Thermal Decay of an Infrared-Laser-Heated Arc Plasma*

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A small region of a magnetically confined, fully ionized arc plasma of density 2×10^{16} cm^{-3} and electron temperature of 1.3 to 1.7 eV is heated by 0.7 eV with pulsed CO_2-laser energy. The measured thermal decay is accounted for by classical collisional diffusion along the magnetic field.

Several proposals have recently been made for the CO_2-laser heating of dense θ-pinch plasmas,[1] and for the breakdown of high-pressure gas and heating to thermonuclear temperatures.[2] Experiments on laser heating of θ-pinch plasmas have been initiated by Engelhardt *et al.*,[3] and by Vlases and Ahlstrom.[4] An extensive experimental study of CO_2-laser gas breakdown and heating was recently reported by George, Bekefi, and Ya'akobi.[5]

For certain basic studies of laser heating of plasmas, it appears that the dense electric arc has several advantages over the breakdown and θ-pinch plasmas: The steady-state arc operation allows the large repetition rate available with pulsed CO_2 lasers to be fully utilized, at densities almost as large as those available in pinches. The arc plasma is stationary and Maxwellian, so that energy absorption in a confined ambient plasma can be studied.

In this Letter we describe exploratory heating experiments and thermal diffusion measurements performed with the 10.6-μm radiation of a pulsed CO_2 laser and a magnetically confined, fully ionized arc column of density $\sim10^{16}$ cm^{-3}. The decay of the temperature increment provides what is probably the first direct measurement of the thermal diffusion coefficient in a very dense magnetically confined plasma. This value is in good agreement with classical electron heat conduction along the magnetic field. In addition, we have observed the propagation of the heat pulse along the magnetic field.

Consider an electromagnetic wave propagating radially through a cylindrical plasma confined by a strong magnetic field, B, in the z direction. Electromagnetic energy is absorbed by inverse bremsstrahlung. If ions and electrons thermalize rapidly, the rate of energy absorption is

$$\frac{3}{2}\frac{(Z+1)}{Z}nk\frac{\partial T}{\partial t}=\frac{W_0}{l^2L}(1-e^{-2L/d})+\frac{\partial}{\partial z}K\frac{\partial T}{\partial z}, \quad (1)$$

where W_0 is the incident power, l is the width and L the length of the absorbing region, T is the temperature of both electrons and ions, n is the electron density, the absorption length is

$$d=2\frac{c}{\nu_e}\left(\frac{\omega}{\omega_p}\right)^2\left(1-\frac{\omega_p^2}{\omega^2}\right)^{1/2}, \quad (2)$$

with ω_p the plasma frequency and ν_e the electron-ion collision frequency, and the electron thermal conductivity along B is[6]

$$K=\frac{1.84\times10^{-12}T^{5/2}}{Z\ ln\Lambda}\ \text{W/cm deg.} \quad (3)$$

The second term on the right-hand side of Eq. (1) can be approximated by $-K(T-T_0)/b^2$, where T_0 is the initial temperature of the ambient plasma and b is the temperature scale length. At small T, this term can be neglected, but as electromagnetic energy is absorbed, this term increases rapidly in magnitude, and a final "equilibrium" temperature T_f determined by electron heat conduction is attained, viz.,

$$T_f^4(T_f-T_0)=8.9\times10^{-17}Z^2W_0n^2(b/l)^2. \quad (4)$$

At the end of the heating pulse, the temperature decays by electron heat conduction along B, if $\omega_{ce}\tau_c>1$. We assume a Gaussian incremental temperature profile at $t=0$: $T(z,0)=T_0+T_1\exp(-z^2/b^2)$. If $T_1\ll T_0$, then K can be regarded as approximately constant. Under these conditions the solution to the heat diffusion equation, Eq. (1), when $W_0=0$ is precisely

$$T(z,t)=T_0+T_1b\exp\left(-\frac{z^2}{b^2+4Dt}\right)(b^2+4Dt)^{-1/2}, \quad (5)$$

where

$$D=2KZ/3(Z+1)nk. \quad (6)$$

The heat pulse propagates along B, and the time it takes for the temperature at z to reach its maximum value $T_M(z)$ is

$$t_M(z)=(2z^2-b^2)/4D, \quad z^2>\tfrac{1}{2}b^2, \quad (7)$$

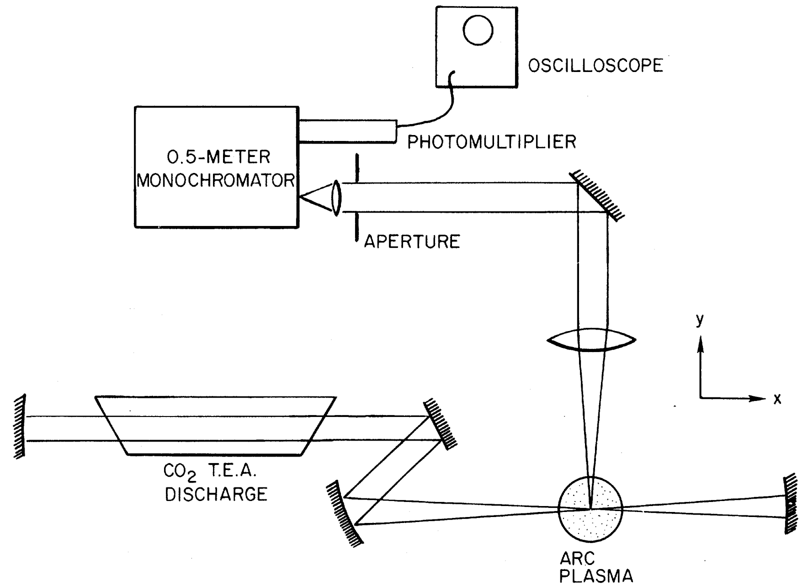

FIG. 1. Experimental setup to measure CO_2-laser heating.

and

$$T_M(z)=T_0+T_1 be^{-1/2}/\sqrt{2}|z|, \quad z^2>\tfrac{1}{2}b^2. \qquad (8)$$

This analysis is valid when the acoustic expansion time is long compared to the thermal diffusion time.[7]

The steady-state electric arc is struck between water-cooled electrodes separated by 8 cm in an axial magnetic field of up to 10 kG.[8] The gas used is argon at a pressure P between 5 and 70 Torr. The arc current J is as large as 800 A in a current channel of 1.3 cm diam. The radial variation of electron temperature T_e and the densities of singly and doubly ionized argon lines are determined by spectroscopy, using Abel inversions. These measurements show that T_e varies by 7%, and the electron density, n, varies by less than 20% between the axis and the edge of the current channel at $r=0.6$ cm. Outside the current channel, both n and T_e decrease rapidly with radius. Midway between the electrodes, T_e is in the range 1.3 to 1.7 eV, depending on the values of B, J, and P. The electron density is in the range (1 to 3) $\times 10^{16}$ cm^{-3}, as determined by spectroscopy and the cutoff of 337-μm laser radiation. No neutral argon lines are observed for $P<60$ Torr and $J>200$ A. This result is expected since calculated thermodynamic properties of argon plasmas[9] show a degree of ionization of 98% or more at $T_e \geq 1.25$ eV at 7.6 Torr or $T_e \geq 1.6$ eV at 76 Torr.

The CO_2 laser is a resistive-pin transversely excited atmospheric laser[10] that normally delivers a total external output of 0.8 J in a pulse of 250 nsec full width at half-maximum, followed by a 1-μsec low-power tail. In order to increase the energy deposited in the plasma, the arc chamber is placed inside the laser cavity[11] (Fig. 1). An intracavity mirror system of 35-cm focal length focuses the cavity energy to a measured focal spot of 2 mm diam at the center of the arc column, and with 4.8 cm depth of focus.[12] Refraction of the 10.6-μm radiation at the plasma densities used has negligible effect on the lasing action.

The electron temperature in the arc is monitored with an optical system feeding a 0.5-m monochromator and a Dumont 6467 photomultiplier (Fig. 1). At the densities used, thermalization of electrons and ions is always completed during the 300-nsec laser pulse. Thus in the following, T_e is also the ion temperature.

Laser-induced enhancement of spectroscopic signals was studied at $B=3$ to 9.5 kG, $J=200$ to 800 A, and $P=5$ to 70 Torr. The resolution of the monochromator was set at 4 Å. Figure 2 shows the photomultiplier output for the Ar II 4348-Å line when $B=7.5$ kG, $J=500$ A, and $P=50$ Torr. The signal rises to its maximum value during the 300-nsec laser pulse, then decays to the undisturbed value in about 10 μsec. (The noise on the traces results from shot noise at the cathode of the photomultiplier.)

The optical receiving system (Fig. 1) has arbitrary resolution in the x and z directions, but views the entire arc current channel in the y direction (Fig. 1). Since T_e and n are nearly uniform throughout the current channel diameter of

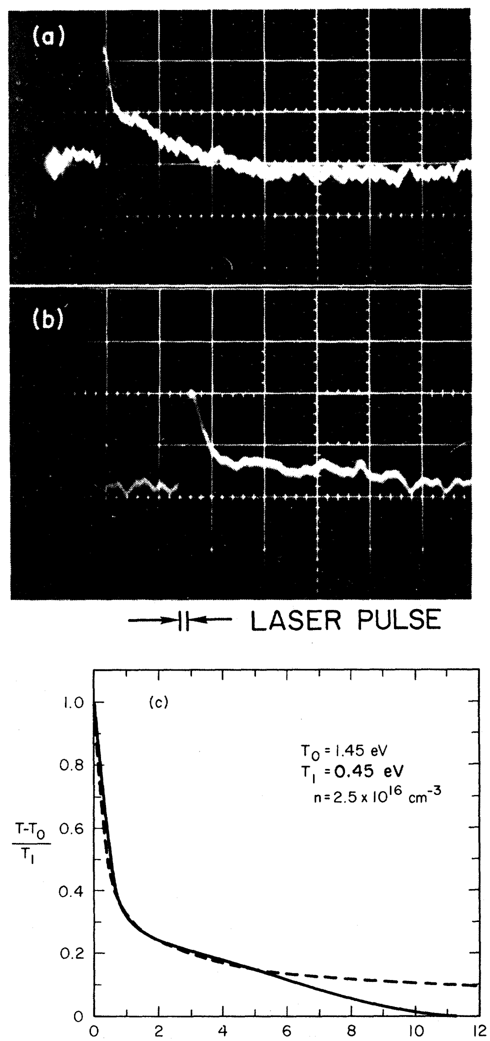

FIG. 2. (a) Photomultiplier output at λ 4348 Å, for B $=7.5$ kG, $J=500$ A, $n=2.5\times10^{16}$ cm^{-3}. Horizontal scale is 5 μsec/cm. Oscilloscope is triggered by the laser discharge current. (b) As in (a), with horizontal scale 2 μsec/cm. (c) Solid line is observed time variation of temperature increment from (b). Dashed line is theoretical variation from Eq. (5).

13 mm, and since the laser spot size is 2 mm, then if S is the spectral line signal and I is the spectral intensity from the heated region, $\Delta I/I_0 = 6.5\Delta S/S_0$, where I_0 and S_0 are the initial undisturbed values. The proportion of Ar II in the plasma, n^+, depends on T_e through the Saha equation, and $I(T_e) \propto n^+(T_e)\exp(-eE_m/kT_e)/U(T_e)$, where E_m is the energy of the upper level of the spectral line, and $U(T_e)$ is the partition function.[13] For the Ar II 4348-Å line, $I(T_e)$ has a maximum at $T_e \approx 1.9$ eV, then falls to 1% of the maximum at $T_e = 2.8$ eV. Since the line intensity S never decreased upon application of the laser energy, the maximum T_e attained was less than 2.8 eV. At the largest density, $n=3\times10^{16}$ cm^{-3}, $\Delta S/S_0$ corresponded to a factor of 7.5 increase in I. This means that the initial T_e of 1.4 eV increased by at least 0.5 eV to the maximum of the $I(T_e)$ curve at 1.9 eV. Boltzmann plots of the line intensities of Ar II 4348, 4549, and 3546 A indicated a maximum T_e of 2.1 eV, or a maximum temperature increment of 0.7 eV.

The intracavity power W_0 is estimated by the method described in Ref. 11, taking into account reflection by the salt windows of the vacuum chamber. The maximum theoretical value of T_e is obtained from Eq. (4), using $W_0 = 5\times10^6$ W, $n=3\times10^{16}$ cm^{-3}, $Z=2$, $b=1.2$ mm, and $l=2$ mm. The calculated T_f is 4.6 eV, requiring 15 mJ; this energy includes the energy for second ionization of argon ions, and for ionization and heating of incident neutrals. The discrepancy between observed and calculated temperatures may be partly due to expansion of the heated region during the laser pulse, or, most probably, to substantial absorption of the intracavity laser energy in the salt windows of the vacuum chamber.[11] (The windows gradually become damaged by radiation from the arc.)

The increase in spectral intensity of λ 4348 Å is a linear function of $T_e - T_0$ provided that T_e is not too close to the maximum ($T_e \approx 1.9$ eV) or to the low-temperature tail of $I(T_e)$. Thus, within these limits the temperature increments can be read directly from the photomultiplier output. Figure 2(c) shows $T_e - T_0$ versus time for the signal of Fig. 2(b).

The theoretical time variation of T_e is given by Eq. (5). For the case of Fig. 2, $T_0 = 1.45$ eV and $T_1 = 1.9$ eV. The quantity D is calculated from Eq. (6) using an "average" $T = 1.6$ eV and $Z = 1.2$. Figure 2(c) shows the theoretical value of $T_e(0,t)$, using an initial Gaussian incremental temperature profile with $b=1.2$ mm. The agreement with experiment is good, implying that the value of thermal conductivity given by Eq. (3) is accurate, and that thermal conduction is principally by electron diffusion along the magnetic field.

The acoustic propagation time across the absorption region of 2 mm is 650 nsec and acoustic expansion would tend to reduce the density in the heated region. However, this process is of minor importance because the rapid decrease of T_e during the 650 nsec reduces the axial pressure gradient, and any decrease in n would result in

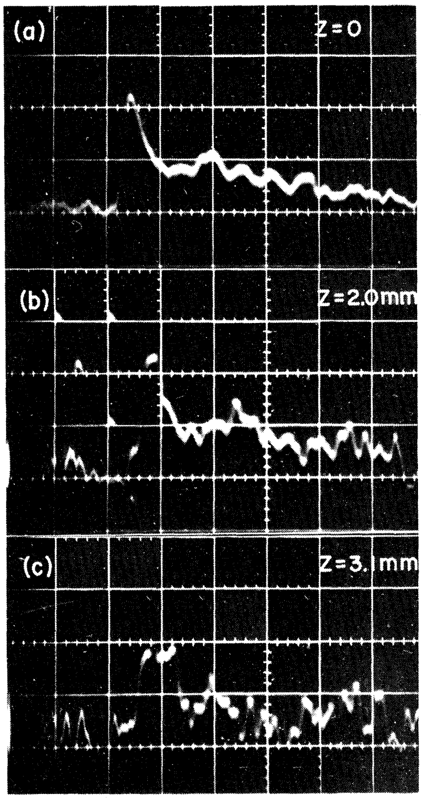

FIG. 3. Photomultiplier output at λ 4348 Å. Quantity z is distance along magnetic field from center of laser focus. Horizontal scale is 2 μsec/cm. Vertical scales are (a) 20 mV/cm, (b) 10 mV/cm, and (c) 5 mV/cm.

an even more rapid decrease of T_e. (In the equilibrium plasma there is no z variation in n or T_e within 1 cm of either side of the laser focal spot.)

The expansion of the temperature pulse along B was observed with a resolution of the optical receiving system of 0.9 mm in the z direction. Photomultiplier signals at $z=0$, 2.0, and 3.1 mm are shown in Fig. 3, the amplitude scale decreasing by a factor of 2 in each successive photograph. At distances $z^2 \gg \frac{1}{2}b^2$, the laser absorption region can be regarded as a point source, and Eq. (5) becomes the Green's function for the heat flow problem.[14] The familiar broadening of the Green's function with distance from the source is evident in Fig. 3. The theoretical maximum amplitude of the temperature pulse is given by Eq. (8), and is in reasonable agreement with the measured axial decrease in maximum amplitude. Equation (7) predicts that at $z=3.1$ mm, maximum temperature should be attained 1.5 μsec after the maximum at $z=0$. This delay is to be compared with the experimental value of 1.0 μsec.

In summary, we have used CO_2-laser energy to heat a stationary, fully ionized, magnetically confined arc plasma by a temperature increment of 0.7 eV. The thermal decay of the heated region is accounted for by classical electron heat conduction along the magnetic field. The laser-heating technique should find use in the determination of other transport properties of very dense plasmas.

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[12]The focused spot size is the distance between $1/e$ amplitude points in the radial intensity profile, at the plane of maximum intensity. This quantity was calculated for the fundamental mode and found to be 0.88 mm. The depth of focus is the distance along the laser axis over which the radiation intensity is at least 90% of the value at the focal spot, and was determined to be 4.8 cm. The calculations were based on the method of H. Kogelnik and T. Li, Proc. IEEE 54, 1312 (1966).

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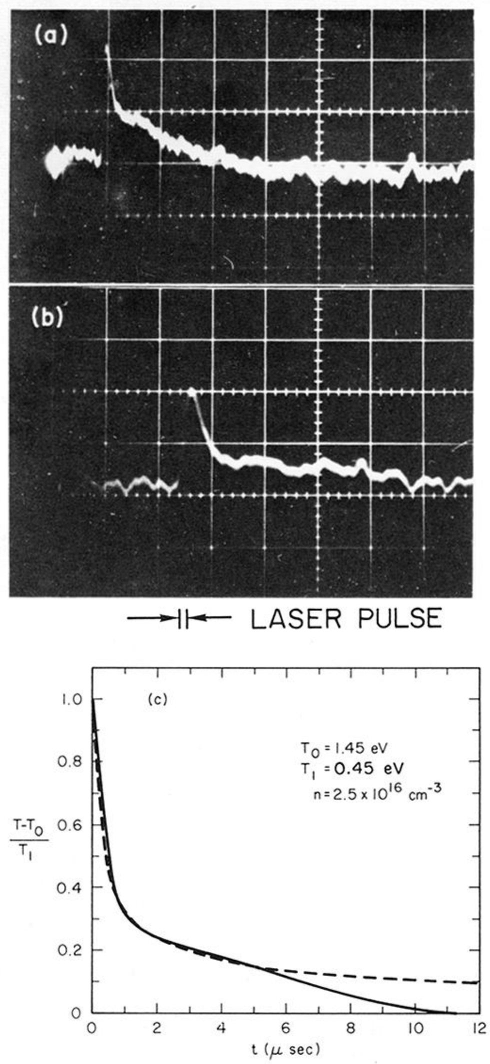

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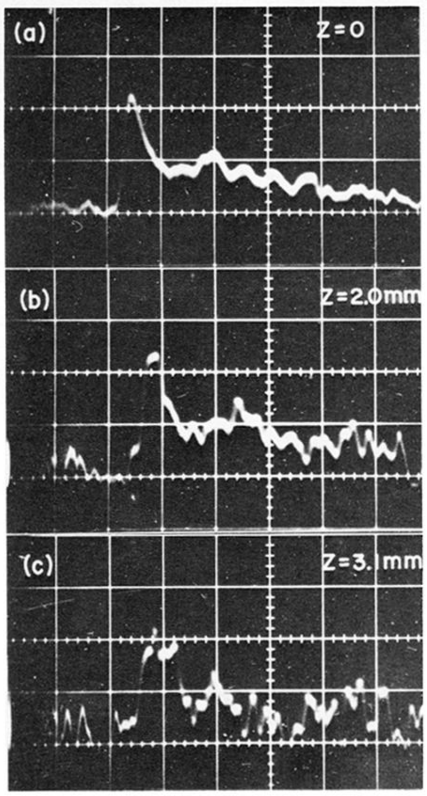

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