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Multiple-Pass Laser Heating of a Magnetically Confined Plasma

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MULTIPLE-PASS LASER HEATING OF A MAGNETICALLY CONFINED PLASMA

by

Stanley Humphries, Jr.

ABSTRACT

If the plasma to be heated is placed inside the optical cavity of a laser, a multiple-pass system allowing on the order of 100 passes through the plasma can result. Plasma conditions necessary to assure a stable cavity are derived. An experiment is described in which it is expected to significantly raise the temperature of plasma produced in a z-pinch entirely by inverse Bremsstrahlung. It may be possible to use the plasma to Q-switch the laser to make more efficient use of the available energy.

I. INTRODUCTION

In this report a multiple-pass arrangement is described for heating a magnetically confined plasma. Figure 1 shows that the plasma is located within the optical cavity of the laser and allows perhaps 100 passes through the plasma. We will show that stable cavities can result even with very long plasma columns. Use of the closed cavity system to investigate laser-plasma interactions in current laboratory plasmas will be emphasized. Numerical examples will be based on an experiment currently in preparation. Using the plasma produced by a stabilized z-pinch should allow possible absorption of almost the entire energy of a 20 J pulsed CO₂ laser. Interpretation of results will be facilitated by the highly uniform radiation density throughout the length of the plasma column.

Dawson et al.¹ show that heating a magnetically confined plasma is a conceivable procedure for obtaining fusion conditions. The long absorption length for the radiation coupled with end losses from the proposed θ -pinch configuration necessitates on the order of a 1-km-long system. The resulting large plasma volume would require a laser with an output power of 1 to 10 MJ. If the end loss problem can be alleviated, the multiple-pass arrangement described may reduce the problem of long absorption lengths.

Fig. 1. Experimental arrangement for multiple-pass laser plasma heating.

II. STABILITY OF THE LASER CAVITY

A hemispherical cavity has been chosen in Fig. 1 to minimize the width of the laser mode within the plasma and to maximize the width in the laser discharge chamber. A primary question is whether or not this configuration can be stable. A simple model using geometric optics will be used to investigate stability criteria. Figure 2 shows an infinite optical cavity equivalent to that of Fig. 1 with appropriate ray transfer matrices² entered under the various elements. The plasma is assumed to have a length d_2 with sharp axial boundaries. Because it is expected that $\omega_p^2 \ll \omega^2$, the average index of refraction closely equals 1, and reflection at the boundaries is negligible. Over the cross-sectional area filled by the laser mode, radial electron density variations are approximated by a parabolic dependence such as

$$n_e(r) = n_{e0} (1 \pm \alpha r^2). \quad (1)$$

In the limit that $\omega_p^2 \ll \omega^2$, the index of refraction varies radially as

$$n(r) \approx 1 \pm n_2 r^2 \text{ where } n_2 = \alpha \frac{\omega_p^2}{\omega^2} \quad (2)$$

For the minus sign (corresponding to a hollow density distribution), the ray transfer matrix for the plasma is that given in Fig. 2. For the plus sign the trigonometric functions are replaced by hyperbolic functions. The total ray transfer matrix for one pass through the system is computed by multiplication of the individual matrices. The system is stable if the magnitude of the trace of the total matrix is less than 2. This implies that

$$\left| \begin{pmatrix} 1 - \frac{2d_1}{R} & \cos 2\sqrt{n_2}d_2 \\ -\left(\frac{1}{R\sqrt{n_2}} + \sqrt{n_2}d_1\left(1 - \frac{d_1}{R}\right)\right) & \sin 2\sqrt{n_2}d_2 \end{pmatrix} \right| < 1 \quad (3)$$

Fig. 2. Optical equivalent of Fig. 1.

for the hollow plasma density distribution. Here R is the radius of curvature of the spherical mirror, and d_1 is the distance from this mirror to the plasma boundary.

When the product $2\sqrt{n_2}d_2$ is of the order of 1 or larger, refraction effects in the plasma are significant. For almost all practical cases density distributions decreasing from the center are unstable. Thus only hollow distributions, such as are expected to occur in the initial implosion of a pinch, will be of use.

For a hollow profile the two terms in Eq. (3) will be considered separately. When $2\sqrt{n_2}d_2 = 0, \pi, 2\pi, \dots$ the condition for stability becomes $-1 < (1 - 2d_1/R) < +1$, equivalent to the result obtained for a normal laser if the length occupied by the plasma is neglected. This occurs because the plasma

ray transfer matrix becomes unity in this limit, and all rays leave the plasma with the same displacement and angle with which they entered. When $2\sqrt{n_2}d_2 \approx \pi/2, 3\pi/2, \dots$, the stability condition is

$$\left| \frac{1}{R\sqrt{n_2}} + d_1\sqrt{n_2}\left(1 - \frac{d_1}{R}\right) \right| < 1 \quad (4)$$

Depending on choices of d_1 and R relative to n_2 , the cavity may be either stable or unstable in this limit.

During the compression phase of the plasma, the average electron density increases, and the radial extent of the plasma decreases. The corresponding increase in n_2 may cause the product $2\sqrt{n_2}d_2$ to pass through one or more of the limits mentioned above. This raises the possibility of switching the laser using the plasma by a suitable choice of parameters so that the limit represented by Eq. (4) is unstable. In this way it may be possible to double pulse the laser to use more efficiently the initial population inversion. It should be remembered, however, that, because of their large gain (over 50%), CO_2 lasers can lase even with an unstable cavity. More detailed calculations are necessary to determine if losses can be made high enough in the unstable limit to prevent lasing.

The following example illustrates that, with parameters typical of the experiment in preparation, it is possible to achieve both stable and unstable limits. The quantity n_{e0} is chosen to equal $5 \times 10^{16} \text{ cm}^{-3}$, giving $\omega_p = 1.3 \times 10^{13} \text{ sec}^{-1}$ compared to the laser frequency (for 10.6μ radiation of $\omega = 1.8 \times 10^{14}$). We assume that there is a 20% rise in density 1 cm from the axis, implying that $n_2 = 10^{-3}$; $d_2 = 30 \text{ cm}$ so that $2\sqrt{n_2}d_2 = 1.9$, well into the refraction dominated case. Hopefully it will be possible to extend $2\sqrt{n_2}d_2$ to 3.14.

Where $2\sqrt{n_2}d_2 = 1.57$, the ratio of d_1 and R can be adjusted, $d_1 = r/\alpha$. Equation (4) becomes

$$R^2 \sqrt{n_2} (1 - 1/\alpha) - R + \frac{1}{\sqrt{n_2}} = 0. \quad (5)$$

A real solution occurs if $1 < \alpha < 1.33$. This constrains R such that $1/\sqrt{n_2} < R < 2/\sqrt{n_2}$. In the

example used, R must be less than 63, and hence d_1 is less than 47 cm. The discharge chamber used has a length of about 1.5 m so that in this limit the cavity should be unstable.

The paraxial ray approximation has been used in the above analysis. It is also necessary to show that the laser mode pattern occupies a small cross-sectional area compared to the plasma. In the following, we assume the TE_{10} mode, $2\sqrt{n_2}d_2 = \pi$, $d_2 = 30$ cm, and $2d_1 = R$. The beam width at the entrance to the plasma is $w_0 = \lambda d_1 / \pi$, and the beam width at the spherical mirror is $w_s = \sqrt{2} w_0$. Rays entering with displacement x_1 and zero entrance angle oscillate about the axis with maximum displacement x_1 . The maximum displacement is of the order of w_0 that, for $d_1 = 2m$, equals 2.6 mm. Rays entering with zero displacement and angle x_1' reach a maximum displacement $x_2 = x_1' / \sqrt{n_2}$. The maximum angle is approximately w_s / d_1 so that the maximum displacement is about 0.3 mm. Thus the mode would be expected to have a width of less than 3 mm, which should be small compared to the radius of the plasma.

There is a case of light propagation through the plasma that has an exact solution and is of particular interest in the heating of a long plasma column. If a Gaussian beam, propagating through a plasma whose index of refraction is given by Eq. (2), has an infinite radius of curvature and a beam width given by

$$w = \left(\frac{\lambda}{\pi} \right)^{\frac{1}{2}} \left(\frac{1}{n_2} \right)^{\frac{1}{4}}, \quad (6)$$

then the beam will propagate indefinitely without a change in its parameters.³ If n_2 is known, additional optics can be introduced into the discharge chamber to match modes at the plasma boundary. Because w is an insensitive function of n_2 , the match need not be exact. Of particular interest is the fact that w is small, even for very small n_2 . For instance, with $\lambda = 10.6 \mu$ and $n_2 = 10^{-3}$, w equals 1 mm. Thus the beam can be made thin compared to the plasma column even for long plasmas. The resulting strong localized heating coupled with the fact that only a small n_2 is necessary makes it more probable that the radiation can maintain a hollow density profile along the axis of the plasma.

A long plasma would thus act as a dielectric

waveguide. Lasers incorporating such waveguides within their optical cavities have been operated successfully.⁴

III. PLASMA REQUIREMENTS

For the experiment to be meaningful, the plasma energy should be changed significantly by the laser radiation. Also if the absorbed energy is comparable to or greater than the initial energy of the plasma, there is a chance that the heating, strongly localized at the center, will help to maintain the hollow density profile. The nature of the plasma is determined mainly by the available laser energy.

To get a rough estimate of the desired parameters, we assume that the plasma has some initial spatially averaged density and electron temperature, n_{e0} and kT_e . The inverse Bremsstrahlung absorption length will be calculated from these quantities. The plasma has length d_2 and cross-sectional area A . Assuming $T_i \sim T_e$, the initial energy is

$$E_p = 2Ad_2 n_{e0} kT_e.$$

The inverse Bremsstrahlung absorption length is given by¹

$$L = \frac{5 \times 10^{27} (kT_e)^{3/2}}{n_{e0}^2 \lambda^2} \quad (7)$$

with n_{e0} in cm^{-3} , kT_e in eV, and λ in cm. For $d_2 \ll L$, the fractional absorption in one pass through the plasma is d_2/L . If T represents the fractional losses due to other causes (i.e., mirror loss), then the fraction of absorbed energy lost per pass through the system is

$$f = \frac{d_2/L}{d_2/L + T}. \quad (8)$$

All energy is eventually lost; therefore the total energy absorbed by the plasma is fE_L , E_L being total energy of the laser pulse. The criterion for significant plasma heating - that the absorbed energy be equal to or greater than the initial plasma energy - can be written

$$fE_L > E_p. \quad (9)$$

Figure 3a shows a plot of permissible values of n_{eo} vs kT_e for the following parameters: $\omega = 1.8 \times 10^{14}$ sec $^{-1}$; $A = 3$ cm 2 ; $d_2 = 30$ cm; and $E = 20$ J. Because mirrors having $R = 0.995$ are currently available, T is chosen equal to 0.005. Figure 3b shows a plot of total energy absorbed for n_{eo} and kT_e on the limiting line of Fig. 3a. The best region is that between $n_{eo} = 10^{16} - 10^{17}$ cm $^{-3}$. Here a large fraction of the laser energy is absorbed, and the highest initial plasma temperatures are permissible.

Fig. 3a. Permissible plasma parameters allowing absorbed energy to be equal to or greater than the initial plasma energy. ($E_l = 20$ J, $T = 0.005$, $A = 3$ cm 2 , $d_2 = 30$ cm)

Fig. 3b. Absorbed energy for n_{eo} and kT_e taken on the limiting curve of Fig. 3a. $E_l = 20$ J.

IV. EXPERIMENTS

A transverse discharge, CO $_2$ -N $_2$, laser with an expected E_l of 20 J is under construction. A 30-cm z-pinch with parameters expected in the range shown in Fig. 3a is also being developed. Because this device is being constructed to test diagnostics measuring $n_e(r)$, kT_e , and kT_i , it will be convenient to incorporate the experiment discussed. The

expected range of parameters of the z-pinch is plotted in Fig. 3a.⁵

Faraday rotation of the laser radiation passing through the plasma column is caused by axial fields. In the z-pinch an axial stabilizing field in excess of 1 kG will be necessary. In one double pass through the plasma, the plane of polarization of the radiation will be rotated an angle

$$\theta = \left(\frac{\omega_p}{\omega} \right)^2 \frac{\omega_b d_2}{c} \quad \text{where } \omega_b = \frac{eB_z}{m_e c}, \quad (10)$$

with $B_z = 1000$ g, $n_{eo} = 5 \times 10^{16}$, and $\theta = 1.8 \times 10^{-2}$. The Brewster windows, which totally transmit only one polarization, will cause excessive losses because the radiation must make many passes through the system. We plan to use dielectric coated Itran windows to separate the discharge chamber from the z-pinch.

If lasing can be achieved, the closed cavity system seems attractive for heating experiments on current laboratory plasmas and also may prove useful in larger plasma devices. Q-switching rise-times of the order of 100 nsec have been achieved in a relatively long CO $_2$ laser⁶ so that plasma switching of the laser should be possible if losses can be made high enough in the unstable limits. This will ensure that the laser fires only when the radiation can be contained by the plasma.

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