UCRL--15663

DE85 012970

MICROWAVE MODELING OF LASER PLASMA INTERACTIONS

FINAL REPORT

AUGUST 1983

Subcontract No. 1072201

TRW SN 36084

Prepared for:

Lawrence Livermore National Laboratory

TRW

DEFENSE AND SPACE SYSTEMS GROUP
ONE SPACE PARK • REDONDO BEACH • CALIFORNIA 90278

CONTENTS

SUMMARY	1
EXPERIMENT DESIGN	2
EXPERIMENT APPARATUS.	4
TARGET PLASMA	
MICROWAVE POWER AND TRANSMISSION SYSTEM	
THEORETICAL CONSIDERATIONS ON . . .	10
THE INTERACTION BETWEEN SBS AND SELF-FOCUSING	
APPENDIX-OBSERVATIONS OF SBS . . .	17
INITIATED BY PONDEROMOTIVE FORCE FLUCTUATIONS	

SUMMARY

For large laser fusion targets and nanosecond pulse lengths, stimulated Brillouin scattering (SBS) and self-focusing are expected to be significant problems. The goal of the contractual effort was to examine certain aspects of these physical phenomena in a wavelength regime ($\lambda \sim 5\text{cm}$) more amenable to detailed diagnostics than that characteristic of laser fusion ($\lambda \sim 1\text{ micron}$). The effort was to include the design, fabrication and operation of a suitable experimental apparatus. In addition, collaboration with Dr. Neville Luhmann and his associates at UCLA and with Dr. Curt Randall of LLNL, on analysis and modelling of the UCLA experiments was continued. Design and fabrication of the TRW experiment is described under "Experiment Design" and "Experimental Apparatus". The design goals for the key elements of the experimental apparatus were met, but final integration and operation of the experiment was not accomplished. Some theoretical considerations on the interaction between Stimulated Brillouin Scattering and Self-Focusing are also presented.

EXPERIMENT DESIGN

For large laser fusion targets and nanosecond pulse lengths, stimulated Brillouin scattering (SBS) and self-focusing are expected to be significant problems. The goal of this contractual effort was to examine certain aspects of these phenomena in a wavelength regime ($\lambda \sim 5\text{cm}$) more amenable to detailed diagnostics than that characteristic of laser fusion ($\lambda \sim 1\text{ micron}$). The experiments were designed cooperatively with Professor Neville Luhmann of UCLA. Utilizing the large TRW QUIPS plasma facility, the proposed experiments address SBS in a parameter regime not accessible in the UCLA experiments, and attempt to create conditions under which self-focusing may occur. In addition, the design attempts to minimize certain effects which complicate interpretation of the UCLA experiments, i.e., electron heating by inverse Bremsstrahlung and the effects of chamber reflectivity.

As has generally been the case in microwave plasma interaction experiments, the accessible parameter range was severely limited by the availability of microwave sources and by the technology of laboratory plasma production. In particular, values of scaled interaction length (L/λ_0) and scaled interaction time ($\omega_0 t$) as large as those characteristic of laser-plasma interactions can rarely be attained. The maximum scale length obtainable was limited by QUIPS chamber dimensions (200cm diameter x 400cm length) to about 350cm, while the wavelength regime in which sufficient microwave power was available extended from 1 to 10cm. On the short wavelength side, choice of λ_0 was constrained by plasma production considerations. We estimated that the plasma production power required to achieve quarter critical density throughout the volume of the QUIPS chamber would be approximately $10^6/\lambda_0^2$ watts. As the cost of an entire new plasma production system was too high to be borne by this contract, it was decided to utilize a TRW owned 100kW peak power pulsed rf source for plasma production. Thus, the minimum wavelength consistent with plasma production considerations was 3.2cm. After evaluating the available microwave tubes, an electromagnetic pump wavelength of 5cm was chosen. At this wavelength, a 1 Megawatt magnetron tube was readily available from surplus tube dealers, and eventual upgrade to a 5 Megawatt Klystron was possible if results warranted this and funding was available. The maximum pulse width obtainable from a microwave tube was

a matter of some uncertainty, and is discussed in more detail under Microwave Power and Transmission System. As a reasonable operating goal, a pulse width of 30 microseconds was chosen, in order to give a least one ion sound transit time across the microwave beam.

The microwave interaction experiments were to be performed in the afterglow of an rf discharge, using plasma production techniques developed at TRW. In order to reduce the effects of inverse Brehmstrahlung heating of electrons, the design required production of a uniform plasma throughout the chamber volume. In this case, the plasma volume would be approximately 10 times the microwave beam - plasma interaction volume, providing a large heat sink for the absorbed energy. Development of the necessary techniques for production of a suitable plasma is described under the heading 'Target Plasma'.

EXPERIMENTAL APPARATUS

The basic experimental facility for the SBS and Self-focusing experiment was the TRW QUIPS Facility, a two meter diameter, four meter long unmagnetized plasma device. The facility was originally developed for Ionospheric Plasma simulation, and was long utilized for studies of critical surface phenomenae in microwave plasma interactions (see for example, Self-Generated Magnetic Fields in the Microwave Plasma Resonant Interaction, W. F. DiVergilio, A. Y. Wong, H. C. Kim, and Y. C. Lee, Phys. Rev. Lett. 38, 1558 (1977)).

For the proposed experiments, significant modification of the QUIPS facility was necessary. Modifications included a large upgrade in the target plasma generation capability, and the design and fabrication of a long pulse, high power microwave system. The upgraded facility is shown schematically in Figure 1, and the new target plasma and microwave systems are described in the following pages.

FIG. 1 EXPERIMENTAL CONFIGURATION IN QUIPS FOR SBS AND SELF-FOCUSING

TARGET PLASMA

The proposed SBS and filamentation experiments required an extremely reproducible, spatially uniform plasma with electron density variable up to quarter critical density, or 10^{11} cm^{-3} for the chosen microwave frequency of 5.96GHz. The required target plasma characteristics were obtained utilizing a Radio Frequency Induction technique of plasma production, developed at TRW and previously applied in various critical surface phenomena experiments. In this technique, electrons are accelerated by the electric fields of a current carrying antenna immersed in the plasma. The antenna, which is dielectrically coated to reduce electrostatic coupling to the plasma, is resonated at the desired operating frequency (usually between .2 and 2MHz) by a network of rf capacitors, and driven by a class C amplifier or oscillator.

In past critical surface phenomena experiments, considerable operating data has been accumulated on rfi production of a non-uniform Argon plasma with peak density of $2 \times 10^{11} \text{ cm}^{-3}$. The antenna for this plasma consisted of a single 130cm diameter loop of insulated 3/8" copper tubing, located approximately 50cm from one end of the 400cm long chamber, and driven by a 10kWatt rf amplifier. Scaling from this data, it was estimated that approximately 40kW of rf power would be necessary to achieve a density of 10^{11} cm^{-3} over the entire chamber with Helium gas fill. A TRW-owned 100kWatt peak power pulsed (1msec pulse length, 10pps) rf oscillator was installed at the Quips facility and matched to the 130cm diameter antenna already in place. Following successful operation of this system with Helium an antenna system suitable for production of a uniform plasma was designed, fabricated and installed in the Quips chamber. The antenna system consisted of two rectangular loops (90 cm x 300 cm) of 1/2" copper tubing oriented with the long dimension parallel to the vacuum chamber axis. The two planes defined by the antenna loops were separated by 1.5 meters, leaving the entire experimental plasma volume free from obstruction. The loops were connected in parallel and formed the inductive element in a 400 kHz tank circuit. A radially and axially uniform Helium plasma of density $n_e > 10^{11} \text{ cm}^{-3}$ was produced with an antenna current of 100 amperes.

MICROWAVE POWER AND TRANSMISSION SYSTEM

The microwave power and transmission system for the SBS and Self-focusing experiments consists of four major subsystems: the pulse modulator, the microwave tube and associated hardware, the transmission line and antenna, and the microwave beam dump. As discussed under Experiment Design, the Varian SFD313 coaxial magnetron was chosen as the microwave tube. This tube was originally a military radar tube and is now readily available on the surplus market. The SFD313 is rated at a minimum power output of 1 Megawatt at 5.9GHz, at a nominal pulse width of 5 microseconds. The desired pulse width for our experiments was 30 microseconds, considerably longer than the nominal tube rating. However, previous experiments at TRW, UCLA and MIT have demonstrated that the nominal pulse width rating of a typical magnetron can be exceeded by a large margin through careful conditioning of the tube. A factor of five increase in pulse width is not uncommon at full peak power rating, and longer pulse widths may be achieved at reduced output powers. In order to achieve long pulse operation, it was necessary to design a variable pulse width modulator for tube conditioning.

The pulse modulator for the SFD313 magnetron is shown schematically as designed and fabricated in Figure 2. The pulse forming network was designed and fabricated under this contract, utilizing available .033 microfarad 30kV pulse capacitors. At full charging voltage, the PFN produced a 4.5Megawatt, 30 microsecond pulse, at a maximum repetition rate of 10pps, with a risetime of 1.5 microsecond. The pulse width could be reduced in 3microsecond increments, to a minimum of 6 microseconds, for magnetron conditioning. The high voltage power supply and switching system was a modification of a TRW-owned system, built previously under an internal research and development program. The pulse transformer, which matched the Pulse Forming Network impedance to the magnetron impedance, was a surplus military unit, obtained from Professor N. Luhmann of UCLA, and rebuilt to match the SFD313 operating characteristics.

Most of the key microwave transmission line components, e. g., circulator (for isolation of magnetron tube from load) and directional couplers (for measurement of incident and reflected power), were military surplus units, supplied by Professor Luhmann, leaving the antenna and antenna feed

systems to be designed and fabricated. Several antenna systems were considered, including a parabolic reflecting antenna, metal plate lens system, and dielectric lens system. Because of the relatively small microwave beam diameter desired ($\leq 10\lambda_0$), a refracting lens system would provide superior side lobe and matching performance. A metal plate lens was chosen over dielectric for ease of vacuum interface and design work was initiated. For initial system checkout and operation, it was decided to use the 125cm diameter parabolic antenna previously used for critical surface phenomena experiments, and a microwave feed system for this antenna was constructed.

The development of an efficient microwave beam dump was considered an important element of the proposed experimental program. Experiments at UCLA have shown that even a small amount ($\sim 1\%$) of chamber reflectivity strongly effects the behavior of SBS (see Appendix), and presumably self-focusing. The design of an effective high power microwave beam dump compatible with high vacuum operation was a particularly challenging technical problem. Tests were conducted with steel wool as an absorber, utilizing the parabolic antenna inside the QUIPS chamber, and performance was found to be unacceptable. The commercially available microwave absorbers were surveyed and most were found to be clearly incompatible with high vacuum operation. Several candidate commercial absorbers were identified and sample quantities were procured for absorption and vacuum compatibility tests. Silicon rubber based materials were found to have acceptable outgassing rates under the estimated heat loads due to plasma production and microwave irradiation. Design of a beam dump utilizing a ferrite-loaded, silicon based absorber material was initiated.

FIGURE 2. PULSE MODULATOR FOR SFD313 MAGNETRON

THEORETICAL CONSIDERATIONS ON THE INTERACTION BETWEEN SBS AND SELF-FOCUSING

The proposed experimental program included studies of the interaction between SBS and Self-focusing. Pursuant to this task, we conducted theoretical investigations of the interaction of SBS and self-focusing and performed numerical calculations to more closely define optimum operating parameters for the TRW experiments.

Consider a laser fusion experiment with long pulse lengths, relevant to Nova size targets. At first, the electron temperature is much higher than the ion temperature, and SBS is in the weakly damped regime. In this regime, it has a much larger growth rate than self-focusing. However, energy transfer to the ions will heat them up to a temperature $T_i \approx ZT_e$ (Z is the ion charge state) on a time scale of tens of picoseconds. Now SBS is in the heavily (Landau-damped) regime, and its growth length is comparable to self-focusing.

The growth of both instabilities are proportional to local light intensity. As the beam shrinks due to self-focusing, the SBS level increases, thus increasing the local intensity since the incident and reflected waves add. This in turn increases the growth rate of self-focusing. This picture leads us to expect two things: the self-focusing length is decreased by about a factor of 2, and after the first focus the beam is drastically depleted. This has important consequences for laser fusion experiments since it suggests that there is a maximum propagation distance for laser light, given by the distance to first focus.

In order to treat this problem, we begin with the wave equation

$$\frac{1}{c^2} \frac{\partial^2}{\partial t^2} E - \nabla^2 E + \frac{\omega_p^2}{c^2} E = 0 \quad (1)$$

Let

$$\frac{\partial^2}{\partial t^2} = -\omega_0^2$$

$$\nabla^2 = -k^2 + ik \frac{\partial}{\partial z} + \nabla_{\perp}^2$$

and $n = \bar{n} + \tilde{n}$, where $\tilde{n}$ is the fluctuating part of the total density.

We obtain

$$+ ik \frac{\partial}{\partial z} E_{\pm} + \nabla_{\perp}^2 E_{\pm} + (k^2 - \omega_0^2 + \omega_{p0}^2) E_{\pm} + \omega_{p0}^2 (n/n_0 - 1) E_{\pm} \quad (2)$$

$$+ \omega_{p0}^2 \tilde{n}_{\pm} E_{\pm} = 0$$

where E_{+} is the incident wave and E_{-} is the reflected wave. Solving the ion density equation, we find

$$n/n_0 = \exp \left[\frac{-e^2(|E_{+}|^2 + |E_{-}|^2)}{4\pi\omega_0^2 (\tau_e + \tau_i/z)} \right]$$

and the heavily damped ion fluctuations are

$$n_{+} = i n \frac{2Ze^2 k^2}{m\omega_0^2 \nu \omega_s} E_{+}^* E_{-}$$

$$n_{-} = -i n \frac{2Ze^2 k^2}{m\omega_0^2 \nu \omega_s} E_{+} E_{-}^*$$

Putting this all together, we have the coupled equations for the normalized amplitudes $a_0 = E_{+}/E_0$, $a_s = E_{-}/E_0$:

$$\frac{i}{k_0} \frac{\partial a_0}{\partial z} + \frac{1}{k_0^2} \nabla_{\perp}^2 a_0 - \left[\frac{\omega_0^2}{k_0^2 c^2} + \frac{\omega_{p0}^2}{k_0^2 c^2} \left(1 - e^{-B(|a_0|^2 + |a_s|^2)} \right) \right] a_0$$

$$= -i \frac{\gamma_0^2}{\omega k_0 c} a_0 |a_s^2| e^{-\beta(|a_0^2| + |a_s^2|)} \quad (3)$$

$$= \frac{1}{k_0} \frac{\partial a_s}{\partial z} + \frac{1}{k_0^2} \nabla_{\perp}^2 a_s - \left[\frac{r^2}{k_0^2 c^2} + \frac{\omega_{po}^2}{k_0^2 c^2} (1 - e^{-\beta(|a_0^2| + |a_s^2|)}) \right] a_s$$

$$= i \frac{\gamma_0^2}{\gamma k_0 c} a_s |a_0^2| e^{-\beta(|a_0^2| + |a_s^2|)} \quad (4)$$

where

$$r^2 = k_0^2 c^2 - \omega_0^2 - \omega_{po}^2$$

$$\beta = v_0^2 / v_e^2$$

and γ_0 is the maximum SBS growth rate. If the right sides are set to zero, the usual self-focusing equations result, with the local field energy set to the sum of the incident and scattered waves. If the bracketed terms are set to zero, we have the SBS equations, with a reduction in growth rate due to density depression.

In general, these equations are difficult to solve. However, we can make some progress if we take the usual SBS relation:

$$|a_s^2| = |a_0^2| - T \quad (5)$$

where T is the total transmissivity. Actually, if Equations 40 and 41 are multiplied by a_0^* and a_s^* respectively and added, we find that

$$\frac{\partial}{\partial \xi} [|a_0^2| - |a_s^2|] = 2 \left[\frac{r^2}{k_0^2 c^2} + \frac{\omega_{po}^2}{k_0^2 c^2} (1 - e^{-\beta(|a_0^2| + |a_s^2|)}) \right]$$

$$\text{Im} \left(a_0^* \frac{\partial^2}{\partial \eta^2} a_0 + a_s^* \frac{\partial^2}{\partial \eta^2} a_s \right) \quad (6)$$

where $\xi = kx$ and $\nabla_{\perp}^2 / k_0^2 = \partial^2 / \partial \eta^2$. We go over to the slab geometry representation for simplicity, where η represents the perpendicular component.

We can use Equation 42, which is valid if the right side of Equation 43 is small, and then check the validity a posteriori.

Substituting (42) into (40); and making the small v_0^2/v_e^2 approximation, we have

$$\begin{aligned} i \frac{\partial a_0}{\partial \xi} + \frac{\partial^2 a_0}{\partial \eta^2} &= \left[\frac{r^2}{k_0^2 c^2} + \frac{\omega_{p0}^2}{k_0^2 c^2} \beta (2|a_0|^2 - T) \right] a_0 \\ &= -i \frac{\gamma_0^2}{v r_0 c} a_0 (|a_0|^2 - T) \end{aligned} \quad (7)$$

Define

$$\frac{r^2}{k_0^2 c^2} \equiv \Delta^2$$

$$\frac{\omega_{p0}^2}{k_0^2 c^2} \beta \equiv B^2$$

$$\frac{\gamma_0^2}{v k_0 c} \equiv k_0$$

Equation 44 may be written

$$i \frac{\partial a_0}{\partial \xi} + \frac{\partial^2 a_0}{\partial \eta^2} = \left[\Delta^2 - B^2(T - 1k_0) \right] a_0 - (2B^2 - 1k_0) |a_0|^2 a_0 = 0 \quad (8)$$

Note that if $T = 0$, the quantity B^2 , which is a measure of the self-focusing strength, is multiplied by a factor of 2. Now let

$$a_0 = \alpha(\eta) e^{ik\xi},$$

giving

$$\alpha'' = [\Delta^2 - 1k - B^2T + 1k_0T] \alpha - (2B^2 - 1k_0) \alpha^3 = 0 \quad (9)$$

multiply by α' and integrate once:

$$\frac{\alpha'^2}{2} - [\Delta^2 - ik - B^2 T + ik_0 T] \frac{\alpha^2}{2} - (2B^2 - ik_0) \frac{\alpha^4}{4} = C \quad (10)$$

To evaluate the constant of integration, note that at $\eta = \infty$, $\alpha' = 0$, $\alpha \rightarrow 0$. Therefore $C = 0$. Now at $\eta = 0$, $\alpha' = 0$, $\alpha = \alpha_0$, giving

$$\Delta^2 - ik - B^2 T + ik_0 T = - (2B^2 - ik_0) \frac{\alpha_0^2}{2} \quad (11)$$

Equating real and imaginary parts

$$\Delta^2 = - B^2 (\alpha_0^2 - T) \quad (12)$$

$$k = - k_0 (\alpha_0^2 / 2 - T^2) \quad (13)$$

Letting $2B^2 - ik_0 = c^2$, Equation 47 can be written

$$\alpha'^2 - c^2 \alpha^2 (1 - \alpha^2) = 0$$

or

$$\int_0^{\alpha(\xi)} \frac{d\alpha}{\alpha \sqrt{1 - \alpha^2}} = \pm c \xi \eta$$

$$= \frac{1}{2} \ln \left[\frac{1 + \sqrt{1 - \alpha^2}}{1 - \sqrt{1 - \alpha^2}} \right] \Big|_{\alpha_0}^{\alpha}$$

with the solution

$$1 - \alpha^2 = \left[\frac{(1 + \sqrt{1 - \alpha_0^2}) e^{2c\eta} - (1 - \sqrt{1 - \alpha_0^2})}{(1 + \sqrt{1 - \alpha_0^2}) e^{2c\eta} + (1 - \sqrt{1 - \alpha_0^2})} \right]^2 \quad (14)$$

This is similar to the usual calculation. The right side of Equation 51 becomes $\tanh^2(c\eta)$ if $\alpha_0 = 1$, leading to $\alpha \sim \text{sech}(c\eta)$ as usual. One consequence of keeping the SBS terms is that now c is complex

$$\begin{aligned}
c &= [2B^2 - ik_0]^{1/2} \\
&= [4B^4 + k_0^2]^{1/4} e^{-i \frac{1}{2} \tan^{-1} (k_0/2B^2)} \\
&= C_R + iC_I
\end{aligned}$$

Suppose $\alpha_0 = 1$, so that

$$\alpha = \frac{1}{\cosh c\eta}$$

The shape of the beam power becomes

$$\alpha^2 \alpha = \frac{2}{\cosh^2(2C_R \eta) + \cos^2(2C_I \eta)} \quad (15)$$

Thus SBS, in this limit affects the beam shape sinusoidally, with the most pronounced dip in the beam center, and a decreasing ripple as η gets large.

Summarizing these calculations, we have found a quasi-steady beam profile, in which the depletion effects of SBS just balance the accumulation effects of self-focusing. We have not yet explained the conditions required for the existence of this profile, but it must depend on the parameters $2B^2$ and k_0 , measuring the strength of the focusing and SBS scattering, respectively. The ratio is

$$\frac{2B^2}{k_0} = \frac{v}{\omega_s}$$

For very strong damping, $v = \omega_s$, and $2B^2 = k_0$. Another parameter that enters is the initial beam power $a_0^2(\xi = 0)$. Our picture is that there are three possible states: 1) SBS dominated, where the beam is dissipated too quickly for focusing to occur, 2) focusing dominated, where a catastrophic focus occurs, with essentially 100% backscatter, and 3) a stationary state where the two effects are balanced, described by the above theory.

In attempting to design an experiment to investigate these effects, we came upon the problem that the microwave pulse (~ 10 -20 usec) is too short to allow significant ion heating and the subsequent evolution of

the beam possible. We therefore hit on the idea of suppressing SBS with a finite bandwidth pump. This will allow us to see pure self-focusing. Then, by reducing the bandwidth, we can control the amount of SBS introduced, hopefully allowing a careful investigation of the interaction.

APPENDIX

OBSERVATIONS OF STIMULATED BRILLOUIN SCATTERING INITIATED
BY PONDEROMOTIVE FORCE DENSITY FLUCTUATIONS

H. E. Huey, A. Mase, N. C. Luhmann Jr.

University of California, Los Angeles, CA 90024

W. F. DiVergilio and J. J. Thomson

TRW, Redondo Beach, CA 90278

Physical Review Letters 45, 795 (1980)

OBSERVATIONS OF STIMULATED BRILLOUIN SCATTERING INITIATED
BY PONDEROMOTIVE FORCE DENSITY FLUCTUATIONS

H.E. Huey, A. Mase*, N.C. Luhmann Jr.

University of California, Los Angeles, CA 90024

W.F. DiVergilio and J.J. Thomson

TRW, Redondo Beach, CA 90278

ABSTRACT

We report the first observations of stimulated Brillouin scattering in microwave interaction with a plasma, as verified by the satisfaction of the frequency and wavelength matching rules and growth rate. A small amount of chamber reflectivity causes ion fluctuations due to the standing wave ponderomotive force, which then serve as an enhanced noise level for the initiation of the instability.

* Permanent address: Faculty of Engineering, Nagoya University,
Nagoya 464, Japan

Stimulated Brillouin scattering (SBS) in a plasma is due to the interaction of an electromagnetic wave and an ion acoustic wave. The resultant wave may be scattered at various angles, but the scattering maximizes in the backward direction, with a characteristic frequency downshift of the ion acoustic frequency, $\omega_s = kc_s$, where c_s is the ion sound speed and k is given by momentum considerations as $2k_0$ where k_0 is the incident wave number. This process is important in laser fusion, since the scattered energy is not available to the compression process. SBS has been observed in laser plasma interactions,^{1,2} identified by the characteristic ω_s frequency shift. Here we report the first observations of SBS in microwave interaction with plasma, finding not only the frequency downshift in the reflected wave, but directly measuring the wavelength of the ion acoustic fluctuations. An interesting feature of these experiments is that a small chamber reflectivity sets up ion fluctuations which then serve as an enhanced noise level for the initiation of the SBS scattered wave. After an initial fast growth time, we find the SBS reflectivity growth rate to agree with the classical calculations.²

The experiments were performed in an unmagnetized plasma of 75 cm diameter and 200cm length, produced by a multifilament dc discharge with surface multipole confinement. Typical operating parameters were: gas filling pressure $1-3 \times 10^{-6}$ Torr, electron density $n_e = 10^{10}-10^{11} \text{ cm}^{-3}$, electron temperature $T_e \approx 2\text{eV}$ and electron-ion temperature ratio $T_e/T_i = 10-12$. Various gases were used including hydrogen, helium, neon and argon. Experiments were performed at a number of microwave pump frequencies in the range 3 - 16 GHz, with peak powers up to 1 MW and pulse widths, τ_p , from .1 - 20 μ s. The wave was launched along the chamber axis by a high gain ($\approx 20\text{dB}$) gridded horn, the radiation pattern of which gave an effective interaction length of 70 - 120 cm. In order to avoid possible complications introduced by effects other than SBS, e.g. the parametric decay instability, the electron density was adjusted to 0.1 of the critical density, n_c , for all experiments.

The incident and backscattered electromagnetic waves were separated for detection using either a circulator or directional coupler, and fed into a square law detector for power measurements or a spectrum analyzer for frequency shift measurements. Ion waves were detected with movable Langmuir probes, after the microwave pump is off, thus avoiding the problem of rf pickup.

Since $T_e/T_i \gg 1$, Landau damping is rather small, and comparable to the damping due to ion collisions with the neutral background. From the discussion of Forslund, et al,³ after a time sufficiently long that a scattered wave has time to traverse the system, one must solve the spatial scattering problem. The growth rate is then

$$\gamma_s = 2\gamma_0 \sqrt{\frac{c_s}{c}} = \omega_0 \frac{c_s}{c} \left(\frac{n_e}{n_c} \frac{v_0^2}{v_e^2} \right)^{\frac{1}{2}} \quad (1)$$

where v_0 (v_e) is the oscillating (electron thermal) velocity, and γ_0 is the maximum growth rate for the temporal problem. Comparing γ_s to the ion damping rate, we obtain the threshold condition.

Convincing evidence for the existence of the SBS above this threshold was obtained by verifying the frequency and wave vector rules: $\omega_0 = \omega + \omega_s$, $\underline{k}_0 = \underline{k} + \underline{k}_s$ ($\omega, \underline{k}$ refer to the scattered wave). We found that the k-selection rule was well satisfied for a variety of incident wavenumbers and ion species. Figure 1 shows representative frequency spectra of the incident and reflected waves. Here the plasma was predominantly H_2^+ , and the pulse length was 20 μsec ($\omega_p \tau_p \approx 25$). The red shifted component of the reflected wave appears when the incident power exceeds threshold. For all ion species and pump wavelengths the measured red shift was found to be in excellent agreement with the appropriate acoustic frequency. The measured threshold power agrees with the theoretical prediction and is obtained by setting γ_s equal to the measured ion wave damping rate ($\approx 5 \times 10^4 \text{ sec}^{-1}$).

For typical experimental conditions, $c_s/c = 3 \times 10^{-5}$, $v_0/v_e = .5$, $n/n_c = .1$, and $c_0 = 2 \times 10^{10} \text{ s}^{-1}$, Eq. (1) predicts a growth time $\tau_s = \gamma_s^{-1} = 7.2 \mu\text{s}$.

In the usual theory of SBS, ion acoustic fluctuations are assumed to grow from a small noise level. From the measured noise level and frequency spectrum in our plasma, and the above growth time, we would expect the SBS driven ion waves to attain an amplitude $\delta n/n = 1\%$ approximately 50 μ s after pump turn-on. However, in these experiments, ion fluctuations at ω_s were observed to grow in a very short time, $\sim \omega_s^{-1}$, to a level of a percent or so, and then to continue growing at the much lower rate predicted by Eq. (1). This unexpected behavior may be explained by taking into account the small, but finite, amount of power reflected from the chamber and wall ($\sim 1\%$), which sets up a standing electromagnetic wave.

It is perhaps surprising that such a small amount of reflectivity can produce significant ripples in the standing wave power. To see this, consider the power standing wave ratio

$$\left(\frac{E_{\max}}{E_{\min}} \right)^2 = \frac{(1 + r^{\frac{1}{2}})^2}{(1 - r^{\frac{1}{2}})^2} \quad (2)$$

where r is the chamber reflectivity. For $r = 1\%$, $(E_{\max}/E_{\min})^2 = 1.5$. The ponderomotive force associated with the electric field pressure gradient drives ion density fluctuations. We will calculate these fluctuations and show that there is a component that directly couples with the SBS backscattered wave.

We express the forward and reflected waves as

$$E_f = E_0 \sin(\omega_0 t - k_0 x) \quad (3)$$

and

$$E_r = r^{\frac{1}{2}} E_0 \sin(\omega_0 t + k_0 x) \quad (4)$$

respectively. The ion acoustic wave equation is

$$\frac{\partial^2 \tilde{n}}{\partial t^2} - c_s^2 \frac{\partial^2 \tilde{n}}{\partial x^2} = 4k_0^2 c_s^2 n_0 r^{\frac{1}{2}} \frac{v_0^2}{v_s^2} \cos 2k_0 x \quad (5)$$

where $\tilde{n}$ is the fluctuating ion density. The right hand side is the ponderomotive source term. The solution of Eq. (5) is:

$$\frac{\tilde{n}}{n_0} = r^{\frac{1}{2}} \left(\frac{v_0}{v_e} \right)^2 \cos(2k_0 x) (1 - \cos \omega_0 t) \quad (6)$$

This consists of a zero frequency component and two traveling waves. The zero frequency mode scatters the incoming wave in the manner of a grid (i.e. Bragg scattering) while the Thomson scattering from the traveling waves results in both red and blue-shifted components to the backscattered radiation.

The backscattered wave equation is:

$$\left(\frac{\partial^2}{\partial t^2} + \omega_{pe}^2 - c^2 \frac{\partial^2}{\partial x^2} \right) E_s = \omega_{pe}^2 \frac{\pi}{2n_0} E_0 \sin(\omega_0 - k_0 x) \quad (7)$$

For the backscattered red-shifted wave, which satisfies the frequency and wavenumber matching conditions for SBS, Eq. (7) becomes

$$2\omega_0 c \left(\partial E_s / \partial x \right) = - \left(\frac{\omega_{pe}^2}{2} \right) r^{\frac{1}{2}} \frac{v_0^2}{v_e^2} E_0 \quad (8)$$

With the chamber end wall boundary condition $E_s(L) = 0$, the solution is

$$E_s = \left(\frac{\omega_{pe}^2 / 2\omega_0}{v_e^2} \right)^2 r^{\frac{1}{2}} \frac{v_0^2}{v_e^2} E_0 k_0 (L-x) \quad (9)$$

The ponderomotive force driven density fluctuations of Eq. (6) and the resultant scattered wave predicted by Eq. (9) occur on the time scale ω_p^{-1} . For longer times, we expect continued growth due to the usual SBS mechanism.

Figure 2(a) shows the normalized density fluctuation level $\tilde{n}/n_0$ observed at a fixed position as a function of time. The ponderomotive force driven fluctuations are clearly visible in the low power He case, where the pump power was below threshold for SBS. In contrast, at powers well above threshold, as seen in the H example, the slowly growing SBS fluctuations are superposed on the ponderomotive force driven fluctuations. Concurrent analysis of the backscattered electromagnetic wave also shows the slow growth of the red-shifted component. It should be noted that the predicted Thomson-scattered blue-shifted component was also observed, with amplitude always more than 10-20 dB below that of the red-shifted component.

Equation 6 also predicts that the peak fluctuation level at the first turning point ($\omega_p t_p = \pi$) is given by

$$\tilde{n}(t_p)/n_0 = 2r^{1/2} (v_0/v_e)^2 \quad (10)$$

In the inset to Fig. 2(a), t_p is plotted as a function of ω_p , which is varied by using different ion species, showing good agreement with theory. Figure 2(b) shows $\tilde{n}(t_p)/n_0$ versus v_0^2/v_e^2 . The best fit is obtained for $r=6\%$, which is consistent with our estimates of 1% obtained from Eq. (9) and the measured power reflected back into the horn. This level of agreement is consistent with our uncertainties in quantities such as $(v_0/v_e)^2$ and interaction length. We have also done experiments with a reflectivity of $\sim 5\%$ and found the scaling of Eqs. (9) and (10) to be valid.

The measured growth time of the backscattered wave, after the initial ponderomotive force driven response, is shown in Fig. 3 as a function of v_0/v_e , for a hydrogen plasma. The agreement with the prediction of Eq. (1) (solid curve) is seen to be excellent. We have run some experiments with $v_0/v_e > 1$ and observed significantly faster growth rates than those predicted by Eq. (1). The cause of this discrepancy is currently under investigation.

It should be noted that the model described here will not be valid for time scales much greater than the ion wave damping time. On these time scales, the traveling wave portion of the ponderomotive force response will damp away and no longer act as an enhanced noise level for SBS⁴. In addition, increased Landau damping due to ion heating may be important. Simulations of these experiments have been performed using a wave optics-hydrodynamics code.⁴ Good agreement with these results were found, including the magnitude of the red shifted component (Fig. 1) and the detailed time history of the ion wave (Fig. 2(a)). A more thorough discussion, including long time effects is forthcoming.

In conclusion, for the first time in microwave plasma interaction, we have observed the stimulated Brillouin scattering instability. The time evolution of the ion fluctuations and reflected electromagnetic radiation are in good agreement with the predictions of an analytic calculation employing a spatially dependent ponderomotive force, giving rise to an enhanced SBS initiation level. In a laser fusion experiment, reflection from the critical surface will play the role that chamber reflectivity played in this experiment. The resultant enhanced noise level may lead to higher levels of reflectivity.

We will discuss in a future publication SBS saturation levels and the effect of finite bandwidth.

ACKNOWLEDGEMENTS

We would like to acknowledge fruitful discussions with Drs. C. J. Randall and D. W. Forslund. The efforts of J. Thomson and W. DiVergilio were supported under DOE Contract DE-AC08079DP400116, while those of H. Huey, A. Mase and N. C. Luhmann were supported by DOE OLF Contract No. DE-AS03-76-SF00034 and AFOSR Contract No. F490620-76-0012.

REFERENCES

1. B. H. Ripin, F. C. Young, J. A. Stamper, C. M. Armstrong, R. Decoste, E. McLean and S. E. Bodner, Phys. Rev. Lett. 29, 611 (1977).
2. D. W. Phillion, W. L. Kruer and V. C. Rupert, Phys. Rev. Lett. 39, 1529 (1977).
3. D. W. Forslund, J. M. Kindel and E. L. Lindman; Phys. Fluids 18, 1002 (1975).
4. C. J. Randall, to be published.

FIGURE CAPTIONS

Fig. 1 Spectrum analyzer traces of incident and reflected microwave signals of both (a) below and (b) above threshold for SBS. The red shift corresponds to the measured ion wave frequency and to the predicted frequency for the predominantly H_3^+ plasma.

$$(a) P_0 = 60 \text{ kW}, v_0/v_e = 0.31$$

$$(b) P_0 = 250 \text{ kW}, v_0/v_e = 0.63$$

Fig. 2(a) Normalized density fluctuation level $\tilde{n}/n_0$ as a function of time. The squares correspond to a helium plasma ($v_0/v_e = 0.37$) while the circles correspond to hydrogen ($v_0/v_e = 0.68$). The inset shows the measured t_p versus f_s together with the predicted $\omega_s t_p = \pi$ curve.

Fig. 2(b) Measured $\tilde{n}(t_p)/n_0$ versus $(v_0/v_e)^2$ together with predicted $\tilde{n}/n_0 = 2\pi^{1/2}(v_0/v_e)^2$ curve.

Fig. 3 Measured growth rate as a function of v_0/v_e compared with theory.

Figure 1

Figure 2(a)

Figure 2(b)

Figure 3