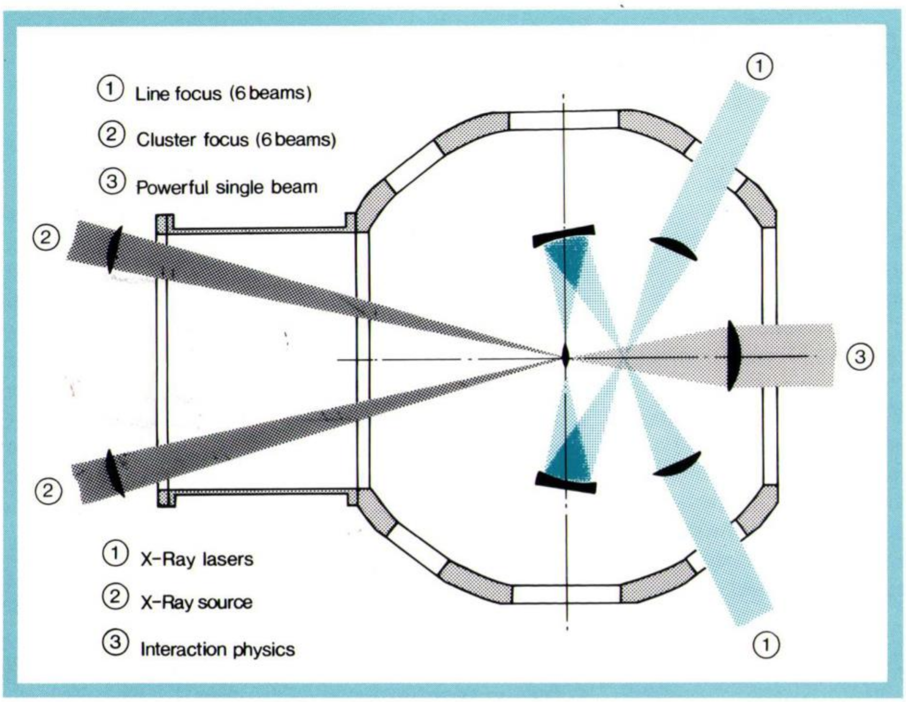


Fig 4.20 Diagram of optical arrangements available in new target chamber (85FC3804).

range of experimental configurations and is equipped with powerful diagnostic instruments. It gives UK universities unique opportunities in the highly topical field of X-ray laser research.

In the beam configuration used in the commissioning experiments, the VULCAN laser was focused by a novel optical system developed at RAL to give an accurately straight line focus 7mm long and 20µm across in which cylindrical fibre or flat thin film targets could be irradiated uniformly over their whole length. The scheme is illustrated in Fig 4.20. It uses off-axis reflection from a spherical mirror illuminated by an aspheric lens to create the line focus. Computer-controlled adjustment of the mirrors and lenses allows all six beams to be focused on one 7mm long target or to be arranged in pairs to irradiate lengths up to 21mm. Laser light of 0.53µm wavelength, the second harmonic of the VULCAN output, is used at power levels of over 1TW in subnanosecond pulses. A two-axis split field projection microscope is used to align targets with a positional accuracy of a few µm and an angular accuracy of 10^{-3}. This ensures that potential X-ray laser emission is directed to the detection system.

The time- and space-resolved spectrum of X-rays emitted parallel to the long axis of the X-ray laser target is recorded with a new instrument of original design. It couples an X-ray streak camera to a grazing incidence spectrometer built around a diffraction grating of variable periodicity. This new type of grating gives a focused spectrum in a flat field in the detection plane of the streak camera. The combination of resolution, spectral range and sensitivity achieved in this way is greatly superior to that in any other system elsewhere.

X-ray Laser Experiments

A programme of X-ray laser research in UK universities has been supported by SERC since the early 1970s. Much progress has been made in basic research, especially into conditions leading to population inversion and amplification in recombining plasmas and, in particular, into recombination from C^{6+} and C^{5+} which is calculated to create an amplification coefficient of up to $10\,cm^{-1}$ on the Balmer transition. The Hull group has led the investigation of this system and reported observing gain at 18.2nm in experiments with a small laser in 1980. Several laser shots were needed to record each spectrum. The factor limiting further progress has been the lack of capability to produce a sufficient length of plasma for the exponential amplification to create obvious 'laser action' along the axis of the plasma. Ideally, the product of the gain coefficient and the length should reach about 14 giving a single transit amplification factor of 10^6 to make an 'amplified spontaneous emission' laser. Previous work and more recent detailed calculations suggest that this condition may be satisfied by irradiating a 7µm diameter carbon fibre 2cm long with an 80J pulse of light of 70ps duration which the new facilities are able to provide. Their completion was delayed at least a year by financial problems in 1983.

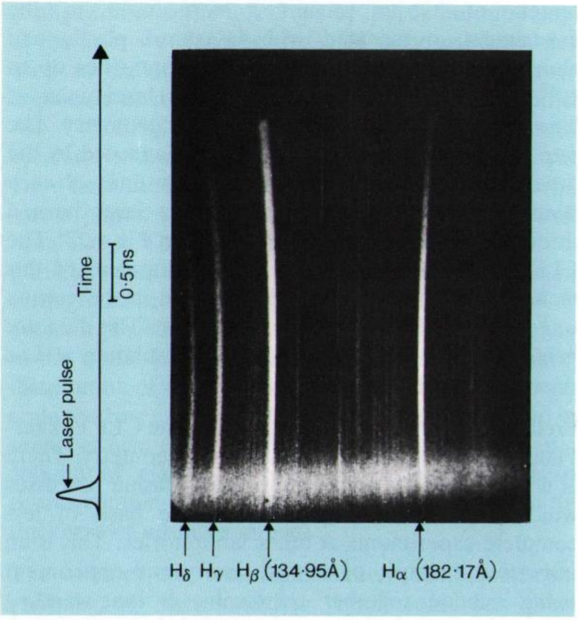


Fig 4.21 Time-resolved spectrum from a carbon fibre plasma showing strong emission in the C VI Balmer series. The Hα line is amplified and peaks in intensity after about 1 ns. Differential filtering suppresses the intensity of Hα which is the most intense line in the spectrum.

The first experiment with the new facilities was designed to make a rapid survey of this system and of 3 other candidate XUV laser schemes, and involved researchers from the Universities of Hull, Belfast, London (Imperial College) and Paris. Extreme precision of alignment is needed to irradiate such small targets successfully and it was a severe test of the new equipment. The first results are highly encouraging. In the carbon fibre experiments, the new time- and space-resolving spectrometer revealed exponentially increasing intensity of the C VI Balmer transition as the length of irradiated fibre was varied from 1 to 10 mm. By contrast, the increase in intensity of the Balmer γ transition was linear. The linear increase is characteristic of an 'optically thin' radiation source with neither amplification nor absorption while the exponential increase is unambiguous evidence of laser amplification. Fig 4.21 is an example of the high quality time-resolved VUV spectra. The data are still being analysed but it is clear at this stage that amplification at 18.2 nm greater than a factor 10 in a length less than 10 mm has been obtained with energy absorbed from the heating laser pulse of less than 4 J in 70 ps. It should now be possible to tune the system for optimum performance. The relatively small energy input needed and the scaling of the wavelength with the inverse square of the nuclear charge makes this single-electron recombination laser scheme even more attractive than the recently demonstrated Se^{24+} 20.6 nm laser in the USA, and 1986 promises to be a year of exciting progress in which SERC and UK universities will be able to play a major part.

Plasma Physics

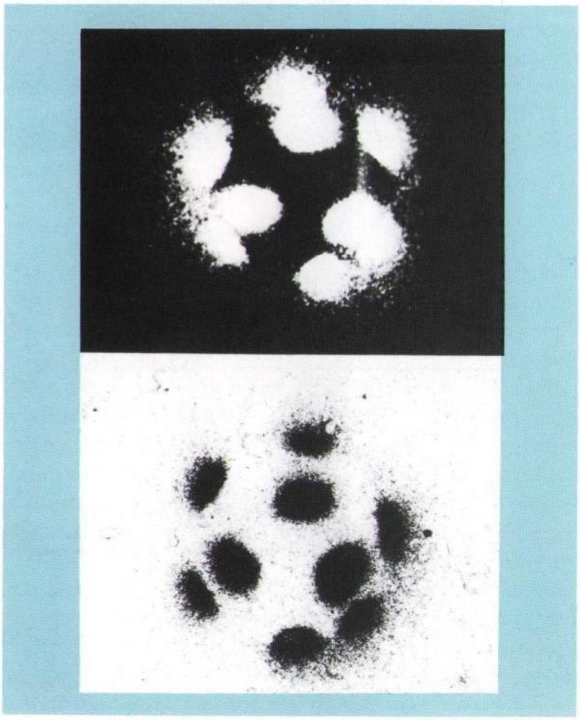
Irradiation Uniformity

Experiments in the 12-beam target area commissioned a year ago depend on the high degree of irradiation uniformity given by this geometry. One of the limiting factors is the accuracy with which the beams can be aligned to point through the target centre and this can be tested by focusing tightly on the target surface. The nearly symmetrical patterns of spots in Fig 4.22 are pinhole camera photographs of X-rays emitted from the target during one such test. They show that pointing accuracy is now better than 9 μm RMS, 6% of the diameter of a typical target. Beams are defocused in normal operation. Uniformity also depends on the quality of each individual beam and two substantial improvements were made during the year. Better cooling of the disc amplifiers has substantially reduced optical aberrations and image relays have been installed at the output of each disc amplifier.

Compression Dynamics

The improved level of uniformity now available with the twelve beams has made it possible to begin the study of systematic variations in implosion behaviour with target geometry. Large thin shells, ie with high aspect ratios, are expected to suffer severe Rayleigh-Taylor instability and the observed behaviour is consistent with this. Targets whose diameters are greater than about 15 times their wall thickness fail to

Fig 4.22 X-ray pinhole photographs of emission from the surface of a target irradiated with tightly-focused beams (85FB2392).



behave as predicted by one-dimensional computer modelling but the spatial resolution in the X-ray images is insufficient as yet to identify the failure mode. The maximum usable target aspect ratio is one of the most crucial parameters for laser fusion targets and strongly affects the laser energy needed to obtain break-even.

Heat Transport in Spherical Geometry

In the extreme conditions found in laser fusion experiments, the approximations of the classical theory of thermal transport become invalid and ad hoc modifications have been employed to force agreement with experiment, giving rise to frequent controversy. Considerable progress has recently been made in the resolution of this vexed topic.

On the theoretical side, the Fokker-Planck methods first developed at the CLF have been extended to include ion dynamics and the effects of spherical geometry. They provide the most sophisticated theory currently available and are in good agreement with measurements made at the CLF two years ago.

In view of continued reports of anomalies, a definitive series of measurements was attempted this year taking advantage of the full range of advanced diagnostic techniques available at the Laboratory. Groups from Imperial College and RAL were joined by teams from the Los Alamos and Lawrence Livermore National Laboratories in the USA. Solid glass microsphere targets of 175μm diameter were used in the experiment, overcoated with layers of plastic and aluminium. They were irradiated at intensities up to 10^{15}W cm^{-2} by a 1.05μm wavelength laser pulse of 0.8nsec duration in 12-beam symmetric geometry. The rate of thermal energy transport was diagnosed by the time taken for the characteristic X-ray lines of each layer to appear and disappear as the laser burned through the target surface, as shown in Fig 4.23. The CLF and its users have led the development of this technique. The electron density profile in the corona was measured by optical interferometry. The data are being analysed using the LASNEX simulation at Los Alamos.

Preliminary results are consistent with the CLF Fokker-Planck model of heat flow in spherical geometry. There is no need to invoke the anomalous plasma processes which have been conjectured on the basis of less complete experiments at other laboratories. This is an important example of careful theory and experiment being needed together to resolve a long-standing problem.

Thermonuclear Particle Analysis

The unique ability of the Bristol group to measure the energies of individual particles recorded in CR-39 plastic detectors was put to a new use in an experiment which also used the flexibility of the VULCAN laser

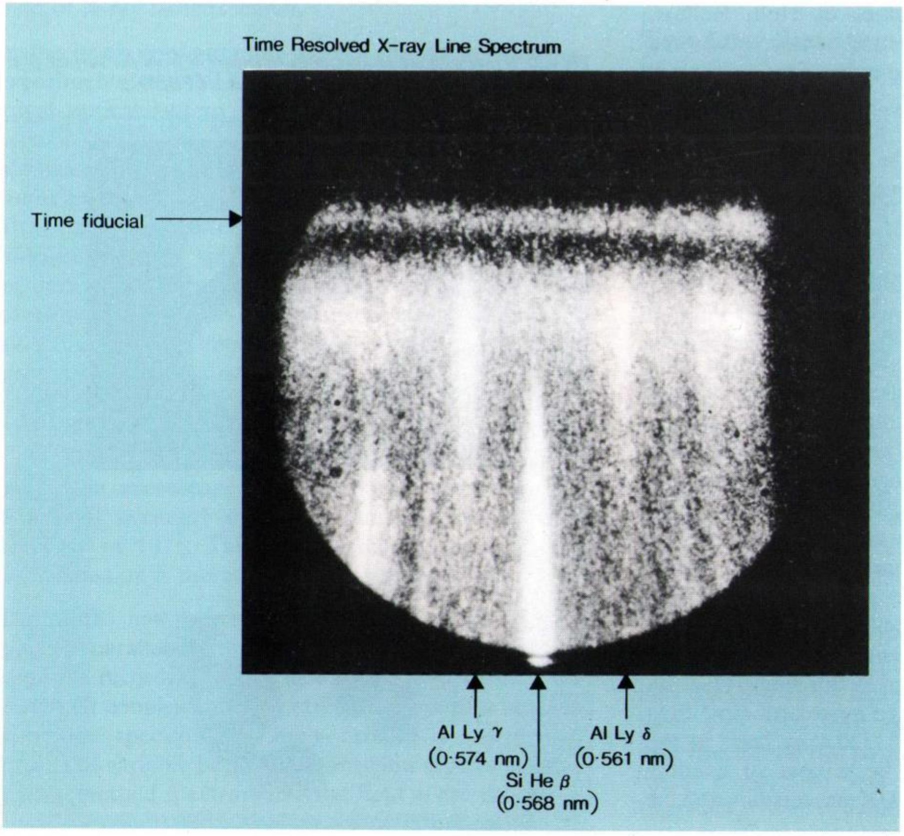


Fig 4.23 Time-resolved spectrum of X-rays from a glass target overcoated with aluminium and polystyrene (85FB5014).

configuration to the full. Four of the six output beams of the laser were fed by the short-pulse oscillator and used to make an exploding pusher thermonuclear implosion in the 12-beam target chamber. The other two VULCAN beams were driven by the long-pulse oscillator and used to accelerate a second target placed 1 mm from the implosion target. The accelerated target was a plastic disc designed to exhibit hydrodynamic instabilities. The residual energies of thermonuclear α-particles emitted from the implosion and passing through the accelerated disc were measured in a CR-39 detector placed 10 cm away. Any redistribution of mass in the unstable target leads to a spread in the energy distribution of the α-particles. Mass redistribution on a scale too fine to be revealed by other techniques can be seen because each particle measures the depth of a column of plasma of negligible width. Preliminary results contain direct evidence of local increases in the thickness of unstable targets.

The value of the track measurement technique in the analysis of thermonuclear implosions has been demonstrated in a number of experiments at the CLF and as a result the Bristol group was invited to participate in experiments at Ecole Polytechnique where a 6-beam laser system with fourth harmonic conversion has recently begun to operate. The spectrum in Fig 4.24 was taken from an implosion generating over 10^7 thermonuclear particles. Its width indicates a core temperature of around 2 keV.

Beat Wave Studies

The need for ever-higher energies in elementary particle physics has led in the last few years to an examination of radically new schemes to produce very large accelerating fields. In the 'beat wave' accelerator, two laser beams having slightly different frequencies excite an electrostatic wave in a plasma whose natural oscillation frequency coincides with the frequency difference between the two laser beams. Small-scale experiments using CO_2 lasers in the USA and Canada have measured fields of 3 GeV/m and have accelerated electrons to 5 MeV in only 1.5 mm. The phase velocity of the waves produced by CO_2 lasers is too small to be of use in high-energy physics accelerators and a more nearly optimum situation is provided by using two wavelengths which can be amplified in Nd-doped glasses, 1.053 μm (phosphate glass) and 1.064 μm (silicate glass). The first stage of an experiment in conjunction with CERN was completed earlier this year with the demonstration that VULCAN could produce a double-wavelength beam. The oscillator which generates the two wavelengths consists of two independent cavities, with mode lockers driven from a single master oscillator and Q-switches driven from a single trigger source. In order to balance the gain at the two wavelengths, the VULCAN chain was run with a mixture of phosphate and silicate glass in a series of tests whose results have been extremely encouraging. A z-pinch apparatus in which beat waves will be generated is now being set up.

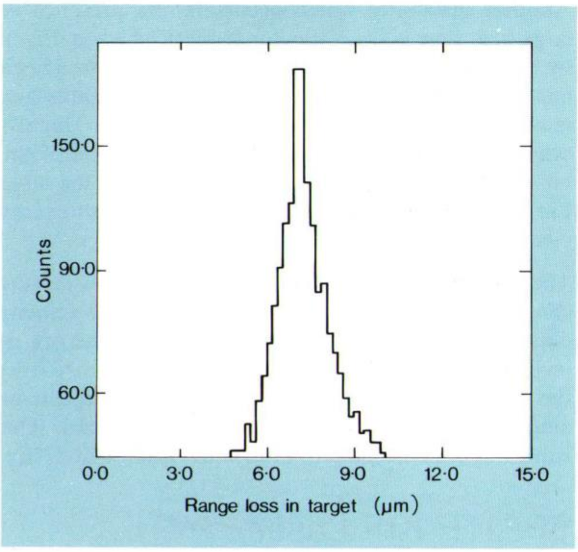


Fig 4.24 Range-loss spectrum for α-particles produced in a thermonuclear micro-implosion at Ecole Polytechnique.

Theoretical studies are also being carried out. An analysis of two-dimensional effects in finite width beams suggests that the frequency shifts of large amplitude waves will be less than in the one-dimensional case, resulting in larger electric fields, but that magnetic fields will be introduced which may complicate the plasma wave behaviour. The magnetic field experienced by particles close to the beam axis will remain small. The transfer of energy from the beat wave to the particle beam has been analysed for the first time, in collaboration with CERN, using the 'wake field' concept. Efficient energy conversion is possible for bunch densities appropriate to a high-energy physics machine but the beam density is greater than the background plasma density. Although this presents no fundamental problem, it does mean that linear 'test-particle' theory becomes invalid and recourse will have to be made to computer simulation.

Instabilities and Magnetic Fields in Heat Flow

When a departure from one-dimensional symmetry is allowed, the large heat flow found in laser-produced plasmas becomes subject to a thermo-magnetic instability which gives rise to filamentation of the heat flow and the generation of magnetic fields. This effect is thought to contribute to the plasma 'jets' observed in many laser-irradiated high-Z targets and was first analysed in a two-fluid model which makes an artificial distinction between different groups of electrons. A more recent model uses an expansion of the Fokker-Planck equation in Cartesian tensors and obtains the zero-order equilibrium from the one-dimensional case. Growth rates and wave numbers of maximum growth are in moderate agreement with the simple two-fluid model and in good agreement with observed growth rates and scale sizes for the plasma jets.

Another instability which occurs in the presence of large heat flow is the Weibel instability which is driven by the anisotropy of the electron pressure. It has been analysed in the collisional and collisionless limits and may limit the uniformity of heat flow in highly-symmetric laser fusion targets. The calculation of the non-linear saturated value is complicated by the large Larmor radius and mean free path of the high-energy electrons responsible for the instability.

The fields generated in these instabilities at low density can be carried to higher densities and, if the velocity dependence of the electron collision frequency is included, the magnetic field is found to be carried by the heat flow rather than the fluid flow and can be amplified as it is carried in to higher densities. This work was done in collaboration with Osaka University.

SPRITE KrF Laser

This year, the research phase of the gas laser research and development programme begun in 1979 came to an end with the demonstration of a high-efficiency, high-power Raman amplifier and the operational phase began with the commissioning of the world's first krypton fluoride laser target irradiation facility.

Waveguide Pumped Raman Amplifier

Although the SPRITE laser can produce some 200 joules of radiation at 248nm in a single pulse, the 50nsec pulselength is too long to be of use in most plasma physics experiments. A staged multiplexer to compress the pulse length to 1nsec has been proposed in which the second stage of pulse compression would be based on a waveguide pumped Raman amplifier. This was the final item to be tested in the gas laser programme. A small part of the large-aperture beam from the SPRITE laser was split into 56 individual beamlets which were injected off-axis into a glass-walled light pipe containing either methane at 3 atmospheres pressure or hydrogen at 1 atmosphere. A low-power seed beam of high optical quality at the Stokes wavelength (268nm in CH_4, 277nm in H_2) sent along the axis of the light guide was amplified by up to a factor 500 and severely depleted the pump beams. Up to 65% of the pump power was converted from the 56 pump beams into the single beam and a maximum output energy of 8.4J was obtained. This is the first demonstration of a high-power multiplexed Raman amplifier and its success is a fitting conclusion to the gas laser programme.

X-ray Microscopy

The first experiment to be carried out in the new SPRITE target area shown in Fig 4.25 was a survey experiment exploiting the flash X-ray microscopy techniques tested last year. Scientists from more than ten laboratories in the UK and three in the USA exposed more than three hundred specimens.

The specimens to be X-rayed, which may be wet and up to 10μm thick, are placed in contact with an X-ray sensitive resist behind a thin silicon nitride window in a sealed enclosure. The assembly is mounted in the evacuated target chamber a few cm from the target on which the laser will be focused. For biological work, a plastic target is used since it gives a spectrum

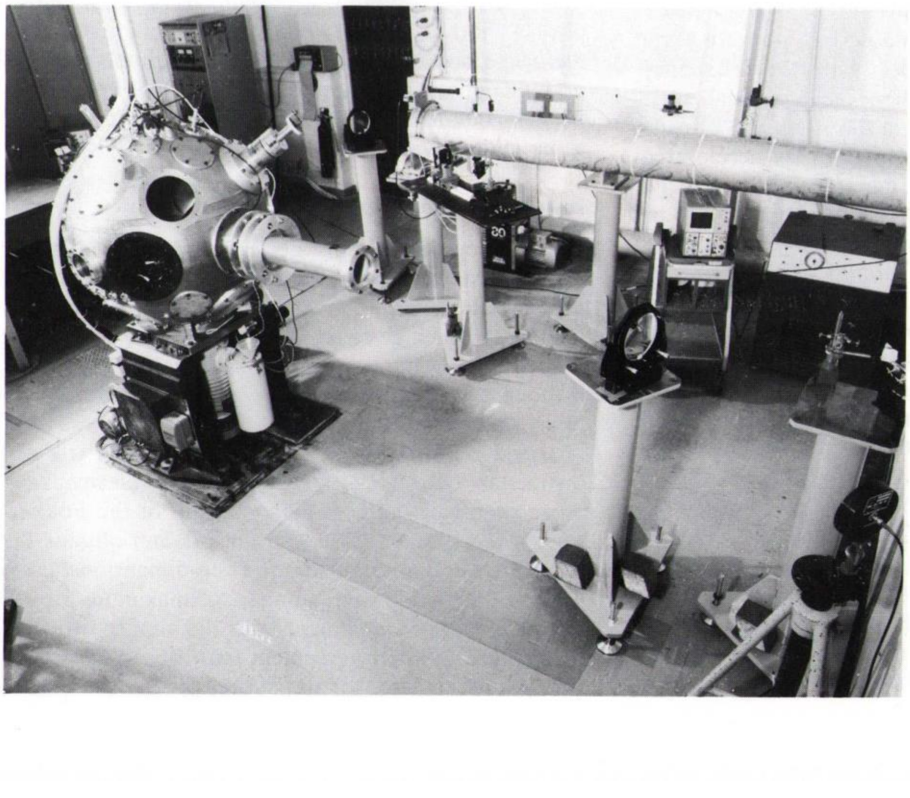


Fig 4.25 New Target Area Facility for the SPRITE KrF laser (85FC2907).

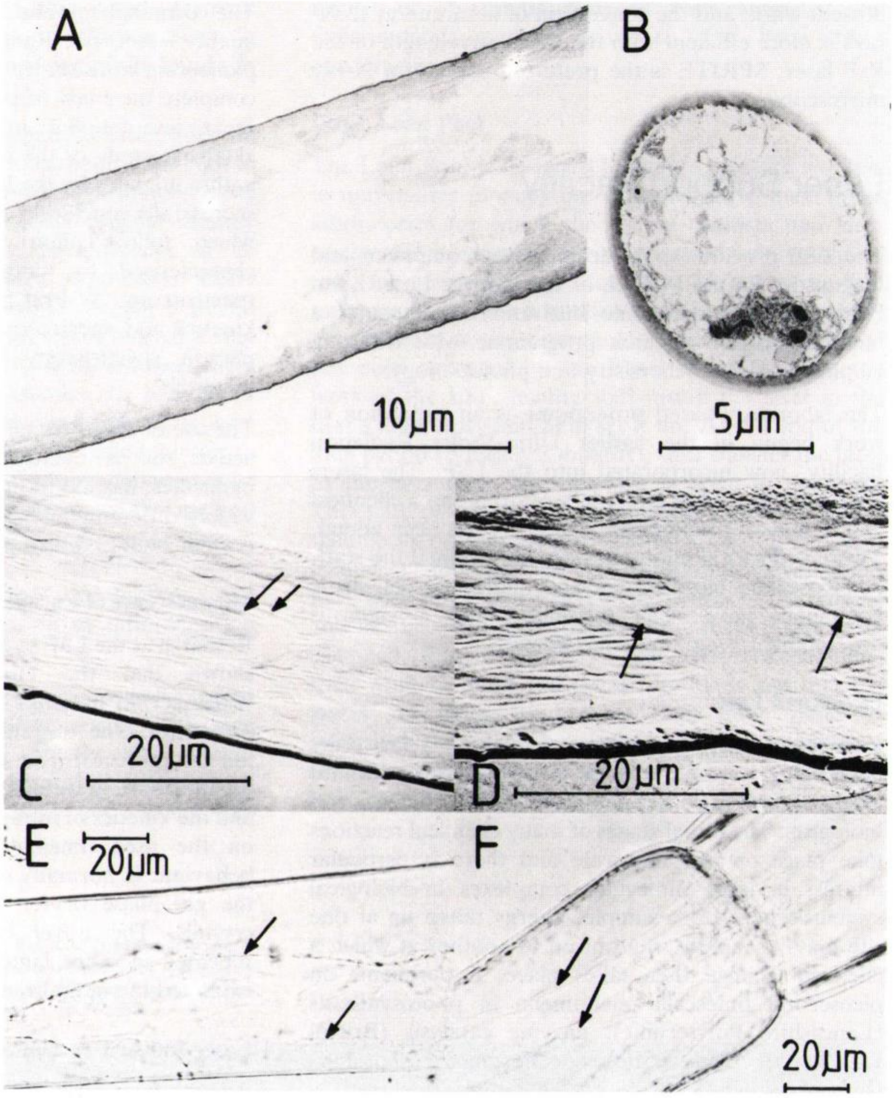


Fig 4.26 Photomicrographs of foxglove epidermal hairs. A,B: Transmission Electron Micrographs of specimens prepared by conventional methods of fixing, drying, staining and sectioning. C,D: Flash X-ray micrographs of unprepared specimens. The photoresist used to record the micrograph has been enlarged by a scanning electron microscope. E,F: Light microscope images of much larger cells (85FB5777).

concentrated in the window between the X-ray absorption edges of carbon and oxygen. This provides a natural contrast requiring no fixing, drying or staining to reveal the distribution of organic material in the presence of water.

A single laser shot giving a burst of X-rays lasting less than 50nsec is sufficient for the exposure. The appearance of living specimens can be recorded despite the lethal radiation dose needed for high resolution because there is no time for any change in morphology to take place. After the shot, the resist is developed to provide a relief image with a resolution better than 100nm. It may then be examined at high magnification with an electron microscope.

The advantages of this new technique are well illustrated by the micrographs of epidermal hairs from a foxglove shown in Fig 4.26. A) and B) are TEM pictures of specimens prepared in the conventional way. C) and D) are SEM enlargements of a photoresist flash X-ray image of the same type of cell but exposed in its natural state. They show substantially more cytoplasm than the TEM pictures and it appears to be arranged in trans-cellular strands which hold within them the various cellular organelles, some of which show substructure. Similar trans-cellular strands can be seen in the light microscope pictures of very much larger basal cells from the same plant shown in C) and D). The discrepancy between the TEM and flash X-ray microscopy pictures is due to the sample preparation treatment and sectioning needed for conventional TEM work.

Follow-up experiments are now in progress. Data of similar quality were also obtained using VULCAN to provide the flash X-ray source. As the shorter pulse length of VULCAN is important for plasma physics experiments, but of no particular advantage in the present work, and the conversion of laser energy to X-rays is more efficient with the short wavelength of the KrF laser, SPRITE is the preferred source for X-ray microscopy.

Laser Support Facility

The LSF provides sophisticated laser equipment and diagnostics for use at RAL or through the Laser Loan Pool, in the user's home institution. It supports a multidisciplinary research programme with a strong emphasis on photochemistry and photobiology.

The laboratory-based programme is an expansion of work begun in the earlier Ultra-Violet Radiation Facility, now incorporated into the LSF. The lasers have been moved to larger laboratories and a chemical and biological preparation laboratory has been added. Two postdoctoral photochemists have joined the staff. A picosecond laser system and additional diagnostic equipment have been purchased and a vigorous development programme has begun.

Picosecond Laser

Picosecond lasers have changed in the last few years from being research projects in laser laboratories into essential tools for other physicists and for chemists and biologists. The initial stages of many chemical reactions take place on this timescale and there is particular interest in large molecular complexes in biological systems where, for example, energy taken up at one site may be rapidly transported to another at which a chemical change then takes place. Experiments on picosecond timescale phenomena in photosynthesis (Lancashire Polytechnic), enzyme catalysis (Bristol University) and diffuse reflectance photolysis (Loughborough University) are being developed in collaboration with RAL.

The basic system is a YAG-pumped dye laser operating in the yellow and red region of the spectrum and producing an 82 MHz train of 3 ps pulses with an average power of 80 mW. An amplifier generates mJ pulses at a 10 Hz repetition rate. The beam quality is high, approaching both the diffraction and the transform limits. It can be focused to a peak intensity well over $10^{15}\,\mathrm{W\,cm^{-2}}$. The output has been frequency-doubled over the wavelength range from 280 to 340 nm and frequency mixing has been tested at 400 nm and at 248 nm. Raman shifting has been used to generate 820 nm and a white light continuum has been produced. Diagnostic equipment includes a scanning autocorrelator, a streak camera and a boxcar integrator system.

Dye and Excimer Lasers

More than 40 individual scheduled runs by 19 user groups took place during the year with over 80% of the time being devoted to chemistry and biochemistry.

The Birmingham and York groups obtained high-quality Resonance Raman spectra to consolidate their pioneering work on transients in enzyme catalysis and complete the study of papain. This work has attracted great international interest and competition. An extensive study of the complex photochemistry of the anthraquinones by the Royal Institution and York was successfully concluded. All five transient intermediates which follow photolysis in solution have been characterised by time-resolved resonance Raman spectroscopy. Several groups are studying gas phase kinetics and spectroscopy while others employ two-photon spectroscopy in the study of crystalline materials.

The use of caged compounds, in which the chemically-active site is enclosed by surrounding atoms or molecules, has led to the interesting new results in the widely different fields of luminescence chemistry and cellular biology which are described below.

Luminescence of Europium Polytungstate

Research at the LSF by the Birkbeck College group has shown that the europium dodecatungstate ion ($EuW_{10}O_{36}^{9-}$) in solution has exceptional luminescent properties. The tungstate cage around the europium ion can protect it from the solvent. As a result, strong luminescence is seen from more than one excited state and the kinetics of intramolecular energy transfer occur on the μsec timescale. This type of luminescent behaviour is normally only observed for molecules in the gas phase or for ions at low concentrations in crystals. The novel behaviour is expected to be repeated in other lanthanide polyanions and will be exploited in energy transfer studies.

Laser-Induced Trapping of Breaks in DNA

An ambitious series of experiments conducted by users from Birmingham and Sussex with the collaboration of the MRC laboratories at Mill Hill and Harwell is taking the LSF programme into novel areas of cell biology. They address the problem that, although developments within cells can be studied by changing the chemistry of the surrounding medium, several stages of a complex process may occur in the time it takes for the chemicals to diffuse into the cells. The experiments are particularly concerned with the study of damage repair in DNA but the methods being developed may well have much wider applicability.

Single strand breaks in DNA can result from absorption of ultra-violet light, bombardment with ionising radiation and exposure to carcinogens and substances which stimulate growth. They also occur transiently in DNA during cellular differentiation and malignant transformation which are two of the most important but least understood areas of biology and medicine. Present methods for the detection of breaks in DNA all involve gross interference with cell structure and metabolism and have very poor time resolution compared with the time scale of break development in many instances. In addition, they do not permit localisation and sequencing of the breaks in the DNA.

In the experiments at the LSF, a pulse of laser radiation at a wavelength of 351 nm, which has been shown not to harm the cultured cells being studied, instantaneously activates a previously inert 'caged' reagent already loaded into the cells. Under the influence of an enzyme-catalysed reaction which synthesises DNA during damage repair, the activated reagent is joined on to the free end of the broken chain in such a way that further growth is prevented. A radioactive tracer incorporated into the reagent enables the number of breaks to be determined. The timing of the short laser pulse used for photoactivation may be varied relative to the damaging event so that fast time resolution may be achieved where required. A variation of the method will allow sequencing of the DNA from the site at which the break occurs. This is expected to prove particularly important in the localisation and characterisation of gene activation in differentiation and malignant transformation.

A recent important finding is that the 'caged' reagent (and therefore also the labelled sequencing nucleotide phosphates) can be loaded directly into human leukaemia cells in culture. Permeabilisation, which disturbs the cellular environment, is not needed. The results of systematic tests of each stage of the experimental method have so far been most encouraging.

Laser Loan Pool

The Loan Pool is designed to enable research workers in universities to carry out experiments in their home laboratories for which the use of sophisticated laser equipment is essential but where the lasers would be used for periods of time too short to justify outright purchase or where a feasibility study is needed to justify the purchase of the equipment. When a loan proposal has been accepted by the Panel which oversees the work of the LSF, facility staff install the laser in the user's laboratory and help set it up. At the end of the loan period (typically 2 months), staff transfer the laser to the next user. Maintenance is done in the field. There are two YAG pumped tunable dye lasers in the scheme at present, one of which has a full range of frequency doubling and mixing options. Seven loans have been made in the first eight months of the scheme and in six cases substantial scientific results have been obtained. Experience shows that users are arranging their work to make full use of the loans and that the lasers are being used more than three times as intensively as single-user lasers. Several additional lasers are now being purchased.

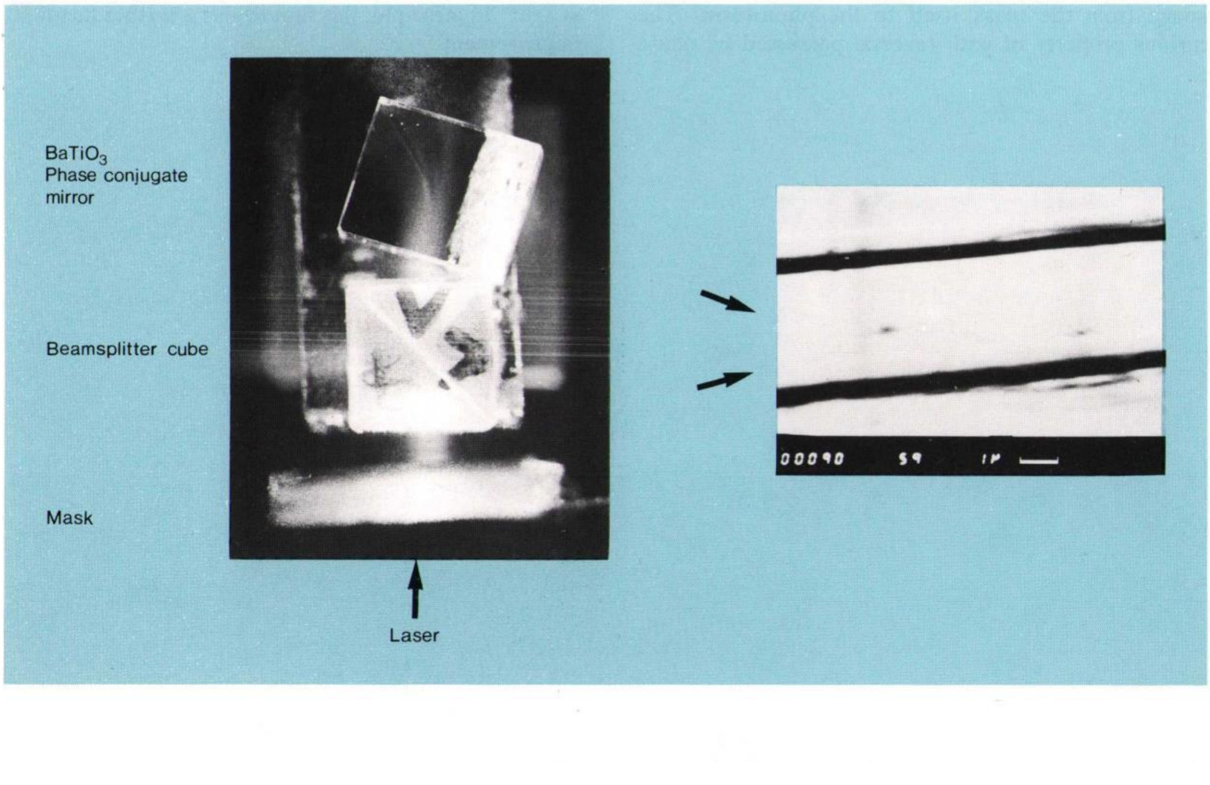


Fig 4.27 Phase-conjugate imaging using $BaTiO_3$. The two dark stripes shown on the photoresist at the right are less than 1 μm wide. They were produced from a mask using the self-aligning optical system shown at the left. The exposure time was 5 s (85FC5775).

Technology Transfer

Research to stimulate the transfer of the latest advances in lasers and optical techniques to the UK semiconductor industry has been funded at RAL since 1983 by the Department of Trade and Industry and the Engineering Board. Effort has been concentrated on developing novel lens-less methods to image mask patterns on to the surface of silicon chips. At present, the best lenses costing as much as £50k each can only image small areas (about 1 cm^2) and resolution is limited to about 1 μm.

Major advances have been made in the development of holographic methods to produce large-area speckle-free images of high resolution with ultra-violet light. A patent has been applied for and industrial exploitation is under investigation. Patents have also been applied for in relation to image projection by a four-wave mixing scheme of novel design which can give a resolution of 0.25 μm, again using ultra-violet light.

In the visible region of the spectrum, a factor of ten reduction has been achieved in the exposure time needed to produce images by phase-conjugate reflection in barium titanate and this material has been used for the first time to relay images with sub-micron resolution.

An example of the high resolution which can be attained is shown in Fig 4.27 together with the simple optical arrangement needed to produce it. The high degree of non-linearity in the $BaTiO_3$ material gives efficient phase conjugation of all light entering it so that every ray re-traces its path precisely. The returning beam therefore forms an exact image of the mask, with no aberrations. The beam splitter cube transfers the image from the mask itself to the photoresist. The curious property of path reversal possessed by phase conjugate 'mirrors' makes this arrangement self-aligning.

NMR Instruments for Biochemistry

In a nuclear magnetic resonance (NMR) spectrum, lines can be assigned to nuclei at different sites in a molecule. During the last decade, this feature has been widely used to investigate the structure of biochemical materials. Most studies have used the hydrogen nucleus because it gives a strong signal and has high natural abundance. In many materials, the carbon nucleus would be an interesting alternative but only the carbon-13 isotope gives an NMR signal. Unfortunately, the signal is weak and carbon-13 has a natural abundance of only 1%. As a result, it is difficult to identify the signals in the background electronic noise of the instrument. Generally, signals can be recovered from noise by using long averaging times but this is not practicable with unstable biochemical samples.

In collaboration with the Oxford Enzyme Group, a technique is being developed to improve the sensitivity of NMR. The noise in the instrument can be reduced by cooling the pick-up coil to about 4 K and by cooling the input amplifier. At present, this technique shows an improvement of about a factor 10 in the time to achieve a given signal-to-noise ratio on a standard sample. This has been achieved with carbon-13 nuclei at a field of 4.3 T. With support from the British Technology Group, the apparatus is now being modified to operate at 8.3 T. In principle, this should give a further factor 10 improvement.