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Laser Beam Trapping and Propagation in Cylindrical Plasma Columns*

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ABSTRACT

An analysis of the scheme to heat magnetically confined plasma columns to kilovolt temperatures with a laser beam(1) requires consideration of two propagation problems. The first question to be answered is whether stable beam trapping is possible. Since the laser beam creates its own density profile by heating the plasma, the propagation of the beam becomes a nonlinear phenomenon, but not necessarily a stable one. In addition, the electron density at a given time depends on the preceding history of both the medium and the laser pulse. A self-consistent time dependent treatment of the beam propagation and the medium hydrodynamics is consequently required to predict the behavior of the laser beam.

Such calculations have been carried out and indicate that propagation of a laser beam in an initially uniform plasma can form a stable filament which alternately focuses and defocuses. This behavior is suggestive of a wave-guide and occurs whether an axial magnetic field is present or not. To our knowledge, this is the first self-consistent theoretical demonstration of stable beam trapping in a plasma column.

An additional question which must be answered is whether diffractive losses associated with long propagation paths are significant. The propagation of the beam over long paths has been treated by calculating the

propagation of the beam through a non-quadratic refractive index profile determined by the breakdown and heating at $z = 0$ resulting from a realistic laser pulse. The non-quadratic nature of the refracting well results in considerable aberration of the beam at the foci, and in substantial ring structure away from the foci. The consequences of this behavior on the overall beam propagation will be discussed.

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The availability of high power CO_2 lasers has created a good deal of interest in the scheme, proposed by Dawson et al(1), for heating a magnetically confined underdense plasma column to kilovolt temperatures with a propagating laser beam. End losses and long absorption lengths at high temperatures require a very long plasma column and hence the propagation of the heating laser beam over considerable distances. Several interesting propagation phenomena are involved in this scheme. In the theoretical results to be presented today, we will show that stable beam trapping in a plasma column is possible, that the beam trapping results in amplitude and frequency modulation of the laser pulse, and that the beam remains well trapped even in a highly non-quadratic trapping well in which case severe beam aberration occurs.

First, because the laser beam, by heating the plasma, creates its own refractive index profile, the propagation becomes a nonlinear phenomenon, and there is no assurance that it will be stable. For example, in media possessing an intensity-dependent refractive index, the so-called cubic nonlinearity, catastrophic self-focusing can result in a collapse of the beam that is limited only by the onset of stimulated scattering processes or by nonlinear absorption. So the first question to be answered is whether stable beam trapping without catastrophic collapse can take place at all. Because the plasma density profile at a given time depends on the previous history of both the medium and the laser pulse, a time-dependent self-consistent treatment of both beam propagation and medium magnetohydrodynamics is required.

We have carried out such calculations in which the full nonlinear MHD equations describing conservation of mass, momentum and energy as well as the equation for the solenoidal magnetic field are solved simultaneously with the Fresnel wave equation describing the propagation of the laser beam. Since these numerical calculations (2) have now been published, we will only briefly sketch the results here. It was found that a Gaussian beam incident on an initially uniform plasma did lead to a portion of the pulse being stably trapped in the resultant refractive index well. In Fig. 1, the half-power radius, defined as the radius through which one half the instantaneous power flows, is plotted as a function of propagation distance for various times in the pulse history of a pulse that was initially spatially and temporally Gaussian. The leading edge (t = 0) diffracts freely since there is no trapping well yet formed; the trailing edge (t = 2) is seen to focus twice. Varying degrees of trapping occur for other time values. In Fig. 2, we show the temporal development of the half-power radius at three different propagation distances. Before the first focus (a), focusing is strongest at the tail end of the pulse where the well is deepest. The tail end focuses first and then starts diverging so the time of minimum beam waist begins moving toward the center of the pulse which is still focusing (b). Finally, at (c), the tail end of the pulse is once again focused. Here we see two parts of the pulse being focused with defocusing in between. As the pulse propagates further, more and more "bumps" are added to the half-power radius. These, in turn correspond to "bumps" in the pulse shape, i.e. to an amplitude modulation stemming from the fact that different parts of the pulse correspond to different focal lengths.

In addition to the amplitude modulation, there is also a frequency modulation of the laser pulse due to the time varying refractive index induced by the electrons. Because of limitations of computer time, it is impractical to carry the full calculation over many foci to see how the amplitude and frequency modulation develops. However, a semi-quantitative treatment can be carried out within the framework of a simple model that assumes a time dependent quadratic refractive index well that develops in the same way at each propagation distance (3). In this case, the Fresnel wave equation can be integrated analytically. Figure (3) shows the pulse shape and corresponding frequency spectrum of an initially Gaussian pulse in a weakly focusing plasma column; the trapping well is assumed to deepen as a function of retarded time at each axial position. Going down the page, the graphs correspond to increasingly longer propagation paths. The amplitude modulation is evident here in the distinct peaks in the pulse shape. The number of such peaks increases monotonically with propagation distance. The pulse spectra, shown at the right, indicate a progressive broadening and red shift with propagation distance. Note that there could be no red shift without frequency modulation. For currently anticipated experiments, the magnitude of spectral changes should not be great.

This movie depicts how the intensity peaks form at the tail of the pulse where focusing is strongest, and then move forward, piling up near the front of the pulse so that the number of peaks keeps increasing with propagation distance.

Besides the questions of self-trapping and pulse modulation, there are other propagation problems connected with long propagation paths. These include possible diffractive losses from the finite depth trapping well, possible propagation instabilities due to density fluctuations induced by the varying laser heating due to alternate focusing and defocusing, and the effect of realistic non-quadratic trapping wells.

In order to study the effect of non-quadratic trapping wells, we carried out a full MHD calculation of the laser induced breakdown of an initially room temperature neutral underdense gas by a 10^{10} w/cm^2 1 usec CO_2 laser pulse. A 25 KG solenoidal magnetic field was present. We then calculated the refractive index profile corresponding to the time of maximum axial intensity, and propagated the beam in this fixed profile. The dielectric coefficient is shown in fig. (4). This waveguide calculation indicates that the non-quadratic well gives rise to severe beam aberration at the foci and considerable ring structure between the foci as is shown in fig. (5) which corresponds to a propagation distance of 4.22 m. Although the propagation is no longer strictly periodic, average properties of the beam, such as the half-power radius shown in the upper part of fig. (6) over a range of 3 to 4 m, still tend to exhibit alternate focusing and defocusing. The axial intensity, however, because of the ring structure, is considerably more erratic as is shown in the upper part of fig. (6).

No evidence of diffractive loss was found. However, this is at least partly due to the fact that the strongest absorption is in the wall of the well so the light reaching the outer boundary of the trapping well tends to be absorbed. Incidentally, the non-periodic behavior found here will tend to quench the propagation instabilities alluded to above. In any case, the laser beam appears to be well contained within the trapping well over distances of more than 40 times the focal length.

In conclusion, a number of interesting propagation phenomena have been studied in connection with the scheme to laser heat plasma columns to fusion temperatures. Besides the first self-consistent theoretical demonstration of stable beam trapping, the existence and extent of amplitude and phase modulation as well as of beam aberration and ring structure have been shown.

References

1. J. M. Dawson, R. E. Kidder, A. Hertzberg, G. C. Vlases, H. G. Ahlstrom, and L. C. Steinhauer, "Plasma Physics and Controlled Nuclear Fusion Research" (IAEA, Vienna, 1971), Vol. I, p. 673.
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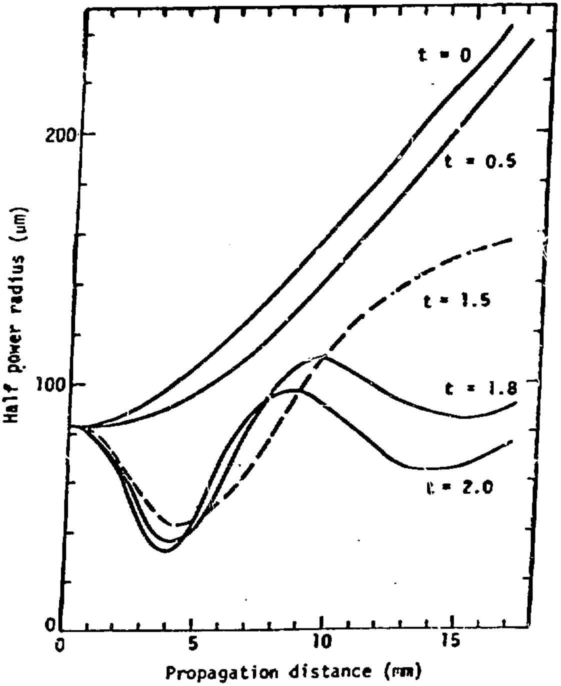
3. M. D. Feit and D. E. Maiden, Appl. Phys. Lett. 28, 331 (15 March 1976); M. D. Feit and J. A. Fleck, Jr., LLL Report UCRL-77992 (March 1976).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t = 0.5
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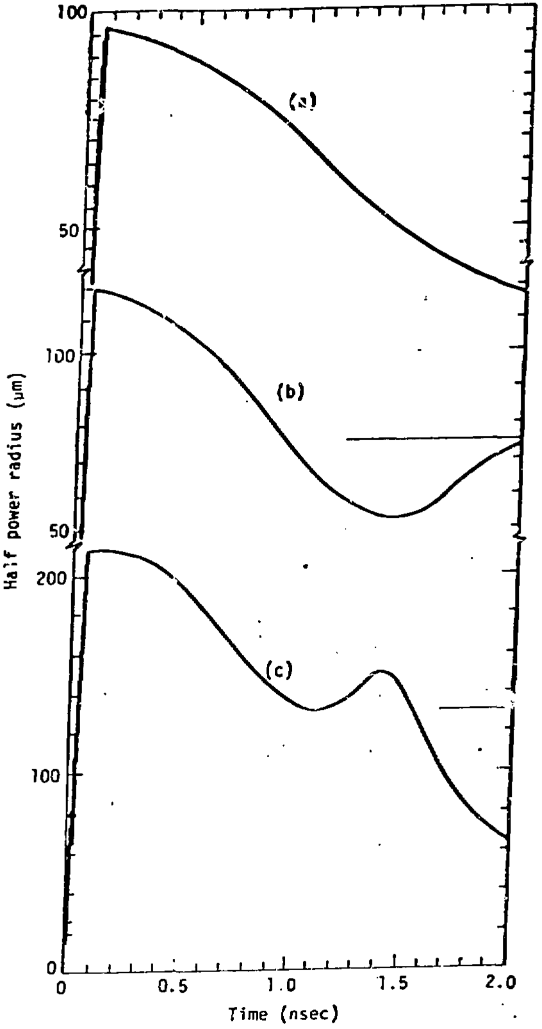
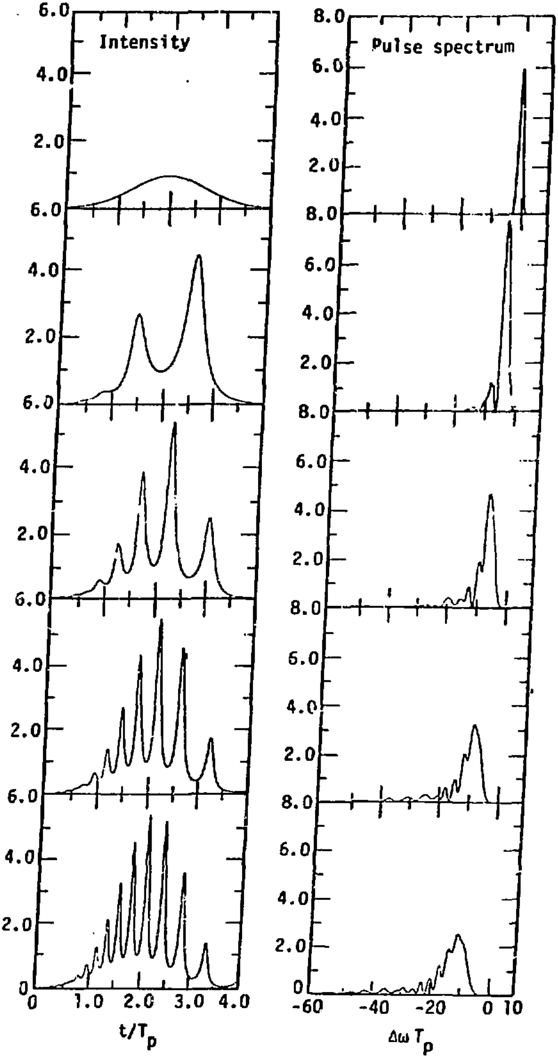
t = 1.8
t = 2.0
200
100
0
0
5
10
15
Half power radius (μm)
Propagation distance (mm)


100
50
100
50
200
100
0
(a)
(b)
(c)
Half power radius (μm)
0
0.5
1.0
1.5
2.0
Time (nsec)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Pulse spectrum
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4.0
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8.0
6.0
4.0
2.0
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0
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2.0
3.0
4.0
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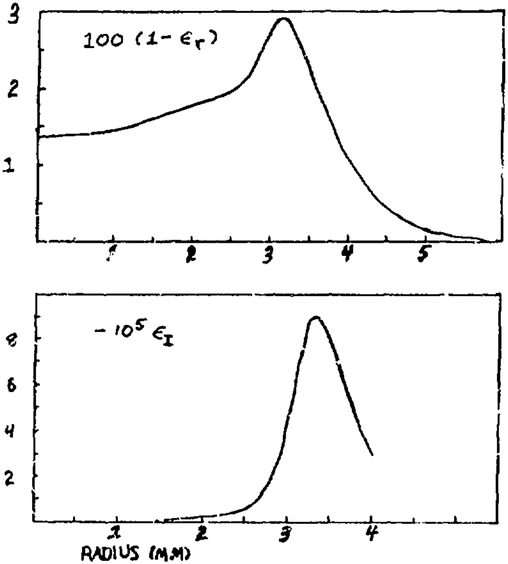
-40
-20
0
10
Δω T_p


3
100 (1 − ε_r)
2
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3
4
5
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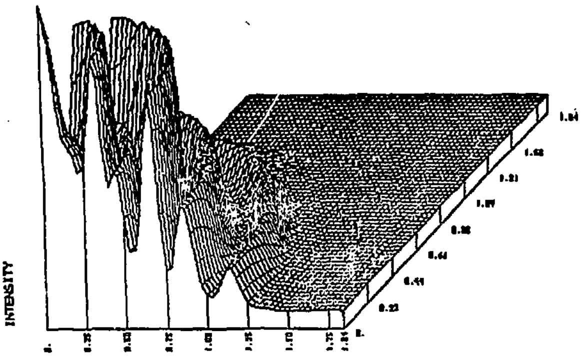
8
6
4
2
1
2
3
4
RADIUS (MM)



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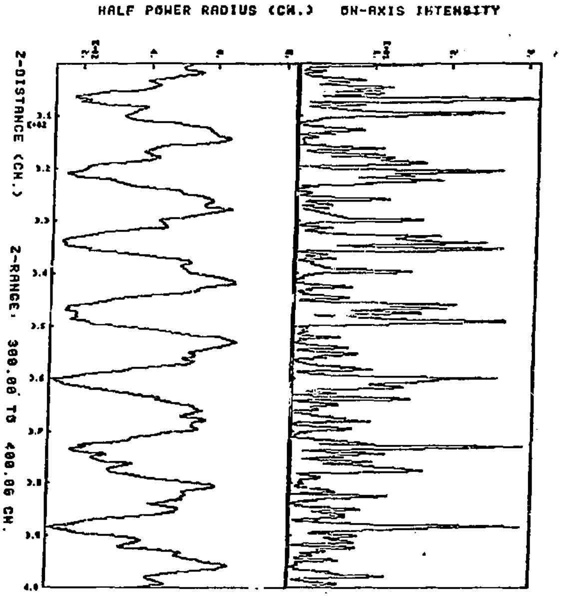
HALF POWER RADIUS (CM.)   ON-AXIS INTENSITY
Z-DISTANCE (CM.)
Z-RANGE: 300.00 TO 400.00 CM.
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E+02
3.2
3.3
3.4
3.5
3.6
3.7
3.8
3.9
4.0