Interaction of Intense Submillimeter Radiation with Plasmas

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Abstract—**Recent advances in the development of high power submillimeter lasers have opened up new areas of investigation in the study of laser plasma interactions. These areas include studies of laser-induced gas breakdown and plasma heating at cyclotron resonance, laser-induced breakdown effects in solids, and studies of laser-generated parametric instabilities in arc plasmas. In addition, high power submillimeter lasers can be used for important diagnostic measurements in Tokamak plasmas. These measurements include the determination of ion temperature by Thomson scattering and the measurement of transverse thermal conductivity by resonant local heating.**

I. INTRODUCTION

RECENT progress in the development of high power pulsed submillimeter lasers and tunable sources of submillimeter radiation has opened up new areas of investigation in the interaction of laser radiation with gaseous and solid state plasmas. Power levels in excess of 10 kW in 200-ns pulses have been achieved with 496-μm CH_3F lasers pumped by high power pulsed CO_2 lasers [1], [2]. The use of higher power CO_2 laser radiation should make it possible to increase the output power of CH_3F lasers to the megawatt range. In addition, the noncollinear difference frequency mixing of two continuous CO_2 lasers has resulted in the production of continuous tunable radiation from 70 μm to 2 mm. The power levels obtained from this technique are in agreement with theoretical predictions [3]. On the basis of these results, it is expected that with further developments of new folded noncollinear configurations and the availability of very large crystals of GaAs, it should be possible to develop pulsed sources of high efficiency which approach the Manley–Rowe limit for the difference frequency mixing of two single mode pulsed CO_2 lasers. Hence, generation of tunable submillimeter radiation at megawatt power levels may be attainable.

The use of these new submillimeter sources combined with the availability of magnetic fields of several hundred kilogauss with continuous and pulsed magnets makes it possible to study the breakdown and heating of plasmas using cyclotron resonance effects. Gas breakdown and heating of plasmas can be achieved by means of the existing pulsed CH_3F lasers. For CH_3F laser radiation cyclotron resonance occurs at 216 kG. The resonant effect should reduce the breakdown threshold by orders of magnitude at low pressures and would heat the plasma electrons very efficiently to relatively high temperatures. High power submillimeter lasers can also be used to study breakdown effects in solids. Shallow donor and acceptor impurities in semiconductors play a role in the breakdown process which is similar to that of atoms in gases. Electrons which are frozen into impurity ground states at low temperature can be readily ionized in an avalanche process with submillimeter lasers. The effect of cyclotron resonance upon this breakdown process should be quite dramatic. In addition, two photon absorption processes between even parity impurity states should be observable.

Another application of high power submillimeter lasers involves their use in the study of parametric instabilities. In contrast to the study of parametric instabilities at shorter wavelengths, submillimeter radiation can be used to irradiate well-defined manageable plasmas such as those produced by arcs.

Probably the most important applications of high power submillimeter radiation lie in its use as a diagnostic tool for such plasma machines as the tokamaks. In these devices the plasma frequency occurs in the millimeter region. Hence, the plasma is transparent to the submillimeter radiation. One of the measurements that should be very useful is the Thomson scattering determination of ion temperature. In future Tokamaks it will be difficult to measure ion temperatures in the relatively clean plasmas produced in these machines. However, if the wavelength of the radiation is comparable to the Debye length then the Thomson scattering is characteristic primarily of the fluctuation due to the ionic motion. Hence, the linewidth of the scattered radiation is determined by the ion temperature. The high power radiation in the submillimeter region can also be used to measure the transport coefficients in a Tokamak plasma by resonantly depositing energy in a small region of the plasma and then monitoring the flow of energy away from the deposition point.

II. PLASMA BREAKDOWN AND HEATING

The theory of laser-induced gas breakdown in a magnetic field has been worked out for the resonant case by simultaneously solving the continuity, diffusion, and energy equations [4]. The threshold power for a square pulse of focused laser radiation is given by the following expression for a resonantly circularly polarized wave:

$$W_{th} = \frac{U_i \pi a^2 \epsilon_0 c m}{e^2} \frac{(\omega - \omega_c)^2 + \nu_c^2}{\nu_c} \cdot \left[\frac{1}{\tau} \ln \frac{n_b}{n_0} + D_0 \left(\frac{1}{\Lambda_r^2 (1 + \omega_c^2/\nu_c^2)}\right) + \frac{1}{\Lambda_z^2} + \frac{P_l}{U_i}\right]$$

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where U_i is the effective ionization energy; a the focal spot radius; ν_c the electron atom collision time; $\omega_c = eB/mc$ the cyclotron frequency; n_0 the electron density at the beginning of the avalanche; n_b the density required for breakdown effects such as a decrease in transmission; D_0 the diffusion coefficient at zero magnetic field; $\wedge_r$ the diffusion length perpendicular to the magnetic field; $\wedge_z$ the diffusion length parallel to the field; and P_l the rate at which the energy of an electron is lost by elastic collisions.

In the so-called "short pulse limit" the first term in the square bracket dominates. This limit is appropriate for a wide range of breakdown conditions using the CH_3F laser. In this limit the ratio of breakdown threshold power at resonance to breakdown threshold power at zero magnetic field is given by

$$\frac{W_{th}(\omega_c = \omega)}{W_{th}(\omega_c = 0)} \approx \frac{\nu_c}{\omega}$$

when $\omega^2 \gg \nu_c^2$. Thus the occurrence of resonance absorption can significantly decrease the breakdown threshold power. The result of calculations for the breakdown threshold power for helium at a number of pressures are shown in Table I. In making these calculations ν_c was taken to be equal to $2.4 \times 10^9\ p$ where p is the neutral gas pressure in torr and a was taken to be 5 mm.

In considering the resonant heating of a plasma we shall assume that all of the laser energy is utilized in heating the plasma. We can then determine the plasma temperature from

$$\mathcal{E}_L \approx (3n/2)k_B(T_e + T_i)AL$$

where $\mathcal{E}_L$ is the laser pulse energy, n is the plasma density, T_e is the electron temperature, T_i is the ion temperature, A is the cross-sectional area of the plasma, and L is its length. In order to determine L we assume that the plasma is heated at the leading edge and expands during the heating with the speed of the ions. The length of the plasma is then given by $L = V_T\tau_l$ where V_T is the ion velocity and τ_l is the laser pulse length. Assuming that the electron temperature is about three times the ion temperature

$$L = (k_BT_e/3M)^{1/2}\tau_L.$$

The electron temperature is then given by

$$(k_BT_e)^{3/2} = \frac{\mathcal{E}_L(3M)^{1/2}}{2nA\tau_L}.$$

For $\mathcal{E}_L = 10^{-2}$ J, $\tau_L = 10^{-6}$ s, $A = 10^{-1}$ cm^2, and $n = 10^{15}$ cm^{-3} we find that a hydrogen plasma can be heated to temperatures on the order of 1000 eV.

TABLE I
SHORT PULSE (τ = 200 ns) CH_3F (494 μm)

Pressure	W_{th} (ω_c = 0)	W_{th} ($\omega_c = \omega$)
100 torr	2.4×10^5 Watts	8.0×10^2 Watts
10 torr	2.6×10^6 Watts	7.2×10^1 Watts
1 torr	2.6×10^7 Watts	6.4 Watts

III. BREAKDOWN IN SOLIDS

If the temperature of an extrinsic semiconductor is lowered to liquid helium temperatures the electrons are "frozen" out of the conduction and valence bands into hydrogenic-like impurity states. The electrons can be removed from these states by an avalanche breakdown process. This process is similar to the breakdown process in a gas except that the ionization energy is reduced to tens of millivolts for shallow impurities in such semiconductors as germanium and silicon. The laser power required for breakdown is given by

$$\frac{e^2E^2\nu_c}{m^*\omega^2\mathcal{E}_i} = \frac{1}{\tau_r}$$

where $\mathcal{E}_i$ is the ionization energy of the bound electron, m^* is its effective mass and electron, and τ_r is the characteristic time for recombination. This expression is based upon the assumption that the electron recombination loss is the dominant mechanism in determining the properties of the breakdown process. The threshold power for breakdown is then given by

$$W_{th} = \frac{\pi a^2\epsilon_0 cm^*\mathcal{E}_i\omega^2}{e^2\tau_r\nu_c}.$$

For materials such as germanium and silicon W_{th} is on the order of a couple of hundred watts. The threshold power can be reduced substantially by employing cyclotron resonance breakdown. At resonance it should be possible to reduce the breakdown threshold power to around 100 mW.

IV. PARAMETRIC INSTABILITIES

Laser heating of a plasma by the excitation of the parametric decay instability at the plasma frequency is a basic physical process which may play a very important role in the use of lasers to create high temperature plasmas. Attempts have been made to study the creation of parametric instabilities in plasmas created by laser irradiation of pellets. However, because of the rapidly changing density profiles, the small dimensions, and the short time scales (a few nanoseconds) characteristic of these plasmas, parametric instabilities have not been clearly identified. It has been pointed out by Jassby [5] that the excitation of the parametric decay instability may be very conveniently studied by irradiating dense arc plasmas with intense submillimeter radiation. These plasmas are characterized by relatively well-defined density gradients and by dimensions which contain many free space wavelengths. In addition, the arc plasmas can be run at either a steady state or at a high repetition rate and the characteristic times for changes of temperature or densities would be in the range of 100 ns to 1 μs (determined by the length of the laser pulse), greatly facilitating the diagnostics of the plasma and the interpretation of data.

The parametric decay instability takes energy from the laser radiation, characterized by frequency ω, and converts it into the energy of a Langmuir wave (ω_l) and an ion acoustic wave (ω_i). The instability can be excited only near the cutoff density n_c, where $\omega \approx \omega_l$. For 496-μm radiation from the CH_3F laser, n_c is equal to about 5×10^{15} cm^{-3}.

The threshold intensity of the pump for the excitation of the parametric decay instability is given by

$$I_c = \frac{1}{G}\frac{4n(T_e + T_i)\gamma_L\gamma_i}{\omega_e\omega_i c}$$

where G is the so-called "linear swelling factor" and γ_L and γ_i are the damping rates of the Langmuir and ion acoustic waves, respectively.

If we assume that the electron temperature in the helium arc is around 4 eV, the Langmuir waves are damped mainly by electron–ion collisions. The principal damping mechanism for the ion acoustic waves is ion Landau damping. γ_i/ω_i is then about equal to 0.2 when $T_e = T_i$. Inserting these values into the expression for I_c, taking G to be equal to 7 (which is appropriate for the density gradient in an arc), and setting $n = n_c$ for 496-μm radiation, one finds that $I_c \approx 4 \times 10^4$ W/cm^2. If we assume that the laser radiation can be focused to about 2 mm, the critical power needed is about 5800 W.

The development of high power submillimeter sources should also make it possible to study other parametric processes such as stimulated Raman scattering and stimulated Brillouin scattering.

V. TOKAMAK DIAGNOSTICS

One of the most difficult measurements that must be made for Tokamak plasma machines is that of the ion temperature. It appears that high power submillimeter lasers will provide a unique tool for performing this measurement [6]. According to the theory of Thomson scattering as worked out by Salpeter, there are two components for scattering which depend upon the laser wavelength and the temperatures of the electrons and ions. The two components are the electron and ion scattering. The relative importance of electron and ion scattering is determined by the value of α where

$$\alpha = \frac{\lambda_0}{4\pi\lambda_d \sin \frac{1}{2}\theta}.$$

Here λ_d is the Debye length and θ is the scattering angle. The electron scattering component dominates when $\alpha < 1$. When $\alpha > 3$ the ion scattering component dominates. In this case the Thomson scattering results from the fluctuations of electrons whose motion is determined by the motion of the ions. Hence, the linewidth of the Thomson scattered radiation is determined by the ion temperature. For $\lambda_0 = 496$ μm, $n_e = 5 \times 10^{13}$, and $T_e = 2$ keV, $\alpha > 3$ for $\theta \leq 30°$. In contrast, in order to use 10.6-μm CO_2 laser radiation for measurements of ion temperature it is necessary to work at $\theta \leq 1°$. Scattering experiments at such small angles are extremely difficult.

An appropriate geometry for performing the Thomson scattering measurements is indicated in Fig. 1. The power scattered from a thermal plasma and received by a detector at angle θ is given by

$$P_s(\theta) = P_0 n_e \sigma l \, d\Omega$$

where P_0 and P_s are the incident and scattered powers, $\sigma = 4 \times 10^{-26}$ cm^2 is the Thomson-scatter cross section (appropriate to $\alpha \gg 1$) per unit solid angle, l is the length of the scattering region in the field of view of the detector aperture, and $d\Omega$ is the solid angle subtended by the detector aperture at the scattering region. For $P_0 = 1$ MW, $n_e = 5 \times 10^{13}$ cm^{-3}, $l = 5$ cm, and $d\Omega = 10^{-3}$, $P_s = 1 \times 10^{-8}$ W. A suitable means of detection is a heterodyne system utilizing a Schottky-barrier diode characterized by a response time < 1 ns and a minimum detectable power of 10^{-16}–10^{-17} W/Hz [7].

Scattering measurements using high power submillimeter radiation can also provide information about plasma fluctuations. The intensity of radiation scattered coherently from plasma fluctuations should be at least 100 times greater than the intensity of ordinary Thomson-scattered radiation.

The ion temperature is determined from the width of the central peak of the scattered spectrum; this width should be about 500 MHz for $\theta = 30°$ and ion temperature $T_i = 2$ keV. For detailed investigation of the spectral shape, the signal must be shunted into a multichanne' spectral analyzer. A distinct plasma fluctuation mod(with wavenumber k, such as an acoustic wave, will revea itself as a small peak in the appropriate channel. Th smallest wave frequency detectable is limited by th linewidth of the 496-μm radiation, viz., about 20 MH or less. The spatial profiles of T_i and fluctuation amplitud can be determined by scanning the focal spot in the radi direction.

Another potential application of high power submill meter laser radiation in the diagnostics of Tokama plasmas is its use in measurements of the transvers thermal conductivity [6]. This measurement would b made by rapidly depositing a large amount of energy in small region of the plasma and measuring the chang of temperature at various positions as the energy flow

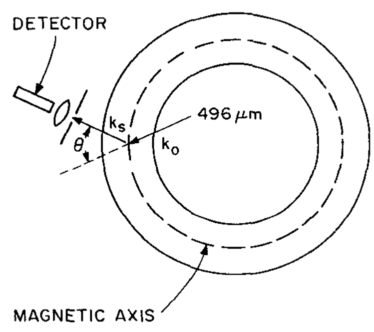

Fig. 1. Geometry for Thomson-scatter experiment.

away from the deposition point. The strong local absorption could be obtained by focusing the submillimeter radiation into a region of the Tokamak where the inhomogeneous field, which varies across the cross section of the plasma, corresponds to a harmonic of the cyclotron resonance frequency.

Heating experiments on Stellerator plasmas with microwaves indicate that it should be possible to obtain 100-percent absorption of the submillimeter radiation at the second harmonic. Quantitive measurements of the absorption must be made in order to evaluate the effectiveness of this technique for heating at the third harmonic or higher. Absorption of CH_3F radiation at the second harmonic requires $B = 108$ kG, so that the use of this laser is presently limited to the M.I.T. Tokamak and the Italian Tokamak at Frascati. However, the development of tunable submillimeter radiation sources by the mixing of CO_2 laser beams in crystals may result in substantial power at $\lambda_0 \approx 1$ mm, giving rise to the possibility of obtaining second harmonic absorption at 50 kG. The advent of tunable high power sources will also allow one to explore the spatial dependence of the plasma properties without varying the magnetic field.

In order to calculate the amounts of local absorption we shall use the following Tokamak parameters: minor radius $a = 30$ cm, major radius $R_0 = 100$ cm, $B_0 = 90$ kG at $r = 0$, where $r < a$ is the plasma radius, and plasma current = 400 kA. We will assume that the plasma is heated with a 1-J 1-μs pulse of submillimeter radiation focused down to a spot 8 mm in width. The geometry involved in the thermal conductivity measurement is shown in Fig. 2. The thickness δ of the resonant absorption layer at $R = 83$ cm results principally from the beam shape and the spatial inhomogeneity of B, and we estimate that $\delta \lesssim 0.5$ cm. A large part of the absorbed energy is carried around the magnetic surface in about 1 μs, and this process leads to negligible heating. However, at a given plasma radius r, a fraction $(r/R)^{1/2}$ of the electrons are trapped in "banana" orbits, this fraction being 45 percent at $r =$ 20 cm, for example. These trapped electrons orbit in banana trajectories of typical length $L \approx 200$ cm and width 0.03 cm. Thus, for an 8-mm focal spot diameter, the volume of the trapped-electron-heated region is $V = 0.8 \times \delta \times L = 80$ cm^3. If 20 percent of an incident energy of 1 J (i.e., a 1-MW 1-μs-long pulse) is absorbed by these electrons, the increase in $T_{e\perp}$ is $\Delta T_{e\perp}/T_{e0} \approx 0.1(T_{e0} = 2.0$ keV, $n_e = 5 \times 10^{13}$ cm^{-3}). Thomson scattering of Ruby laser radiation from electrons can be used to monitor $T_e(t)$ in the absorption layer, as shown in Fig. 2. For

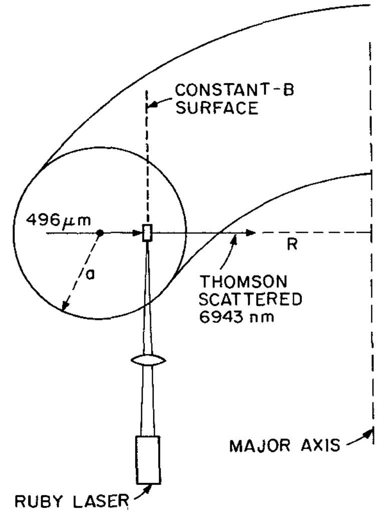

Fig. 2. Geometry for local heating experiment.

$\Delta T_e/T_{e0} \ll 1$, we may assume a constant transverse thermal conductivity. If the incremental temperature has a Gaussian profile of width δ, and toroidal loss can be neglected, then

$$T_e(t) = T_{e0} + \frac{\Delta T_e \frac{1}{2}\delta}{[(\frac{1}{2}\delta)^2 + 4D_\perp t]^{1/2}}$$

where $D_\perp$ is the transverse heat diffusivity and ΔT_e is the temperature increment at the end of the laser pulse. By varying the toroidal field current, the position of the absorption layer $(\omega = 2\omega_{ce})$ can be varied, so that $D_\perp$ can be determined as a function of radius.

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