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Laser Pulse Propagation through Ionizable Media

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by

Dale B. Henderson

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LASER PULSE PROPAGATION THROUGH IONIZABLE MEDIA

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Dale B. Henderson

ABSTRACT

The self-unfocusing of an intense laser pulse due to an ionizable atmosphere is studied. Computer codes are developed and applied to cases of interest to laser fusion power reactors. Self-unfocusing is found to place a significant limit on the background density, the final impact of which must await further study.

INTRODUCTION

The propagation of a giant laser pulse through an ionizable atmosphere may involve significant refraction, even at low density, because the gradients in the refractive index travel with the pulse. This effect is important to laser fusion research owing to its implications for both future controlled thermonuclear reactors and present pulsed laser experiments. This report covers our research toward understanding the phenomena, in developing computer codes to calculate the effect, and in applying those codes to the reactor problem.

The reactor application arises because most serious laser fusion reactor concepts involve pulse transport through lithium vapor. The lithium vapor is that ablated from the protective layer in the wetted-wall concept,¹ from the liquid vortex in the blascon concept,² or from a similar source. It must be pumped out and/or condensed between pulses to some acceptable background pressure. The magnitude of that acceptable pressure affects the required pumping speed, the pulse repetition rate, and the plant economics. Because the refractive effects studied here may be far more restrictive than simple transparency ($\omega_p^2 \ll \omega^2$), they are important in reactor systems studies. The applications in this report concern the wetted-wall reactor described in our previous reports.¹ We anticipate the general

use of the computer codes developed here as one component of the current systems study of laser fusion reactors at LASL.³

Some experiments show that the presence of a low-density background gas quenches the phenomena of interest, such as neutron production. It has been suggested that these phenomena may depend upon the focal intensity's being above a threshold value, and that refraction due to the gas, as described here, might reduce the focal intensity below that threshold.⁴ The codes developed here may also be applied to such experiments, the only required modification being inclusion of the ionization rate of the gas in question.

Finally we note that the theoretical treatments of the ionization due to tunnelling under an intense electric field do not seem adequate for this problem. Because the refraction discussed here indicates both a need for an extended treatment and a possible means of experimentally verifying it, such a treatment should perhaps be developed.

ESTIMATE

We consider the situation sketched in Fig. 1. The laser pulse enters the region of significant gas density at $s = 0$ with a radius R . If the gas were absent, the focal point would be at $s = S$; that is,

$$\dot{g} = (1-g) P_1(E_p) + g(1-g) P_2(E_p),$$

in which $(1-g)$ represents the number density of neutral atoms available for ionization and gives the saturation at $g = 1$. The first term represents multiphoton absorption or tunnelling, and the second represents electron cascade. We have assumed that there will be only first ionization of the gas, which is not necessarily correct. More general expressions for $\dot{g}$ can be put into the code to account for subsequent ionization when such detailed results are warranted by the application.

There are a number of well-known published results of focused breakdown experiments. For instance, in cesium and rubidium vapor at 10^{16} atoms/cm³ one finds breakdown at 10^8 to 10^{10} W/cm² when using 50- to 65-nsec pulses from a ruby laser.⁵ Various published calculations lead us to explain such experiments on the basis of multiphoton absorption P_1 to produce a few electrons in the focal volume, followed by cascade P_2 to breakdown. This familiar picture stands in contrast to that developed here for higher powers which uses P_1 alone.

Keldysh has pointed out that ionization by electron tunnelling and ionization by multiphoton absorption are two limits of the same process, rather than two separate physical processes.⁶ In his unified treatment, he introduces a dimensionless parameter

$$\gamma = \omega(2\pi I_0)^{1/2}/e E_p,$$

in which I_0 is the ionization potential, and ω and E_p are the laser frequency and peak field magnitude, respectively. The limit of large γ (high frequency and small fields) is that of multiphoton absorption; the limit of small γ (low frequency and large fields) is that of tunnelling. In Fig. 2 we plot γ as a function of laser power density for neodymium and carbon-dioxide lasers and for lithium vapor. From the figure it is clear that laser fusion will tend toward the opposite limit from that of focused breakdown experiments.

In the same paper Keldysh gives an expression for the ionization rate P_1 , which may be simplified in the limit of $\gamma \ll 1$. We have plotted this rate

Fig. 2. Keldysh's parameter, γ , vs power density.

for the first ionization of lithium in Fig. 3. For comparison,⁷ we have indicated a maximum possible rate P_2 due to electron cascade at 10^{16} atoms/cm³. This maximum is simply the maximum of $\langle \sigma v \rangle$ computed from a published cross section⁸ times the maximum density. We see that cascade effects may be neglected relative to tunnelling above 10^{12} W/cm².

We note a theoretical difficulty in the Keldysh rate at extremely high power in that the rate decreases as shown in Fig. 3. This is because

Fig. 3. Ionization rate from Keldysh's theory.

saturation of the tunnelling transmission leaves only the pre-exponential factor

$$P \approx \frac{\sqrt{6\pi}}{4} \frac{m^{\frac{1}{4}} I_0^{\frac{7}{4}}}{h^{\frac{3}{2}} (eE_p)^{\frac{1}{2}}} \exp \left[- \frac{\sqrt{32}}{3} \frac{m^{\frac{1}{2}} I_0^{\frac{3}{2}}}{h (eE_p)} \right]$$

Landau and Lifshitz⁹ give a different result in which $P \sim E^{-1} \exp(---)$. Neither of these results satisfies our intuition that P ought to increase, or at least become constant. Perhaps these formulae cannot be carried to electric fields strong enough to open the Coulomb well.

In the codes, we have held the rate constant beyond the maximum shown in Fig. 3. In practice, this whole difficulty does not matter because the pulse must rise from zero intensity to extreme values, and at the maximum the gradient length is only $P_{\max}/c \approx 10^{-6}$ cm. Thus, in any real case, the gas must be fully ionized before the question arises. We have also completely neglected the cascade term, which might become important in some cases to be studied with our codes. In such instances a more complete expression can be substituted without difficulty.

CODES

Our first attempt at numerical solution of the problem used a modification of the code developed by D. O. Dickman and B. R. Suydam¹⁰ for the study of self-focusing in optical materials. This code demonstrated the effect in question, but could be applied only to cases involving up to 1% of the gas density of interest. This was because Suydam's equation for the propagation of the envelope of a wave packet¹¹ requires more information about our highly distorted wave fronts than can be retained in the computer. We therefore wrote a new code in the limit of geometric optics; that is, without the diffraction effects that are retained by the envelope equation.

The new code, called GOPTC, is Langrangian in format, following the motion of wave fronts in the most obvious way. It is successful in studying cases up to that specified by the wetted-wall reactor problem, but it cannot be carried farther because

the formation of caustics convolutes the Langrangian mesh. We have, therefore, written another code, called PHOTON, which is PIC-like in format, following the motion of macroscopic "photons" through a gas grid somewhat as do the particle-in-cell codes. This code has been adequate for all cases attempted, and it is recommended for further work. Both are of continued interest, however, because GOPTC is faster and cheaper to run and because the two serve as checks upon each other.

GOPTC - The initial grid set up by the code GOPTC is shown in Fig. 4. The wavefronts are the curved vertical lines, curved to give the initial (vacuum) focal point. The axial divisions are arranged to include an equal energy flux within each cell $\Delta r \Delta z$, the initial profile being Gaussian in r as shown in Fig. 5. At each time step, the cell nodes are transported a distance $c \Delta t/n$ in the direction normal to the wave front, where n is the local index of refraction. The index is computed from the local free-electron density, obtained from integration of the ionization rate equation. After travelling most of the way to the vacuum focal point, the grid is distorted by the refraction as shown in Figs. 6 and 7.

Although these figures show clearly that refraction distorts the pulse, they do not supply the quantitative information required: how much of the energy will be incident on the target? To obtain this measure, we extrapolate each cell toward the target station x_{target} and compute how many will intercept it. Clearly, this depends upon the target size and location. The plots of the fraction of the energy incident are severely distorted from the initial result, Fig. 8, to that shown in Fig. 9. The maxima of the curves in Fig. 9 are the fractions that may be incident targets of given sizes, if they are optimally displaced from the vacuum focus at $x_{\text{target}} = 0$.

The distortion of the grid due to the formation of caustics is quite evident in Fig. 10, which is the same computation carried up to the point where the leading edge of the pulse is at the vacuum focus. Fortunately, refraction is a turning process, and we are concerned with displacement, the next integration as indicated in the "Estimate" section. Therefore, being able to carry the computation up to the

Fig. 4. Lagrangian grid of wave fronts at initial time. Curvature gives focus 200 cm to the right. Note that the radial scale (vertical, 0 cm to 30 cm) differs from the axial scale (horizontal, -2 to 18 cm).

Fig. 5. Power density vs radius for laser pulse in Fig. 4. Curve A is taken at x = 2.2 cm, B at 6.4 cm, and C at 14.9 cm.

Fig. 6. Langrangian grid containing 10^6 J at 10.6μ after travelling through 180 cm of lithium vapor at 5×10^{15} atoms/cm³. Compare with Fig. 4. Note the change in radial scale, 0 to 5 cm in box.

Fig. 7. Power density vs radius curves corresponding to Fig. 6. Compare with Fig. 5.

Fig. 8. Fraction of energy delivered to target vs target displacement from vacuum focal point extrapolated from initial data of Fig. 4. Curve A corresponds to target radius of 0.01 cm, B to 0.02 cm, C to 0.05 cm, D to 0.10 cm, and E to 0.20 cm.

Fig. 9. Fraction of energy delivered extrapolated from data of Fig. 6; i.e., after 180 cm. A, B, C, D, E, as in Fig. 8.

TIME = 6.671E-09 SEC, TRAVEL = 200.00 CM

Fig. 10. Lagrangian grid of Figs. 4 and 6 after 200 cm of travel; i.e., up to vacuum focal point.

point of Figs. 6, 7, and 9 is adequate; the additional turning from there to the target will cause little additional displacement. This is clear from the saturation of the fraction-of-energy-incident curves as the pulse propagates into the medium. It is also interesting that although the grid distortion in Fig. 10 seems quite severe, the effect upon the target curve is less severe, as shown by comparison of Figs. 9 and 11.

A plot of points showing the maxima of the fraction of energy for several different size targets as a function of gas density is shown in Fig. 12, which is a comparison to the PHOTON code. The legend "1 nsec, square" means that the pulse was square in axial extent and 1 nsec or 30 cm long. The wave-front code was written only as square in time and Gaussian in radius, whereas the PHOTON (PIC-like) code can be easily adapted to any form by using weighted particles. The main point of the figure is that where both codes may be used, the

results are in reasonable agreement; especially if one asks a question such as "What pressure may be allowed if we require an efficiency of 75%?"

PHOTON - Our final code, called PHOTON, is similar in spirit to the particle-in-cell (PIC) fluid codes. A number of particles (macroscopic photons) are started with a distribution in space and direction that simulates the initial pulse shape with its vacuum focus. These particles are assigned weights to represent energy to give the distribution of pulse intensity in radius and in time or axial dimension. As the particles are moved, their directions $\hat{r}$ are refracted according to

$$d(n\hat{r})/ds = \nabla n,$$

where n is the local index of refraction, a property of the space grid. The particles are also moved according to the grid's group speed, although this

Fig. 11. Fraction of energy delivered, from data of Fig. 10. Note the similarity to Fig. 9, in spite of the distortions evident in Fig. 10.

Fig. 12. Fraction of energy delivered (maxima) vs lithium-vapor density. A comparison of results from two computer codes.

refinement is not important in the applications considered to date.

Between time steps the grid is updated by integrating the ionization rate equation according to the energy density found in each cell. New un-ionized material is added ahead of the pulse, and "used" material is discarded behind as required. The grid is also stretched or shrunk radially to maintain significance with a given number of cells.

Examples of the particle plots from this code are shown in Fig. 13. The small numbers are at the particle locations and give approximately the relative weights assigned. The small vectors indicate the particle directions. A 625-member subset of the 40,000 particles carried is plotted for clarity in reading. The space grid of 4000 cells (divided as 40 in x and 100 in r) is outlined by the box indicated.

Fig. 13a. Particle plot from PIC-like code after 200 cm of travel; i.e., up to vacuum focus at axial (horizontal) position at 0.0 cm. Note that the radial (vertical) scale is stretched out. The lithium density is $1 \times 10^{14} \text{ cm}^{-3}$.

Fig. 13b. Particle plot after 200 cm of travel through lithium density of $1 \times 10^{15} \text{ cm}^{-3}$.

Fig. 13c. Particle plot after 200 cm of travel through lithium density of $1 \times 10^{16} \text{ cm}^{-3}$. Compare these with Figs. 6 and 10.

The particles in Fig. 13 were focused at $s = 0$, initially 200 cm downstream. The distribution in energy is Gaussian in r and square in x , as may be inferred from the small numbers. Corresponding particle plots for cases in which the initial axial distribution of intensity was half-Gaussian are shown in Fig. 14. Again we are interested in the fraction of the energy incident upon a target of given size. This is calculated as in GOPTC, as shown in Figs. 15 and 16. The results are discussed further in the next section.

The code PHOTON is equipped with dump, re-start, and postprocessor packages. The cases shown in Figs. 13 and 14 each require about 30 min of 7600 computing time altogether. The data are input through cards read in and are easily varied. The initial form of the pulse and the ionization-rate equations are in FORTRAN, but may be easily changed to suit other problems.

APPLICATION

This problem was motivated by, and grew out of, LASL's study of the wetted-wall laser fusion reactor concept.¹ Therefore, the cases run to date correspond approximately to parameters used in that study. Without further justification, we list the relevant physical parameters and the values taken in Table I. As the table shows, we considered four pulse shapes and computed seven gas densities for each. These 28 cases do not, of course, constitute a complete investigation of the parametric trade-offs available, but they do illustrate the effect for a well-constructed example. A more complete study is part of our current systems-study program.

From the maxima of curves like those in Figs. 15 and 16, we compute the maximum possible fraction of the energy on a target of a specified size, as plotted in Fig. 17. The curious inflections in Figs. 17 a and 17 c at 2×10^{16} atoms/cm³ seem to correspond to cases in which a significant number

of "photons" are refracted enough to never focus at any axial station.

Obviously the four parts of Fig. 17 are very similar. An overlay of the four curves for $R_T = 0.05$ cm, (Fig. 18), shows them to be identical for all practical purposes. This indicates that the results are independent of pulse shape over the limited range covered.

Another quantity of interest is the (downstream) axial target displacement necessary to find the optima indicated in Figs. 17 and 18. This displacement is plotted in Fig. 19 for the cases in Fig. 18. Here we see differences; the coincidence in Fig. 18 may be partly fortuitous. The discontinuities in Fig. 19 correspond to points where the maxima in curves such as those in Figs. 15 and 16 change from one branch to the other. The importance of this displacement is that it complicates the tracking, pointing, and aiming problems in the reactor. In some cases this may limit the allowed gas density more than the fraction possible on target.

From the several cases studied thus far, it is clear that self-unfocusing will pose important restrictions on the gas densities to be allowed in laser fusion reactors. We have not yet investigated the sensitivity to the parameters indicated in Table I. Note, however, that to lowest order the effects will go as (ω_p^2/ω^2) , so that higher-wavelength laser pulses will be refracted much less. If a 10- μ laser remains the best for high energy, it may be desirable to first ionize the focal cone with a lower-energy higher-frequency prepulse. These matters are left to further study.

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Fig. 14a. Particle plot corresponding to Fig. 13a, except that the intensity is half-Gaussian in the axial direction. The vacuum focus is at axial station 0.0; some of the photons have passed through. The lithium density is $1 \times 10^{14} \text{ cm}^{-3}$.

Fig. 14b. Particle plot after 200 cm of travel through lithium density of $1 \times 10^{15} \text{ cm}^{-3}$ for half-Gaussian pulse.

Fig. 14c. Particle plot after 200 cm of travel through lithium density of $1 \times 10^{16} \text{ cm}^{-3}$ for half-Gaussian pulse.

Fig. 15. Fraction-of-energy-delivered curves corresponding to Fig. 13 c. Curves A, B, C, D, E are as in Fig. 8.

Fig. 16. Fraction-of-energy-delivered curves corresponding to Fig. 14 c.

17a

17c

17b

17d

Fig. 17. Fraction of energy delivered (maxima) vs lithium-vapor density for axially square and half-Gaussian pulses of 1- and 1/2-nsec characteristic durations, as marked.

Fig. 18. Superposition of target radius = 0.05 cm curves from Fig. 17.

Fig. 19. Target displacement required to obtain optimum fraction of energy delivered vs lithium-vapor density for target radius = 0.05 cm.

TABLE I
PHYSICAL PARAMETERS TO BE SPECIFIED IN
APPLICATION TO FUSION-POWER REACTOR AND
CASES DONE TO DATE

Physical Parameter	Value(s) Used
Pulse wavelength	10.6- μ (CO ₂ laser)
Pulse energy	10 ⁶ J
Pulse shape in r	Gaussian, 1/e at 10 cm
Pulse shape in t	Square, 1 nsec Square, 1/2 nsec Half-Gaussian, 1/e at 1 nsec Half-Gaussian, 1/e at 1/2 nsec
Distance to vacuum focus	200 cm
Atmospheric composition	Lithium vapor
Atmospheric density	10 ¹⁴ to 10 ¹⁷ cm ⁻³ in 7 steps

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