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**LASER-FUSION PROGRAM
SEMIANNUAL REPORT — JANUARY-JUNE 1972**

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Foreword

This is the second semiannual progress report on the laser-fusion program at Lawrence Livermore Laboratory. With it we adopt the policy of publishing the main semiannual report for each period in unclassified form, and issuing a classified supplement when there are classified topics to be reported on. There will be no classified supplement to the report for this period of January-June 1972.

Some of the articles in this report make reference to company or product names. Such reference does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

Inquiries about the information presented in this report should be addressed to the Director's Office, Lawrence Livermore Laboratory, Livermore, California 94550, attention Scientific Editor, Laser-Fusion Program Semiannual Report.

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INTRODUCTION AND SUMMARY

Introduction

There are two basic tasks in the initial phases of the laser-fusion program: one is to determine the kind of laser output pulse — in terms of energy, duration, wavelength, coherence, and symmetry — that will be required to compress a pellet of thermonuclear fuel to burn conditions; the other is to design and build a laser that will produce this output pulse.

Hot electrons play a key role in compression of the pellet. The laser-plasma interaction heats the electrons, and energy is transported from the plasma to the more dense pellet region by these electrons. Heating of the pellet surface generates the implosion pressures. In order to reach very high compressions, shaping of the laser pulse (or multiple pulses) will be required with the final power level rising by several orders of magnitude from the initial power level.

Four milestones can be set down to measure our progress:

1. Demonstrate laser-induced implosion in which the fusion energy produced is greater than 1% of the light energy from the laser, and compressions greater than tenfold are achieved.
2. Proof of principle: Achieve compressions greater than a hundredfold and fusion energy outputs greater than 10% of laser light energy.
3. Light energy break-even: Raise the pellet burn efficiency so that the fusion energy produced is of the same magnitude as the laser light energy.
4. Net energy gain: Raise the system efficiency of the laser-imploded pellet to the point where the fusion energy output substantially exceeds the input energy to the laser.

Our present estimates of the laser technology needed to reach these milestones are given in Table 1.

For the next few years (FY 1973-1975), the Laboratory plans to perform basic laser-matter experiments using moderate-size lasers. Pulse energies will range from tens of joules to approximately a thousand joules; the pulse lengths, from the low nanosecond region to tens of picoseconds. The main purpose will be to provide data for theoretical calculations, so as to develop the capability to predict with more confidence the key laser and target parameters necessary to obtain thermonuclear burn. We hope to attain the first milestone and possibly the second one during this time period. The Laboratory will also work on obtaining sources of laser-produced x rays, which could be used for x-ray simulation experiments.

Glass lasers are now the best understood of the high-energy, short-pulse-duration lasers. Unfortunately they do not now appear to offer the long range potential of the other laser approaches. Their upper limit is probably on the order of 10 kJ. Their pumping efficiency is low (less than 1%), and their basic medium (neodymium-glass) is rather costly.

We expect, however, that our glass laser effort will offer the most reliable path to accomplishing our near-term goals. A good neodymium-glass disk laser (the Long Path Laser) has been constructed, giving an energy output of 200 J in 5 nsec and 100 J in 2 nsec. Under preliminary development is a high-quality neodymium-glass rod system which should achieve 200 J with a pulse duration of about

Table 1. Laser technology requirements to meet the four laser-fusion milestones

Milestone	$E_{\text{fusion}}/E_{\text{light}}$	Laser requirements	
		Energy (J)	Pulse length ^a (psec)
1. Laser-induced implosion	10^{-2}	10^2 - 10^3	20-100
2. Proof of principle	10^{-1}	10^3 - 10^4	100-200
3. Light energy break-even	10^0	10^4 - 10^5	50-200 (with shaping)
4. Net energy gain	$\geq 10^1$	10^5 - 10^6	100-1000 (with shaping) ^b

^aTime to deliver about the last 50% of the laser energy. A prepulse of gradually increasing intensity preceding this may have a duration of tens of nanoseconds.

^bAssuming 5% laser efficiency.

200 psec. Disk amplifiers will be required for the higher energy levels and the shorter pulse durations. Our goal with glass systems is to have approximately 10^4 J with 100-200 psec pulse duration within FY 1976. We are also investigating other solid-state lasing media such as ruby and Nd:YAG (yttrium-aluminum-garnet). Nd:YAG oscillators are being used to provide bandwidth-limited pulse durations from 0.25 to 2.5 nsec.

Gas lasers appear to offer more potential in terms of higher efficiency, lower cost, and higher pulse-repetition rate. It appears that an appropriately configured CO_2 laser system may be capable of providing sufficiently energetic pulses (10^5 - 10^6 J) of the required short duration (nanosecond at most) with only a modest sacrifice in efficiency. At present we have single-pulse oscillators and various preamplifiers and amplifiers. Using these components we should have a 100-J, 1-nsec CO_2 laser system in FY 1973, and a megajoule, subnanosecond laser by the end of FY 1975.

Energy decoupling and preheat effects, during target implosion have been found which may make it less

desirable to use laser radiation of as long wavelength as that produced by the CO_2 laser (10.6 μm). However, as both problems may be alleviated to a certain extent by using shorter wavelength radiation, an effort is being made to see if other electric-discharge-pumped gas laser systems can be found which share the advantages of the CO_2 system but radiate light at much shorter wavelengths. We have for example observed stimulated emission (1716 Å) in xenon at pressures greater than 200 psi.

Pulsed chemical lasers appear to offer the greatest potential for weapons applications ultimately, because they may have the ability to store large amounts of energy in a reasonable volume and weight. We are still in the very early research stage with this concept, however, and plan only a modest level of effort in the near future.

For all of these systems, diagnostics capability is of paramount importance — especially for the detection of laser light pulses of subnanosecond duration. We have a program addressing this technology, with particular emphasis on streak cameras having a resolution of 10 psec or less.

Summary

SOLID STATE LASERS

- Modifications to our bandwidth-limited Nd:YAG oscillator have improved the output energy per pulse to 1-2 mJ, with bandwidth-limited pulse durations ranging from about 0.25 to 2.5 nsec. This oscillator is electronically Q-switched. We have also continued our investigation of passively Q-switched Nd:YAG oscillators, using bandwidth-limiting etalons in the cavity to obtain reproducible 250-psec, 2-mJ single pulses. A comparison of the temporal characteristics (made with our high-speed streak camera) of three different nanosecond oscillators without special bandwidth controls shows that only the rotating-prism-Q-switched oscillator produces smooth pulses.

- Experimental and calculational studies of the properties of Nd-doped glass and YAG amplifiers (rod and disk) to be used in the Intermediate Laser System have continued. The ILS will consist of a subnanosecond oscillator of variable pulse length, a rod amplifier chain, and a glass disk amplifier with an initial design goal of 400 J in 1 nsec and 200 J in 700 psec.

- Electronics reliability problems involved in large multipath laser arrays such as the ILS are under continuing study.

- A technique for measuring preexisting stress in flashlamps has recently been demonstrated by the University of Colorado (under an LLL contract) to be useful in culling out flasilamps having a high risk of early failure.

- High-durability optical isolators of 16-, 25-, and 50-mm aperture are being designed and built for use in various high-gain laser chains.

- Electrooptical Pockels cells have been developed at LLL with a ring electrode geometry which is optimum for uniformity of transmission across the cell aperture as well as for obtaining fast (i.e., subnanosecond) switching capability.

- A reliable, TEM_{00} , single-frequency ruby laser system has been developed which produces single-frequency Gaussian shaped pulses 6 to 12 nsec FWHM that are reproducible to within 15% for better than 500 pulses.

GAS LASERS (CO_2)

- A single-pulse oscillator and double-discharge preamplifiers have been tested for eventual use in a high-power CO_2 system. Single 1/2-mJ, 1-nsec pulses have been switched out of a mode-locked CO_2 TEA oscillator with pulse extinction ratios of 900:1.

- Small-signal gain measurements of a 1-meter longitudinal double-discharge TEA laser show a peak gain of approximately 2-2.5%/cm. Holographic techniques show wavefront distortions on two separate double-discharge systems to be no worse than $\lambda/30$ on one and $\lambda/40$ on the other at CO_2 wavelengths.

- In order to provide a basis for understanding and calculating double-discharge behavior, an equivalent circuit model has been formulated.

- A 1-m-long by 20-cm-wide CO_2 laser initiated by a hot-cathode electron gun has been designed, built, and placed in operation at LLL.

- Three different prototype electron guns have been designed and are being built: (1) A highly convergent Pierce-diode gun with a curved dispenser cathode. (2) A planar diode with a flat dispenser cathode and a transparent mesh extractor anode. (3) A tetrode gun with thoriated tungsten wire cathode.

- A potential bleachable isolator system (necessary for use between amplifier stages) with SF_6 as the saturable absorber and $\text{CCl}_2 = \text{CF}_2$ and CF_2Cl_2 as sideband absorbers was tested. The bleached transmission of the system was too low because of the high pressures of the nonbleaching sideband absorbers, and therefore new systems will have to be tested.

GAS LASERS (OTHER)

- The spontaneous vacuum-ultraviolet emission spectra of rare gases (argon, krypton, and xenon) excited by pulses of high energy electrons have been studied in an effort to understand the processes that give rise to this radiation. The rare gases form two-atom excited states whose populations in high-density rare gases can be high enough to cause emission of coherent light.

- Stimulated emission has been observed in xenon at pressures greater than 200 psi. The radiation was centered at 1716 Å with a 17-Å bandwidth.

CHEMICAL LASERS

- A three-level model and other theoretical techniques have been further refined. In particular, a rigorous matrix-expansion procedure has been devised to calculate chemically generated population inversions for an arbitrary number of simultaneous lasing transitions.

- Chemical modeling has been used to study the effect of chain branching rates on laser energy output and to develop an approximate analytic model which correlates reasonably well with LLL experiments.

- Experiments have concentrated on (1) operating HF chemical lasers based on more energetic and

reactive compounds, (2) using CO_2 lasers, electron beams, double discharges, and adiabatic compression for initiating reactions in reactive gases, and (3) using probe lasers and other techniques for studying the chemical reactions per se in these mixtures. More reactive systems have produced overall laser efficiencies higher by more than an order of magnitude than efficiencies previously measured at LLL.

NONLINEAR OPTICS

- Experiments on the Short Path Laser have demonstrated that the self-focusing in high-peak-power lasers is governed mainly by incidental and often unavoidable diffraction effects or transverse mode perturbations. This results in bulk rod damage at powers substantially below the levels which would be permissible if only large-scale self-focusing of the entire beam were involved. These experimental observations have been quantitatively corroborated by computer calculations.

- A large amount of accumulated experimental data indicates that a nonlinear refractive index plays an important role in the amplification of short pulses from ruby lasers. In particular, ~20-psec pulses generated in the ruby oscillator can develop temporal structure of ~5-10 psec while being amplified, and bandwidths as large as 14 cm^{-1} have been observed at the output of a 9-in.-long amplifier whose input pulse bandwidths were $\leq 7 \text{ cm}^{-1}$. Those experimental results have been correlated to numerical calculations.

- The analytical work on self-focusing in amplifying media has been extended to approximately include gain saturation due to upper level depletion.

LASER-PRODUCED PLASMAS

- Investigations of laser-produced plasmas have continued, using the Long Path Laser system to provide nanosecond pulses and the Plasma X laser for the subnanosecond regime. An extended study of the soft x-ray yield from laser-produced plasmas, carried out with the Plasma X laser, indicates that up to 0.1% of the incident laser pulse energy is converted to x rays above 1-2 keV. Computational results predict much higher x-ray yields, and investigations are under way to resolve the discrepancy.

- Ultrafast streak spectra of the Long Path Laser pulse have been obtained using the 10-psec-resolution streak camera in conjunction with a spectrometer. This technique reveals complex modulation and spectral features of the pulse that may affect the character of the laser-plasma interaction. A limited number of x-ray yield measurements have been made on plasmas

produced with the Long Path Laser. The results suggest conversion efficiencies that are slightly lower than those obtained with the shorter-pulse Plasma X laser. Neutron emission (using a time-of-flight method to separate neutrons from x rays) and the spectral character of the laser light reflected from the plasma have been measured.

- Empirical rules have been obtained from plasma simulations for the electron distribution functions produced by instability heating, and are used as an electron source term for LASNEX. For the simplest model of a laser pulse the heating is mostly into energetic electrons. This can result in serious preheat or decoupling problems. To reduce these problems, we have investigated amplitude and frequency modulation of the laser and the effects of magnetic fields and finite laser focal-spot dimensions in reducing the mean energy of the heated electrons. Work is continuing to find the optimum laser characteristics for plasma heating. The instability heating has been found to be diffusive in nature, and agrees semiquantitatively with turbulence theory calculations.

DIAGNOSTICS

- The 10-psec-resolution streak camera has been in use for the diagnostics of several lasers at LLL. We have continued the study of computer-generated electron beam trajectories and other developmental work on this camera, with the aim of eventually obtaining time resolutions approaching 1 psec.

- Several volume absorption and surface absorption calorimeters have been developed and tested for use with high-power 10.6- μm CO_2 lasers.

- Image converter tubes are being used to monitor the energy density distribution of mode-locked 1.06- μm laser beams.

- A technique using saturable absorbers has been demonstrated which gives estimates of the pulse peak intensity and the fraction of beam energy that is carried by short-duration pulses.

LASER FUSION

- In the laser-fusion microexplosion approach to CTR, fuel confinement is inertial. It appears that Lawson numbers greater than 10^{16} may be achieved by laser-energized subsonic ablative implosion of milligram-size spherical DT pellets to densities about 10^4 times liquid density. The corresponding inertial confinement times are approximately 20 psec. Thus the laser energy required for CTR applications is reduced to about 10^3 - 10^6 J, assuming laser pumping

and thermal-to-electric efficiencies of 10% and 40% respectively. The important considerations in this approach are discussed here: pressure, entropy, symmetry, stability, laser-plasma coupling, inertia, and thermonuclear self-heating.

- Recent x-ray measurements from laser-produced plasmas have suggested that the plasma electrons may be far from thermal equilibrium. In order to calculate these experiments and to further study the effects of suprathermal electrons on laser target designs, we have incorporated multigroup treatments of both electrons and photons into the LASNEX code. The techniques used to calculate these nonequilibrium aspects of laser-produced plasmas are outlined, and the single-group alpha particle scheme used in the LASNEX code is presented.

- Long-wavelength lasers are less effective than short-wavelength lasers for compression of fusion pellets because of electron decoupling and preheat effects. Computer calculations with recently developed versions of the LASNEX code show that decoupling can be largely compensated for by use of hollow pellets. However, these calculations also show that — irrespective of laser wavelength — fusion pellets may be disastrously preheated by high energy electrons if the laser light is absorbed by means of plasma instabilities. In order to avoid preheat, plasma-instability-free pellet designs have been developed. The threshold for excitation of instabilities is raised, and the absorption of laser light by inverse bremsstrahlung sufficiently enhanced, by seeding the pellet with high-Z material (e.g., 0.1 at.%) and by use of short-wavelength lasers ($\lambda \lesssim 1 \mu\text{m}$).

- Three major technical aspects of using laser fusion in CTR power production are being investigated: (1) laser pulse generation and target (pellet) irradiation, (2) design and operation of the fusion-fuel combustion chamber, and (3) conversion of the fusion microexplosion energy into electricity. These areas are discussed here, including a design concept for the combustion chamber. In addition, basic economic constraints and potentialities for laser-fusion CTR plants are being considered. Near-term possibilities are suggested for hybrid fusion-fission power systems and for substantial synthesis of high transuranic elements and antimatter.

ENVIRONMENTAL STUDIES

- A laser dilatometer has been developed for making absolute measurements of thermal expansion of materials with very low coefficients of expansion such as are used in laser oscillators.

- An experimental laboratory has been set up to study quantitatively the consequences of environmental

effects (e.g., vibration and thermal gradients) on laser performance.

MANPOWER AND FACILITIES

• During the second half of fiscal year 1972 the Laser-Fusion Program grew from a December level of 167 direct heads to a June endpoint of approximately 215, resulting in a total for the year of 172 man-years. Of this total, approximately 25% were scientific personnel. The remaining 75% were engineers, technicians, and various other support personnel. The planned laser-fusion effort

for FY '73 is 248 heads, to be reached by October 1972.

• Total operating costs for FY '72 were \$9.5M. In FY '73 the operating cost plan is expected to be approximately \$13M.

• Capital equipment expenditures for FY '72 totaled \$975K. In FY '73 a minimum of \$1.3M will be required.

• Approximately \$800K of GPP funds were committed in FY '72 to upgrade existing facilities. In FY '73 GPP funds (\$300K) will be used to upgrade the chemical laser area. Plans for the \$6.8M laser R&D facility are well under way with funding approval expected by November 1972. Occupancy would not occur before June 1974.

LASER RESEARCH AND DEVELOPMENT

Solid State Lasers

INCREASED OUTPUT ENERGY FOR BANDWIDTH-LIMITED NANOSECOND OSCILLATOR

Our previous report¹ described in detail a self-driven Nd:YAG laser oscillator system which directly produces *Q*-switched, bandwidth-limited pulses at 1.06 μm with durations ranging from 500 psec to 2.5 nsec. By replacing the original *Q*-switch gate with a faster switching, synchronously driven system, the energy/pulse available in the output has been improved by about a factor of 10 (to 1-2 mJ/pulse) while the bandwidth-limited character of the pulses is maintained. The potentially available range of bandwidth-limited pulse durations for the oscillator has been extended to include the region from about 0.25 to 2.5 nsec.

Bandwidth-limited pulses (i.e., pulses for which $\Delta\omega\Delta\tau \approx 1/2$, where $\Delta\omega$ is bandwidth and $\Delta\tau$ is pulse duration), due to their unmodulated character, are desirable for laser fusion research and numerous other laser experiments and applications requiring well-defined input pulses. The "smooth" unmodulated nature of these pulses makes them more suitable for amplification to high energy densities in a consistent and controllable manner. An oscillator capable of delivering pulses of this type, therefore, could serve as the front end of a wide range of 1.06- μm laser amplifier chains, e.g., the Long Path Laser or the Intermediate Laser System. By way of review, the key to the performance of our oscillator system is the separate and independent controls provided within the oscillator cavity for determining the pulse duration and frequency content. The pulse duration is determined initially by a fast, time-symmetrical *Q*-switch gate. The pulse frequency content is then controlled by narrow-band optical elements in order to insure satisfaction of the bandwidth limit for any desired pulse duration.

One element of the system on which we have concentrated our recent efforts is the high voltage switch for the Pockels cell *Q*-switch gate. In order to obtain the fastest possible switching time for the gate, we have replaced the original krytron trigger circuit (risetime ≈ 4 nsec) with an electrically triggered spark gap (risetime $< 1/2$ nsec). The improved switching speed of this device has enabled us to extend the range of available bandwidth-limited pulses to shorter durations, and to confirm bandwidth-limited operation of the oscillator at those durations.

A second element of the system which has received attention is the Pockels cell itself. We have replaced the original KD*P commercial cell with a unit of our own design. The new cell is a cylindrical, z-cut KD*P crystal with ring electrodes attached. These cylindrical, ring-electrode (CRE) cells have desirable properties for high-speed switching application (e.g., low capacitance, impedance-matched geometry) as well as other features which are described in a later section of this report entitled "Electrooptic Components." The CRE Pockels cell, when operated in conjunction with the electrically triggered spark gap, exhibited an estimated 10-90% risetime of $< 1/2$ nsec (scope-detector limit). Since the temporal width of the initially gated noise pulse is approximately equal to one-half the risetime on the switching cell,¹ it is now possible to introduce pulses of < 250 psec into the cavity. Hence the potential capability of the oscillator has been extended to the pulse duration region of 250 psec or less.

Operation of the Nd:YAG oscillator as a self-driven optical resonator¹ forces the gated pulse to build up with the cavity in a relatively low *Q* (lossy) state. While this mode of operation is adequate for many situations, it has a disadvantage in that a substantial portion of the pulse energy is rejected. To eliminate this disadvantage, we devised a method which appreciably increases the available energy in the output pulse while maintaining the other advantages of the self-driven oscillator system.

In our new method, instead of gating the initial pulse with a single sweep of the Pockels cell as in the self-driven case, the Pockels cell sweep, once initiated, is then synchronously gated coincident with the cavity round-trip time for the initial pulse. This "ringing" of the intracavity *Q*-switch has the function of providing a high-*Q* (low-loss) gate for the original pulse on each round-trip pass, while maintaining the cavity in a low-*Q* state otherwise. Hence, the desired pulse is preferentially amplified at the expense of other intracavity optical noise. This technique is similar to standard AM (loss) modulation in some respects but differs in that it also provides the *Q*-switching function and fast-risetime ($< 1/2$ -nsec), square-waveform pulse to the Pockels cell.

Figure 1a is a schematic of the synchronously driven Pockels cell oscillator. The Pockels cell is biased

Fig. 1. Schematic of synchronously driven Nd:YAG oscillator. Multiple sweeps of a Pockels cell, instead of a single sweep, are used to provide preferential amplification for the selected pulse at the expense of other intracavity noise. The sweeps are synchronously gated to coincide with the cavity round-trip time for the pulse.

initially at its quarter-wave retardation value by the high voltage supply through a charging resistor R . At the appropriate time (approximately the time of maximum inversion of the laser medium), a 4-kV trigger pulse is initiated through a delay unit and pulse amplifier to a trigger electrode placed in the cathode of an electrically triggered, high-pressure-nitrogen spark gap with the cathode shorted to ground ($Z_L = 0 \Omega$). The pulse forming network (PFN) permits the initial negative voltage pulse to "ring" back and forth in the circuit, changing polarity after each transit time Δt . The resultant voltage waveform across the Pockels cell is indicated in Fig. 1b, where we show an exponentially

damped envelope for the waveform due to circuit losses. The optical cavity is arranged so as to exhibit maximum transmission with zero voltage on the Pockels cell; i.e., at the crossover points in Fig. 1b. By adjusting the PFN length we can readily provide a Δt which coincides with the round-trip transit time for the optical cavity (typically ~ 7 nsec), and thus assure operation of the oscillator in the synchronously driven mode; i.e., preferential amplification of the originally gated pulse.

Figure 2 is a photograph of the synchronously driven oscillator system. From left to right on the Gaertner bench, the following elements are shown:

Fig. 2. Photo of synchronously driven Nd:YAG oscillator system.

electrically triggered spark gap; bandwidth-selecting resonant reflector rear mirror (in Lansing mount); synchronously driven CRE Pockels cell Q-switch gate (placed as close as possible to rear mirror to avoid multiple pulse effects); Glan prism polarizer; helical-lamp-pumped Nd:YAG head with power supply cable and water cooling connections; dye cell (optional) containing a small concentration of EK9860 in dichloroethane solvent to eliminate background oscillations, and the front output mirror.

In a series of preliminary experiments, output pulses from this oscillator have been used as inputs for the Long Path Laser. Early results obtained on the Long

Fig. 3. Pulses from a Nd-glass oscillator and the synchronously driven Nd:YAG oscillator as photographed by the 10-psec-resolution streaking camera after passage through the Long Path Laser. (a) Pulse from Nd-glass oscillator shows substantial intensity variations across the time sweep. (b) Pulse from the synchronously driven Nd:YAG oscillator is smooth with little intensity variation.

Path Laser system indicated that while the pulses did exhibit some spectral broadening (to 10 Å from the original bandwidth limit), the original smooth temporal characteristics of the input pulses were maintained through the amplifier chain. This is in sharp contrast to the performance obtained on this system with the existing Nd:glass oscillator where the input pulses showed considerable AM modulation and a spectral width of 100 Å or more. For comparison purposes, Fig. 3 shows photographs, taken with a 10-psec-resolution streaking camera, of output pulses from the Long Path Laser. The approximate pulse energy in each case was 60 J. Figure 3a shows the pulse obtained with the Nd:glass oscillator input. The intensity variations apparent across the time sweep indicate a substantial amplitude modulation for this pulse. Figure 3b is a streak photograph taken under identical conditions to those of Fig. 3a, but with the synchronously driven bandwidth-limited Nd:YAG oscillator. The smooth temporal nature of the output pulse resulting from the Nd:YAG oscillator is readily

apparent. (The Long Path Laser results are discussed in greater detail in a later section of this report.)

The results obtained to date on the synchronously driven oscillator have been encouraging. With the Pockels cell gate and cavity bandwidth adjusted for 1-nsec pulses, the system has shown approximately a 5-to-10-fold increase in energy/pulse; i.e. from about 0.25 mJ/pulse to 1-2 mJ/pulse, while still maintaining the bandwidth limit for these pulses. This result confirms the fact that synchronous driving permits us to withdraw the stored energy of the inverted medium considerably faster and to concentrate it more effectively in the desired output than we could with the self-driven oscillator.

In summary, the synchronous gating technique has permitted us to operate the oscillator with up to an order of magnitude improvement in efficiency over the self-driven oscillator, while still maintaining the salient features of the self-driven oscillator: i.e., independent time and frequency control used to achieve bandwidth-limited output pulses.

MODE-LOCKED Nd:YAG OSCILLATOR STUDIES

In our search to provide a source of subnanosecond pulses for amplification in the Intermediate Laser System (discussed later in this report) we have been investigating the properties of a mode-locked Nd:YAG oscillator. We have performed detailed diagnostics on a mode-locked Nd:YAG oscillator that employs a bandwidth-limiting etalon in the oscillator cavity to increase the pulse duration. Using a fused quartz etalon we obtained pulses of about 250 psec FWHM with single (switched-out) pulse energies of 2 mJ and less than 1 mrad beam divergence. An improved design of this oscillator will be built for the Intermediate Laser System.

For the Intermediate Laser System we want an oscillator which produces pulses with the following characteristics:

1. At least 10^{-3} J in the fundamental transverse mode (TEM_{00}).
2. Bandwidth-limited pulse duration.
3. Pulse length variable from 0.05 to 1.0 nsec.
4. Wavelength near the amplification line center of Nd:glass.
5. High reliability and reproducibility.

Mode locked oscillators of Nd:YAG are superior in most of these characteristics to those of Nd:glass. This is presumably because of the higher gain of Nd:YAG and the reduced nonlinear optical qualities of the YAG host material. Mode-locked YAG oscillators produce bandwidth-limited pulses of about 30 psec time duration. The time duration of the pulses from such

an oscillator can be varied from 30 psec to 1 nsec, it has been reported,² by using bandwidth-limiting etalons in the oscillator cavity.

A schematic drawing of the oscillator, single-pulse switchout, and diagnostic apparatus used in the present investigation is shown in Fig. 4. The oscillator is similar in design to one built at the Naval Research Laboratory. We studied the temporal, spatial, and spectral characteristics of pulse trains and of single pulses switched out of the trains near the maximum single-pulse energy. For diagnostics we used fast photodiodes and Tektronix 519 oscilloscopes to measure the characteristics of the pulse trains, integrating photodiodes and a calorimeter to measure energy, near-field and far-field image-converter cameras to study the beam spatial characteristics, a two-photon-fluorescence (TPF) camera and a 10-psec-resolution streaking camera to measure the pulse duration and temporal structure, and a 1-m grating spectrograph to study the spectral properties.

The lasing medium in the oscillator consists of a 1/4-in.-diam by 3-in.-long Nd:YAG laser rod pumped by a single 6-mm-bore flashlamp in an elliptical pump cavity. A quartz thermal cladding is used around the laser rod to minimize thermal gradients in the rod.³ Both the flashlamp and the laser rod are water-cooled. Mode locking was done with a solution of Eastman Kodak 9740 mode-locking dye in dichloroethane in a 0.015-in.-thick cell in contact with the rear mirror, the dye being continuously circulated during operation of

Fig. 4. Schematic of mode-locked Nd:YAG oscillator, single-pulse switchout, and diagnostic equipment.

the laser. The flashlamp capacitor bank was 75 μF with a characteristic time of 50 μsec . The oscillator was run with repetition rates up to 1 pulse per second. Front mirror reflectivity was 25%. Lasing threshold of the oscillator was found to be about 9 J (flashlamp

pump energy; without mode-locking dye in the cell, 18 J with the dye.

The oscillator was first set up without an etalon in the laser cavity and the lasing characteristics were studied. During this part of the study, diagnostics

Fig. 5. Measured pulse train energy from mode-locked Nd:YAG oscillator as a function of dye cell transmission.

consisted of a fast photodiode and a Tektronix 519 oscilloscope to monitor the pulse train, a calorimeter to measure the pulse train energy, and a TPF camera to measure the pulse duration. We found that total pulse train energy and the number of individual pulses in the train changed with the mode-locking dye concentration. As the unsaturated transmission of the dye cell decreased (dye concentration increasing) the train energy increased and the number of pulses in the train decreased. Figure 5 shows the pulse train energy measured with the calorimeter for various dye-cell transmission values. Below 50% dye transmission the 100% mirror in contact with the dye would become damaged after a few shots and the oscillator output would become unreliable. We used an unsaturated dye-cell transmission of 50% for most of the work described here. The pulse width measured with the TPF camera appeared to be about 30 psec with these operating conditions. A 2.5-mm-diam aperture was found to be necessary to obtain single-transverse-mode operation (observed with the near-field camera).

Several uncoated etalons (3.2- and 5-mm-thick sapphire and 2- and 4-mm-thick fused quartz) were next tried in the oscillator cavity (approximately perpendicular to the axis, i.e., slightly offset), to increase the pulse length. The pulse length measured with the TPF camera showed an apparent increase which was proportional to the etalon optical thickness.

A detailed analysis however revealed that the pulse duration with any single etalon was not reproducible and the TPF contrast ratio also changed from shot to shot.

A 2-mm-thick fused quartz etalon with 20% reflecting mirrors on the faces was next tried. With this etalon pulses of about 200 psec FWHM and with a contrast ratio of approximately 3 to 1 were consistently measured with the TPF camera. Since this is a pulse length of interest for the Intermediate Laser System we decided to do more detailed diagnostics of the oscillator output with this particular etalon in the cavity. A single-pulse switchout was placed at the oscillator output and the near-field, far-field, and fast streaking cameras and the spectrograph diagnostics were added. A typical pulse train and switched-out pulse are shown in Fig. 6. A plot of relative intensity vs time derived from a typical streaking camera record is shown in Fig. 7. In shots that have been analyzed in detail (over three days of runs) the pulse duration ranges from about 235 to 340 psec. All pulses are smooth and show no structure greater than 10 psec in the time direction. There is some indication that the pulse duration variation from day to day is larger than that in a number of shots taken in sequence. This might arise from a variation of the pulse length with temperature, mechanical adjustment, or some other parameter of the oscillator which is not well controlled over an extended period of time.

Fig. 6. Typical pulse train from the mode-locked Nd:YAG oscillator for 10-nsec spacing between pulses. (a) Pulse train after switchout of the selected single pulse, (b) The switched-out pulse.

Fig. 7. Relative intensity vs time for a pulse from the mode-locked Nd:YAG oscillator. The data are derived from a 10-psec-resolution streaking camera record.

A typical near-field intensity profile is shown in Fig. 8. The near-field pattern was symmetric ($1/e$ diam of 0.76 mm) and is approximately Gaussian in shape ($1/e$ diameter ~ 0.6 mm as estimated theoretically for the fundamental transverse mode).

A typical far field of a single pulse is shown in Figs. 9 and 10. Figure 9 shows an isodensity plot of the beam focused by a 10-m lens. Figure 10 shows profile plots of this same data along the long and short axes reduced to relative intensity vs angle. The reason for the unsymmetric far-field intensity pattern is not yet understood but may be related to the Pockels cell shutter.

Single-pulse energy measured for the oscillator in this configuration is about 2 mJ after passing through the single-pulse switchout. Shot-to-shot reproducibility of the pulse energy is within $\pm 10\%$.

Fig. 8. Typical near-field intensity profile of a pulse from the mode-locked Nd:YAG oscillator.

Fig. 9. Isodensity plot of a far-field record of a pulse from the mode-locked Nd:YAG oscillator, taken with a 10-m-focal-length lens.

Fig. 10. Profiles along the long and short axes of the isodensity plot of Fig. 9.

Only preliminary spectral data had been taken at the time this report was written, and more detailed spectral measurements remain to be performed. From

the data we have taken it appears that this mode-locked Nd:YAG oscillator will provide a suitable source of subnanosecond pulses for the Intermediate Laser System. The oscillator produces more than 2×10^{-3} J per single pulse in the fundamental transverse mode with a reproducibility of $\pm 10\%$. The beam divergence is less than 0.8 mrad full width at the $1/e$ intensity points. The nominal pulse duration with a 2-mm-thick fused quartz etalon with 20% reflecting mirrors is 250 psec with some pulses measured as long as 340 psec. There is no temporal structure longer than 10 psec (the streaking camera's resolution limit) in the pulse, and TPF measurements indicate no substructure. From this data it appears to be possible by choosing the appropriate etalon to obtain any pulse length from 30 to 250 psec. We have no data on producing pulses longer than this. A well-engineered version of this oscillator is being designed for the Intermediate Laser System; it should give improved stability over the present benchtop arrangement. The better environmental control (vibration isolation, and good temperature and dust control) in the Intermediate Laser Laboratory should also aid in improving the reproducibility of this oscillator.

PULSE AMPLITUDE MODULATION IN Q-SWITCHED Nd:GLASS OSCILLATORS

We have previously reported⁴ the use of the ultrafast streaking camera to measure the intensity profile of the output of the Pockels-cell Q-switched and cavity-dumped Nd⁺⁺⁺:glass laser oscillator used on the LLL Long Path Laser. On the basis of fast photodiode measurements the pulse had appeared smooth and regular. Using the 10-psec-resolution camera, however, we observed strong regular intensity modulation at 20-psec intervals throughout the 2-nsec pulse. We surmised that the origin of this modulation might be beating of modes generated by resonant subcavities within the oscillator cavity. This observation led us to look at the pulses from two other types of Q-switched Nd:glass oscillators — one Q-switched by a simple rotating prism, the other by a nitrobenzene Kerr cell. The rotating prism arrangement, with a relatively clean cavity, produced a smooth pulse with little modulation, while the Kerr cell arrangement, with a relatively cluttered cavity, produced a deeply modulated pulse.

Figure 11 shows the oscillator Q-switched by a simple rotating prism. Inset in the figure is a streak camera photograph of a portion of the 35-nsec pulse produced. The high background level in the photograph is the result of the laser pulse being very long compared to the camera sweep time. This

1.75-nsec segment is approximately in the center of the pulse. The intensity is relatively smooth with little evidence of regular or strong modulation although some irregular structure is apparent.

The rotating prism of Fig. 11 was replaced by a nitrobenzene Kerr cell Q-switch, shown in Fig. 12. The streak record from this oscillator is inset in the figure. Again this streak is the central 1.75-nsec section of a pulse about 60 nsec long. Deeply modulated structure with a 25-psec period is evident. We attribute this structure to the subcavities introduced by the Kerr cell windows.

In the cavity containing several internal elements (Fig. 12) the amplitude modulation is pronounced. However, in the rotating prism cavity (Fig. 11), containing only one possible element, this temporal

Table 2. Pulse bandwidth measurements

Oscillator Q-switch mechanism	Bandwidth (cm^{-1})
Pockels cell (Long Path Laser)	53
Rotating prism	24
Kerr cell	26

Fig. 11. Schematic of Nd-glass oscillator that is Q-switched by a simple rotating prism, and streaking camera photo (inset) of a segment of the pulse produced. The 1.75-nsec segment, taken from near the center of the 35-nsec-long pulse, is relatively smooth and unmodulated.

structure is absent. We conclude from these comparisons that the source of the modulation observed in the Long Path Laser oscillator is most probably beating between cavity and subcavity modes. To produce smooth pulses it thus appears that we need either an optically clean, simple cavity (e.g., the rotating prism), or the more complex but carefully mode-controlled oscillators described elsewhere in this report.

The bandwidth of the output from these oscillators was measured simultaneously with the taking of the streak camera data. The results are given in Table 2.

These bandwidths are broad enough to support the pulses observed. Since self-phase-modulation is improbable because of low peak intensities, the bandwidths may be evidence of additional amplitude modulation unresolved on our present detection time scale.

Fig. 12. Schematic of Nd:glass oscillator that is Q-switched by a nitrobenzene Kerr cell, and streaking camera photo (inset) of a segment of the pulse produced. The 1.75-nsec segment, taken from near the center of the 60-nsec-long pulse, shows deeply modulated structure with a 35-psec period.

DEVELOPMENT AND EVALUATION OF NEODYMIUM LASER AMPLIFIERS

Experimental and calculational studies of the properties of Nd^{+++} -doped glass and YAG amplifiers have been continued using the techniques described in the previous semiannual report.⁵ Most of the work completed during this semiannual period has been directed toward determining the properties of components to be used in the Intermediate Laser System (see following article). Experimental work has included the extension of measurements on the pumping uniformity of 2-in.-diam laser rods, and measurements of the gain of a YAG rod amplifier and of the CILAS V-16 and V-32 glass rod amplifiers. Calculational work to check the agreement of calculated results with the experimental measurements, and thus learn the deficiencies in the calculational

routes, has continued along with calculational studies of various disk-amplifier configurations.

The results of pumping uniformity measurements on 2-in.-diam Owens-Illinois ED-2 laser rods in LLL-designed amplifier heads are summarized in Fig. 13. (The internal consistency of these measurements is about $\pm 3\%$. Systematic errors have been investigated and are believed to be less than 10%.) New data taken during this period were the data on the pumping uniformity of the rod with 1% Nd_2O_3 doping. For a 2-in.-diam rod surrounded by a water-cooling jacket the 1% Nd_2O_3 doping appears to be the best choice. Pumping uniformity of the 2% rod in air is comparable to that of the 1% rod in a water jacket but the efficiency is poorer.

Fig. 13. Pumping uniformity measurements on 2-in.-diam Owens Illinois ED-2 laser rods in an amplifier head with helical flashlamps. Results are shown for the rod in air and for the rod surrounded by a water jacket.

Figure 14 shows the small-signal gain measured at $1.06 \mu\text{m}$ by a small-diameter probe beam (cw Nd:YAG) along the axis of a Nd:YAG laser rod in an amplifier head with four linear flashlamps. Figure 14 also includes our estimate of the energy stored in the rod, based on these data and the published stimulated-emission cross section for Nd-doped YAG.⁶ For this rod, the maximum small-signal gain appears to be about 30, with a maximum stored energy (in the R_2 level of the $^4F_{3/2}$ manifold) of about 0.09 J/cm^3 . This limit appears to be imposed by amplified spontaneous-emission losses from the YAG rod. The efficiency of conversion of flashlamp energy to population inversion in the YAG rod in this amplifier head is about 10^{-3} . Nd:YAG operating in the subnanosecond-pulse region has a saturation energy of about 0.1 to 0.2 J/cm^2 .

From these data we conclude that Nd-doped YAG, with its high gain, can be used to advantage in amplifiers for specific beam energies up to a few tenths J/cm^2 . At higher specific energies, one should use glass to take advantage of its greater storage capability and

Fig. 14. Measured small-signal gain at $1.064 \mu\text{m}$ along the axis of a 3/8-in.-diam by 3-3/4-in.-long Nd:YAG laser rod pumped by four linear flashlamps, and estimated stored energy. (See Fig. 8 of Ref. 5 for experimental setup.)

Fig. 15. Measured small-signal gain at $1.064 \mu\text{m}$ along the axis of the CILAS V-16 glass rod amplifier, and estimated stored energy. Rod is Schott LG-56 laser glass 16 mm in diam and 460 mm long, pumped by two helical flashlamps.

Fig. 16. Measured small-signal gain at $1.064 \mu\text{m}$ along the axis of the CILAS V-32 glass rod amplifier, and estimated stored energy. Rod is 32 mm in diam and 460 mm long, pumped by four helical flashlamps. Data were taken with both Schott LG-56 and Owens Illinois ED-2 rods.

higher saturation energy. We are planning to use YAG in preamplifier stages to amplify the output from a mode-locked YAG oscillator as a source for the Intermediate Laser System.

Figures 15 and 16 show the small-signal gain of the CILAS V-16 and V-32 glass-rod amplifiers measured at $1.064 \mu\text{m}$ and our estimates of the energy stored along the centerline of the rod. With the V-32 amplifier, gain measurements were made with both Schott LG-56 and Owens-Illinois laser rods. The Schott rod was doped with 3% Nd_2O_3 as supplied by CILAS, the Owens-Illinois rod was doped with 2% Nd_2O_3 which we determined to be near optimum for a

32-mm-diam rod from our gain uniformity measurements. The stored energy was estimated from the small-signal gain measurements and published data on the maximum stimulated-emission cross sections and fluorescence line shapes for the two laser glasses.⁷⁻⁹ We are using these data to help determine the laser glass and capacitor bank characteristics to be used in the Intermediate Laser System.

We have continued to compare calculations made by the Monte Carlo computer code PAZ and the flashlamp code GENEFF with results of the rod amplifier experiments in order to study the shortcomings of the codes (the Monte Carlo code was run long enough to give 5% or better statistical accuracy). Such data are important for understanding the limitations of the codes in applying them to calculate new laser amplifier designs. Excellent agreement between the calculations and the measurements of pumping uniformity were obtained by including some fuzzing of the rays at the rod surface to account for the fine grind surface on the barrel of the laser rods. This is illustrated in Fig. 17 where the calculations for a 2-in.-diam 1% doped rod are compared with experiment. Calculations are shown for pure Fresnel reflection and refraction at the rod boundary and for fuzzing at the boundary.

Agreement between the calculated and measured pumping efficiencies was poorer. This is illustrated in Table 3 where the calculated and measured efficiencies are compared for a number of cases. The reasons for the discrepancy are not yet understood in detail but we believe they are related to (1) inaccuracies in the model used for calculating the flashlamp output and (2) losses arising from the amplification of spontaneous emission in the laser material that are not accounted for in the calculations. Even with these weaknesses, the codes have been useful in comparing amplifier designs and in evaluating improvements in design.

A calculational routine has been written for PAZ which calculates the amplification of spontaneous

Table 3. Calculated and measured pumping efficiencies of Owens-Illinois ED-2 laser rods in LLL-designed amplifier heads with helical flashlamps

Rod diam	Nd_2O_3 doping	Bank energy (kJ)	Calculated current density (A/cm^2)	Calculated efficiency	Measured efficiency
1 in., water-cooled	3%	14.3	1500	0.029	0.011
			2500	0.025	-
2 in., water-cooled	2%	14.2	2500	0.038	0.024
	1%	14.2	2500	0.037	0.021
2 in., air-cooled	2%	17.2	2500	0.035	0.017

Fig. 17. Calculations of pumping uniformity agree much better with measurements if a fuzzed rod boundary (to account for fine grind surface) is assumed rather than a Fresnel rod boundary.

Fig. 18. Pumping efficiency vs flashlamp current density for the NRL disk amplifier, calculated using PAZ and GENEFF codes.

emission in the laser material. This routine calculates the effective lifetime for spontaneous emission for the laser geometry as a function of the population inversion. We have found that the results are sensitive to the boundary conditions assumed for the laser material. For glass disks we have assumed the disk edges are perfect absorbers and the disk faces obey Fresnel laws for reflection and refraction. This can be realized experimentally by coating the disk edge by a layer of absorbing glass whose refractive index matches the laser glass.

We have applied this routine together with pumping efficiency calculations from PAZ and GENEFF to calculate the pumping of the NRL disk amplifier. The results of the pumping efficiency calculation as a function of the current density in the flashlamp are shown in Fig. 18. This efficiency together with the calculated power input to the lamp and the effective lifetime for spontaneous emission have been used to calculate the population inversion during the pumping cycle, shown in Fig. 19. Experimental data obtained from NRL are also shown for comparison. A large discrepancy remains between the experimental and calculated data.

An attempt is also being made to compare the calculations with direct measurements of flashlamp output. Results of this study are not complete enough to report, but preliminary evidence indicates the codes are overestimating the flashlamp output.

Calculations are being done with PAZ and GENEFF to study disk amplifier designs. Designs being calculated are variations of the NRL disk amplifier, the General Electric Zigzag face-pumped laser, and a 64-mm-aperture disk amplifier module. Results are not yet complete enough to report.

Fig. 19. Calculations of population inversion in NRL disk amplifier as a function of time, based on efficiency calculations of Fig. 18. Experimental data shown for comparison indicate that a large discrepancy still exists between calculation and experiment.

INTERMEDIATE LASER SYSTEM

The Intermediate Laser System (ILS) is being designed and constructed to verify the feasibility of building a 10^4 -J Nd^{+++} -doped glass laser system to operate with subnanosecond pulses. Damage threshold limitations of glass dictate that the energy density of the beam be low, and thus to obtain such high energy a multiarm system is required. The objective of the ILS is to construct within the next two fiscal years a representative portion of such a multiarm system. The ILS will provide the opportunity to investigate optical, electrical, and mechanical components and their reliability, damage thresholds, integrated system performance, thermal and vibrational sensitivity, diagnostic techniques, and other aspects of large laser system design. It will also provide the capability for target irradiation with about 1 kJ of beam energy.

To start toward the accomplishment of these objectives an amplifier train has been purchased from CILAS (Marcoussis, France). This amplifier train consists of five rod-amplifier stages from 16 mm to 64 mm in diameter. Initially a subnanosecond pulse from a mode-locked Nd^{+++} -doped YAG oscillator will be amplified by two 3/8-by-3-3/4-in. YAG rod preamplifiers and fed into the CILAS train. This is shown in Fig. 20. The system is designed so that other oscillators can easily be coupled into the train. The diagnostics (not shown in Fig. 20) monitor the gain of each amplifier and the beam quality throughout the system. Other diagnostics such as flashlamp current, flashlamp bank voltage, coolant temperature, etc., will be incorporated.

A Faraday-effect optical isolator will be placed between the 46-mm-diam and 64-mm-diam amplifier

Fig. 20. Artist's rendering of the Intermediate Laser System (ILS). This system is designed to verify the feasibility of building a multibeam laser system using Nd^{+++} -doped glass and capable of producing subnanosecond pulses with 10^4 J energy.

heads. This isolator is also being ordered from CILAS. It is a high-field unit (30,000 G) which operates with a low-Verdet-constant, high-damage-threshold glass. Polarizers are provided by glass plates at Brewster's angle. Smaller aperture Faraday-effect and Pockels-cell isolators are available and can be added to the system if they are required.

A mode-locked YAG oscillator (described in an earlier section, p. 9) which produces 0.2-nsec pulses is now operating and its characteristics are being studied. Two YAG preamplifiers and two glass-rod amplifiers complete with flashlamp capacitor banks and firing circuitry are available to amplify this pulse. Characteristics of these amplifiers have been measured and the construction of the first stages of the amplifier train has begun. The remainder of the amplifier train and the Faraday effect isolator are expected to arrive in Livermore during the month of July. The limiting items in the assembly of the CILAS rod-amplifier train are the flashlamp capacitor banks and the control

circuitry, which are expected to be completed in October. The rod amplifier train is expected to be operational by December. The anticipated output is approximately 100 J, the limit being imposed by the damage threshold of the laser glass with subnanosecond pulses ($\sim 4 \text{ J/cm}^2$).

A disk amplifier will be used to further amplify the beam from the CILAS train. Presently, a copy of the Naval Research Laboratory disk amplifier is being constructed for test and evaluation. If tests are satisfactory this amplifier will be added to the system early next calendar year. A modular disk-amplifier system is also being investigated. It is hoped this investigation will produce an efficient, versatile two-or-three-disk module which will comprise the basic amplifier of a multiarm amplifier system.

Other areas currently being investigated are beam splitting techniques, optical isolator development, and reliability studies of both components and systems.

Electronics reliability problems involved in large multipath laser arrays are being studied. In general, any multipath laser system to be considered will consist of the major elements shown in the block diagram of Fig. 21. A thorough analysis of operational reliability would require assessment of the probability that all of these elements will simultaneously perform within acceptable limits for a minimum required number of operations at any time during the desired life of the complete system.

As an example we consider the reliability of the major components of a nine-path glass laser array (Fig. 22). A total of 6571 electronic components are required (see Table 4). Power supplies are treated as components, based on the premise that there will be complete standby units available to quickly replace a

failed unit which would then be repaired independent of system operation.

Using the above model with the severe constraint that a single major-component failure represents complete system failure, we may conduct a preliminary system reliability analysis. On the basis of presently available component failure data, we find that the system has a 90% probability of producing one pulse without failure and a 33% probability of producing ten pulses without failure. However, these results are not necessarily realistic, since, for example, a bank of 40 flashlamps with 4 inoperable may not appreciably degrade the lasing performance, i.e., the experiments could go on. More complicated modes are required for a correct analysis. We are now in the process of studying such models.

Fig. 21. Block diagram of general multipath laser system considered in reliability studies.

Fig. 22. Nine-path glass laser array considered in the reliability studies reported here.

Table 4. Summary of major electronic components considered in evaluating the reliability of the system of Fig. 22

Component description	Number required
Power supply for oscillator (including flashlamp trigger)	1
Power supply for Pockels cell pulse	1
Power supply for charging capacitor bank	37
Power supply for oscillator pulse	12
Flashlamps	705
Capacitors (14.5 μ F, 20 kV, 3000 J)	2222
Cables	705
Cable connectors	1410
Inductors	705
Switch tubes	68
Charge resistors	705
Total required	6571

AN OPTICAL TECHNIQUE FOR MEASURING PREEXISTING STRESS IN FLASHLAMPS

A major problem in the construction of very high power neodymium-glass lasers is the limited life of the xenon flashlamps used for optically pumping the laser rods and disks. Not enough is known about the physics of how these flashlamps fail, and therefore we have supported for the past year a study of the failure modes in xenon flashlamps at the University of Colorado.¹⁰ An important outcome of this study has been the implementation of an optical system for measuring preexisting stress in linear flashlamps, based on a concept adopted from earlier work on locating and measuring stresses in electron tubes.¹¹ The immediate benefit of the system to LLL is that it will enable us to cull out potentially bad flashlamps and thereby reduce the number of premature explosions of flashlamps in laser heads, which can extensively damage the lasers. Also, the availability of this technique will enable us to write meaningful acceptance-test procedures into specifications for future flashlamp orders.

A schematic of the test setup is shown in Fig. 23. With the crossed polarizers and the quarter-wave plate set for minimum intensity, a fringe pattern is seen in the regions of greatest axial stress in the wall of the lamp. The pattern appears as a dark ring, which can be made to shrink into a single line by rotating the analyzer. The amount of rotation of the analyzer is then a direct measure of the axial stress, which is given by the following formula¹¹:

$$G_{max} = \frac{W\lambda}{4C(ah)^{1/2}} \frac{\alpha}{180},$$

where W is a dimensionless weighting factor, G_{max} is the maximum axial stress, λ is the wavelength of the light, C is the stress-optical coefficient of quartz, a is the radius of the flashlamp, $2h$ is the thickness of the flashlamp wall, and α is the rotation of the analyzer.

In tests of a variety of flashlamps by this technique, stresses as high as 1.75 kg/mm^2 have been found. Assuming that the yield strength of the glass tubing is about 5 kg/mm^2 (on the basis of rough estimates found in the literature), this means that some of the lamps had preexisting stresses up to 35% of their expected yield strength. Such high built-in stresses would most likely account for many of the premature failures of some of the lamps currently in use.

To use this technique as an acceptance test, one would rotate the analyzer to a setting corresponding to an acceptable stress level (probably a G_{max} of 0.6 kg/mm^2) and observe the entire length of the flashlamp while rotating it about its axis. If a dark ring appeared in the outer part of the tube wall at

any point, the flashlamp should be rejected. If a dark ring appeared in the center of the tube wall (where the weighting factor is lower), one would increase the rotation of the analyzer by a factor of 1.5,¹¹ and if the ring persisted, the lamp should be rejected.

This optical stress-measuring technique will be useful in reducing the large number of burn-in shots (from 10 to 100) that are now often required for new flashlamps to minimize premature failure of flashlamps in laser heads. A limited burn-in — about 10% of what would be required without this test — is still advisable, however, to identify lamps having other kinds of faults, such as poor electrode joints and seals.

Fig. 23. Schematic of the optical system for measuring preexisting stresses in linear flashlamps. Potentially bad flashlamps can be identified and culled out in advance, thus reducing the number of premature explosions of flashlamps which can severely damage laser heads.

We have constructed a stress analyzer with which we can check flashlamps up to 6 ft long, and we

intend to write the acceptance-test procedure into future specifications for large orders of flashlamps.

FARADAY ISOLATOR DEVELOPMENT

Interstage and target isolation is a requirement for high-gain, high-energy solid-state laser chains. The function of the isolation is to allow light to travel in only the desired direction (i.e., toward the target or experiment) or at the desired time. Thus, spontaneous emission and target reflections traveling back through the amplifier chain toward the smaller diameter amplifiers and oscillator are rejected from the optical signal path. The consequence of inadequate isolation is damage to optical components including laser rods, as well as energy dumping by superfluorescence.

One of the most readily available means of providing a unidirectional optical element is the Faraday effect, in which rotation of a material's optical plane of polarization is induced by a magnetic field. The rotation is proportional to the Verdet constant (the rotation per unit path and per unit field strength) of the material, the strength of the magnetic field, and the length of the material in the magnetic field. Some tradeoffs are possible among the three parameters. There are additional qualities to be considered for the Faraday effect material which are not explicit in the rotation expression, namely optical damage threshold and optical distortion.

Our present efforts on one-way isolators are directed toward providing pulsed Faraday isolators of high optical quality and high damage threshold with apertures of 16, 25, and 50 mm. Our 16-mm isolator was designed with a glass of relatively low damage threshold and consequently its life has been limited due to optical damage; Owens-Illinois EY-1 glass is on order to replace it. The 25-mm rotator has been designed and built (see Fig. 24), and the design of the 50-mm unit is completed and fabrication is in progress. In both the 25- and 50-mm rotators, Owens-Illinois ED-2 laser glass is used as the Faraday material since it has the same damage threshold as the laser amplifier rods as well as high optical quality, i.e., low stress birefringence. However, this material has a low Verdet constant and consequently requires magnetic fields in the tens of kilogauss range and a glass length of 150 to 250 mm. Although this length of glass in the beam path could be detrimental in terms of nonlinear effects, it is preferred to alternative materials which have higher Verdet constants but lower damage thresholds.

Implicit in the design of high-quality Faraday rotators is the need for high-quality polarizer-analyzer units. We have used commercially available calcite and

Fig. 24. Components of 25-mm Faraday-effect isolator.

quartz prisms, but as apertures increase above about 25 mm calcite prisms are not available, and for distances of less than about 10 ft between isolator and amplifier head, quartz prisms give insufficient angular discrimination. Therefore we are investigating alternative polarizing techniques. For example, we are looking into the possibilities of stacked glass plates, which have been used by other laboratories.

Since the rejection ratio of the rotating element with polarizers is to be optimized, the design includes consideration of the magnetic field uniformity, laser bandwidth, laser divergence, and material birefringence. Rejection ratio measurements of a 16-mm isolator using SF-6 glass give a value greater than 250:1, which is limited, we believe, by material optical quality. Rejection ratios for the laser glass isolators are expected to be improved by a factor of 2. The 50-mm-aperture unit will be inserted in the multipass disk laser where the Brewster angle disks act as polarizer-analyzers.

Our efforts are concentrated on investigating and applying high-durability materials for Faraday isolators.

The hardware for providing the magnetic field is then designed to complement the chosen material.

CYLINDRICAL, RING-ELECTRODE POCKELS CELL FOR ISOLATING FAST PULSES

Many of the laser applications of interest at LLL, especially laser-fusion experiments, require single, sharp laser-light pulses of very short (subnanosecond) duration. Such pulses can deliver energy to a target before the energy can be dissipated by explosion or thermal conduction. Electrooptical devices such as Q-switches, Pockels cells, and ultrafast shutters can be used to extract these short pulses from laser beams. We describe here a Pockels cell we have developed that offers an order-of-magnitude improvement in pulse quality over previous designs.

In a Pockels cell, a voltage applied to the crystalline material that makes up the cell will cause the crystal to become birefringent — that is, the crystal will separate the incoming beam of polarized light into two parts and change the phase of the parts relative to each other. The amount of polarization rotation resulting from this phase change depends on the applied voltage. By using a calcite prism or Brewster-angle plate as an analyzer (i.e., an element which passes only light that is polarized in the proper direction), a rotated beam can be extracted from an unrotated beam. (The analyzer is oriented to pass light whose plane of polarization has been rotated 90° from the incident polarization direction, since the Pockels cell is most efficient at this rotation.) Thus, by applying very sharp, short electrical pulses of the proper voltage to a Pockels cell located between a polarizer and an analyzer, one can extract very sharp, short light pulses from a laser beam.

The properties of a Pockels cell that are critical to its performance are (1) the voltage required to produce the 90° rotation; (2) the uniformity (across the diameter of the light beam) with which the cell transmits and rotates the beam; (3) the losses in the cell due to reflection from the faces, absorption in the crystal, and birefringence due to stress in the crystal; and (4) the speed with which the optical signal can be affected. Our efforts to develop an improved Pockels cell were directed specifically toward maximizing the speed of response and minimizing transmission nonuniformities in the cell, while at the same time developing techniques for accurately monitoring the fast light pulses and determining the quality of the cell material.

Our new Pockels cell is made of potassium dideuterium phosphate (KD_2PO_4). This is the deuterated isomorph of potassium dihydrogen phosphate (KH_2PO_4), which has been produced

commercially since the 1940s. KD_2PO_4 is a uniaxial crystal; i.e., it has only one axis of optical symmetry. When a wave of polarized light from an yttrium-aluminum-garnet (YAG) laser, which has a wavelength of $1.06 \mu m$, is propagating along this axis, about 10 kV must be applied to the crystal (also along the optical axis) to obtain maximum transmission through an analyzer oriented to pass light rotated 90° to that entering the crystal.

The crystal we use is cylindrical, 12 mm in diameter and 25 mm long; the axis of the cylinder approximately coincides with the optical axis of the crystal. The two electrodes which apply voltage to the crystal are 8-mm-wide brass rings placed around the ends of the cylinder (see Fig. 25). Our prototype assembly is enclosed in a Lucite sleeve to insulate the cell from air currents and to protect experimenters against the high voltage. This cylindrical, ring-electrode (CRE) design represents a substantial advance in the

Fig. 25. Prototype cylindrical, ring-electrode (CRE) Pockels cell is a KD_2PO_4 crystal inside a Lucite sleeve.

Fig. 26. Experimental arrangement for extracting subnanosecond pulses with a fast Pockels cell. Polarizer and analyzer are crossed 90° to each other, so that the analyzer passes light only when the Pockels cell receives a 10-kV pulse from the spark gap (which is triggered by the laser pulse) and briefly rotates a component of the beam by 90° . The two oscilloscope traces show the pulse extracted by the Pockels cell and the remainder of the longer pulse generated by the laser.

technology of Pockels cells with respect to both switching speed and uniformity of transmission.

In assembling such a cell, we are careful to avoid straining the crystal, which would alter its optical properties by causing stress birefringence. The electrodes are machined to a tolerance of about 0.001 in. and carefully fitted over the ends of the crystal, and all soldering necessary to attach cables to the electrodes is done before the electrodes are placed on the crystal. Having taken these precautions, we find that after the electrodes are attached, the transmission pattern of the cell between crossed polarizers is identical to that of the original crystal blank.

For the cell to have an optimum time response, the capacitance between the electrodes and the inductance of the cable connecting them must be minimized. The cylindrical electrode design automatically provides the minimum-capacitance configuration, and we minimize the inductance of the connecting cable by placing the exposed cable as close as possible to the surface of the cylinder.

The performance of a cell of this kind has been treated theoretically by Vitkov¹² for a rectangular cell with electrodes attached as bands around the ends of the cell. For our cell, conversion of his results to cylindrical coordinates yields a predicted non-uniformity in rotation of about 2.2% between the

center and the edge of the crystal. We checked this prediction experimentally by placing a CRE cell between polarizers and observing the variation in the voltage required to rotate a light beam 90° . The observed nonuniformity in rotation was about 2%, which agrees well with the theoretical prediction. (A rotational nonuniformity in this range implies a 0.04% nonuniformity in the amount of light transmitted.)

With the same experimental setup, we also checked the extinction ratio (the ratio of the intensity of light transmitted by the analyzer when the voltage is applied to the Pockels cell to that transmitted when the voltage is off) over the entire aperture for two different CRE cells. We found it to be greater than 1500:1.

These results represent order-of-magnitude improvements over commercially available KD_2PO_4 cells, which typically have rotational nonuniformities of about 13% and extinction ratios of about 200:1 over the same aperture.

Figure 26 illustrates the experimental use of a fast Pockels cell for obtaining subnanosecond laser pulses. A 30-nsec pulse is generated by the Q-switched YAG laser oscillator. When sufficiently intense light is focused onto a spark gap, it generates an electrical signal of 0.5-nsec half-width which is impressed across the Pockels cell. An optical signal, whose half-width is determined by the response of the Pockels cell to

the electrical pulse, is then passed by the analyzer. After correcting the observed optical signal for the response time of the detecting system, we conservatively estimate that the half-width

of the "chopped" light pulse is less than 0.7 nsec. We expect that this light pulse can be made shorter by further shortening the electrical driving pulse.

SINGLE-FREQUENCY RUBY LASER

We have developed a reliable, TEM_{00} , single frequency ruby laser system for nonlinear optical experiments and pulsed holography.^{13,14} The laser now produces single-frequency Gaussian-shaped pulses 6 to 12 nsec FWHM which are reproducible to within 15% for better than 500 pulses. The energy per pulse is 2-4 mJ.

A schematic of the laser cavity is shown in Fig. 27. The water-cooled head consists of a plane-ended ruby rod 1/4 in. in diameter and 3 in. long. The laser has been run successfully with the rod ends hard AR-coated and uncoated, but the alignment is much more critical with the uncoated rods. A close-coupled helical xenon flashlamp pumps the ruby rod. Two watertight sapphire sleeves hold the rod so that its entire surface is pumped. The flash cavity is a stainless steel cylinder polished on the inside and has glazed ceramic end plates. The rest of the head contains buswork for the flashlamp and safety shields that also serve as mounts.

In the laser cavity are a 99.9% dielectric mirror, a dye cell, the head, an iris, and the output resonant reflector, as shown by Fig. 27. Other positions of the dye cell and the iris were tried and they worked, but not as well. The iris is adjusted to a 1.5- to 2.0-mm-diam opening, and the dye cell is placed at a 20 to 30° angle of incidence. Total cavity length is kept as short as possible, about 28 cm.

Three different Q -switch bleachable dye solutions were used: vanadyl phthalocyanine in nitrobenzene, cryptocyanine in acetonitrile, and cryptocyanine in methanol. All three mixtures work very well but the cryptocyanine in methanol is the safest to handle, and using a 1.7-mm-thick dye cell it produces 7-to-8-nsec FWHM pulses that are repeatable for a counted high in excess of 500 shots with a 15% variation in amplitude. We have observed that the optical frequency shifts monotonically during the pulse some 200 to 350 MHz, the greater shift being associated with the shorter pulses.¹⁵ The frequency spectrum was

Fig. 27. Schematic of single-frequency ruby laser cavity used for nonlinear optical experiments and pulsed holography.

measured with a Fabry-Perot (two 95% reflecting dielectric mirrors spaced 2 cm apart). Energies of 2-4 mJ per pulse were estimated on the basis of thermopile measurements of amplified pulse trains.

The resonant reflector consists of two sapphire flats (1 in. diam, 3.2 mm thick, 0° orientation) cut from the same blank. They were lapped together to make them the same thickness, and the sides are parallel to less than 1 sec of arc with better than 10th-wave flatness.¹⁵ By experimentation we determined that the inner surfaces of the two flats should be spaced 20 mm apart. Checking the flats and their proper alignment is very important.^{15,16}

The head is water-cooled with the temperature constant at $15 \pm 0.1^\circ\text{C}$. As a result of using

stainless steel plus plastic in the water cooler, gold-flashed brass fittings, and a deionizer, the head runs in excess of 100 shots before cleaning is required.

The capacitor bank is a 10-keV, 250- μF bank with a 350- μH series inductor. It is triggered by series injection using a trigger transformer. The bank is charged anywhere from 3.8 to 4.2 kV for single-frequency output, producing a current pulse that is typically 1.1 msec long FWHM.

We have attempted to make the laser run single-frequency with a Pockels cell Q -switch instead of the dye cell. So far we can achieve single transverse mode but have not done better than two to three longitudinal modes.

CO₂ Lasers

PHASE 1 HIGH-POWER CO₂ LASER SYSTEM

The Phase 1 system (Fig. 28) will be a CO₂ oscillator-amplifier chain which will provide an overall

gain of 4×10^5 in energy for a single 1/2-mJ light pulse. This system will allow us to gain experience with

Fig. 28. Schematic of the Phase 1 high-power CO₂ laser system.

short-pulse CO_2 systems and should, through the process of solving the inevitable problems, provide a basis for building larger systems.

The input pulse is produced by electronically switching out one pulse from a train of such pulses generated in a low-energy mode-locked oscillator, as described in detail on pp. 9-13 of this report. As indicated in Fig. 28, the oscillator beam is only 5 mm in diameter. It is expanded twice during amplification in order to avoid saturation of the gain medium en the way to the final stage. In the final stage, saturation occurs almost immediately so that a large fraction of the final-stage stored energy is swept out by the beam. Total path length in the various media is minimized so as to minimize degradation of beam quality.

Goals for the system are summarized in Table 5. These goals should be achieved by the beginning of calendar year 1973. Most of the components, with the exception of the electron beam gun assembly, have been tested and are ready for use in the Phase I oscillator-amplifier chain. Figure 29 is a photograph of the Phase I oscillator-amplifier area, looking toward

the E-gun final amplifier area, which is located behind the door in the rear. Part of the isolator test area is seen next to the wall at the left of the photograph. The Phase I oscillator and Dumanchin-Pan^{17,18} laser

Table 5. Goals for the Phase I CO_2 laser system

Output pulse energy	200 J
Output pulse duration	1 nsec
Repetition rate	1 ppm ^a
Beam quality	1/20 wave
Aperture	20 cm
Beam divergence	5 times diffraction limit
Shot-to-shot reproducibility	±20%

^aPulse per minute.

Fig. 29. Photograph of the Phase I oscillator/amplifier area.

amplifier presently in use are pointed out in the picture.

The final amplifier stage is an electron-beam-initiated atmospheric pressure discharge. This stage may be operated at pressures up to 5 atm to augment output energy while awaiting the second final-amplifier stage planned for the next phase. The E-gun amplifier is described fully later in this report (p. 41).

For all other gain stages, "double-discharge"¹⁸ transversely excited atmospheric-pressure (TEA) lasers are employed. We are now using the trigger structure invented by Dumanchin¹⁷ and developed extensively here,¹⁸ but other double-discharge structures (see next section) are under development for later insertion in the system. Double discharge devices are being extensively investigated because they are basically simple devices that are reliable, cheap, and of high optical quality.

TEA Laser Initiation Schemes

In this section we give a brief review of double-discharge TEA lasers, illustrating the different initiation mechanisms which distinguish them.

To achieve direct electrical excitation of most gas-laser media, the appropriate electron temperatures are found in the glow discharge regime. Within the glow regime, electron temperature and many other parameters are functions of the single variable E/p , the electric field intensity per torr. For CO_2 lasers in particular, efficient electrical excitation is achieved in a range of E/p from about 5 to 15 V/cm-Torr.¹⁹ At atmospheric pressure, this E/p corresponds to a range from about 4 to 12 kV/cm, so that convenience dictates transverse excitation (rather than longitudinal) for other than very small lasers.

A glow discharge must have both an initiation mechanism and a feedback mechanism to operate. The initiation mechanism may be ion bombardment of the cathode, photoionization at the cathode, electron bombardment of the gas volume from an external source, etc. Bombardment of the cathode by the positive ions created in the gas volume is the feedback mechanism required to "bootstrap" the stable, self-sustaining Townsend discharge into the higher-current glow regime.

In an atmospheric-pressure glow discharge, any attempt to operate at current densities sufficient to produce useful optical gain leads to a glow-to-arc transition in a few microseconds. So far, the only solution to this problem has been transient excitation of the laser medium, combined with uniform initiation to delay arc formation. When an arc does form, all the energy goes into the arc with none left to pump the entire volume.

Several schemes for uniform discharge initiation have been developed in the last two years. These schemes are all three-electrode structures, or "double discharges." While the exact mechanisms of initiation in these lasers have not been resolved quantitatively, there are three basic categories, namely cathode photoelectron production, plasma cathode formation, and volumetric electron-impact preionization. All double discharges are operated with a main-discharge electric field well below the infinite-plane sparking potential (although not necessarily below the self-initiation field for the finite electrodes employed). The initiating mechanism then rapidly causes "tunneling" of the operating point through the Townsend region and energy storage is adjusted so that the ensuing main discharge ceases before the arc has time to form.

Cathode Photoelectron Production. Very early studies of transient electron mobility employed test chambers with quartz or fluoroite windows through which an ultraviolet beam could be aimed at the cathode to initiate a glow discharge.²⁰ The same scheme is employed in the recently invented Richardson and Séguin lasers^{21,22} (see Fig. 30). Both structures feature trigger discharges behind a screen anode whose sole purpose is to generate intense short arcs. In the Richardson structure, the arcs occur between numerous sharp needles and the screen, and in the Séguin device, between pairs of needle electrodes. The discharge cathode is illuminated more efficiently in the latter case because of favorable arc orientation and use of a reflector R behind the arc array. In both devices, it should be noted that volumetric electron-impact ionization is ruled out by the electrode polarities.

Plasma Cathode Formation. The earliest double discharge was the Dumanchin¹⁷ structure in which initiation is achieved by the simple expedient of creating a sheet glow discharge at the cathode (see Fig. 30). This is accomplished by dielectric-covered trigger wires embedded in a finned cathode. Uniformity of the sheet is insured by sufficiently high dielectric impedance at the trigger drive frequency (and by careful construction) so that the trigger current density depends only on the trigger-voltage rise rate rather than on the local plasma state. A trigger pulse dV/dt of the order of 100 kV/ μsec is sufficient to create the sheet discharge.

The Garmworthy²³ structure is commonly cited as a "plasma cathode" device, but it will be described in the next section because it has more in common with electron-beam injection devices. In the Dumanchin device, plasma cathode formation is probably the dominant initiation mechanism, because

Fig. 30. Schematics of various double-discharge trigger schemes. K = cathode, A = anode, T = trigger, e = dielectric, d = separation, R = reflector.

uv illumination of the anode will not initiate a glow discharge, and because this cathode is an ineffective electron accelerator.

Volumetric Preionization by Electron Impact.* Daugherty and others have demonstrated an initiation mechanism which is conceptually the simplest yet advanced, although it is undoubtedly the most difficult

to build.²⁴ This is direct injection of a large-aperture, high-energy electron beam which intersects the entire volume of the main discharge, instantly initiating the glow mode by impact ionization. Uniform initiation is achieved by using electron energies in the 100-keV range, so that the absorption distance for the beam is the same order as the dimension of the discharge region.

The so-called "plasma cathode" initiation scheme due to Garnsworthy²⁴ is really another compact-beam-injection double discharge. It is similar to the Daugherty structure in that the electron beam sustains the discharge as well as initiating it, and differs

*The patent for these devices is held by Barton Krawetz of LLL (see "Patent Issued" section later in this report). The experimental demonstration was performed at AVCO by Daugherty et al. in February 1970.²⁴

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only in that the beam source is a low-pressure-gas-filled diode rather than a vacuum diode or triode.

Laflamme Device. In the Laflamme structure²⁵ a current pulse flows between the trigger and the cathode depositing electrons on the cathode screen. As in the Dumanchin device, the dielectric insures uniform current density. But because the Laflamme cathode can accelerate electrons into the laser volume, this device is also a compact-electron-gun-initiated discharge.

The Lamberton²⁵ Structure. The Lamberton structure employs electrodes which are Rogowski profiles.²⁷ This profile guarantees that the electric field is maximal in the uniform field region where the electrodes are plane parallel, or in other words, that there is not a favorable self-breakdown point in the structure, provided the electrodes are very carefully made. The trigger system is a simple pair of fine wires stretched midway between the electrodes and to either side. In qualitative terms, this design requires as much care in design and construction of the main electrodes as the others do in their trigger systems. The initiation mechanism is not well understood, but it probably involves photoelectron production at the cathode, due to ultraviolet illumination by the sheath which forms

around the fine trigger wires when they are pulsed, much as in a Geiger-Mueller counter.

Summary. Different stages of development make some of these initiation schemes appear more favorable than others currently, especially the Richardson-Séguin and Laflamme structures and the Daugherty structure. Nevertheless, no measurements or calculations exist to indicate that any of them are inherently more favorable in terms of achievable stored laser energy and gain. Accordingly, we are devoting major attention to the development of very compact and efficient amplifier structures, including the Daugherty one, but certainly not excluding the others.

Dumanchin Amplifier Investigation

The preceding section and the previous semiannual report describe the Dumanchin double-discharge TEA laser amplifier employed in the Phase I system. This device was tested extensively during the present reporting period. The tests fall into two categories: (1) electrical characterization, and (2) gain and gain-medium characterization.

Electrical Characterization. A switched passive network provides the discharge pulse for our TEA amplifiers, as shown in Fig. 31. (The anode-cathode

Fig. 31. Operating circuit for Dumanchin double-discharge trigger scheme.

spacing is 5 cm, with the total volume 10 by 11 by 100 cm.) This driving circuit requires careful shaping of the voltage pulse to prevent arc formation, since the trigger voltage pulse is synchronous with and proportional to the anode pulse. Separate timing of the two pulses is an obvious improvement which will be made if we decide that the Dumanchin structure has more advantages than the other types discussed.

In the simple shaping circuit of Fig. 31, C_1 provides energy storage while C_2 controls the pulse voltage risetime for proper initiation and to avoid excessive transients in the discharge structure. The resistance R_1 , much greater than the plasma resistance R_p , insures against trigger electrode destruction from voltage doubling if the main discharge fails to fire. C_1 is always several times C_2 , so that the unloaded oscillation period of the circuit is determined by $\sqrt{LC_2}$.

Initial selection of component values is achieved by simultaneously requiring that $2\pi\sqrt{LC_2}$ be less than the arc formation time of 5-10 μ sec, that $\sqrt{L/C_2} \approx 2R_p$ for approximate damping of the parallel network mesh (L, C_2, R_p), and that $\sqrt{L/C_1} \approx R_p/2$ for approximate damping of the series network mesh (C_1, L, R_p). Since the driving impedance of the discharge is highly nonlinear and since its actual voltage-current characteristic is excitation-dependent, optimization of the circuit parameters for best laser performance is presently achieved most easily in the laboratory. (For a discussion of discharge characteristics independent of lasing, and the use of an equivalent circuit model, see p. 44.)

Figure 32 shows some of the data obtained during this procedure. All data are for one cathode-anode section only, although each pulse-forming network drives two of these sections in parallel. From Fig. 32a it can be seen that the two sections can be characterized electrically as a dc source whose value decreases monotonically with helium richness in series with an incremental plasma resistance of about 4 Ω . This data is always terminated on the high end by a glow-to-arc transition, which seems to occur at a current density of no more than 3.5 A/cm². In any case, operation of the device is clearly in the "abnormal glow region" for which the incremental resistance is always positive. This behavior occurs when the cathode is completely covered by discharge sites.

The other data, picked with the optimum value of $\sqrt{L/C}$ uppermost, indicate that $\sqrt{L/C_1} = R_p/2$ and $\sqrt{L/C_2} = 2R_p$ for best operation, as predicted. No combination of conditions yielded a larger glow-to-arc transition current density than 3.6 A/cm². The maximum possible energy input to the gas mixture was found to be 94 J/liter; energy input was a moderately fast but nonsingular function of parameter changes away from the optimum combination. Based on these

Fig. 32. Data on Dumanchin current-voltage characteristics obtained in experiments to optimize the circuit parameters of Fig. 31. (a) For various gas mixtures (He:N₂:CO₂); $C_1 = 0.5 \mu$ F, $L = 11 \mu$ H, and energy input at 60 kV = 82 J/liter of mixed gas (except for upper curve, for which $C_1 = 0.75 \mu$ F, $L = 8 \mu$ H, and energy input at 60 kV = 94 J/liter of mixed gas). (b) For three values of the parameter $\sqrt{L/C_1}$ (shown on curves); $C_1 = 0.5 \mu$ F, energy input at 60 kV = 82 J/liter of mixed gas. (c) For two values of the parameter $\sqrt{L/C_1}$ (shown on curves).

measurements, a modular pulse generator for these amplifiers was designed, and parts were ordered for four such generators.

Gain and Gain-Medium Characterization. At present, small-signal gain measurements in the Phase I double

discharge show peak gain of about 0.025 cm^{-1} , with circuit parameters chosen for reliable operation. With this gain, two amplifiers will provide enough gain length (with multiple passes) to achieve the desired preamplifier output energy of 10 J. Higher gain will be possible if required, but might contribute to transverse superfluorescent depletion of stored energy in the amplifier.

In May, Dr. Ralph Wuerker of TRW Systems assisted us in completing a gain-medium quality survey of our Dumanchin structure by means of holographic interferometry. More than 100 double-exposure holograms were completed, using a pulsed ruby laser as light source. Figure 33 shows two typical reconstructions of holograms taken during amplifier operation.

These are transmission holograms, exposure being the result of interference of a reference beam and a beam transmitted through the laser medium. The first exposure is made with the discharge turned off, and the second at a selected time picked with reference to the previously measured gain curve. The presence of fringes in the double-exposed hologram is due to nonuniformities during the discharge which produce differences in the optical path length through the medium at $6943 \text{ \AA}$. Since electron densities are expected to be no more than 10^{13} cm^{-3} while neutral densities will be about $2.5 \times 10^{19} \text{ cm}^{-3}$ at 1 atm, electron density fluctuations will play a negligible part in changing the refractive index. The change in refractive index due to the presence of such low

electron densities at this wavelength will be $-dn_e/n_{\text{gas}} \approx 10^{-22}$, $n_e = 10^9$. On the other hand, the holographic technique will generate one fringe per half-wavelength of total path change between exposures, so that a single fringe corresponds to an average index change of 3.5×10^{-7} along the 1-meter path length through our laser at the ruby wavelength. Therefore, electron density changes will be unresolvable. In summary, one fringe will correspond to a neutral density nonuniformity of $dn_{\text{gas}}/n_{\text{gas}} = 0.3\%$, or, equivalently, a medium distortion of about $\lambda/30$ at the CO_2 wavelength.

In both pictures shown in Fig. 33, very little distortion is seen in the central region of the discharge. For reference, the twin cathodes are at either edge of the picture and the anode in the middle. Figure 33a shows the situation at peak gain. No visible distortion is present in the useful amplifier aperture. The periodic structure adjacent to the cathodes consists of repeating small density variations associated with the individual trigger electrodes, which are longitudinal (parallel to the line of sight) in the present amplifier. In Fig. 33b, we see that distortion close to the cathodes easily amounts to three fringes late in the discharge. This picture is included primarily because it shows a textbook example of arc formation in the right-hand amplifier section. A local avalanche has already progressed from cathode to anode at the time of the picture, and a dense return anode stroke or "streamer" has progressed almost halfway back to the cathode (cf. Fig. 12.2 of Ref. 20).

Fig. 33. Typical reconstructions of holograms taken during operation of the Phase 1 Dumanchin amplifier. (a) At peak gain. (b) $4 \mu\text{sec}$ after peak gain.

GENERATION OF SINGLE 1-NANOSECOND PULSES AT 10.6 MICRONS

As previously reported²⁸ we have produced single 1-nsec pulses (from a mode-locked pulse train) at 10.6 μm with peak powers of about 1 MW. These pulses will be the input for our high-energy, short-pulse CO_2 system and will also serve as a short pulse source for various support experiments.

The single pulses are switched out of a train of pulses produced by our mode-locked CO_2 TEA laser. The pulse selection technique, which incorporates a GaAs electrooptic crystal, features an inherently high extinction ratio and ease of selecting pulses near the peak of the train. We have continued to study the characteristics of the pulse train, and we have determined the pulse extinction ratio given by the single-pulse selection technique to be approximately 900:1.

By way of background, development of the CO_2 TEA laser²⁹ was a significant step toward obtaining single intense infrared pulses of short duration. These lasers, operating as they do at pressures near 1 atm and with rapid pulsed excitation, make short intense pulses possible. At these pressures the individual laser transitions in CO_2 have large collision-broadened linewidths which are necessary for the generation and amplification of short pulses. The 3-GHz width of an individual P or R branch line³⁰ will support in theory 0.1-nsec pulses. In addition the high pressure produces high molecular densities which, when coupled with the fast intense pumping, yield high gain and high stored

energy densities, both of which are important in obtaining intense pulses. A second step forward was achieved more recently when active mode-locking of a CO_2 TEA laser was demonstrated,³¹ producing pulse trains with individual pulses approximately 1 nsec in duration and peak powers in excess of 1 MW.

Experimental Setup

Our system²⁸ consists of a mode-locked TEA oscillator followed by a single-pulse selection stage as shown in Fig. 34. Our discharge tube is similar to one previously reported by Robinson³² and was described in the previous semiannual.²⁸ The discharge appears to be uniform. A mixture of 89% He + 11% CO_2 flows through the tube at 50 cfh and 1 atm pressure. The usual gas mixture for such a laser contains nitrogen as well as helium and carbon dioxide; in our case we found that removing the nitrogen resulted in greater shot-to-shot reproducibility without significantly affecting the laser's peak power.

Mode-locking of the laser is achieved with an acousto-optic loss modulator consisting of a germanium single crystal to which is bonded a LiNbO_3 piezoelectric transducer. The transducer is resonant at 25 MHz and has sufficient bandwidth to encompass several resonances of the germanium crystal (separated by about 150 kHz). Since amplitude modulation occurs at twice the rf drive frequency of the modulator³³ and mode-locking occurs when the AM

Fig. 34. Schematic of mode-locked CO_2 TEA oscillator and single-pulse selector.

modulation frequency is just equal to the cavity mode spacing³⁴ ($c/2L$), the cavity length was carefully set at approximately 3 m (50-MHz mode spacing). The modulator was operated at 1 W drive power which produced approximately 20% depth of modulation. Its insertion loss was 6% single pass. Placement of the modulator near a cavity mirror is dictated by the desire to obtain the minimum mode-locked pulsewidth.

A single intense pulse is switched out of the mode-locked pulse train by the pulse selector shown in Fig. 34. The pulse train makes a double pass through the polarizer (a germanium flat placed at Brewster's angle) and an electrooptic modulator ($5 \times 5 \times 50$ -mm GaAs crystal) with the aid of mirror *M-3* (99% R); the mirror is slightly misaligned to prevent the beam from reentering the laser cavity. The 1% of the pulse transmitted by mirror *M-3* is detected by a fast-response-time Ge:Cu(Sb) detector which drives an electronic circuit containing a pulse height discriminator. At a preselected pulse intensity a high-voltage Marx generator is triggered by the discriminator, applying a 10-nsec-long pulse to the electrodes of the GaAs crystal. By introducing the appropriate time delay the high voltage pulse is synchronized with the arrival of a particular pulse in the mode-locked train (20 nsec is the spacing of the pulses). Application of the quarter-wave voltage (about 6 kV in this case) to the crystal rotates the plane of polarization by 90° after a double transit through the crystal. The pulse whose polarization has been rotated is reflected out of the beam line at the Brewster's angle flat.

Some important features of the switchout electronics are its low delay-time jitter, ease of selecting a pulse near the peak of the train, and the small amount of radiant power required to operate the circuit. In Fig. 35 an overlay of 20 voltage pulses indicates that the delay time jitter is approximately

1 nsec; the total delay from triggering is approximately 50 nsec. Since the mode-locked pulses are separated by 20 nsec the jitter is no problem. A pulse near the maximum of the pulse train envelope is selected simply by adjusting the discriminator trigger level with the aid of a panel-mounted potentiometer so that the appropriate pulse earlier in the train triggers the Marx generator. Precise timing is accomplished with a variable passive delay chassis between the detector and the pulse height discriminator. Since *M-3* is a 99% reflecting mirror only about 1% of the beam is used to trigger the switchout device.

Operating Characteristics

The temporal and spatial characteristics of the output beam from the mode-locked oscillator described above have been experimentally determined. Typical output pulse trains from the device are 250 nsec long with pulses separated by 20 nsec. The peak power is approximately 1 MW with individual detected pulsewidths of 1.8 nsec (FWHM). Since the risetime of the detector and oscilloscope combined is 1.3 nsec, the "true" pulsewidth may be 1.3 nsec. The beam intensity profile and divergence were measured with the laser operating at 0.5 pulse per second by stepping a pinhole across the beam diameter in the near and far fields respectively. Figure 36 plots the intensity (entire pulse train) vs position across the beam for the near and far fields. From Fig. 36a one can see that the mode pattern approximates the TEM_{00} mode calculated for this cavity. This is to be expected due to the presence of the iris in the cavity which is stopped down to the calculated TEM_{00} mode beam waist (8 mm at the $(1/e)^2$ power points). A 2.0-mrad beam divergence (full width at the $1/e$ power points) is calculated from the data in Fig. 36b, the diffraction-limited divergence being 1.2 mrad for a TEM_{00} mode. The spectrum of the output beam has not been determined; however, others have reported finding oscillations only on the $P(18)$ line in the $10.6\text{-}\mu\text{m}$ band.³¹

We determined the pulse extinction ratio when a single pulse is selected from a mode-locked pulse train as follows: Fig. 37 is an oscillogram of a single pulse as detected in the switched-out leg of the pulse selector. The peak power of the pulse is about 40% of the peak power in the pulse train. The loss is due to the insertion loss of the GaAs crystal (about 12% per pass), its finite aperture, and the less than unity reflection from the Ge flat. To determine the extinction ratio, the sensitivity of the switched-out pulse detector was increased by a factor of 100 — by removing beam attenuations — and the beam intensity was again recorded as in Fig. 38. By comparing the intensity of the pulse in Fig. 37 with the intensity

Fig. 35. Overlay of 20 shots showing voltage vs time from the electrooptic modulator driver circuit (3 kV/division vertical, 2 nsec/division horizontal). Sweep started 40 nsec after a 1-nsec pulse was applied to the pulse height discriminator.

Fig. 36. Beam intensity profiles. (a) Near-field intensity plotted as a function of position along a beam diameter at a point 1.7 m from mirror *M*-2. A 0.5-mm pinhole was stepped across the beam while operating the laser at 0.5 pps. (b) Far-field beam intensity (divergence) plotted as a function of position along a spot diameter at the focal plane of a 2-m-radius-of-curvature mirror focused slightly off axis. A 0.25-mm pinhole was stepped across the beam while operating the laser at 0.5 pps.

Fig. 37. A single pulse switched out by the pulse selector (10 nsec/division). The anomaly 12 nsec after the pulse is due to a reflection at an impedance mismatch point in the detector circuit.

of the precursor pulses in Fig. 38 a pulse extinction ratio of approximately 900:1 is calculated. The amplitudes of the two pulse trains were determined to be approximately equal by monitoring the signal into the pulse height discriminator during the two shots. Although the first pulse after the selected pulse is typically four times the amplitude of the precursor pulses — due to a residual voltage on the crystal — the extinction ratio in the prepulse time region is more important for most applications.

Discussion

The high extinction ratio we observed is due in part to the pulse selection scheme employed (i.e., the single-plate polarizer-analyzer technique). If the germanium plate is at Brewster's angle to the oscillator output beam, in the absence of beam divergence and electrooptic crystal depolarization scattering, the precursor pulses do not get into the switched-out leg. Compare this reflection technique to the usual transmission technique of analyzing (as when mirror *M*-3 is replaced by another germanium plate rotated by 90° about the beam direction from Brewster's angle). Since the plate transmits part of the unwanted polarization, a finite extinction ratio is imposed. This ratio can be made larger in theory by using a stack of plates but then it becomes difficult to align them all to the proper orientation.

Extension of the techniques discussed herein to other wavelengths, shorter pulses, and higher peak powers is possible. Other *P* and *R* branch lines in the 10.6- and 9.6- μ m bands of CO_2 can be chosen by using a grating in the cavity. Still shorter pulses should be possible by increasing the pressure in the discharge tube, and the depth of modulation and frequency of the modulator.³⁵ Higher peak powers can be obtained by amplifying the single pulse with a chain of TEA amplifiers. A high prepulse extinction ratio will be very desirable in case the amplifiers are operated at saturation.

Fig. 38. Intensity of the beam in the switched-out leg (20 nsec/division). The sensitivity here is 100 times greater than in Fig. 37. The switched-out pulse is off scale in this oscillogram.

ONE-METER ELECTRON GUN

It is well established that large volumes of high pressure CO_2 can be pumped to high inversion densities by injecting an electron beam of densities greater than a few mA/cm^2 and energies greater than 100 keV from an external source. In this technique, a thin metal window separates the low-pressure electron gun cavity from the high-pressure gas cavity. The level of electron density is determined by the balance between recombination losses and the ionization caused by the primary electrons. A sustaining electric field (E) which causes no ionization in the absence of the primary electron beam is then applied to the gas medium (pressure p), and the energy of the secondary electrons is determined by the ratio E/p . Hence the electron density and E/p can be controlled independently, allowing for efficient excitation of the low-lying molecular vibration states.

Design

A 1-m-long by 20-cm-wide hot-cathode electron gun has been designed and constructed at LLL. In vacuum tube industry terminology, the gun would be described as a planar geometry, triode beam power tube. It is capable of electron energies in excess of 200 keV and has attained current densities in excess of 200 mA/cm^2 at the cathode. A schematic of the gun is shown in Fig. 39. The cathode is constructed of 100 pure tungsten filaments each 20 cm long and spaced 1 cm apart to achieve the active length of 100 cm. A grid spaced 2 cm from the cathode and composed of 160 40-mil-diam wires is used to control the beam current density. A 0.0015-in.-thick aluminum window is located 14 cm from the grid and separates the gun and gas cavities. The gas cavity has a circular aperture of 10 cm radius (31.4 liters of active volume) and

Fig. 39. Schematic of the 1-m electron gun for pumping large volumes of high pressure CO_2 to high inversion densities. T1 = filament powerstat (0-560 V ac), T2 = filament isolation transformer, C1 = grid bias capacitor (14.7 μF), SG1 = grid bias spark gap, R1 = grid bias resistor (100 $\text{k}\Omega$), C2 = gas sustainer bank (6 μF).

incorporates a protective grid of 14-gauge (0.083-in.-diam) brass wires located 2 cm from the electron window and electrically connected to it. The function of this grid is to intercept arcs from the anode and thus provide protection for the thin window. The ends of the cavity are equipped with Brewster-angle salt windows and the entire structure is capable of operating at up to 5 atm pressure.

Part of the design philosophy of the 1-m electron gun was dictated by test experience formed early in the year on the 10-by-20-cm (2-lite), test model. The test model was never made to operate satisfactorily as a triode. Apparently the most crucial problems were associated with poor vacuum conditions coupled with the high temperatures required for operation of the pure tungsten filaments. Outgassing from the filaments and field emission from sharp points in the filament-grid space caused plasma formation which shorted the grid to the filaments and made grid control impossible. Essentially the test model behaved like a pseudo-plasma cathode diode.

These problems have been overcome in the large electron gun by shielding sharp points in the

filament-grid space, maintaining clean ("white gloves") assembly conditions including washdown of all internal parts with alcohol followed by dry nitrogen, and improved vacuum conditions. The base pressure is approximately 6×10^{-8} Torr with a pressure rise to less than 10^{-6} Torr during operation of the filaments.

Experimental Effort

Figure 40 shows the experimental area. Much of the experimental effort the last three months has been directed toward characterizing the electron gun. The filament voltage-current characteristics have been established, and the triode curves have been obtained. Space charge and thermionic limits have been measured and the effective gain of the tube, μ , has been calculated from the space-charge-limited current flow ($\mu \approx 50$).

The negative 200-kV pulse for the electron gun is derived from a six-stage, 7.5-kJ Marx generator incorporating a series 50- Ω resistor for current limiting in case of an arc in the gun. Grid bias is provided by a simple combination of capacitor, resistor, and spark gap as indicated in Fig. 39. In practice the grid

Fig. 40. Experimental area for testing the 1-m electron gun.

bias capacitor, C1 in Fig. 39, is precharged to the desired gap, SG1, to overvoltage and bias the grid. The 20-mil tungsten filaments require 40 kW of power and are heated for 3 to 5 sec before application of the 200-kV pulse. Filament power is obtained from a variable powerstat which drives a filament transformer that is isolated for 250 kV dc primary to secondary. The powerstat, filament transformer combination is capable of 300 kW for 20 min on, 40 min off, thereby providing the ability to operate more than seven of the existing guns simultaneously. The gas sustainer capacitor bank is a straightforward 6- μ F, 100-kV bank without switching.* This bank is precharged to the desired voltage (less than the voltage required to produce breakdown in the gas) and is switched automatically by the electron beam entering the gas cavity.

One of the more serious problems for the large gun has been the development of adequate high-voltage, air-to-vacuum feedthroughs. The feedthroughs currently employed are commercial units; however, they are unsatisfactory from the standpoint of total system inductance because each feedthrough admits only one conductor into the electron gun cavity with no provisions for shielding. A feedthrough development effort has been under way at LLL and has recently resulted in the design of a coaxial feedthrough. A feedthrough test chamber has been built, and testing of the coaxial units is in progress.

Because of the enormous radiated power from pure tungsten filaments (which are operated at temperatures near 2800°K) and the poor mechanical properties (brittleness), a search for better filament materials is

being conducted. Among the materials being investigated are thoriated tungsten, tantalum, and rhenium. Results with tantalum have shown that it is not stable mechanically. We hope that one of the other materials will provide more current density at lower temperatures with better mechanical stability than pure tungsten.

A chopped, tunable, continuous-wave CO₂ probe laser is being employed to perform small-signal gain measurements including gain uniformity and reproducibility. Results are still preliminary. A single short pulse ($t_p \approx 1$ nsec) originating in a mode-locked pin oscillator and preamplified in several double-discharge lasers will eventually be available for amplification in the electron-gun-initiated power amplifier.

The projection for the next six months calls for parametrization of the short pulse properties of CO₂. Such data as gain, gain uniformity, gain reproducibility, saturation intensity, and breakdown intensity will be obtained as functions of pressure, pump power, and gas mixture. Other parameters to be investigated include maximum stored energy and energy available for short pulse applications.

As described elsewhere in this report (see for example the following article), several alternate electron-gun designs are in various stages of completion and could be incorporated as preamplifiers to extract all the energy available in the 31-liter electron gun described here. The result of this effort should soon culminate in the availability of a 100-J, 1-nsec pulse for preliminary target investigations.

ELECTRON-GUN DEVELOPMENT FOR LASER DISCHARGE STABILIZATION

A large-area electron gun capable of injecting electrons into a gas discharge region at pressures of 1 to 5 atm is required for high-energy CO₂ lasers and to study laser phenomena in other gases. Its function is to supply a uniform distribution of electrons in the gas volume so that a homogeneous discharge will be initiated in the presence of an applied electric field. The required current density and time duration of the pulse of electrons to be injected into the gas were determined from parametric studies using the four-temperature CO₂ laser computer code (CO2L4T) already developed at LLL.³⁶ The electron window material and thickness determine the accelerating potential required for optimum transmission through

the window. From these studies the final design parameters chosen were 200 kV accelerating potential with 2 A/cm² impinging on a 0.0005-in. titanium window with a pulse duration variable from 3 to 8 μ sec.

Three different prototype electron guns have been designed and are now being built: (1) a highly convergent Pierce diode gun with a curved dispenser cathode, (2) a planar diode gun with a flat dispenser cathode and a transparent mesh extractor anode, (3) a tetrode gun with a cathode of thoriated tungsten wire.

The design of these electron guns has been greatly facilitated by an electron-optics code that accounts for the lens effect of the anode, the beam space charge, and relativistic effects that are important for a 200-kV beam.³⁷ The code has proven very useful and is being rewritten from PL-1 to Fortran so that it can be utilized on the LLL computers.

*We realize that the 6 μ F is too small, and a 20- μ F, 100-kV bank is in planning and preliminary design.

Curved Cathode Diode

A basic electron gun using electrostatic focusing is a unipotential Pierce lens. The Pierce lens is a high-current-density lens in which the cathode and anode electrodes are shaped to match the space charge potential in the beam for a parallel beam between the cathode and anode. In the actual design of a Pierce diode gun the anode must have a hole for the beam to emerge. The hole has a negative lens effect that must be compensated for, and the cathode is shaped

accordingly. (A complete discussion of the Pierce gun is given in Ref. 38.)

The curved dispenser cathode (radius of curvature 1 m) is shown schematically in cross section in Fig. 41a. A highly convergent curved cathode was chosen so that the anode would thermally shield the thin electron window from the hot dispenser cathode.

The dispenser cathode used by this Pierce diode gun and the planar diode gun has several advantages over directly heated refractory cathodes.³⁹ It can be let up to atmospheric pressure many times, with little or no

Fig. 41. (A) Pierce diode electron gun has shaped anode with pass-through hole for electrons and curved dispenser cathode (radius of curvature 1 m). (b) For diagnostics, electrons striking the tungsten window are converted to x rays which are recorded on film as an indication of the electron distribution at the window.

degradation in performance after reactivation, and it operates at the relatively low temperature of 1025 to 1125°C which greatly reduces problems caused by heat radiation from the cathode. A dispenser cathode is formed by heating a sintered tungsten shape with a slurry of barium calcium aluminate in a hydrogen furnace. Electron emission is from the thin film surface of low-work-function oxides. The surface film is constantly being replaced by the diffusion of the oxides from the core of the cathode.

A full scale model of the computer lens design was made to verify the lens design and provide for final adjustment of the lens before fabrication. The model (in a glass bell jar) was also useful in determining high-voltage weak points in the insulator design and in shielding of unwanted field emission, as well as in diagnosing such thermodynamic problems as cathode temperature distribution and the effectiveness of the heat shielding.

The exit window in the model is a 2-mil tungsten sheet that acts as a transmission-type converter of target electrons to photons (x rays). The x rays penetrate through the glass bell jar and are imaged at the film plane by a pinhole camera fabricated from a sheet of lead as shown in Fig. 41b. This arrangement gives simple diagnostics of the electron distribution at the window.

The electron model work has been temporarily discontinued because of the large quantities of x rays being generated. Meanwhile the system is being modified to accommodate more effective lead shielding.

A high voltage pulser (output 200 kV, 200 A, 3- μ sec pulse width) was designed, built, and has been successfully used for testing electron gun models. The pulser is capable of repetition rates of 1 to 30 pulses per second at 200 kV. The minimum repetition rate is determined by the leakage current through the charging diodes of the resonant charging circuit. The dc voltage is stepped up to 100 kV by a resonant charging choke through charging diodes. A 100-kV Thyratron 5 is used as the HV switch.⁴⁰ A 100-kV pulse-forming network with an impedance of 40 Ω and a pulse length of 3 μ sec is used. A Pearson HV pulse transformer was modified to a 5:1 to step up the 50-kV pulse generated by the network to about 225 kV.

Flat Cathode Diode

A flat dispenser cathode gun with a transparent mesh anode has also been designed. This gun is shown in cross section in Fig. 42. It will be simpler to build than the curved cathode and will be able to give a very uniform distribution of electrons across the entire

Fig. 42. Flat-dispenser cathode gun with transparent mesh anode. This design is easier to build than the curved-dispenser cathode gun and should give a very uniform distribution of electrons across the face of the electron window.

face of the electron window. An electron model of this gun will also be tested as described for the curved cathode diode.

Tetrode

A more complex multigridded-structure electron gun can provide more versatility in operation where a variable current density and variable accelerating potential are required. These characteristics are desirable for determining optimum laser parameters for the CO₂ laser systems and for studying other gases for laser phenomena. The triode structure is the next complication over a diode. The control grid can be used to modulate the current at the anode, but in pulse operation with risetimes in the microsecond region,

control grids tend to self-oscillate; therefore an additional screen grid is required. This tetrode structure is utilized quite successfully in beam power transmitter tubes with cathode areas of the same order as required for laser electron guns. (A purchase order for a tetrode gun structure installed in an LLL vacuum envelope has been initiated with Eimac Division of Varian Associates, who manufacture beam power tetrodes. They are using the SLAC electron-optics codes to determine the appropriate electrode placement for uniformly illuminating the window. If these codes demonstrate a uniform current distribution, Varian will fabricate a gun structure to this design and will install it in an LLL envelope.)

Other Developments

A stainless steel envelope has been designed that will house each of the electron guns fabricated. It will weigh approximately 350 lb and will be capable of withstanding a 400°C bake during processing. This fully bakeable system will allow sealed-off vacuum operation except when the electron window ruptures. Two of these envelopes are now in fabrication.

A gas-laser discharge chamber has been designed and is being fabricated that will connect directly onto the electron gun. Both will be mounted on a portable stand.

We expect that the flat dispenser cathode gun will be completed by mid-July and will be used first in studying gain and gain uniformity in high-pressure short-pulse CO₂ lasers.

ATMOSPHERIC-PRESSURE DOUBLE DISCHARGE STUDIES

Our objectives are to gain an understanding of the principles of operation of atmospheric-pressure double discharge devices and to apply that understanding to the development of high-specific-energy gas lasers. In order to achieve these objectives the double discharge devices have been studied experimentally to determine their characteristics as electrical devices and to establish a model which describes the essential features of their operation. The laser characteristics of these devices have not been included in this study (see next article). The result of this investigation is an equivalent circuit model which describes the principal features of the double discharge device, points out the scaling laws and limiting features, and provides a basis for design of double discharge devices and associated discharge circuitry.

The first double-discharge laser was that reported by Dumanchin in 1970.¹⁷ Since that time the literature has been deluged with reports of a multitude of different double-discharge devices.^{17,25,26} Each has some specific merit relative to the others, but they all have the common features of a primary discharge between a cathode-anode electrode pair and a third or trigger electrode in the discharge region. The term "double discharge" results from the technique of pulsing the trigger electrode relative to the anode or cathode and thereby creating a discharge which is effective in initiating the main discharge in a uniform manner. This principle of operation is shared by all the various double-discharge devices, and it is the basis for formulating the equivalent circuit model described below.

Using several double-discharge devices⁴¹ of the Dumanchin type (one of which is shown in Fig. 43), we made experimental measurements of the device

characteristics using a wide range of external circuits, discharge electrode configurations, and gas mixtures. From these data several features of the double discharge are immediately seen:

1. General features of the discharge such as peak current, pulse shape, and pulse length are determined by the external circuitry.

2. It is possible to treat the entire double discharge as a simple electrical circuit by formulation of a nonlinear equivalent circuit element to represent the gas discharge. Such a treatment allows calculation of double discharge behavior which is both quantitatively and qualitatively accurate.

3. Most of the pumping limitations that result from arcing are the result of cathode processes which are controlled by the gas mixture, cathode material, and cathode heating.

One essential piece of information which is useful in formulation of an equivalent circuit element for the discharge and in generally understanding the double discharge device is the dynamic current-voltage characteristic of the device as shown in Fig. 44. Also plotted in Fig. 44 is the inferred static current-voltage characteristic which is a locus through the points on the dynamic characteristics that correspond to zero values of the time derivative of current. The glow discharge nature of the main discharge is seen from the zero derivative characteristic which has typical direct-current glow characteristics.⁴² The departure of the high-pressure dynamic characteristics from the dc glow curve is then the result of two inductive-type effects in the discharge. The first is just circuit inductance while the second is the inductancelike effect caused by a time lag in generation of current carriers by the glow discharge processes. Consideration

Fig. 43. Dumanchin type double-discharge device is used for experimental analysis of a wide range of atmospheric-pressure double-discharge devices by varying external circuits, discharge electrode configurations, and gas mixtures.

of the data of other investigators indicates that other types of double discharges operate in the same mode, and in fact the pin-type discharges also have the same type of characteristics when the voltage drop across the ballast resistors is taken into account. The conclusion drawn from data like that of Fig. 44 and supported by other experimental data is that the double discharge devices can be characterized as pulsed high-pressure glow discharges.

The glow discharge has been widely studied and is well understood.⁴² The existing theory can be extended to the high pressure case provided that heating of the gas and cathode are carefully considered. Briefly then, the high pressure glow is a constant voltage device and the total current is determined by the external circuit parameters. Before the discharge can operate in a normal glow region it is necessary to increase the voltage across the gap to the "breakdown" voltage which is typically about twice the operating voltage. It is essential that the circuitry have enough impedance to limit the peak current to a value which will not result in arcing behavior. This impedance is provided by resistance in the pin lasers

and by inductance in the case of the double discharge devices. The cathode current density in a simple glow discharge is described by the relation⁴³

$$j = J_0 p^2 \text{ (A/cm}^2\text{)},$$

where J_0 is a constant which depends on gas mixture and cathode material and p is pressure in Torr. (Typical values of J_0 range from 2×10^{-6} A/cm²-Torr² for He to 400×10^{-6} A/cm²-Torr² for N₂.) Because the cathode current density is constant for glow discharges, the emitting surface area must change as total current changes. This points out that for lower current operation of the device only a small fraction of the cathode surface is emitting. Uniformity must be insured by uniform distribution of initial discharge over the cathode surface. This of course is caused by the trigger discharge, which provides a uniform distribution of electrons near the cathode surface. These initial electrons result from a geometry-dependent combination of direct ionization and cathode photoemission. The presence of the initial electrons reduces the high breakdown voltage normally

associated with the glow discharge and allows more reliable operation in the constant voltage region of the current-voltage characteristic.

The glow discharge has a characteristic uniform-field region called the positive column which occupies most of the discharge volume. A very thin ($\ll 1$ mm) high-field region called the cathode fall is also present and represents a few hundred volts potential drop. The positive column is characterized by a ratio of electric field to pressure (E/p) which is constant for a given gas mixture. Data showing the voltage drop measured at peak current for several gas mixtures as a function of electrode separation are shown in Fig. 45. These data verify that the electric field is uniform across the gap and they also show that the ratio E/p is constant for a given gas mixture. These measurements show that the value of E/p is consistent with low pressure measurements but somewhat lower than the values often given for double discharge devices. This likely

reflects the common use of capacitor charging voltage instead of gas voltage drop for computing E/p values.

The use of the equivalent circuit model of constant-voltage glow discharge allows calculation and interpretation of the basic features of the double discharge devices. The model has been used successfully, both to analyze resonant discharge circuits and to design a 5- μ sec lumped line to give constant-current pulses as shown in Fig. 46. This model promises to be a systematic tool for designing future discharge devices and circuitry and a basis for more detailed understanding of them.

An understanding of these discharge features will aid the laser development in a more basic way than just to increase discharge current. From the data of Fig. 45 it becomes clear that each of these discharges operates at a fixed value of E/p . This value allows calculation of laser pumping for the double discharge using a parameter which is directly related to the electron

Fig. 44 Dynamic voltage-current characteristics for a 10-by-10-cm Dumanchin double-discharge device with 5-cm electrode spacing. Gas mixture is $\text{He}:\text{CO}_2:\text{N}_2 = 90:5:5$, pressure = 760 Torr, capacitance = 0.04 pF, and total pulse length = 2 μ sec.

Fig. 45. Variation of cathode-anode potential with gas mixture, cathode-anode separation, and pressure. Potential is measured when the derivative of current is zero (i.e., at peak current).

temperature and distribution. Measurement of that value for different mixtures will allow a choice of gas mixture based on double-discharge pumping efficiency once such calculations have been made. The use of an approximately constant current pulse as shown in Fig. 46 will allow calculations which can be realistically compared to experiment.

This effort is continuing in conjunction with experiments to investigate the role of ultraviolet light in the triggering mechanism.

Fig. 46. Voltage (top) and current (bottom) from a matched pulse-forming network. Total sweep length = 8 μ sec, sensitivity = 7 kV/division and 850 A/division, capacitor voltage = 13.5 kV, total capacitance = 0.4 μ F, and the gas is He at 760 Torr.

As reported in the previous semiannual⁴¹ we have obtained typical laser output energies of 17 J/liter with our double-discharge TEA CO₂ laser. Since then we have concentrated our efforts in the following four areas:

1. Study of the medium homogeneity of the inverted gas. This determines the uniformity of the laser output intensity and can also affect the beam divergence.

2. Measurement of the small-signal gain. This indicates the degree of inversion achieved in the excited medium and allows one to calculate the pulse amplification obtainable.

3. Mode-locking of a CO₂ double-discharge laser and amplification of mode-locked pulses.

4. Scaling to larger discharge gap.

We discuss each item in more detail below.

Our original work involved a longitudinal double-discharge system with the laser axis parallel to the direction of the cathode strips and the trigger glass rods.^{18,41} However, the discharge current from different cathode strips will not, in general, be the same. This can cause gain variations in the medium which show up as laser output variations. To remove, at least in part, these spatial inhomogeneities, we constructed and operated a 1-m transverse system with the direction of the cathode strips and the trigger glass rods perpendicular to the laser axis. The variation in discharge currents from the different cathode strips should not be observed in such a system.

The medium homogeneity of the 1-m longitudinal and transverse systems was measured with a double-pulsed ruby holography technique by R. Wuerker of TRW. The wavefront distortion of the gas for the 1-m longitudinal system at the time of peak gain (approximately 7 μ sec after initiation) is, at the worst, $\lambda/40$ for CO₂ wavelengths. The holograms for the 1-m transverse system have not been analyzed in depth, but initial results indicate an improvement in medium homogeneity over the 1-m longitudinal system. The improvement is, however, not as large as anticipated. The results do show that the medium homogeneity is very good even for the longitudinal system.

Several attempts were made to obtain the small-signal gain measurements. However, mechanical vibrations, thermal turbulence, and electrical interferences prevented reliable determinations. The best measurements indicate that the peak gain is approximately 2%/cm for the 1-m longitudinal system. Although peak gains of about 4%/cm have been obtained with double discharge systems, reliable operations (no arcing) usually require more conservative operating conditions which result in a

peak gain of 2-2.5%/cm.⁴⁴ Gain measurements as a function of gas mixture, discharge conditions, wavelengths, and pulse width will be performed.

Self-mode-locking and active mode-locking of a 0.5-m transverse system were attempted. The pulse train obtained in the active mode-locking case for the TEM₀₀ mode typically contained pulses of about 1.5 nsec in width as observed by a photon drag detector and displayed on a Tektronix 7904 scope. We note, however, that in about 20% of the pulses we see indications that the mode locking is not perfect. We still have not found the cause of this problem.

The energy of a single pulse in the train can be obtained by measuring the area enclosed by the pulse as displayed on the scope. The energy estimated in this manner for the most energetic pulse in the train contained about 5 mJ. This is to be compared to about 1-mJ output pulses obtained from the typical pin mode-locked systems (see for example, the article on CO₂ oscillators).

When a mode-locked pulse train was propagated through a 1-m longitudinal system, amplification of about a factor of 3 was observed. We note, however, that the spectral content of the mode-locked pulse train did not correspond to that of the amplifier because of the different operating conditions, hence lowering the gain of the amplifier for such pulses. We will shortly be attempting to switch out and amplify a single mode-locked pulse.

Scaling of double discharge systems to larger apertures is of twofold importance:

1. High laser output intensity from small-aperture amplifier systems causes breakdown in gases.

2. We would like to pump more volume for higher energy outputs.

We have increased the discharge gas for a 1-m longitudinal system to 10 cm and operated the system with a He:CO₂:N₂ mixture of 10:1:1 at about 60 kV across the discharge gap. The maximum main discharge current was approximately one-half of the current obtained with the same system at 5 cm discharge gap. Preliminary energy measurements indicate that the laser energy output/volume is also halved. Attempts to increase the voltage and thereby increase the discharge current resulted in streamer formation from the anode across the discharge gap to the cathode. We have tried to overcome this problem by the addition of a trace of xylene to the gas mixture.⁴⁵ We found an increase in the discharge current, but this increase in current did not enhance the laser output. On the contrary, we found that the addition of xylene quenched the laser action. Other techniques of scaling the output aperture will be tried.

In the high-powered CO_2 laser systems under development, optical isolators will be required between adjacent amplifiers to prevent amplified superfluorescence from depleting the population inversions prior to the main pulse. We tested a potential bleachable isolator system consisting of SF_6 as the saturable absorber and $\text{CCl}_2 = \text{CF}_2$ and CF_2Cl_2 to absorb those CO_2 frequencies not absorbed by SF_6 . The bleached transmission of the system was too low because of the high pressures of the nonbleaching "sideband" absorbers required to attenuate all CO_2 laser lines by more than 95%. We are continuing to investigate other isolator systems.

The function of the optical isolator system will be to absorb the spontaneous emission at all CO_2 lasing frequencies (especially the high-gain frequencies) sufficiently for successful operation of the amplifier system. The optical isolator must bleach, i.e., become transparent, at the frequency of the CO_2 laser pulse to be amplified by the system (the ~ 1 -nsec pulse switched out from the mode-locked laser). Bleaching occurs when there is equal population of the upper and lower vibration-rotation states of the absorber. Absorption and stimulated emission are equal in such a system, and it thus becomes transparent at the frequency of the transition between the states.

The frequencies of the CO_2 molecular transitions $00^0 1 \rightarrow 10^0 0$ and $00^0 1 \rightarrow 02^0 0$ are shown in Fig. 47. These are the well-known CO_2 laser transitions. The high-gain P branch lines of the $00^0 1 \rightarrow 10^0 0$ (10.4- μm) band are on the left with successively lower gain branches to the right. The rotational distribution is peaked near $J = 20$ to represent a system near room temperature. The intensity distribution is only approximate and is meant

Fig. 47. Frequencies of the molecular $00^0 1 \rightarrow 10^0 0$ and $00^0 1 \rightarrow 02^0 0$ laser transitions in CO_2 .

to show all lines that should be attenuated by the isolator system.

With the exception of heated CO_2 ,^{*} no single gas can be expected to absorb strongly at all CO_2 laser frequencies and to bleach at the frequencies expected from the mode-locked CO_2 laser ($P(16)$ to $P(22)$ of $00^0 1 \rightarrow 10^0 0$, usually $P(18)$ or $P(20)$). Gases such as SF_6 (Ref. 48), BCl_3 (Ref. 49), PF_5 (Ref. 50), vinyl chloride (Ref. 51), and propylene (Ref. 47) are known to absorb and bleach at these frequencies. Many other gases absorb at CO_2 laser frequencies and will probably bleach.^{52,53}

The bleaching of SF_6 has been studied extensively by others.^{54,55} We have tested an isolator system based on SF_6 as the bleachable absorber and 1,1 dichloro-2,2 difluoroethylene and dichloro-difluoromethane to absorb the CO_2 laser lines not sufficiently attenuated by SF_6 . The absorptions of these gases in the CO_2 laser line region is shown in Fig. 48. SF_6 at 20 Torr-cm (pressure times path length) absorbs from $P(10)$ to $P(30)$ and is nearly completely absorbing from $P(12)$ to $P(26)$ of the 10.4- μm band. CF_2Cl_2 at 300 Torr-cm absorbs $P(30)$ and higher P lines of the 10.4- μm band and the R branch lines of the 9.4- μm band. The 2000 Torr-cm of $\text{CF}_2 = \text{CCl}_2$ absorbs the P branch lines of the 9.4- μm band and most of the R branch lines of the 10.4 band. In order to absorb the low R and P branch lines of the 10.4 band, we increased the amount of $\text{CF}_2 = \text{CCl}_2$ to 4000 Torr-cm in our test.

We tested this system of gases in the configuration shown in Fig. 49. The system was tested at two powers. The low-signal transmission was tested with a Coherent Radiation model 42 cw laser equipped with a grating to permit operation on most of the lines shown in Fig. 44. The output power could be adjusted from 1 to 40 W for the high-gain lines of each branch, but it was generally maintained below 3 W when testing low-signal transmissions. The high-power transmission was tested with a 215-pin TEA laser: that has an output pulse with 200 nsec half-width and 0.4 J energy. The beam area is about 0.5 cm^2 , corresponding to a power of about $4 \times 10^6 \text{ W/cm}^2$. We examined the output of the TEA laser with a monochromator and found it to be maximum (over 90% of the energy) at one of four lines near 10.6 μm : $P(16)$, $P(18)$, $P(20)$, or $P(22)$.

The absorber cells are 20 cm long and are provided with NaCl Brewster-angle windows and a sidearm trap

* Heated CO_2 may not absorb strongly enough to act as a good attenuator and yet be efficiently bleached. It has been demonstrated that heated CO_2 does saturate and bleach.⁴⁷

for freezing out the absorber gas. The transmittance of the system is determined with all gases removed and with any combination or all of the gases in the

Fig. 48. Absorption of three isolator system gases in the CO_2 laser frequency region. Absorption patterns are overlaid on the frequency distribution of Fig. 47.

laser beam. The system of 20 Torr-cm SF_6 , 4000 Torr-cm $\text{CF}_2 = \text{CCl}_2$, and 300 Torr-cm CF_2Cl_2 absorbed all the CO_2 lines except about 2 to 3% of $P(6)$ to $P(10)$ of the $10.4\text{-}\mu\text{m}$ band at low signal. The transmission of this system with the high-power ($4 \times 10^6\text{-W/cm}^2$) pulse was only 35%. The high-power transmission with the SF_6 removed was 37%. Approximately the same low-signal transmission was found for the system without SF_6 at $P(18)$ with the cw laser. The transmission of each of the individual gases for the high-power TEA laser pulse was 94% for SF_6 , 94% for CF_2Cl_2 , and 40% for $\text{CF}_2 = \text{CCl}_2$. Accuracy of the transmission measurements is about $\pm 2\%$.

The transmission of the system for the TEA laser pulse could be increased to nearly the value for SF_6 alone by reducing the amount of the other two absorbers, especially the $\text{CF}_2 = \text{CCl}_2$. However, this would increase the low-power transmission of the low P and R lines of the $10.4\text{-}\mu\text{m}$ band to nearly 100%. Compounds with absorption bands centered near $10.4\text{ }\mu\text{m}$ could attenuate these lines. Two such compounds, CH_3CF_3 and $\text{CF}_3\text{CF}_2\text{Cl}$, are currently being evaluated.

The narrow width ($\sim 10\text{ cm}^{-1}$ at 20 Torr-cm) of the SF_6 absorption band is the major problem of the system. Most infrared absorption bands are not sharp cutoffs, and finding compounds to precisely match the areas of CO_2 emission not absorbed by SF_6 is difficult. A better solution would be to use a saturable absorber gas that absorbs all or most of the P branch lines of the $10.4\text{-}\mu\text{m}$ band and possibly some of the R branch lines. The compounds BCl_3 and PF_5 both have wider bandwidths than SF_6 . The PF_5 absorption maximum is centered near $P(20)$, while BCl_3 has a band from $^{11}\text{BCl}_3$ ($\sim 81\%$) absorbing P branch lines and a band from $^{10}\text{BCl}_3$ ($\sim 19\%$) absorbing R branch lines.

Systems based on these two compounds and other saturable absorbers with broad bands will be investigated.

Fig. 49. Schematic of apparatus for observing the transmission of bleachable isolator systems. The laser may be a cw tunable laser or a pin TEA laser, there may be any number of absorber cells with various gas phase absorbers, and the detector may be a calorimeter or a Ge(Au) detector.

Gas Laser Research

VACUUM-ULTRAVIOLET STUDIES OF RARE GASES EXCITED BY PULSED HIGH-ENERGY ELECTRON BEAMS

Atoms of the rare gases (helium, neon, argon, krypton, xenon, and radon) in their ground states normally repel each other. However, all the rare gases form fairly stable positively charged ions consisting of two atoms (dimer ions) such as He_2^+ , Xe_2^+ , etc. Adding an electron to these dimer ions can give rise to many excited molecular electronic states — He_2^+ , Xe_2^+ , etc. — where the asterisk denotes an excited molecule or atom. When these excited rare-gas dimers return to their ground state (in which the two atoms fly apart, since the ground state is repulsive), they emit radiation in the vacuum or far-ultraviolet (500-2000 Å) and the near-ultraviolet (2000-3000 Å) regions of the electromagnetic spectrum. This radiation is continuous; that is, it is emitted over a broad band of wavelengths rather than being confined to certain discrete wavelengths. These continuous emissions of the excited rare gases have been known for some 40 years,⁵⁶ and more recently they have found application as convenient light sources covering essentially the entire vacuum ultraviolet region for wavelengths longer than about 1000 Å.⁵⁷

Certain of these continuous bands of radiation are observed with very similar characteristics in all three phases of the excited substance — gas, liquid, and solid. For example, the argon continuum centered near 1300 Å resulting from excitation by americium α -particles exhibits essentially identical lineshapes (within about 10%) for all three phases. On the basis of this observation one is strongly motivated to conclude that the excited species in all cases very closely resemble the gaseous dimer which is only negligibly influenced by the weak van der Waals (attractive) forces of the surrounding neighbors in the liquid and solid. This immediately suggests the possibility that these systems may be successfully operated at liquid or solid density. In this connection it is interesting to note that at an active density of $2 \times 10^{19} \text{ cm}^{-3}$ (about 1 atm), and assuming roughly 1 Ry (rydberg) per system, the stored energy density corresponds to nearly 50 kJ/liter, a figure that is in the same ballpark with the 10^5 to 10^6 J of laser pulse energy estimated to be required for anticipated laser-fusion applications.

Recent Soviet experiments with xenon excited by high energy electrons, reported by Basov et al.,⁵⁸ have demonstrated the feasibility of coherent generation (i.e., lasing) with these systems at liquid density. The Russian workers have also indicated in private

communication that they have obtained similar results in high-pressure xenon gas. It is anticipated that lasing may be obtained from the other rare gases in a similar way.

The basic purpose of the work reported here is to provide a more detailed experimental analysis of rare gas systems under excitation by pulsed, high-current, relativistic electron beams. In order to achieve this goal we have begun experiments which enable us to measure the time-resolved spontaneous emission spectra of the rare gases excited by an electron beam. In this way we have obtained data concerning the kinetic steps and time scales associated with these systems. We present here some preliminary data and analysis relating to our experiments in examining Ar, Kr, and Xe at pressures from zero to 5 atm.

Electronic States in the Rare Gases

Figure 50 shows the potential energy of the excited and ground states of the rare gas dimers as a function of the separation R between the two nuclei. Normally there are two series of excited states, the triplet and

Fig. 50. Potential energy as a function of internuclear separation, R , for ground state, $V(R)$, and typical lowest excited molecular states, $V^*(R)$.

the singlet states. Characteristically, the triplet state lies at a slightly lower energy than the singlet state.

At a specific internuclear separation R_0 there is a substantial minimum in potential energy — a region of stability — which supports several energy levels that represent different vibrational states of the rare gas molecule. By contrast, the ground state is strongly repulsive at internuclear separations near R_0 , which is why the rare gases normally exist as single atoms. The ground state of the rare gas dimers shows only a very slight potential minimum; this is due to van der Waals attractions, which arise when two atoms near each other displace the center of the negatively charged electron cloud from the center of the positively charged nucleus, thus creating weak electric dipoles that can interact.

The precise locations of these excited-state curves are not known for many of the individual rare-gas dimers, although the literature contains considerable data for He_2 and Xe_2 . These molecular systems are extremely complex; more than 60 electronic states are known for the simplest one, He_2^+ .

To a very good approximation, these excited molecular dimers can be regarded as Rydberg states. A Rydberg state is an electronic state in which a single excited electron orbits largely outside the region occupied by the (usually) singly charged molecular-ion core — e.g., He_2^+ . This approximation allows us to calculate such properties as energy levels and the rates of transition between them on the basis of an essentially one-electron picture. The other electrons, present in the core, need not be considered individually. The potential curves given by Ginter and Battino⁵⁹ for He_2^+ strikingly indicate the validity of this approximate model.

Mechanisms Operating in the Rare-Gas Molecular Systems

Although the rare gases are normally considered to comprise one of the simplest classes of materials, we nevertheless find that several processes contribute to the kinetic scheme which leads to neutral molecular formation. Some of these processes, illustrated by the example of Xe, are the following:

Reactions (1) and (2) represent the excitation and ionization generated by both the high-energy primary electrons as well as the sufficiently energetic secondaries. Electrons can also lose energy radiatively. However, for the electron energies of interest this loss is low, being less than 8% in the highest Z case, xenon. These excited and ionized atoms will then combine in three-body processes to form the corresponding molecule and molecular ion as represented by (3) and (4). The dissociative recombination process (5) then provides a channel to convert the ionized material into excited atomic species. Process (6) illustrates a spontaneous radiative bound-free transition of the molecular system corresponding, for example, to the $3\Sigma_u^+ \rightarrow 1\Sigma_g^+$ transition shown in Fig. 50. In the higher Z materials (e.g., Kr₂ and Xe₂) it is anticipated that the spin selection rule is quite ineffective, as it is in the atomic case. Atomic and molecular relaxation processes are indicated in (7), (8), and (9). Processes (10) and (11) represent photoionization and Penning ionization. These losses can severely limit laser performance by competition with the stimulated rates and by collisional loss to the ionic state.

Experimental Apparatus

A schematic of the experimental apparatus is shown in Fig. 51. The output of the electron beam machine (Field Emission Corporation model 705) enters the gas chamber through a thin (~3-mil) titanium window where it is guided magnetically by a focusing coil energized by a 20-kV capacitor bank. Since the response time of the magnetic guide-field circuit is very long (>50 μsec) on the time scale of interest (<400 nsec), the value of the magnetic field during the experiment can be regarded as constant. At the far end of the magnetic coil it is observed that the electron beam rapidly expands and terminates on the tube walls. Spatial profiles of the time-integrated electron current density for the beam propagating in 1 atm of air are shown in Fig. 52. The profiles correspond to various distances along the axis of the gas chamber tube in the region where the axial external guide field is effective. These densitometer readings show that the beam propagates with essentially cylindrical symmetry very nearly down the center of the tube.

Experimental Results

Data was taken on pure Ar, Kr, and Xe as well as Ar-Xe mixtures at gas pressures between zero and 5 atm. In addition, some preliminary measurements were performed on H₂ and H₂-Ar mixtures.

Pure argon, krypton, and xenon samples were studied over a wide range of densities. These investigations examined the spectral features of the

Fig. 51. Schematic of experimental equipment for making vacuum ultraviolet studies of rare gases excited by a pulsed high-energy electron beam.

Fig. 52. Isodensitometer recordings of time-integrated electron deposition (in 1 atm air) at various distances from the electron-beam source plane. The beam profile is roughly Gaussian with 90% of the energy inside a 2-cm diameter.

emitted radiation in order to appraise the detailed properties of each substance including the time dependence of the atomic and molecular populations. The major fraction of the data was taken in the wavelength region from 1100 to 2500 Å with a resolution of 50 Å at gas pressures varying from 250 to 850 Torr. In the later stages of these experiments a strengthened gas chamber was used, enabling us to examine gases up to pressures of 10 atm.

As an example of the results, spectral data for pure krypton at 850 Torr are plotted in Fig. 53 for early times (50, 100, and 150 nsec). The spectral feature

located at 1500 Å is at the position of the expected molecular continuum originating from transitions between the lowest-lying bound excited states and the repulsive ground state. Very probably this radiation arises primarily from a set of completely vibrationally thermalized levels of the $^3\Sigma_u^+$ state, although we cannot rule out the presence of a contribution from the $^1\Sigma_u^+$ state on the basis of these and other data taken at higher resolution. As in the case of argon, a substantial amount of radiation centered at approximately 2200 Å is observed at longer wavelengths. The component at 2200 Å which is

Fig. 53. Computer-generated, time-resolved spectra for xenon gas at 850 Torr and a magnetic field of 12 kG.

Fig. 54. Normalized line profiles for krypton gas at 1 and 5 atm. Magnetic field strength at all points is 12 kG, resolution of wavelength measurement is ~ 2.5 Å.

strong and broad at early times relaxes initially to a narrower feature and then decays in amplitude at longer times. The time dependence of the 1500-Å continuum, however, is observed to have a roughly reciprocal behavior in relation to the 2200-Å component; it is relatively weak at early times and grows to its maximum as the 2200-Å emission diminishes in strength. This type of response is very suggestive of a radiative cascade process in which the higher states radiating at about 2200 Å produce population in the levels responsible for the 1500-Å continuum. Nevertheless, it has not been possible to

positively identify the origin of the longer wavelength 2200-Å component. In certain respects this situation is analogous to the observations in argon and to other experimental results reported for xenon. We will return to this point later.

Since the molecular formation process (3) is a three-body event, the rate should scale like the square of the gas density. The excited state populations of Kr_2^* should then be greatly enhanced at higher densities. With this in mind, we decided to examine the 1500-Å continuum of krypton under higher resolution as a function of density in order to detect the presence of gain narrowing of the spontaneous emission line (see Fig. 54). The instrumental resolution in both cases is < 5.0 Å. The wings of the line are very nearly the same while a clearly discernible narrowing occurs in the vicinity of the maximum of the 5-atm curve. This is precisely the type of behavior expected for a gain-narrowed resonance; the greatest effect should occur at the peak of the line.

In order to verify the interpretation of the gain narrowing as amplified spontaneous emission, we are now building a high pressure cell in a transverse geometry (optical axis perpendicular to electron beam axis) which will enable an optical cavity to be coupled to the excited medium. If optical gain is present, coherent oscillation should be observed under these conditions.

Discussion of Results

The continua of argon, krypton, and xenon at approximately 1300, 1500, and 1700 Å respectively have been observed when these substances were excited with relativistic electron beams. These bands are attributed to transitions from the lower excited states of the excited homonuclear dimers to the $1\Sigma_g^+$ ground repulsive state. In addition, we have seen considerable radiation displaced to longer wavelengths in argon and krypton. A similar result has also been reported in xenon at about 3000 Å.⁵⁸ Such longer wavelength continua appear to be systematic phenomena. In these experiments it seems quite unlikely that they are generated by impurities or fluorescence of the LiF window. Although the evidence for this conclusion is presently far short of a proof and further diagnostics will be required to explicitly verify this issue, this view appears quite reasonable in light of the fact that these continua are characteristic of the specific materials and that the LiF window showed no indication of radiation damage.

At this point the precise origin of these longer wavelength continua is not clear. Initially, it is tempting to associate them with transitions between higher excited states of the Rydberg series of the

excited dimers. Difficulty with this interpretation, however, is encountered immediately. For example in krypton, the available energy range between the Kr_2 ($3\Sigma_g^+$) state and the lowest corresponding ionic state $Kr_2^+ + e^-$ is not sufficient to accommodate a transition at 2200 Å. The same conclusion follows in argon and also for xenon in the case of the ~3000-Å continuum as pointed out by Mulliken.⁵⁹ If one wishes to assign the origin of these spectral features to the rare-gas dimer states, it appears that an alternative description is required. One possibility, although quite

speculative, is the presence of additional states based upon an excited core configuration as suggested by Mulliken in the example of xenon.⁵⁹

From the point of view of energy storage for pulsed laser applications, the heavier rare-gas molecular systems (i.e., Kr_2^* and Xe_2^*) do not have conveniently long radiative lifetimes. But to a great extent this difficulty is circumvented by energy transfer to a metastable state which may occur with impressive efficiency, as the measurements on the Ar-Xe mixtures appear to indicate.

STIMULATED VACUUM-ULTRAVIOLET EMISSION OF HIGH PRESSURE XENON EXCITED BY PULSED HIGH-ENERGY ELECTRON BEAMS

Most experimental studies of the continuum emission by the rare gases in the vacuum-ultraviolet region have been done at gas pressures less than 20 psi.^{57,60-62} The gases have usually been excited by electrical discharge or microwaves, although some recent studies⁶³⁻⁶⁷ have used high-energy charged particles. Current interest in the vacuum-uv emission from the rare gases stems from the possibility that these elements can undergo high-power vacuum-uv lasing.^{58,68,69} Since little information is available on the emission from high-pressure rare gases excited by high-current, high-energy electron beams, we have studied the emission characteristics of xenon gas under those conditions.⁷⁰ Experiments were carried out at pressures of 15 to 450 psi and stimulated emission was observed for pressures above 200 psi.

Experimental Apparatus

The experimental apparatus, shown schematically in Fig. 55, consisted of a source of electrons, electron beam monitors (not shown), a gas cell capable of holding pressures up to 1000 psi, and optical sensors for measuring the temporal, spatial, and spectral characteristics of the emission.

We used two electron-beam guns: one produces 2-MeV electrons in pulses having durations of 50 nsec FWHM (full width at half maximum), and the other produces 0.6-MeV electrons in pulses having durations of less than 2 nsec FWHM. Both generate electron currents of about 7000 A. The entrance window for the electron beams was a thin (0.013-cm) stainless steel sheet, which was supported by a perforated steel plate to minimize bulging due to the high gas pressure.

The central volume of the gas was viewed through 2-mm-thick LiF or sapphire windows. The uv windows were mounted at the outer ends of 10-cm-long line-of-sight pipes that extended from the central volume of the gas cell. Two of the windows were

perpendicular to the axis of the electron beam, and a third faced directly along the axis. The line-of-sight pipes were filled with xenon gas at the same pressure as in the central volume of the gas cell. The uv windows were protected by collimators from stray electrons and x rays which could cause the windows to become opaque to uv radiation.

Fig. 55. Experimental apparatus for studying stimulated vacuum-ultraviolet emission in high pressure Xe excited by high-current relativistic electron beams.

Three different sensors were used for observing the vacuum-uv radiation. The spatial characteristics of the emission were measured with a pinhole in front of a lensless Nikonos II underwater camera with Kodak type 101-10 uv-sensitive film. The same camera was used to obtain spectral information, in conjunction with a McPherson model 235 vacuum spectrograph (with a dispersion of 17 Å/mm). Measurements of the time dependence of the emission were made with an ITT 4115 planar photodiode (sensitivity 20 ± 2 mA/W at 1700 Å⁷¹) having a 2.5-mm-thick MgF₂ window and a CsTe photocathode. A vacuum of less than 10^{-3} Torr was maintained in the line-of-sight pipe between the uv windows and these sensors.

The xenon gas was reagent grade; the impurities in it were 12 ppm H₂, 3 ppm O₂, 6 ppm N₂, and about 100 ppm Kr. Gas pressure ranged from 15 to 450 psi. We made no attempt to maintain uniform gas temperature, but we found that our results were not reproducible unless the entrance window was kept cool by blowing precooled dry nitrogen on it.

Results

Measurements made with the vacuum spectrograph showed that xenon emits a nearly symmetrical band 150 Å wide FWHM (full width at half density) centered at 1700 Å. This spectrum was independent of pressure, although we observed some narrowing of the band when we decreased the current density of the electron beam (but kept the xenon pressure constant). No other emission was observed out to 7000 Å.

The 0.6-MeV electron pulse has an FWHM of about 2 nsec. Except at very high pressures, this approximates an impulse. Consequently it can be used to determine the lifetimes of some of the species it creates. Figure 56 shows the variation with time of the 1700-Å radiation emitted by xenon at different pressures when the gas is excited by the short pulse of electrons. We found that the time dependence of the intensity I of the emission pulse could be approximated by the difference of two exponentials,

$$I(t) = I_0 [\exp(-\lambda_1 t) - \exp(-\lambda_2 t)], \quad (1)$$

where λ_1 and λ_2 are the rates of decay and buildup, respectively, of the emission pulse. We numerically fitted the observed pulses to Eq. (1) and determined that for pressures less than 150 psi, λ_2 varied as the 1.7 power of the pressure P . Above 150 psi the pressure dependence of λ_2 could not be accurately determined because the buildup time, $1/\lambda_2$, approached the width of the 0.6-MeV excitation pulse. We analyzed the decay for times up to 40 nsec after peak intensity and found it to be essentially

independent of pressure: $1/\lambda_1 \approx 2 \times 10^{-8}$ sec.

When the xenon was excited by the wide (50-nsec FWHM) 2-MeV electron pulse, the peak uv output intensity varied as $P^{1.5}$ and the FWHM of the emission pulse varied as $P^{0.5}$. Thus, the uv energy output, which is given by the product of the peak intensity and the FWHM of the pulse, varied linearly with pressure. This pressure dependence was expected, since the amount of electron energy deposited in the gas increases linearly with pressure.

It was also found that the uv emission intensity of xenon at 150 psi varied linearly with the current of the electron beam between 130 and 3300 Å. The pulse shape did not change with the change in current.

To estimate the efficiency with which xenon converts the kinetic energy of the electrons into uv photons, we calculated the photon output from

Fig. 56. Spontaneous 1700-Å emission in Xe at different pressures after excitation by a 2-nsec-long burst of 0.6-MeV electrons.

photodiode measurements and estimated the energy deposited in the gas from the characteristics of the electron beams. The estimated energy W deposited in the gas is

$$W \approx I\tau \frac{dE}{dx} \rho x, \quad (2)$$

where I is the electron beam current, τ is the FWHM of the electron beam, dE/dx is the rate of electron energy loss by collisions, ρ is the density of the gas, and x is the length along the beam axis that is observed through the defining collimators.

Using Eq. (2) we calculated that the efficiency of conversion of electron energy to uv radiation in xenon at 250 psi was about 20% in our experiments. This corresponds, for example, to a peak uv power output of about 300 MW and a uv photon density of about 1 J/cm^3 . These results compare favorably with those of Hurst et al.,⁶⁶ who measured the efficiency with which the rare gases at low pressures are excited by protons.

Our overall results are consistent with the kinetic model, which predicts that excited xenon atoms and ions are deexcited through the formation of excited diatomic molecules (dimers) which subsequently decay through photon emission. The excited dimers are

formed in a three-body reaction; the rate of this reaction should be proportional to P^2 . The observed buildup of uv emission showed approximately this P^2 dependence.

The results further show that the dimers decay radiatively with a mean lifetime of about 20 nsec. In most of our measurements with the 0.6-MeV electron pulse at pressures greater than 200 psi, a very fast uv component with a mean lifetime on the order of 2 nsec was also present. This component followed the electron excitation pulse. We concluded that it was evidence of stimulated emission.

To support this conclusion, we made additional measurements with the 2-MeV beam using mirrors to form an optical cavity (see Fig. 55). To make alignment less critical, the mirrors had a 1-m radius of curvature. In this experiment, the previously observed 150-Å-wide emission band centered at 1700 Å narrowed to a sharp emission line about 17 Å wide and centered at 1716 Å. This gain narrowing indicates that stimulated emission occurred. Pinhole camera photographs showed a high-intensity, well-defined beam spot along the axis of the optical cavity (perpendicular to the electron beam), and the FWHM of the photodiode output narrowed from 50 nsec to 3 nsec.

Chemical Lasers

CHEMICAL LASER THEORY

In the previous semiannual report a basic procedure for analyzing chemical laser performance characteristics and determining their limiting mechanisms was reported.⁷² Since that time the basic analysis has been refined, extended considerably, and applied to several problems of interest to chemical lasers.^{73,74} We review here some of the salient features.

A rigorous matrix-expansion procedure was devised to calculate chemically generated population inversions, given values of chemical source strength (rate of chemical production of lasing species per unit volume), collisional deactivation probability per unit time, and stimulated emission probability per unit time. This procedure, combined with a more approximate analysis based on the assumption of linear ground-state buildup in time (after an initial very short transient) shows that the population inversion obeys a general time-dependent form⁷⁴ regardless of the number of levels and/or the number of simultaneous transitions of the lasing molecules. Differences between

these cases affect only the values of chemical probability parameters entering the equations.

One consequence of this general treatment is the recognition that terms in the population inversion expression which are responsible for *excitation* of the lasing transitions are proportional to the chemical *rate* of production of the lasing molecule, whereas terms corresponding to *deexcitation* are proportional to the *amount* of the lasing species produced chemically. As a result, the population inversion vanishes when the rate of production is balanced by the product of the collisional deactivation probability (per unit time) times the amount of production. This is a fundamental limiting mechanism for chemical lasers, and it applies regardless of the form of the chemical source time dependence. In the absence of photon loss from the cavity, such a time coincides with the time of maximum output intensity.

When the general population-inversion equation is combined with a radiation rate equation, one obtains solutions for the laser output intensity as a function

of time, the laser pulse width, and the total output energy density (of a given transition). In Refs. 73 and 74 these relations are applied to three forms of chemical source:

1. A constant source strength.
2. An exponentially varying source strength.
3. A chain reaction source.

At low pressure, the chain reaction source behaves like both of the first two cases — i.e., if the chain reaction is complete, laser output results resemble those of a constant source, whereas if it is incomplete, results are those of an exponentially declining source.

The constant source solutions show that the width of the small-signal gain profiles depends more strongly on the chemical probability parameter than does the magnitude of the gain. Within a limited range of variation, one can probably tailor the gain profile by choice of probability parameter (equivalent to choice of chemical reactants and/or temperature).

The exponential source solutions show the expected improvement in performance to be obtained when the exponential is positive and represents the effect of a chemically branching chain. In Ref. 74, reasons are given for the expectation that chain branching lasers can function only on material branching reactions, not on energetic branching reactions. In the case of a negative exponential, the solutions represent an incomplete chain reaction — i.e., a reaction in which the production of the lasing species consumes free radicals which are *not* replaced during the course of the lasing. Such a reaction has a very short chain length in contrast to a complete chain reaction in which the necessary free radicals are replenished through subsidiary reactions. Diagnostic relations derived for this case are useful for separating chemical reaction effects from collisional deactivation effects. Specifically, when the photon mean lifetime in the cavity is smaller than any other characteristic time parameter (as is usually the case in current LLL experiments) and when collisional deactivation is slower than chemical consumption of radicals, the intensity profile reduces to the simple exponential form assumed by Kompa et al.⁷⁵ and by Creighton⁷⁶ in their analyses of laser pulse shapes to obtain chemical reaction-rate coefficients. By varying the photon lifetime using mirrors of various reflectances, one can obtain (from both the intensity profile and the total energy output) separate measurements of the chemical reaction rate, the collisional deactivation rate, and the product of the chemical probability parameter times the initial free-radical density.

In the third case considered (chain reaction source), the same results as described above are obtained at low pressure. At high pressure (such that three-body termination effects are as fast as chemical production effects), one encounters a nonmonotonic pressure

dependence of laser output observed extensively in HF lasers whose reactants do not include F_2 .⁷⁷⁻⁷⁹ Whether such "pressure turnover" occurs in current experiments when F_2 is a reactant is not at all clear, because most such experiments have used large concentrations of helium or some other inert diluent. As a consequence, reactant partial pressures have been as low as a few Torr even though total pressures have been atmospheric or higher. The experiments of Pearson et al.^{77,79} show that pressure turnover occurs for reactant pressures in the range of a few tens to a hundred Torr for a variety of reactant systems.

Although additional theoretical and experimental studies will be required to fully understand the pressure turnover phenomenon, analysis of two types of three-body termination mechanisms suggests the following qualitative features: If the pressure turnover occurs because of formation of H_2F_2 , it should be independent of the choice of reactants used to produce HF. If it results from enhanced three-body recombination, i.e., reactive recombination, the peak energy density should be higher in chemical systems having a complete chain reaction (one in which the "hot" reaction replenishes F radicals consumed by the "cold" reaction) than in systems having an incomplete chain.

Ordinary three-body recombination of F radicals in the presence of an inert third body has a rate coefficient of about $3 \times 10^{15} \text{ cm}^6/\text{mole}^2\text{-sec}$ at room temperature.⁸⁰ Such a reaction is 10^4 times too slow to explain the pressure turnover. An alternate possibility is a two-step, reactive process in which the intermediate species H_2F (which normally decays into $HF + H$) is struck by an additional F radical to form two unexcited HF molecules. The rate coefficient for such a process is the product of the rate coefficient for formation of HF in the normal ("cold") reaction times the rate coefficient for the destruction of the H_2F intermediate by collision with F divided by the unimolecular decay coefficient for the channel $H_2F \rightarrow HF + H$. Depending on the relative barrier heights, such a "reactive recombination" process may have a strong temperature dependence, which might be exploited to circumvent the pressure turnover phenomenon. Although no *reliable** measurements have ever been made of the reactive three-body termination effects in an HF system, the analogous effects are known to be dominant in the reaction system producing HI. It may be reasonably expected that such effects should be quite fast in an HF system.

*Lewis attempted measurements of three-body termination rates in a reacting flow of $H_2 + F_2$,⁸¹ but later retracted them on the basis of the predominance of surface effects on the disappearance of F radicals.⁸²

Computer code development has progressed to the point where we are able to report results of two chemical-modeling studies: (1) a study of the effect of energy chain branching rates on laser energy output, and (2) an approximate analytic model which correlates reasonably well with experiments conducted at LLL. In addition, code development continues. We are adapting the RESALE code (obtained from Aerospace Corporation) to the LLL computer system, and are adding laser subroutines to the MINOTAR code.

Study of Chain Branching Rates

In discussions of the HF laser system, chain branching is always referred to as the "key" in unlocking tremendous energy. A study of an HF system (using the computer code NEST on a 68-equation description of an HF laser) was undertaken to see to what extent energetic chain branching is the "key" in an ideal case.⁸³

Chain branching was added to the laser system by adding the following equations:

These equations were arrived at by considering the dissociation energy of F_2 and the difference in HF vibrational energy. Equation (4) is the form usually suggested,^{84,85} but the others were added to allow for branching interaction between the other vibrational levels.

In determining the upper limit on the rate constants for these equations, a collision frequency between $\text{HF}(0)$ and F_2 was calculated. This was found to be about 10^{18} – 10^{19} collisions/cm³·sec. The lower limit on the rate constants was found by observing the value at which the computer output started to change compared to the output for a nonbranching case. This was found to be 10^{10} cm³/mole·sec. This lower limit agrees very well with the value listed in the LASL report.⁸⁴

For the initial starting conditions of $\text{F}_2:\text{H}_2:\text{F}:\text{SF}_6$ mixed at 1:1:0.1:20 concentration units (1 unit is 9.407×10^{-7} mole/cm³ = 17.5 Torr at 300°F), the following was observed: The stored energy with the addition of chain branching was found to be only double what it was in the nonbranching case. Chain branching was found to cause higher-power, shorter-width laser pulses, but the gain in power was not significant. With chain branching added,

the cold reaction pumping into $\text{HF}(2)$, i.e., $\text{F} + \text{H}_2(0) \rightleftharpoons \text{HF}(2) + \text{H}$, and the collisional deactivation of $\text{HF}(\nu)$ by HF , i.e., $\text{HF}(2) + \text{M} \rightleftharpoons \text{HF}(1) + \text{M}$, $\text{M} = \text{HF}(0), \dots, \text{HF}(8)$, were found to be the dominant production/reduction equations for the $\text{HF}(2)$ to $\text{HF}(1)$ inversion. For the $\text{HF}(1)$ to $\text{HF}(0)$ inversion, the production/reduction mechanisms were controlled by the vibrational deactivation equations: $\text{HF}(\nu) + \text{M} \rightleftharpoons \text{HF}(\nu - 1) + \text{M}$, $\text{M} = \text{HF}(0), \dots, \text{HF}(8)$. This indicates a cascading effect. For both the $\text{HF}(2)$ to $\text{HF}(1)$ and $\text{HF}(1)$ to $\text{HF}(0)$ inversions, $P(3)$, $P(4)$, and $P(5)$ are the dominant P-branched transitions.

Approximate Analytic Model

In the process of constructing the laser model for the MINOTAR code, we discovered that a simple analytic model gave an approximate quantitative description of our experiments with NF_3 and hydrogen donors initiated by a 70-nsec transverse electric discharge.⁷⁶

The model assumes that the discharge dissociates a fraction of the NF_3 to create an initial concentration F_0 of fluorine atoms. The principal reaction creating vibrationally excited HF is

Vibrational deactivation of HF is neglected because it is an order of magnitude slower than creation in the early part of the pulse. There is evidence that any chain reactions are too slow to affect the lasing.

It is well known that the output power of a laser operating at steady state is proportional to the pump power, in this case proportional to the rate of formation of HF. Experiments were typically conducted with an output mirror of 10% reflectivity so that laser transients are damped in about 10 nsec and steady state operation continues for 250 to 1000 nsec. A typical laser pulse is shown in Fig. 57. The first peak is light from transitions between the $\nu = 2$ and $\nu = 1$ states, and the second peak is from $\nu = 1$ to $\nu = 0$ transitions. The delay between the discharge and the first peak is the time required to build up the threshold inversion.

It is easily shown that the rate of formation of HF is proportional to $\text{F}_0 e^{-t/\tau}$, and the laser pulse should have this same shape, as shown in Fig. 58. The pulse shape for a chain reaction, also shown, is qualitatively different in that it reaches a steady rate and remains there until the hydrogen is consumed. If the second step in the chain is very slow the chain reaction has

the same pulse shape as the single reaction. The decay of the pulse is due to consumption of F atoms, and the pulsewidth $\tau = 1/k_1 H_0$, where H_0 is the initial concentration of H_2 . If the system is lean in hydrogen, the pulse shape will be nearly the same but the time constant will be $\tau = 1/k_1 F_0$. As long as H_0 is large compared to F_0 , the time constant is a function only of k_1 and H_0 , and since H_0 is known we can obtain the value of the rate constant k_1 from experimental data. The analysis is valid for other hydrogen donors, and we have measured the rate constants for a number of compounds as shown in Table 6. The rate constants for half of these had previously been published and agree with our measured data within about 30%. Kompa and Wanner⁷⁵ have measured rates for H_2 and CH_4 using a flashlamp-initiated HF laser. Their rates are roughly double ours. To put the accuracy of these measurements in perspective it should be noted that competent investigators frequently disagree by an

Fig. 57. Structure of typical laser pulse.

Fig. 58. Comparison of pulse shapes for chain reaction and single reaction.

Table 6. Rate constants (k_1) measured at LLL for various hydrogen donors used with NF_3 in HF lasers. Published values are given for comparison where available

Hydrogen donor	Rate constants	
	Measured	Published ^a
H_2	1.8	2.1
CH_4	3.0	3.7
C_2H_6	7.5	6.0
$cy-C_3H_8$	3.6	2.9
C_3H_8	3.3	3.3
$n-C_4H_{10}$	4.4	2.7
$i-C_4H_{10}$	9 ^b	4.5
$neo-C_5H_{12}$	4 ^b	5.6
D_2	0.89	—
C_2H_6	3	—
$i-C_4H_{10}$	4.4	—
$cy-C_6H_{14}$	10	—
$C_6H_5(CH_3)_2$	6.9	—
SiH_4	10	—
AsH_3	3.4	—
GeH_4	10 ^b	—
SbH_3	9 ^b	—

^aA. S. Trotman-Dickenson, *Tables of Bimolecular Gas Reactions* (Natl. Bur. Stds., U.S. Govt. Printing Office, Washington, D.C., 1967).

^bLess accurate, measured at high mole ratio.

order of magnitude in measuring chemical reaction rates as fast as these.

Code Development

The computer code RESALE was received from the Aerospace Corporation. This is a program for calculating conditions in a chemically reacting gas situated inside an optical laser cavity. RESALE differs from NEST^{*} in that NEST calculates only the chemistry in a chemically reacting system (without emission), whereas RESALE puts mirrors on the ends of the cavity and allows the chemically reacting system to have stimulated emission. The RESALE code is now being adapted to CDC 7600 machines at LLL.

The MINOTAR code is being modified to treat laser radiation, as reported previously.⁸⁶ The laser will be treated in a quasi-steady-state approximation, similarly to other codes such as RESALE, but finite rotational relaxation times will be included, whereas other codes have assumed infinitely fast rotational relaxation. This

*NEST is another Aerospace Corporation code in use at LLL.

will permit several rotational levels to lase simultaneously, as they do in actual lasers. This work has been delayed because of time devoted to the analytic model.

Pressure Turnover Study

A joint modeling-experimental study is being undertaken to determine what causes the pressure

turnover that is experienced in the laboratory. This phenomenon was reported in the last semiannual⁸⁶ and is also discussed in the preceding article in this report. Different reaction schemes (three-body recombination, dimerization) are now being tried to simulate this pressure turnover effect and better understand what causes it. This study will involve both numerical and analytic modeling.

CHEMICAL LASER EXPERIMENTATION

The primary emphasis of the experimental portion of the chemical laser program is to develop energetic pulsed lasers with a high efficiency for converting the input energy required for reaction initiation into output laser energy. One approach we are investigating is the development of a chemical laser based on a branched chain reaction. To find an efficient chemical laser, we have recently concentrated on (1) operating chemical lasers based on more energetic and reactive compounds, (2) developing better techniques for initiating reactions in these reactive gas mixtures, and (3) developing techniques to study the chemical reactions *per se* in these mixtures.

We have found chemical systems exhibiting an order of magnitude greater overall efficiency than the less reactive systems studied previously. However, the energy density in these systems does not appear to be significantly higher than that previously observed. To study the behavior of our reaction systems and in particular to look for evidence of chain branching reactions, we have begun experiments to measure chemical reaction rates with a probe laser. We are also measuring the spontaneous explosion limits of inhibited and uninhibited gas mixtures which react to produce HF. Our work on better initiation techniques includes operation of a volumetric gas initiation system based on absorption of CO₂ laser light, construction of a double-discharge volume initiation apparatus, experiments involving an electron-beam initiation system, and planning for heated laser systems in which rapid chemical reactions can occur. Some work has also been done on a CO₂ transfer laser in searching for a chemical CO₂ laser, and a 1.3- μ m iodine laser based on electronically excited iodine.

New Initiation Techniques

The pin-discharge chemical lasers currently being used at LLL inhomogeneously initiate an unknown fraction of the room temperature gas in the laser cavity. We are studying several initiation techniques which could homogeneously initiate the entire gas

mixture in the laser cavity and/or rapidly drive the reactant gas mixture into pressure-temperature regimes where chain branching reactions might occur.

CO₂ Laser Preheat. We have assembled the pin-discharge chemical laser shown in Fig. 59, in which the reactive gases can be rapidly preheated by a pulse of 10.6- μ m radiation (up to 90 J in 2 μ sec) from a double-discharge TEA CO₂ laser.⁸⁷ The objective is to rapidly shift the reactant mixture from a stable region into a region where branched chain reactions can contribute to laser action. The preheat mechanism used is rapid V-T transfer from a vibrationally excited reactant, such as N₂F₄, or diluent such as SF₆. We can achieve temperature jumps of at least a few hundred °K in microsecond risetimes with less than 20% SF₆ diluent. The kinetic temperature at the time of the 80-nsec pin discharge can be varied either by varying the time delay between the CO₂ laser pulse and the discharge, since gas temperature should increase as more V-T transfer occurs, by varying the absorber concentration, or by focusing the CO₂ laser output. With this system we have been able to (1) search for chemical laser action initiated purely by CO₂ laser radiation, (2) search for evidence of branched chain reactions, and (3) study implicitly the temperature dependence of some chemical laser systems.

Initial investigations have been performed on various NF₃-H₂-SF₆ and N₂F₄-H₂ mixtures. So far no chemical laser oscillation has been observed in explosions initiated by the CO₂ laser alone, and the appearance of chemiluminescence has been rather slow with risetimes greater than 100 μ sec. The total HF laser energy output in preheated discharges decreased monotonically as the delay between CO₂ laser irradiation and pin discharge was increased (see Fig. 60a), except for those mixtures which did not explode upon CO₂ laser irradiation alone. In the latter situation the HF laser output with CO₂ laser irradiation approached the output observed without irradiation at delay times of >100 msec. In some

Fig. 59. Schematic of pin-discharge chemical laser in which the reactive gases can be rapidly preheated by a pulse from a CO_2 laser, causing the reactant mixture to shift suddenly from a stable region into a region where branched chain reactions can contribute to laser action.

cases, however, there appears to be enhancement of the power in the first $\text{HF}(\nu = 2) \rightarrow \text{HF}(\nu = 1)$ peak (see Fig. 60b).

The evidence so far is indicative of thermal explosions rather than branching chain reactions. Our main conclusion is that the techniques described above are simple and fast ways to search for branched chain reactions contributing to laser output and to demonstrate the feasibility of the efficient pulsed-chemical-laser concept. We will continue, therefore, to investigate more promising chemical systems, e.g., $\text{N}_2\text{F}_4\text{-SiH}_4$, $\text{ClF}_3\text{-H}_2\text{-SF}_6$, $\text{ClF}_3\text{-H}_2\text{-SF}_6$, etc. In addition, the $\text{H}_2\text{-F}_2\text{-SF}_6$ system should probably be studied since it has shown chain contribution to laser output.

Electron Beam Initiation. An axially directed pulsed electron beam, with electron energy about 1.5 MeV, has been used to initiate an $\text{H}_2\text{-NF}_3$ mixture in a laser

amplifier. Since these beams travel near the speed of light, extremely fast and uniform initiation was achieved. This oscillator-amplifier experiment used a spiral pin laser oscillator which contained an $\text{SF}_6\text{-H}_2$ mixture as the source of HF. The oscillator beam was passed through an amplifier section filled with an $\text{NF}_3\text{-H}_2$ mixture. Immediately after establishing the stimulating flux from the oscillator, the amplifier was initiated with the electron beam.

Only modest quantities of energy were extracted from the exploding gas in the electron-beam-initiated amplifier. The failure to obtain large energy amplification is not necessarily due to the electron beam initiation. All HF chemical lasers at LLL based on the $\text{NF}_3\text{-H}_2$ system, with whatever type of initiation, have given similar low energy outputs.

An interesting aspect of this work was the first observation of a new kind of nonlinear am-

Fig. 60. Laser energy and pulse shapes from HF chemical laser with gas mixture preheated by discharge from CO_2 laser. Total pressure of gas mixture 25 Torr. (a) HF laser energy as a function of delay time between CO_2 preheat pulse and HF laser discharge, for three different $\text{NF}_3/\text{H}_2/\text{SF}_6$ mixtures. (b) Sample pulse shapes from HF laser for various delays between CO_2 preheat pulse and HF laser discharge.

plication.⁸⁸ This behavior is characteristic of an oscillator pulse which enters a high-gain medium and during its traverse of the medium builds up sufficient field strength to interact strongly with the material polarizability.⁸⁹ Under these conditions one can generate substantially shorter pulses than in the linear amplification regime.

A photograph of the experiment showing the spiral gas laser, the electron beam generator (the large tank), and the amplifier wrapped in an electron-beam-focusing coil is shown in Fig. 61.

Double-Discharge Volumetric Initiation. A laser shown in Fig. 62 using a volumetric initiation scheme based on a version of the "French" or Dumanchin double-discharge concept has been designed to work with various flowing gas mixtures at pressures up to 1 atm.¹⁸ Operation of this laser with a mixture of 0.06 CH_4 -0.94 SF_6 at 100 Torr produced 3.2 J/liter of laser energy in an 11-cm³ laser volume. The laser did prove to be sensitive to gas composition and pressure, and several improved volume-discharge lasers are now under construction.

Adiabatic Compression. Also under construction is a device to adiabatically compress a gas into a laser cavity. The concept of this lasing system is that an inhibited reactant mixture will be so rapidly compressed that no appreciable prereaction will occur during compression. The adiabatically heated mixture will then be ignited by an electric discharge.

Techniques for Studying Chemical Reactions

Frobe Laser. A number of experiments have been performed to study reaction-associated phenomena. We have used a stable cw CO_2 laser to probe exploding $\text{SiH}_4\text{-N}_2\text{F}_4$ mixtures, inhibited with C_4H_8 , by measuring absorption of a CO_2 line during the explosion. We found the $(00^0 1)-(02^0 0)$ band $P(34)$ CO_2 laser line at 9.6759 μm was measurably absorbed by N_2F_4 , but not significantly absorbed by SiH_4 or C_4H_8 . This line was a relatively weak line in the CO_2 laser, but it was strong enough to drive the Hg-Cd-Te detector. Mixtures were initiated with an electric discharge in an existing pin-laser cavity.

Following the explosion initiation we typically observed an oscilloscope trace of the detector output similar to Fig. 63. The explosion trace 2 was calibrated by traces 1, 3, and 4. Segment (a) of the detector output (trace 2) is apparently related to disappearance of N_2F_4 in the electrode region, and it shows an exponential disappearance of N_2F_4 with time. This portion of the curve was not observed at pressures above 40 Torr. Segment (b) is apparently due to reactions of N_2F_4 in the end portions of the laser tube, since the rate of burning implied by this curve is the

Fig. 61. Experimental setup for initiating an H_2-NF_3 mixture with a pulsed electron beam of about 1.5 MeV energy.

same as that observed when the gas is initiated at a single point. The increase in absorption in segment (c) may be due to growth of chemical species which absorb in the $10\text{-}\mu\text{m}$ region, such as Si-F bonds.

The major conclusion drawn from these data is that lasing in the $N_2F_4-SiH_4$ system is over long before the bulk chemical reaction has occurred. Measured reaction rates may not be intrinsic properties of these gas mixtures because the pin initiation is inhomogeneous in space and time. We plan to continue measurement of reaction rates using probe lasers with the volume-initiated cavities discussed above. We will then be measuring reaction rates in gas mixtures initiated uniformly in space and time.

Monitoring Heat and Light Output. An apparatus has been built to examine some features of spontaneously reacting systems by monitoring the heat and light output with sensitive photodetectors and thermopiles. The apparatus is capable of measuring explosion limits as a function of temperature and pressure. It is also capable of differentiating between dark reactions and luminous burns and possibly

between thermal and chain-branching explosions. Spontaneous explosions preceded by no appreciable rise of temperature are one characteristic of chain branching reactions.⁹⁰ This type of explosion needs to be differentiated from that caused by thermal runaway due to an increase in reaction rate following relatively slow self-heating by exothermic reaction. Chemical lasers based on thermal runaway explosions might produce less laser energy, because the HF that is slowly formed in lower vibrational states, before the reaction rates become reasonably fast, could lower the HF inversion.

We are using this apparatus to test "consumable inhibitors" which will prevent burning or will delay explosions and then lose their inhibiting action when HF-forming reactions become fast. This inhibiting action will permit investigation of spontaneously exploding systems and will enable us to heat very reactive mixtures by relatively slow processes like adiabatic compression.

We have measured the delay between reactant mixing and observed explosion time in a series of

Fig. 62. Volume discharge laser uses an initiation scheme based on the Dumanchin double-discharge concept, works with various flowing gas mixtures at pressures up to 1 atm.

experiments at constant total pressure with the $\text{N}_2\text{F}_4\text{-SiH}_4$ system inhibited by C_4H_8 . The delay varied from seconds to minutes when the concentration of C_4H_8 was changed by only hundredths of a percent. We also found in experiments

Fig. 63. Conditions inside an exploding $\text{H}_2\text{-N}_2\text{F}_4$ mixture inhibited with C_4H_8 are studied by observing the transmission of a cw probe laser beam through the explosion zone. Trace 1 shows transmission through the explosion, trace 2 shows transmission through the empty cavity, trace 3 transmission through the gas-filled cavity before ignition, and trace 4 zero transmission. Gas mixture 0.32 SiH_4 , 0.67 N_2F_4 , 0.01 C_4H_8 ; pressure 4.1 Torr, horizontal scale 20 $\mu\text{sec/division}$.

at various pressures that the explosion delay time was quite dependent on the inhibitor pressure in the previous run, implying that the absorption of inhibitor on the wall may be influencing a wall-catalyzed reaction. The only materials exposed to the gas in these experiments were stainless steel and Teflon. The system is being redesigned in an attempt to measure only homogeneous gas phase effects.

Attempts to inhibit $\text{ClF}_3\text{-SiH}_4$ mixtures with C_2H_4 , CO_2 , NO , cyclo- C_3F_8 , NO_2 , C_3F_6 , and SF_6 were unsuccessful. The $\text{ClF}_3\text{-SiH}_4$ mixtures always burned spontaneously, but never exploded. Addition of ClF_3 to $\text{H}_2\text{-SiH}_4$ mixtures at low pressures eliminated the chemiluminescence of the mixtures, but not the observed temperature rise. $\text{H}_2\text{-ClF}_3$ mixtures exhibit no detectable spontaneous reactions. $\text{ClF}_3\text{-C}_3\text{H}_8$ mixtures can be inhibited by a few percent C_3F_6 . The delayed explosion occurs by thermal runaway.

Other Experiments. A laser shown in Fig. 64 has been built that can be operated in the temperature range from 100°C below room temperature to 100°C above room temperature. Parametric studies with this laser system at various temperatures, compositions, and

Fig. 64. Effect of gas mixture temperature on laser performance is studied with this laser, which can operate with gas temperatures in the range $\pm 100^\circ\text{C}$ from room temperature.

pressures will be used to test the theoretical predictions described above.

We have also done a few experiments with a pin-discharge transfer laser in a $\text{D}_2\text{-CF}_4\text{-CO}_2$ system. The experiments were performed to determine if energy transfer from DF was rapid enough to reduce vibrational deactivation of DF and thus raise the laser energy output. Energy transfer from excited DF to CO_2 did occur since lasing at the $10.6\text{-}\mu\text{m}$ CO_2 frequency was observed. However, severe arcing prevented evaluation of laser performance in this experimental facility.

Continuing Experiments

Reactant Survey. We are continuing the survey of weakly-bonded-hydrogen-donor, weakly-bonded-fluorine-donor reactant systems with the aim of finding a HF chemical laser in which a chaining or chain-branching reaction contributes to the laser output. The pin laser systems used in the survey to date are essentially the same as those described in the previous semiannual report.⁹¹ Figure 65 shows some potential reactants for this survey ranked according to hydrogen or fluorine bond strength. We have observed the approximate stability regions indicated in Fig. 65 during our survey of $\text{NF}_3\text{-RH}$ mixtures and the beginning of the subsequent fluorine-donor survey. Note that this chart indicates trends only and does

not define the stability of every possible binary combination of reactants.

Mixtures of the reactants with stronger bonds are generally stable. These mixtures are often flammable at pressures above a few tens of Torr and at compositions near those required for the complete reaction to $\text{HF} + \text{RF}$ (flammable in the sense that they will burn when initiated with the pin laser discharge). Mixtures of reactants with weaker bonds tend to spontaneously burn or explode during or shortly after mixing at room temperature. These spontaneous exploding systems are promising candidates for chain branching reactions. However, they will require some time to survey, since the two additional parameters of type and concentration of "consumable inhibitor" are needed in these survey experiments.

We have completed laser energy evaluation studies of a total of 18 hydrogen donors, each paired with the same NF_3 fluorine donor, and results are shown in Fig. 66, where B_2H_6 , GeH_4 , and $\text{neo-C}_5\text{H}_{12}$, at optimum concentrations for laser energy output, have been added to the figure presented in the previous semiannual report.⁹¹

We have also tested several systems with new fluorine donors including N_2F_4 , ClF_3 , XeF_4 , and OF_2 , whose average fluorine bond energies are 64.5, 61, 30, and 44 kcal/mole, respectively. A plot of laser energy

Fig. 65. Room-temperature stability chart for mixtures of weakly bonded H donors and F donors. Chart is approximate, indicates trends only.

vs pressure at the optimum composition is shown in Fig. 67 for several reactant systems containing these fluorine donors. Other systems currently under investigation include ClF₅-H₂ and XeF₄-C₃H₈.

Systems found to be spontaneously flammable and which are candidates for inhibition research are ClF₅-B₂H₆, ClF₃-SiH₄, ClF₅-C₃H₈, ClF₅-GeH₄, and F₂O-SiH₄.

We have studied the N₂F₄-SiH₄-C₄H₈ and the ClF₅-H₂ systems in HF chemical lasers in some detail. The C₄H₈ inhibitor was added at the few percent level.

The N₂F₄-SiH₄ system is interesting because it shows high overall efficiencies (see Fig. 68). Under some conditions the overall efficiency reached 12%, where overall efficiency is defined as laser energy output divided by the initiation energy absorbed in the gas. The overall efficiencies of NF₃-RH systems tended to be a few percent.

Another feature of these two systems is that, unlike NF₃-RH mixtures, laser energy output does not monotonically increase with initiation energy input. In fact, as shown in Fig. 69, when the initiation energy

is increased by about an order of magnitude (i.e., when a current-limiting resistor between the power supply and the laser is changed from a few hundred ohms to a few ohms), the laser energy maximizes at a pressure of about 10 Torr. At the lower initiation energies the pressure of maximum energy is higher and the maximum laser energy may also be higher. It is possible that overinitiation dissociates the reactants,

producing radicals which are known to rapidly deactivate HF^+ .^{9,2} An interesting characteristic of these systems is that in some cases the laser pulses are unusually long at low initiation energies, which might be an indication of chaining reactions.

Short-Pulse HF Oscillator. The short-pulse HF oscillator that was described in the last semiannual

Fig. 66. Laser energy vs pressure at optimum mole ratio for a number of NF_3 -RH systems (numbers in parenthesis represent optimum NF_3 /RH mole ratios). This figure is similar to the one given in the previous semiannual report (UCRL-50021-71, Fig. 53), but here all the experiments are run with the same electrical circuitry, i.e., with no resistor between Marx bank and laser, and the curve for diborane (B_2H_6) has been added.

Fig. 67. Optimum laser energy vs pressure for some fluorine-donor/hydrogen-donor systems. Numbers in parenthesis give the optimum mole ratio of fluorine compound to hydrogen compound.

report⁹³ has been reworked to produce a single-mode output by cutting the length of the cavity from 40 to 20 cm. The effect of the shortening is to separate the cavity mode spacing so that the linewidth will not support lasing on more than one mode. Single-mode output is required to produce data which can be used, if necessary, to design scaled-up oscillator-amplifier experiments.

Other Chemical Lasers

In a series of experiments with a CO chemical laser based on the photolytically initiated reaction of (1) CS_2 with oxygen or (2) CS_2 with ozone, we have observed that the laser energy output is essentially the

Fig. 68. Overall efficiency (ratio of energy absorbed by gas to laser output) vs pressure for a 0.18 SiH_4 -0.78 N_2F_4 -0.04 C_4H_8 mixture with a 235- Ω current-limiting resistor.

Fig. 69. Normalized laser output energy vs pressure for $\text{ClF}_5\text{-H}_2$ with current-limiting resistors of 0 and 235 Ω , and for $\text{N}_2\text{F}_4\text{-SiH}_4$ with current-limiting resistors of 25, 500, and 1000 Ω . Dashed line is 0.56 ClF_5 -0.44 H_2 , solid curves are 0.82 N_2F_4 -0.18 SiH_4 .

same for either reaction. Since the reaction forming vibrationally excited CO is known to be

and the concentration of oxygen atoms is much higher in the ozone reaction, we believe the rate-determining step in this CO laser is the photolytic dissociation of CS_2 to CS plus S.

We have recently attempted to produce a chemical CO_2 laser by the reaction

since it has been proposed this reaction might produce vibrationally excited CO_2 . Pulsed discharge initiation in pin lasers was tried at $\text{CO}/\text{N}_2\text{O}$ reactant ratios of 1 to 2 with H_2 additions of 0-3% and total pressures from 30 to 120 Torr. No explosions were produced and no CO_2 was detected in mixtures without H_2 . With added H_2 , explosions and CO_2 were produced, but no CO_2 lasing was observed.

Gas lasers deriving energy from electronically excited iodine have recently shown promise as sources of short, energetic light pulses at $1.3 \mu\text{m}$.⁹⁴ We have operated an iodine laser based on photodissociation of $\text{C}_3\text{F}_7\text{I}$ and plan a series of experiments designed to improve the output of iodine lasers.

Nonlinear Phenomena

EXPERIMENTAL AND THEORETICAL OBSERVATION OF SELF-FOCUSING IN Nd:GLASS AMPLIFIERS

The output of the Short Path Laser⁹⁵ has been limited to unacceptably low intensities due to self-focusing damage in the Nd:glass amplifier rods. Experiments on this laser have demonstrated that the self-focusing in high-peak-power lasers is governed mainly by incidental and often unavoidable diffraction effects or transverse mode perturbations. Thus, bulk rod damage can occur at powers substantially below the levels which would be permissible if only large-scale self-focusing of the entire beam were to occur. These experimental observations have been quantitatively corroborated by computer calculations.

Experimental

The Short Path Laser consists of a mode-locked Nd:glass oscillator, single-pulse switchout, and rod amplifier chain (Fig. 70). The oscillator provides 15-psec pulses (as seen by two-photon fluorescence) with bandwidths of about 50 Å. The detailed structure of these pulses is not known. Following a 1/2-in. "preamplifier," a lens-pinhole-lens spatial filter gives a diffraction-limited spatially smooth beam that is expanded from the 4-mm oscillator output up to about 1.3 cm. An aperture after the spatial filter may be used to restrict the beam entering the next 1/2-in.

Fig. 70. Portion of Short Path Laser involved in self-focusing experiments.

amplifier. The beam incident on this aperture is an Airy pattern produced by the spatial filter.

The next 1/2-in. amplifier is situated 108 cm from the aperture and is followed by two more amplifiers separated by 19 cm each. The amplifiers are pumped with up to 12 kJ apiece, giving small-signal gains of about 10. The system is capable of about 2 J out of the 1/2-in. chain, in a nearly diffraction-limited beam.

Firing about 50 shots, all under 0.5 J, out of the 1/2-in. chain resulted in severe damage to the last 1/2-in. laser rod. The damage takes the form of a Fresnel diffraction pattern which results from the aperture following the spatial filter. Careful inspection reveals that the ring pattern is composed of straight trains of damage sites which begin 8 cm from the exit face and become more numerous close to the face (Fig. 71). It is significant that, on the same shots that produced damage, far-field divergence measurements indicated a nearly diffraction-limited beam; only a small fraction of the beam energy was involved in the self-focusing.

Removal of the aperture after the spatial filter eliminated the diffraction ring pattern, but the diffraction from the edges of the rods introduced slight (less than 20%) fluctuations in the intensity distribution out of the 1/2-in. rods. After many days of firing at low energy (less than 0.25 J), new damage was observed at about the same place as before, but with a less distinct pattern.

Theoretical

Figure 72 shows the computational results of propagating a beam through 145 cm of air and then through 59 cm of an amplifying glass medium. The Gaussian beam is initially passed through a 1-cm circular aperture which leads to the developing Fresnel diffraction structure in the radial intensity profile. The input pulse contains 2 mJ and is assumed to be 15 psec FWHM. The rod gain is adjusted so that the

Fig. 71. Damage observed at end of last 1/2-in.-diam glass amplifier rod.

Fig. 72. Self-focusing occurs in rings determined by Fresnel diffraction patterns. Shown here are radial intensity profiles of Fresnel patterns at maximum intensity on axis after beam has traversed (a) 145 cm of air, (b) 145 cm of air plus 45 cm of laser rod, (c) 145 cm of air plus 59 cm of laser rod.

output pulse energy is 0.5 J. These conditions represent an excellent approximation to the actual experimental conditions encountered in the Short Path Laser experiment.

If the value $n_2 = 2 \times 10^{-13}$ esu of Duguay and Shapiro⁹⁶ is employed, the agreement between experiment and theory on the nature of the self-focusing is remarkable. First of all, seven fringes are observed in the etched damage pattern at the end of the last glass rod in the amplifier. This is precisely the number of fringes that exhibit self-focusing in the numerical calculation. Furthermore, the onset of self-focusing leads to appreciable intensities at 59 cm in the amplifier, which is 9 cm from the end of the chain. (Actual self-focusing commences a few centimeters later.)

An additional calculation based on a 1-cm-diam Gaussian beam with a 10% intensity perturbation of 400 μ m radius at the center led to self-focusing within a few centimeters of the end of the amplifier chain. This result was also in agreement with the experiment. Propagation of a smooth 1-cm-diam beam through the

amplifier system led to an increase in output energy of a factor of 8 before self-focusing resulted.

Conclusions

It is clear from both the foregoing experimental and theoretical results that in any practical system, damage levels will be governed by conditions of the beam quality, which is so readily altered by apertures.

Experimental elimination of diffraction effects will require underfilling the rods, so that the edges aperture the beam at a point of very low intensity. This will be accomplished by reducing the expansion of the spatial filter. However, the most promising solution to self-focusing problems is to use a longer pulse, perhaps 100 psec or more. Toward this end, a YAG oscillator is being assembled in the Short Path Laser. By narrowing the bandwidth of the YAG oscillator with intercavity etalons, a longer pulse will be produced. Even if this effort does not give 100-psec pulses, at least a bandwidth-limited pulse will be obtainable from YAG. Then further investigation of self-focusing can be pursued, using a well-understood pulse.

EXPERIMENTAL AND CALCULATIONAL STUDIES OF PICOSECOND RUBY AMPLIFIER SYSTEM

A large amount of accumulated experimental data indicates that a nonlinear refractive index plays an important role in the amplification of short pulses from ruby lasers and in fact glass lasers. In particular, oscillator-amplifier experiments have shown that 20-psec pulses generated in the ruby oscillator can develop temporal structure of 5-10 psec while being amplified. In addition, amplified pulse bandwidths of as large as 14 cm^{-1} have been observed at the output of a 9-in.-long ruby amplifier whose input pulse bandwidths were $\leq 7 \text{ cm}^{-1}$. (Note that the output pulse bandwidth is substantially broader than the $\sim 11 \text{ cm}^{-1}$ width of the fluorescence line of ruby at room temperature.) Numerical calculations have been carried out using a nonlinear optics code which solves the time-dependent parabolic Maxwell equations for a medium with a nonlinear refractive index together with the Bloch equations for a two-level system, assuming a two-dimensional cylindrically symmetric amplifier geometry. A discussion of the code results and their correlation with experiments is presented here, where we assumed $n_2 = 10^{-14}$ esu, consistent with the results of Giuliano and Marburger.⁹⁷

First we summarize the numerical results. Figure 73 shows the calculated on-axis temporal pulse shape after propagation through a 9-in.-long ruby amplifier. The

pulse shape was initially Gaussian with a full width of 20 psec when it entered the amplifier. The severe pulse distortion is due to the effect of

Fig. 73. Calculated pulse shape resulting from amplification of an initial 20-psec Gaussian pulse in ruby. The steep fall at the rear of the pulse is due to absorption from "rapid passage."⁹⁸

self-phase-modulation of the pulse, induced by interaction between the medium's nonlinear refractive index and its coherent amplifying characteristics. Pulse energy is 20 mJ. (The input pulse energy and amplifier characteristics were chosen to give the output energy required for the experiment described later in this section.)

The steep fall on the back side of the pulse in Fig. 73 is due to absorption of energy by the two-level system, even though this system is inverted. The

Fig. 74. Calculated phase lead of the optical electric field with respect to the material polarization.

Fig. 75. Calculated shift in on-axis pulse center frequency as a function of time in pulse, for a point at an intermediate position inside a ruby amplifier.

Fig. 76. Calculated pulse spectrum corresponding to Fig. 75.

absorption is due to the effect known as "rapid passage" first explored by Treacy⁹⁸ in the optical part of the spectrum. An optical field applied with a continuously varying frequency which sweeps across the resonant line in a time short compared to the transition dephasing time can cause an absorbing medium to amplify during part of the sweep and likewise can cause an amplifying medium to absorb. This effect occurs whenever the phase of the applied optical field leads or lags the optimum-gain phase of the induced polarization by a value in excess of $\pi/2$. Figure 74 shows the calculated phase lead for the pulse in Fig. 73. (Both the amplitude modulation and the possibility of overriding these rapid passage effects under very high gain conditions have been previously reported.⁹⁹)

Finally, we examine the calculated pulse frequency content. In Fig. 75 is shown the calculated on-axis center frequency shift over the pulse duration at an intermediate position inside the amplifier. The frequency excursion is due to the self-phase-modulation of the pulse induced by the index nonlinearity. Note that the maximum frequency excursion corresponds to the total extent of the pulse spectrum shown in Fig. 76. The spectrum in Fig. 76 is typical of self-phase-modulated pulses. In the frequency plot we note a nearly linear variation with time which swings over almost the whole integrated pulse bandwidth. By using a grating pair, first introduced by Treacy,¹⁰⁰ the portion of the pulse containing the linear frequency chirp can be

compressed to a duration which corresponds to the inverse of the linear chirp range. The experimental success of this method of pulse compression is consistent with these calculations.

Thus far we have obtained qualitative agreement between experiment and calculation. In Fig. 77 are shown the results of simultaneously recording the input and output pulse TPF displays for a 9-3/4-in.-long ruby amplifier, 9 in. of which is pumped. The overall observed gain was 10, while the output pulse energy was 20 mJ. The input beam was TEM₀₀ mode with an e⁻¹ diameter of 1.2 mm. (Note that this operating condition corresponds to $\sim 5 \times 10^{11}$ W/cm² maximum intensity.) The input TPF display corresponds to a smooth pulse about 20 psec long while the output pattern reveals a structure corresponding to about 10 psec. A similar pulse shortening was indicated by the calculations.

Close examination of the spectral content of the collimated beam at both the input and the output of

Fig. 77. Experimental TPF displays of the input and output pulses for a 9-3/4-in.-long ruby amplifier with an observed gain of 10. The acquired temporal structure is in agreement with that predicted due to rapid passage effects.

Fig. 78. Experimental pulse spectrum of the output of the 9-3/4-in.-long ruby amplifier. The total pulse spectral extent is 14 cm^{-1} . Note that the total bandwidth varies in the vertical direction consistent with the $I(r)$ dependence of the pulse, and the integrated pulse bandwidth exceeds the fluorescence linewidth of the amplifier. When the instantaneous center frequency of the pulse lies outside the fluorescence linewidth, this part of the pulse experiences no gain. The result is additional shortening of the pulse duration (see Fig. 77) and reduced effective pulse energy gain.

the same amplifier reveals a typical phase-modulated spectrum, as shown in Fig. 78. Note that the spectrum has less extent at the top and bottom than in the middle, as expected because of the spatial variation of the intensity of the TEM₀₀ mode. The spectrum shown in Fig. 78 is similar to that displayed in Fig. 76.

We are continuing our efforts to obtain a quantitative comparison between the code and experiments for ruby amplifiers. This will require a more careful monitoring of the input and output pulse characteristics using a streak camera combined with other forms of simultaneous diagnostics.

NONLINEAR OPTICS STUDIES

This effort is concerned with both theoretical and experimental studies of nonlinear optical phenomena. Theoretical efforts in progress include:

1. Computer calculations to study the spectrum of nonlinearly propagating pulses. We are presently trying to find a correct interpretation of the reported experimental determinations of orientational relaxation times in simple liquids (e.g., CS₂).

2. A study of self-phase-modulation in materials which are linearly dispersive (and possibly active).

3. A study of the role of a dc electrical field in certain nonlinear scattering phenomena.

Experimental efforts that are under way include the following:

1. A setup is in operation for optical pumping, excited-state spectroscopy, and excited-state photoconductivity of certain materials (e.g., ruby and Nd:glass). The source is a frequency-doubled, mode-locked Nd:glass laser, and the samples are mounted in an optical double Dewar (cold-finger

Fig. 79. Experimental setup for nonlinear optics research. Capabilities include optical pumping, excited state spectroscopy, and excited state photoconductivity of certain materials.

type), as shown in Fig. 79. At present the apparatus is used in an attempt to make an optically pumped color-center laser oscillator. (An optically pumped color-center amplifier has previously been demonstrated.¹⁰¹)

2. An effort is under way to make both

frequency-tunable short pulses and high-spectral-purity cw beams with dye lasers. These would aid our diagnostics capabilities and allow the study of resonant nonlinear phenomena in materials which heretofore could not be studied. This facility will also be capable of high-resolution and saturation spectroscopy.

ANALYSIS OF SELF-FOCUSING AND SELF-PHASE-MODULATION IN AMPLIFYING MEDIA AT SATURATED GAIN

In the last semiannual report a discussion of the effect of exponential gain or loss on self-focusing and self-phase-modulation was presented.^{10,2} Here this work is generalized to include the effects of gain saturation due to upper level depletion. Numerical evaluation of the solutions in one very limited case provides some insight into the nature of the problem. Clear statements of the limitations of this approach are also given.

The first integral of the eikonal equation* is

$$\frac{\partial r}{\partial z} = \sqrt{\frac{2n_2 |E(r, z, t)|^2}{n_0}}, \quad (1)$$

which is completely general within the paraxial ray approximation. However, rather than assuming a gain G which is exponentiating in z , we can generalize this function to be an arbitrary function of z , but not r . Under these conditions, the general solution of equation (1) is

$$\int_0^x \sqrt{G(z')} dz' = 1, \quad (2)$$

where x is a normalized distance parameter, namely the ratio of the self-focusing distance in the presence of gain to the self-focusing distance with no gain, i.e., $x = z_{sf}(g)/z_{sf}(0)$, while z' is a normalized integration parameter, namely the ratio of the propagation distance (l) into the nonlinear medium to the self-focusing length with no gain, $z' = l/z_{sf}(0)$.

Within the thin-lens limit of self-focusing, where only a small convergence is self-induced, the effect of gain on convergence can also be simply stated, namely

$$\frac{\theta_{conv}(g)}{\theta_{conv}(0)} = \left[\int_0^1 \sqrt{G(z'')} dz'' \right]^2, \quad (3)$$

where z'' is normalized to the total length of the nonlinear medium.

A similar pair of relationships can be written down for the case of self-phase-modulation in a saturated gain situation. The effect of gain on self-phase-modulation can be related to the self-phase-modulation distance without gain by the relationship

$$\int_0^y G(z') dz' = 1, \quad (4)$$

where y is the ratio of the self-phase-modulation length with gain, $z_{spm}(g)$, to that without gain, $z_{spm}(0)$, and z' is normalized to $z_{spm}(0)$. Here the self-phase-modulation length, analogous to the self-focusing length, is defined as the propagation path length at which the full extent of the pulse bandwidth due to the host becomes equal to the fluorescence bandwidth of the gain medium. Of course, gain affects the magnitude of the self-phase-modulation length.

Finally, one can also evaluate the maximum phase-modulation-induced pulse bandwidth Ω_{max} for arbitrary $G(z)$, when $\Omega_{max}(g) <$ the gain bandwidth. This again is most simply expressed in terms of a ratio.

$$\frac{\Omega_{max}(g)}{\Omega_{max}(0)} = \int_0^1 G(z'') dz''.$$

where z'' is again normalized to the length of the nonlinear medium.

In order to explore some of the consequences of saturation, let us evaluate the situation for the most simple form of saturation, namely upper level depletion at a rate slow compared to t_2 . We also assume that depletion does not proceed so far that the energy gain and intensity gain are the same. In this case $G(z)$ is given by

$$G(z) = \left(\frac{W_{in}}{W_{sat}} \right) \ln \left\{ 1 + [\exp (W_{in}/W_{sat}) \cdot l] \exp (gz) \right\}. \quad (5)$$

Plots of $z_{sf}(g)/z_{sf}(0)$, $z_{spm}(g)/z_{spm}(0)$, $\theta_{conv}(g)/\theta_{conv}(0)$, and $\Omega_{max}(g)/\Omega_{max}(0)$ versus gain or normalized gain coefficient (gz) are given in Figs. 80 through 83. Also, the gain coefficient versus fraction of saturation energy (W_{in}/W_{sat}) for various gains is presented for the hypothesized $G(z)$ in Fig. 84. Qualitatively, we find that the effect of this kind of limitation on energy gain is just about right to allow a saturated amplifier of total gain G to be approximated by the same length of unsaturated amplifier of total gain G .

*The Eikonal equation is the starting point for deriving the self-focusing equations for exponential gain materials. While strictly correct only under energy conserving situations, this description has been shown to agree well with other more general and complex descriptions.

Of course, Eq. (5) is nowhere near realistic in approximating amplifier gain saturation of the intensity in a pulse duration regime where index nonlinearities are currently believed to be important. Qualitatively we would expect that the laser pulse

Fig. 80. Plots of $z_{sf}(g)/z_{sf}(0)$ vs normalized gain coefficient $g z_{sf}$ for several values of W_{in}/W_{sat} .

Fig. 81. Plots of $z_{spm}(g)/z_{spm}(0)$ vs normalized gain coefficient $g z_{spm}$ for several values of W_{in}/W_{sat} .

Fig. 82. Plot of $\theta_{conv}(g)/\theta_{conv}(0)$ vs saturated gain for various values of W_{in}/W_{sat} shown on curves.

duration would lie near enough to t_2 for the amplifier, thus leading to the possibility of coherency effects, namely a gain-dependent pulse duration due to population inversions less than zero during part of the pulse. These effects tend to increase the intensity over that estimated by Eq. (5), as does the different z dependence of $G(z)$. Therefore we qualitatively expect that unsaturated-gain amplifiers lead to lesser index-nonlinearity effects than saturated amplifiers, independent of the other limitations on these calculations.

Specifically there are at least three very consequential interactions of gain, self-focusing, and self-phase-modulation which the current theory is incapable of handling.

1. Due to the gain (or loss), there is a resonant contribution to n_2 beyond that of the host which in the presence of a time-dependent center frequency* leads to a time-dependent n_2 . This is seen from the fact that the presence of the resonance leads to a reduction in n_2 on one side of line center and an increase in n_2 on the other side.

2. Due to self-focusing, the center of the beam (or any spatial structure) can intensify sufficiently to partially saturate the gain by upper level depletion in the spatial area of intensification, leading to a radially dependent gain $G(r,z)$. Also, due to the higher intensity in the center of the beam (or any spatial structure), self-phase-modulation can cause the pulse bandwidth to instantaneously exceed the fluorescence bandwidth, leading to locally reduced gain or $G(r,z,t)$. In fact, most practical amplifiers are not uniformly pumped, which also leads to a $G(r,z)$. If the r and z dependence are separable it is possible to easily include this effect in the integration above. Otherwise, more elaborate schemes are necessary to approximate the problem.

3. Due to self-phase-modulation, it is possible for the phase of the material polarization to either lag or lead the phase of the optical electric field. If this phase difference becomes greater than $\pi/2$, instead of gain the pulse instantaneously experiences loss. This effect was first realized as a result of the runs with Fleck's nonlinear optics propagation code¹⁰³ and has been called phase-induced nutation due to its essential similarity to the usual coherency effect called nutation.

The value of this work is not in fitting experimental data but in the fact that it allows various simplified theories for $G(z)$ to be used to qualitatively predict the nature of the complete two-dimensional time-dependent solutions obtained numerically by Fleck's code.

*Time-dependent in the moving coordinate frame.

Fig. 83. Plots of $\Omega_{max}(g)/\Omega_{max}(0)$ vs saturated gain for various values of W_{in}/W_{sat} shown on curves.

Fig. 84. Plots of gain coefficient gL vs W_{in}/W_{sat} for various gain values shown on curves. Scale of unsaturated gain is given at right of figure.

LASER-PRODUCED PLASMAS

X-RAY CONVERSION EFFICIENCIES OF LASER-PRODUCED PLASMAS

A short, high-energy pulse of laser light focused on a target can convert a small portion of the target to a hot, dense plasma that emits x rays. If the process by which laser light is converted to x rays can be made efficient enough, laser-produced plasmas could be useful in applications that require a sharp burst of x rays — e.g., flash x-ray photography or simulation of the x-ray output of nuclear explosives.

We have completed a survey of the x-ray yields and conversion efficiencies of plasmas produced when a pulse of light from the Plasma X neodymium-glass infrared laser is focused on targets of various materials. As well as providing information on the possible use of laser-produced plasmas as a source of short-pulse x rays, the results of the survey also provide a test of theoretical calculations based on a hydrodynamic radiation code.

The experimental setup is shown schematically in Fig. 85. The energy output of the laser, which was measured by the photodiode, averaged about 2 J, and the pulse width was about 120 psec. The laser beam entered a chamber evacuated to a pressure of about

10^{-4} Torr and was focused on a target to a spot about 100 μm in diameter.

We considered several different detectors for measuring the x radiation emitted by the resulting plasma, including calorimeters, solid-state detectors, and ionization chambers. An ionization chamber was chosen because it is easy to calibrate and because its sensitivity in the normal operating region is nearly independent of the x-ray energy, so that interpretation of the data does not depend on the x-ray energy spectrum.

The ionization chamber is a flowing gas counter (90% argon, 10% methane). X rays enter the chamber through a 1/2-in.-diam window which is offset from the high-voltage electrode in the center of the chamber. The window material determines the lower limit of x-ray energies the counter can detect. We used two materials, 1-mil-thick Mylar and 0.6-mil-thick beryllium, and carried out measurements on the various targets with each window. The lowest energies at which these windows transmit at least half of the x radiation are 1.3 and 2.5 keV for the beryllium and Mylar respectively.

Fig. 85. Experimental arrangement for measuring the x-ray yields and conversion efficiencies of laser-produced plasmas. The basic design of the ionization chamber is also shown.

The upper limit of the detector's energy response is determined by its length. We arbitrarily selected a detector length (36 cm) that corresponds to two mean free paths for 10-keV x rays in argon. A detector of this length can capture 87% of the 10-keV x rays.

We calibrated the counter not only by using a known radiation source, ^{238}Pu (α particles), but also electronically, by using voltage pulses of known

characteristics. Both methods lead us to conclude that the counter's accuracy in terms of absolute charge collection is at least $\pm 10\%$.

Figure 86 shows our results for the conversion efficiency (the ratio of x-ray energy to laser energy) as a function of the atomic number of the target material. The polyethylene data are plotted at atomic number 3, which is approximately the average atomic

Fig. 86. X-ray conversion efficiency of the plasma produced when the Plasma X laser beam strikes targets of various atomic numbers, assuming isotropic x-ray emission. The beryllium and Mylar windows transmit x rays with energies above ~ 1.3 and ~ 2.5 keV respectively.

number of CH_2 . With the high-Z targets (having an atomic number of at least 40) the conversion efficiency is about 10^{-4} for the $>2.5\text{-keV}$ x rays that pass through the Mylar window and about 10^{-3} for the $>1.3\text{-keV}$ x rays that pass through the beryllium window.

For sulfur ($Z = 16$), this order-of-magnitude difference is not observed. This indicates that the sulfur target is emitting relatively few x rays with energies between 1.3 and 2.5 keV. The K x-rays of atomic sulfur have energies near 2.4 keV, and the transmissions of these x rays by the two windows actually differ by only about a factor of 2. Thus, the sulfur data suggest that most of the sulfur x rays above about 1.3 keV are emitted in K x-ray lines. The same conclusion can be drawn from the data on aluminum ($Z = 13$), since the ratio of the transmissions of the two window materials for the aluminum atomic K x-rays (having energies of about 1.4 keV) is roughly the same as the ratio of the aluminum target yields — namely, about a factor of 10.

Since the x-ray line radiation from the carbon and CH_2 targets is of too low an energy to pass through either window material, the transmitted radiation must consist of continuum x radiation, which is due to recombination processes or bremsstrahlung or both. Assuming that the plasma is in thermal equilibrium (i.e., that it is emitting bremsstrahlung), the electron temperatures corresponding to the carbon and CH_2 data are about 0.4 and 0.2 keV, respectively.

We used the MONTE-WAZER code to try to theoretically reproduce some of the experimental

results. In this code the populations of the bound states of the target elements are not assumed to be in local thermodynamic equilibrium. This means that both the equation of state and the opacity of the plasma are much more complicated than in equilibrium problems.

Our calculations for a gold target, in which it was assumed that all the laser energy was absorbed by the target, indicated that about 30% of the energy is emitted from the front surface of the target in the form of x rays. The x-ray energy below 1 keV should account for 85% of the total x rays emitted. In addition, we predicted discrete line radiation at energies of 2.65 and 3.55 keV; the line at 2.65 keV should be about five times stronger than the one at 3.55 keV. This agrees fairly well with the observations reported in the previous semi-annual — UCRL-50021-71, pp. 58-60 — which show a line radiation at an energy of about 2.4 keV. (MONTE-WAZER uses an approximate procedure to compute line energies, so the difference between 2.4 and 2.65 keV is not significant.)

We calculated further that the total energy emitted from the gold target in the form of x rays should be 2.6% of the absorbed laser energy. This result is more than an order of magnitude greater than the value inferred from the x-ray yield measurements (Fig. 86 shows that the conversion efficiency for a gold target with a beryllium window is about 6×10^{-4}). Additional investigations are being carried out in an attempt to understand the discrepancies between the computed and the experimental results.

RECENT RESULTS WITH THE LONG PATH LASER

We have changed the Long Path Laser so that the beam now makes only five passes through the disk amplifier section instead of nine passes as before. Tests show that five-pass operation should give greater beam energy, although some problems remain to be solved before the expected improvement is realized. Considerable work has been done on beam diagnostics with the 10-psec-resolution streaking camera and a high-resolution spectrograph, with the result that pulse characteristics at various points along the beam path are better understood. We have continued the experiments in which we produce plasmas by focusing the Long Path Laser beam (with the new five-pass arrangement) on targets of CD_2 and CH_2 and measure the x-ray and neutron production and the reflected light intensity. Neutron production with five passes seems about the same as it was with the previous

nine-pass setup, but x radiation and reflected light intensity are several times higher.

Changeover to Five-Pass Operation

The Long Path Laser¹⁰⁴ was originally designed so that the beam made nine passes through the disk amplifier section. After the system was completed and in operation, beam energy measurements at various points along the beam path showed greatest energy after the fifth pass. We therefore decided to change over to five-pass operation.

Figure 87 shows measurements of fifth-pass energy as a function of input energy from the glass-rod amplifier chain; these measurements were made while the system was operating in the nine-path configuration. As can be seen, output energy is about

Fig. 87. Beam energy after five passes through the disk amplifiers in the Long Path Laser plotted as a function of input beam energy. These measurements were made while the Long Path Laser was still in the nine-pass configuration.

200 J for 10 J of input energy. We expected similar performance after the changeover to five-pass operation, but found that we obtained only about 100 J output for 10 J input. We suspect that the input beam divergence may be greater now than when the measurements of Fig. 87 were made. This possibility and others are being checked.

Beam Diagnostics

Our recent work on beam diagnostics is summarized in Table 7. Energy and pulse duration were measured with conventional calorimeter and photodiode

techniques. Streak intensity was observed with a 10-psec-resolution streaking camera.⁴ The spectrum was recorded by a 3.4-meter Jarrell-Ash Ebert spectrograph whose characteristics are given in Table 8, and the streak spectrum was recorded by combining the spectrograph and the 10-psec streaking camera. Focal spot size was determined by methods previously described.¹⁰⁵

The 20-psec structure and 1.2-Å spectrum periodicities observed in Figs. 88 and 90a, respectively, originate in the oscillator from a 3-mm-thick window in a Pockels cell used for Q-switching. The 200-psec structure and 0.14-Å spectrum periodicities are due to a spacing of about 28 mm between KD*P crystal faces of the Pockels cell. (The appropriate etalon relation is $\tau\Delta\lambda = 37.5 \text{ psec}\cdot\text{Å}$.)

The spectrum after either five or nine passes through the disk amplifier section is not greatly altered from that of the oscillator or rod amplifier chain. The major difference is the expanded bandwidth and the "filing in" between lines. This effect has been reported previously by DeShazer.¹⁰⁶

Streak intensity photos presented in Figs. 89a,b show the 20-psec modulation early in the pulse but a temporally smooth central portion, with the 20-psec modulation reappearing at the tail of the pulse. At the

Fig. 88. Streak camera photo of pulse from glass-rod amplifier chain of Long Path Laser, before passing through the disk amplifiers. Note 20-psec substructure of pulse.

Table 7. Summary of beam diagnostics on Long-Path Laser

	Output from rod amplifier chain ^a	Output from disk amplifier section	
		After nine passes	After five passes
Energy (J)	0.1-10	~100	~100
Pulse duration (nsec)	2	3	2.5
Streak intensity	See Fig. 88	See Figs. 89a, b	—
Spectrum	See Fig. 90a	See Fig. 90b	See Fig. 90c
Streak spectrum	See Fig. 91	See Fig. 92	—
Focal spot size (μm)	—	50 by 100	50 by 100

^aThis is the input to the disk amplifier section.

Fig. 89. Streak camera photos of pulse from Long Path Laser after nine passes through the disk amplifiers. (a) Early part of pulse, (b) Center of pulse.

Table 8. Characteristics of the 3.4-m Jarrell-Ash Ebert spectrograph

Grating	590 lines/mm	
Ruled width	152 mm	
Focal length	3.333 m	
	1st order	2nd order
Reciprocal dispersion (Å/mm)	4.86	2.17
Resolution (Å)	0.14	0.058
f-number	31.3	34.6

moment, we can only speculate that the smoothing is caused by self-phase-modulation. If this were so, the spectrum should be broadened and smeared. We observe broadening but little smearing, and moreover the broadening may be due to other causes (see article by DeShazer).¹⁰⁶

When we record a streak spectrum (as in Figs. 91 and 92) we introduce an instrumental 300-psec time integration due to transit time spread in the 3.4-m Jarrell-Ash spectrograph. The streak spectrum of the beam from the rod chain is temporally smooth (to 300 psec) so that we cannot unequivocally describe the 20-psec and 200-psec features as due to mode beating. The streak spectrum of the nine-pass beam is extremely complicated as can be seen from Fig. 92. We are not yet prepared to speculate as to the causes

Fig. 90. Pulse spectra from the Long Path Laser recorded with a 3.4-m Jarrell-Ash spectrograph. (a) Pulse from rod amplifier chain, energy 0.55 J. (b) Pulse after nine passes through disk amplifiers, energy 47.6 J. (c) Pulse after five passes through disk amplifiers and before striking CD_2 target, energy 32.4 J. (d) Pulse reflected from CD_2 target.

of the details observed in this streak spectrum. In comparison to the streak spectrum of the rod chain output, taken with the same experimental arrangement, some pronounced spectral changes have certainly occurred.

Plasma Experiments

Experiments described in the previous semiannual report,¹⁰⁷ in which the beam from the nine-pass Long Path Laser was focused on a target of CH_2 or CD_2 to produce a plasma, have been continued with the five-pass beam. In these experiments we measure x rays and neutrons produced by the plasma and the intensity of laser light reflected from it. Our recent neutron experiments have been inconclusive because of x-ray shielding problems. Our normal procedure for

Fig. 91. Streak spectrum of pulse from rod amplifier chain of Long Path Laser is temporally smooth. Streak spectra are made by combining the 3.4-m Jarrell-Ash spectrometer and the 10-psec-resolution streaking camera.

Fig. 92. Streak spectrum of Long Path Laser pulse after nine passes through the disk amplifiers. Note complex structure as compared with Fig. 91 spectrum of the pulse before passing through the disk amplifiers.

neutron measurements is to produce CH_2 plasmas, look at the x-ray signals from our neutron detector, and shield it with enough lead to reduce the x-ray signal to noise level. This required 1/2 to 3/4 in. of Pb with the nine-pass beam, but for plasmas produced with the five-pass beam we had to use about 1-3/4 in. of Pb. The only difference in the pulses in the two cases appears to be the spectral width (see Fig. 90b,c). Also, W. Mead's x-ray measurements using 1/8-in. Ni absorbers indicate no excessive x rays. We do not yet understand this discrepancy.

Neutrons were not observed in the well-shielded setup described above. We believe the Pb shielding reduced the neutron signal to the noise level also. (Neutron attenuation by Pb was a factor of 6.) We then moved the neutron detector to a position 1.5 m from the target so as to separate neutrons from x rays by time of flight. We did observe neutrons in this arrangement. The size of the signal corresponded to work reported in the previous semiannual.¹⁰⁷

We recorded the spectrum of the reflected light from CH_2 , CD_2 , Pb, and Zr targets. A spectrogram for CD_2 is shown in Fig. 90d. The reflected light spectra from CH_2 and CD_2 look nothing like the incident spectra (see Fig. 90c), while the reflected light spectra from Pb and Zr were identical to the incident spectra. We are studying this effect.

Fig. 93. Plots of power vs time for incident and reflected pulse striking a CH_4 target after five passes through the disk amplifiers of the Long Path Laser.

The intensity of the reflected light with the five-pass beam was higher by a factor of 3-5 than that with the nine-pass beam. A record of the nine-pass reflected intensity is given in Ref. 108. Figure 93 shows the five-pass reflected intensity. Again, the only discernible difference between the two cases is that the spectral width is greater for the nine-pass incident beam.

LASER-PLASMA COUPLING

Our main effort has been devoted to calculating the energy distribution of the electrons heated by the electrostatic instabilities that are excited in the plasma by the laser. We have found that the electron energy distribution is quasi-Maxwellian for fast-rising, very high intensity laser pulses (Fig. 94).¹⁰⁹ However, for typical pulse intensities and risetimes, the distribution is heavily weighted with very high energy electrons. The shape of the distribution is important because it is a critical factor in designing target pellets for laser-plasma production.

We have also continued our calculations of plasma absorption of very intense laser light using the two-dimensional relativistic code REL. We expected that the pressure of the electromagnetic wave would cause a sharp density gradient in the plasma which would inhibit absorption of the laser energy. These calculations are not yet complete, but the preliminary results indicate that although a sharp density gradient is formed at first, as soon as the plasma instabilities grow sufficiently the plasma still absorbs the laser energy.

We have begun a study of the coupling of the plasma core electrons with the corona electrons.* The low-density corona electrons are heated by the laser to high temperatures and can have a collisional mean free time that is very long. Thus the rate of heating of the corona electrons can be faster than the rate at which energy is given to the core electrons, so that the corona decouples from the core and it then becomes very hard to heat the core. There is a mechanism by which the undesirably long mean free time for collision is reduced: The corona electrons interpenetrating the core are unstable with respect to two kinds of plasma instabilities, and unstable electromagnetic fields grow up in the plasma as a result and decrease the mean free time for collision. We have just begun these

*The corona is the outer region of the plasma, in which the electrons are directly heated by the laser. The inner region - the plasma core - is not penetrated by the laser light and therefore its electrons must be heated indirectly, e.g., by absorbing energy from the laser-heated electrons in the corona.

Modifications in Progress

We are currently rebuilding the rod amplifier chain, to add 1-in. and 2-in. Faraday-rotator isolators and to install a 2-in.-diam rod amplifier. A new disk amplifier is being designed to improve the five-pass gain. A large plasma experiment area (with electronic shielding) is being added to facilitate better and more elaborate experiments.

Fig. 94. Calculated electron velocity distribution during the later heating phase ($\omega_{pe}t = 18$); $a_e = (2KT_e/m_e)^{1/2}$.

calculations. Our preliminary results indicate that the mean free time is significantly reduced for a pulse length of a few picoseconds.

Calculations of Electron Energy Distribution

The one-dimensional CYCLOPS calculations showed roughly that for low intensities the instability-heated electron energy distribution is $f(v) \propto 1/v^2$ (with a normalization $\int f(v) dv = n$) up to an energy of roughly 100 times the initial temperature, beyond which the distribution drops off very sharply. This result applies to pulses with laser electric fields of $E_0 \leq 0.6(4\pi nKT_e)^{1/2}$ (i.e., to all pulses except very fast rising ones), where n is the plasma density, K is Boltzmann's constant, and T_e is the electron temperature.

We have improved the calculational model for the electron energy distribution in three ways:

1. Putting in phase modulation of the laser pulse.
2. Using a two-dimensional code (MINOTAUR).

Fig. 95. Calculated electron velocity distribution parallel to the external electric field; $\frac{1}{2} m_e \omega^2 = 6.8$ keV.

Fig. 96. Calculated electron velocity distribution perpendicular to the external electric field; $\frac{1}{2} m_e \omega^2 = 3.3$ keV.

3. Modeling the loss of electrons from the anomalous region.

The results of these improvements are as follows:

Phase modulation decreases the instability growth rate and changes the energy distribution to more like $f(v) \propto 1/v^4$ and the maximum energy to about 60 times the initial temperature. The distribution change varies slowly with phase modulation frequency.

The results from the two-dimensional code MINOTAUR show that along the laser electric field the distribution is the same as obtained from CYCLOPS (Fig. 95). However, in the perpendicular direction, the distribution drops off much more sharply (Fig. 96). Thus electrons leaving the anomalously heated region will travel largely parallel to the laser electric field.

The calculations so far have been performed in an infinite medium. Thus the flow of heated electrons out of the anomalous region and the flow of cold electrons back in have been ignored. We have modeled this flow process in a one-dimensional code called DENSE. Clearly the gains and losses will affect the energy distribution because the heated electrons spend a finite amount of time in the anomalous region. The results are not yet complete, but they indicate that the distribution does drop off somewhat faster and the cutoff energy is lowered.

Calculations of Electromagnetic Pressure Effect

A very intense laser pulse produces density striations in the plasma due to the electromagnetic pressure exerted on the plasma. It is possible that this process could significantly reduce absorption of the laser

Fig. 97. Normalized electron and ion densities as determined by two-dimensional, relativistic, fully electromagnetic calculations.

energy by the plasma. We have performed two-dimensional, relativistic, fully electromagnetic calculations to investigate this effect. A rather steep density gradient is included in these calculations. The preliminary results indicate that the density striations are indeed set up in the plasma (Fig. 97). But a little later in the calculation the instabilities appear and cause strong heating. The net effect is that the sharp density gradients caused by the laser increase the absorption length somewhat, but still the absorption should be nearly complete. These calculations are being continued.

Calculations of Corona-Core Coupling

As described in the previous semiannual report,¹¹⁰ when a target pellet in vacuum is illuminated from many sides by a powerful focused laser pulse, the surface of the pellet is strongly heated and the pellet is quickly engulfed in a hot, low-density plasma. The laser penetrates this plasma only to a depth where the plasma frequency equals the laser frequency. For a CO₂ laser (10.6 μm) this critical depth occurs at the extremely low density of 10^{19} cm^{-3} . The plasma region outside the critical depth, in which the electrons are directly heated by the laser, is called the corona. In the region inside the critical depth, called the core, the electrons must be heated by indirect means — e.g., by the hot electrons from the corona.

The corona electrons can be very hot, with a mean free time for collision so long that effectively the core and corona are decoupled, so that the heating of the core stops while the corona electrons continue to increase in temperature. The reason for this undesirable occurrence is that the mean free time of the corona electrons increases rapidly with temperature. However,

the corona electrons moving through the core are unstable with respect to two kinds of plasma instabilities. One is the so-called Weibel instability, which occurs in a plasma with an anisotropic distribution of particles. We have used the two-dimensional electromagnetic code SYLLA to simulate this instability. Our results are not complete, but they indicate that the decrease in the mean free time due to the effect is probably small. The system is also unstable with respect to the two-stream instability, which occurs because a beam of particles (the corona electrons) are moving through the core plasma. We have constructed a code called INJECT to calculate how effective this instability is in reducing the mean free time. INJECT is a one-dimensional electrostatic code. We have made a few runs with the code and have observed a significant decrease in the time required for the core electrons to absorb the hot electrons. The length of time over which the effect will extend is estimated to be a few picoseconds. We are presently continuing this study to calculate the decrease in the mean free time and the time over which this effect applies.

WAVELENGTH DEPENDENCE OF LASER-LIGHT ABSORPTION BY SOLID DEUTERIUM

We have performed calculations indicating that solid deuterium absorbs laser light more efficiently as the wavelength of the light decreases. This implies that lasers producing light in the ultraviolet region might be more practical for heating deuterium than the longer-wavelength lasers that we are now working with.

When solid deuterium is heated by a laser beam, the heating occurs not inside the solid but in regions of much lower densities in the plume of plasma that blows off the solid. The ratio of absorption to reflection of laser light in this plume is a crucial parameter for fusion-power designs because the laser-energy input required is inversely proportional to the fourth power of the efficiency of absorption.¹¹¹

Although many analytical and computational studies have been done, both here and elsewhere, on the absorption of laser light as a function of light intensity, pulse duration, and target design, these studies have all been based on available laser wavelengths — i.e., 0.69 μm for ruby, 1.06 μm for neodymium, and 10.6 μm for CO₂. To determine if some other laser wavelengths would lead to higher absorption efficiencies, we conducted a computer study of absorption as a function of wavelength, using the numerical code WAZER.¹¹² The problems were simple: the targets had one-dimensional slab geometry, and no "prepulse" was included to build up a gradient-density plasma plume beforehand — the

plume blew off the solid surface during the calculation.

Two absorption models were used: first, only "classical" electron-ion collisional absorption (inverse bremsstrahlung); second, both classical and "anomalous" (collisionless) absorption. The anomalous term was based on the parametric ion-acoustic instability, whose intensity threshold can be exceeded in a narrow range of densities just below the cutoff density.¹¹³ For those plasma regions which met these restrictive intensity and density criteria, the additional anomalous absorption was assumed to be saturated and was approximated by $\nu^* \approx \omega_{pi}$, where ν^* is the anomalous collision frequency and ω_{pi} is the ion plasma frequency. This is admittedly only a crude approximation, but it does seem to roughly match simulation-code calculations.

The results of a series of computer runs are presented in Fig. 98, which shows that greater fractions of light are absorbed at longer pulse durations and shorter wavelengths. As expected, the absorption fraction is also increased when anomalous absorption is included in the calculations, especially at longer wavelengths. At the shorter pulse length, however, the anomalous model did not contribute to the absorption as much as expected.

These results can be qualitatively understood by means of an absorption estimate in which the absorption fraction A is calculated by an integral that

Fig. 98. Absorption of laser light on a deuterium slab as a function of wavelength, as calculated with classical (curve A) and anomalous (curve B) absorption models. Top: Results for a long pulse with a duration of about 4 nsec and an intensity of 2×10^{14} W/cm². Bottom: Results for a short pulse with a duration of about 0.1 nsec and an intensity of 10^{15} W/cm².

follows the laser light through the plasma to the reflection point (at the cutoff density), and then back out:

$$A = 1 - \exp \left(-2 \int_0^H K dx \right),$$

where H is the position of the reflection point, K is the linear absorption coefficient, and x is the distance the light has traveled in the plasma. In carrying out the integration, we assume that the density gradient

is linear. When the classical absorption coefficient is substituted for K , the result is¹¹⁴

$$A_{\text{class}} = 1 - \exp \left(- \frac{C_0}{T_e^{3/2}} \frac{H}{\lambda^2} \right),$$

where C_0 is (almost) a constant, T_e is the electron temperature, and λ is the wavelength of the laser light.

With our approximate anomalous-absorption model, one obtains an even simpler result:

$$A_{\text{anom}} = 1 - \exp \left(- \frac{5H}{\lambda} \right).$$

In either case, we want H to be large enough to keep the absorption fraction close to 1. And in both processes, absorption is related to wavelength in such a way that, for a given H , the absorption increases as the wavelength decreases. These general statements are confirmed by the code runs (Fig. 98). Further work is needed to find the best wavelength for a specific target model; our calculations simply show the general trend.

Thus, this work does not rule out the possibility that the absorption efficiency might be increased to more tolerable levels through ingenuity — such as using carefully programmed pulse shapes. It does imply, however, that designing around the problem becomes more difficult at longer wavelengths, whereas the inherently better absorption at shorter wavelengths permits greater freedom in target design.

We believe that the results of these calculations present a challenge to develop lasers that are more suitable for heating deuterium.¹¹⁵ Today, neodymium-doped glass and nitrogen/carbon-dioxide lasers are the most technically advanced and most promising for preliminary and intermediate laser-fusion experiments. But for the long term, a powerful, efficient, pulsed ultraviolet laser may be the most promising.

DIAGNOSTICS

DIAGNOSTICS SUMMARY

The 10-psec-resolution streak camera⁴ has been widely used in diagnosing several types of lasers at Lawrence Livermore Laboratory. Extensive data has been accumulated on the Long Path Laser (see p. 82). Data have also been taken on two different versions of a Q-switched Nd:glass laser (see p. 13) and on a Q-switched YAG oscillator (see p. 6). Most recently the camera has been used to study the systematics of "stretching" the pulses from a mode-locked Nd:YAG oscillator (see p. 9).

We have recently designed a compact, portable, and versatile version of the 10-psec streak camera. The principal saving in space and complexity is achieved by using a small, microchannel-plate image intensifier instead of a large magnetically focused tube. Additional savings result from miniaturization of the power supplies and control circuits. The new camera is a totally self-contained unit which is easily adaptable to a variety of experimental requirements. The mechanical and electronic design of the camera is complete, and most of the parts are on hand, so we can complete the assembly and testing of the first one in the next few months. We plan to build five of these cameras initially.

Development has continued on a streak camera tube capable of providing time resolution approaching 1 psec. Details of the concept and the accomplishments to date are provided separately (see p. 98).

We have designed and built a "Littrow configuration" spectrograph that analyzes laser wavelengths of approximately $1.06\text{ }\mu\text{m}$. The optical arrangement of the spectrograph is shown in Fig. 99. It is compact (about 1 m long), and it uses an infrared-sensitive image converter for convenient data recording. The resolution of the instrument in its present form is about $0.5\text{ }\text{\AA}$. The first of these instruments is being used to monitor the linewidth emitted by the pulse-stretched YAG oscillator.

A mode-locked, atmospheric-pressure CO_2 oscillator of LLL design (Ref. 28) has been set up and operated in the diagnostics laboratory. Considerable effort has been spent in characterizing the pulse and in varying the oscillator parameters to optimize the power available in a spatially smooth beam. The oscillator will be used as a source for the development of $10.6\text{-}\mu\text{m}$ diagnostics techniques. We are presently attempting to use our ultrafast streak camera to measure a CO_2 pulse with 10-psec time resolution. The fact that the

Fig. 99. Optical arrangement of Littrow-configuration spectrograph for analyzing wavelengths in the $1.06\text{-}\mu\text{m}$ range. Image converter tube is infrared-sensitive for convenient recording of data.

photocathode in the streak camera will not respond to 10.6- μ m light requires an indirect approach. Through the intermediary of the optical Kerr effect in CS₂, the mode-locked CO₂ pulse can be made to modulate the transmission of a reference light beam directed through crossed polarizers. This reference beam has a wavelength to which the streak camera's photocathode is sensitive. The time response of the CS₂ optical modulation is 2 psec.¹¹⁶ Figure 100 is a photograph of the oscillator setup for this experiment.

Under a Laboratory contract, R. F. Wuerker of TRW Systems brought his pulsed ruby holocamera to LLL to photograph the optical inhomogeneities in electric-discharge gas lasers. The technique of double-pulsed holographic interferometry provides a sensitive detector for refraction index variations. This application of the camera was successfully completed. Results are contained in the sections on the various devices (see p. 35 and p. 48).

More effort is being devoted to the study and development of techniques for diagnostics of laser-target interactions. We are fabricating a simple curved-plate electrostatic analyzer* for charged particle spectroscopy. In addition, designs for more versatile and comprehensive analyzers are being considered. The goal is to provide instruments that will obtain the widest possible range of data from each irradiation. Preliminary experimentation with holographic techniques is under way. We are developing pulsed holographic interferometry with Q-switched and mode-locked laser pulses for the diagnosis of density distributions in laser-produced plasmas.

Work on the development of calorimeters capable of measuring high-power CO₂ laser pulser is discussed in the following articles. Also a convenient image-converter technique is described for monitoring near-field patterns.

*Design provided by Sandia Laboratories, Albuquerque, N. Mex.

Fig. 100. Experimental setup of the mode-locked atmospheric-pressure CO₂ oscillator used for development of fast 10.6- μ m detection technique employing the LLL 10-psec-resolution streaking camera.

SILICON DISK CALORIMETERS TO MEASURE BEAM ENERGY OF HIGH-POWER 10.6- μ m LASERS

To meet a need for calibrated calorimeters that can conveniently measure energy of high-power pulsed CO₂ lasers up to several kilojoules, two assemblies using silicon disks as absorbing cells have been built, tested, calibrated, and put into use.

The principle of operation of a cell calorimeter is to dissipate the entering laser beam energy throughout a substantial volume of material. This avoids local high temperatures with consequent melting, cracking, or chemical change. The resulting temperature rise of the absorbing volume of material (the cell) can then be used as a valid measurement of the beam energy deposited.^{117,118}

Figure 101 shows a conventional solid-cell calorimeter system. The temperature of the cell is measured with reference to that of a heat sink, which must stay at effectively constant temperature during the measurement. The difference voltage read out from the thermocouples is recorded as a function of time by the recorder.

Application of Silicon to CO₂ Laser Calorimeters

High-purity silicon has moderate absorption near 10 μ m (Fig. 102), permitting design of solid cells with about 3 in. of absorbing path which will absorb 99% of entering CO₂ laser beam energy. However, not all the incident beam enters; about 30% is reflected at the first surface for normal incidence. (Coating the entrance surface could reduce the reflection loss to about 2%, but would lower the damage threshold.) More than 99% could be absorbed (shared) by two uncoated prisms placed in succession with their optically flat entrance faces at Brewster angle to the beam and crossed 90°. In lower grade silicon,

impurities increase the amount of absorption, thus permitting the use of smaller absorbing cells.

Silicon has the following advantages for use as the absorbing material in a cell calorimeter:

- High melting point.
- Low coefficient of thermal expansion, giving resistance to thermal shock.
- Chemically unreactive and insoluble.
- High thermal conductivity, giving a rapid rise to peak cell temperature during measurements.
- Small variation of refractive index with wavelength, so that reflection losses remain constant to 0.03% from 8 to 11 μ m.
- Can be ground and polished to produce surfaces of high optical quality.¹¹⁹

Silicon has two evident disadvantages besides its high refractive index. One is the rapid increase of absorption with temperature above 200°C.¹¹⁹ This could cause "thermal runaway," with strong local heating and damage, but it is probably the least constraint on the temperature range of operation. For example, the temperature rise of a 50-cm³ silicon prism is only about 10°C/kJ. In this connection the nonlinearity of thermocouple operation over large temperature variations poses a more serious problem. If 1% accuracy is required in the energy measurement, either the thermocouple nonlinearity can be held to 1% by limiting the operating range to no more than 12°C changes above room temperature, or (with a 50-cm³ cell) one could limit the measurement to a single shot of about 1 kJ. The time it would take for the cell to cool down to within 10 to 20% of equilibrium so as to be ready for another 1-kJ shot depends on the design of the calorimeter case, but it is typically 30 min. If about 5% accuracy is enough, a single shot of at least 20 kJ could be measured. Beyond a cell temperature of 50°C above equilibrium the cooling rate becomes so high that graphical interpolation to find small superimposed temperature rises becomes inaccurate.

The other evident disadvantage, which silicon shares with many other "partial absorbers" in the 9-to-11- μ m region, is the nonuniformity of absorption coefficient as a function of wavelength over the range of possible CO₂ transitions (Fig. 102). If measurements are to be made with a single calorimeter at unknown wavelengths over a substantial range, the calorimeter must be made effectively independent of wavelength over that range. This can be done with silicon by designing the system to totally absorb the whole range.

Fig. 101. Schematic of solid-cell calorimeter system. The cell absorbs the laser energy in the form of heat which is distributed uniformly throughout the cell. Hence the cell temperature is a valid indicator of the amount of energy absorbed.

Fig. 102. Typical published transmission curve for uncoated silicon.¹²³ The silicon disk sample is 2 mm thick and polished on both sides; the curve includes Fresnel reflection losses from both surfaces. Silicon's intrinsic absorption is increased by impurities - for example, the sharp dip in transmission at 9 μm is a reaction to SiO.

Fig. 103. Schematic of calibration system for silicon disk calorimeters. The reference calorimeter is calibrated electrically and then compared with the test calorimeter. The spectrograph monitors laser wavelength.

Test System

The silicon calorimeters were tested and calibrated using the system shown in Fig. 103. The test CO_2 laser beam was chopped, i.e., power was delivered for a measured time. The reference calorimeter (a cw power meter) was calibrated by dc electrical substitution power dissipated in a heater winding at the rim of its receiver disk.

The laser beam was directed alternately between the reference calorimeter and the test unit to check for drift. Beam exposures from 1.5 to 30 sec were used with powers ranging from 8 to 30 W. Although the accuracy of the system was about 5%, its repeatability or precision was nearer 1%.

Silicon Disk Calorimeters

The pieces of silicon used in this work were standard 5-cm-diam by 0.5-cm-thick laser mirrors polished flat to 1/40 wave and coated to greater than 98% reflectivity (both at $10.6\ \mu\text{m}$) on one side, and fine ground on the other.

During testing the laser beam was fired at normal incidence into the ground side of the disk. Reflection at the mirror surface gave a nominal absorbing path of 1 cm. The temperature rise of the disk was measured with reference to an aluminum cylindrical heat sink which surrounded the disk. Free convection kept the heat sink substantially at room temperature. On the basis of the measured temperature rise and the specific heat of silicon, we estimate that 68% of the incident energy is absorbed. When allowance is made for the nominal 30% reflection at the front surface, this means that about 97% of the energy that entered the silicon was absorbed. This high absorption is probably due to impurities, since the mirror substrates were "off-the-shelf," low-purity silicon.

Other tests showed the response to be stable and linear within 5% for pulses from 35 to 620 J, even for sequences of shots at 2-min intervals, for total temperature rises under 50°C . The spectral response was uniform within 5% for the narrow range of transitions normally emitted by the test lasers used (10.55 to $10.65\ \mu\text{m}$).

Since it was obvious that even these simple disks would be useful as calorimeter cells, two were assembled into calorimeters (Fig. 104), following an NBS design for a liquid cell calorimeter.¹²⁰ The copper sleeve was added to protect the foam supports and the heat sink from the diffuse reflected radiation from the ground front surface of the cell.

Testing the assemblies showed excellent linearity for shots at equilibrium (i.e., room temperature), but the linearity was degraded to about 10% for shots at 2-min intervals. Replacing the foam solid pack with thin foam vanes did not help measurably.

The external case is actually undesirable for high-repetition-rate operation, since it prevents the heat sink from cooling rapidly enough to get rid of the heat it has absorbed from the cell before another pulse is absorbed. Both the principle of isoperibol (constant temperature surroundings) calorimetry¹¹⁷ and the elementary requirement that the reference junction remain at a fixed temperature are violated.

Damage tests were begun. One of the calorimeters showed the same average calibration constant within 1% (measured from equilibrium), both before and after some dozens of shots from a CO_2 TEA laser at about $0.2\ \text{J}/\text{cm}^2$. There were no surface effects observed on the disk when it was cleaned by fine sandblasting.

The silicon disk calorimeter concept has been tested and appears valid. The calibrations and limits are now known for two calorimeters, which are in use on pulsed CO_2 lasers in the laboratory.

Work in Progress

• Five new calorimeter cases have been built, in which the heat sink is the external part and depends on free convection for cooling. They will be assembled into calorimeters using the same type of silicon mirror

Fig. 104. Design details of one form of the LLL silicon disk calorimeter.

disks as the absorbing cells. Each case is different in shape or size; the calorimeters will be tested to determine whether any of the cases gives significantly better linearity.

- The test system instrumentation is being improved to eventually give 1% accuracy or better.

- A spectrometer has been assembled that will permit unambiguous measurement of the absorption

and reflection of silicon samples, to permit control of cell design.

- A reference calorimeter* is being built incorporating the silicon prisms crossed successively at Brewster's angle to the beam. It should absorb 99% of the incident energy. The temperature of its heat sink and surroundings will be stabilized by a heater and control circuit.¹²² It will be calibrated directly by dc electrical power for use with pulsed lasers.

DEVELOPMENT OF CALORIMETERS TO MEASURE BEAM ENERGY OF HIGH-POWER PULSED LASERS

We are developing instruments to accurately measure the energy of single laser pulses of high power and short duration. The previous article discussed using silicon disks to measure energies up to several kilojoules. In this article we discuss calorimeters using similar techniques but different absorbing materials, and we also discuss new techniques we have tried. In particular we have investigated volume-absorption calorimeters (using various organic liquids and plastics) and a new type of surface-absorption calorimeter of tubular geometry. Initial measurements have been performed with small-diameter beams of 10.6- μ m wavelength, but there is a major effort to design systems capable of extension to arbitrarily large beam diameters and to other wavelengths.

The characteristic problem in the calorimetric measurement of high-power laser pulses is to insure absorption of all the energy or an adequately well known fraction of it. In general, it is not possible to obtain nearly complete absorption on a single-surface (disk) calorimeter; black coatings are rapidly destroyed by the high surface temperatures. The most common solution has been to use durable polished metallic surfaces arranged in a geometry (cone or hollow sphere) such that a ray must undergo a large number of reflections before escaping from the calorimeter. Alternatively, the radiation may be absorbed in a material having a substantial transmittance, so that the energy deposition is distributed throughout a considerable volume of material and the temperature rise is not excessive at any point. This method has in the past been exploited mainly in the use of unstirred aqueous solutions for absorbing radiation in the visible and near infrared. The volume absorption principle is the most promising for measurement of large-diameter laser beams without focusing lenses or mirrors.

The various calorimeters described below use thermostatted jackets or massive insulated aluminum blocks to give a controlled environment. They are

operated by the isoperibol method, in which a corrected temperature rise is deduced from the time-temperature curves, heat exchange with the environment being assumed to follow Newton's law. Time-temperature points over a period of about 4 min are normally used, but measurements of only slightly reduced precision can be obtained in a much shorter period, except with the stirred-liquid calorimeters. Thermistors and bridges are used for temperature measurement in the LC-1 and LC-2 series, and multijunction thermopiles for the rest. All of the calorimeters are calibrated electrically, using manganin wire heaters cemented on the surface.

Volume-Absorption Calorimeters

Various organic liquids and plastics have been used to absorb 10.6- μ m pulses. The absorption spectra of these materials are of course highly dependent on wavelength, but suitable materials could be selected for most wavelengths. Our measurements were based on two assumptions. First, it would be improbable for several different chemically distinct materials, having quite different absorption spectra, to all have large, nearly equal systematic errors. Second, nonlinearities of response (due to excessive surface heating or saturation of the absorption process) could be detected by measuring a convergent beam at different positions, so that the total energy would be the same but the energy densities would be different.

The receivers of the stirred-liquid calorimeters, LC-1 series (Fig. 105), are copper cups 35 mm in i.d. and 18 mm deep. They contain a magnetic stirrer and are fitted with sodium chloride or plastic-film windows. The receivers of the plastic calorimeters, LC-2 series, are 38 mm in diameter and consist of plastic sheets 0.8 mm thick cemented to copper disks 6.4 mm

* A variation on the double-reflecting plate calorimeter.¹²¹

Fig. 105. Stirred-liquid calorimeter (LC-1). Coils control external temperature of calorimeter, while magnetic stirring distributes the absorbed heat from the receiver uniformly throughout the liquid.

thick; they were suspended in the same jackets used for the LC-1 series.

The absorbing materials studied were kerosene, chlorobenzene, carbon tetrachloride, methylcyclohexane, Teflon, polystyrene, polyvinyl chloride, and Plexiglas. Measurements were made with a double-discharge CO_2 laser¹²³ having a pulse width of about 100 nsec. A 50% beam splitter was used, with a reference calorimeter (LC-2A) in one beam and a germanium lens in the other. Each beam delivered about 800 mJ. The calorimeter faces were located at positions where the spot diameter was 14.6, 6.0, and 2.3 mm. Readings were normalized to a constant value for the reference calorimeter.

Results for all of the materials agreed within a few percent for the 14.6- and 6.0-mm spots (except polyvinyl chloride, which was 30% low for 6.0 mm). However, the sodium chloride windows were cracked by the 2.3-mm spot and results were unreliable; Mylar windows were ruptured by the 6.0-mm spot. The plastic calorimeters all gave low results for the 2.3-mm spot; all of them except Teflon showed depressed spots with evidence of melting.

The plastic disk calorimeters are more convenient to use than the stirred-liquid type, and Teflon seems

to be the most satisfactory of the four plastics tested for 10.6- μm radiation. Accordingly, we have built two additional types of Teflon-disk calorimeters. For further convenience, both have multijunction thermopiles (with junctions uniformly distributed over the metal disk) rather than a thermistor, and both use massive insulated aluminum jackets rather than a jacket through which water is circulated from an external thermostatted bath. The LC-3 calorimeter (Fig. 106) is a twin type (the two absorbers allow differential temperature measurements); the receivers each have an 0.8-mm-thick layer of Teflon cemented to a 3.2-mm-thick aluminum disk 38 mm in diameter. The LC-5 calorimeter (Fig. 107) is a single-disk type, with 0.8-mm Teflon cemented to a 6.4-mm-thick copper disk 203 mm in diameter.

Tubular Surface-Absorption Calorimeter

Cone calorimeters, the type most commonly used for high-power laser pulses, concentrate the energy near the tip of the cone, sometimes resulting in high transient surface temperatures and an air spark. In the course of our work, it occurred to us that a tubular ("lightpipe") calorimeter would avoid this focusing and permit use of a larger number of reflections. Tests were made with three different lengths of copper

Fig. 106. Plastic double-disk calorimeter (LC-3). Receivers are Teflon-coated aluminum disks.

Fig. 107. Plastic single-disk calorimeter (LC-5). Receiver is Teflon-coated copper.

tubing - 140, 292, and 598 mm - which had a 17.3-mm i.d. and was nickel-plated and polished. Pulses from the CO_2 laser¹²³ entered at an angle of 45° to the tube axis, and the transmitted fraction was measured by calorimeter LC-2B (Teflon), whose surface was 3 mm from the opposite end of the tubes. Semilog plots of transmission vs tube length were linear, with a half-length that was 74 mm when the polarization was parallel to the plane that contained the beam axis and tube axis, and 128 mm when perpendicular to the plane.

The resultant calorimeter (Fig. 108) is 458 mm long; a nickel-plated copper disk cemented on the far end functions as a mirror, effectively doubling the

absorbing length. Thirty-six thermopile junctions are uniformly distributed on the tube. A stable output signal was obtained within a few seconds after a pulse. The calorimeter was compared with LC-3 by a single-beam (no splitter) method, alternating the two calorimeters behind a 10-mm-diam aperture. Results for the two agreed, at 400 mJ, within the reproducibility of the laser pulses (about 10%).

This design's absorption efficiency will have a much smaller wavelength dependency than the volume-absorption calorimeters, and this dependency is easily tested. While not itself adaptable to large diameter beams (without focusing), it could be used for calibrating volume-absorption calorimeters at any wavelength. For further details see Ref. 124.

Future Plans

The various calorimeters will be compared more accurately at low power densities using a cw CO_2 laser and an accurately timed shutter. A Scientech model 3701 twin-reflecting-plate calorimeter will be included in this series and will serve as a beam monitor; its jacket is now being modified to give more stable operation. We will measure reflectance from the surfaces of the calorimeters with a cw laser and an Eppler radiation thermopile, now on order.

Fig. 108. Tubular "light-pipe" calorimeter admits laser beam into a long copper tube where its energy is absorbed through multiple internal reflections.

THEORY OF PHOTON-DRAG EFFECT IN POLAR CRYSTALS

Photon-drag detector operation is based on the principle of transferring momentum from the photon to the free carriers in the conduction band through the photon-electron-phonon interaction. Because the relaxation time of the free carriers is very short (of the order of 10^{-11} to 10^{-13} sec) and because the photon-drag effect is not dependent upon the bound electrons around the impurity for the absorption of the photon, this detector is capable of measuring short pulses at room temperature. Up to now, most of the experimental and theoretical work has been done on elemental semiconductors such as Ge. However, the efficiency of the Ge photon-drag detector is poor, giving only about 100 to 200 mV per MW at the $10.6\text{-}\mu\text{m}$ wavelength of the CO_2 laser, as compared with several volts per megawatt for a gold-doped Ge detector. Furthermore, the Ge photon detector is not useful in measuring other high-power lasers such as Nd:glass ($1.06\text{ }\mu\text{m}$) because direct band-gap excitation occurs at this wavelength. For the two reasons just mentioned we have carried out a theoretical

investigation of the photon-drag effect in polar crystals to see whether we can select a crystal that offers a more efficient detector and at the same time is capable of detecting neodymium laser wavelengths.

In the polar crystal, especially at room temperature, the polar phonon is the one that is most effective in helping the free carriers to absorb the photon. For this reason, we have to consider the total Hamiltonian for interactions between electrons, polar phonons, and photons. In treating the polar phonon-electron interaction, we use Fröhlich's approximation.^{1,25} For the electron-photon interaction we use the $\vec{A} \cdot \vec{P}$ form.

We use the Hamiltonian to calculate the matrix elements responsible for all the possible transitions that can affect the distribution function of the electron. Using these matrix elements together with Boltzmann's linear transport equation, we can then calculate the current and voltage induced in the crystal by the laser beam. Further details and results can be found in Ref. 127.

MODIFICATIONS TO STREAK CAMERA TUBE TO IMPROVE TIME RESOLUTION

A streak camera tube is a photoelectronic vacuum-tube device that can make linear measurements of a laser-pulse intensity profile with picosecond-range time resolution.⁴ At this Laboratory an improved streak camera tube is being developed using the narrow-angle electron beam optics of a commercially available cathode-ray tube (CRT). A tube with a narrow beam angle, as contrasted to one with a wide beam angle (e.g., the RCA C73435T tube), has three advantages: (1) a higher electric field at the photocathode, (2) more efficient aperturing of aberrant electrons, and (3) room for a second set of deflectors, permitting a circular or helical scan on the phosphor screen. Triggering problems for synchronizing the sweep signal at the deflector to the laser pulse are greatly simplified with a circular streak system. Two sine waves in quadrature can continuously scan, whereas for a linear streak system dead time must be allowed for the retrace scan.

Specifically, for the LLL streak camera tube, a modified EG&G model KR-23 CRT is being used. Two of these tubes have been ordered, and the modifications will be done at LLL. The tube

modification requires the substitution of a photocathode in the place of the existing thermionic oxide cathode. The electric field at the photocathode can be made as high as 10^4 V/cm. The electron beam optics should allow a transit time dispersion of less than 2 psec with a tracewidth of 0.005 cm on the phosphor screen. Two sets of deflectors with a 3.6-GHz bandwidth will be used to produce a circular scan 1.27 cm in diameter. With the 0.005-cm tracewidth or 800 resolvable points in the scan, the 280-psec scan period will allow a time of 0.35 psec per tracewidth.

The status of our preparations to modify the tubes is summarized below.

- The photocathode processing and transferring station is 80% complete. In addition, the prototype and installation of the Cs processing furnace is nearly complete.

- A smaller vacuum station has been built for investigation of the processing technique for the S-1 photocathode. Deposition techniques for these photocathodes are being tested in small vacuum tubes.

- The prototype of a lock-in mechanism for the cathode-grid section has been demonstrated already.

Fig. 109. Typical computer-calculated electron trajectories for a triode electron-beam gun. Trajectories are plotted for various initial radial positions at the cathode. The vertical lines represent equipotentials.

Work is progressing on the assembly of the triode (cathode-grid-anode) section.

- Electron beam trajectories are being investigated with a computer-aided program. Studies will be made to optimize the electron beam optics in the triode

region. Trajectory plots for one triode geometry are shown in Fig. 109 as an example.

- When we receive the KR-23 tubes, they will be opened and modified to accommodate the photocathode electron-gun structure, and then testing will begin.

MONITORING ENERGY DENSITY DISTRIBUTION OF MODE-LOCKED 1.06- μ m LASER BEAMS

With high-power lasers it is very desirable to have a uniform energy density over the cross section of the laser beam to avoid energy "peaking" in any local area and thereby subjecting that area to damage. We have developed a new method for measuring the energy density distribution which is fast, sensitive, and requires only a small part of the beam.

Indication of the energy density distribution over the beam cross-section area is commonly obtained by interposing a piece of exposed photographic paper in the beam path and noting the configuration and intensity of the resulting burn pattern produced by the laser beam. This method is coarse but quick; a drawback, however, is that it soaks up the whole beam.

A more refined method is to split off part of the infrared beam and send it through a camera to expose an infrared film, then develop the film. The exposed

area on the infrared film then indicates the beam density distribution. This technique does not soak up the entire beam, but infrared film is more difficult to handle and process than ordinary or Polaroid films.

We have devised a new method of indicating the energy density distribution over the laser beam's cross section.¹²⁷ A part of the beam is split off and projected onto an image converter tube. An inexpensive tube with an S-1 photocathode converts the input image into a corresponding output in the visible frequency range. This visible light output is then photographed by a Polaroid camera. The Polaroid film immediately produces a picture which indicates the energy density distribution over the laser beam's cross-section area.

This method is less direct, and it entails the extra cost of the image converter. However, it is sensitive, fast, and requires only a small part of the beam. Hence,

Fig. 110. New method of measuring energy distribution in cross section of laser beam splits off a small part of the beam and projects it on an image converter tube for photographic recording, giving orders of magnitude improvement in sensitivity over conventional method. (a) Near-field pattern of a beam at oscillator mirror, made by new method. (b) Pattern of same beam taken 2 ft from the mirror with conventional film-burning method.

adjustment of the laser system optics to achieve the best energy-density distribution in the beam can be carried out while the energy density measurements are being made.

To test this technique, a mode-locked Nd:YAG oscillator was used. Figure 110a shows a near-field photograph of the intensity pattern at the oscillator mirror. Figure 110b shows the burn on exposed Polaroid film of the same shot, but made some distance from the output mirror.

The sensitivity of the image converter system is about four orders of magnitude greater than the sensitivity of the burn technique. This allows the beam to be monitored while two-photon fluorescence or other diagnostics are performed downstream.

ESTIMATING THE PEAK INTENSITY AND ENERGY CONTENT OF SHORT-DURATION PULSES USING SATURABLE ABSORBERS

We have demonstrated a relatively simple diagnostic technique for short-duration mode-locked laser pulses, which gives estimates of (1) the pulse's peak intensity, (2) the fraction of beam energy carried by the pulse, and (3) the average noise level accompanying the pulse.¹²⁸ This information is obtained solely from measurements of the amount of beam energy that is transmitted through various thicknesses of a saturable absorbing medium. In particular, the technique avoids reliance on fast-response photodiodes, photographic film, etc., which are hard to come by in the infrared region of the spectrum. It might therefore be especially useful in analyzing some of the longer wavelength lasers, such as the CO₂ laser at 10.6 μ m.

The technique consists of splitting the beam from a mode-locked oscillator into a "reference" beam and a "signal" beam, the latter being filtered through different thicknesses of saturable absorber on successive laser shots. Both beams are directed into energy calorimeters, resulting in data on energy transmission T as a function of absorber path length l traversed by the signal beam (Fig. 111).

We have calculated (see Fig. 111) the expected dependence of $T(l)$ on the three parameters: peak intensity of the pulse $(I_0)_p$, average noise intensity $(I_0)_n$, and fraction of energy carried by the pulse (ϵ_0) . Estimates of these parameters for a given laser are obtained by matching the experimental data for $T(l)$ with a theoretical curve, selecting the values of the three parameters which give a best fit.

Our experiments used a Nd:glass laser oscillator (not of high quality) and Kodak 9740 saturable dye. Transmission data for dye thicknesses as large as 3 cm were recorded using the full (unamplified) output beam, which consisted of a 200-nsec train of

Fig. 111. Normalized transmitted beam intensity as a function of dye absorber thickness, calculated for various values of the normalized incident intensity, I_0/I_{sat} . Symbols: $\alpha_0 = N\sigma$ is the small-signal absorption coefficient, $I_{sat} = (2\sigma\tau)^{-1}$ photons/cm²-sec, σ is the absorption cross section per absorber molecule, τ is the time required for the absorber to return to equilibrium after excitation. For this dye, $\sigma \approx 2 \times 10^{-16}$ cm²/molecule, $\tau \approx 8 \times 10^{-12}$ sec, and at the Nd:glass wavelength $I_{sat}(h\nu_0) \approx 4.5 \times 10^7$ W/cm².

Fig. 112. Fit of experimental data to curves of transmission vs absorber thickness calculated for parameter values of $(I_o)_p = 5 I_{sat}$, $(I_o)_n = 0.05 I_{sat}$, and ϵ_o as shown. The measured value of α_o is 3 cm^{-1} .

70-psec-duration pulses spaced 10 nsec apart. From the data fit we concluded that the average peak intensity of the mode-locked pulses was about $2.3 \times 10^8 \text{ W/cm}^2$, that the noise intensity was at

least 100 times smaller, and that the fraction of beam energy carried by the mode-locked pulses was only 15 to 20% (Fig. 112).

A useful feature of this technique is that in obtaining the diagnostic information, the pulse-to-noise ratio is simultaneously improved. That is, the filtering process increases the fraction of beam energy carried by the pulses, since the noise is more severely attenuated (Fig. 113). We found, for example, that after filtering the beam through 10 mm of Kodak 9740 dye, the beam energy was attenuated to about 14% of its initial value, and about 68% of this remaining energy resided in the pulses.

Fig. 113. Effect of dye absorber in increasing the signal-to-noise ratio in the pulse. $(I_o)_p = 5 I_{sat}$, $(I_o)_n = 0.05 I_{sat}$, and ϵ_o as indicated.

LASER FUSION

SUPERHIGH-DENSITY LASER FUSION

In the laser-fusion microexplosion approach to CTR, fuel confinement is inertial. Lawson numbers greater than 10^{16} may apparently be achieved by laser-energized, subsonic ablative implosion of spherical DT pellets weighing more than 10^{-4} g to densities of $\sim 5 \times 10^{26} \text{ cm}^{-3}$ ($\sim 10^4$ times liquid density). The corresponding inertial confinement times are $\geq 2 \times 10^{-11} \text{ sec.}^*$ The laser energy required for CTR applications is thus reduced to about 10^5 - 10^6 J, assuming laser pumping and thermal-to-electric efficiencies of 10% and 40% respectively.¹²⁹

Laser implosion of fusile matter to these high densities and the subsequent thermonuclear microexplosion involve important considerations of pressure, entropy (electron Fermi-degeneracy), symmetry, stability, laser-plasma coupling, inertia, and thermonuclear self-heating.

Required Pressure

The required pressure and energy are a minimum determined by quantum statistics, if the electrons are Fermi-degenerate. Then the (degenerate electron) pressure is given by¹³⁰

$$P = \frac{2}{3} n_e \epsilon_F \left[\frac{3}{5} + \frac{\pi^2}{4} \left(\frac{kT}{\epsilon_F} \right)^2 + \dots \right],$$

where n_e is the electron density,

$$\epsilon_F = \frac{h^2}{8m} \left(\frac{3}{\pi} n_e \right)^{2/3}$$

is the Fermi energy, kT is the thermal energy, h is Planck's constant, and m is the electron mass. At $n_e \approx 5 \times 10^{26} \text{ cm}^{-3}$, the minimum pressure of hydrogen occurs when $kT \ll \epsilon_F \approx 1 \text{ keV}$, and is $\sim 10^{12} \text{ atm}$. For comparison, at this density and $kT = 5 \text{ keV}$ (both electrons and ions), the pressure is $\sim 10^{13} \text{ atm}$.

Implosion

The required pressures can be generated with intense light by a combination of subsonic ablation and

implosion. Laser light has been focused to intensities greater than $10^{17} \text{ W cm}^{-2}$.¹³¹ Typical matter blowoff velocities associated with such laser intensities are 10^8 cm/sec (approximately sound speed at temperature of 10 keV). The corresponding ablation pressure, which is proportional to laser energy flux divided by reaction velocity, is more than 10^{10} atm . The ablation pressure can then be further multiplied to more than 10^{12} atm by a laser-driven ablative implosion in which high convergent compressions occur. The pressure applied to an implosion system does PdV work, generating kinetic energy which is subsequently converted to internal energy concentrated in the compressed volume in a nearly isentropic fashion. Since pressure is energy per unit volume, the maximum average pressure so obtained equals the applied imploding pressure multiplied by the compression ratio. Additional pressure multiplication occurs near the center because of convergence effects.¹³² The pressure multiplication factor may be increased by implosion of hollow spheres, in which the externally applied pressure acts over a larger volume.

Optimal Pulse Shape

Compression in the Fermi-degenerate state -- which minimizes the required implosion pressure and energy -- may be performed by shaping of the applied laser pulse in time. At the commencement of the implosion, the laser power is set so that the initial shock speed in the imploding matter is comparable to sound speed (involving postshock pressures of 10^5 - 10^6 atm); later the power is set so that the compression is near-isentropic (i.e., such that the hydrodynamic characteristics intersect only near the center of the sphere). Due to extreme convergence effects, and by adjusting the pulse shape so that the characteristics intersect just before the pellet center is reached, a small fraction of the pellet mass in the central region is strongly heated during compression, producing thermonuclear ignition. The laser power history which generates an optimal, isentropic compression of a sphere of degenerate fuel is approximately

$$\dot{E} = \dot{E}_0 \tau^{-s},$$

where $\tau = 1 - t/t'$, t is time, t' (which is greater than t) is the collapse time, and $s = 3\gamma/(\gamma + 1) = 15/8$ for dense, electron-degenerate fuel ($\gamma = 5/3$).

* A plasma sphere of radius R and sound speed C has an effective inertial confinement time of approximately $R/4C$. A 10^{-4} -g DT sphere, heated to 10 keV by 10^5 J , has a radius when compressed to $5 \times 10^{26} \text{ cm}^{-3}$ of $2 \times 10^{-3} \text{ cm}$, and an inertial time of $2 \times 10^{-11} \text{ sec}$ ($C \approx 10^8 \text{ cm sec}^{-1}$).

Computer calculations of spherical implosions show that this power history generates a near-optimal pressure history, and that this pressure history is (for a Lagrangian surface):

$$P = P_0 \left(\frac{h}{h_0} \right)^{\frac{2}{3} s}, \quad h = \int_0^R \rho \, dr,$$

where h_0 and P_0 are the values corresponding to $\dot{E}_0$.

Implosion calculations show that the optimal power history for 10^4 -fold compressions can be satisfactorily approximated by a sequence of five or more adjoining, square laser pulses. Starting with the final shortest, most intense pulse (which need not be accurately shaped) the preceding pulses can be generated with sufficient accuracy with beam splitters, attenuators, and optical paths of various lengths (e.g., by splitting a pulse into two equal parts, time shifting one part by a pulse width, recombining, and amplifying and/or attenuating, a pulse with twice the duration and arbitrary amplitude may be generated).

Symmetry

In compression of a sphere by 10^4 -fold, the radius decreases somewhat more than 20-fold. If, after compression, spherical symmetry is required to within 1/2 the compressed radius — or 1/40 the initial radius — then the implosion velocity (and time) must be spatially uniform (and synchronized) to about one part in 40, or a few percent. In general, for a spherical implosion in which the ratio of initial to final volumes is η , and in which the tolerable error in the final radius is w , the associated tolerable fractional error in the product of velocity and time is

$$\frac{\Delta(vt)}{vt} \approx \frac{w}{\eta^{1/3}}, \quad \eta \gg 1.$$

Implosion errors may be reduced to less than 20% by a many-sided irradiation system, consisting of beam splitters, mirrors, lenses, and other optical elements. This error can then be reduced to less than 1% by means of an atmosphere, generated by ablation with a laser prepulse and continually regenerated by pellet ablation during implosion, extending to several pellet radii and with density slightly greater than the critical density at which the laser optical frequency equals the electron plasma frequency. Laser light is absorbed and heats electrons in the outer atmosphere via inverse bremsstrahlung and plasma instabilities.¹³³ Asymmetries are reduced during energy transport by electrons through several mean free paths of atmosphere to heat the surface of the pellet. In addition, each point on the relatively small pellet

"sees" (is heated by) — and averages over — a large fraction of the hot absorbing region in the outer atmosphere.

Stability

The implosion of the pellet by diffusion-driven, ablation-generated pressures is hydrodynamically stable, except for relatively long-wavelength surface perturbations, which grow too slowly to be damaging. The amplitude of a perturbation on the droplet surface grows during implosion as $A_0 e^{xt}$, where A_0 is the initial amplitude of surface roughness, and

$$\sigma^2 = ak - \frac{\kappa^2 P_A}{\rho}$$

for acceleration a , surface roughness wavelength $\lambda = 2\pi/\kappa$, ablation pressure P_A , and density ρ . The first term ak is associated with the well-known Rayleigh-Taylor instability.¹³⁴ If Δx is the thickness of a shell of matter, then using $a = P_A/\rho\Delta x$ (from $F = ma$), σ^2 is negative (implying stable acceleration) for $\lambda \lesssim 2\pi\Delta x$.^{*} In part, ablative stabilization occurs because the peaks of surface perturbations are effectively closer to the heat source (radius at which the critical density occurs) so that the temperature gradient is steeper. Consequently more rapid ablation occurs, and the higher pressures generated reduce the amplitude of the perturbation. "Fire polishing" (e.g., as in glass blowing) also reduces the amplitude of the perturbation.

Thermonuclear Burn

The inertial confinement time of a sphere of hot plasma is proportional to the radius divided by the sound speed. Therefore, since the burn rate is proportional to density, the burn efficiency is proportional to the product of the density and radius, ρr . In spherical compression, ρr increases because the density increases more rapidly than the radius decreases. At constant ρr (burn efficiency), the spherical mass is inversely proportional to the density squared. The laser energy required to effect compression is roughly proportional to the pellet mass. Very high spherical compressions produce a product of radius and density so large that the energetic charged particles from the fusion reaction are absorbed within the dense pellet,[†] and the ion-electron coupling

^{*}This condition precludes implosion of hollow pellets with ratios of shell thickness to radius less than a few percent.

[†]In DT at 10 keV electron temperature, the effective range of the 3.6-MeV alpha particles produced by DT fusion is ~ 0.3 g/cm². At $10^4 \times$ liquid density the corresponding spherical mass is ~ 30 ng. This mass is heated to 10 keV by 30 J.

time (itself proportional to $1/\rho r$) becomes shorter than the inertial confinement time. This makes possible thermonuclear self-heating, which reduces the laser energy required for effective fuel ignition by more than an order of magnitude. Strong compression also provides a means of heating the fuel ions near the pellet center to ignition temperatures. The advantages of compression are partially offset by energy losses associated with escaping ablated material. These losses are related to the implosion and blowoff velocities via rocketlike considerations. (Unlike conventional rockets, the blowoff is continually heated and is near-isothermal.)

Computer Calculations

Laser compression and fusion microexplosions are calculated at LLL with the LASNEX computer program. LASNEX was described in the previous progress report (UCRL-50021-71, pp. 74-77) and is also discussed in the following article in this report.

Computer calculations of a 10,000-fold compression of a fusion pellet and the resulting thermonuclear microexplosion are shown in Figs. 114 and 115. In these calculations a 60-kJ, 1- μm -wavelength laser light implodes a 0.4-mm-radius spherical liquid drop of equimolar deuterium-tritium (DT) located in a vacuum

Fig. 114. Computer calculations of a 10,000-fold compression of a fusion pellet and the resulting thermonuclear microexplosion. (a) Laser pulse power rises in steps to approximate ideal pulse shape shown by dashed curve. (b) Corresponding electron temperature in critical density region.

chamber. A laser prepulse ablates the pellet, generating an initial atmosphere of DT which extends to a radius of $\sim 1000 \mu\text{m}$ with a density greater than $4 \times 10^{-3} \text{ g/cm}^3$. The applied laser power then increases near optimally in eight pulses from $\sim 10^{11}$ to

$\sim 10^{15} \text{ W}$ in $\sim 10 \text{ nsec}$. Figure 114a* shows the energy and duration of each pulse. The dashed line

*In these figures, $t = 0$ corresponds to the end of the laser prepulse.

Fig. 115. Computer calculations (continued) of a 10,000-fold compression of a fusion pellet and the resulting thermonuclear microexplosion. (a) Density and electron temperature vs radius at times of 5 and 9 nsec. (b) Radius vs time (dashed lines are weak shocks from steps in pulse power, implosion pressures are shown in megabars). (c) Typical calculated laser implosion isentrope and ideal isentrope. (d) Density and electron temperature vs radius at ignition.

is the ideal power history described previously. The ideal curve and stepped approximation produce the same fusion energy yield to within a few percent.

The laser light is absorbed in the outer atmosphere, generating hot electrons. In this calculation the hot electrons are assumed to be tightly coupled to the thermal electrons by a sufficiently strong combination of collisional and collisionless processes, forming a near-Maxwellian distribution. The outer atmosphere is heated to electron temperatures which increase from about 3×10^6 to 10^8 °K during the implosion (Fig. 114b). The surface of the pellet is heated and ablated, generating implosion pressures which increase optimally from 10^6 to 10^{11} atm. The many-orders-of-magnitude increase in implosion pressure occurs during the transit time of the initial shock to the droplet center, so that the unablated outer part of the pellet is gradually compressed into a spherical shell with density >100 g/cm³, while at the same time this shell is inwardly accelerated to velocities which increase from 10^6 to 3×10^7 cm/sec. Figure 115a shows the variation of density and electron temperature with radius at 5 and 9 nsec. Figure 115b shows the variation of radius with time. Dashed lines indicate weak shocks formed by pulse transitions in the power history. Numbers indicate implosion pressures in megabars. The outer solid line indicates the surface of the dense pellet, and the inner solid line separates ablated material from fuel. As the internal pressure becomes larger than the ablation pressure, the rapidly converging shell slows down and is compressed, still near-isentropically, at sub-Fermi-energy temperatures, to densities greater than 1000 g/cm³. Figure 115c shows a typical isentrope, the ideal isentrope, and the DT ignition energy. The low-density non-Fermi-degenerate central region is compressed by the shell to densities approaching 1000 g/cm³, and heated in the process to ion and electron temperatures greater than 10^8 °K, initiating thermonuclear burn (Fig. 115d). About 1200 kJ of fusion energy is produced in less than 10^{-11} sec. Since 60 kJ of laser light was input, net electrical energy production would be possible with a 15% efficient laser and a 40% thermal-electric efficiency.

Calculations with only collisional electron coupling between the suprathermal* non-Maxwellian electrons (generated by laser-driven plasma instabilities) and the thermal electrons show that the suprathermal electrons preheat the fuel during compression, precluding

Fig. 116. Calculated gain G_L (ratio of fusion energy output to laser light energy input) as a function of fuel compression η for several different laser light energy inputs. At compressions less than about 10^3 , the gain increases strongly with increasing compression because of increasing burn efficiency and alpha-particle self-heating of the fuel. The gain decreases with compressions much greater than 10^4 because of depletion of the DT and because ablative energy losses increase and the energy of compression (against degeneracy pressures) becomes dominant.

attainment of superhigh densities, and effectively energetically decouple from the atmosphere. Decoupling of thermal electrons may also occur.¹³⁵ Decoupling effects are worst with long-wavelength lasers (e.g., CO₂), because laser light absorption occurs at a lower plasma density. Generation of suprathermal electrons can be minimized by imploding the pellet without exciting the laser-plasma instabilities. The instability thresholds can be increased, and inverse bremsstrahlung absorption simultaneously enhanced, by use of uv lasers and by seeding the pellet with small amounts of high-Z material (~0.1 at.%) to increase the electron-ion collision frequency. Decoupling acts to limit the maximum rapidly developable ablation pressure. This can be compensated for by use of hollow pellets — provided that suprathermal electron preheat is avoided. In calculations assuming only collisional self-coupling of electrons using uv lasers and seeded pellets, results similar to those described above have been achieved

Thermonuclear Gain. Figure 116 shows the scaling of the gain, G_L (ratio of fusion energy to applied laser pulse energy), with compression and laser pulse energy. Relative to the applied laser energy, gains approaching

*Preliminary LLL plasma-simulation calculations by J. Katz, J. DeGroot, and others predict electron spectra varying as V_e^{-2} out to $10 V_e$ (thermal), where V_e is the electron velocity.

100 are predicted for laser energies of 10^6 J. At compressions less than $\sim 10^3$, the gain increases strongly with increasing compression because of increasing burn efficiency and alpha particle self-heating of the fuel. The gain reaches a maximum and decreases with compressions much greater than 10^4 because of depletion of the DT during burn, because symmetry considerations limit the attainable self-heating gains, and because the energy of compression (against degeneracy pressures) becomes dominant, due in part to the monotonically decreasing energetic efficiency of ablative compression.

CTR Considerations. The electrical gain, G_e (ratio of electrical energy output to electrical laser pumping energy), is

$$G_e = G_L \phi_t \phi_L,$$

where ϕ_t is the power-plant thermal efficiency and ϕ_L is the laser pumping efficiency. If $\phi_t = 40\%$ and $\phi_L = 10\%$, $G_e > 25$, which occurs for a laser energy, L , less than 50 kJ for $\eta = 10^4$ (Fig. 116). Also, less than 1 kJ of light energy is sufficient to generate an equal quantity of thermonuclear energy, if optimally employed (Fig. 116). Multigigawatt electric average power levels may be achieved by initiating of the order of one hundred $10^7 - 10^8$ J microexplosions per second. One or more specially designed explosion chambers will be required to withstand the x-ray, neutron, and plasma pulses of such microexplosions;

such chambers appear to be feasible.¹³⁶ (See third article following this one, "Laser-Fusion CTR Applications.")

Cheap fuel pellets are required. Ten million joules of electrical energy is currently worth roughly one cent. In the scheme described here the pellet may be a droplet of DT (or deuterium, using multimegajoule lasers) ejected from a sophisticated eyedropper and spherized by surface tension and viscosity effects.

Conventional thermal cycles may be used to generate electricity if the neutrons are absorbed in lithium blankets. A large fraction of the plasma energy may ultimately be recoverable by expanding the microexplosion fireball in an externally imposed magnetic field.¹³⁷ (See "Laser-Fusion CTR Applications" later in this section.)

Problem Areas. Important problem areas include those involving suprathermal electron coupling and pellet preheat, effects of magnetic fields generated by laser-driven gradients in the pellet atmosphere's electron pressure and density, engineering design of a sufficiently cheap reactor system which will function for more than 10^{10} microexplosions, and development of the required lasers. In the theoretical/computational plasma physics area, considerable effort is presently directed toward predicting the spectrum of suprathermal electrons generated by plasma instabilities and the interaction of these suprathermal electrons with colder electrons via possible collisionless processes.

IMPROVEMENTS IN THE LASNEX CODE

The basic physical processes calculated by the LASNEX laser-fusion code were described in the previous semiannual report.¹³⁸ Since that time several new techniques for calculating the nonequilibrium nature of laser-heated plasmas have been incorporated into the code. The two major improvements discussed here are the multigroup treatments of (1) laser-heated (suprathermal) electrons and (2) photons. The method LASNEX uses to transport alpha particles produced by the DT thermonuclear reaction is also presented.

Multigroup Electrons

Since electron-electron collision times are often longer than either laser pulse lengths or hydrodynamic times of laser-heated plasmas, it is important to consider the non-Maxwellian nature of the electron distribution function. The two dominant processes by which laser energy is transferred to electrons are inverse bremsstrahlung and laser-induced plasma instabilities. The former is calculated in the unscreened

Born approximation and results in an electron distribution function of the form

$$f_{IB}(v) \propto v e^{-mv^2/2kT},$$

where v is the electron speed and $\int f(v) dv \equiv 1$. The rate of electron heating due to plasma instabilities is determined from detailed plasma simulation calculations* which predict an electron distribution of

$$f_{PI}(v) \propto v^{-n}, n \approx 2.$$

LASNEX calculates the heating rate due to each of these two processes and distributes the energy among electron groups according to the distribution functions given above.

* See article by DeGroot et al. entitled "Laser-Plasma Coupling" earlier in this report, p. 86.

Numerically speaking, the laser is a source to the multigroup electron scheme just as thermonuclear burn is a source to a multigroup neutron scheme. Unlike neutrons, however, electrons are charged and thus their transport can be strongly affected by electric fields. Although externally applied electric fields are not considered, internal ones will naturally arise in opposition to electron pressure gradients. If we ignore magnetic fields* the steady-state electric field must satisfy the condition of no net current. We write the current for the i th electron group in the form

$$\vec{j}_i = \sigma_i \left[\vec{E} + \frac{\nabla p_i}{en_i} \right],$$

where σ_i , n_i , and ∇p_i are the conductivity, number density, and pressure gradient of the i th group. Summing over all groups (including the thermal group) and setting the total current to zero yields

$$\vec{E} = - \left(\sum_i \frac{\sigma_i}{e n_i} \nabla p_i \right) / \left(\sum_i \sigma_i \right).$$

Using this electric field we calculate the current for each group (and thus the particle and energy flow). The conductivities used here include the resistive effects of Coulomb collisions with thermal electrons and ions as well as a flux-limiting term that restricts the magnitude of each current to less than

$$|\vec{j}_i|_{fl} \approx en_i v_i,$$

where v_i is the average speed of an electron in the i th group.

Several processes that redistribute electron energy among the groups are calculated. The two most important are the work done on (or by) the electric field ($\vec{j}_i \cdot \vec{E}$), and the loss of energy due to Coulomb collisions with thermal electrons. The former results in an energy loss to those groups creating the electric field; the total $\vec{j} \cdot \vec{E}$ work is zero since the total current is zero. We handle energy loss from collisions in a manner similar to that used in a multigroup neutron scheme. Unlike neutrons, however, electrons lose only a small fraction of their energy during any given collision. This somewhat simplifies the treatment of electron thermalization.

Multigroup Photons

Because of the small size of most laser targets, radiation produced by the plasma will generally not

have time to equilibrate before it escapes. This means that the photon distribution will differ substantially from that of a blackbody. But a misrepresentation of the photon spectrum may have only a small effect on the subsequent behavior of the plasma; this was the argument given previously^{1,38} in favor of treating the radiation as a blackbody with its own temperature. For many laser-plasma configurations this argument is still valid, but for some plasmas containing high- Z materials it is not. This fact, coupled with the desire to calculate x-ray output spectra from experimental laser-produced plasmas, has led us to incorporate multigroup photonics in LASNEX.

The technique used is a two-dimensional generalization of the multigroup, flux-limited diffusion method used in the GURU code.¹³⁹ Frequency-dependent opacities are calculated using the XSNB package¹⁴⁰ which considers the effects of bound-bound, bound-free, and free-free processes. The redistribution of photon energies resulting from Compton scattering is not considered, but it has essentially no effect for any laser-heated plasma of near-term experimental interest. The flux-limited radiation transport equation is differenced implicitly with the electron heating equation in such a way as to insure analytic solutions in limiting cases.

Alpha Particle Transport

The small size and time scales of laser-produced plasmas imply that it is inappropriate to assume deposition of thermonuclear reaction energy "locally and instantaneously." LASNEX currently assumes that the neutron from the $D + T \rightarrow n + \alpha$ reaction escapes from the plasma without interaction. The alpha particle is handled by a single-group, flux-limited diffusion scheme which calculates the transport and deposition of the particle's mass, momentum, and energy.

Use of a single-group transport scheme requires a priori knowledge of the shape of the distribution function. In systems that are thin to alpha particles this function will be a sharp peak at the alpha birth velocity. In thick systems the distribution is determined by a steady-state balance between the production and thermalization rates for alpha particles. Since alpha particle deposition is not important in very thin systems we have decided to use the distribution function determined from the steady-state assumption.

This distribution function is derived by considering the rates at which an alpha particle slows down from Coulomb collisions with thermal electrons and ions. These rates are respectively

$$-\frac{\partial v}{\partial t} \Big|_e = C_e v \text{ and } -\frac{\partial v}{\partial t} \Big|_i = C_i v^2,$$

*A treatment of magnetic fields is currently being implemented.

where v is the alpha particle speed, and C_e and C_i are constants that depend on plasma density, composition, and electron temperature but are essentially independent of v . The distribution function whose shape can exist in steady state against such slowing terms is

$$f(v) = \frac{1}{C_i v^2 + C_e v} \cdot \frac{3C_e}{m \left(1 + \frac{C_e v_b^3}{C_i} \right)},$$

where v_b is alpha-particle birth velocity and $\int_0^{v_b} f(v) dv \equiv 1$.

Using this distribution function we find the total alpha-energy deposition rate per unit volume to be

$$\begin{aligned} n_\alpha \int_0^{v_b} f(v) m_\alpha v \left(\frac{\partial v}{\partial t} \Big|_e + \frac{\partial v}{\partial t} \Big|_i \right) dv \\ = n_\alpha \frac{1}{2} m_\alpha v_b^2 \frac{3C_e}{m \left(1 + \frac{C_e v_b^3}{C_i} \right)}, \end{aligned}$$

where n_α and m_α are the alpha-particle number density and mass. The energy given separately to electrons and ions is found by integrating the slowing terms separately.

The alpha-particle transport is handled by a diffusion model in which the number flux is given by

$$\text{flux} = \frac{\bar{v} \nabla n_\alpha}{\frac{3}{\lambda} + 2 \frac{|\nabla n_\alpha|}{n_\alpha}}.$$

The mean free path (λ) includes the effects of ion deflections as well as the slowing terms discussed above. For large λ , normal diffusion theory breaks down and the flux is limited to $\frac{1}{2} n_\alpha \bar{v}$.

The hydrodynamic effects of the alpha particles are included by using an alpha pressure given by

$$p_\alpha = \frac{n_\alpha m_\alpha \bar{v}^2}{3 + 2\lambda \frac{|\nabla n_\alpha|}{n_\alpha}}.$$

Where λ is small this reduces to a perfect gas pressure; when λ is large the momentum deposition rate per unit volume (∇p_α) becomes ϵ_α/λ , where ϵ_α is the alpha-particle energy density.

LASER FUSION PELLETS

Long-wavelength lasers are less effective than short-wavelength lasers for compression of fusion pellets because of electron decoupling and preheat effects. Computer calculations with recently developed versions of the LASNEX code show that decoupling can be partly compensated for by use of hollow pellets. However, these calculations also show that, irrespective of laser wavelength, fusion pellets may be disastrously preheated by high energy electrons if the laser light is absorbed by means of plasma instabilities. In order to avoid preheat, pellets have been designed which do not utilize plasma instabilities to absorb the laser light. The threshold for excitation of instabilities is raised, and the absorption of laser light by inverse bremsstrahlung enhanced, by seeding the pellet with high-Z material (e.g., 0.1 at.% of high-Z material) and by use of short-wavelength lasers ($\lambda < 1 \mu\text{m}$). The required laser light intensity is minimized by use of the hollow pellets which perform approximately as well in computer calculations as those reported previously (in which preheat and decoupling effects were not considered).

Decoupling

Computer calculations with the two-electron-temperature LASNEX code show that the implosion of hollow pellets with 10- μm laser light can produce substantial thermonuclear yields despite corona-core decoupling.* However, the yields are significantly degraded compared to those with 1- μm light. In these calculations, about 1 MJ of optimally pulse shaped 10- μm light was used to implode spherical hollow pellets of frozen DT. The initial radius-to-thickness ratio was 30 to 1, so that the requirements of Taylor instability and implosion symmetry were satisfied. The calculated ratios of

* The maximum implosion pressures that can be generated are limited by the rate of coupling (to the plasma) of the suprathermal electrons generated by absorption of intense laser light, particularly long-wavelength laser light.

fusion energy produced to laser light energy input as a function of laser wavelength were as follows:

Wavelength (10^{-4} cm)	Fusion energy/ laser energy
10	~20
5	~40
1	~60
<1	~60

In these calculations it was assumed that anomalous (collisionless) electron-plasma coupling was negligible. If such coupling is substantial, but not excessive, the yields with 10- μ m light would be comparable to those produced with 1- μ m light.

Use of hollow pellets compensates for effects of corona-core decoupling in at least two ways:

1. The main effect of decoupling is to reduce the maximum implosion pressure that can be generated. However, if this smaller pressure acts over a larger volume, the same implosion energy can be generated as with larger pressures on solid pellets. The volume is increased by making the pellet hollow.

2. Increasing the pellet volume also increases the coupling of the hot electrons to the pellet via the increases in surface area and solid angle (as seen from the critical radius where the hot electrons are generated).

Use of higher laser energies and correspondingly larger pellets also tends to compensate for decoupling. The hot-electron coupling time depends on the plasma critical density, and the characteristic hydrodynamic time of the pellet increases with the cube root of the pellet mass.

Corona ablation temperatures as high as thermonuclear ignition temperatures need not be achieved in order to ignite the pellet because the implosion process itself generates high central fuel temperatures. Use of hollow pellets increases the fuel temperature that may be generated with a given corona-ablation temperature, because the implosion pressure acts over a greater volume.

The two-electron-temperature LASNEX calculations in effect assume — as does the corona-core decoupling theory — that the energy of the hot electrons is determined by an appropriate form of the Maxwellian-averaged flux limiter equation. However, plasma simulation calculations predict that the hot electrons are strongly non-Maxwellian (i.e., fewer, more energetic electrons are generated). With long-wavelength lasers the excitation of these plasma instabilities — and the generation of non-Maxwellian electrons — probably cannot be avoided in laser fusion implosions of interest. Even if some means were found to avoid excitation of these instabilities,

efficient absorption of the long-wavelength laser light by inverse bremsstrahlung would not be possible because of the low plasma critical density.

Electron Preheat

Computer calculations with the multigroup electron-transport version of LASNEX show that the energetic non-Maxwellian electrons generated by laser-induced plasma instabilities may severely preheat fusion pellets. These calculations assume that the suprathermal electron spectrum falls off exponentially with the electron velocity,* and that anomalous absorption of the suprathermal electrons by electron-plasma instabilities does not occur. With a long-wavelength laser (e.g., CO₂) the instability threshold is lower and the inverse bremsstrahlung absorption is weaker, so that it is probably not possible to avoid generating energetic electrons while at the same time efficiently absorbing the laser light, even at the reduced intensities required to implode hollow pellets.

In many implosion systems, preheat is excessive even if only a small fraction of the electrons are suprathermal. The optimum initial implosion pressure is <1 Mbar, in order to minimize the required total implosion energy (however, this argument is not significantly changed if a 10-Mbar initial pressure is assumed). This pressure generates an initial implosion velocity of about 1 cm/ μ sec. The product of this pressure and velocity, $P_i V_p$, is the rate (per unit area) at which compressional work is being done on the pellet. Typically when this implosion pressure is being generated the thermal electron temperature in the region of laser light absorption is $\sim 1/2$ keV. Hence with CO₂ light, where critical density is about 4×10^{-5} g/cm³, the thermal electron pressure is $\sim 10^{-2}$ Mbar. Assume that some fraction, f , of the electron energy is in suprathermal electrons, with velocity V_{es} and a range long compared to the laser-light absorption radius. The number density of these suprathermal electrons within the absorption radius and outside the dense pellet radius will be roughly constant. Consequently the suprathermal electron power per unit area incident on the surface of the dense pellet is approximately

$$f P_e V_{es}$$

If the suprathermal electron range in the dense pellet is comparable to the pellet radius (which it usually

*This spectrum may be too hard — hopefully it represents a worst case.

is) then the implosion certainly is not isentropic when the rate of suprathermal heating is comparable to the rate of compressional work,

$$P_i V_i \approx P_e V_{es}.$$

Or, very roughly, the tolerable fraction of electron energy in suprathermal electrons is

$$f \lesssim \frac{P_i V_i}{P_e V_{es}}.$$

For the case described above, $P_i \approx 1$ Mbar, $V_i \approx 1$ cm/ μ sec, $P_e \approx 10^{-2}$ Mbar, $V_{es} \approx 10^4$ cm/ μ sec, and $f < 10^{-2}$. For Nd light P_e is 100 times larger, and the tolerable f is only $\sim 10^{-4}$. In the last stages of the Nd implosion P_i has increased by $\sim 3 \times 10^4$, V_i by ~ 30 -fold, P_e by ~ 20 -fold, and a large f can be tolerated. However, for uv lasers the acceptable f is still small.

The rate of compressional work is very small compared to the product of the thermal electron pressure and velocity because about 95% of the ablation energy is lost to the ablated material. The ablation velocity is large compared to the implosion velocity, and in order to ablate more material, energy must be transported through already ablated material, which is heated to higher and higher temperatures as required by the ideal pulse shape.

If the range of the suprathermal electrons were small compared to the pellet thickness, they would be absorbed near the pellet surface and preheat would not be a problem. However, in liquid-density DT the range of a 40-keV electron is ~ 100 μ m, and about half the pellet mass is within 100 μ m of the surface of a 400- μ m-radius pellet. (A pellet of this radius could be imploded by a 60-kJ laser.) Laser-plasma interaction calculations predict that electrons with energies of 40 keV are generated by plasma instabilities when the plasma electron temperature is about a kilovolt (provided that the laser light intensity exceeds the instability threshold).

LASER-FUSION CTR APPLICATIONS

The laser-fusion calculational group has continued its informal study efforts on laser fusion CTR and related applications. Three major technical aspects of laser fusion CTR are being investigated: (1) laser pulse generation and target (pellet) irradiation, (2) design and operation of the fusion-fuel combustion chamber, and (3) conversion of the fusion microexplosion energy into electricity. These areas are discussed here, including a design concept for the combustion chamber. In addition, basic economic constraints and

Plasma-Instability-Free Pellets

Because of pellet preheat and other possible complications which may arise due to plasma instabilities, pellet designs have been developed in which plasma instabilities do not occur. The instability thresholds are sufficiently increased, and the inverse bremsstrahlung absorption is sufficiently enhanced (so that instabilities are not needed to absorb the laser light), by two means: (1) the collision frequency is increased by seeding the pellet with high-Z material (e.g., 0.1 at.% of high-Z material), and (2) short-wavelength laser light (less than about 1 μ m) is used. In addition, the required peak laser power is minimized by use of hollow pellets. These plasma-instability-free pellets perform nearly as well in computer calculations as those which have been reported previously.

In order to calculate the effects of the x rays radiated by the high-Z material, the multigroup photonics version of LASNEX was used. These calculations show that radiation losses are energetically tolerable ($\lesssim 20\%$), and that significant x-ray preheat effects do not occur.

Because of the implosion symmetry problem, it may be necessary to use long-wavelength laser light in the initial stages of the implosion. (The initial intensities are low enough that moderately long wavelength light can be used without exceeding the instability thresholds.) Implosion symmetry is degraded with short-wavelength light in the early part of the implosion because absorption of laser light occurs at a higher density in the atmosphere near the pellet surface where the electron mean free path is relatively short. In the final part of the implosion, absorption of short-wavelength light occurs sufficiently far from the surface of the pellet (which has imploded to a small radius while the radius at which absorption occurs remains roughly unchanged), and the electron mean free path has greatly increased because the electron energy is much higher.

potentialities for laser-fusion CTR plants are being considered. Near-term possibilities are suggested for hybrid fusion-fission power systems and for substantial synthesis of high transuranic elements and antimatter (electron-positron plasma); these are examples of possible fruitful areas of CTR-related study.

Introduction

The CTR aspects of laser-induced fusion micro-explosions have been under informal study at this

Laboratory since early 1970. In these studies we have considered technical feasibility and economic viability to the extent possible in view of the numerous uncertainties and unknowns in the laser and laser-fusion physics and technology. We have used a laser fusion scheme which involves very high ($>10^3$) convergent compressions of thermonuclear fuel above liquid density, via subsonic-ablation-driven implosion of a fuel pellet energized by a symmetrically applied, optimally time-tailored laser pulse. Plausibility arguments and computer simulation verification of the attainability of such compressions have been presented elsewhere.¹⁴¹⁻¹⁴³

The requirement of economic viability imposes a number of severe, independent constraints on laser-fusion power plant design. For example, the current market value of 10^6 J (1 MJ) of high grade ($\geq 500^\circ\text{C}$) heat is about \$0.001; laser-fusion CTR schemes involving microexplosions producing 10-1000 MJ of energy must therefore use pellets costing considerably less than \$0.01-\$1.00 each, for most of the market value of the explosion-engendered heat must pay capital charges on the laser system and the fusion-fuel combustion chamber, as well as their operating and maintenance costs. Our pellet design studies have therefore been directed primarily toward liquid droplets or solid spherical shells made of thermonuclear fuels such as DT, D^3He , and DD (the droplets could be formed by sophisticated eyedroppers, and the solid shells by bubble pipes with subsequent vapor deposition on the bubbles in drop towers).

Economic viability considerations of course demand pulsed laser systems, fusion-fuel combustion chamber systems, etc., having an aggregate cost of no more than a few hundred dollars per kilowatt (electric), since a conventional steam-thermal generator will also be required in most systems (see, however, the later section on energy conversion). However, fusion microexplosion systems deliver pulsed energy, while their allowable cost is based on their average power. There is therefore a natural bias toward building a relatively inexpensive microexplosion system with small energy per pulse and operating it at a relatively high repetition rate. This minimizes the cost of system components, most of which scale more strongly with microexplosion size than with repetition rate (e.g., the laser and its pulsed power supply, the combustion chamber and its optical components); these less expensive components are simply used more often to produce the same average fusion power.

The technical aspects of laser-fusion CTR systems may be rather naturally resolved into four classes: (1) producing cheap enough fusion pellets, (2) producing a sufficiently energetic time-varying

laser pulse and directing it upon the fusion fuel pellet to engender the microexplosion, (3) constructing the fusion-fuel combustion chamber and operating it on a long-term basis in the thermonuclear microexplosion environment, and (4) transforming the fusion energy into electricity. The cost of suitable fusion pellets depends not only on technological considerations, but also on the laser-plasma interaction physics, which is still in the exploratory phase both theoretically and experimentally. The means we have conceived of for performing the latter three functions are sketched in outline below; they have been elaborated on more fully elsewhere.^{136,144}

Laser Pulse Production and Pellet Implosion

Detailed calculations performed at LLL indicate that about 1 kJ of optimally employed laser light is sufficient to produce a comparable quantity of fusion energy from a DT droplet of appropriate mass. However, in order to produce *net* electrical energy in a laser-fusion power plant, the inefficiencies of thermal cycles and laser pumping (henceforth considered to be electrical in nature) must be overcome. The burn efficiency of a DT fusion microexplosion is nearly directly proportional to the product of fuel density ρ and radius r , for ρr products less than 1 or 2 g/cm² (Ref. 141). At a constant density, the ρr product is proportional to the cube root of the fuel mass and thus to the cube root of the compressional work done on the fuel mass. The required fuel ignition energy increases considerably more slowly with fuel mass, inasmuch as only the central few tenths of a g/cm² need be brought to an effective ignition temperature of about 10 keV by compressional work. The efficiency with which laser light may be employed for both compression and ignition is mass- and ρr -dependent. For a given mass at the corresponding ρr value which maximizes thermonuclear burn multiplication of the input laser energy around the CTR break-even point, the combined compressional ignition efficiency is of the order of 5%. Efficiency in laser pumping, laser energy extraction, and thermal-electric conversion thus enter at somewhat less than the third power in determining the figure of merit of a laser-fusion power system at moderate ρr values; at lower ρr values, the dependence is even steeper.

For example, if one assumes a laser pumping-energy extraction efficiency of 0.1, a thermal-electric efficiency of 0.4, and a pumped compression-ignition efficiency of 0.05, several hundred times as much thermonuclear energy must be generated as was hydrodynamically injected into the pellet. This requires ρr values of greater than 1 g/cm² and total pulse-shaped laser energies of the order of 10^5 J to

break even electrically,* and results in a pellet energy yield of about 3×10^6 J. Efficiency products lower by only a factor of 2 require twofold greater ρr and order-of-magnitude greater laser energy pulses for comparable thermonuclear multiplication of input laser pump energy. Conversely, higher efficiency products (e.g., a laser pumping efficiency of 20%) would be just as sharply beneficial. Attainment of arbitrarily high densities is precluded by considerations of attainable implosion pressures and symmetries and decreasing compression-ignition efficiencies at increasing density.

An optimal pulse shape has been described in the previous semiannual report¹⁴⁵ as well as in recent publications^{141,146} (see also Fig. 1:4 of this report). At the 10^5 J laser pulse level, the leading edge of the pulse must rise faster than exponentially over about four orders of magnitude in power over about a 30-nsec period for pellets consisting simply of droplets of DT, with the last half of the pulse energy being delivered in about 100 psec (about 10^6 GW peak laser power) to effect final droplet compression and ignition. Such a DT pellet will produce several megajoules of thermonuclear energy, which is a representative figure for the remainder of this discussion. A hollow pellet of DT — a thick bubble — may be employed in lieu of a solid or liquid droplet, requiring order-of-magnitude lower peak implosion pressures (and thus similarly lower laser powers); essentially the same laser energies are required for a given fusion energy production, however. Optimum laser pulses of more than an order of magnitude greater energy and peak power — $>10^6$ J and 10^7 GW — and somewhat greater compressions will suffice to efficiently burn deuterium mixed with only a small amount of tritium. The plasma “ash” of the ensuing DD burn would contain several dozen times as much tritium in the exploding pellet plasma as would be needed to subsequently facilitate ignition of such pellets, allowing such power systems to be lithium-free and, moreover, to have very low tritium inventories. Intermediate energies and powers would suffice to efficiently burn the D^3He fuel, which is rich in charged reaction products, and this might be preferable for some

purposes (see energy conversion section later). However, pellets with high ρr (e.g., 10 g/cm^2), which produce more of the total microexplosion energy in charged particle form, also produce more x rays (about 20% of the energy). The larger quantity of x rays generated makes design of the CTR fusion reaction chamber more difficult, so that although there is an increased percentage of charged particles for direct conversion, the overall efficiency may not be much greater than in pellets of lower ρr .

The required laser pulse shapes may apparently be generated with sufficient accuracy by performing the operations of splitting, attenuating (or amplifying), and time-delaying and recombining on a low-energy, ~ 100 -psec oscillator pulse, which may then be amplified to the required energies.^{141,145,147} Amplification of the pulse to the desired shape may be achieved in an optical power-amplifier chain which gain-saturates (in a predetermined fashion) only in the last portion of the pulse, whose initial shape may be preadjusted for such effects. A properly shaped pulse may thus be reliably produced from an energy-efficient optical amplifier. (See Fig. 117.) In this connection, detailed computer calculations have verified that the applied laser power can vary $\pm 10\%$ over significant fractions of the pulse history without significantly degrading the pellet yield.¹⁴³ Since the variations that occur in state-of-the-art high-power laser systems are much less than $\pm 10\%$, this should present no problem.

Implosion symmetry considerations dictate the required degree of spatial uniformity of the laser-energy input to the pellet implosion region, since all portions of the ablating surface of the pellet must experience approximately the same driving temperature. This may be assured by directing a substantial number of equivalent laser beams toward the pellet from symmetrical locations around it. The pellet is provided with an atmosphere (created for example by a very low energy, extremely symmetrically applied laser prepulse) which acts to smooth intensity inhomogeneities in the laser heating pulse as the thermal energy is transported inward to the ablating pellet surface. Spatial “tailoring” of the input laser beams via reflection off significantly aspheric, nonaxisymmetric mirrors may be made to produce an arbitrarily uniform irradiation of the critical density region of the pellet atmosphere, where the laser light couples most strongly to the plasma; such sophisticated spatial tailoring of the laser beams might possibly eliminate the need to generate an atmosphere around the pellet prior to commencing the implosion.

From an implosion symmetry standpoint, longer wavelength lasers are preferable to shorter wavelength ones because their stronger interaction with the outlying portions of the pellet atmosphere affords

* It might be noted in passing that the fusion energy carried out of the microexplosion chamber by 14-MeV neutrons may be multiplied by an average of about 50-fold, by causing fissions in a surrounding natural-uranium blanket which accumulates subsequently fissioned ^{239}Pu . A 10%-efficient, 1-kJ laser, or a 1%-efficient, 10-kJ laser, would then produce fusion microexplosions of sufficient magnitude to break even electrically in such a hybrid fusion-fission scheme. Such a scheme would incidentally constitute means to efficiently burn natural or even depleted uranium in a neutronically subcritical, non-plutonium-processing fashion.

Fig. 117. Scheme for accurately shaping and amplifying a pulse with an energy-efficient optical amplifier chain.

more opportunity for transport processes to smooth out thermal irregularities during the flow of the energy over the greater distances to the ablating surface. However, as discussed in the previous article, the utility of far-infrared lasers (e.g., CO_2) for laser-fusion power plant applications is currently uncertain. Visible or near-ultraviolet lasers would assuredly be the systems of choice (except for their inferior implosion-symmetry qualities), were they at a comparably advanced state with respect to pulsed energy and peak power.

As indicated above, it is highly desirable that the laser beams have no severe unplanned spatial or temporal irregularities. However, the beam quality requirements as far as intrinsic divergence is concerned are not severe; an ability to focus to ten times diffraction limit is quite sufficient — the pellet atmosphere is typically several hundred wavelengths across at the critical density layer, for light from the far-ir to the near-uv.

Fusion-Fuel Combustion Chamber

The fusion-fuel combustion chamber must not only serve to admit the fuel pellet and direct the laser beams upon it, but must also endure perhaps as many as 100 multimegajoule thermonuclear microexplosions per second for time scales of the order of years, and be technically and economically feasible to construct and maintain. The fusion microexplosion effects consist of an x-ray pulse, a neutron pulse, and blast and thermal effects from the plasma explosion debris. The x-ray pulse is fortunately heavily attenuated in the softest (10-1000 eV), most wall-threatening portion of the spectrum by inverse bremsstrahlung in the superdense fireball. (See Fig. 118.) The neutron spectrum is predictably dominated by a 14-MeV peak.* (See Fig. 119.) Calculations involving x-ray opacities, neutron cross sections, specific heats, thermal expansion coefficients, and compressibilities indicate that a chamber of about 3-m radius with a wall of a few layers of properly chosen low-to-moderate-Z materials (e.g., ~0.01 cm of beryllium backed by titanium, niobium, or vanadium) will therefore readily endure the x-ray and neutron pulses of a 10^7 -J microexplosion. If surfaced with a thin, low-Z liquid layer (e.g., Li a few hundred μm thick) by continuous exudation, the plasma pulse of a 10^7 -J explosion may also be repetitively endured by such a "moistened wall" combustion chamber. (This concept has also been studied at LASL.¹⁴⁹)

The impulse associated with an explosion determines the size and material strength of a chamber which must contain it; this impulse is of course proportional to the square root of the product of the explosion energy and the mass of the explosion debris.^{141,146} Relative

to a chemical explosion of the same energy production, a fusion microexplosion involves about six orders of magnitude less explosion debris mass and thus about three orders of magnitude less impulse which an

Fig. 118. X-ray pulse spectrum of a megajoule-level DT fusion microexplosion, as calculated with the LASNEX code. Note the large self-absorption of the superdense fireball at low photon energies.

* An interesting additional experiment should be noted. Our calculations indicate time-integrated 14-MeV neutron fluxes (i.e., fluences) of about 10 moles/cm² in DT pellets for ρ products of the order of 1 g/cm³. Reasonably moderated neutron fluences of interest for transuranic-element-synthesizing experiments could thus be generated with ~10-g/cm³ microexplosions.¹⁴³ Such microexplosions would permit recovery of synthesized elements for high speed analysis on microsecond time scales, an important consideration for many short-lived nuclides. The possibility of quickly (<1 sec) recovering transuranic elements synthesized in one explosion and running them through another microexplosion is also a most intriguing one; it offers the prospect of avoiding the "beta-decay bottleneck" on the "neutron-drip line" which has plagued the Plowshare heavy-element program, thus of synthesizing very-high-Z transuranic elements. Preliminary calculations also indicate that 10 g/cm³ burn of D-³He might also be used to produce antimatter plasma (a gas plasma of electron-positron pairs) with about 1% energy efficiency, which would automatically separate from the explosion debris and could be collected and manipulated for short periods before it self-annihilated. However, the flux for neutrons <1 MeV (which are effective in producing transuranic elements) is about 10⁻²³ mole/cm².

Fig. 119. Neutron pulse spectrum of a megajoule-level DT fusion microexplosion, as calculated by a sophisticated LLL thermonuclear burn code. Note the neutron energy peaks produced by single and double 14-MeV neutron scatterings from deuterons and tritons, and the 3.5-MeV DD burn neutron peak.

explosion chamber must absorb. A 10^7 -J fusion microexplosion thus produces no more impulse than a large firecracker.

This very convenient feature of fusion microexplosions may be lost or degraded, however, if the energy of the microexplosion debris is allowed to significantly ablate material from the explosion chamber wall. The peak pressures imposed on such walls may be multiplied as much as a thousandfold in a careless design involving extensive wall blowoff (these characteristic velocities will be comparable to those of HE debris), and unacceptably high peak pressures (≥ 1 kbar) may thus be engendered. A crucial advantage of not vaporizing the lithium on the wall is that the chamber pumpdown time does not severely limit the microexplosion repetition rate.

About 1 J/cm^2 of microexplosion plasma fluence may be directed against a chamber wall "moistened" with a several-hundred-micron layer of liquid lithium before significant blowoff is produced. The associated

suprathermal ion fluence (e.g., 3.5-MeV alpha particles, knock-on deuterons and tritons) associated with a 1-J/cm^2 thermal plasma fluence poses no blowoff hazard, since it penetrates the moist layer relatively deeply and deposits its energy in a large amount of matter. Ten-megajoule moistened-wall explosion chambers of ~ 3 m radius would thus be satisfactory from a plasma wall-loading standpoint.

If the explosion chamber wall were to be shielded from the explosion debris, by, for instance, a minimum- B magnetic field imposed from without, the surface area requirement for the explosion chamber would then be determined by x-ray loading considerations. Chambers with radii half the size of those whose walls were also subjected to plasma pulses would thus be feasible. The use of such shielding magnetic fields would also have other potential advantages (see energy conversion section below).

The chamber wall could also be satisfactorily shielded from the plasma pulse, as well as from a portion of the x-ray pulse, by pulsed injection of gas through the dry walls of the microexplosion chamber. (See MHD hot gas conversion section below.) However, the real mass injection rates are very large.

A very important problem for laser-fusion reactor design is how to input the laser light and target pellet while at the same time maintaining adequate neutron and x-ray shielding. Laser beams from one or more suitable lasers might be admitted through readily substitutable windows in the outer vacuum wall, passed through the neutron shield in neutronic-baffling dogleg tunnels on mirror trains, and focused onto the pellet atmosphere by strongly aspheric mirrors facing into the explosion chamber through apertures in the inner wall. Continuous low- Z liquid-metal exudation surfacing of the mirrors would suffice to eliminate any possible long-term reflection reduction due to the thermonuclear microexplosion environment for laser wavelengths $> 0.2 \text{ }\mu\text{m}$. The several-mm-sized fuel pellet, free-falling or electrostatically projected into the combustion chamber, might have an atmosphere formed around it by a laser prepulse, and would then be imploded and ignited by the main laser pulse. See Fig. 120.

Tritium recovery, necessary for pure DT burning, would be conducted by use of a lithium-rich neutron shield (with a properly dispersed, adequate void fraction, say $\sim 1\%$ of the shield volume, to permit mechanically nondestructive pulsing of the lithium volume under the pulsed neutron heating) standing between the explosion chamber wall and the outer vacuum wall, similar to those being considered for conventional CTR approaches. Facilities for separation of hydrogen isotopes (i.e., tritium from deuterium and hydrogen) and for breaking down LiT

Fig. 120. Section of conceptual design of 1000-MW-scale laser-fusion electric power plant with direct conversion of explosion energy to electricity. Operating rate is 100 microexplosions per second.

to recover the tritium are required, but these are technically feasible.

Fusion Microexplosion Energy Conversion

Fusion microexplosions, as very versatile and extremely high grade energy sources, apparently admit of several very different means of converting their energy into electricity, depending on pellet fuel composition, the pr value at which the fuel is burned, and the combustion chamber system design and operation. Three types of systems have been identified so far: (1) ordinary thermal conversion, (2) MHD hot-gas-generator conversion, and (3) MHD plasma conversion.

Thermal Conversion. For first-generation laser fusion power plants, which would probably burn DT pellets in a low pr configuration in a maximally simple combustion chamber, ordinary steam-thermal conversion of microexplosion energy, deposited mostly in a tritium breeding blanket, seems preferable. Such systems would, however, be relatively capital-intensive ($\geq \$150/\text{kWe}$) and energy-inefficient ($\leq 50\%$).

MHD Hot-Gas Conversion. If a substantial fraction of the total microexplosion energy is deposited within the initially extremely hot ($\sim 10^9^\circ\text{C}$) explosion debris, it is appropriate to consider recovering this energy with other than a classical heat engine. For example, the combustion chamber wall may be shielded from the explosion plasma pulse by a transiently formed gas layer near its surface (provided high enough injection rates are attained). The substantial mass of hot gas generated thereby might be exhausted from the chamber through a relatively inexpensive, pulsed MHD hot-gas generator, as several atmospheres stagnation pressure at a few thousand degrees temperature could readily be produced. A large fraction of the microexplosion debris energy might be inexpensively ($\leq \$100/\text{kWe}$) converted to electricity in such an approach, which would employ already-demonstrated technology. Such a system would apparently permit low-cost electricity generation with high total efficiency ($\sim 70\%$) for moderate ($\sim 10\text{-g}/\text{cm}^2$) pellet DT or DD burn, or for a $5\text{-g}/\text{cm}^2$, high-charged-particle-fraction (e.g., D^3He) pellet burning. This might be a useful stage of intermediate sophistication in laser-fusion energy conversion. The ultimate efficiency of this level of approach seems likely to be limited by the efficiency with which the substantial microexplosion x-ray output may be used to produce energy, as well as by the pulsed MHD hot-gas energy conversion technology.

MHD Plasma Conversion. Since a fusion microexplosion produces a blob of extremely hot, electrically conductive plasma expanding at very high

velocities, it is natural to consider means by which these streams of radially directed charged particles may be *directly* converted to usable electrical energy. However, since the characteristic (Debye) length of the plasmas involved is very small, it is more appropriate from a physics standpoint to interact the plasma as a collective entity with a magnetic field than as individual charged particles with an electric field, in order to effect such a transformation. In particular, the fusion fireball may be made to do magnetohydrodynamic work on a magnetic field imposed from outside the combustion chamber, transforming its energy into that of a compressed magnetic field. Induction coils suspended from the combustion chamber walls might be used to transform the compressed field energy directly into electricity, in a manner basically very similar to the way an ordinary power transformer works. The expanding fusion fireball would effectively be made to do electromagnetic work directly on some electrical load outside the combustion chamber,¹⁴⁷ such as an electric power grid. The basic feasibility of these means of fireball-to-electricity energy conversion has already been demonstrated.¹³⁷ Very-low-capital-cost ($\leq \$75/\text{kWe}$), high-efficiency ($\geq 70\%$)^{*} electrical energy generation may thus be ultimately attainable, in advanced laser-fusion CTR systems. If properly configured (e.g., a minimum- B topology), the imposed magnetic field could serve the dual purpose of shielding the chamber wall from the plasma explosion.

Economics

It is quite premature to consider in any detail the possible economic aspects of laser fusion. However, the following illustration and considerations may be of interest. Ignoring inexpensive energy-conversion possibilities, the heat from $100 \cdot 10^7\text{-J}$ (low-pellet-cost) microexplosions per second could be used to generate about 400 MW of electricity. Such a power plant would cost perhaps \$80 million, of which perhaps \$20 million could be devoted to the laser system. Laser structure and gas manipulating gear might be expected to consume about half of this, leaving \$10 million to pay for a 10^6-J , 100-pps power supply (assuming 10% laser pumping efficiency). Various estimates indicate that this amount (\$10/J) will possibly suffice to purchase such a long-lived, moderate-repetition-rate system of this scale.

By eliminating essentially all the normal steam-thermal power plant gear from a direct-conversion laser-fusion power generating system, the capital cost

^{*}The efficiency is limited primarily by x-ray energy losses as noted earlier in this discussion.

of such a system might be lowered to less than half of that of an equivalent conventional power plant.

Savings in capital costs for long distance transmission systems made possible by location of relatively very-low-hazard laser-fusion power plants in

urban-industrial load centers might reasonably be expected to combine with such advanced energy conversion system and fuel cost savings to halve the cost of electricity to the average residential/commercial consumer.

SUPPORT ACTIVITIES

Mechanical stability is essential for top laser performance. This means mounting the laser on a surface that is free of vibrations and thermal drift, and providing adequate control of the ambient temperature as well as any special cooling that may be required to dissipate the intense heat pulse from the flashlamps.

Both articles in this section are concerned with mechanical stability — in particular, with the effects of temperature change on mechanical stability. One

reports on a laser dilatometer that has been developed to measure the absolute thermal expansion of materials with very low coefficients of expansion — i.e., materials of interest to laser designers because of their mechanical stability. The other summarizes a number of temperature-control applications used at LLL and describes a study which compared various cooling methods for the "four-leaf clover" linear flashlamp head.

LASER DILATOMETER FOR THERMAL EXPANSION MEASUREMENTS

We have developed a laser-interferometer dilatometer for making absolute measurements of thermal expansion in materials having very low coefficients of expansion. The dilatometer has been built and tested on two materials to date, giving valuable information on these materials from the viewpoint of laser design.

The need for such an instrument grew out of the effort to develop very stable oscillators for the gas-laser research program. One important way to improve the stability of a laser cavity is to decrease the effects of temperature change on the materials that maintain the cavity spacing. This is done by choosing materials that have a very low coefficient of thermal expansion in

the operating temperature range. Measurements of temperature effects on such materials are of course difficult to make because of the low expansion coefficient, but they are nevertheless necessary to determine the absolute behavior of each cavity-spacing component. We needed an accurate, reliable, and convenient means of making these measurements, so we set out to develop the dilatometer described here.

Figure 121 is a photograph of the dilatometer. Basically, the system controls and programs the temperature of a 1-meter-long test bar while stabilizing the temperature of the rest of the apparatus. Movement at one end of the test bar is measured interferometrically, and the resultant fringes are

Fig. 121. Laser-interferometer dilatometer for absolute measurements of thermal expansion of materials with very low expansion coefficients.

recorded. So far we have obtained data on two materials: fused silica and Super Invar. The fused silica shows regular and repeatable expansion characteristics, but the Super Invar (which has a lower expansion coefficient) shows expansion characteristics that are a function of time as well as temperature.

Future plans for this laser dilatometer system include adding automatic fringe counting and data reduction electronics to speed up the testing process. In addition to testing expansion characteristics of various materials of interest, we will also test techniques for lowering the expansion coefficient.

IMPROVING THERMAL STABILITY IN LASER SYSTEMS

It has been known qualitatively for some time that vibrations and temperature changes are the most critical of the environmental factors affecting laser oscillator performance. This qualitative knowledge is reflected in such statements as "work at night when the streetcars don't bother" (N. G. Basov, USSR), or "achieved better results in morning" (J. E. Swain, this Laboratory). As a part of our effort at LLL to develop stable laser oscillators for fusion systems we have been studying these environmental effects quantitatively, particularly temperature effects. We have set up an experimental laboratory for this purpose which is equipped to study both water and air as thermal stabilizers for laser systems and to make temperature sensitivity analyses of individual components. The laboratory includes an oven for component testing whose internal temperature can be controlled within $\pm 0.1^\circ\text{F}$; in this oven the response of the tested component to temperature changes is observed optically.

One early result of our thermal effects studies was the discovery of bimetallic structure in a popular type of component mount. The temperature-sensitive mount was designed with steel and aluminum in parallel mechanical paths, producing thermal instability. The design was accordingly changed to an all-steel one.

Temperature control techniques developed at LLL¹⁵⁰ for machine tool applications are being adapted to laser use. These include the use of flowing liquids to thermally stabilize optical tables and benches as well as components, and electronic thermistor control of air conditioning to increase the cycling frequency and hold a narrower temperature range. In our laboratory studies we are evaluating various

configurations for sources of temperature-controlled liquids to cool systems with pulsed heat input such as flashlamp-pumped laser heads. The system currently in use is a primary loop controlled to $\pm 1^\circ\text{F}$ in combination with a $\pm 0.1^\circ\text{F}$ secondary loop, with control by reheat.

As an example of our laboratory evaluation, we are studying the cooling requirements of a laser head pumped by four linear flashlamps in a "four-leaf clover" arrangement.¹⁵¹ Water cooling is used, and we have been studying such things as the effects of flow rate, tubing size, and separate or combined cooling of the flashlamps and head. Figure 122 shows the thermal recovery times of the water from the laser head and lamps for various coolant flow rates, with separate and with combined cooling of head and lamps. Data of this kind were needed to design the cooling system for the new glass-laser research facility. Further tests will be made to measure thermal recovery times of laser rods and cavities directly and to determine the effects of a mismatch between laser-rod cooling water and flashlamp cooling water.

The quantitative data from these studies should result in substantial cost savings as well as improved system performance. By matching the recovery time to anticipated firing rates for the laser system we can minimize the cooling costs. Reducing coolant pressure requirements and using common cooling water where feasible (e.g., the same water for both flashlamps and rods) simplifies system design and brings additional savings. In our studies we have demonstrated the use of a central cooler and simple secondary loops for laser applications, as well as the use of inexpensive on-off thermistor controllers -- both of which contribute to simpler, less expensive systems.

Fig. 122. Experimental data from cooling tests on four-leaf clover arrangement of four linear flashlamps around a laser rod. Comparisons are shown for common cooling of flashlamps and head and separate cooling.

MANPOWER AND FACILITIES

MANPOWER

During the second half of fiscal year 1972 the Laser-Fusion Program has grown from a December level of 167 direct heads to a June endpoint of approximately 215, resulting in a yearly total of 172 man-years. Of this total, approximately 25% were scientific personnel. The remaining 75% were engineers, technicians, and various other support personnel. The effort distribution by task for FY '72 is as follows:

Administration (program administration, clerical, facilities)	7%
Solid state laser R&D (glass, YAG, ruby)	30%

Gas laser R&D (CO ₂ , other gas media)	34%
Chemical laser	10%
Special diagnostics	10%
Other (laser theory, targets)	9%

The planned laser-fusion effort for FY '73 is 248 heads. This level will be reached by October 1972. Emphasis has been placed on enhancing the experimental and theoretical scientific areas. As a result, the scientific staff will represent approximately 30% of the laser-fusion effort in FY '73 versus the present 25%. Without additional allocations, support personnel will remain at a reduced level until FY '74.

OPERATING COSTS

Total operating costs for FY '72 were \$9.5M, which includes wage expenses, procurements, travel, overhead, and major instrument recharges (computers). This represents a substantial increase over the original July 1971 plan of \$6.5M. Procurements and

manpower-related costs accounted for essentially all of the increase.

In FY '73 the operating costs are expected to be approximately \$13M. The procurement portion of this plan is of a particularly tight nature.

CAPITAL EQUIPMENT

Capital equipment expenditures for FY '72 total \$975K. This increase of \$250K over the July 1971 allocation has helped relieve a serious equipment shortage, particularly in oscilloscopes and spectral measurement equipment. Although this increase relieved a serious

deficit, capital equipment funding will continue to be one of the more critical resources. Most of the requirements are for new capabilities unique to the laser-fusion effort and therefore unavailable from present inventories. In FY '73 a minimum of \$1.3M will be required.

FACILITIES

Approximately \$800K of GPP funds were committed in FY '72 to upgrade existing facilities. Construction modifications to the solid state research, solid-state oscillator development, and Nd rod/disk laser facilities have been completed and are in the process of being activated. Construction is ready to begin on the special diagnostics building, and the CO₂ systems facility is in the final design stages.

In FY '73 GPP funds (\$300K) will be used to

upgrade the chemical laser and gas research areas.

Consolidation of office personnel will be completed by October 1972. Trailer complexes from Central Nevada and NTS are in the process of being relocated to the laser laboratory area. Up to 150 scientists and engineers can be housed in these units.

Plans for the \$6.8M laser R&D facility are well under way with funding approval expected in the fall of 1972. Occupancy will not occur before FY 1975.

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Bibliography of Recent Publications

Listed here are recent publications by LLL authors dealing with laser-related work. Brief abstracts accompany most of the listings.

Carman, R. L., J. Kysilka, and L. W. Coleman, *Sources of Interpulse Noise and Their Elimination in Picosecond Mode Locked Laser Pulse Trains*, Lawrence Livermore Laboratory, UCRL-73619 Abstract (1972). Presented at Minsk Nonlinear Optics Conference, Minsk, USSR, July 1972.

Sources of noise pulses have been found and eliminated in various cavity geometries by using simultaneous extensive diagnostics. These diagnostics include an ultrafast streak camera (about 5-psec detectivity), high-resolution near- and far-field framing cameras, photodiodes, and high-resolution streaked spectrograms.

Carman, R. L., and M. E. Mack, "Experimental Investigation of Transient Stimulated Raman Scattering in a Linearly Dispersionless Medium," *Phys. Rev. A* 5, 341 (1972).

The results of numerical calculations of the transient stimulated Raman scattering reported previously have been verified experimentally under conditions where both linear dispersion and self-focusing effects were negligible. The existence of a delay between maxima of the laser and Stokes pulses is experimentally demonstrated for the first time, while the pulse shortening in time via Raman scattering is established more firmly than in previous work. The incident-laser-pulse duration, generated-Stokes-pulse duration, and delay between intensity maxima for the laser and Stokes pulses were measured with the two-photon-absorption fluorescence technique. The effective phonon-dephasing time is determined via spontaneous Raman scattering. By using these measured quantities, inferences are made as to the magnitude of the transient gain and the shape of the exciting picosecond laser pulse.

Chase, J. B., J. L. LeBlanc, and J. R. Wilson, *The Role of Spontaneous Magnetic Fields in a Laser Created Deuterium Plasma*, Lawrence Livermore Laboratory, UCRL-73914 Preprint (May 9, 1972). Submitted to *Phys. Fluids*.

The effect of thermally generated magnetic fields on the neutron production of a laser-heated, flat, solid deuterium target was examined. Using numerical simulation on a computer, we found that, with the inclusion of magnetic fields, a narrow hole was burrowed into the target. In addition, the absorbed energy from a 4-nsec, 80-J laser pulse was found to be very sensitive to the model used to represent the anomalous effects due to plasma instabilities. The number of neutrons produced was also a strong function of the model. In one case, including the effects of fields, about 3×10^4 neutrons were produced in 2 nsec and the electron temperature rose as high as 15 keV.

Coleman, L. W., R. L. Carman, R. L. Schrieffer, and J. E. Swain, *Direct Observation of Picosecond Structure in the Amplified Output of a Pockels Cell Q-Switched Nd:Glass Oscillator*, Lawrence Livermore Laboratory, Rept. UCRL-73624 Abstract (1972). Presented at the 7th Quantum Electronics Conference, Montreal, Canada, May 1972.

Ultrafast streak camera photographs (detectivity about 5 psec) have revealed modulation periods of about 10 and 100 psec in the glass laser output. The existence of this structure is supported by other diagnostics, and it is repeatable.

Creighton, J. R., R. K. Pearson, J. O. Cowles, G. L. Hermann, and D. W. Gregg, *Kinetic Reaction Rates from Transverse Discharge Chemical Laser Systems*, Lawrence Livermore Laboratory, Rept. UCRL-73335 Abstract (March 28, 1972). Presented at the 3rd Conference on Chemical and Molecular Lasers, St. Louis, Mo., May 1972.

An ultrasimple model is presented for a chemically pumped HF laser, using NF_3 and hydrogen compounds and initiated by a 70-nsec transverse electric discharge. It is assumed that the electric discharge dissociates a fraction of the NF_3 to give an initial concentration of F atoms. The dominant reaction is

with most of the HF vibrationally excited. After a time delay to build up gain, the laser operates saturated with the output power roughly proportional to

$$d[\text{HF}]/dt = k_1 [F_0] [RH_0] \exp(-k_1 [RH_0] t),$$

where F_0 and RH_0 are initial densities.

Rate constants from chemical laser experiments are within 30% of published rates for H_2 , CH_4 , C_2H_6 , cyclo- C_3H_6 , C_3H_8 , $n\text{-C}_4\text{H}_{10}$, and neo- C_5H_{12} . It appears that this system can be used to obtain kinetic rates for fluorine-atom/hydrogen-compound reactions. Using the above assumptions, reaction rates near room temperature obtained from experimental time constants are: D_2 (0.89×10^{13}), iso- C_4H_8 (4.4×10^{13}), cyclo- C_6H_{12} (10×10^{13}), $\text{C}_6\text{H}_4(\text{CH}_3)_2$ (6.9×10^{13}), AsH_3 (3.4×10^{13}), SiH_4 (10×10^{13}), $n\text{-C}_3\text{H}_6$ (3.0×10^{13}); and with a larger experimental error GeH_4 (10×10^{13}) and SbH_3 ($9 \times 10^{13} \text{ cm}^3 \text{ mole}^{-1} \text{ sec}^{-1}$).

Davis, D. T., D. L. Smith, and J. S. Koval, *Generation of Single One Nanosecond Pulses at 10.6 Microns*, Lawrence Livermore Laboratory, Rept. UCRL-73919 Preprint (May 10, 1972). Submitted to *Optics Comm.*

Single pulses of 1-nsec duration have been generated at 10.6- μm wavelength using a pulse selection scheme in conjunction with an actively mode-locked CO_2 TEA oscillator. The experimental setup and its operating characteristics are presented. A technique is described which yields pulse extinction ratios of approximately 900:1.

DeGroot, J. S., and J. I. Katz, *Anomalous Plasma Heating Induced by a Very Strong High Frequency Electric Field*, Lawrence Livermore Laboratory, Rept. UCRL-73785 Preprint (March 14, 1972). Submitted to *Phys. Fluids*.

Simulation calculations and theory are used to show that a very strong electric field, with a frequency near the plasma frequency, parametrically excites electrostatic turbulence. The plasma is strongly heated with the electrons receiving most of the energy. A simple electron-trapping theory accounts for the saturation electric field. After the plasma becomes turbulent, the real part of the frequency of the ion mode is drastically changed from the linear value.

Fleck, J. A., Jr., and R. L. Carman, *Effect of Relaxation on Small-Scale Filament Formation by Ultrashort Light Pulses*, Lawrence Livermore Laboratory, Rept. UCRL-73475 Preprint (October 7, 1971). Published in *Appl. Phys. Letters* 20, 290 (1972).

The development of filamentary structure associated with the self-focusing of ultrashort pulses in the presence of dielectric relaxation is examined. Numerical solutions to the equations of self-focusing and relaxation display filament formation, although filament stabilization is strongly dependent on power. This suggests that further ingredients may be required for a complete theory of filament formation.

Gunn, S. R., *A Tubular Calorimeter for High-Power Laser Pulses*, Lawrence Livermore Laboratory, Rept. UCRL-73894 Preprint (May 2, 1972). Submitted to *Rev. Sci. Instr.*

Harney, R. C., *Cathodoluminescence in ZnS Phosphors*, Lawrence Livermore Laboratory, Rept. UCRL-51211 (April 10, 1972).

Zinc sulfide (ZnS) phosphors have found wide use in many optoelectronic devices, such as oscilloscopes and image converters. The physics of the cathodoluminescent process in this class of phosphors is discussed. Solution of the rate equations yields a relation for the luminescent response that is in close agreement with previous experimental results. A response that is linear in the incident electron current density is obtained for current densities that are sufficiently low. Analysis of the assumptions made in obtaining the linear relation shows that current saturation (a less-than-linear increase in the luminescent response with increasing current density) occurs for high current densities. An equation is given that yields an approximate relation for the current density at which saturation begins to occur. Both saturation and the linearity of the response are discussed in the context of these relations for both pulsed and steady state input conditions.

Hermann, G. L., K. J. Pettipiece, and D. W. Gregg, *Pressure Dependency of the $\text{NF}_3\text{-H}_2$ Transverse Pulse-Initiated HF Chemical Laser*, Lawrence Livermore Laboratory, Rept. UCRL-73606 Preprint (Dec. 28, 1971). Presented at the 3rd Conference on Chemical and Molecular Lasers, St. Louis, Mo., May 1972.

We found that the energy output of several pulsed $\text{NF}_3\text{-H}_2$ chemical lasers (with various $\text{NF}_3\text{-H}_2$ compositions) was a maximum at pressures from 10 to 100 Torr. The pressure of maximum laser energy was higher for lasers with shorter initiation pulses. At the chemical composition producing maximum energy ($\text{NF}_3/\text{H}_2 \approx 5$), both the maximum chemical efficiency ($\sim 1\%$) and the maximum overall electrical efficiency ($\sim 1\%$) occurred at pressures below the pressure of maximum energy. At low pressures, the $V_{2,1}$ transitions lase first and comprise more than 70% of the energy of lasing, followed by about 20% of the total laser energy in $V_{1,0}$ and 10% in $V_{3,2}$. A plot of the laser pulse width at half-maximum vs inverse pressure gave a straight line, indicating that the termination of the laser may be due to collisional relaxation phenomena. We detected no change in the slope of the laser energy-pressure curve while going from a nonexploding to an exploding regime. The addition of helium to $\text{NF}_3\text{-H}_2$ mixtures increased laser energy at low reactant pressures and decreased laser energy at high reactant pressures. At low pressures, laser energy was proportional to $P(\text{NF}_3)$ at low $P(\text{NF}_3)$ and to $P(\text{H}_2)$ at low $P(\text{H}_2)$. The above data imply that (1) lasing HF molecules are produced from species generated in the electric discharge rather than by chain reactions, and (2) decreases in efficiency and total laser energy at higher pressures are due to radical recombination processes.

Koehler, H. A., L. J. Ferderber, D. L. Redhead, and P. J. Ebert, *Stimulated VUV Emission in High Pressure Xenon Excited by High Current Relativistic Electron Beams*, Lawrence Livermore Laboratory, Rept. UCRL-73924 Preprint (May 12, 1972). Submitted to *Appl. Phys. Letters*.

VUV (vacuum-ultraviolet) emission characteristics of xenon for pressures from 15 to 450 psi are presented. Stimulated emission was observed above 200 psi. Experiments were run both with and without mirrors. Without mirrors, the emission was 150 Å wide centered at 1700 Å, and the mean radiative lifetime was 2×10^{-8} sec. Energy conversion efficiency was about 20%. With mirrors, above 200 psi, the emission width narrowed to 17 Å centered at 1716 Å, and the output was highly directional. The pulse width narrowed from 50 nsec to about 3 nsec.

Mead, S. W., R. E. Kidder, J. E. Swain, F. Rainer, and J. Petrucci, *Preliminary Measurements of X-Ray and Neutron Emission from Laser-Produced Plasmas*, Lawrence Livermore Laboratory, Rept. UCRL-73356 Preprint (Aug. 17, 1971). Published in *Appl. Opt.* 11, 345 (1972).

Two Nd-glass laser systems have been assembled for producing high-temperature plasmas. The smaller laser, which gives subnanosecond pulses of about 5 J, has been used primarily for x-ray studies. The spectrum above 2 keV is being explored using Bragg reflection from a cylindrically curved graphite crystal. Line radiation appears to be present in the spectra measured for laser-produced plasmas of lead and gold. Plasma temperatures implied by x-ray transmission measurements are found to vary with absorber thickness. Temperatures of a few tens of keV, inferred from thick-absorber measurements of low-Z plasmas, suggest the operation of anomalous heating mechanisms. A second glass laser system, involving face-pumped disks 14 cm in diameter, is also in use for plasma-heating experiments and has led to the production of D-D neutrons. This system has been used to produce pulses of several tens of joules in a few nanoseconds for recent experiments. A calibrated plastic scintillator with two photomultipliers is used for neutron detection. Targets of CD_2 have produced total yields of more than 10^4 neutrons. Effective neutron production appears to require laser pulses longer than 2 nsec and to be accompanied by a large reflected pulse.

Mead, S. W., C. E. Violet, W. H. Grasberger, J. Petrucci, and J. W. Shearer, *X-Ray Measurements of Laser-Produced Plasmas*, Lawrence Livermore Laboratory, Rept. UCRL-73614 Abstract (1972). Presented at the 7th Quantum Electronics Conference, Montreal, Canada, May 1972.

The x-ray spectra emitted by laser-produced plasmas have been explored with a simple Bragg spectrometer. Intense line emission is evident. X-ray transmission ratios measured with thick absorbers suggest the operation of anomalous heating mechanisms.

Pan, Y.-L., A. F. Bernhardt, and J. R. Simpson, *Construction and Operation of a Double-Discharge TEA CO_2 Laser*, Lawrence Livermore Laboratory, Rept. UCRL-73442 Preprint (September 22, 1971). Published in *Rev. Sci. Instr.* 43, 662 (1972).

We have operated a double-discharge transversely excited atmospheric pressure (TEA) CO_2 laser with a Marx bank system at high output energies and efficiencies over a large discharge volume. The typical laser energy output is approximately 17 J/liter at an efficiency of 24% and a pulse-to-pulse variation of less than 10%. The parameters that govern the operation of the system are discussed.

Pearson, R. K., J. O. Cowles, G. L. Hermann, and D. W. Gregg, *Relative Performance of a Variety of NF₃ + Hydrogen-Donor Transverse Discharge HF Chemical Laser Systems*, Lawrence Livermore Laboratory, Rept. UCRL-73663 Abstract (1972). Presented at 3rd Conference on Chemical and Molecular Lasers, St. Louis, Mo., May 1972.

(See abstract in next bibliography entry.)

Pearson, R. K., J. O. Cowles, G. L. Hermann, D. W. Gregg and J. R. Creighton, *Relative Performance of a Variety of NF₃ + Hydrogen-Donor Transverse Discharge HF Chemical Laser Systems*, Lawrence Livermore Laboratory, Rept. UCRL-73663 Preprint (June 19, 1972). Submitted to *IEEE J. Quant. Electron.*

The performance of 18 NF₃/hydrogen-donor reactant systems has been determined in a pin-discharge HF chemical laser. Laser energy, laser pulse shape, and the time delay between initiation and lasing were measured in experiments with all 18 reactant systems, and lasing lines were measured in 10 systems. It was found that, in general, saturated aliphatic hydrocarbons produced the most laser energy, other hydrocarbons produced less laser energy, and inorganic hydrides produced the least laser energy. Rates of hydrogen abstraction by fluorine atoms have been determined from calculations based on pulse shape data for the hydrogen compounds used in this study. Ten of these rates have not previously been reported.

Pearson, R. K., J. O. Cowles, G. L. Hermann, K. J. Pettipiece, and D. W. Gregg, *Pressure Dependency of the NF₃-H₂ Transverse-Discharge-Pulse-Initiated HF Chemical Laser*, Lawrence Livermore Laboratory, Rept. UCRL-73606 Preprint (Dec. 28, 1971). Submitted to *J. Chem. Phys.*

The pressure dependency of the performance of the NF₃-H₂ chemical laser system has been evaluated. The laser energies for various chemical compositions and initiation discharge energies are presented as functions of pressure. Overall efficiency, laser pulse width, and effects of additive gases are also presented. For all compositions, the laser energy is maximized, at a pressure referred to as P_{max} below. P_{max} was observed to be dependent on the pulse width of the initiation discharge. At pressures below P_{max} the laser energy was proportional to the partial pressure of NF₃ or H₂. No change in slope of the laser-energy-vs-pressure curve was observed in going from low-pressure, nonexploding regimes to high-pressure, exploding regimes, implying that the reactions causing the explosion did not contribute to the lasing. Lasing usually occurred in two peaks, the first containing HF($v = 2$) $\rightarrow$ HF($v = 1$) lines and the second containing HF($v = 3$) $\rightarrow$ HF($v = 2$) and HF($v = 1$) $\rightarrow$ HF($v = 0$) lines. These data indicate that lasing is due to the reaction sequence: (1) $\text{NF}_3 + e^- \rightarrow \cdot\text{NF}_2 + \text{F} \cdot + e^-$, (2) $\text{F} \cdot + \text{H}_2 = \text{HF}^+(v) + \text{H} \cdot$, and (3) $\text{HF}^+(v) + h\nu = \text{HF}(v-1) + 2h\nu$.

Pettipiece, K. J., *A TEM₀₀ Short-Pulse HF Oscillator*, Lawrence Livermore Laboratory, Rept. UCRL-73553 Preprint (Feb. 3, 1972). Published in *Chem. Phys. Letters* 14, 261 (1972).

(See abstract in next bibliography entry.)

Pettipiece, K. J., *A TEM₀₀ Short Pulse HF Oscillator*, Lawrence Livermore Laboratory, Rept. UCRL-73553 Rev. 1 (Feb. 3, 1972). Presented at 3rd Conference on Chemical and Molecular Lasers, St. Louis, Mo. May 1972.

A single-mode HF chemical laser oscillator with a pulse of less than 5 nsec FWHM and a peak output of greater than 0.1 MW has been built and evaluated. A flowing mixture of SF₆/CH₄ was used in our helical TEA laser. The output mirror had a 2-m concave surface with a 50% reflective coating. The rear mirror was a gold coating on a flat substrate or a 625-line grating which could be adjusted for a single line. There was an adjustable aperture inside the cavity for transverse mode control. The cavity was stabilized with four Super Invar rods and was less than 40 cm long to control longitudinal modes. A pulser that generated 6 J in less than 50 nsec was used to supply the electrical input pulse.

The profile of the laser output was scanned in both the near and the far field revealing a pulse with a divergence of 1.4 times diffraction limit and a TEM₀₀ mode. A time resolution of the pulse was displayed on a Tektronix 519 scope using a liquid-helium-cooled Ge-Cu detector, revealing a pulse less than 5 nsec FWHM and a TEM₀₀ mode. The above was done with a P₂(5) line at a pressure of 190 Torr. Using a monochromator we found almost all of the output of this oscillator in the four lines P₂(4)-P₂(7).

Rapagnani, N. L., *The Effects of Various Chain-Branching Rates on the Pulsed HF Chemical Laser*, Lawrence Livermore Laboratory, Rept. UCID-16006 (March 8, 1972).

Chain-branching equations were added to a computer-simulated, pulsed HF chemical laser to determine their effect. The resulting increase in stored energy was found to be twice the increase obtained in the nonbranching case. The cold reactions pumping into HF(2) and the collisional deactivation of HF(v) by HF were found to be dominant populating/depopping mechanisms for the HF(2)-HF(1) inversion. For the HF(1)-HF(0) inversion, the populating/depopping mechanisms were controlled by vibrational deactivation of HF(v) by HF. For both the 2-1 and 1-0 inversions, P(3), P(4), and P(5) are the dominant P-branched transitions.

Reintjes, J., and R. L. Carman, *Direct Observation of the Orientational Kerr Effect in the Self-Focusing of Picosecond Pulses*, Lawrence Livermore Laboratory, Rept. UCRL-73330 Preprint (August 1, 1971). Published in *Phys. Rev. Letters* **28**, 1697 (1972).

Direct measurements of the relaxation time of the birefringence within the self-focusing region of mode-locked laser pulses in several anisotropic liquids establish the importance of the orientational Kerr effect in the picosecond time regime. This result leads to some speculation as to the origin of the high degree of symmetry in the phase-modulated filament spectra observed with picosecond pulses.

Schriever, R. L., *Uniform Direct Current Discharges in Atmospheric Pressure He/N₂/CO₂ Mixtures Using Gas Additives*, Lawrence Livermore Laboratory, Rept. UCRL-73661 Preprint. Published in *Appl. Phys. Letters* **20**, 354 (1972).

Shearer, J. W., S. Bodner, and R. Kidder, *Anomalous Absorption from Plasma Acceleration by Means of Stresses Produced by Electromagnetic Waves*, Lawrence Livermore Laboratory, Rept. UCRL-73735 Abstract (February 8, 1972).

The optical stresses exerted on the plasma electrons by an intense electromagnetic wave become important when the intensity I approaches the nonlinear intensity I_{nl} :

$$I_{nl} = 2 \sqrt{\frac{\epsilon_0}{\mu_0}} \frac{m}{e^2} \omega_0 k T_e \left(1 + \frac{1}{Z} \frac{T_i}{T_e} \right).$$

A derivation of the equation of motion shows that the two transverse stresses are equal, but differ from the longitudinal stress. The transverse stresses change the plasma density distribution so as to produce self-focusing. The longitudinal stresses push the plasma away from any focal point, and also produce a density discontinuity near the cutoff density. Some of these effects are important even at low plasma densities. They can be thought of as direct coupling between the electromagnetic wave and acoustic waves of small k .

Shearer, J. W., and J. J. Duderstadt, *Wavelength Dependence of Laser Light Absorption by a Solid Deuterium Target*, Lawrence Livermore Laboratory, Rept. UCRL-73617 Abstract.

Computations of the absorption of intense light at the surface of solid deuterium show that absorption is greater at shorter wavelengths. An efficient ultraviolet laser is needed for the laser pellet-fusion application.

Shearer, J. W., S. W. Mead, J. Petrucci, F. Rainer, J. E. Swain, and C. E. Violet, *Experimental Indications of Plasma Instabilities Induced by Laser Heating*, Lawrence Livermore Laboratory, Rept. UCRL-73489 Preprint Rev. 1 (March 24, 1972). Accepted for publication in *Phys. Rev. A*.

The detection of about 100-keV x radiation and of directly backscattered light is described for neodymium-glass laser light pulses focused on a polyethylene target. These observations can be explained in terms of the nonlinear excitation of plasma waves by the laser light.

Thomas, S. W., and L. W. Coleman, *Laser-Triggered Avalanche-Transistor Voltage Generator for a Picosecond Streak Camera*, Lawrence Livermore Laboratory, Rept. UCRL-73454 Preprint (Sept. 1971). Published in *Appl. Phys. Letters* **20**, No. 5 (1972).

Direct optical triggering of an avalanche transistor with a short laser pulse has been demonstrated. In some applications this system provides a compact low-jitter replacement for a laser-triggered spark gap. The technique has been applied to generating the gating and sweep voltages in a picosecond streak camera for laser pulse diagnostics, where it eliminates the need for multiple beam splitters and long delays. The "trigger" avalanche transistor was placed as one of a series string of avalanche transistors. A portion of the switched-out laser

pulse to be diagnosed was focused onto the trigger transistor chip. Nanosecond-rise kilovolt waveforms are thus generated with time jitter of the entire system being less than 100 psec.

Thomas, S. W., G. R. Tripp, and L. W. Coleman, *Ultrafast Streaking Camera for Picosecond Laser Diagnostics*, Lawrence Livermore Laboratory, Rept. UCRL-73734 Preprint (1972). Presented at the 10th International Congress on High Speed Photography, Nice, France, Sept. 25-30, 1972.

A compact, ultrafast streaking camera, small and light enough to be carried about in a suitcase-size package, is described. Powering requirements are low. A 10-psec resolution allows pulse widths to be resolved to between 4 and 7 psec. Photon-triggered, avalanche transistor sweep circuitry produces less than 100-psec of jitter between the trigger initiation and the start of the sweep. Electronic circuitry and construction details are provided. A 1-psec-resolution system development effort is described.

Turner, C. E., Jr., and Y.-L. Pan, *Effects of Intense CO₂ Radiation on Pulsed HF Chemical Laser Systems*, Lawrence Livermore Laboratory, Rept. UCRL-73963 Abstract (1972). Presented at the 3rd Conference on Chemical and Molecular Lasers, St. Louis, Mo., May 1972.

In certain pulsed chemical laser systems, for example, those in which vibrationally excited HF is produced, it appears that chain branching reactions uniformly initiated over large volumes will be required to overcome the detrimental effects of vibrational relaxation and three-body recombination in order to obtain high energy and power operation at attractive efficiency. Pulsed operation also requires the ability to premix the reactive gases under conditions of pressure and temperature which are stable until initiation. With the above requirements in mind we have assembled a test system consisting of a chemical laser cavity and a double-discharge TEA CO₂ laser. The CO₂ laser produces an output of about 1.5 J/cm² in less than 2 μ sec over an aperture of 60 cm². The chemical cell is equipped with an electric discharge capability transverse to both the CO₂ laser and the chemical laser output. Visible fluorescence indicating rapid chemical combustion has been initiated by the unfocused CO₂ beam in mixtures containing either NF₃ or N₂F₄. Under the conditions studied thus far no laser action has been observed. Comparison of laser performance between an electric discharge initiation and CO₂ laser preinitiation followed by a discharge indicates an increase in the output power for the latter in mixtures containing various combinations of N₂F₄, NF₃, SF₆, and H₂.

Yee, J. H., *Three-Photon Absorption in Semiconductors*, Lawrence Livermore Laboratory, Rept. UCRL-73345 Preprint (Aug. 12, 1971). Published in *Phys. Rev. B* 5, 449 (1972).

The three-photon-transition absorption process is theoretically considered for different types of the energy-band model. It is shown that the present result reduces to the previous existing result for the case of the two-band model. It is also shown that if the effective mass of the electrons and the holes is anisotropic, the absorption process is dependent, in a very complicated way, on the polarization of the incident light.

Yee, J. H., *Theory of Photon-Drag Effect in Polar Crystals*, Lawrence Livermore Laboratory, Rept. UCRL-73802 Preprint (March 13, 1972).

The theory of the photon-drag effect in polar crystals is considered using Fröhlich's model for the electron-phonon interaction. An equation is derived for the electric field generated by this effect. Numerical examples are given for CdS crystals.

PATENTS

PATENT ISSUED

Patent No. 3,641,454 (Issued February 1972)

Title. Electron-beam-pumped gas laser system.

Inventor. Barton Krawetz.

Abstract. In this gas laser system the electrical discharge is initiated by a high-power electron beam. The gaseous lasing medium is in an optical cavity

contained in a vessel having two large electrodes electrically insulated from each other, and a charged-particle accelerator directs an electron beam through the gaseous medium perpendicular or parallel to the optical path. The system can produce pulses having total energy on the order of 20 kJ and with a pulse duration of 0.5 μ sec, giving a power rating on the order of 10^4 MW.

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