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The Scientific Case for a High Power Laser Facility

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Plans to establish a joint programme were abandoned in June 1975 and the SRC now intends to establish its own Central Laser Facility at the Rutherford Laboratory. This document still forms the basic scientific justification for the new project which, though more modest in scale, still has the same scientific objectives.
Council approved the proposal for an SRC facility at its July 1975 meeting and has sought Government approval to proceed.

THE SCIENTIFIC CASE FOR A HIGH-POWER LASER FACILITY

Contents

FOREWORD

This presentation contains contributions from many scientists active in the use of lasers in UK universities. The proposal has appeared previously in several forms, the first being that prepared early in 1973 by the Plasma Physics Panel of the Physics Committee of the Science Board. It has now been revised to take account of the most recent developments in laser use and technology.

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1. SUMMARY

This document presents a scientific case for the establishment of a central high-power laser laboratory for the use of University groups. It outlines the basic investigations into laser-induced compression of matter, for the production of superdense high-temperature plasma, and the general study of high-power laser-matter interactions. The possibilities for intense XUV and X-ray generation, and for the production of energy by controlled thermonuclear reaction, are considered, since work of the kind now proposed would be an essential step towards both of these goals. Other scientific aspects are briefly discussed.

The laser requirements for these investigations are considered and a continuing programme of research and development in laser and optics technology is outlined.

2. INTRODUCTION

This report outlines proposals for a cooperative research programme involving the use of high-powered laser pulses. In particular, it recommends the establishment of a central laboratory with high-power lasers and ancillary equipment to be used by University groups.

This is a field in which there is intense activity abroad. A published figure of $40M per annum is being spent on investigations of laser fusion in the United States. The 1972 declassification of the results of computer studies of laser-induced compression stimulated much of the recent rapid expansion of interest in this field. In the USSR, a nine-channel neodymium:glass laser system has already been built and in 1973 construction of a 16-channel system was in progress. A large new institute has also recently been established in the USSR for the intensive study of high-density plasma. Smaller but substantial programmes are also in progress in Japan, France and Germany.

While the quality of research in this field in the UK has hitherto enjoyed an international standing (it has in fact developed many of the experimental techniques now finding widespread application overseas) we have now reached the stage at which an internationally competitive programme can only be maintained if we move to a scale of operation appropriate to a central facility. The existence of such a facility would also greatly extend the opportunities for the training of research students and postdoctoral workers in high-power laser techniques, and an important by-product of the programme would be the establishment of a cadre of physicists and engineers with experience in the handling of high-density plasmas, who will be urgently needed if the production of energy by thermonuclear fusion (which does not figure in the present proposals) should ever become an important technology. Fusion apart, laser technology will undoubtedly attain great commercial importance in its own right, and the pool of trained manpower, centred on the facility, will be an important national resource.

The principal scientific objectives of the proposal are:

(i) to create and study in the laboratory superdense plasmas generated by laser compression;

(ii) to study nonlinear interactions of very intense laser radiation with matter;

(iii) to develop more efficient and new high-power lasers for future experiments in laser compression and other fields.

The proposed installation would also provide facilities for other new investigations in basic physics making use of high-power laser beams at a variety of wavelengths.

The work to be carried out at the facility would be a logical extension of substantial activity already in progress in several UK university laboratories. As the following discussion sets out, work on laser-matter interaction has now reached a stage at which we need lasers of a size and cost beyond the scope of University workers, and whose building and maintenance require sophisticated engineering expertise of the quality to be found in a major research establishment.

A significant part of the underlying technology already exists in this country, and we already have a sufficient body of trained research workers in lasers, optics and plasma physics to make effective use of the facility in its initial stages of operation.

The experimental programme would fall into two parts. There would be one relatively inexpensive part which would need lasers of intermediate power; much of this would be an extension of laser-matter interaction studies already in progress. The other, and in some respects more challenging, part of the programme would require high-power systems capable of creating highly dense states of matter. The instruments would be constructed in a flexible arrangement to make possible their use in a range of configurations, including both linear and multibeam arrays, according to the requirements of different experiments.

3. LASER-INDUCED COMPRESSION OF MATTER

A major objective of the present proposal is the study of laser compression of matter to create super-dense plasmas. With focussed power densities above 10^{15}W cm^{-2} present day lasers produce higher power densities than any other system. In compressing material this power density is to be further amplified by geometrical and physical effects to compress ultimately to about 10^4 times the solid density.

Laser radiation incident on the surface of a spherical target is absorbed to form a high temperature plasma, with a density near the critical density at which the local plasma frequency equals the laser frequency. Energy is rapidly conducted away from this absorption zone to heat the higher density plasma. As a result pressure multiplication of approximately 10 times is obtained on the surface of a cold, unheated core. It is this cold core which will be compressed. A number of different pressure and laser time histories have been proposed in which the core is compressed adiabatically or by spherically convergent shock waves. The most efficient compression to a high density is obtained for an adiabatic flow, but this leaves the compressed core in a cold final state. To produce high temperature plasma or to ignite a fusion reaction it is necessary that some shocks be produced. Hollow shell compression occurs in a similar manner to that of solid spheres. However as the non-adiabatic compression occurs mainly as a result of radial implosion momentum the laser pulse shaping requirements are considerably relaxed. Calculations related to an experimental situation at KMS Fusion Inc., USA, show that for $(CD_2)_n$ spheres 260J in 1.2ns is required to achieve a compression of about 80. Similar results have been obtained for shell targets.

There are a number of important problems, however, which must be overcome before compression on a "large" scale can become a reality. The failure of classical thermal conduction and absorption is discussed later. Anisotropic behaviour may severely limit the compression obtained. In addition to the generation of magnetic fields by anisotropic thermal fields, gross deformation of the compressing plasmas may lead to "jetting". There is however evidence that smoothing by thermal conduction, called "fire polishing", may generally eliminate this anisotropic problem.

Currently most published work has concentrated on pure hydrogen isotope targets. However it is possible that using heavy metal clad targets, which will produce high Z ions in the plasma of the absorption and thermal conduction zones, some of the problems of non-linear absorption may be overcome by operating in a classical regime. Radiative diffusion may also be expected to play a significant role in the energy transfer processes, thereby easing some of the restrictions associated with the flux limitations of thermal conduction.

The choice of laser for compression experiments appears at present to be restricted to Nd^{3+}:glass systems. Although CO_2 lasers are capable of achieving the necessary energies, limitations discussed below associated with the transfer of heat by thermal conduction would at present seem to prevent them being used as effective compression sources. Shells offer several advantages over spheres as targets, notably the pulse shaping flexibility discussed earlier, and reduction of the overall focussed laser power density required. In general, since shells have a larger external radius than spheres, the collapse time and hence the permitted laser pulse duration is longer than for spheres. The surface area is also correspondingly larger. Both of these parameters permit a reduction in laser power density.

The time scale of the existence of matter in these highly compressed high temperature conditions is determined purely by inertia since no pressure balance is possible. Typically it is of the order of 10^{-11} to 10^{-12} sec.

Computer Calculations

The basic problem of achieving significant compression is the specification of the form of the laser pulse in terms of energy, duration, wavelength and symmetry. Recent years have seen a rapid expansion of computer simulation of laser-induced compression. Laser compression, which presents many experimental difficulties is especially suited to computer simulation studies. These involve the development in time of a macroscopic system governed by interaction of electromagnetic radiation with matter, and the propagation of thermal and compression wavefronts. These are aspects in common with galactic objects and liquid systems, the study of which is also responsive to computer simulation methods. As a consequence much effort has been directed towards theoretical studies in this field, both in this country and overseas.

While the physical assumptions underlying the various computer codes vary there is general agreement in their conclusions. The results suggest, for example, that a suitably tailored laser pulse of total energy of about 1 kilojoule irradiating a DT target will produce a density increase of about 10^4 (corresponding to a density of 10^{26} particles cm^{-3}) at a temperature of 5×10^8 K. The pressure of the compressed matter would be 10^{12} atmospheres (or about ten times that of the centre of the sun). Such calculations indicate that there is the possibility of creating in the laboratory in a controlled manner superdense matter similar to that which exists in stellar interiors. This is in effect the production of an entirely new state of terrestrial matter. It opens up a new area of physics, which in addition to its intrinsic interest also has great relevance to studies of nuclear fusion, and thus for the development of new methods of energy production. With a deuterium-tritium target pellet sufficient thermonuclear reactions may occur during the inertial confinement time of the plasma (about 10ps) to yield fusion energy equal to (break even) or greater than the input laser energy. Calculations have suggested break even for as little as 130J absorbed energy. In fact detailed computational studies of the parametric behaviour of the yield of deuterium-tritium spheres has shown that, with an optimum pulse, yield ratios of 0.9 can be obtained with only 50J. However for such low energies the laser pulse shape required involves a picosecond spike. Experimental work with higher energies, longer pulses and greater target mass are more practical.

It must be appreciated that the preceding discussion has considered only the theoretical aspects of compression. At present the detailed behaviour of laser energy absorption and transfer within the plasma is not well understood. As a result it may be expected that these predictions will have to be modified as improved modelling becomes possible. In addition most predictions of implosion generating compression ratios of between 10^3-10^4 have been made using optimally shaped laser pulses by which the input absorbed energy is minimised. In practice it may be expected that the necessary input energy using a more realistic laser pulse will be significantly larger; probably of the order of 1kJ being necessary to obtain compressions greater than 10^3.

Experimental Studies

Experimental studies of compression are now under development in at least 8 major laboratories, but only a few preliminary results are available at present (October 1974). Although 9 beam irradiation of solid $(CD_2)_n$ spheres, with typically 200J of neodymium laser energy in 6ns pulses, was experimentally investigated by Basov et al in the USSR in 1972, it was not until 1974 that laser compression of spherical targets was directly demonstrated by work at KMS Fusion Inc. in the USA.

Since this KMS work gives important experimental evidence of the feasibility of compression it may usefully be described here. The main result obtained was the compression of spherical glass shells, filled with high pressure D_2 or DT gas, by average volumetric ratios of x 50. The resulting peak particle densities were at least $6 \times 10^{23} cm^{-3}$ at a temperature of 1000eV for a duration of 10^{-11} secs, yielding up to 10^6 thermonuclear fusion neutrons from the compressed plasma. The experimental measurement resolution limited the accuracy of the determination of the compressed volume and it was possible that the computer predicted peak density of 10^{25} cm^{-3} was achieved.

Recent (September 1974) declassification of work on hollow shell targets in the USA has released important details of this new technology and allowed publication of the full description of the KMS experiments. The target shells are of a high degree of sphericity and uniformity, being typically 50 microns in diameter and 1 micron thick with up to 100 atmospheres gas filling. The method of manufacture is new but presents no great problem and shells can also be bought commercially.

Laser irradiation of the target with a high degree of spherical uniformity and near normal incidence was obtained with a novel elliptical mirror/aspherical lens optical system in which 2 laser beams were focussed into a 144^{o} cone angle from opposite sides of the target. (The important role of optimum optical design is emphasized by the KMS experiments). This type of system was ideal for initial compression studies though limited ultimately by the maximum power available in a single laser beam. Shaped pulses of from 30psec to 1 nsec duration were obtained by stacking up to 20 pulses of 30psec duration. Laser powers up to 0.6 terawatt were generated in 2 beams using disc amplifiers but the compression studies were carried out with 50J, 300psec pulses (0.17 terawatt). The experimental data showed significant compression of shells (volume compression of greater than 10) for laser energies above 1J/nanogram of matter in the shell.

It is important to note that the use of these shells increases the implosion time and thus reduces the laser power required for a given energy input. This is of considerable practical importance since glass lasers are <u>power</u> limited by non-linear effects but can deliver <u>energy</u> proportional to the pulse duration.

The fairly extensive diagnostic studies carried out by the KMS group are typical of what is required although much more needs to be done. Ion collectors give expansion symmetry, total energy in the plasma, and ion energies in the ablating plasma. Neutron yield and time-of-flight measurements gave data on ion energies and densities in the compressed plasma. X-ray spectroscopy yields information about the electron energy distribution and electron density and optical interferometry allows study of the ablation plasma parameters. The single most convincing diagnostic was time integrated X-ray photography of the collapsing shell. In this connection it might be noted that the X-ray streak cameras developed in the UK are now of great interest for following the implosion dynamics.

This KMS experiment illustrates the practical feasibility of entering the field of compression studies with existing laser technology. Full understanding and optimisation of the process will require extensive experimental work. Further progress towards the predicted compression of $\sim 10^4$ (capable of achieving fusion break even) will involve larger and more sophisticated multi-beam lasers.

4. LASER-MATTER INTERACTION PHYSICS

In this section we refer to the phenomena of energy transduction within plasmas, whose study would generally be accessible with single beam lasers. The study of laser-plasma interactions is a field of scientific interest in its own right, and is also an essential basis of other novel areas of experimental physics. It is also a necessary complement to the investigations of compression of plasma by laser beams.

We first mention the processes which occur when electromagnetic waves of comparatively small amplitude enter the plasma, and then extend the discussion to the very high energy radiation with which we are concerned here. When a wave of small amplitude enters a plasma, absorption occurs principally by the process of inverse bremsstrahlung during classical electron-ion collisions. If the wave penetrates to a region where the electron density rises to a critical value so that the plasma frequency approaches the frequency of the wave, the wave will then be reflected. Such linear effects are well understood in principle, although some of the details of the processes occurring when a plasma is generated by focussing light on to a solid target and the density gradient is extremely steep, are still poorly modelled. As the amplitude of the electromagnetic radiation is increased the interaction with the plasma becomes strongly non-linear and new effects set in. When the velocity of electrons oscillating in the electric field equals the thermal velocity, the rate of energy absorption due to inverse bremsstrahlung reaches a maximum, imposing a limit on the rate at which the plasma is heated. At relativistic electron velocities there is an interaction with the electric field of the electromagnetic radiation, which can lead to charge separation and propagation in over-dense plasma.

These processes are insufficient to absorb an appreciable fraction of laser energy at the very high flux densities with which we are concerned. As the plasma is heated, the electron collision frequency decreases and inverse bremsstrahlung becomes a progressively more inefficient absorption mechanism. In consequence reflection occurring at or near the critical surface becomes increasingly dominant as the flux density increases. If these effects were the only ones operating most of the incident light would be reflected at intensities greater than about 10^{10}W cm^{-2} at a wavelength of 10.6μ, and of about 10^{14}W cm^{-2} at 1.06μ. There exists, however, an entirely separate class of interaction, which involves collective effects as distinct from the binary effects mentioned above. Collective interaction effects appear on theoretical grounds to be the dominant factor in the regime where driven electrical oscillations become comparable with the thermal energy of the electrons in the plasma. These collective effects provide alternative mechanisms for the absorption of energy.

There are, however, significant ways in which they can also lead to reflection. Since they occur only at high electron energies they are confined to very high flux densities in the case of the optical frequency fields with which we are concerned here. This is not so at radio or microwave frequencies, and experimental evidence of collective phenomena is therefore largely confined to low density plasmas and microwave radiation. (Some account of what has been done at higher frequencies is given later). These collective processes are an important area of basic physics in their own right and their study forms an important part of the present proposal. In our present state of knowledge, and with the instrumentation now available, theory is well ahead of experiment, and the following short account of various collective instability effects is based entirely on theory.

Collective Interactions

One class of interaction is termed electrostatic, because it arises from coupling of the laser wave electric vector with plasma waves. (i) The parametric decay instability occurs at densities typically 10% below the critical density. Above a certain threshold of the intensity of the laser electric field unstable growth of the plasma waves sets in, absorbing energy from the laser beam which gives energy to those electrons at the high energy end of the distribution function. Theoretical predictions suggest that laser energy would be absorbed efficiently at flux densities above the threshold of 10^{14}W cm^{-2} at the wavelength of 1.06μ of the neodymium-glass laser beam and 10^{10}W cm^{-2} at the 10.6μ of the carbon dioxide laser. At present, saturation effects which limit the rate of energy deposition for fluxes much above the threshold are poorly understood, as are the limitations on the growth of wave amplitude imposed by convection out of the region of instability, and the effects of density gradients on the instability. This process also has the important effect of generating energetic runaway electrons which could lead to preheating of the target core and thus inhibit the compression process. (ii) The oscillating two-stream instability is similar in effect to the parametric decay. The net effect is again to feed energy into electron plasma oscillations which through their damping heat the electrons. (iii) The two-plasmon decay instability occurs at densities of one quarter of the critical density, and could in principle absorb energy before it reached the critical density region. The instability threshold occurs, typically, at intensities of incident radiation some hundred times greater than in the two previous cases. (iv) Resonance absorption can provide a strong energy absorption mechanism at the critical density surface of the plasma at high intensities of radiation. It arises under circumstances where the incidence of the laser beam at the critical surface density is not perpendicular, enabling the electric field of the laser to couple directly to electron plasma waves, which may themselves drive new wave instabilities.

All the electrostatic processes described above lead to enhanced absorption. There is, however, another class of instability, which can be described as electromagnetic, which leads to stimulated back-scattering of the incident radiation, and hence to a reduction of absorbed energy. Potentially the most important of these is Brillouin back-scattering, which exhibits a threshold above which exponential growth of the back-scattered radiation may occur, leading in principle to a complete conversion of the incident flux to back-scattered photons. Computer simulations have indicated that Brillouin scattering may be very important when the particle oscillations have an energy comparable to the thermal energy of the particles. Brillouin scattering does not demand any particular density for its operation and could, therefore, reflect most of the laser energy before it reached the anomalous absorption zone. Other electromagnetic instabilities, which would appear to play a less important role, are Raman back-scattering and stimulated Compton scattering, and if an additional magnetic field is present (perhaps generated through asymmetric heating of the plasma), there is a possibility of another absorption mechanism through the excitation and damping of whistler waves.

Energy Transfer

The transfer of energy from the region of radiation absorption to the surrounding plasma plays an important role in all laser-plasma interactions. In laser compression experiments it is however crucial. Effective pressure increase by heating plasma at densities above the critical density is important in generating the forces necessary to compress the core of a target. In addition the lateral transfer of heat enables surface irregularities to be smoothed out by "fire polishing". Calculations at Los Alamos have indicated that this effect may be extremely efficient for eliminating anisotropy in a collapsing shell provided the thermal conduction is classical. As a result the degree of isotropy required in the incoming laser beam in the compression experiment may be reasonably low. Unfortunately however at high thermal fluxes the departures from classical behaviour which occur, are not at present well understood.

At low energy fluxes energy transfer is well described by the usual Chapman-Enskog perturbation analysis of the distribution function leading to classical thermal conduction. However when the scale length of the temperature variation becomes comparable with the mean free path, severe distortion of the distribution function occurs. In the extreme case a two-temperature electron distribution may result. The heat flow is then due to the flow of hot electrons. However this current is limited by charge separation fields, which ensure that the nett electron flux is zero. Thus the heat flow is limited by the return cold electron flux. This phenomenon is known as "flux limitation" and has been found to be of considerable importance in laser-plasma interaction studies.

The "flux limited" heat flow is determined by the cold electron current, whose value will depend on whether the current is collisional or collision-free. Clearly the maximum current is the collision-free kinetic flux of $\frac{1}{4}n_e v_e$. However if the Debye length is longer than the mean free path of the "cold" electrons the current will simply be σE, determined by the electrical conductivity, σ, in the field, E, of the "hot" electron sheath. The mean free path of the "cold" electron component thus limits the heat flow by the hot electrons.

The situation is further complicated by an increase in the effective collision frequency of the electrons due to micro-turbulence. Such behaviour may be expected from two-stream instabilities between the electrons and the background ions, but also, and perhaps more importantly, from the turbulent nature of the plasma associated with instability heating.

The intense electric fields produced in the "sheaths" in laser heated plasma lead to ion acceleration out of the plasma body into the low density plasma region. If flux limitation is particularly severe this may represent a substantial loss of plasma energy away from the high density region where it is needed to drive the compression.

The details of this behaviour are not well understood at present. However it should be appreciated that "flux limitation" is a problem common to all compression schemes. It is a particularly severe problem for CO_2 laser compression where the low density of the absorption zone (due to the long laser wavelength of 10μm) requires an efficient energy transfer mechanism. In addition the low threshold for instability absorption ensures that the plasma in the absorption zone is highly turbulent, further aggravating these problems. In view of these effects the suitability of CO_2 lasers on their own for high compression experiments is now doubtful.

A further thermal conduction limitation occurs due to self-generation of magnetic fields. In the presence of non-parallel gradients in the density and temperature fields resulting from anisotropy in the laser heating, thermo-electric currents may generate intense magnetic fields of several Mgauss. As these fields are generated by temperature and density gradients we may expect that their strength will be greatest in the region of conduction. At high fields the heat transfer will be dominated by the $(B_\wedge \nabla T)$ Hall term which is perpendicular to the temperature gradient. There is a corresponding reduction in the heat flux parallel to the gradient. Thus although the total magnitude of the heat flow is not changed by the magnetic field its direction may not be conducive to smoothing surface irregularities. At present it is not known what terms determine the diffusion of the magnetic field. Thus if micro-turbulence is important we may expect that the field decay will be described by a Bohm term. However if the thermal conductivity is classical then so is the magnetic diffusion. Thus magnetic fields inhibit free thermal conduction predominantly in the classical regime. It may appear from this argument that thermal conduction will be strongly inhibited under all conditions. However it should be remembered that the strength of the magnetic field is strongly dependent on the steepness of both the longitudinal and transverse gradients, and that as a result these effects may be minimised by careful design of the compression experiment to achieve symmetrical illuminations of the target.

Experimental results

Experimental study of laser plasma interactions has been underway for several years and a considerable body of information has been accumulated at low flux densities. This has proved very important for the development of understanding of possible applications of laser produced plasmas through the revelation of several important processes and effects not previously considered in theoretical extrapolations and modelling. The study of interaction phenomena is at present incomplete in the sense that really systematic experiments have not yet been conducted at the high focussed flux densities, 10^{14}-10^{16} watts cm^{-2}, required in laser compression, laser fusion, X-ray generation and X-ray laser studies. Such experiments will be possible with the lasers proposed here.

The absorption of laser energy, its reflection coefficient and spectral line shape in both diffuse and collimated back-scatter, and the generation of scattered harmonics and sub-harmonics of the laser frequency, have been intensively studied yielding evidence for the excitation of the parametric and two-plasmon decay instabilities, Brillouin back-scatter and resonance absorption.

However the most significant result of such studies is that the predicted large reflection of laser energy by back-scatter instabilities at intensities above 10^{14} watts cm^{-2} at 1μm, or 10^{10} watts cm^{-2} at 10μm, does not occur. Clarification of the processes responsible for this is one important current problem. Also significant has been the observation of non-thermal X-ray bremsstrahlung, as a result of the generation of energetic electrons in the collisionless damping of instability driven plasma waves and the flux limits on heat conduction. Quantitative correlation of experiment and theory leading to an adequate understanding of the effect of the energetic electrons in preheating the target material, due to their long mean path, and of the acceleration of ions due to their intense space charge fields is now needed. The measurement of ion energies and charges, their angular distribution and total flux, has been important in the developing understanding of anomalous reductions of heat conduction in laser plasmas. In particular the observation of nearly 90% conversion of absorbed energy into fast ions, accelerated by a typically 60keV space charge field, when CO_2 laser radiation is absorbed at 10^{14} watts cm^{-2} has raised serious doubts about the feasibility of compression with CO_2 lasers. Further study of this effect with CO_2 lasers and also with shorter wavelength lasers at scaled flux densities of 10^{16} watts cm^{-2} is of great interest and significance. Further evidence of flux limitations has emerged from the use of thin target foils which have permitted the study of energy transport through known depths of matter. Extension of this type of work is expected to yield further important results leading to a better understanding of the phenomenon. Analysis of the production of neutrons in the interaction, while initially interpreted as due to thermal processes, was later shown to be frequently due to deuteron acceleration in the space charge fields as discussed above. However in current compression work the thermal origins of neutrons have been proved by several experimental tests, notably those involving the absence of neutrons when compression symmetry is absent. The development of diagnostic methods generally is an area which is closely related to interaction studies and is essential for both interaction and compression work. Over the years UK workers have developed considerable experience in this field.

5. XUV AND X-RAY GENERATION

Several important areas of basic physics would be accessible using high-powered lasers. First among these in importance is the generation of intense XUV and X-ray sources, including X-ray lasers. We discuss these possibilities briefly.

The generation of intense incoherent X-ray sources

Current experiments in association with theoretical analyses have shown that laser plasmas can act as exceptionally powerful and efficient flash X-ray sources. With plasmas of light atoms the X-radiation is relatively weak, arising from bremsstrahlung originating in collisions of electrons with bare nuclei. When heavy atoms are present they are not, in general, stripped of all their electrons. Bremsstrahlung is then relatively weak but the recombination of the most highly ionised atoms provides an intense source of continuum radiation. In addition, the bound electrons give rise to two types of X-radiation: (i) through normal optical transitions excited by collisions with energetic plasma electrons and (ii) through screened transitions in which an electron in an inner shell is excited. The resultant line spectrum can be very complex but at the limit of high plasma temperature and high atomic number a highly efficient conversion of laser power into X-ray power is achieved. Efficiencies of about 20% have been reported. Inertially confined laser plasmas will emit X-ray pulses of duration < 0.1 nanoseconds when heated by ultra-short laser pulses. With pumping laser powers of up to 10^{12} watts, the X-ray power from a source of dimensions of about 100 microns could reach 10^{11} watts. The spectrum, a mixture of the recombination continuum and line radiation, is most intense in the spectral region of the resonance lines of the most highly ionised species present. As the power of the laser is increased more highly ionised species and shorter wavelength X-radiation are produced. X-rays of energies about 50keV should be attainable. Recent measurements of the X-ray spectra of copper and iron targets under a focussed laser pulse of wavelength 1.06μm, 100J energy, 1 nanosecond duration, focussed to a spot diameter 100μm, have indicated conversion efficiencies as large as 25% for the range 0.3-1.5keV photon energy. Further work is needed to determine the effects of variation of the duration and shape of the pumping laser pulse.

The generation of intense soft X-ray fluxes by laser-produced plasmas offers the possibility of supplementing conventional X-ray sources. Demonstration experiments at Batelle Institute, USA, have already recorded high spatial resolution X-ray photographs through living tissue, including bees and dogs' hearts. In contrast to conventional X-ray sources, which emit a steady low flux for a long time, laser pumped X-ray sources radiate a short, but very intense pulse, which may simplify certain types of radiological treatment. In addition short highly intense radiation pulses may also have industrial applications. The production of intense X-ray sources also has implications for several areas of physics: the study of the source itself; the ionisation, recombination and excitation of inner and outer electrons; the generation of ionic spectra not otherwise produced in the laboratory; the use of the X-ray source for subnanosecond resolution absorption spectroscopy and X-ray transmission photography. The latter technique could be very useful in studying plasmas produced by laser compression. Powerful X-rays could also be employed in the study of photoionisation processes.

X-ray and vacuum ultra-violet lasers

The availability of multiterawatt laser pulses of duration from 5×10^{-12} sec to 10^{-10}sec opens the way to exploration of various approaches to the generation of high-powered lasers in the vacuum ultra-violet and X-ray spectral regions. Tunable lasers in the far ultra-violet and X-ray regions would have many applications in plasma diagnosis, laboratory astrophysics and in spectroscopy. There is particular interest in intense tunable VUV sources for photoemission studies at wavelengths down to the soft X-ray region, complementing synchrotron radiation. Since it is almost certain that the X-ray laser will involve high density plasmas, many of the problems of plasma heating will also arise here, and the same basic laser system will be used for X-ray laser studies as for the other laser plasma investigations.

X-ray laser action is theoretically possible when broad band incoherent X-rays at energies just above the K absorption edge, excite K shell fluorescence in atoms of $Z > 13$. The K vacancies thus produced radiatively decay to L vacancies which themselves decay by an Auger process at a rate greater than the K shell fluorescence to maintain a population inversion. Calculations indicate that gain sufficient to overcome the L shell photoionization losses requires a pump rate of 10^{15} watts cm^{-2} of incoherent X-rays, for the case of Si Kα at 7.1Å and that an active medium length of about 100μm would give super-fluorescent laser action. The necessary X-ray pump power could probably be obtainable with laser plasma incoherent X-ray sources of the type discussed above and studies to investigate this possibility could be carried out with a single laser beam of ∿ 1 TW.

Another approach to X-ray laser action makes use of n=3 to n=2 transitions in hydrogen-type ions of high atomic number, in a plasma whose electrons have been heated more quickly than their hydrodynamic relaxation times. Subsequently the super-cooled plasma undergoes collisional recombination which fills the upper levels faster than the lower to give population inversion. Calculations indicate that a plasma of hydrogen type ions of atomic number 13, created by irradiating a wire target of radius 0.5μm with a 10J, picosecond laser pulse, will show a gain of 35 cm^{-1} at 39Å. Similar schemes operating in the vacuum ultra-violet have been considered, and show that significant gains may be obtained under more feasible experimental conditions.

A third possibility involves transitions of the type np→ns which have already been used successfully for ion lasers in the visible region. The lower ns state usually has a lifetime considerably shorter than has the np level, making population inversion possible. Population inversion in the 4s→3p transition created by electron-impact excitation of the 4s level of isoelectronic neon-type ions has also shown to be possible by calculations on Fe XVIII and Cu XX.

6. THE PROSPECTS FOR LASER-INDUCED CONTROLLED THERMONUCLEAR FUSION

We have emphasised that we see the justification for this proposal as the study in its own right of a novel and important state of matter. Nevertheless the main impetus for much of the world-wide effort in this field, particularly in the United States, is the goal of the development of economic laser-induced controlled nuclear fusion. Because of its importance, and because we see the kind of work now proposed as a necessary stage in any national effort on laser fusion that might subsequently be mounted, we give here a simple account of the use of lasers in energy production.

Much of the earlier work on the development of thermonuclear reactors confined the plasma by magnetic means, but, as has already been stated, in the case of laser fusion the only restraint on the expansion of the plasma is inertial. Energy must therefore be transferred to the plasma by a succession of suitably tailored short laser pulses, with the thermonuclear reaction taking place in the time in which the plasma is contained by inertia. Under these circumstances an appreciable proportion of the energy transferred to the plasma goes to heating it.

The conditions under which there is a net gain of energy from thermonuclear reaction (the Lawson criterion) can be established by comparing the components (kinetic and electromagnetic) of the input energy with the components (kinetic, electromagnetic and thermonuclear) of the energy emitted by the plasma, ascribing a plausible value to the efficiency of feedback to the input of the energy thus produced. Two necessary conditions are found which must be satisfied - a minimum plasma temperature, and a minimum value of the product of the ion density n in the plasma and the confinement time t. In the case of deuterium-tritium (the most favourable for achieving thermonuclear fusion) the minimum temperature proves to be 5×10^8K and the minimum value of nt, 10^{14} cm^{-3} sec.

The importance of high compressions can be seen if we translate the Lawson criterion into terms of the energy contained in an inertially confined sphere (of deuterium) at 5×10^8K. The requirement for thermonuclear break-even then becomes $E > 10^{50}\ n^{-2}$ kilojoules, where n is expressed in cm^{-3}. This inverse square relationship means that an increase of 10^4 in the compression of the target reduces the energy necessary for fusion by a factor of 10^8.

In a typical laser compression experiment the surface of a spherical pellet is ablated by a laser prepulse to create a low density atmosphere surrounding it. As much as 95% of the laser energy absorbed by the pellet would be lost in the ablation process. Under these circumstances, if the theoretical calculations mentioned above are correct, a compression giving an ion density of $10^{26}cm^{-3}$ at a temperature of 5×10^8K should be feasible with a deuterium-tritium target and a suitably tailored laser pulse of a few kJ energy. To achieve a useful controlled thermonuclear reaction, however, the energy produced would have to exceed the input energy by a further factor of about 20 (corresponding to an overall gain of at least 1000) to take account of the practical limitations on the recycling of the thermonuclear energy generated to energise the laser source.

No positive claim has yet been made that controlled thermonuclear reactions will necessarily prove a practicable proposition, and some plasma physicists feel that Tokamak-like machines are more likely to furnish the first practical sources of thermonuclear fusion energy. Nevertheless there is strong support for the view that laser fusion will probably be the basis of the first laboratory demonstration of break-even. Considerations of this kind provide the incentive for heavy expenditures overseas on experimental programmes aiming at the development of laser fusion processes.

7. LASER REQUIREMENTS

Possible Laser Systems

The degree to which a particular laser medium is capable of generating high power pulses depends on fundamental parameters, such as the Einstein B coefficient of the transition used and the pumping quantum efficiency, and on engineering problems associated with the excitation of large volumes, self damage at high radiation intensities, etc. Of the many hundreds of known laser media there are only a few which at the present time seem potentially capable of meeting the requirement to produce multi-kilojoule pulses of duration of order 100 picoseconds or less. These include neodymium doped glass, carbon dioxide, iodine and hydrogen fluoride. It should, however, be stressed that the situation can change very rapidly, as exemplified by the HF laser: laser action in this system was first observed in 1966 when a few hundred microjoules per pulse was obtained. Since then the maximum observed output has increased by roughly a factor of ten per annum, the highest published value being 2.5 kilojoules in a 30 nanosecond pulse.

Apart from laser performance, an important criterion in plasma generation and compression is the wavelength of the emitted radiation. This puts a premium on short wavelengths, which is unfortunate since the shortest wavelength obtainable from the above three lasers is that from Nd:glass, which is also the least efficient. For research purposes, however, the wavelength dependence is an important parameter and at least two wavelengths would be desirable. A brief summary of the properties of the most advanced laser systems follows, with an indication of their potential capabilities.

Nd:glass Lasers

Emitting at a wavelength of 1.06μm, Nd:glass lasers are normally optically pumped by xenon flash discharge lamps. Efficiency (including the flash lamps) is well below 1%. High power systems consist of a master oscillator followed by a series of amplifiers in the form of rods and discs of steadily increasing diameter to keep the power density within acceptable limits. To obtain near symmetric irradiation of a target at least two amplifier chains (fed from the same oscillator) are required and possibly as many as eight.

At the present time the leading US laboratories have obtained outputs of the order of 100 joules in 100 psec in a single chain, an order of magnitude less than required for fusion break-even. The limiting factor in current performance appears to be self-focussing. This arises because the refractive index of glass (and, indeed, any substance) is intensity dependent at high intensities, the sign of the effect being such that any relatively high intensity spot in the plane of the beam grows in intensity by self-focussing, leading ultimately to destruction of the amplifier. The effect can be minimised by the use of highly uniform glass rods (particularly in the oscillator) to reduce the likelihood of high intensity spots developing, by expanding the beam to reduce the average intensity and by choosing glasses with low non-linear optical coefficients. Each of these alternatives makes formidable demands on amplifier fabrication techniques. Alternatively, large gaps may be left between thin amplifiers to allow non-uniformities in beam profile to disperse, but these are costly in space and increase the number of glass-air interfaces, which is undesirable.

Gas Lasers

Carbon dioxide, hydrogen fluoride and iodine are gas lasers. Though each has special features, all gas lasers have advantages in common. Laser medium uniformity is relatively easy to achieve and self-focussing, even if it occurs, is destructive only of relatively cheap components like windows. A disadvantage is the relatively low density of gases so that, unless high pressures are used, large active volumes are usually required. A summary of the important properties of CO_2, HF and I follows.

(i) CO_2 Lasers

CO_2 lasers operate on two groups of rotational lines centred on 10.6μm and 9.5μm. They are normally excited by electric discharge in the gas after preionisation by photoionisation or by electron beams. Normal operating pressure is one atmosphere with current research aiming towards 10 atmosphere operation. At one atmosphere efficiency is around 5% for 1 nsec pulses, falling to near 1% for 100 psec pulses if operation is on one line only.

Though the long wavelength of the emission is a disadvantage the higher efficiency (and potentially very high efficiency, since the quantum efficiency is over 40%) coupled with ease of fabrication makes CO_2 an important contender.

It also happens that, due primarily to work in UK universities and government establishments, the UK has some competitive advantage over the US in some aspects of CO_2 laser technology. The problems which limit the performance of CO_2 oscillator-amplifier systems at the present time are associated with the relatively low intensity at which amplifier gain saturates (compared with Nd:glass) and the poor extraction of energy from the amplifier that occurs when short pulses are used. Both are improved by increasing gas pressure. The latter problem also occurs in Nd:glass amplifiers but parasitic oscillations due to feedback after the pulse has passed through the amplifier is avoided by the use of non-reciprocal Faraday isolators. Similar components of sufficient size can be, but have not been, made for use at 10.6μm.

(ii) HF Lasers

A reaction between, for example, SF_6 and H_2, initiated by an electric discharge, results in the formation of HF molecules in vibrationally excited states. Many fluorine compounds and almost any volatile hydrogen donor will do. Laser action follows. Since population inversion arises as a consequence of the release of chemical energy the electrical efficiency can exceed 100% (180% has been observed) but normal operating efficiencies are around 20%*. The emission takes place on a number of lines around 2.7μm and therefore falls conveniently between CO_2 and Nd:glass. Following initiation of the reaction, the various lines are emitted sequentially in time.

The gain of HF lasers is unusually high (of order 100dB per metre at low intensities) which leads to problems of parasitic emission and poor control of oscillation modes. As a recent addition to the league of high power laser media, the technology of HF is, as yet, poorly developed and the peripheral equipment required for full exploitation of its potential hardly developed at all. On the other hand, HF has the inherent simplicity associated with any gas laser and can, like CO_2, be initiated by electron beams.

*Footnote. In the context of fusion power breakeven, this efficiency is somewhat illusory, since energy must be provided to reform the original constituents.

It should, however, be stressed that the 2.5 kjoule output quoted above referred to a 30 nanosecond pulse and there is at present no simple way of reducing the pulse length (at constant energy) to anything approaching 100 picoseconds.

(iii) Iodine Lasers

Photo-dissociation of molecules like C_3F_7I produces free iodine in an electronically excited state. Iodine lasers are therefore pumped by flash discharge tubes, like Nd:glass, but the overall efficiency is higher (about 0.5%). Emission occurs at 1.315μm. Like HF, the gain is high enough to make amplified spontaneous emission a problem but, unlike HF, the reaction is largely reversible and, provided pumping is not too strong, almost all the original C_3F_7I is reformed by recombination. The highest reported power from an iodine laser system (oscillator, electro-optic pulse slicer and two amplifiers) is 60 joule in 700 picoseconds.

The Choice of Lasers for use in the Centre

Amongst the factors to be considered are:

(i) The need to provide, as quickly as possible, a laser capable of producing compression and;

(ii) the inevitable limitations imposed by a finite rate of staff build up.

The only laser system with proven compression capability is Nd:glass. Furthermore the components needed to obtain, say, 500 joules in 300 picoseconds in two beams are available commercially. It is therefore reasonable to assume that such a laser could be installed and operating in well under two years.

In addition to the large Nd:glass system referred to in the previous paragraph it is proposed that a smaller single beam system capable of delivering about 10 joules in 100 picoseconds should be provided. This will relieve the load on the bigger laser and will provide a vehicle for testing components, plasma diagnostic techniques and development generally.

Notwithstanding the above it will be clear from the introductory description of possible laser systems that Nd:glass is unlikely to prove wholly satisfactory in the long term. Higher efficiency lasers, possibly at different wavelengths, will be required in the future. It will therefore be necessary to develop other laser systems. Reference has already been made to the inherent advantages of gas laser systems. Many of these (CO_2 and HF are examples) can be excited and/or initiated by energetic electron beams. Research in this area therefore seems essential but a final choice of system can be delayed since the effort available to the centre must initially be fully committed to commissioning the proposed Nd:glass laser.

In view of the immediate importance of Nd:glass, a more detailed description of a possible design follows. We return to the subject of new lasers in Section 8.

The neodymium: glass laser design

The neodymium glass laser is at present the most suitable for compression studies. The wavelength of 1.06 microns is short enough that the problems of heat transfer afflicting the longer wavelength CO_2 laser, as discussed above, are not serious at the 10^{14} - 10^{15} watt cm^{-2} flux density levels required in compression experiments. Since the laser will be operating in the small signal gain region with little pulse distortion, shaping can be obtained by pulse stacking at the input stage. Furthermore the laser bandwidth allows simple generation and amplification of the typically 20 picosecond duration pulses required for pulse stacking. There is now a good understanding of short pulse propagation in neodymium glass lasers resulting from extensive experimental and theoretical studies. The intensity dependent, non-linear refractive index, results in the amplification of spatial intensity fluctuations in the beam, with an exponent of the amplification factor proportional to $\int_0^{\ell} n_2 \, I dl$ where I is the beam intensity and l is the path length in glass. By analogy with current round a loop, this factor is colloquially referred to as the "B integral".

There is thus a maximum nonlinear amplification of the fluctuations beyond which the beam becomes strongly divergent due to the large amplitude of the intensity fluctuations. Thus a laser system must be designed with a constraint on the value of "B integral". It follows from the theory of the process that the maximum power density obtainable in a beam of acceptable divergence is proportional to the laser gain coefficient obtained in the glass.

Laser rod amplifiers have a gain coefficient decreasing linearly with diameter, for the same pumping energy density. It is thus advantageous to use face pumped disc amplifiers for diameters exceeding that at which rods become relatively inefficient. With due regard to the constraints on the non-linear integral value, it is still possible to construct a laser on a modular and extendible basis. However, optimisation implies that on adding amplifiers, the intensity level from the previous final stage be reduced, with the maximum intensity and hence the maximum value of the non-linear integral, being shifted to the new final stage of larger diameter. The nett result is an increase in beam power but a reduction of beam intensity, since power increases are not simply proportional to beam area.

The configuration of a possible laser system is then as shown in Fig.(1). This consists of an oscillator, a pulse shaper, and an amplifier chain up to a branching point. Amplification beyond the branching point of the 'n' beams, up to the level obtainable in a single beam can be achieved with available disc laser technology. While glass rod laser technology is now well understood there are still some uncertainties about the level of population inversion and the maximum practical diameter obtainable in disc arrays. However, it is clear that powers of 0.2 to 0.3 terawatt are available from amplifiers of 9 cm diameter while discs are able to extend these power levels to the region of one terawatt.

In the present situation it is logical to construct a laser in stages. A single beam system is required for interaction and general physics studies while an initially 2 beam, and subsequently multi-beam, laser is needed for compression studies. With modular construction these systems may be operated at any point and later extended. Thus the laser installation should be designed on the principle of growth, in relation to technological feasibility (disc development) and the experimental requirements.

For compression studies the work at KMS has shown the need for at least 2 beams with a minimum total power of 0.1 terawatt delivered to the target (50J 500 ps). To produce compression ratios of 100 to 1000 will require 1 to 2 terawatts. according to calculations at Los Alamos, and 10 terawatts would be needed for the laser fusion requirement of 10^3 - 10^4 compression.

8. LASER AND OPTICS DEVELOPMENT

The proposed laser laboratory would play an important role in stimulating laser technology in the UK. Already substantial advances have been made in this country in the past decade. These include the development of high quality laser oscillators, operating in the visible or near infra-red regions; tunable frequency dye lasers and spin-flip Raman lasers; and high-resolution interferometers. Perhaps the most significant contributions have been in the fields of picosecond pulse generation and measurement and in CO_2 laser technology. Electro-optical streak cameras with picosecond time resolution, and photon-drag detectors for CO_2 laser radiation, invented here, are now internationally used. Double-discharge, electron-beam initiated, and photoioniser CO_2 lasers have been constructed for high energy amplification and for the generation of sub-nanosecond pulses. More recently highly efficient, coaxial electron-beam pumped, tunable VUV noble gas lasers have been developed. Some of these developments have been carried through to the stage of small-scale production by manufacturers.

On the other hand there are areas where the UK lags behind, in which developments will only be stimulated by assembling high-powered lasers as now proposed. No research or development is being conducted at present into the important systems required for the largest laser beam diameters ie face pumped disc amplifiers. Large system electro-optical control is the key to successful large lasers. The technological requirements are large diameter electro-optical shutters using Faraday rotation and large diameter Pockels cells. Large diameter optics for high power beams, such as aspherical focussing lenses, low aberration mirror systems, and high power resistant beam splitters and polarizers for multi-channel lasers, represents another area where the UK lags behind. There is also a need for the development of large aperture optical components and of electro-optical material for switching and isolation in the infra-red and a more detailed study of damage mechanisms. Fortunately the UK is well endowed with general optical expertise, and has played a leading role internationally in the design of large optical systems including astronomical telescopes and spectroscopes, and bubble chamber optics.

It is clearly not possible for the UK to lead, or even keep up with the leaders, in all aspects of laser technology. We should, however, attempt to lead in some selected areas.

New Laser Systems

At the present time the most likely candidates for new high-power lasers are the electron-beam pumped HF chemical laser and the noble gas quasi-molecular systems. Peak powers of $\sim$ 500MW (10J, 20nsecs) have been obtained in the VUV by relativistic electron beam pumping of pure Xenon and Xe-Ar and Xe-Ne gas mixtures. With such bound-free laser systems an energy storage efficiency of 10% has already been achieved, with higher efficiencies possible, but at the shorter wavelengths there is severe two-photon absorption in all optical materials at power levels of 10^{11}-10^{12} W cm^{-2}. However the energy stored in noble gas quasi-molecules may be transferred to other molecular systems by charge transfer (N_2^+ laser at 427nm), or by excitation transfer (Xe-O_2 laser at 550nm; Ar-N_2 laser at 357nm) to produce laser action at longer wavelengths. Quasi-molecular lasers have the added attraction of being capable of efficient frequency tuning, as has been achieved with dye-lasers. The highly efficient coaxial diode systems are particularly suitable for both frequency tuning and scaling up for amplification.

Frequency Conversion

Research should also be carried out, using the high power laser facility, on frequency up-conversion using metal vapours rather than non-linear crystals as the use of gases should minimise damage problems and still be capable of efficiently generating higher frequencies. Based on numbers so far achieved by Harris (Stanford University) it would seem possible to generate 3300Å radiation with about 50% efficiency in heat pipes of 100 square centimetres cross-section. Further processes in other combinations of gases can lead to efficient generation into the vacuum UV and soft X-ray regions. Alternatively, the power and energy available at 3300Å could be used to efficiently pump large volume dye lasers and in particular to study vapour phase dye lasers. Since the pulse durations are considerably less than the lifetimes of the transitions in these dyes, very high conversion efficiencies of the order of 20% may be expected. By this route one could generate tunable radiation throughout the visible at power levels between one and ten per cent of the initiating Nd laser output power.

With typical damage threshold of solids of the order of 10^9 watts cm^{-2} for short pulses a 100 gigawatt CO_2 laser could be used with areas of about 100 square centimetres. It would then be possible to construct a large volume tunable infra-red spin-flip Raman laser. For powers up to 20 kilowatts it has already been shown that the power generated increases linearly with the cross-sectional area. Crystals of

InSb can be readily grown to 10 centimetres diameter in adequate purity and it is therefore possible to predict, with conversion efficiencies even as low as a few per cent, output powers of the order of gigawatts. This will provide very high power tunable infra-red radiation which could, through mixing, extend throughout the entire infra-red spectrum.

Apart from the obvious applications in the further study of laser-matter interactions the new high power light sources obtained by frequency shifting the Nd:glass and CO_2 lasers would be directly relevant to techniques in photochemistry.

9. FURTHER SCIENTIFIC ASPECTS

The creation in the laboratory of high density, high temperature matter, and the availability of high power lasers, will inevitably influence other branches of science. It is perhaps too early to attempt to predict what will be the most significant areas of interaction but already some possibilities can be listed.

(i) Nuclear interactions

In a nuclear fission reaction the neutron free path prior to multiplication is inversely proportional to the density of the nuclei. An increase in the nuclear density by laser compression can therefore, increase the effective utilisation of the fission neutrons and decrease both the critical dimension and the critical mass. Pulsed microcritical masses might be used to obtain neutron and neutrino fluxes of high intensity. It may also be possible to create transuranic elements by compression.

(ii) High Magnetic Fields

Flux compression is a well-known way of producing very high intensity magnetic fields from an initial low coil-produced flux density, and explosive compression has been considered and investigated experimentally. Laser super-compression carries such possibilities a stage further.

(iii) Quantum Electrodynamics

Intense radiation fluxes of about 10^{17} W cm^{-2} open the possibility of performing a number of interesting quantum electrodynamical experiments. Experiments, which have been suggested, include a test of the electron mass shift, stimulated Compton scattering, electron-photon bremsstrahlung production and γ-ray production by electron or neutron beam scattering. Pair production involving intensities of about 10^{30} W cm^{-2} is unlikely to be feasible.

(iv) Magneto-Optics

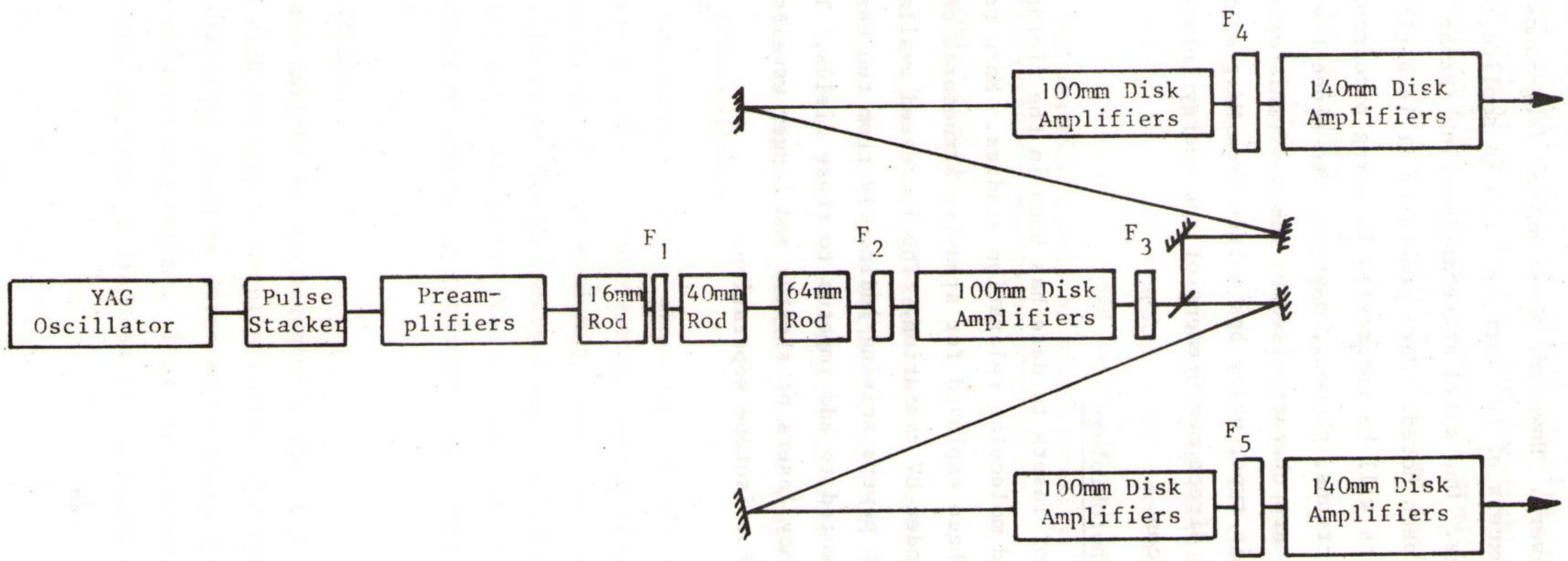
A separate subject is the magneto-optics of a compressed plasma. This could yield a rich variety of novel effects. For example, the presence of relativistic electrons could be detected by Raman spectra which are forbidden in the non-relativistic regime. Thus one can both study new magneto-optic effects and use them to diagnose the presence of relativistic electrons.

(v) Solid State Physics

The application of lasers to the study of solids is obviously limited to relatively low powers. However, short pulses (sub-nanosecond) with power densities in excess of 10^9 watt cm^{-2} can be applied to many solids without damage. One solid state application (Raman spin-flip lasers) has already been noted. More generally it is anticipated that solid state physicists will be interested in using picosecond duration pulses to excite electrons, phonons, magnons, etc since their various scattering processes are characterised by times of this order. At least one experiment of this type, using 5ps pulses from Nd:glass, has already been done permitting direct measurement of the energy relaxation time of electrons in silicon.

(vi) Photochemistry and Photobiology

The greatest impact of lasers to date has been in the fields of nanosecond and picosecond molecular relaxation studies. More recently tunable lasers have been employed for studying structural changes in carbonyl compounds under UV radiation. The increased availability of short pulses and high powers arising indirectly from the Laser Centre programme can be expected to add impetus to these fields. The development of high efficiency lasers at shorter and longer wavelengths could also be significant for isotope separation.



F_1 - F_5 - FARADAY ROTATOR ISOLATORS

FIGURE 1. LAYOUT OF HIGH POWER LASER

rutherford laboratory
reproduction section