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MICROWAVE SCALING OF LASER
PLASMA INTERACTIONS

FINAL REPORT

MASTER

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1.0 INTRODUCTION AND SUMMARY

Experimental efforts in TRW's Microwave Modeling of Laser Plasma Interactions program have concentrated over the last two years on investigations of electron heating and transport at high incident microwave power ($v_o/v_t \approx 1$). The results of experimental investigations in the QUIPS facility (a four meter long, two meter diameter discharge plasma device) using a 10.6cm wavelength, 1MW peak power microwave pump were described in the December 1978 Final Report for DoE Contract No. EY-76-C-03-1281. Though these investigations successfully addressed some of the physics of heating at the critical surface, they also revealed some of the inherent limitations in modeling laser plasma interactions by microwave interaction with typical discharge plasmas. The target plasmas used at TRW and elsewhere have had properties which make them poorly suited to model many aspects of laser plasma interactions. Our efforts this year have been directed toward the development of more suitable target plasmas, in particular, plasmas with much higher fractional ionization and with boundary conditions approximating those of laser produced plasmas.

The limitations of previous target plasmas and the requirements for improved target plasmas are discussed in Section 2. Two distinctly different approaches were pursued successfully. The first approach, described in Section 3, represents a relatively minor modification of the discharge techniques previously used in the QUIPS facility. Utilizing a combination of the pulsed rf plasma production techniques developed under the previous year's contract with a new pulsed magnetic field technique, we have produced a target plasma possessing all of the desirable properties of previous target plasmas, with an order of magnitude higher fractional ionization and improved boundary conditions. Experiments utilizing this target plasma were halted in favor of pursuing a second technique which represents a major departure from all previous microwave simulation experiments.

The second target plasma production technique is based on plasma production by intense, short pulse laser irradiation of a solid target. The resulting blowoff plasma expands into vacuum and, after a suitable delay time, is irradiated by a pulsed microwave beam. The blowoff plasma properties and preliminary results of microwave interaction experiments are described in Section 4. Our results prove the viability of the technique, and indicate a high potential for impact on the laser fusion program.

2.0 TARGET PLASMAS FOR MICROWAVE SIMULATION OF LASER PLASMA INTERACTIONS

We limit consideration here to inhomogeneous target plasmas with a critical surface present, noting that a target plasma designed for examination of, e.g., Brillouin scatter could have considerably different characteristics. To be in the same pump field regime as is typical of laser plasma interactions, we require $v_o/v_t \sim 1$, and we also require a reasonable irradiated spot size, say $10\lambda_o^2$, where λ_o is the microwave free space wavelength. In the 3cm to 30cm wavelength regime, the maximum source power available at present is ~ 1 MW, limiting the maximum acceptable target plasma electron temperature to a few eV. An important aspect of critical surface phenomena at this pump field intensity is profile steepening. In order for profile steepening to occur during the experimental period, the initial inhomogeneity scale length of the target plasma must be sufficiently short, of order a few λ_o .

The requirements on electron temperature and inhomogeneity scale length are easily met in conventional discharge plasmas, and considerable progress has been made in the investigation of critical surface heating in such plasmas. However, since the heated electrons are highly mobile, electron transport, and indirectly the local heating processes themselves, are greatly affected by the plasma boundary conditions. Laser plasma interactions are characterized by a vacuum-plasma interface on the underdense side, and a dense ($>10^2 n_c$) collisional plasma on the overdense side. In contrast, conventional discharge plasmas are in contact with chamber walls at all boundaries, and the maximum plasma density in the chamber can rarely exceed a few times critical.

In Section 2.1, we describe the characteristics of unmagnetized discharge plasmas used in the past in microwave plasma simulations and examine their limitations.

2.1 UNMAGNETIZED DISCHARGE PLASMA PROPERTIES

The properties of the discharge target plasmas used in the past in the TRW Microwave Simulation program have been described in some detail in references 1 - 5. An rf induction coil or dc discharge cathode at one end of the four meter long QUIPS device (Figure 1) produces a population of

energetic (20-100eV) electrons which create a plasma by impact ionization of an inert gas or Hydrogen. An axial density gradient ($n(z) = n_c(1+z/L)$, $L \geq 50\text{cm}$) is obtained by operating at a sufficiently high neutral gas pressure to confine production to the discharge end of the chamber. A typical axial density profile and the dependence of L on neutral pressure is shown in Figure 2. Microwave plasma interaction experiments are generally conducted in the afterglow of the discharge, when the initial electron distribution is Maxwellian with a temperature which can be varied from .1 to 2.5eV by varying the delay time between shutoff of the discharge and turn on of the microwave pump.

The use of this type of target plasma is severely limited by ionization by energetic electrons produced by microwave absorption. In order to obtain initial inhomogeneity scale length of 50-100 cm, it is necessary to operate at neutral densities $n_n = 2 \times 10^{13} \text{cm}^{-3}$ in Argon. At an incident power of 330kW ($v_o/v_t = .5$), with a microwave pump wavelength of 10.6cm ($n_c = 10^{11} \text{cm}^{-3}$), we measure a hot electron density of $n_h = 1.5 \times 10^{10} \text{cm}^{-3}$ and a hot electron temperature of $T_h \approx 20\text{eV}$ close to the critical layer. The rate of electron-ion pair production by impact ionization of neutrals is then:

$$dn_e/dt = n_h n_n \langle \sigma v_h \rangle$$

where $\langle \sigma v_h \rangle$ is the ionization cross section averaged over the hot electron distribution function. For a Maxwellian hot distribution of temperature 20eV, $\langle \sigma v_h \rangle \approx 3 \times 10^{-8} \text{cm}^3/\text{s}$ in Argon. Using the above parameters for n_h and n_n , we obtain

$$dn_e/dt \approx 10^{16} \text{cm}^{-3} \text{s}^{-1}$$

We have observed this ionization rate in the laboratory, and find that, after 2-3 μs , ionization is the dominant mechanism for profile modification. Since some tens of microseconds are required to reach a steady state profile (due to modification by ponderomotive force), it is clear that the operating neutral density must be reduced by at least an order of magnitude.

Figure 1 - Schematic of QUIPS experimental facility.

FIGURE 2. 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

3.0 PULSED MAGNETIC FIELD, PULSED RF DISCHARGE TARGET PLASMA

As discussed in the preceding section, previous target plasma production methods have relied on fairly high neutral densities (e.g., $2 \times 10^{13} \text{ cm}^{-3}$ in Argon) to confine plasma production to one end of the discharge device. In this new production technique, plasma production is confined to one end of the four meter long QUIPS vessel by applying a weak (≤ 10 Gauss) magnetic field transverse to the chamber axis and placing the source of ionizing electrons (rf induction coil) in the magnetized region. The magnetic field is pulsed off during the microwave plasma interaction experimental interval in order to avoid possible effects of the field on electron heating and transport.

The experimental configuration is shown schematically in Figure 3a. The field coils (80 cm dia., 80 cm apart) produce a steady state 1.5:1 mirror field (5 Gauss at the midplane) transverse to the chamber axis. The rf antenna is a three turn spiral located just inside the mirror throat. Timing of the target plasma production sequence is shown in Fig. 3b. Plasma density in the midplane reaches a steady state value about 400 μ sec into the rf pulse (250 kHz, 5 kW), at which time the rf is shut off. The field coil current is reduced to ~ 0 in 45 μ sec by discharging a 40 μ f capacitor into the coil through a 1 Ω resistor. The midplane field, measured with a magnetic loop probe, with and without plasma present is illustrated in Fig. 3b. Decay of the field is observed to be slowed to some degree by the plasma, but an experimental period of 40 μ sec is available in which the field is less than the earth's field.

A typical axial density profile, sampled in the afterglow of the discharge, with the magnetic field pulsed to 0, is shown in Fig. 3c. We note that at this time the plasma is not yet in contact with the walls, but is rather expanding into vacuum. This configuration thus provides, at least on the underdense side, a boundary condition similar to that encountered in laser-target experiments. Near critical density, the inhomogeneity scale length is 20 cm ($k_0 L = 12$), which, at an operating neutral density $3 \times 10^{12} \text{ cm}^{-3}$, is an order of magnitude smaller than that obtained with the production mechanism previously used. Longer scale lengths, as well as shaped profiles, may be obtained by variations in the timing of production, magnetic field, and experimental time in the afterglow.

This plasma production technique allows an order of magnitude reduction in operating neutral density, and thus an order of magnitude increase in maximum microwave pulse width.

Figure 3. Pulsed rf, pulsed magnetic field plasma production
 a. Schematic of experimental apparatus
 b. Temporal behavior of rf plasma production pulse, measured magnetic field, and plasma density
 c. Axial plasma density profile during the microwave experimental period, obtained by Langmuir probe measurements

4.0 LASER PRODUCED TARGET PLASMA

In this section we describe the results of an experimental investigation of the interaction of a focussed microwave beam with an expanding plasma produced by a laser pulse focussed on a solid target. The experimental arrangement and characteristics of the blowoff plasma are described in Sections 4.1 and 4.2. Next, results of experiments on the heating of the plasma by the microwave beam are described.

4.1 EXPERIMENTAL ARRANGEMENT

The experiments were performed in a 76cm diameter, 120cm long aluminum vacuum vessel, shown schematically in Figure 4. A one joule, 100ns CO_2 laser pulse is focussed (2mm spot diameter) by a 50cm focal length lense onto one end of a .6cm diameter, 2.5cm long cylinder of Barium. The cylindrical target is supported by a 1/4" diameter copper rod inserted into the vacuum system through a nylon feedthru, allowing external control of the target potential with respect to the chamber wall. The laser was a Gentec DD300, which could be operated at a pulse repetition rate of up to 300 pps.

3cm microwaves were focussed on the blowoff plasma with a 70cm diameter parabolic antenna, fed by a low gain horn. The feed horn and waveguide were maintained at atmospheric pressure by enclosing the horn in a vacuum tight quartz radome. The microwave source was a 4J50 magnetron driven by a line type pulser. The magnetron output power was adjustable from 20kW to 150kW by adjusting the voltage, and the pulse width could be chosen as a .4, 1.75, or 2.25 μ s through the switch selectable multi-tap pulse forming network.

Diagnostics consisted of both optical and probe diagnostics. A retarding grid ion energy analyzer enabled combined energy and time of flight diagnosis of the blowoff ion distribution. The analyzer was located on the chamber axis, 50cm from the target, well outside the interaction region. A radial and axial moveable Langmuir probe was used for measurement of the blowoff plasma density profile. Arcing between the probe and target during the interaction period prevented measurements at distances

closer than 3cm from the target. Light from the blowoff plasma was collected by an f/8 system whose optical axis was perpendicular to the chamber axis, and focussed on the entrance slit of a McPherson .3 meter scanning monochromator. The optical signal was detected by a photomultiplier tube and recorded either photographically or by repetitive sampling techniques. A rotatable mirror allowed axial scanning of the plasma.

4.2 BLOWOFF PLASMA CHARACTERISTICS

As discussed in Sections 1 and 2, a number of basic characteristics are required in a target plasma for microwave simulation of laser plasma interactions. Given the limitations on available microwave sources, the target plasma electron temperature must be less than a few eV in order to obtain significant values for v_o/v_t . For studies of critical surface phenomena, the initial density inhomogeneity scale length should be of order $10\lambda_o$ or less. At high incident microwave intensities, the target plasma must be highly ionized, or ionization by heated electrons will be the dominant mechanism for profile modification. In addition to these basic requirements, a target plasma geometry similar to that encountered in laser pellet fusion is desirable. Lastly, a reproducible target plasma is required in order to facilitate the detailed measurements which make microwave simulation experiments attractive.

During the first phase of the investigation, the characteristics of the blowoff plasma without microwave heating were explored in order to determine to what degree the desired characteristics could be approached. It is obvious that the boundary conditions of a laser produced target plasma will closely approximate the desired ones. In particular, the blowoff plasma is characterised by a vacuum interface in the underdense region, in contrast to discharge plasmas which are in contact with chamber walls. The maximum plasma density at turn on of the microwave pulse may be varied from much less than critical to much greater than critical ($\sim 10^{19} \text{ cm}^{-3} = 10^7 n_c$) by varying the delay time between the laser and microwave pulses.

The characteristics of laser produced plasmas have been studied by numerous⁽⁶⁾ investigators since the advent of high power pulsed lasers. At irradiance levels of $10^8 - 10^9$ w/cm², the maximum plasma density is of order 10^{19} cm⁻³ and the maximum electron temperature of order 20 eV. In the first few hundred nanoseconds of plasma expansion, the electrons cool rapidly to less than 1 eV. Langmuir probe measurements indicate an electron temperature of approximately .2 eV in the blowoff plasma 5 μ s after the laser pulse, satisfying the requirement for a low temperature target plasma.

A typical measurement of the blowoff ion distribution by time of flight is shown in Figure 5. In contrast to reported⁽⁶⁾ experiments at high irradiance levels ($>10^{10}$ w/cm²), where two peaks in the ion energy distribution are observed, we find at 2×10^8 w/cm², a distribution with a single peak at approximately 20 eV. We note that, with an electron temperature of .2 eV, the plasma flow speed is highly supersonic ($\sim M10$). This type of target plasma provides an interesting contrast to the subsonic flows encountered in discharge target plasmas.

The degree of ionization was determined through barium neutral to ion line ratios. At distances of more than a few cm from the target surface, the plasma is 97 - 99% ionized. Combined ion energy and time of flight analysis indicates that the density of Ba⁺⁺ is about 10% that of Ba⁺.

The target plasma reproducibility was found to be surprisingly good, a fact attributable to the low surface erosion rate at the low irradiances employed (the ion production rate was approximately 10^{15} /shot). Typically several thousand shots could be made with a variation of $\pm 10\%$ in received ion current at any time on a time of flight probe, discounting laser misfires. This reproducibility was obtainable at any laser repetition rate up to about 7 pps. At higher rep rates, heating of the target surface resulted in ejection of macroscopic size particles, with resulting loss of reproducibility.

FIGURE 4 - Schematic of experimental apparatus for laser produced plasma.

FIGURE 5 - Blowoff ion current received on time of flight analyser located 48cm from Barium target, as a function of the time after 100ns laser pulse.

4.3 EXPERIMENTS ON THE INTERACTION OF PULSED MICROWAVES WITH THE LASER PRODUCED TARGET PLASMA

4.3.1 Electron Heating

Figure 6 shows time integrated single shot photographs of the laser produced plasma with and without microwave heating, taken with an ordinary camera. Without microwave heating, the plasma is luminous out to a distance of about one centimeter from the barium target surface, a result of the rapid electron cooling during plasma expansion. In the second photograph, the blowoff plasma is irradiated with a $2.25\mu\text{s}$, 150 kW microwave pulse initiated $7\mu\text{s}$ after the laser pulse. The greatly increased region of high luminosity indicates that the electron temperature is raised sufficiently by microwave heating to excite Barium ion transitions ($T_e > 2\text{eV}$). As Ba^+ line intensity is fairly insensitive to electron temperature for temperatures above a few eV, Helium was bled into the chamber ($n_{\text{He}} = 10^{13}$) and the H_e singlet to triplet line ratio technique used as a measure of electron temperature. The characteristics of the target plasma and of the microwave plasma interaction were not affected measurably by the addition of the He gas, an observation consistent with the very small electron atom collision cross sections for Helium compared to Barium. The electron temperature, assuming Maxwellian, is given by ⁽⁷⁾

$$T_e = 17.2 I_{4921}/I_{4713} \text{ eV}$$

over the range $6 \text{ eV} < T_e < 90 \text{ eV}$, where I_{4921} and I_{4713} are the intensities of the $4921\text{\AA}$ and $4713\text{\AA}$ lines respectively. Dependence of the 4921 line intensity and T_e determined by the line ratio on distance from the target surface is shown in Figure 7. The data were obtained in a 100ns sampling period starting one microsecond after turn-on of a 150 kW, $2.25\mu\text{s}$ pulse width microwave pulse. The microwave pulse was initiated $9\mu\text{s}$ after the laser pulse. An electron temperature of approximately 60eV is indicated, independent of distance from the target surface. As the data is integrated along a line of sight which passes through both underdense and overdense regions, no definitive information on heat transport can be expected from this technique.

4.3.2 Ion Acceleration

An aspect of the interaction of an intense laser with a solid which has received a great deal of attention is the generation of an energetic ion group, accelerated by the ambipolar fields produced by hot electrons in the underdense region. Observations of the energetic ion distribution have provided important insights into the heated electron distribution and electron heat transport in laser plasma interactions.

This phenomenon of ion acceleration has been completely absent from microwave plasma interaction experiments due to the very different boundary conditions. Since the discharge plasmas used in the past have been in good contact with the chamber walls, the ambipolar potential associated with the electron temperature appears in the plasma sheath at the wall. In the laser produced target plasma we expect ambipolar potentials to develop in the underdense plasma, where a vacuum plasma interface is found. Figure 8 shows the high energy portion of the blowoff ion distribution with and without microwave heating, showing a large increase in the flux of energetic ions with microwave heating.

4.3.3 Target Potential and Electron Heating in Laser Plasma Interaction and Microwave Interaction with Laser Produced Plasma

Some attention has been focussed on the role of the chamber and target holder in laser plasma interactions. Energetic electrons can escape from the target to the chamber walls, charging the target to potentials of order the hot electron temperature. Pearlman and Dahlbacka⁽⁸⁾ first measured the potential of isolated targets irradiated by intense laser light and presented a simple theory relating electron temperature and target potential. Recently, Benjamin, et al⁽⁹⁾ measured target potentials of 180 keV on a large aluminum target irradiated with a 1.2ns CO₂ laser pulse focussed to an irradiance of approximately 1.6×10^{15} w/cm². In an elegant experiment using a glass microballoon target, they demonstrated that large return currents are driven through the target holder (10 μ m glass fibers). This return current may modify electron heating and transport, e.g. by modifying the magnet field structure around the target.

We report here preliminary results of an investigation of the effects of target potential on microwave heating of a laser produced plasma. When the Ba target is floating, target potential reaches 1 kV within 200ns of turn-on of the microwave pulse. The measured target potential and measured (line ratio technique) electron temperature of 70 eV are in rough agreement with the predictions of the model of Pearlman and Dahlbacka. We have examined differences between floating and grounded targets on electron heating and ion acceleration due to microwave absorption. Electron temperature appears to be rather insensitive to whether the target is floating or grounded, but heated electron density in the vicinity of critical density was approximately a factor of two higher for the floating target. The maximum fast ion energy and total fast ion flux were also higher in the case of the floating target. These observations may indicate that the electron temperature is determined by microscopic effects, but that transport, and hence hot electron density and fast ion flux, is dependent on macroscopic electric fields, which are strongly effected by target conditions.

These results, preliminary as they are, indicate that investigations of microwave interactions with laser produced plasmas may have the potential to strongly impact the field of laser target design.

without microwave heating

with microwave heating

Figure 6 - Laser produced plasma, with and without microwave heating.

FIGURE 7. Intensity of HeI4921Å line, and T_e obtained from 4713/4921 line intensity ratio, as a function of distance from target surface. Observations were made one microsecond after microwave turnon, 10 microseconds after laser pulse.

FIGURE 8 - Tail of ion blowoff distribution with and without microwave heating.

REFERENCES

1. R.L. Stenzel, A.Y. Wong, and H.C. Kim, Phys. Rev. Lett., 32, 654, (1975)
2. A.Y. Wong and R.L. Stenzel, Phys. Rev. Lett., 34, 727 (1975)
3. W.F. DiVergilio, A.Y. Wong, H.C. Kim, and Y.C. Lee, Phys. Rev. Lett., 38, 541 (1977)
4. Microwave Simulation of Laser Plasma Interactions, Final Report, LLL Contract 7950105; TRW Report No. 26265-6003-RU-00, May 1977
5. Microwave Scaling of Laser Plasma Interactions, Final Report, U.S. DOE Contract #EY-76-C-03-1281, December 1978
6. A review and references are contained in "Plasmas and Laser Light", T.P. Hughes, 1975, J. Wiley and Sons, New York
7. "Spectral Intensities", R.W.P. McWhirter in "Plasma Diagnostic Techniques", R. Huddleston and S. Leonard, 1965, Academic Press, New York
8. J.S. Pearlman and G.H. Dahlbacka, Appl. Phys. Lett., 31, 414 (1977)
9. R.F. Benjamin, G.H. McCall, and A.W. Ehler, Phys. Rev. Lett., 42, 890 (1979)