MASTER

TRW

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MICROWAVE SIMULATION OF

LASER PLASMA INTERACTIONS

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Synopsis of Final Report - Major Results

Experimental Systems

Various electron and ion current, electric field, and magnetic field probes were developed and tested during the course of the investigation. A three dimensional probe drive system was constructed in order to investigate two and three dimensional phenomena occurring in the microwave plasma interaction.

In most of the experiments reported here, a 1 GHz, 40 kilowatt, pulsed rf source (Applied Microwave), was used. The antenna was a 20° horn. A dipole fed parabolic antenna system capable of producing a focussed microwave beam at 2.3 GHz was developed and bench tested. This system will be used in future investigations at higher power levels ($E_0^2/8\pi nkT > 1$).

Density Profile Modification

Modification of an initially linear density profile by rf fields in the vicinity of the critical layer was investigated for incident field strengths $10^{-5} \leq E_0^2/8\pi nkT \equiv \beta \leq 3 \times 10^{-2}$. At low powers ($\beta < 10^{-4}$), the density modification is small ($\sim 1\%$) and the modified profile possesses an Airy-like form. At higher powers density cavities are formed ($\delta n/n = .3$ for $\beta = 10^{-2}$). In time (2000 - 5000 plasma periods), the profile develops into an underdense plateau region in front of a sharp density step to supercritical density.

In the early stages of profile modification, when the density cavity growth rate is extremely high ($-n^{-1} dn/dt \geq .25f_{pi}$), a burst of fast ions, streaming toward the underdense region, is generated. The ion energy is observed to increase with power to the maximum available power, though the cavity depth saturates.

Magnetic Field Generation

Quasistatic magnetic fields ($B_{\max} \approx .05$ Gauss at $\beta = 1.5 \times 10^{-2}$) are generated in the critical region with orientation perpendicular to the density gradient and the incident wave polarization. By application of Ampere's law to the observed field, it is concluded that the fields are due to the current carried by the linearly converted electron plasma waves. The field geometry is consistent with the results of computer simulations of the laser - plasma resonant interaction.

Electron Distribution Measurements

Probe measurements of the electron distribution during the rf burst were found to produce erroneous or ambiguous results. A program has been instituted to develop optical techniques for electron measurements. Preliminary results qualitatively, but unambiguously, demonstrate the production of a hot electron tail in the critical region. Techniques for the improvement of space, time, and energy resolution will continue to be developed under ERDA contract number E(04-3)-1281.

Section A - Experimental Systems

Plasma Properties

Experimental investigations of the microwave plasma interaction are carried out in the QUIPS plasma facility (Fig. A1.), a four meter long, two meter diameter chamber, lined with over 10,000 permanent magnets for plasma confinement. The plasma is produced by a DC discharge in an inert gas, usually Argon, at a pressure of 10^{-5} to 2×10^{-3} torr. Fractional ionization is ten percent at most, with a maximum steady state density of approximately $2 \times 10^{11} \text{ cm}^{-3}$. Densities of over 10^{12} can be obtained in the pulsed state. Electron temperature is a decreasing function of neutral pressure, with a value of about 1eV at the typical operating pressure of 6×10^{-4} torr. A complete table of plasma parameters is given in Fig. A2.

A steady state density gradient is established by limiting the region of the cathode (one to three rings of 25 to 50 tungsten filaments each) to one end of the chamber. Two factors contribute to the formation of the gradient. At high neutral pressures, production is confined largely to the cathode end of the chamber. Ambipolar diffusion, balanced by ion-neutral collisions, results in a density gradient which is nearly linear ($n = n_0 (1 + z/L)$) for approximately one meter along the chamber axis. The gradient length, L , as a function of neutral pressure is shown in Fig. A3 along with a density profile under typical experimental conditions.

Microwave Systems

A table of the parameters of the various rf sources used is given in Fig. A4. In most of the experiments described in this report, the 40 kilowatt, 1 GHz₂ source was used. The antenna was a 20° compound horn

with linear polarization, fed by a water cooled coaxial line. With the critical surface 75 cm from the mouth of the horn, one kilowatt of input power gives an incident wave energy density of

$$E_0^2/8\pi \approx 1.7 \times 10^{-3} n_c \times T_e$$

Thus, at the maximum power of 40 kW

$$\beta \equiv E_0^2/8\pi n_c \times T_e \approx 6.8 \times 10^{-2}$$

Future experiments are planned at incident wave energy densities $\beta \approx 1$. The feasibility of a focussed microwave beam in order to achieve the desired intensity levels at minimum power was studied. A focussed beam is diffraction limited to a spot size of order λ^2 , limiting the maximum energy density for a given incident power to $E_0^2/8\pi \approx P/\lambda^2$. The required energy density to achieve a given β at fixed T_e is proportional to $n_c \lambda^2$. Thus, assuming optimal focussing, the power required to achieve a given β is independent of frequency. The difficulties encountered in plasma production and diagnostics generally increase with density for densities above 10^9 , making low frequency operation desirable. However, in order to focus significantly, an antenna must have a diameter $D \gtrsim 10\lambda$. The maximum feasible antenna size in the QUIPS chamber is about 150 cm, giving a minimum frequency of 2 GHz.

An antenna system, consisting of a 125 cm diameter parabolic dish of focal length 31.25 cm, fed by a dipole disk feed*, which produces a dipole radiation pattern in a half space. Figure A5 is a contour plot of the measured radiation pattern in the H plane, where the dipole feed

point was 36 cm from the vertex of the parabola and the frequency was 2.3 GHz. Results in the E plane were essentially the same, with small differences in the side lobes. In the maximum intensity region, 175 cm from the vertex, the main lobe was Gaussian in shape in the direction perpendicular to the antenna axis:

$$I = I_0 e^{-r^2/r_0^2} \quad r_0 = 16 \text{ cm}$$

Approximately one third of the radiated power is carried away by divergent side lobes of intensities typically 20 dB below that of the main lobe. From the measured radiation pattern, including side lobe loss, we estimate that a total incident power of 380 kilowatts will be required to achieve $S = 1$.

Probe Systems

A probe drive system with three degrees of mechanical freedom was constructed in order to facilitate the study of two and three dimensional phenomena such as the generation of magnetic fields and the stability of the critical surface. The probe shaft enters the vacuum system through a flexible stainless steel bellows and is driven externally by three coupled mechanical drives (Fig. A6 a). The probe shaft carries five coaxial cables to an interchangeable probe tip (Fig. A6 b).

A variety of probes were designed, constructed and tested during the project (Fig. A7). Density measurements were made by sampling ion or electron saturation current collected on a 4mm diameter plane Langmuir probe. The probe is sampled 1 to 2 microseconds after rf shutoff in order to avoid the problem of rectified rf current on the probe. We have determined

*Silver, Microwave Antenna Theory and Design MIT Rad. Lab. Series, McGraw-Hill, New York, 1948.

experimentally that the time scale for density change after rf shutoff is determined by the acoustic speed ($c_s \approx 10^5$ cm/S), so that the time delay of 1-2 microseconds introduces only a small error in density measurement.

A directional Langmuir probe, consisting of two plane probes separated by an insulating disk, was used to search for the presence of streaming electrons. This investigation is described in appendix D.

Ion distribution measurements were made with a two gridded electrostatic ion energy analyser. In the conventional mode of operation, the first grid is held negative with respect to the plasma potential in order to repel electrons. The second, or discriminator, grid has a variable potential, $\phi_p + V$, to discriminate against ions of velocity $v_{11} < \sqrt{eV/M}$, where v_{11} is the ion velocity component normal to the grid. The collector, held at a constant negative potential, collects ions with velocity above $\sqrt{eV/M}$. Experimentally, the analyser has an upper density limit of operation of about 10^{10} cm⁻³, apparently due to space charge effects around the discriminator grid. However, we find that by reversing the roles of the first and second grids, the space charge problem is eliminated and the upper density limit is increased by at least an order of magnitude, though energy discrimination is degraded from .1 eV to .3 eV. The most serious limitation on energy analyser performance is frequency response. We have determined, by detecting grid launched ion acoustic waves with both an energy analyser and a Langmuir probe, that the analyser response is comparable to the probe response at frequencies up to a few hundred kilohertz. At one megahertz, however, the analyser response is down 10 dB

referenced to the Langmuir probe response. The frequency response may be limited at least in part by transit time effects, and may be improved by reducing the intergrid spacing.

Initial measurements with a two turn magnetic loop probe revealed the presence of microwave generated signals of amplitude $dB/dt \approx 50$ kG/s, with variation time scales on the order of 100 nanoseconds. The probe signal also contained large electrostatic components, with magnitudes as great as several times the magnetic signal. Based on these measurements, new magnetic probes were designed for optimum signal to noise ratio. The probe consisted of ten or twenty turns of enameled copper wire surrounded by a grounded toroidal shield of major radius one cm and minor radius 1.5 mm. The twenty turn coil provided a sensitivity of 6.3×10^{-4} mV/(G/s) for a typical signal level of 30 mV. After subtracting the outputs of the coil ends, referenced to the center tap, the electrostatic signal was reduced to a typical value of 5 mV maximum, or about 1/6 of the magnetic signal. The frequency response of the coils was tested to 10 MHz. As a further check on frequency response, a ten turn coil and a twenty turn coil were used concurrently to measure the microwave generated DC magnetic fields. Received signals were identical in form and differed in amplitude by almost exactly a factor of two, indicating that the probe bandwidth exceeded the signal bandwidth by a large margin.

Electric field measurements were found to present the greatest difficulties in probe diagnostics. The probe used most often for such measurements, a coaxial line terminated with a floating cylindrical probe, was found to give totally erroneous results. Figure A-8a shows electric field amplitude

as a function of position from $n \approx n_c/2$ to the supercritical region as measured by such a probe. The microwave source was a parabolic antenna radiating a nearly plane wave at 2.3 GHz. The received signal decreases by two orders of magnitude as the probe position is varied from that corresponding to $n_c/2$ to $.8 n_c$. This behavior may be caused by an increasingly poor impedance match between the probe and electromagnetic wave, as the wave propagates into the plasma. The probe also appears to be extremely sensitive to the formation of standing waves on the probe shaft. Results more consistent with theoretical expectations are obtained with a resonant high impedance probe*. The probe consists of a short dipole antenna, loosely coupled to a 50 Ω coaxial line through a quarter wave transmission line. Results obtained with this probe, under the same conditions as described above for the cylindrical probe, are shown in Fig. A-8 b. Note that the electric field amplitude shows the characteristic Airy behavior as predicted by cold plasma theory. However, as is evident in Fig. A-8 b, even the high impedance probe exhibits reduced sensitivity at the critical surface, where $\epsilon \rightarrow 0$.

*H. C. Kim, UCLA PRd-177 (June 1974)

FIGURE A-1: Schematic of QUIPS chamber

(a) Capability

$$n_e \leq 2 \times 10^{11} \text{ cm}^{-3}$$

$$0.5 \text{ eV} \leq T_e \leq 3 \text{ eV}, \quad 0.05 \text{ eV} \leq T_i \leq 0.3 \text{ eV}$$

$$L \geq 50 \text{ cm, where } n = n_c \left(1 + \frac{Z}{L}\right)$$

(b) For 1 GHz experiment

$$n_c = 10^{10} \text{ cm}^{-3}$$

$$\nu_{ee} = 8.9 \times 10^5 \text{ Hz}$$

$$T_e \sim 1 \text{ eV}$$

$$\nu_{ei} = 4.5 \times 10^5 \text{ Hz}$$

$$T_i \sim 0.1 \text{ eV}$$

$$\nu_{ie} = 28 \text{ Hz}$$

$$L \sim 100 \text{ cm} = 3\lambda_0$$

$$\nu_{ii} = 10^5 \text{ Hz}$$

$$f_{pe} = 10^9 \text{ Hz}$$

$$\nu_{en} = 3 \times 10^5 \text{ Hz}$$

$$f_{pi} = 3.7 \times 10^6 \text{ Hz}$$

$$\nu_{in} \leq 10^4 \text{ Hz}$$

Figure A-2. Plasma Parameters; (a) Capabilities of the QUIPS Facility, (b) Parameters Used for 1 GHz Experiment

AXIAL POSITION - CM

FIGURE A-3: Steady state density profile in the absence of rf

- (a) Density profile under typical operating conditions, Argon neutral pressure 6×10^{-4} torr, showing uniform density in production region and linear gradient region.
- (b) Gradient scale length in linear region as a function of pressure.

1 GHz Source (1-1.2 GHz)

Power - 0-40 kilowatts

$E_0^2/8-nkT_e$ - 0-0.06

Pulse Width - 200 nsec-20 μ sec

2.4 GHz Source

Power - 0-5 kilowatts

Pulse Width - 200 nsec-20 μ sec

CW Sources

Power - 0-10 watts

Frequency - 1-4 GHz

Pulse Width - $\geq$ 20 nsec

Phase Coherent

Fig. A-4 Microwave Sources Used

FIGURE A-5: Radiation Pattern of Parabolic Antenna -
Lines of constant intensity are labeled in dB below maximum.

a)

b)

FIG. A-6 - 3-D Probe Drive System

a) Mechanical drive system and bellows feed-thru.

b) Interchangeable probe tip - Shown here with two electric field probes and a Langmuir probe.

FIGURE A-7: Probes

FIGURE A-8: rf Electric Field amplitude as measured by
 (a) cylindrical probe and (b) High impedance probe.
 The incident wave was a nearly plane wave of frequency 2.3 GHz.

Section B-Density Profile Modification

Modification of the density profile by rf fields in the vicinity of the critical layer has been studied as a function of time and space over a range of nearly four orders of magnitude in incident power.

Figure B-1 plots maximum density perturbation as a function of incident power, where the rf (1.2 GHz) was pulsed on for 700 nsec ($840t_{pe}$) and the density measured by sampling electron saturation current to a probe.* Three characteristic regions of profile modification appear. In region I (example c), the profile shows the characteristic Airy function shape. The density is modified by the ponderomotive force of the linearly converted electron plasma waves, but the modification is not severe enough to strongly alter the linear conversion process. As the incident power is increased, the Airy shape is distorted and a large density perturbation, or "caviton", becomes the most significant feature of the profile (example b in Fig. B-1). The magnitude of the perturbation increases throughout region II and the Airy-like characteristics of the profile gradually disappear. In region III, $\delta n/n$ saturates, but the width of the "caviton" in the z direction continues to increase, and the formation of multiple cavitons is observed. This transition from Airy like profile modification to the formation of density cavities has

* Note: The two sets of data points shown in Fig. B-1 were obtained in different data runs with different probes. Simultaneous measurements with both probes showed that the one-sided probe (top curve) consistently gives $\delta n/n$ a factor of two greater than the ordinary Langmuir probe (bottom curve). As the reason for this discrepancy is not fully understood, neither data set was corrected.

been observed by Morales and Lee* in an analytic treatment of the problem, but saturation as a function of power has not been examined. Future plans include an investigation of the transition from region III, where the profile modification due to the electron plasma wave ponderomotive force appears to saturate, to the regime where the ponderomotive of the incident electromagnetic wave becomes important ($E_0^2/8\pi nkT=1$).

The complete space time dependence of the density profile modification was studied at high power densities (regions II and III). A caviton generated at the critical surface propagates down the density gradient, leaving behind a new critical surface at which a second density cavity forms. As this process continues, the region just below critical density becomes more and more turbulent, with smaller density fluctuations. The profile develops into a density plateau (typically 15 cm wide) in front of a density step (typically $.85 n_c$ to $1.1 n_c$ in 3cm). An example of this space time development is given in Fig. B-2, obtained by sampling a Langmuir probe 2 microseconds after shutoff of an rf pulse whose width was varied from .2 to 7.5 microseconds. The plateau and density step have been observed to persist for 18 microseconds, the longest pulse width presently available, and are believed to represent a steady state configuration.

Bursts of fast ions, streaming down the density gradient, are observed to be generated concurrently with the formation of the first

* G.J. Morales and Y.C. Lee, UCLA PPG-292
G.J. Morales and Y.C. Lee, Phys. Rev. Lett. 33, 1016 (1974).

density cavity. The ions possess a maxwellian-like distribution in the streaming direction with a "temperature" $T = 6\text{eV} \approx 30 T_{iu}$ at incident power of 29 kWatt ($E_0^2/8\pi kT_e \approx 5 \times 10^{-2}$). Ion velocity is an increasing function of incident power throughout the range previously identified as region III, to the maximum available power. The fast ions are the result of plasma expulsion from the cavity region, and thus their velocity is a function of the growth rate of the cavity, which continues to increase in region III, though the cavity depth is saturated. In the initial stages of profile modification ($t \leq .2\mu\text{sec} \approx 240 t_{pe}$) the "growth" rate is

$$-\frac{1}{n} \frac{\partial n}{\partial t} \geq 1/\mu\text{sec} \approx .25 f_{pi}.$$

In later stages of profile modification, where typically

$$-\frac{1}{n} \frac{\partial n}{\partial t} \geq .15/\mu\text{sec},$$

no significant ion acceleration has yet been observed.

FIGURE B-1: Power dependence of density profile modification

FIGURE B-2: Space and time development of density profile modification at an incident rf power of 5kwatts at 1GHz.

Section C

SELF-GENERATED MAGNETIC FIELDS IN THE MICROWAVE PLASMA
RESONANT INTERACTION*

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ABSTRACT

The laser plasma interaction is simulated by the interaction of a microwave beam with an inhomogeneous, collisionless plasma. Magnetic fields are generated perpendicular to the density gradient and to the incident wave polarization. The observed sharp reversal of field direction in the resonant region supports resonance absorption as the generation mechanism.

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Self generated DC magnetic fields have recently been observed both in laser plasma interactions^{1,2} and in computer simulations.^{3,4} Observations of the laser plasma have provided measurements of the magnitude of the field, but not the detailed geometry in the source region. Knowledge of the field geometry may lend important insight into which of the various proposed physical generation mechanisms³⁻⁶ is dominant. We have studied the resonant interaction of an electromagnetic wave with a laboratory plasma amenable to detailed probe diagnostics.

The plasma is produced by a DC discharge at one end of a large (2 meter diameter, 4 meter long) multidipole device, such that the plasma possesses a linear density gradient of typical scale length $L = 100-200$ cm ($n = n_c [1 + \frac{z}{L}]$). Typical operating parameters are: Argon neutral pressure $3-9 \times 10^{-4}$ torr, maximum density $4 \times 10^{10} \text{ cm}^{-3}$, $T_e \approx 1 \text{ eV}$, $T_i \approx 0.1 \text{ eV}$. Electrons are essentially collisionless, with $\nu_{ee} \approx \nu_{ei} \approx \nu_{en} \lesssim 10^{-3} \nu_{pe}$. A 20° horn at the low density end of the chamber radiates an rf burst (maximum peak power 15 kW, pulse length .4-14 μsec at 1.2 GHz), which exhibits a strong resonant interaction with the plasma at the critical density layer ($n_c = 1.8 \times 10^{10} \text{ cm}^{-3}$). One kilowatt of incident power corresponds to a maximum power density of approximately 3 kW/m^2 , or $E_0^2 / 8 - nkT_e \approx 1.7 \times 10^{-3}$ at critical density, where E_0 is the electric field in the absence of the plasma. A detailed description of the device and some of the characteristics of the resonant interaction have been previously published.^{7,8}

Magnetic field measurements were made by detecting the time derivative of the field with a 2 cm diameter, 10 turn center tapped, electrostatically shielded magnetic loop probe. Pickup was found to be a major problem due to the large rf fields present. The center tap of the coil was grounded and the difference between the coil end outputs taken with a Tektronix 1A1 amplifier

to further eliminate pickup. The magnetic probe was mounted on a movable probe shaft along with a Langmuir probe for density measurements. Three dimensional probing of the interaction region was made possible by inserting the probe shaft into the system axially through a bellows and driving the shaft with a system of three coupled mechanical drives. The magnetic loop could be rotated to measure B_x and B_y , the field components perpendicular to the density gradient. A second magnetic loop entered the system radially for measurement of B_y and B_z .

A quasistatic magnetic field was observed to be generated in the resonance region by the incident electromagnetic wave. The magnetic field, B , is perpendicular to the density gradient and to the incident wave polarization. Fig. 1 illustrates the spatial dependence of B_y in the x - z plane ($y=0$), where the density gradient is along z and the incident wave is polarized in the x direction. The traces in Fig. 1 a) were obtained by sampling the integrated probe output near the end of a 2.5 μ sec microwave burst of peak power 7kW.

As a function of z , for a given radial position, x , B_y is seen to peak near the critical density and reverse sign 5-10 cm below critical, indicating the presence of a current layer in the resonant region flowing in the x direction. B_y also changes sign in the radial direction, with $B_y = 0$ at $x = 0$. This geometry is explained by the following physical picture. The incident wave undergoes strong absorption in the resonant region. The x component of the absorbed wave momentum drives an electron current along the critical layer, while space charge forces along the density gradient transfer the z component of momentum to the ions. Referring to Fig. 1 b), we note that the divergent incident wave drives a current in opposite directions on either side of $x = 0$, resulting in the observed radial sign change in B_y . The field geometry is

essentially identical to that predicted by Thomson, Max and Estabrook,³ when their results are extended to a divergent source. The orthogonal relationship between the quasistatic magnetic field and the incident wave polarization was found to be preserved when the polarization was changed by rotating the microwave horn. In the rest of this paper, the polarization will be taken to be in the x direction.

Away from the plane $y = 0$, the functional form of $B_y(x, z)$ is unchanged, while the magnitude falls off as the microwave power density decreases. The maximum values of B_x and B_z were found to be always less than .2 of the maximum value of B_y . Some of these features are illustrated in Fig. 2, which shows B_x and B_y components in a plane of constant axial position, z . Probe orientation is the angle between the magnetic loop axis and the y axis. Note that B_y changes sign as a function of x , as previously discussed, and falls off monotonically in the y direction away from $y = 0$. The smaller B_x signal may be due to a component of polarization in the y direction or to slight misalignment of the probe with respect to the horn.

We have assumed up to this point that constant density surfaces lie in the x-y plane, and therefore, that the point of normal wave incidence is at $x = y = 0$. Note with reference to Fig. 2 that the radial sign reversal does not occur exactly at $y = 0$, but may be shifted as much as 10 to 15 cm off axis. This asymmetry was found to correlate well with a slight radial density gradient present in the plasma. Constant density surfaces are actually inclined at an angle, α ($0^\circ < \alpha < 10^\circ$), with respect to the x-y plane, moving the point of normal incidence to a position off the chamber axis. Radial density gradients should also have the effect of producing smaller components of magnetic field ($\sim B_y \sin \alpha$) in the x and z directions.

The magnetic field initially grows at the critical density and spreads to the underdense region. Typical time dependence of dB/dt and integrated B close to the critical layer is shown in Fig. 3. B rises to $B_{\max}/2$ in a time $\sim 500 f_{pe}^{-1}$ and saturates at $\sim 1800 f_{pe}^{-1}$. The steady state field pattern illustrated in Figs. 1 and 2 is fully developed by $2000 f_{pe}^{-1}$. Langmuir probe measurements reveal that a density cavity is created at the resonant location by the expulsion of particles by the ponderomotive force. The density cavity develops in time into a plateau (typically 15 cm in extent in the z direction) in front of a sharp density step ($.85n_c$ to $1.1n_c$ in 3 cm). The time development of the plateau is illustrated in Fig. 3d and is seen to correlate well with the establishment of the steady state B field. Both the density step and steady state magnetic field have been observed to persist for as long as $17000 f_{pe}^{-1}$, the maximum microwave pulse length available. We infer from concurrent density and magnetic field measurements that the field source is a current sheet flowing perpendicular to the density gradient at the position of the density step.

The source current is identified as the time averaged current carried by the linearly converted electron plasma waves;

$$\langle J_y \rangle = \langle n_1 e v_{y1} \rangle = - \frac{e}{i4\pi m \omega} \frac{\omega^2}{\omega^2} \langle (\nabla_x \cdot \vec{E}) \vec{E} \rangle, \quad (1)$$

where Poisson's equation and the equation of motion have been used to obtain the right hand expression. This expression points out that a rotation of the polarization field, $\vec{E}$, causes a rotation in the current, $\vec{J}$, and hence in the magnetic field. A wave polarized in the x - z plane generates electron plasma waves with electric field, $\vec{E}$, and hence current, $\vec{J}$, components in the x and z directions. In the long time limit, space charge forces cancel the current component along the density gradient, leaving only the perpendicular component, $\langle J_x \rangle$.

An upper limit on the current density may be obtained by considering the flow of the x component of momentum from the incident wave to the electrostatic wave. In the steady state, momentum is carried into the resonant region at the speed of light and is carried out at some characteristic group velocity, v_g . The direction of momentum flow is in the direction of wave propagation, i.e., the z direction. We may write a momentum flow balance equation

$$p_x^{es} v_g = a p_x^{em} c \quad (2)$$

where a is the absorption coefficient and p_x^{em} and p_x^{es} are respectively the x components of the electromagnetic and electrostatic wave momentum densities. p_x^{es} is obtained from the observed B field through Ampere's Law,

$$\frac{e}{m} p_x^{es} = -J_x = + \frac{c}{4\pi} \frac{\partial B_y}{\partial z} = 10^7 \text{ cgs-esu } [= .03 n_0 \text{ ev}_{the}]. \quad (3)$$

at an incident power of 8 kW, or $\frac{E_0^2}{8\pi nTe} = 1.4 \times 10^{-2}$, and an incidence angle of 10° . The group velocity, v_g in equation (2), has been experimentally measured⁹ by irradiating the plasma with two incident waves, ω_1 and ω_2 , with frequency difference $\Delta\omega$, $\Delta\omega/\omega \approx 10^{-4}$. The beat pattern between the two linearly converted plasma waves gives a measurement of the group velocity $v_g = \frac{\Delta\omega}{\Delta k} \approx 10^6$ cm/sec in the vicinity of the resonant location. With p_x^{em} from the known incident power and horn radiation pattern, we obtain the reasonable value of .2 for the absorption coefficient, a .

The observed field geometry would appear to be inconsistent with a thermoelectric source. Since, at late times, v_n is monotonic, the sign

reversal of B as a function of axial position would require that ∇T reverse sign in one tenth the electron mean free path. Possible effects associated with the ambient magnetic field (measured as .4 gauss in the vertical direction) were ruled out by rotating the microwave horn to establish the independence of the self-generated fields from the ambient field.

We are grateful to Dr. D. Arnush for his discussions and support. The technical assistance of Mr. M.D. Plummer in construction of the three dimensional probe system is acknowledged.

FIGURE CAPTIONS

- Fig. 1 a) Steady state B_y as a function of axial position, z , and radial position, x . Positive B_y corresponds to field in positive y direction, which is into paper in b).
- b) Diagram of results shown in a), indicating geometry of field with respect to microwave source. Inferred electron current paths are shown by solid lines and possible return paths by dotted lines.
- c) Axial density gradient before rf turn on. Position scale applies to b) and c).

- Fig. 2 Radial components of magnetic field at fixed axial position of maximum field, a) as a function of x for $y = 10$ cm, b) as a function of y for $x = 10$ cm. The fixed y and x positions for a) and b) respectively were chosen to be far from lines of $B = 0$. Note the signal sign reversal for probe orientations differing by 180° , indicating the magnetic origin of the signal.

- Fig. 3 Typical time dependence of magnetic field near critical layer.
- a) Incident rf power as detected by a crystal detector.
- b) Magnetic loop probe signal, dB/dt .
- c) Integrated probe signal, B . Long decay time of B is caused by long tail in rf pulse.
- d) Spatially averaged density depletion, $(1/L) \int (dn/n) dz$, near the critical layer, observed under similar plasma conditions as magnetic field data but not concurrently. The resultant density profile becomes steeper.

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FIG. 2

FIG. 3

Section D - Electron Distribution Measurements

In computer simulations of the laser plasma interaction, a large fraction of the absorbed energy is found in a hot electron tail. In the microwave plasma interaction experiment, the flight time of fast electrons out of the experimental region is comparable to the rf shutoff time (~ 200 nsec), necessitating measurement of the electron distribution function during the rf burst. Such measurements are complicated by the well known phenomenon of rf rectification, which has been studied both experimentally^{*} and theoretically[†] for the case of a dc plus an rf potential applied to a probe. To the best of our knowledge, no treatment has been made for the case of a probe at fixed dc bias, collecting current in the presence of a electromagnetic wave propagating in a plasma. However, our probe measurements reveal that, in the underdense region, rectification of the rf field results in an apparent high energy tail in the electron distribution. This observed tail is localized spatially to the maximum electric field regions of the standing electromagnetic wave. This localization is inconsistent with the fact that all electron collision mean free paths are longer than one quarter of the electromagnetic wavelength, indicating that the apparent high energy tail is a rectification effect.

^{*} Takayama, et al, Phys. Rev. Lett. 5, 238 (1960).

[†] Buckley, Proc. Roy. Soc. (London) A290, 186(1966).

An attempt was made to measure the electron distribution function in the overdense region, where rf effects are minimal. In the initial measurements, a hot electron component was detected ($T_h \sim 5T_c$, $n_h \sim 0.1n_c$), but more detailed investigations showed that no unambiguous distinction between actual heating and rf rectification effects could be made. Additionally, measurement of the electron distribution function in the overdense region only is not sufficient to totally characterize the absorption process. Information on the spatial origin of the fast electrons is desirable. The phenomenon of wavebreaking of the linearly converted electron plasma waves, for example, accelerates electrons toward the underdense plasma region, where they may escape the plasma at the chamber boundary without detection. It is apparent that an independent technique must be developed to complement and supplement the probe measurements. To this end we have recently instituted a program for the optical detection of fast electrons.

A half-meter Jarrel Ash monochromator was installed at the QUIPS chamber with line of sight perpendicular to the density gradient and 50 cm in front of the microwave horn. Various Argon neutral and ion lines, whose initial state energies all lie 15 to 20 eV above the ground state, were monitored. The plasma was produced by pulsing the discharge voltage to 60-80 Volts, and line emission was studied during the discharge, in the afterglow, and during the rf, which was pulsed on in the afterglow. Timing of the experiments, and behavior of the plasma density and ArII 4880 Å line emission is sketched in Fig. D-1. In the twenty micro-seconds required to shut off the discharge

voltage, light emission is observed to fall by more than two orders of magnitude, to below detection noise level. In this time, electron density changes negligibly ($\approx 1\%$), and background electron temperature falls from 1.35 eV to 1.20 eV (Fig. D-2). The change in 4880 emission cannot be explained by the small change in background electron temperature, but is due rather to the loss of primary electrons when the discharge voltage is shut off. Thus, line emission is a sensitive measure of energetic electrons.

When the rf is pulsed on in the afterglow, 4880 intensity is observed to increase to a level typically five times that during the discharge, indicating the presence of a high energy tail in the electron distribution. Though the monochromator position was fixed, the "spatial" dependence of light emission could be studied by varying the plasma density in order to change the position of the critical surface relative to the monochromator line of sight. A typical result is shown in Fig. D-3, where the rf was pulsed on for 5 microseconds and density was measured with a Langmuir probe positioned in the monochromator line of sight. Emission is observed to peak near the critical surface, as would be expected if acceleration was due primarily to the resonance absorption process, but the very strong "spatial" dependence was unexpected. It is currently believed that at least two mechanisms are responsible for the observed behavior.

1. Global effects - As the critical surface position is varied, the coupling between the microwave horn and the plasma changes. The change in coupling can be observed by monitoring the reflected microwave power, which varies together with the light emission.

2. Oscillatory electron energy - Electrons in the regions of strong electric field may possess enough energy (dc velocity + oscillatory velocity)² to excite optical transitions. In this case light emission would be a measure of the amplitude of the localized electric fields. By varying the position of a lens in front of the monochromator, a limited spatial scan (15 cm) of the plasma was obtained. It was ascertained that localized peaks in emission indeed are present.

In order to separate the global and local effects described above, a complete spatial scan of the experimental region is necessary. An internal probe drive and optical system is currently under construction, utilizing a light pipe to transmit the optical signal to the monochromator. This work will be continued under ERDA contract number E(04-3)-1281.

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FIGURE D-1: TIMING - SPECTROSCOPIC MEASUREMENTS

FIGURE D-2: a) ArII 4880 Å line emission as a function of time at end of discharge pulse.
b) Langmuir probe characteristics during discharge (A) and in afterglow (B).

FIGURE D-3: ArII 4880 Å emission (sampled during the rf burst [5 μsec , 8kwatt, 1GHz]) and plasma density (sampled after the rf burst), as a function of plasma density at the position of the light intensity measurement.

FIGURE D-3: ArII 4880 Å emission (sampled during the rf burst [5 μsec , 8kwatt, 1GHz]) and plasma density (sampled after the rf burst), as a function of plasma density at the position of the light intensity measurement.