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**Final Report
Laser Scattering from
Long Scalelength Plasmas on Omega**

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TABLE OF CONTENTS

Introduction	3
Background of the Project	3
Characterization Experiments	9
Software Development	11
Instrumentation Development	12
Design of Thomson scattering experiments.	13
Conclusion.....	20
References.....	21

Introduction

This is the final report on the project, "Laser Scattering From Long Scalelength Plasmas on Omega", funded by the National Laser User Facility" program from Oct. 1, 1996 to Sept. 30, 1998. In this project, we accomplished the tasks called for in the revised statement of work associated with this grant.

Specifically, we accomplished:

1. Active participation in the design of long-scalelength plasmas for Omega and in experiments to characterize these plasmas.
2. Development of software that permits the rapid evaluation of laser-scattering diagnostic possibilities involving the standard parametric instabilities. It must be able to account for all 60 beams in Omega in addition to a probe beam and variable detector locations.
3. Design, purchase of components for, and assembly of instrumentation to make such measurements, providing for long-term versatility in the type of measurement.

The project background and these accomplishments are discussed herein.

Background of the Project

There remain significant unresolved issues in the behavior of waves, parametric interactions, and the resulting turbulence in plasmas. Early experiments, discussed in major reviews,^{1,2} used CO₂ lasers or microwaves to observe a number of waves and parametric processes. These experiments investigated saturation effects in the regime in which the electromagnetic pump strongly perturbed the plasma distribution functions and strongly drove the waves. The same experiments were less-well-suited to observe threshold phenomena. More recently, it has proven possible to work in a regime where the plasma is not strongly disturbed by the pump which drives the parametric

interaction. This regime is of relevance to high-gain laser fusion targets and is also well suited to the study of threshold phenomena.

Much work in this regime has studied stimulated laser scattering and related optical emissions from well-characterized plasmas produced by solid-state lasers.³⁻⁹ This has led to the observation of some additional, fundamental waves and interactions¹⁰⁻¹³ and to studies of the onset of parametric instabilities.¹⁴⁻²² What has resulted is a substantial but not yet complete understanding of the thresholds and onset of several parametric instabilities. In sharp contrast, we have achieved comparatively little understanding regarding the saturation of parametric instabilities under such conditions. The available data are limited primarily to scalings of stimulated emission. We have very little evidence regarding the fundamental behavior of driven turbulence within the plasma.

The means to improve this situation has become available with the application of Thomson scattering techniques^{23,8} to this type of laser plasma. These experiments work in an untraditional regime of Thomson scattering. Traditionally, Thomson scattering has been done with probe lasers of very high frequency compared to the plasma frequency, leading to very small deflection angles and negligible refraction of the probe beam. In contrast, the experiments in plasmas produced by high-frequency lasers use very large scattering angles. Refraction of the probe is not negligible, but is small enough to contribute small uncertainties in the context of a large scattering angle.

A number of experiments of this type have focused on the direct observation of the modes of the plasma,²⁴⁻²⁹ usually driven by some instability. This is the first step toward a more detailed understanding. Some work to date has produced scaling data or other evidence that begins to take the next step of observing the dynamics that may be involved in wave saturation.³⁰⁻³³ (Two

related areas of active research, which we do not attempt to review further here, are the study of relativistic Langmuir waves driven in lower-density plasmas for the purpose of electron acceleration and the study of Langmuir turbulence driven near the critical layer in the ionosphere.)

The (upgraded) Omega laser should prove to be a uniquely capable tool for the study of waves, parametric interactions, and turbulence in plasmas. Because of the large amount of available UV energy on target, Omega produces plasmas which are larger and/or hotter than those studied in past experiments. In addition, Omega produces plasmas whose variations in time and space are quite slow, in the sense that all parameters change slowly on the time and spatial scales of the oscillations of the waves of interest. Further, it offers the real potential to drive and probe these waves using some of Omega's many beams.

Work to deliberately produce long-scalelength, laser-produced plasmas dates back less than two decades, as reviewed in reference ⁷. Such efforts have long been limited by a lack of laser energy. In laser facilities having much less energy than Omega, significant compromises must be made in producing plasmas for the study of waves and turbulence. In general, the plasmas produced will be in some combination smaller, colder, and more rapidly varying than those produced on Omega. For example, one can produce a plasma using a line focus which varies slowly in space along the direction of the line but more rapidly in other directions. It is desirable to have larger plasmas so that spatial variations do not confuse the determination of the experimental conditions, to have warmer plasmas so that the plasma is less collisional as are high gain laser-fusion targets and collisionless plasma³⁴ environments, and to have more-slowly-varying plasmas so that time variations do not impact the physics.³⁵

Only the Nova laser has enough raw energy to produce conditions close to those which can be achieved on Omega. Experiments on Nova have

concentrated on the production of large, fairly uniform plasmas using gas bags³⁶ and gas-filled hohlraums.³⁷ Complications are introduced by the bag material and by complicated flows within the hohlraum, but such plasmas are important because they are relevant to indirect-drive laser fusion. In contrast, the experiments on Omega will concentrate on producing very-well-understood, expanding plasmas that are more relevant to direct drive. The Nova experiments face a serious challenge in diagnosing the plasma, because of the limited number of laser beams and the lack of a probe beam. Omega should prove to be a very effective facility both for the detailed characterization of plasma and for the detailed examination of waves and turbulence.

With regard to the saturation of Langmuir waves driven for many cycles, it is now clear that Langmuir turbulence is likely to control the long-term behavior. Depending upon how strongly the waves are driven, an initial transient may reach the wavebreaking amplitude or some other saturation limit. In the long run, however, the much lower thresholds of Langmuir decay and Langmuir collapse imply that these are likely to be the controlling factor. It now appears from modeling³⁸⁻⁴⁰ that the Langmuir turbulence in general involves a competition between decay cascades, in which the Langmuir waves progressively decay into acoustic waves and lower-frequency Langmuir waves, and Langmuir collapse,⁴¹ in which the Langmuir-wave energy becomes concentrated into localized cavities which collapse and in the end give the energy to electrons. The decay cascade consists of a sequence of backscattering events, in which each successive Langmuir wave is going approximately the opposite direction of its predecessor and is lower in frequency by about $2c_s k$, where k is the wavenumber of the Langmuir wave and c_s is the acoustic phase velocity. The reduction in the k of the Langmuir wave in each decay step, Δk , is approximately given by $\Delta k/k = (2/3)(c_s/v_{th})(1/k\lambda_D) \sim 10\%$, where λ_D is the Debye

length and the electron thermal velocity is $v_{th} = \sqrt{T_e / m}$, where m and T_e are the electron mass and temperature, respectively.

The competition between decay and collapse can be described in terms of $k\lambda_D$. In general, a transition is anticipated from Langmuir collapse at small $k\lambda_D$ (~ 0.1) to decay cascades at large $k\lambda_D$ (~ 0.25). There is some evidence in support of this picture from ionospheric experiments.^{42,43} One expects to see a decay cascade in the cascade regime and no cascade but a broadening of the Langmuir wave spectrum (and a zero-frequency peak in the acoustic wave spectrum) in the collapse regime. However, the simulations are limited and the ionospheric experiments can only observe a small region in k space (which does not include the wavevectors where the turbulence is most strongly driven).^{44,45} Furthermore, there is as yet no simple criterion to describe the transition between the cascade and collapse regimes. Moreover, it appears that collisions may affect the transition.⁴⁰ This project prepared for experiments that can directly examine the important regions of k space, can explore the transition between the two regimes, and can examine the dependences on pump strength and collisionality.

With regard to the saturation of Langmuir waves driven by stimulated Raman scattering, there is an important regime in which the driven Langmuir waves grow until they are unstable to Langmuir Decay and then saturate by driving Langmuir turbulence. Modeling and simulation results have identified this regime and provide some scaling relations for SRS reflectivity.⁴⁶⁻⁴⁹ Experiments which examine the scaling of the SRS light have found^{50,51} a dependence upon the ion wave damping. These support the basic picture of the saturation behavior just described, by demonstrating that the coupling of Langmuir waves and ion waves is involved in the saturation. However, the experiments have not confirmed the precise scaling relations predicted by the models. The models, however, were based upon examinations of the Langmuir

turbulence at a single value of $k\lambda_D$. Current modeling⁵² is finding, as one expects, that the behavior of the turbulence varies with $k\lambda_D$. In addition, it has been discovered that the decay of the Langmuir wave into an electromagnetic wave and an acoustic wave may at times play a role,^{53,50} although this process is usually unimportant because of its low growth rate.

The dynamics of Langmuir wave saturation also plays a role in the saturation of both the Parametric (or Ion Acoustic) Decay Instability (PDI) near the critical density and the Two-Plasmon Decay (TPD) instability near the quarter-critical density. Observations of the spectrum of second-harmonic emission, attributed to PDI, provided indirect evidence of decay cascades in laser plasmas.⁵⁴ In both PDI and TPD, the situation is more complicated than it is for SRS because the instabilities inherently drive a broad spectrum of Langmuir waves (and ion waves, in the case of PDI). The understanding of Langmuir-wave dynamics that would follow from the experiments we prepared for would provide key pieces of the puzzle with regard to how these more complicated systems saturate.

It is therefore worthwhile, from the point of view of Langmuir turbulence in general and SRS in particular, to directly examine the saturation of Langmuir waves in this regime. The project prepared us to conduct experiments to do just this. In two precursor experiments, carried out as Ph.D. thesis research by a prior student of the Principal Investigator, the Langmuir wave driven by SRS^{24,53} was identified and the oppositely directed Langmuir wave produced by the first decay instability have been observed.^{53,33,56} Both the SRS Langmuir wave and the decay Langmuir wave have since been studied further and in more detail in some very elegant experiments in France.^{55,57} Neither the Langmuir decay cascade nor Langmuir collapse have been directly observed in a laser plasma.

To come to a complete understanding of the dynamics of saturation requires several further observations. One should: (1) Observe the decay cascade regime including the scaling of the wave amplitudes with pump strength so as to test the scaling models. (2) Observe the collapse regime including again the scaling of the wave amplitudes with pump strength. (3) Observe the transition between these regimes. (4) Seek evidence of collapse in the collapse regime. (5) Observe the angular distribution of the turbulence as a test of the 2D model predictions. (6) Measure the spatial coherence of the saturated waves, with the aim of understanding the level and spectrum of the Raman light they produce. (7) Study the structure of the driven acoustic turbulence, which may provide additional evidence of collapse and also may interact with stimulated Brillouin scattering. (In the course of such experiments one should make further measurements that have the potential to detect any beam-driven plasma waves that may be present.⁵⁸)

Characterization Experiments

We have completed a basic sequence of plasma characterization experiments on Omega, so that a standard, long-scale-length plasma now exists which can be used for the proposed experiments. The target is a CH disk 1.2 mm in diameter and 18 μm thick. It is flash-coated with a thin layer of aluminum for structural stability and may include a tracer layer for x-ray diagnostic measurements. The target is oriented so that it is initially perpendicular to two of the Omega beams (25 and 46), and the irradiation is designed so that these beams are incident on the target along the axis of symmetry. Either can be used to drive instabilities. All the laser beams use 1 ns square pulses. A total of 18 "primary" beams, in two groups which are staggered by 1 ns in time, is used to explode the target and produce the plasma. Up to 20

"secondary" beams, delayed 2 ns from the first primary beams, then heat the plasma and drive further expansion. The pump beams and any probe beams can be independently timed to access any chosen density. We also found that by using Distributed Phase Plates (DPP's) for beam smoothing on all these beams, we can drive SRS under conditions for which there is no evidence of stimulated Brillouin scattering (SBS). This is ideal for the study of Langmuir wave saturation proposed here. It is desirable to minimize SBS, since SRS and SBS sometimes appear to compete.⁶⁵

Measurements of electron temperature, T_e , with x-ray spectroscopy, and of maximum density, from the stimulated Raman scattering spectrum, have confirmed the calculated evolution of the target shown in Figure 1. The maximum density on axis drops to about 20% n_c , where n_c is the critical density, by 2 ns and then is held between 10% n_c and 20% n_c by the inflow of matter from larger radii. The heating by the secondary beams then drives T_e above 3 keV.

Figure 1. Simulations of the central density and temperature in the target, showing a period from 1.8 ns to 4 ns suitable for the studies proposed here.

When they end, the plasma cools more quickly than the density drops. Lower-temperature conditions can be accessed two ways -- by waiting longer in the standard plasma or by using fewer secondary beams to obtain less heating. After 3 ns, the FWHM of the density profile is above 1 mm and the plasma is quasi-spherical. It is a good environment for experiments which require long scalelengths of the plasma parameters. A publication reporting these characterization experiments is in preparation.

Software Development

We have developed software tools to cope with the complexity of carrying out laser scattering in an environment having 60 laser beams. This is necessary to rapidly assess both opportunities for experiments and sources of unwanted interfering signals. During experiments using the original, 24-beam Omega system, we found the identification of possible scattering geometries to be a limiting problem in understanding the data, guiding the experiment, and identifying new options in response to difficulties. We now have in hand the required tools for the design of Thomson scattering experiments on Omega.

Specifically, the software takes as input the plasma properties and pump beam location and uses an initial subroutine to define the properties of the plasma waves or ion waves one desires to detect. The core of the calculation determines which of the 60 Omega beams can act as probe beams (intended or otherwise) to produce either upscattered or downscattered signals to any specific detector location. This calculation, which was far from trivial to develop and implement, includes the finite f /number of the Omega beams and determines whether additional angular spreading of the detected wave can allow detection. The calculation can include refraction when appropriate. This core calculation can be readily implemented for a variety of purposes. In different

implementations of the code to date, it has been used to find probe beam and detector pairs to detect specific driven waves or to find the most feasible probe beam to detect a given wave with a specified detector location. This code is written in IDL. A paper describing the software has been submitted for publication⁶⁴ and a paper discussing the design of experiments for Omega using the software is in preparation.

Instrumentation Development

Second, we have developed instrumentation to detect scattered signals from experiments on Omega. The Michigan Optical Spectroscopy System is a self-contained, portable instrument which includes alignment hardware, a timing system, optical signal processing, a high quality spectrometer, a streak camera, a digital data recording system, controls, and data storage. Using the Michigan streak camera, it is capable of detecting Thomson downscattering signals from Omega, as discussed further below. We took this instrument to the Trident laser

facility at Los Alamos in order to debug, test, and improve it by detecting Thomson scattered signals from ion acoustic waves. This was successful, producing data such as that shown in Figure 2.

Figure 2. Thomson scattering from ion waves obtained with the instrumentation system. The two widely spread features at 2.7 ns are ion waves driven by a pump beam.

Design of Thomson scattering experiments.

We also completed the design of an experiment to detect a Langmuir decay cascade using these tools. Such an experiment is described in the following excerpt from an experiment proposal.

The experiments have three components discussed in the following:

- (a) Create a standard long scalelength plasma
- (b) Drive Langmuir waves using SRS
- (c) Detect the decay cascade by Thomson scattering

Create a standard long scalelength plasma: Figure 3 shows how the beams will be used in the proposed experiment. The plasma will be produced using the standard long scalelength configuration which has already been tested and is discussed above. The beams labeled "P" are the primary beams which explode the target and produce the plasma. The beams labeled "S" are the secondary beams which then further heat the underdense target. The beam labeled "pump" is normally incident to the original target, and is either beam 25 (Fig. 3a) or beam 46 (Fig. 3b). The near-backward and near-forward SRS driven by these pumps will be detected through ports H4 and H16. This has been accomplished; an example of near-backward data is shown in Figure 4.

Drive Langmuir waves using SRS: In SRS, the Langmuir wave properties are determined by the electron density and the electron temperature. The SRS matching conditions imply that the resonant k increases from $k_{3\omega_0}$ to $2k_{3\omega_0}$ as the density decreases from $n_c/4$ to low density. (Here $k_{3\omega_0}$ is the wavenumber of the pump laser at the interaction location.) However, this full range is not available, because of Landau damping. Fig. 5 shows the dependence of $k\lambda_D$ upon density, for two temperatures. For $T_e = 1$ keV and $T_e = 4$ keV the minimum value of $k\lambda_D$ approaches 0.1 and 0.2, respectively, for SRS driven by a

(a)

(b)

Figure 3. Projections of the chamber showing the beams used for proposed experiments. The plasma is produced by the primary beams, labeled "P". It is then heated by the secondary beams, labeled "S". Either (a) beam 25 or (b) beam 46, which opposes 25, can be used as a pump, labeled "pump". The SRS light will be detected through ports H4 and H16. We will detect all the cascade steps through the port labeled "Detector", using the light-shaded probe beams labeled "DS". The beam labeled "P/DS-1" in (a) can be used to scatter from the first decay Langmuir wave into port H4. These drawings show the required combinations of pump and probes to detect the cascades by downscattering. Other probes have been identified which could be used for upscattering.

Figure 4. SRS data from the characterization experiments at a pump intensity of 10^{15} W/cm^2 .

$3\omega_0$ pump, where ω_0 is the frequency of the $1.053 \mu\text{m}$ glass laser. One should work at densities below $0.2 n_c$, where $k \sim 1.1 \omega_0/c$ and $\omega \sim 1.4 \omega_0$, to avoid interference from the two-plasmon decay instability. We plan to work with maximum densities of $0.1 n_c$ to $0.15 n_c$ in these experiments.

We will adjust the pump intensity if necessary to control the spectral and angular width of SRS. Figure 4 was obtained with a fairly intense pump (10^{15} W/cm^2), timed 2 ns after the initial primary beams. The signals near 700 nm are produced at a density of

Figure 5. The dependence of $k\lambda_D$ upon density is shown for SRS driven by $3\omega_0$ light at the two electron temperatures indicated.

$n_c/4$, beginning when the primary beams fire. A broad SRS spectrum extends to lower density while the pump beam and the secondary beams are on. The SRS spectrum can be reduced in width either by reducing the pump intensity⁶⁷ or by delaying the pump to let the plasma density drop. We will run the pump 0.5 to 1 ns later than the secondary beams in order to access a density

near $0.15 n_c$ and $T_e \sim 2$ keV. In the course of the experiments, we will vary the pump beam intensity to observe how the cascade Langmuir waves vary in response. Based on past measurements, the SRS signals will be strongest near backscatter.^{66,7} The oblique and forward scattering must be kept small enough that it does not interfere with the Thomson downscatter measurements. This may impose an upper limit on the pump intensity.

Detect the decay cascade by Thomson scattering: We will detect the Langmuir waves which result from the decay cascade by using a distinct Omega beam as a probe for each cascade step. Figure 6 shows a schematic of the irradiation geometry (a) and the direction and magnitudes of the resulting cascade of Langmuir waves (b). Fig. 6(c) shows a schematic of the detection of one of the cascade steps by a probe beam. In Fig. 3, the probe beams are indicated by "DS-x", with x being the number of the cascade step that each probe beam can detect by scattering a signal to the detector. As the plasma wavenumber decreases with subsequent cascade steps, the required scattering geometry moves from near backscatter to near sidescatter. We can detect the rearward-going (odd-number) cascade steps using beam 46 as the pump and the even-number cascade steps using beam 25. Our calculations showed that cascade step 4 probably cannot be detected in this geometry, so no probe is shown for it. As shown in Fig. 3a, we also can detect the first cascade step using

Table 1. Required angular spreading for detection

Pump	Cascade step	Probe beam	Required spreading beyond 10°
25	1	17	none
25	2	50	none
25	6	24	60°
46	1	45	29°
46	3	69	2°
46	5	67	20°

the existing Raman scattering diagnostic on port H4, by firing the beam labeled "P/DS-1" as a probe beam when 25 is used as the pump.

Detection of the cascade steps requires minimal angular spreading in most cases, because of the many

possible probe beams available on Omega. In general, finding a match for Thomson scattering requires that the electrostatic waves be spread some amount in angle from their initial, central direction. The $f/6$ lens of the pump provides at least 10° of spreading in the initial driven Langmuir wave. Because the growth rate for Langmuir decay is only weakly peaked in angle, each subsequent decay step will be significantly more spread. Simulations indicate that the Langmuir waves become nearly isotropic in 3 to 4 steps.⁵² Table 1 shows the spreading required (beyond the 10° introduced by the pump) to detect the cascade steps in this experiment. As discussed above, we have two ways to detect the first cascade step. One requires no additional spreading and the other requires about 30° , so this will provide some indication of the angular extent of this step. The other steps should readily be spread in angle by the amount required.

Figure 6. A schematic of a) the irradiation, b) the cascade, and c) the diagnostic method.

While we can detect the steps in the cascade because each step requires a different probe beam, it would also be useful to be able to detect several steps simultaneously, which would provide direct evidence that the cascade was all present at once. This should be feasible, assuming that we can mask the probe beams to restrict their angular extent. For $0.15 n_c$ and 2 keV, we find that the spectrum is shifted about 5 nm between even (or odd) steps. The SRS light spectrum, by comparison, is much broader (150 nm in Fig. 5). The Thomson scattering spectrum produced by any given probe beam will be narrower, because detection is only possible for waves that are resonant both for their cascade interaction and for Thomson scattering. The maximum width is about 50 nm, but it can be less if the probe direction is not optimal. By masking the probe beam from

$f/6$ to more than $f/60$, we can both separate the spectra from distinct cascade steps and reduce the probe intensity to the required level, as discussed next. (From past experience, we expect masking the beams to be feasible, although this clearly requires input from the Omega facility. We stress here that this is an optional and not a required feature of the proposed project.)

The signal strength will be large enough to be detected, based on previous experience involving the P.I. and some of the co-investigators. Thomson scattering can in principle be designed to scatter the probe light either up or down in frequency. We are proposing to do Thomson downscatter, as we have all the equipment in hand for this. This requires that the SRS from the pump be sufficiently restricted in angle (see the discussion of driving Langmuir waves using SRS). It also requires that the probe intensity be kept below the SRS threshold, as a probe which drove SRS would both produce spurious signals and interfere with the conditions in the plasma one is trying to observe. In addition, if we allow only 10% of the nominal probe beam energy to reach the target, either by using an $f/60$ mask or by reducing the actual energy, we will (a) keep the probe beam intensity below the SRS threshold due to damping (at 2 keV) and (b) approximately duplicate the conditions under which a less sensitive instrumentation system detected Thomson scattering from plasma waves in a previous experiment.²⁵ (As independent confirmation that the experiment is feasible, researchers at LLNL have detected unstimulated plasma waves, weaker than those we plan to measure here, by Thomson downscattering on Nova.⁶⁸)

Issues of polarization and refraction have also been considered. The strength of the Thomson scattering signal depends on the polarization of the probe relative to the detector direction. It is strongest when the angle between the scattering plane and the probe electric field direction is 90° . The dependence is gradual, with the scattered signal dropping less than an order magnitude so

long as the angle is above 20° . Even when the angle is 0° (the worst case), finite f number guarantees some signal. During our preparations for the experiment, we will determine the polarization of each probe beam and adjust our plans if necessary.

Refraction will not pose a significant problem. We will use very large scattering angles and work at densities below $n_c/4$ for the waves involved. In this case, refraction contributes to the experimental uncertainties but has no qualitative consequences. In particular, it may alter the wavevector directions by a few degrees. Refractive effects can be completely avoided if the Thomson scattering interactions occur in the center of a spherical plasma. The maximum refraction would occur in a planar plasma. However, over the $500\text{ }\mu\text{m}$ size of this plasma (which has a 1 mm scale length), the maximum refraction of light scattered at its quarter-critical density in a planar plasma would be $< 7^\circ$. The actual scattering in this experiment will occur near the center of a quasi-spherical plasma, making refraction smaller than this.

Conclusion

In summary, we have completed a project in which we prepared to create a standard long scalelength plasma by proven techniques and to drive Langmuir waves using SRS. We prepared the hardware and software needed to allow us to attempt the first direct observations of a Langmuir decay cascade by Thomson scattering. These measurements would provide key evidence regarding the nature of Langmuir wave saturation in plasmas. This project is uniquely well-suited for the Omega facility.

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