Naval Research Laboratory
Washington, DC 20375-5000

NRL Memorandum Report 6751

Elimination of Laser Prepulse by Relativistic Guiding in a Plasma

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Fairfax, VA

November 27, 1990

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
1990 November 27

3. REPORT TYPE AND DATES COVERED
Interim

4. TITLE AND SUBTITLE
Elimination of Laser Prepulse by Relativistic Guiding in a Plasma

5. FUNDING NUMBERS
DOE contract #
DOE-AI05-83ER40117

SDIO
JO # 47-3593-00

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Washington, DC 20375-5000

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL Memorandum Report 6751

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
SDIO/T/IS
The Pentagon
Washington, DC 20301

DOE
Washington, DC 20545

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
*FM Technologies, Inc., Fairfax, VA

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A method is proposed for eliminating prepulses associated with high power, ultrashort laser pulses. In this method the high power portion of the pulse is refractively guided due to relativistic effects associated with the plasma electrons. The low power prepulse, however, is unaffected by the plasma and diffracts away. Optical guiding is achieved by appropriately choosing the plasma density, laser power and wavelength. In addition, a wavebreaking stabilization mechanism for the Raman backscattering instability for intense laser pulses is proposed. This stabilization mechanism indicates that the intense laser pulse should not be significantly backscattered by the plasma.

14. SUBJECT TERMS
Laser prepulse
Relativistic guiding

15. NUMBER OF PAGES
15

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18

CONTENTS

ELIMINATION OF LASER PREPULSE BY RELATIVISTIC GUIDING IN A PLASMA

I. Introduction

Recent advances in the development of subpicosecond, ultra-high power lasers[1] make possible the generation of very high energy density plasmas. Laser systems,[2] such as KrF excimer lasers, are currently capable of delivering 1 J at a pulse duration of 100 fsec (10 TW). These pulsed lasers can potentially achieve energy levels as high as 100 J (1 PW) with focused intensities of 10^{23} W/cm^2 and power densities of 10^{27} W/cm^3. At these high electric field values, a number of new phenomena have been predicted.[3,4] For example, the electron quiver velocity becomes highly relativistic at laser intensities of ~ 10^{19} W/cm^2 (for a laser wavelength of $\lambda \sim 0.25$ μm), thus allowing for optical guiding and coherent harmonic generation within a plasma.[4] Deposition of a subpicosecond laser pulse on a solid target can lead to the production of an ultra short x-ray pulse. The solid surface allows for a rapid cooling of the plasma and thus production of a short burst of incoherent x-rays. These x-rays can be used to probe fast chemical reactions, as well as phase transitions in solid or biological samples, with unprecedented temporal resolution. One of the most exciting applications involves coherent x-ray lasing by photo-ionizing inner shell electrons of cold, nearly neutral elements. In this application, a short, intense x-ray pulse is required in order to defeat Auger processes which are capable of destroying inversion due to rapid radiationless transitions. Thus, the production of short pulse photo-ionizing sources may lead to an inexpensive, compact, table top x-ray laser. At still higher intensities, ~ 10^{25} W/cm^2, nonlinear Thomson and Compton scattering can be achieved and Cerenkov emission can be observed in vacuum.[3]

Manuscript approved September 12, 1990.

Associated with subpicosecond, ultra-high power laser pulses are low power prepulses of nanosecond time durations. In high gain lasers, the prepulse arises from the amplification of spontaneous emission and is a major concern for many laser-matter interactions studies. The relatively low density plasma which is generated by the prepulse can alter and dominate the interaction process. In this paper we propose a method to dramatically reduce the prepulse associated with high power, ultra-short laser pulses by using a relativistic optical guiding effect in a plasma.

II. Relativistic Optical Guiding and Prepulse Diffraction

Relativistic optical guiding is a result of the modification of the index of refraction due to the relativistic quiver motion of the plasma electrons by the laser field. Diffractive spreading of the laser field can be balanced by refractive focusing. Relativistic optical guiding of a laser pulse within a plasma occurs when the laser power exceeds a critical power which, in units of gigawatts, is given by[4-8]

$$P_c[GW] = 17.4(\lambda_p/\lambda)^2, \tag{1}$$

where λ is the radiation wavelength, $\lambda_p = 2\pi c/\omega_p$ is the plasma wavelength, $\omega_p = (4\pi|e|^2 n/m_o)^{1/2}$ and n is the plasma density. Typically, the power in the prepulse P_p is many orders of magnitude below that of the main pulse P_o, $P_o >> P_p$, as shown in Fig. 1. Thus, if the condition $P_o \gtrsim P_c >> P_p$ can be realized by choosing an appropriate plasma density, the prepulse will diffract as in vacuum and the main pulse will be refractively guided through the plasma by the relativistic guiding effect, as shown in Fig. 2. Hence, after propagating several vacuum Rayleigh lengths, the prepulse can be substantially reduced in comparison to the main pulse.

a) Wave Equation

Recently, a fully self consistent, 1D, nonlinear fluid model[4] describing the interaction of intense laser pulses in plasmas has been developed. This model, under certain conditions, can be generalized to include 3D effects.[8] If σ_L is the characteristic laser pulse length, and r_s is the laser spot size, then in the limit that $\sigma_L >> r_s >> \lambda$ the wave equation for the complex amplitude $\hat{a}$ is given by[7,8]

$$\left(\nabla_\perp^2 + \frac{2ik}{c}\frac{\partial}{\partial\tau}\right)\hat{a} = k_p^2\,(1+|\hat{a}|^2/2)^{-1/2}\,(1+\delta n/n)\hat{a}, \tag{2}$$

where $a = |e|A/m_o c^2 = (\hat{a}/2)\exp(ik\xi) + c.c.$, A is the vector potential associated with the linearly polarized radiation field, $k = 2\pi/\lambda$, $\xi = z - ct$ is the longitudinal spatial variable and $\tau = t$ is the temporal variable in the speed of light frame and $k_p = 2\pi/\lambda_p$. In obtaining Eq. (2) it has been assumed that $(\lambda/\lambda_p)^2 << 1$ and $\hat{a}$ is slowly varying in τ, i.e. $|\partial\hat{a}/\partial\tau| << (c/\sigma_L)|\hat{a}|$. The plasma density perturbation, δn, is given by

$$\delta n/n = k_p^{-2}\,\nabla_\perp^2\,(1 + |\hat{a}|^2/2)^{1/2}, \tag{3}$$

where it has been assumed that $\delta n/n < 1$.

b) Radiation Beam Envelope Equation

An envelope equation governing the laser spot size, as a function of propagation time, τ, can be obtained from the wave equation, Eq. (2). The radiation beam is assumed to have a Gaussian profile of the form

$$|\hat{a}| = a_o(r_o/r_s)e^{-r^2/r_s^2}, \tag{4}$$

where $r_s = r_s(\tau)$ is the spot size, r_o is the minimum spot size and a_o is the peak amplitude of the normalized vector potential. In vacuum, $r_s = r_o(1+c^2(\tau-\tau_o)^2/z_R^2)^{1/2}$ where $z_R = \pi r_o^2/\lambda$ is the Rayleigh length and τ_o is the time the minimum spot size occurs. Applying the source dependent expansion (SDE) method[9] to the wave equation in Eq. (2) yields the following envelope equation, in the limit $|a_o|^2 << 1$,

$$\frac{d^2 r_s}{d\tau^2} = \frac{(c\lambda/\pi)^2}{r_s^3}\left[1 - \frac{P_o}{P_c}\left(1 + \frac{8}{k_p^2 r_s^2}\right)\right], \tag{5}$$

where $P_o/P_c = (k_p a_o r_o)^2/32$, P_c is given in Eq. (1) and the pulse power in units of gigawatts is $P_o[GW] = 21.5(a_o r_o/\lambda)^2$ for a linearly polarized field. The first term on the right-hand side of (5) represents vacuum diffraction, whereas the second and third terms represent the focusing contributions from the plasma. When the defocusing and focusing terms are equal, the radiation beam propagates with a constant spot size. The condition for optical guiding is,

$$\frac{P_o}{P_c} = (1+8/k_p^2 r_s^2)^{-1} \simeq 1, \tag{6}$$

where the approximate equality sign implies $r_s^2 >> \lambda_p^2$.

c) Example

As an example, consider a 1 J, KrF laser pulse ($\lambda = 0.25$ μm) of pulse length 0.6 psec ($\sigma_L = 180$ μm). The power in the main pulse is $P_o = 1.7$ TW. Setting $P_o = P_c$ indicates $\lambda_p/\lambda = 10$ and hence $\lambda_p = 2.5$ μm. This corresponds to an electron plasma density of $n = 1.8 \times 10^{20}$ cm^{-3}, which can be produced by low power capillary discharges.[10] The vacuum Rayleigh length is $z_R = \pi r_s^2/\lambda \approx 0.13$ cm, assuming $r_s = 10$ μm ($a_o = 0.23$). Hence, a plasma of a centimeter in length should be sufficient to remove the prepulse by diffraction.

III. Laser-Plasma Instabilities

Laser plasma instabilities may limit the laser pulse propagation distance. The instabilities with the largest growth rates are the Raman instabilities.[11] The growth rate for Raman back scattering (RBS) is

$$\Gamma_B = (a_o/2)\omega_p(\omega/\omega_p)^{1/2}. \qquad (7a)$$

The Raman forward scattering (RFS) growth rate is

$$\Gamma_F = (a_o/2\sqrt{2})\omega_p(\omega_p/\omega), \qquad (7b)$$

where $\Gamma_B \gg \Gamma_F$, since $\omega/\omega_p \gg 1$. To avoid degradation of the laser it is necessary to have a small number of e-folds, $N_e = \Gamma\sigma_L/c$, of the instability within the pulse. An optically guided pulse ($P_o = P_c$) has $a_o = 4\sqrt{2}/(k_p r_s)$ which indicates that the number of e-folds of the RBS instability is

$$N_e = 2(\sigma_L/r_s)(2\lambda_p/\lambda)^{1/2}. \qquad (8)$$

Requiring N_e to be a small number, i.e., $N_e < 4$, puts a limit on the minimum spot size necessary to avoid significant growth of the RBS instability, $r_s > \sigma_L(\lambda_p/2\lambda)^{1/2}$. This implies a Rayleigh length of $z_R > (\pi/2)(\sigma_L/\lambda)^2\lambda_p$. For a 1 J, 0.6 psec, KrF laser, as in the above example, the requirement that $N_e < 4$ gives a spot size $r_s > 400$ μm ($a_o < 0.006$), which corresponds to $z_R > 2$ m. This example shows that unless the RBS instability can be suppressed, a plasma length greater than 2 m would be required to eliminate the prepulse while avoiding the RBS instability.

IV. Stabilization of the RBS Instability

Stabilization of the RBS instability cannot be achieved by thermalization of the plasma due to the exceedingly high temperature required. However, for a sufficiently intense incident laser field, the RBS instability in a highly underdense cold plasma may be stabilized by wavebreaking of the plasma wave. The backward traveling electromagnetic field excited in the RBS instability couples with the incident field, via the $\underset{\sim}{v}x\underset{\sim}{B}$ term in the force equation, to produce a forward traveling, longitudinal ponderomotive wave. The ponderomotive wave is given by

$$E_p = a_o E_1 \cos(2\omega z/c - \omega_p t), \tag{9}$$

where E_1 is the transverse electric field associated with the RBS instability. For an initially cold plasma, wavebreaking of the excited plasma wave occurs when the longitudinal electron quiver velocity equals the plasma wave phase velocity,

$$\frac{|e|a_o E_1}{m_o \omega_p} = v_{ph}, \tag{10}$$

where $v_{ph} = c\ (\omega_p/2\omega)$ is the phase velocity of the plasma wave. The condition for wavebreaking in the RBS instability can be written as

$$a_o a_1 = \frac{1}{2}\ (\omega_p/\omega\ )^2, \tag{11}$$

where $a_1 = |e|E_1/(m_o\omega c)$, $|a_o| \geq |a_1|$ and it is assumed that $|a_o|^2 << 1$.

The reflection coefficient at saturation, i.e., the ratio of the reflected to incident electromagnetic power at wavebreaking, is

$$\eta = \frac{P_1}{P_o} \simeq (1/4)\left(\frac{\omega_p/\omega}{a_o}\right)^4, \qquad (12)$$

where it is assumed that the transverse dimension of the incident and reflected wave is the same. If wavebreaking saturates the RBS instability, the incident laser intensity must be above a threshold value, $a_o > (\omega_p/\omega)/\sqrt{2}$. Hence, the incident laser power, in units of gigawatts, must satisfy,

$$P_o[GW] = 21.5\ (a_o r_o/\lambda)^2 > 11\ (r_o/\lambda_p)^2. \qquad (13)$$

If this condition on the incident laser power is not well satisfied, the RBS process will be stabilized by some other mechanism, such as pump depletion or plasma thermalization. In our example, where P_o = 1.7 TW, λ_p = 2.5 μm, r_o = 10 μm and z_R = 0.13 cm, the reflection coefficient is 1% and the RBS instability should not be a problem.

V. Conclusion

In this paper we have proposed a mechanism for eliminating prepulses using a relativistic optical guiding effect in plasmas. In this mechanism, the laser pulse propagates through an underdense plasma, such that the main part of the pulse is optically guided while the prepulse diffracts away. In addition, a stabilization mechanism for the RBS instability, involving wavebreaking of the excited plasma wave, has been proposed for intense laser pulses. This stabilization mechanism indicates that the intense laser pulse should not be significantly reflected by the RBS instability as it passes through the plasma.

Acknowledgments

This work was supported by SDIO/T/IS, ONR and DOE.

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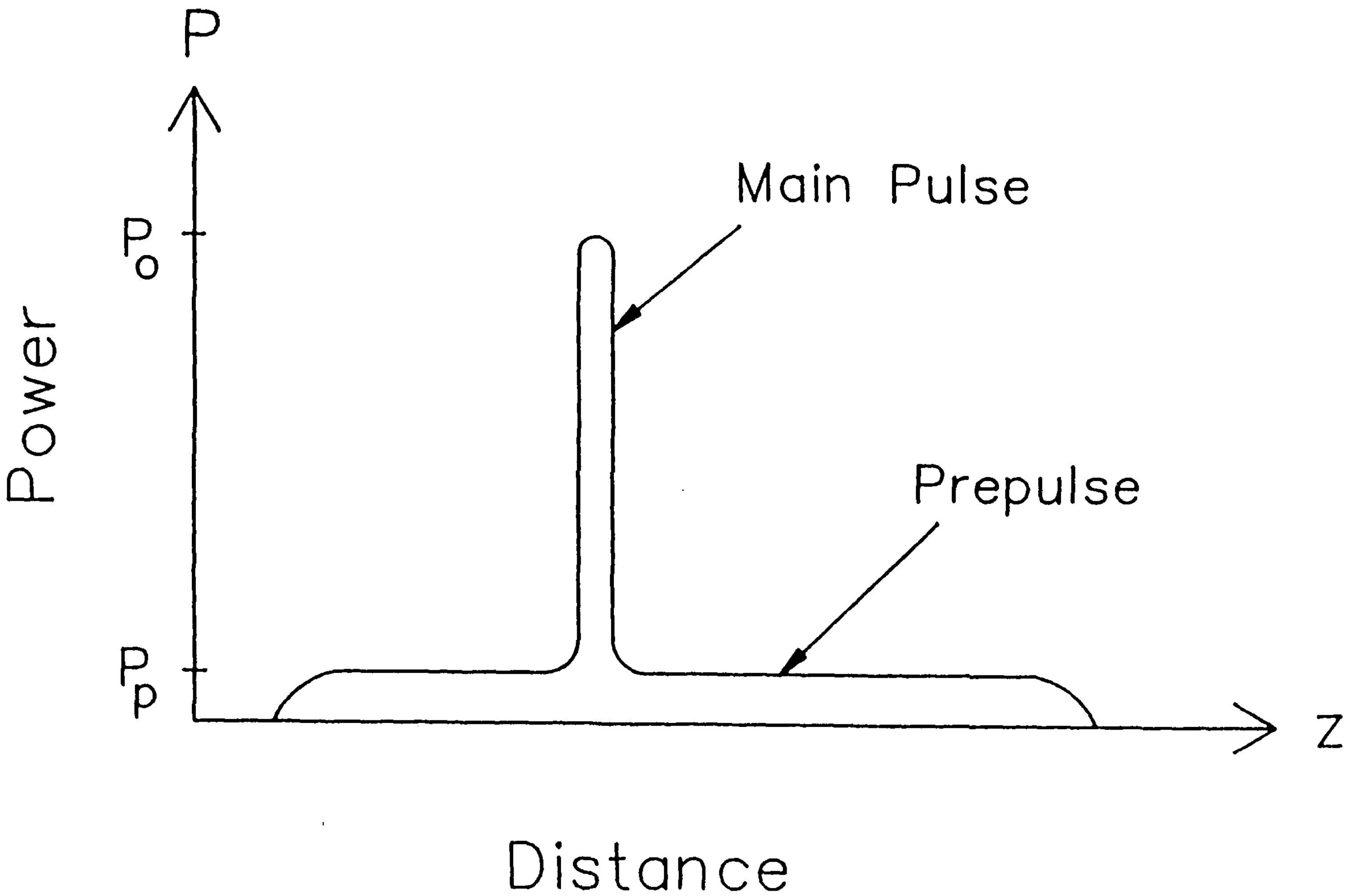

Fig. 1 — Schematic of a typical profile of a high power, short laser pulse where P_o is the power in the main pulse and $P_p << P_o$ is the power in the prepulse.

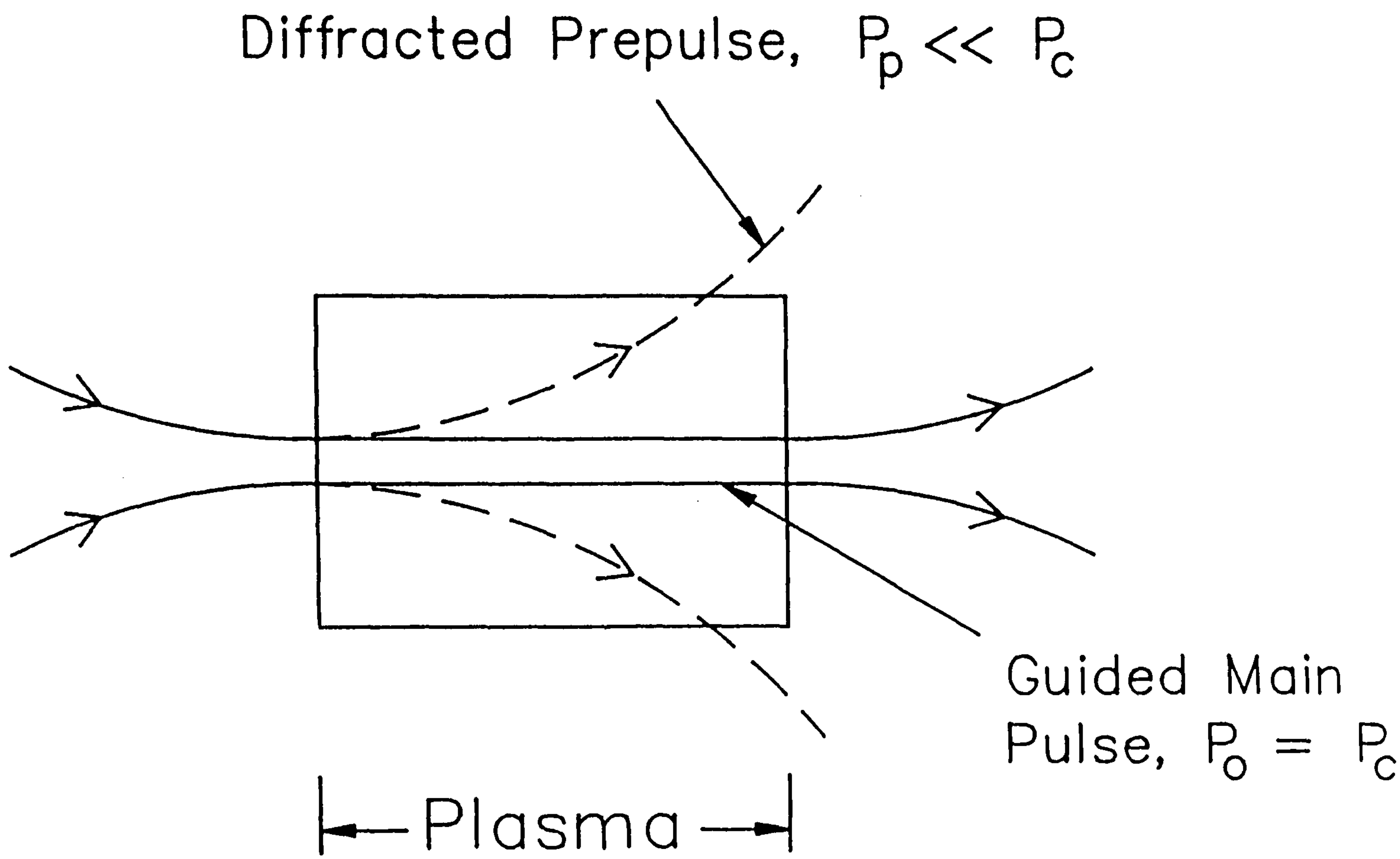

Fig. 2 — Schematic of pulse propagation through the plasma in which the main pulse with $P_o = P_c$ is optically guided, whereas the prepulse with $P_p << P_c$ continuously diffracts.