Calspan

Technical Report

MASTER

Calspan Corporation
Buffalo, New York 14221

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ABSORPTION OF ELECTROMAGNETIC WAVES NEAR THE CRITICAL DENSITY

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PREPARED BY:

John Daiber
Dr. J.W. Daiber
Principal Investigator

APPROVED BY:

Charles E. Treanor
Dr. C.E. Treanor
Department Head

Ronald Kelm
Dr. R.G. Kelm

Herbert M. Thompson
Mr. H.M. Thompson

MASTER

Calspan Corporation
Buffalo, New York 14221

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FOREWORD

This program has been carried out at Calspan Corporation, Buffalo, New York 14221 under Contract No. AT(11-1)-2288 for the Division of Controlled Thermonuclear Research of the U.S. Atomic Energy Commission under the technical cognizance of Dr. Bennett Miller. The research reported herein was performed during the period 1 December 1972 through 30 November 1973. A proposal to extend the research program has been submitted. Hence, this report is written in the format of an annual report rather than a final report.

ABSTRACT

The program is an experimental study of the interaction of high-intensity ruby laser radiation with hydrogen gas in a free-jet. In these experiments both laser intensity and the plasma frequency can be varied. By monitoring several parameters, including incident and reflected power, x-ray emission and the kinematics of plasma growth, the existence of an anomalous threshold for coupling radiation into plasma energy should be determinable. A discussion of the status of the Calspan experiment and of the status of other anomalous coupling studies at laser frequencies is presented.

OBJECTIVE

This program is directed at studying the absorption of laser light by a plasma. The electron density is adjustable in the experiments so that studies can be made with plasma frequencies both above and below the laser frequency. The measurements are being made in the free-jet/ruby laser facility of Calspan. A theoretical modeling of the experiments is also being carried out.

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1. INTRODUCTION

Several years ago a scheme for producing fusion by laser-generated implosions was proposed¹; the basic scheme has received much attention in recent years². The coupling of the laser energy to a solid surface required for implementation of this scheme is still a question of fundamental concern. It is recognized that laser heating by inverse Bremsstrahlung becomes inefficient as the temperature of the plasma increases. Therefore, to heat plasmas to fusion temperatures by laser radiation is extremely difficult if this classical mechanism accounts for all the absorption.

However, analyses of coupling to plasma by high-intensity electromagnetic radiation have shown that instabilities can be excited in a plasma when the frequency of the wave approaches combinations of natural frequencies of the plasma. These instabilities offer the possibility for enhanced coupling to the material of high-intensity laser radiation, and therefore of increased probability of success of the laser-implosion scheme.

A unique approach for studying the anomalous heating of a plasma target by high-intensity laser radiation has been developed³. A Q-switched laser is used to irradiate axially a free-jet expansion of a high-pressure gas into a vacuum. The intensity thresholds for anomalous coupling can be delineated experimentally for electromagnetic waves at the ruby-laser frequency with a target in which the density can be varied from below to above the critical value. The peak laser power can also be varied between experiments so that the existence of an anomalous coupling threshold at each ratio of laser frequency to plasma frequency can be determined. Consequently, the nature of the non-linear effects responsible for anomalous coupling can be examined in detail.

In this report the status of the experiments on the free jet is presented. In addition a review of anomalous coupling studies at laser frequencies is given; this review has been used to aid selection of diagnostics for the free-jet experiments and to guide interpretation of experimental results.

Nominally, this study has been underway for a year, and this report is an annual report. However, since the contract for this study was not signed until March 1973, the effort has been less than one year long. It is anticipated that the study will be continued, and additional results will be reported later.

2. STATUS OF THE FREE-JET EXPERIMENTS

2.1 GENERAL DESCRIPTION OF THE EXPERIMENTS

The objective of the program is to study the anomalous coupling threshold of electromagnetic waves at laser frequencies with plasmas. The laser being used in this program is a Calspan owned ruby system capable of power outputs in the Q-switched mode of 1 GW. It is focused with a lens to an 80 micron diameter focal spot; thus the peak intensity is the order of 10^{13} W/cm². The target is a free gas jet which is illuminated on the symmetry axis. The natural density gradient is very steep going from plenum density to near zero in a distance of order 1 mm. The advantage of this target is that the maximum possible electron density is controllable and thus a critical value for instability excitation can be determined. The effects of the gradient on the thresholds have been estimated and do not appear to increase the thresholds above the available intensity.

A schematic diagram of the experiment showing the relative location of its components, a streak record of the growth of the laser heated luminous plasma and the calculated density profile is shown in Figure 1. The following two subsections discuss the laser and free jet in detail.

2.2 DESCRIPTION OF CALSPAN RUBY LASER FACILITY

The Calspan ruby laser system consists of a high-quality oscillator stage followed by two stages of amplification. A schematic diagram and photographs of the laser facility and of the oscillator are shown in Figures 2, 3a and 3b. The entire system is maintained at constant temperatures (± 0.1 °C) by a high capacity water cooler. The laser can be operated at power levels from 100 MW to 1 GW with a repetition rate of 1 shot every 5 minutes.

Figure 1 SCHEMATIC DIAGRAM OF THE EXPERIMENT SHOWING THE TEST CHAMBER AND A STREAK RECORD OF LUMINOUS PLASMA GROWTH. THE DASHED LINE SHOWS THE POSITION OF THE END WALL IN THE STREAK RECORD AND CALCULATED DENSITY PROFILE.

Figure 2 SCHEMATIC DIAGRAM OF THE CALSPAN RUBY LASER FACILITY

Figure 3a RUBY LASER SYSTEM SHOWING THE VACUUM CHAMBER WHICH CONTAINS THE FREE JET

Figure 3b

PHOTOGRAPH OF THE LASER OSCILLATOR

The oscillator cavity is Q-switched with a Pockel's cell operated in the passive mode (see Figure 3b). A constant voltage is applied to the cell so that the cavity is biased to maximum attenuation by the Brewster plate polarizer. The voltage is removed with a switching time of 10 nsec which permits a rapid build up of the oscillator's laser pulse. The voltage pulser also provides a low-jitter synchronization pulse which can be used to operate auxiliary equipment, such as the image-converter camera. The oscillator rod is 0.625-in in diameter and 4-in long. It is made of select Czochralski ruby having an optical distortion of 1.4 fringes at 632.8 nm over the full diameter.

The cavity mirrors consist of a 99.8% reflectance flat rear mirror and either a one, two or three etalon output reflector. The multi-etalon resonant, output reflectors are of high quality quartz polished to $1/20$ of a wave flatness and aligned parallel to within 0.5 arcsec. By selection of the output reflector and the pumping energy, the oscillator pulse duration may be varied from 10 to 40 nsec. When the power level of the oscillator is kept below 50 MW the beam divergence is less than 0.5 mr full angle, and there is little chance of optical damage within the oscillator components. To obtain this beam divergence it is necessary to adjust the oscillator rod temperature so that the maximum gain of the ruby can be shifted to correspond to the resonant modes of the multi-etalon reflector.

The beam divergence for the oscillator is now less than half a milliradian. This divergence should be contrasted with the beam divergence of the previous laser arrangement, which has been obtained by system improvements during the present program. New ruby rods have been placed in both amplifier stages. A multi-etalon output reflector has been added to the oscillator and the alignment technique for the system has been upgraded with the addition of a more sensitive alignment telescope.

A planned improvement to the laser system is the pulse shaping shutter shown with dashed lines in Figure 2. This stage is an active mode Pockel's cell placed between crossed polarizers. The Pockel's cell would be driven by a fast line pulser capable of providing laser pulse widths of 2 to 5 nsec with a 1-nsec rise time. This improvement would provide a more direct means of comparing the results of the proposed experimental studies with other laser-matter-interaction experiments performed with lasers having pulse durations in the 1- to 2-nsec range.

The oscillator beam is then transmitted through two amplifier stages cooled to the same temperature as the oscillator. The amplifier rods are 0.75-in in diameter and 9.5-in long (tip to tip). The amplifier rubies are of standard material. The 0.5 mr diverging beam of the oscillator is allowed to pass through the center of the amplifiers and fill the rod aperture without additional optical shaping. The amplifier system is prevented from oscillating or pre-pulsing by the cyptocyanine-methanol dye cells shown in Figure 2. The amplifier stages are run at a gain of 2 to 5 per stage. The principal damage mechanism for these stages is self focusing. The damage threshold for these rods can only be inferred from past experience; however we have noted considerable decrease in the appearance of self-focusing damage as a result of the near single longitudinal mode operation of the oscillator.

The output beam from the amplifier is elliptical and has an average, near field beam divergence of 1.5 mr full angle. This beam divergence was measured using an adjustable aperture combined with a calorimeter to measure the size of the elliptical aperture which contained one half the laser power. Since the measurement was made in the near field and burn patterns show that the laser beam has a larger divergence along the minor beam axis, it is felt that this measurement gives a maximum value for the beam divergence. However, since the focusing lens is placed close to the same near-field position, this value is the correct one to use in determining focus spot diameters.

At the present time the laser is focused onto the target by a 61-mm focal length bi-convex lens. Measurements of the focal plane intensity distribution using a helium-neon beam which was adjusted to have a divergence of 1.5 mr showed that the diameter of the focal spot at the point of one half of peak beam intensity is 80 microns. Thus at 500 MW the maximum laser intensity on target is expected to be $1.1 \times 10^{13} \text{ W/cm}^2$.

2.3 DESCRIPTION OF FREE-JET TARGET

The target is the gas in a supersonic free jet which is axially aligned with the incident focused laser beam, see Figure 1. The axial density gradient in the free jet is very large. For a diatomic gas the maximum density gradient for a 1-mm radius orifice and a reservoir density of $2.3 \times 10^{21} \text{ cm}^{-3}$ is $5 \times 10^{22} \text{ cm}^{-4}$. A plot of calculated density normalized by the reservoir density versus distance normalized by orifice diameter is shown in Figure 4. The density gradient, defined as the change in normalized density with normalized distance, is also plotted in Figure 4.

The gas feed for the free jet is shown schematically in Figure 5a. In Figure 5b a photograph of the free jet is shown including the gas plenum, the orifice and the vacuum chamber.

To achieve plasma densities greater than the critical density it has been necessary during the present contract to redesign both the free-jet reservoir and the fast-acting gas valve connecting this reservoir to the vacuum tank so that higher plenum pressures can be used. In the present free-jet experiments the reservoir is connected to a vacuum tank through a fast-acting valve. The valve opens allowing gas to enter the evacuated chamber through the orifice and establishing the free-jet, see Figure 5. The new system has been designed to accomodate 130 atmospheres in the reservoir. (About 45 atmospheres pressure at room temperature will produce an electron density of $2.3 \times 10^{21} \text{ cm}^{-3}$, which is the critical electron density for ruby-laser radiation, when the gas is doubly ionized.)

Figure 4 CALCULATED VARIATION OF THE DENSITY AND DENSITY GRADIENT ALONG THE AXIS OF AN AXISYMMETRIC FREE JET IN A DIATOMIC GAS

Figure 5a SCHEMATIC OF THE FREE JET

Figure 5b PHOTOGRAPH OF FREE JET

A fast-responding-solenoid valve for the new high pressure free-jet has been obtained. This valve was specified for 2500 psi helium service with an opening time of less than 20 msec. By using a capacitive discharge an opening time of 2.5 msec has been obtained. The free-jet apparatus had been limited to pressures of 135 psi absolute due to leakage of the solenoid valve. With the new solenoid valve the limitation of the present apparatus was the side viewing windows used for obtaining streak records. Now the viewing windows have been supported to withstand pressures of up to 2000 psi.

In addition, the new free-jet system has been designed to allow measurement of soft x-ray emission for electron temperature determination. As discussed in the quarterly progress reports, these modifications are being made under AFOSR contract, which is concerned with two-dimensional effect caused by laser heating. The design and rebuilding of this complete, new free-jet and diagnostic system is being performed concurrently. Measurement of soft x-rays were not made in the previous free-jet experiments, and these measurements will provide a very valuable diagnostic tool.

A schematic diagram of the diagnostics is shown in Figure 6, and the diagnostics which are in place are shown in Figure 7. A Fabry-Perot interferometer will be used to measure mode patterns of the incident beam and the width of the reflected spectrum. This data will allow determination of the doppler shifts. A 0.75 meter spectrometer has been adapted with a photomultiplier to record the time history of the reflected light as the laser frequency ω_0 and $2\omega_0$, $(3/2)\omega_0$ and soon at $(1/2)\omega_0$. Spectrograms can also be taken when desired. Transmitted, reflected and incident powers are being measured within the present experiments. A relative calibration of these channels is planned. The laser system is now operating routinely and data from these diagnostics will be soon forthcoming. At the present time, low-power reflectivity measurements are being made over the range of plenum pressures from 100 to 1000 psi. It is anticipated that an enhancement will be observed when the plasma becomes overdense.

Figure 6 INSTRUMENTATION SCHEMATIC – LASER HEATING EXPERIMENTS

Figure 7 PHOTOGRAPH OF DIAGNOSTIC INSTRUMENTATION

3. STATUS OF ANOMALOUS COUPLING STUDIES AT LASER FREQUENCIES

Study of laser energy coupling to plasmas has become a field of intense interest over the past few years. It is recognized that laser heating by inverse Bremsstrahlung becomes inefficient as the temperature of the plasma increases. Therefore, to heat plasmas to fusion temperatures by laser radiation is extremely difficult if this classical mechanism accounts for all the absorption during heating.

However, early theoretical analyses of coupling to plasma by high-intensity electromagnetic radiation have shown that a variety of instabilities can be excited in a homogeneous plasma when the frequency of the wave approaches various natural frequencies or combinations of natural frequencies of the plasma. These analyses have shown furthermore that for each instability the intensity of the radiation must exceed a threshold value, this threshold being required for growth of the mode to overcome the natural dissipation mechanisms within the plasma.

Recently there has been a great proliferation of analyses of laser-induced instabilities in plasmas and of coupling of high-intensity electromagnetic fields with plasma modes. Some attempts have been made to survey and summarize these results,^{4,5,6} but generally there has not been a concerted attempt to compare theories and to make the idealized theoretical results applicable to the multiple processes occurring in laser experiments. As a result a considerable variation in calculated thresholds and growth rates for the various laser-induced instabilities in actual experiments still exists. In fact, most of the theoretical calculations for these quantities must be used with care because of the idealizations introduced in the analyses.

Figure 8 is a table which shows a summary of theoretical results for four EM radiation-plasma instabilities. These four, stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), parametric-decay instability and the oscillating-two-stream instability (OTS), represent four of the most extensively studied instabilities for laser-plasma interactions. The second column of this table shows the qualitative behavior expected when laser radiation impinges upon a plasma exciting this instability. In the third column is the threshold intensities calculated to excite each instability in a homogeneous plasma with electron density of 10^{21} cm^{-3} and an electron temperature of 1 keV. For most instabilities more than one threshold value is quoted. Along with each quoted intensity threshold is the name of the investigator^{4,5,6} by whom it was obtained. In the fourth column the threshold intensity in an inhomogeneous plasma is quoted along with the source of the quote. For these calculations the scale length for the inhomogeneity (or the gradient length for the change in plasma density) has been taken to be 1 mm, which is the approximate length characterizing the density gradient in the free gaseous jet. In all cases the threshold intensity has been increased by the presence of the plasma density gradient, the scattering instabilities being affected much more severely than the absorptive instabilities.

Examination of this table, as well as a survey of other theoretical analyses of laser-induced plasma instabilities, shows that there remains large variations in the threshold intensities which are calculated to excite the various instabilities. This appears to be the result of the varied assumptions used in the analyses and selection of parameters characterizing the plasma and the laser radiation. Therefore, the primary value of the detailed theoretical analyses at this time is not in the precise numbers which are calculated for thresholds and growth rates, but rather for the qualitative and semi-quantitative results obtained.

INSTABILITY	QUALITATIVE BEHAVIOR	THRESHOLD INTENSITY HOMOGENEOUS PLASMA $n \sim 10^{21} \text{ cm}^{-3}$, $T_e = 1 \text{ KeV}$		THRESHOLD INTENSITY INHOMOGENEOUS PLASMA, GRADIENT LENGTH = 1mm	
SRS	ENHANCED BACKSCATTER	10^{13} W/cm^2	DUBOIS	10^{17} W/cm^2	DUBOIS
		10^{11} W/cm^2	NISHIKAWA	$2 \times 10^{14} \text{ W/cm}^2$	NISHIKAWA
		10^{10} W/cm^2	DAWSON		
SBS	ENHANCED BACKSCATTER	10^{13} W/cm^2	DUBOIS	10^{14} W/cm^2	DUBOIS
		10^{11} W/cm^2	NISHIKAWA		
		10^{14} W/cm^2	DAWSON	10^{16} W/cm^2	DAWSON
PARAMETRIC DECAY e-i	ENHANCED ABSORPTION	10^{13} W/cm^2	DUBOIS	10^{13} W/cm^2	DUBOIS
		10^{11} W/cm^2	DUBOIS ($T_e \gg T_i$)	10^{11} W/cm^2	DUBOIS ($T_e \gg T_i$)
		10^{12} W/cm^2	NISHIKAWA		
		10^{14} W/cm^2	DAWSON		
OTS	ENHANCED ABSORPTION	10^{13} W/cm^2	DAWSON ($T_e \gg T_i$)		
HARMONIC GENERATION	RADIATION AT $2\omega_o$, $\frac{3\omega_o}{2}$, $\frac{\omega_o}{2}$				

Figure 8 A TABLE SHOWING THE PREDICTED ANOMALOUS COUPLING THRESHOLDS IN HOMOGENEOUS AND INHOMOGENEOUS PLASMAS

For experiments on laser heating of a target, other theoretical considerations in addition to the four instability analyses in homogeneous and inhomogeneous plasmas cited above should be kept in mind. These involve excitation of harmonics and subharmonics,^{5,7} side scatter of incident radiation from plasma modes,⁸ non-normal incidence of laser radiation on a plasma density gradient,⁹ filamentation of the laser light in the plasma,¹⁰ laser frequency spread (pump purity)¹¹ and the effects of self-induced magnetic fields.¹² The influence on the qualitative behavior of measurable quantities of each of these effects should be determined and any quantitative comparisons should be made with theoretical predictions when results of experiments are interpreted. However, at present quantitative comparisons between theory and experiment is difficult.

Figure 9 is a table summarizing the experimental results from several laboratories on anomalous coupling between laser radiation and solid targets. In the first column the name of the experimenter and the reference for the information quoted in the table are given. The second column lists the peak power reported for the experiments and whether the laser pulse width is in the ones or tens of nanosecond range or in the subnanosecond range (tens or hundreds of picoseconds). The third column lists the type of target used in each experiment. In the next six columns are listed the diagnostic measurements made in each experiment; comments are given on many of the results of the diagnostic measurements, particularly on the results of measuring reflected and scattered radiation. A cross in any of the columns indicates that the diagnostic measurement was performed during experiments. Finally, in the last column is listed the threshold intensity reported for the phenomena observed.

Several conclusions can be drawn from this table. First, in many of the experiments there have been observed effects which may be associated with anomalous coupling of the laser radiation to the plasma. However, a threshold intensity for a change in behavior in the coupling has been reported only in four of these experiments. The reported threshold intensity for the change in plasma response for three of the experiments is in the range 5×10^{12} W/cm² to 10^{13} W/cm²; only one set of experiments report a threshold intensity of

EXPERIMENTER	PEAK INTENSITY PULSE DURATION	TARGETS	REFLECTED LIGHT	SOFT X-RAYS	ION COLLECTION	NEUTRONS	STREAK CAMERA	MAGNETIC FIELD	THRESHOLD INTENSITY
CARUSO ¹³	10^{16} W/cm ² , psec	SOLID D ₂	10% BACKSCATTER, 180° & 90° SHG						
CARUSO ¹³	4×10^{13} W/cm ² , nsec	SOLID D ₂			INCREASE IN NO. AND ENERGY WITH INTENSITY	ABOVE THRESHOLD			6×10^{12} W/cm ²
YAMANAKA ¹⁴	2×10^{14} W/cm ² , nsec	SOLID SURFACES	INCREASES WITH INTENSITY	CHANGE IN DEPENDENCE OF T _e ON INTENSITY	FAST IONS ABOVE THRESHOLD	ABOVE THRESHOLD	X	X	10^{13} W/cm ²
SKLIZKOV ¹⁵	10^{14} W/cm ² , nsec	SOLID SURFACES	SHG, GHz MODULA- TION, DECREASES WITH INTENSITY						5×10^{12} W/cm ²
SIGEL ¹⁶	5×10^{14} W/cm ² nsec	SOLID SURFACES	LARGE VARIATION WITH POSITION OF FOCAL SPOT, SHG	X	FAST IONS ABOVE THRESHOLD	X			
BOBIN ¹⁷	10^{13} W/cm ² , nsec	SOLID H ₂	AT 45° OBSERVED: SHG, $(3/2)\omega_0$ & $(1/2)\omega_0$ TIME RE- SOLVED, LINES BROADENED AND ASYMMETRIC	X		X			
McCALL ¹⁸	3×10^{16} W/cm ² , psec	SOLID CH ₂	THRESHOLD BEHAVIOR, SHG AND $(3/2)\omega_0$ OBSERVED	SPECTRUM & POLARIZATION	X			X	
SHEARER ¹⁹	2×10^{14} W/cm ² , nsec	SOLID CD ₂	TIME RESOLVED BACKSCATTER	NO UNIQUE T _e		X			
BRUECKNER ²⁰	7×10^{15} W/cm ² , nsec	SOLID CD ₂	DECREASES WITH INCREASING INTENSITY		FAST IONS ABOVE THRESHOLD	X			4×10^{14} W/cm ²
LUBIN ²¹	10^{16} W/cm ² , psec	SOLID SPHERES	MULTIPULSE GIVES HIGHER REFLEC- TIVITY	MAXWELLIAN AND NON- MAXWELLIAN		X			

Figure 9 A TABLE SUMMARIZING THE EXPERIMENTAL RESULTS ON LASER-MATTER INTERACTION STUDIES

greater than 10^{14} W/cm². Finally, in all of the experiments listed in Figure 9, the target is a solid so that the density in the plasma produced by the laser is dependent upon solid density and the time history of the pulse.

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