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SUMMARY

In the United Kingdom there is no national inertial confinement programme directed towards civil reactor use. The programme for Controlled Fusion Research, which forms part of the UKAEA Research Group activities, is located at the Culham Laboratory. At this centre, fusion research is devoted entirely to magnetic confinement systems. A fraction of the total effort involves the development and use of powerful lasers for diagnostic purposes, for toroidal plasma refuelling schemes, for basic studies of laser-plasma interactions, highly-ionised atoms and XUV light gain experiments, and for certain commercial applications.

Within the universities there is a widespread interest in laser systems and laser-plasma interactions. The substantial research facilities in the Laser Division of the Rutherford Laboratory (SRC) provides a focus for these activities. These lasers are operated as a university users' facility. A two beam, neodymium in phosphate, glass laser (operating at 0.6 TW/beam, but presently being upgraded) is the Rutherford Laboratory's major laser system for implosion and compression studies. Sophisticated radiation diagnostics are a feature of this work. In a single-beam mode, the glass laser has been used for a great deal of laser-plasma interaction physics

e.g. non-linear absorption, inhibited heat conduction and harmonic self-generation. Atomic structure of highly-ionised atoms, plasma line broadening and XUV light gain experiments are also active research topics. Concurrent with upgrading the glass laser facility to 6 x 1 TW beams, experiments on harmonic conversion of the output to $2\omega_0$, $4\omega_0$ are being pursued. Electron beam-pumped, rare-gas halide, excimer systems operating in the blue region of the spectrum are also being investigated. The universities provide a considerable back-up for the work at the Rutherford Laser Division, firstly through theoretical studies of non-linear processes, line broadening and compression modelling and secondly, through technical expertise in such areas as optics, spectroscopy, quantum electronics and new laser systems.

The reference list titles give an overview of the UK activities in laser-plasma research while Table 1 lists the major supporting laser facilities.

2. LASER-PLASMA RESEARCH AT THE CULHAM LABORATORY

Relevant work at Culham falls under four headings

- (i) refuelling and heating of toroidal plasmas by laser irradiation of solid pellets
- (ii) laser-beam diagnostics
- (iii) basic studies of laser-plasma interactions, highly-charged ions and XUV light gain experiments
- (iv) theory

- 2.(i) Irradiation by the "TROJAN" 2Kj gain-switched CO_2 laser, of solid free-falling D_2 pellets, which contain typically 4×10^{18} atoms, routinely produces a preionised and preheated plasma in the CLEO stellerator. The laser energy absorption is $\sim 65\%$. Under conditions where the irradiation intensity is $\sim 10^{12} \text{ W cm}^{-2}$ and where the pellet burn-through is incomplete, ablative acceleration, $\sim 10^{12} \text{ cm sec}^{-2}$, leads to break-up of the pellet with fragment velocities reaching $\sim 10^6 \text{ cm sec}^{-1}$. The possibility of using ablative acceleration for refuelling toroidal systems is therefore being examined. A wide range of single transverse-mode driving oscillator pulse-shapes including single axial mode 1-300ns pulses as well as longer, 1-100 μs , pulses are available for the

work.

2. (ii) Existing CO₂ lasers operating at 10 to 100 GW are being considered for collective light scattering measurements in dilute toroidal plasmas. These 10 μ m laser sources are also used at the Culham Laboratory as optical pumps for multi-MW, single mode FIR injection lasing in gases, typically D₂O ($\lambda_0 \sim 380\mu\text{m}$) CH₃F (496 μ m) etc. Such FIR laser parameters have potentially useful light scattering applications in magnetically-confined plasmas and may be used also to study basic non-linear absorption in controlled low density plasma interaction experiments.

In collaboration with staff at Essex University and at the Rutherford Laboratory, recent measurements in Ge of the photon drag response to intense FIR irradiation has resolved the long standing problem of the proper expression for the momentum of radiation in a refractive medium.

2. (iii) The single beam 0.1 TW, silicate glass laser continues to be used for atomic structure studies of highly-ionised atoms. Recent investigations have included $\Delta n = 0$ ($80\text{\AA} < \lambda < 200\text{\AA}$) and $\Delta n > 0$ ($\lambda < 10\text{\AA}$) transitions in metallic ions iso-electronic with neon-shell elements. Other basic studies being pursued include Lamb shifts in 2 electron systems, pressure broadening by plasma microfields and pressure narrowing (by Doppler cancellation when $\lambda_0 > \lambda_{\text{coll}}$). Optical coupling of energy-matching transitions in laser-produced plasma has failed to produce enhanced population inversion in the $n=3, 4/n=2$ levels in He-like ions despite the use of side-by-side, line focus optics for the source and target plasmas. These preliminary schemes for demonstrating XUV light gain by stimulated emission will continue.

2. (iv) Numerical modelling of laser-irradiated targets has been continued with the publication of the CASTOR-2 code. CASTOR-2 gives a two dimensional, three temperature MHD description of laser-irradiated targets and is intended as a frame-work for calculating physical quantities such as reflected light, particle temperature, magnetic fields, ion diffusion etc which are of

interest in laboratory experiments. The inclusion of time-dependent atomic rate processes and radiation transport makes the code particularly useful for comparison with observations of the emitted radiation spectrum.

Both the CASTOR-2 code and the 1-D MEDUSA code, now in widespread use for calculations of compression and projected thermonuclear burn, are available from the CPC International Physics Program Library, Queens University, Belfast.

- 2.(v) The CO₂ laser heating, diagnostic, and re-fuelling programme is undertaken within a larger group, ~ 40 staff, involved in various aspects of UKAEA and industrial applications of lasers. Other laser diagnostics, laser-plasma interaction physics and theory is supported by about 8 staff, with at least the same number of temporary attached staff from the UK universities.

3. CENTRAL LASER FACILITY (SRC - the Rutherford Laboratory) -
UK UNIVERSITIES

3.(i) The Laser Division of the Rutherford Laboratory, operated by the Science Research Council, provides laser facilities for the university community. The immediate physics programme of the division is decided by a large, variegated committee of laser division staff and interested, mainly university, scientists. According to their interests the scientists belong to one or more of several groups, e.g. laser-plasma interaction physics, transport and particle emission, atomic and radiation physics, ablative compression, XUV lasers, theory and computational modelling, facility development etc. The overall programme and long term objectives of the central laser facility is subject to approval by a Laser Facility Committee, composed mainly of senior university scientists, who in turn are responsible to the Science Board of the SRC for scientific investigations involving powerful lasers.

3.(ii) Scale of Operations

The annual operational budget of the central laser facility (including salaries) $\approx \text{£}1 \times 10^6$ /annum

Capital spend $\approx$ £0.5 - 1.0 x 10⁶ /annum

Direct Staff $\approx$ 45

Total Staff (including attachments from other divisions)
 $\approx$ 50

University and other participants: members of the
scientific programme and scheduling committee
 $\approx$ 100

3.(iii) Facilities

The main laser system is a 2-beam phosphate glass laser
with 10.8 cm diameter final disc amplifiers

Max. output power = 1 TW/beam

Pulse duration = 20 ps to 2 ns

Max. output energy = 10J to 200J/Beam (corresponding to above
pulse durations)

6-beam irradiation of targets has recently been accomplished
by passively splitting the 2-beam output energy. Active amplification of the six beams to 1TW/beam, using double passes through additional disc amplifiers, is planned before October 1980.

With a view to even longer term requirements for new powerful lasers, electron beam-pumped eximer systems are being studied. The electron beam generator ELF used for these studies has output characteristics of 1.5 MV and 60 KA with a pulse duration of 50 ns. The anticipated output from a single beam-pumped eximer laser is of the order of 200J/Beam. Pulse stacking of separately amplified, sequentially injected pulses is a favoured route for reducing the final output pulse to approx. 1 ns. Two target-interaction areas are provided. In one of these implosion and compression physics are studied using multiple laser beam irradiation of isolated targets. In the second experimental area which is devoted to non-symmetrical irradiation experiments, multiple beams, often required for diagnostic developments, can be effected by subdivision of the main beam. In this area, laser absorption, harmonic self-generation, heat flux inhibition, atomic term structure, XUV light gain experiments and wavelength scaling of ablative pressure are studied.

3.(iv) Physics and Technical Progress

The results of the Central Laser Facility's activities are documented in the annual reports published by the Laser Division of the Rutherford Laboratory, see e.g. RL-79-036 (1979). In this section we summarise and update some of the more noteworthy developments.

3.(iv)a Compression:

Material Compression experiments carried out prior to 1978 at the Central Laser Facility have involved high intensity $> 10^{15}$ Watts/cm² illumination of microspheres. The abrupt energy deposition from supra-thermal electrons in the outer shell in these 'explosive-pusher' experiments caused shock heating of the core plasma to high temperatures $T_e \sim 10^7$ K, and relatively low compressions, with density $n_e \leq 10^{23}$ cm⁻³ i.e. $\rho \sim 0.3$ gm cm⁻³. Since 1978 attempts have been made to reach higher densities by ablatively-driven (rocket-like), implosion. In this implosion mode the shell thickness is increased beyond the energy deposition length for the electrons. The supra-thermal electron temperature $[T_H \propto (\phi_0 \lambda^2)^\delta (W \mu m^2 / cm^2)]$ with $\delta = 0.2$ to 0.6] is reduced by decreasing the flux intensity $\phi < 10^{14}$ W/cm⁻². The wall composition is typically $\sim 1 \mu m$ of glass overcoated with $\sim 5 \mu m$ of polymer. The pulse duration is increased to a value ≥ 1 ns so as to match the longer ablation period. Core densities ~ 10 gm cm⁻³ and $\rho r \sim 2 \times 10^{-2}$ gm cm⁻² have been approached in these ablatively-driven implosions with $T_e \sim 0.5$ keV. X-ray back-lighting experiments suggest that there is some mixing of the separate wall layers early in the implosion due to Rayleigh Taylor instabilities and this may be a limiting factor to the overall compression.

3.(iv)b Diagnostics:

The development of radiation diagnostic techniques is a feature of the laser-plasma interaction studies at the Central Laser Facility. For example, the relatively cool but dense plasma produced by ablatively-driven compression has been shadowgraphed using subsidiary laser-produced x-ray sources. Time-resolved shadowgrams are quantitatively interpreted and yield information on instability-mixing in the outer shells, implosion velocities and the compressed core characteristics. Also, space-and time-

resolved XUV emission line profiles are interpreted in terms of intrinsic (plasma-induced) line broadening and radiation transfer. Improved plasma microfield calculations include ion dynamics, fine structure splitting, Debye screening and particle correlations. These line broadening calculations are incorporated with radiation transfer codes describing photon transport in inhomogeneous plasmas, the codes being used to derive values of the core parameters $\rho \text{ cm}^{-3}$ and $\langle \rho r \rangle \text{ cm}^{-2}$.

Technical developments in time-resolution of x-ray images and increasing the quantum efficiency of image intensifiers (using low density CsI coatings) have proved useful. Highly resolved line spectra features and wide-band x-ray emission are time-resolved in the streak mode. Multiple framing-mode cameras are being developed.

Faraday rotation and phase -change measurements using visible laser beam probes are used routinely for spatial magnetic field mapping and for density profiles

3.(iv)c Fast Electron Transport:

The energy transported by supra-thermal electrons has been measured by quantitative analysis of the K_{α} fluorescence in diagnostic fluor layers inserted into multi-layer plane targets. In high intensity irradiation experiments $\Phi > 10^{15} \text{ W cm}^{-2}$ the heat transport rate of fast electrons can be $\sim 10\%$ of the incident photon flux. Classically, the fast electron range is constant in terms of $\langle \rho r \rangle$. Recent laser-irradiation experiments using Au absorber layers have demonstrated that the $\langle \rho r \rangle$ range can be reduced in low-density, spongy Au by resistive inhibition of the 'cold electron return-current resulting from its effectively longer path length in the low-density material.

3.iv(d) Wavelength scaling of ablation pressure:

Comparisons of ablative pressure at the fundamental frequency and at the second (and planned fourth) harmonics of the Nd glass laser are underway. Preliminary results indicate that green beam irradiation has the desirable consequences of higher ablative pressure and reduced supra-thermal electron energy. Pressure ~ 50 megabars with $T_H \leq 2 \text{ keV}$ are typical of

the ablative plasma produced by $4 \times 10^{14} \text{ W cm}^{-2}$ of green beam intensity.

3.(iv)e 6-beam experiments:

Symmetrical irradiation of microspheres has been demonstrated using 6-beam illumination. In these initial experiments each of the two output beams from the 10.8 cm diameter amplifiers is split three ways. Within the next year intensity amplification of the 6 beams to the 1 TW/beam level will be completed. Results from the experiments on wavelength scaling (above) will determine the priority in converting the total system to green beam illumination.

3.(iv)f Theory:

The main code used for predicting hydrodynamic phenomena in compression experiments is the 1-D MEDUSA code. Modifications to the published version include atomic physics, fast electron pre-heat and radiation. The CASTOR-2, 2-D code is now also being used to predict physical quantities such as magnetic fields and heat and particle transport in plane-target irradiation experiments. Particle codes are most useful for simulating non-linear interactions. $1\frac{1}{2}$ -D PIC codes are routinely used for simulating resonance absorption, harmonic generation, Brillouin scattering etc. A $2\frac{1}{2}$ -D version of these PIC codes is being developed. Analytical theory has been applied to the study of parametric instabilities, resonance absorption and the effect on absorption of rippled surfaces.

3.(iv)g Heavy-Ion Fusion:

Interest in heavy-ion beam fusion among particle physicists has triggered a number of small scale numerical studies in an attempt to define areas of physics e.g. α -particle heating, recoil electron spectra which have a bearing on target design. No experimental work is funded for heavy-ion beam fusion.

SUMMARY OF UK LASER FACILITIES - TABLE 1

LASER	TOTAL ENERGY (J)	No. BEAMS	PULSE DURATION (ns)	PEAK POWER (TW)	TRANSVERSE MODE	REF.
Nd:Glass	1-30	1	10ps/10ns	0.1	Single	Queens' Univ. Belfast
1.06 μ m (Silicate)	10	1	0.1	0.1	Single	Hull Univ.
	160	1	3.5	0.05	"	Culham Lab.
	(200 to 4)	1	(4 to 0.04)	(0.05 to 0.1)	"	Culham Lab.
1.054 μ m (Phosphate)	200J (Max)/Beam	2	2 to 0.02	1TW (Max)/Beam	"	Rutherford Lab. SRC
	(200J (Max)/Beam)	6 Optics tested with 6 Beams	2 to 0.02	(1TW (Max)/Beam)	"	Rutherford Lab. SRC, (Oct. '80)
0.53 μ m (Green)	30 to 10	1	1 to 0.1	0.03 to 0.1	"	Rutherford Lab. SRC
	(50 to 100J/Beam)	6	1 to 0.1	(0.5TW (Max)/Beam)	"	Rutherford Lab. SRC (data depends on outcome of green beam ablation pressure studies)
XeCl	(200J/Beam)	1	(40 reducing to 1) (using pulse stacking)	(1TW/Beam)	"	Rutherford Lab. (future development)
KrF	using 1.4 MV 60 KA electron beam pulse 50 ns duration	"	"	"	"	"
CO ₂	> 2500	1	2000	0.03	"	Culham Lab.
	(5000)	1	2000	(0.06	"	Culham Lab.
	(170-350)	1	1	(0.17 - 0.35)	"	Culham Lab.
Xe ₂ (0.172 μ m)	0.05	1	1	5 x 10 ⁻⁶	Multiple	Imperial College
KrF (0.249 μ m)	2.0	1	20	10 ⁻⁴	"	Imperial College

NB (Projected performance is indicated in parenthesis)

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