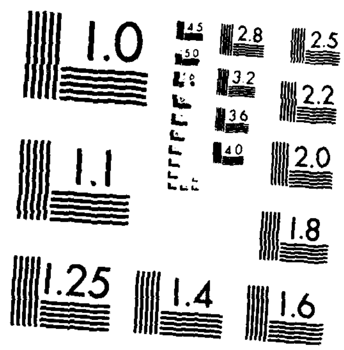
AD-A200 301 LASER WAKEFIELD ACCELERATION AND RELATIVISTIC OPTICAL 1/1
GUIDING(U) NAVAL RESEARCH LAB WASHINGTON DC
P SPRANGLE ET AL. 12 SEP 88 NRL-MR-6267

UNCLASSIFIED F/G 20/7 NL

UNC


1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

(2)

Naval Research Laboratory

Washington, DC 20375-5000

NRL Memorandum Report 6267

Laser Wakefield Acceleration and Relativistic Optical Guiding

P. SPRANGLE

Plasma Theory Branch
Plasma Physics Division

E. ESAREY AND A. TING

Berkeley Research Associates, Inc.
Springfield, VA 22150

G. JOYCE

Plasma Theory Branch
Plasma Physics Division

September 12, 1988

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S): NRL Memorandum Report 6267	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION: Naval Research Laboratory; 6b OFFICE SYMBOL (If applicable): Code 4790	7a NAME OF MONITORING ORGANIZATION
6c ADDRESS (City, State, and ZIP Code): Washington, DC 20375-5000	7b ADDRESS (City, State, and ZIP Code)
8a NAME OF FUNDING/SPONSORING ORGANIZATION: U.S. Department of Energy; 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c ADDRESS (City, State, and ZIP Code): Washington, DC 20545	10 SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. DOE; PROJECT NO. A105-83 ER40117 Mod A004; TASK NO.; WORK UNIT ACCESSION NO.

11 TITLE (Include Security Classification)

Laser Wakefield Acceleration and Relativistic Optical Guiding

12 PERSONAL AUTHOR(S)

Sprangle, P., Esarey,* E., Ting,* A. and Joyce, G.

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
	FROM ___ TO ___	1988 September 12	28

16 SUPPLEMENTARY NOTATION

*Berkeley Research Assoc., Inc., Springfield, VA 22150

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Laser, Accelerator, Wakefield

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

An electron acceleratin method is investigated which employs a short ($\tau_L \sim 2\pi\,\omega_p^{-1} \sim 1$ picosec), high power ($P \geq 10^{15}$ W), single frequency laser pulse to generate large amplitude ($E \geq 1$ GeV/m) plasma waves (wakefields). At sufficiently high laser powers ($P \geq 17\,(\omega/\omega_p)^2$ GW), relativistic optical guiding may be used to prevent the pulse from diffracting within the plasma.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT: [X] UNCLASSIFIED/UNLIMITED [ ] SAME AS RPT. [ ] DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED
22a NAME OF RESPONSIBLE INDIVIDUAL: P. Sprangle	22b TELEPHONE (Include Area Code): (202) 767-3493; 22c OFFICE SYMBOL: Code 4790

DD Form 1473, JUN 86

Previous editions are obsolete.

S/N 0102-LF-014-6603

CONTENTS

INTRODUCTION 1

OPTICAL GUIDING 3

ACCELERATION MECHANISM 5

NUMERICAL RESULTS 8

DISCUSSION 8

ACKNOWLEDGEMENTS 10

REFERENCES 11

DISTRIBUTION LIST 17

LASER WAKEFIELD ACCELERATION AND RELATIVISTIC OPTICAL GUIDING

Introduction

It has been suggested that the next generation of high energy linear electron accelerators utilize the extremely high gradients associated with plasma waves. Excitation of plasma waves having gradients as high as several tens of GeV/m can be accomplished in a number of related ways. The plasma based acceleration schemes which have received the most attention are the plasma beat wave accelerator[1] (PBWA) and the plasma wakefield accelerator[2] (PWFA).

The purpose of this report is to propose a laser plasma electron acceleration scheme[3] which utilizes a relativistic optical guiding mechanism. Relativistic optical guiding[4,5] may allow a sufficiently high power laser pulse to propagate long distances within a plasma. The principle of this optically guided laser wakefield accelerator (LWFA) is that a short ($\tau_L \sim 2\pi/\omega_p \sim 1$ picosec), high power ($P \gtrsim 10^{15}$ W), single frequency laser pulse could propagate long distances in a plasma and produce accelerating wakefields in a manner analogous to that in the PWFA (see Fig. 1). In the LWFA, however, the plasma responds to the ponderomotive forces of the laser pulse as opposed to the self-fields of the electron beam as in the PWFA. In addition, in the LWFA the plasma wave is not resonantly excited as it is in the PBWA. Therefore, the plasma density in the LWFA concept does not have to be finely adjusted to achieve large amplitude accelerating fields. The idea of generating a plasma wave using a single frequency, short pulse laser was suggested by Tajima and Dawson,[1] but apparently was not pursued. More detailed consideration of the laser propagation issues, along with recent advances in laser technology, indicate that the single frequency, short pulse LWFA together with relativistic optical guiding may have advantages over the PBWA and PWFA schemes.

Manuscript approved July 6, 1988.

In the PBWA the plasma wave is excited by the beating of two relatively low power, long pulse laser beams having a frequency difference equal to the plasma frequency. The beat (ponderomotive) wave resonantly drives the plasma wave to large amplitudes. In the PWFA concept, a low energy, high current relativistic electron beam (driver) having an appropriate current profile travels through a plasma leaving behind a large amplitude plasma wave (wakefield). The wakefield accelerates a second low current, high energy relativistic electron beam. A necessary criteria for successful operation of either the PBWA or the PWFA is that the driver, i.e., radiation or electron beam, must be capable of propagating a sufficiently long distance within the plasma.

Both the PBWA and the PWFA concepts have a number of unresolved issues. In the PBWA, these include fine tuning of the laser frequencies and plasma density to within a fraction of a percent to allow for resonant growth of the plasma wave.[6] Also the laser beams must propagate large distances within the plasma, avoiding i) diffraction, ii) laser-plasma instabilities, iii) phase detuning between the plasma waves and the accelerated electrons, as well as iv) energy depletion of the driving laser beams.[7] The problems regarding the PWFA involve the technology of producing a high current driving beam with a slow rise time and a very rapid fall time,[8] of the order of picoseconds, as well as the stable propagation of such a beam over large distances within the plasma. Multiple acceleration stages, all sequentially phase synchronized, have been proposed to overcome the propagation distance limitation in both the PBWA and PWFA. Multi-staging appears to be extremely difficult from a practical point of view.

Optical Guiding

The need for optical guiding in the LWFA becomes apparent when the various limitations placed on the acceleration distance are considered. One limitation on the acceleration distance is the diffraction length, L_d, which characterizes the distance over which the laser beam spreads transversely. In the absence of some form of optical guiding, the diffraction length is given by the vacuum Rayleigh length, $L_d = \pi r_L^2/\lambda$, where r_L is the laser spot size and λ is the wavelength. Another limitation on the acceleration length is the phase detuning distance,[1,7] $L_t \equiv 2\gamma_L^2\lambda_p \simeq 2(1+\lambda_p^2/4r_L^2)^{-1}(\lambda_p/\lambda)^2\lambda_p$, where $\gamma_L^{-2} = (1-v_g^2/c^2)$, v_g is the group velocity of the laser pulse and λ_p is the plasma wavelength. The phase detuning length is the distance over which an ultra relativistic electron outruns the wakefield of the radiation pulse and no longer gains energy. In addition to L_d and L_t there is also the laser depletion length,[9] $L_p \equiv E_L^2\ell_L/E_z^2 \simeq \ell_L(\ell_L/\lambda)^2/a_{Lo}^2$, where E_L is the laser electric field, ℓ_L is the laser pulse length, E_z is the axial wake electric field and a_{Lo} is the normalized vector potential amplitude of the radiation field, $a_{Lo} = |e|A_{Lo}/(m_oc^2)$. When the pulse travels a distance L_p, the energy in the trailing plasma wakefield becomes comparable to the laser pulse energy. Typical values for L_d, L_t and L_p are ~ 1 m, ~ 100 m and ~ 1000 m respectively. In obtaining these estimates the following parameters were used: $\lambda \sim 1\ \mu m$, $a_{Lo} \sim 0.5$ and $\ell_L \sim r_L \sim \lambda_p \sim 0.5$ mm. The primary limitation on the acceleration distance is due to diffraction, L_d. Clearly, some form of optical guiding within the plasma is necessary to avoid the need for multi-stage acceleration.

The optical guiding mechanism which may be appropriate for the intense, short laser pulse in the LWFA is that of relativistic guiding.[4,5] Physically, relativistic guiding results from the quiver motion of the plasma electrons in the radiation field, $v_q = ca_L/\gamma_\perp$, where $\gamma_\perp(r) = (1+a_L^2(r))^{1/2}$. This gives an index of refraction $n(r) = (1-(\omega_{po}^2/\omega^2)/\gamma_\perp(r))^{1/2}$, where ω_{po} is the ambient electron plasma frequency and ω is the laser frequency. If the radiation beam is peaked on axis, then $\partial n/\partial r < 0$, which is a necessary requirement for refractive guiding to occur. Relativistic optical guiding occurs on a fast time scale of order ω^{-1}; hence, it can affect short pulse radiation, $\omega^{-1} << \ell_L/c \lesssim \omega_p^{-1}$.

Using the ray equations from geometric optics, it is possible to derive an envelope equation[5] for the evolution of the normalized spot size $x \equiv r_L/(a_{Lo}r_{Lo})$ of the radiation beam, where r_{Lo} is the initial spot size. The envelope equation is of the form of a particle moving in an effective potential, $d^2x/dt^2 = -V_o\ \partial V/\partial x$. The effective potential $V(x)$ is given by $\partial V/\partial x = -x^{-3} + 16\alpha x[g(x) - 2\ln(g(x)/2+1)]$, where $V_o = (2c^2/(\omega r_{Lo}^2 a_{Lo}^2))^2$, $\alpha = (\omega_{po}a_{Lo}r_{Lo}/(4c))^2$, and $g(x) = (1+x^{-2})^{1/2}-1$. Analysis[5] indicates that the effective potential contains a minimum provided $\alpha > 1$, thus allowing for matched beam (constant spot size) solutions. Physically, α can be written, in terms of the laser power P, as $\alpha = P/P_{cr}$, where $P_{cr} \simeq 17(\omega/\omega_p)^2$ GW is the critical power threshold for relativistic optical guiding. The high power levels needed for relativistic optical guiding in plasmas are consistent with the intense laser pulses needed in the LWFA.

Two points should be mentioned with regard to the propagation of finite length pulses of duration $\ell_L/c \lesssim \omega_p^{-1}$. The first is that relativistic optical guiding may also lead to "pulse clipping". That is, the front and back regions of the pulse where $P < P_{cr}$ will not be guided but instead will diffract away, leaving a shortened pulse. Only the central region of the pulse, where $P > P_{cr}$, will propagate. The second point concerns longitudinal dispersive spreading. It can be shown that after propagating a detuning length L_t, the intrinsic frequency spread of the beam $\Delta\omega$ causes the pulse to spread by the amount $\Delta\ell_L \simeq 2(\Delta\omega/\omega)\lambda_p$. Since $|\Delta\omega/\omega| << 1$, longitudinal dispersive spreading should not be a problem.

Acceleration Mechanism

In the relativistically guided LWFA concept the short pulse, high power laser beam provides both a radial and axial ponderomotive force on the plasma electrons. The radial ponderomotive force expels electrons radially outward while the front (back) of the laser pulse exerts a forward (backward) force on the electrons. In this sense, the laser pulse acts approximately like a negatively charged macro particle propagating through the plasma (see Fig. 1). As the plasma electrons flow around the laser pulse, large amplitude plasma waves are generated.

The ponderomotive force, exerted by the laser pulse on the plasma, moves at the pulse's group velocity and is given by $\underset{\sim}{F}_{pond} = |e|\nabla\Phi_L(r,z,t)$, where the ponderomotive potential is $\Phi_L \simeq -m_o c^2 a_L^2/(2|e|)$. Note that the axial ponderomotive force from the laser pulse cannot be used directly to accelerate electrons to high energies. The ponderomotive force on the accelerated electrons is smaller than that on the plasma electrons by the factor $1/\gamma$, where γ is the relativistic factor associated with the accelerated electrons. The laser pulse must first excite a plasma wave which, in turn, can be used for acceleration. In this analysis the laser beam is assumed to be circularly polarized, although a linearly polarized laser, apart from generating harmonics, would have been equally satisfactory.

The wave equation for the plasma response or wakefield is

$$\nabla^2 \underset{\sim}{E} - \frac{1}{c^2}\frac{\partial^2 \underset{\sim}{E}}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial \delta \underset{\sim}{J}_p}{\partial t} - 4\pi|e|\nabla \delta n_p, \tag{1}$$

where $\delta \underset{\sim}{J}_p$ and δn_p are the plasma response electron current and number density respectively. It proves convenient to perform an algebraic transformation to the speed of light frame ($\zeta = z-ct$, $\tau = t$). The transformation should actually be to the laser pulse group velocity frame, but the differences can be neglected for the present purposes. Furthermore, a temporal steady state, $\partial/\partial\tau = 0$, in the laser pulse frame is assumed. It can be shown that for short laser pulses with $a_{Lo}^2/2 << 1$, the plasma quantities remain linear and nonrelativistic. The plasma, therefore, is assumed to be described by the linear, nonrelativistic, cold fluid equations. Using this fluid response, $\delta \underset{\sim}{J}_p$ and δn_p, in the wave equation, the plasma response fields and density are given by

$$\left(\frac{\partial^2}{\partial\zeta^2} + k_p^2\right)\underset{\sim}{E}(r,\zeta) = k_p^2\, \underset{\sim}{\nabla}\phi_L(r,\zeta), \tag{2}$$

$$\left(\frac{\partial^2}{\partial\zeta^2} + k_p^2\right)\delta n_p(r,\zeta) = -\frac{|e|n_{po}}{m_o c^2}\nabla^2 \phi_L(r,\zeta), \tag{3}$$

where $k_p = \omega_{po}/c$ and $\underset{\sim}{\nabla} = \hat{e}_r \partial/\partial_r + \hat{e}_z \partial/\partial\zeta$. Note that even in the two-dimensional case the response field, $\underset{\sim}{E}$, is derivable from a scalar potential and hence, there is no response magnetic field.

From (2), the axial wakefield is given by

$$E_z(r,\zeta) = -k_p^2 \int_\zeta^\infty \cos k_p(\zeta - \zeta')\phi_L(r,\zeta')d\zeta'. \tag{4}$$

From (2) and (3) it can be shown that the transverse wakefield and plasma density are given by $\partial E_r/\partial\zeta = \partial E_z/\partial r$ and $\partial \delta n_p/\partial\zeta = -(4\pi|e|)^{-1}\nabla^2 E_z$.

As an illustration, consider a laser pulse profile of the form $a_L(r,\zeta) = a_{Lo}\sin(\pi\zeta/\ell_L)\exp(-r^2/r_L^2)$ for $0 \le \zeta \le \ell_L$ and 0 otherwise. Then the axial wakefield and response plasma density within the laser pulse, $0 \le \zeta \le \ell_L$, and behind the pulse, $\zeta \le 0$, are given by

$$E_z(\zeta,r) = -\frac{2\pi^2 k_p \phi_{Lo}(r)}{4\pi^2 - k_p^2\ell_L^2}\left[\sin k_p\ell_L(1-\tilde{\zeta}) + h\sin\left(k_p\ell_L\tilde{\zeta}/h\right)\right], \quad (5)$$

and

$$\frac{\delta n_p(z)}{n_{po}} = -\frac{2|e|}{m_o c^2}\,\frac{\pi^2\phi_{Lo}(r)}{\left(4\pi^2 - k_p^2\ell_L^2\right)}\left\{\cos k_p\ell_L(1-\tilde{\zeta}) - \cos\left(k_p\ell_L\tilde{\zeta}/h\right)\right.$$

$$\left. + \frac{8}{k_p^2 r_L^2}\left(1 - \frac{2r^2}{r_L^2}\right)\left[\cos k_p\ell_L(1-\tilde{\zeta}) - 1 - h^2\left(\cos\left(k_p\ell_L\tilde{\zeta}/h\right) - 1\right)\right]\right\}, \quad (6)$$

where $\tilde{\zeta} = \zeta/\ell_L$, $k_p = 2\pi/\lambda_p$, $\phi_{Lo}(r) = -(m_o c^2/2|e|)a_{Lo}^2\exp(-2r^2/r_L^2)$ and where $h = k_p\ell_L/2\pi$ for $0 \le \tilde{\zeta} \le 1$ and $h = 1$ for $\tilde{\zeta} \le 0$. The transverse wakefield is easily calculated from (5) by the relation $\partial E_\perp/\partial\zeta = \partial E_z/\partial r$. It can be shown, as is true of PWFA, that there exists a region of length $\lambda_p/4$ in the laser pulse frame over which the accelerated electrons experience both an accelerating axial field as well as a focusing radial field.

The axial wakefield in (5) is maximum when the laser pulse length is nearly equal to the plasma wavelength, $\ell_L \simeq \lambda_p$. For $\ell_L = \lambda_p$, the maximum accelerating field is approximately π times larger than the maximum ponderomotive axial field $E_{z,max} \simeq \pi E_{pond,max} = \pi^2\phi_{Lo}/\ell_L$. It can be shown that the maximum accelerating field is fairly insensitive to changes in the laser pulse length and/or the ambient plasma density. It should be noted that (5) and (6) also indicate that it is possible to operate the LWFA in a "wakeless" regime (i.e., the plasma response is nonzero only within the region of the laser pulse) when $\ell_L = m\lambda_p$, where m is an integer ≥ 2.

Numerical Results

The results for the plasma response given by (5) and (6) are plotted in Fig. 2 for the parameters $\ell_L = \lambda_p = 0.03$ cm, $a_{Lo}^2 = 0.31$ and $r_L = 0.038$ cm. The values of a_{Lo} and r_L are those required[5] for a relativistic optical guided beam when $\alpha = P/P_{cr} = 1.2$. The axial wakefield is shown by the solid curve and the density wake is shown by the dashed curve. The maximum accelerating gradient for this example is 2.6 GeV/m. Recall that the laser pulse extends over the region $0 \leq \tilde{\zeta} \leq 1$.

In order to further examine the principles of the LWFA, a full scale simulation was performed using the electromagnetic particle code[10] FRIEZR. FRIEZR is a 2 1/2D, fully relativistic, electromagnetic PIC code for electrons with a fluid ion background. The simulation is carried out in the transformed laboratory frame of $\zeta = z - ct$. The laser field was modeled by a fixed external ponderomotive force moving at the speed of light. The resulting axial wakefield is shown in Fig. 3 for the same parameters as used in Fig. 2. The results shown in Fig. 3 are in good agreement with analytic theory.

Discussion

The above analysis indicates that the LWFA is capable of generating acceleration gradients on the order of a few GeV/m by propagating a single, short pulse, high power laser beam through a plasma. Equation (5) gives a maximum acceleration gradient of $E_{max} \simeq m_o(c\pi a_{Lo})^2/(2|e|\ell_L)$. In addition, relativistic optical guiding occurs for sufficiently high radiation powers, $P \geq P_{cr}$. If the radiation pulse is optically guided, the acceleration distance will be limited to the phase detuning length, L_t, instead of the much shorter free space Rayleigh length, L_d. This indicates a maximum single stage energy gain of $\mathcal{E} \equiv L_t E_{max} \simeq 2\alpha\lambda_p^4/(\lambda r_L)^2$, where $\alpha = P/P_{cr}$. Table 1 summarizes these results for a CO_2, an Nd glass and a KrF laser, each of 1 psec pulse duration. In each case $\alpha = 1.2$ which implies $a_{Lo}^2 = 0.31$ and $r_L = 0.038$ cm for a matched beam propagation in the relativistic optically guided[5] propagation mode.

The present analysis of relativistic optical guiding neglects the effects of the electron density response on the laser pulse. Such an approximation is appropriate when $\delta n_p/n_{po} \ll a_{Lo}^2/2$. For the present analysis, however, this condition is only marginally satisfied for parameters of interest. In addition, laser-plasma instabilities[11,12] such as the filamentation, self-modulation or Raman scattering processes have not been considered for relativistically guided short pulses. It is anticipated that by keeping the dimensions of the laser pulse small, $\ell_L \sim r_L \leq \lambda_p$, the effects of these instabilities may be minimized. For example, Raman scattering processes[12] occur through the development of plasma waves within the laser pulse. Since the length scale for the development of plasma waves is λ_p, such effects may be suppressed if $\ell_L \lesssim \lambda_p$. In addition, relativistic filamentation[11] is a result of unstable transverse modes with $k_\perp^{-1} > \lambda_p$. Again, this instability may be suppressed in laser pulses with $r_L \sim \lambda_p$. Furthermore, random fluctuations in the plasma density will result in spreading of the laser spot size. A more self-consistent model of relativistic optical guiding for finite pulse lengths is currently being pursued by the authors.

The LWFA may have advantages over both the PWFA and the PBWA. For example, in the PWFA, it is necessary to use a high current (tens of kA) driving electron beam with a long rise time ($\gg \omega_p^{-1}$) and a rapid fall time

($\ll \omega_p^{-1}$).[8] Stable propagation within a plasma of a high current electron beam which has a pulse length greater than ω_p^{-1} may be difficult. Similarly, in the PBWA, resonant amplification of the plasma wave requires that the laser beams have long pulse lengths (many plasma periods in extent). It is likely that propagation of these long pulse beams will be plagued by the usual laser-plasma instabilities. In addition, such resonant amplification requires fine tuning between the frequency differences of the two lasers and the plasma frequency.[6] This fine tuning, which is not necessary in the LWFA, may be difficult to achieve in practice. Although the maximum gradients attainable in the LWFA may be lower than in the PBWA, the many apparent advantages (i.e., relativistic optical guiding, stability and simplicity) of using a single, intense, short pulse laser beam, makes the LWFA an attractive acceleration scheme.

Acknowledgments

The authors would like to acknowledge useful discussions with C. M. Tang and J. Krall. This work was supported by U. S. Department of Energy.

References

1. T. Tajima and J. M. Dawson, Phys. Rev. Lett. 43, 267 (1979).
2. P. Chen, J. M. Dawson, R. W. Huff and T. Katsouleas, Phys. Rev. Lett. 54, 693 (1985).
3. P. Sprangle, E. Esarey, A. Ting and G. Joyce, presented at the Nonneutral Plasma Physics Symposium, National Academy of Sciences, Washington, DC, March 28-29, 1988; also presented at the Spring Meeting of the American Physical Society, Baltimore, MD, April 18-21, 1988.
4. C. Max, J. Arons and A. B. Langdon, Phys. Rev. Lett. 33, 209 (1974); G. Schmidt and W. Horton, Comments Plasma Phys. 9, 85 (1985); G. Z. Sun, E. Ott, Y. C. Lee and P. Guzdar, Phys. Fluids 30, 526 (1987).
5. P. Sprangle and C. M. Tang, in Laser Acceleration of Particles, ed. by C. Joshi and T. Katsouleas, AIP Conf. Proc. No. 130 (Amer. Inst. Phys., New York, 1985), p. 156; P. Sprangle, C. M. Tang and E. Esarey, IEEE Trans. Plasma Sci. PS-15, 145 (1987).
6. C. M. Tang, P. Sprangle and R. N. Sudan, Appl. Phys. Lett. 45, 375 (1984); Phys. Fluids 28, 1974 (1985).
7. T. Katsouleas, C. Joshi, J. M. Dawson, F. F. Chen, C. E. Clayton, W. B. Mori, C. Darrow and D. Umstadter, in Laser Acceleration of Particles, ed. by C. Joshi and T. Katsouleas, AIP Conf. Proc. No. 130, (Amer. Inst. Phys., New York, 1985), p. 63.
8. P. Chen and J. M. Dawson, in Laser Acceleration, ed. by C. Joshi and T. Katsouleas, AIP Conf. Proc. No. 130 (Amer. Inst. Phys., New York, 1985), p. 201.
9. W. Horton and T. Tajima, in Laser Acceleration of Particles, ed. by C. Joshi and T. Katsouleas, AIP Conf. Proc. No. 130 (Amer. Inst. Phys., New York, 1985), p. 179; Phys. Rev. A 34, 4110 (1986).

10. G. Joyce, Bull. Amer. Phys. Soc. 32, 1766 (1987).

11. C. Max, J. Arons and A. B. Langdon, Phys. Rev. Lett. 33, 209 (1974).

12. D. W. Forslund, J. M. Kindel and E. L. Lindman, Phys. Fluids 18, 1002 (1975).

Table 1 The laser power (P), diffraction length (free space Rayleigh length, l_d), detuning length (L_t) and single stage energy gain ($\mathcal{E} = E_z L_t$) for three lasers: CO_2, Nd glass and KrF. The parameters are chosen to correspond to a relativistic optically guided beam with $P/P_{cr} = 1.2$, $a_{Lo}^2 = 0.31$ and $r_L = 0.038$ cm. This gives an acceleration gradient of $E_z = 2.6$ GeV/m for $\ell_L = \lambda_p = 0.03$ cm.

Laser	λ[μm]	P[W]	L_d[m]	L_t[m]	$\mathcal{E}$[GeV]
CO_2	10.6	1.9×10^{13}	0.045	0.54	1.4
Nd-glass	1.06	1.9×10^{15}	0.45	54	140
KrF	0.26	3.0×10^{16}	1.8	860	2200

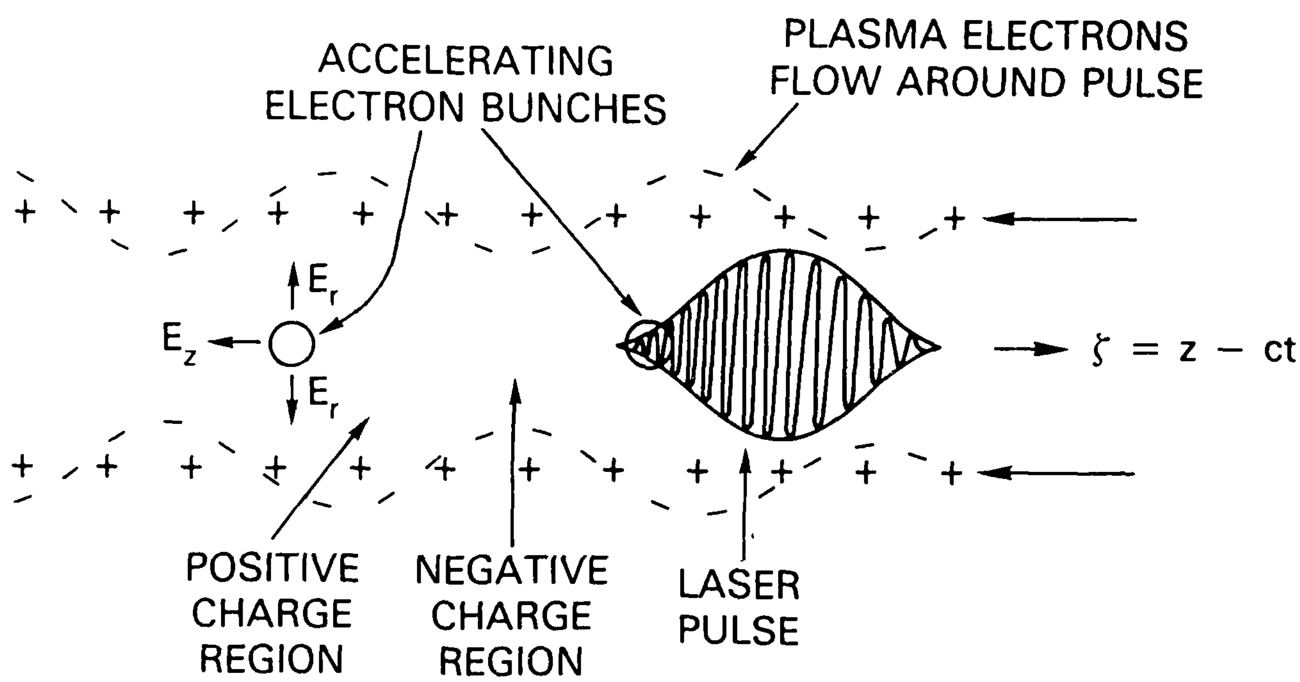


Fig. 1 Schematic of the LWFA showing the ponderomotive force from an intense short pulse laser generating a plasma wave wake as it propagates through the plasma. Roughly speaking, the laser pulse acts like an intense negative charge by repelling electrons in both the radial and axial directions.

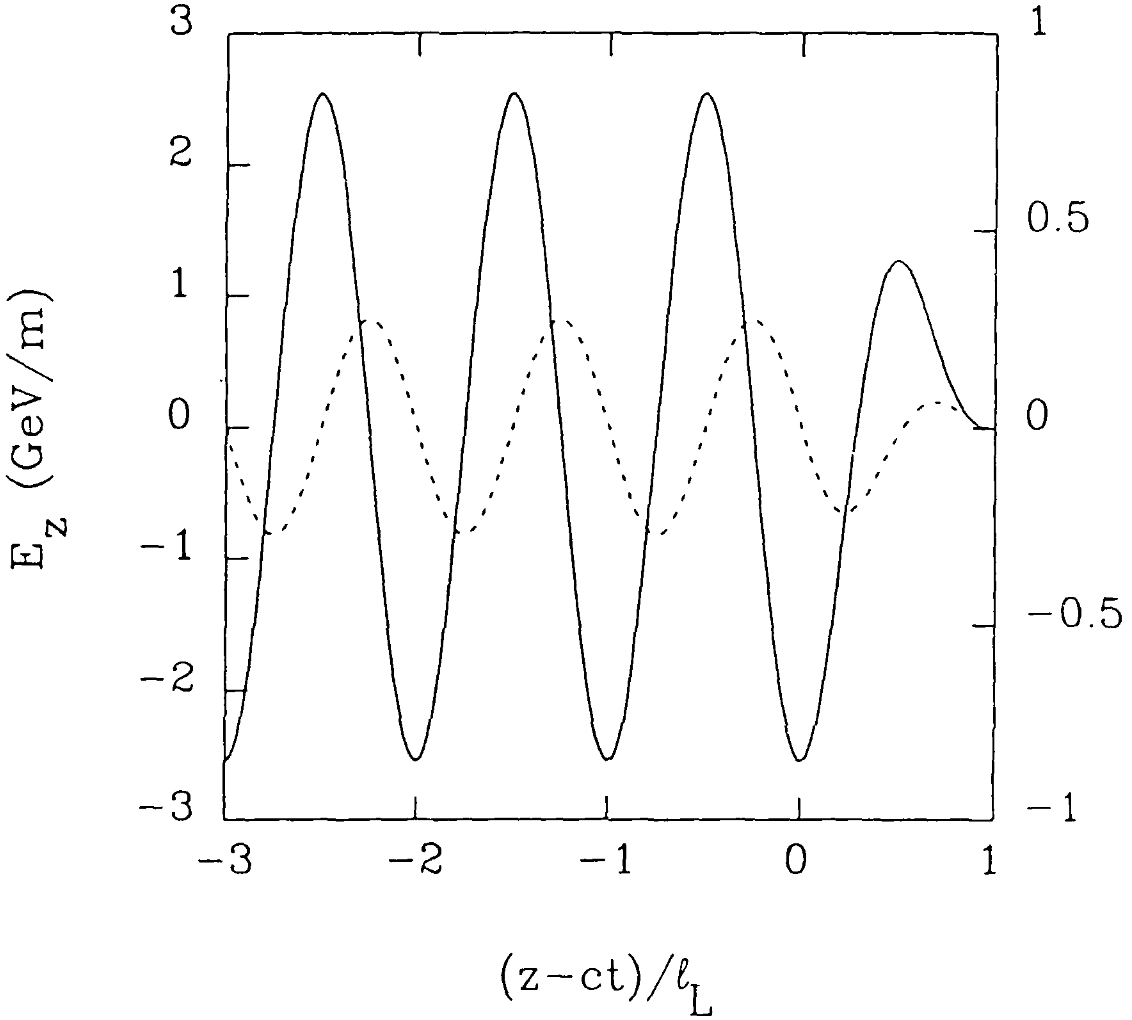


Fig. 2 The axial wakefield (solid curve) and density wake (dashed curve) for for $\ell_L = \lambda_p = 0.03$ cm, $a_{Lo}^2 = 0.31$ and $r_L = 0.038$ cm. The laser pulse extends over the region $0 \leq (z-ct)/\ell_L \leq 1$.

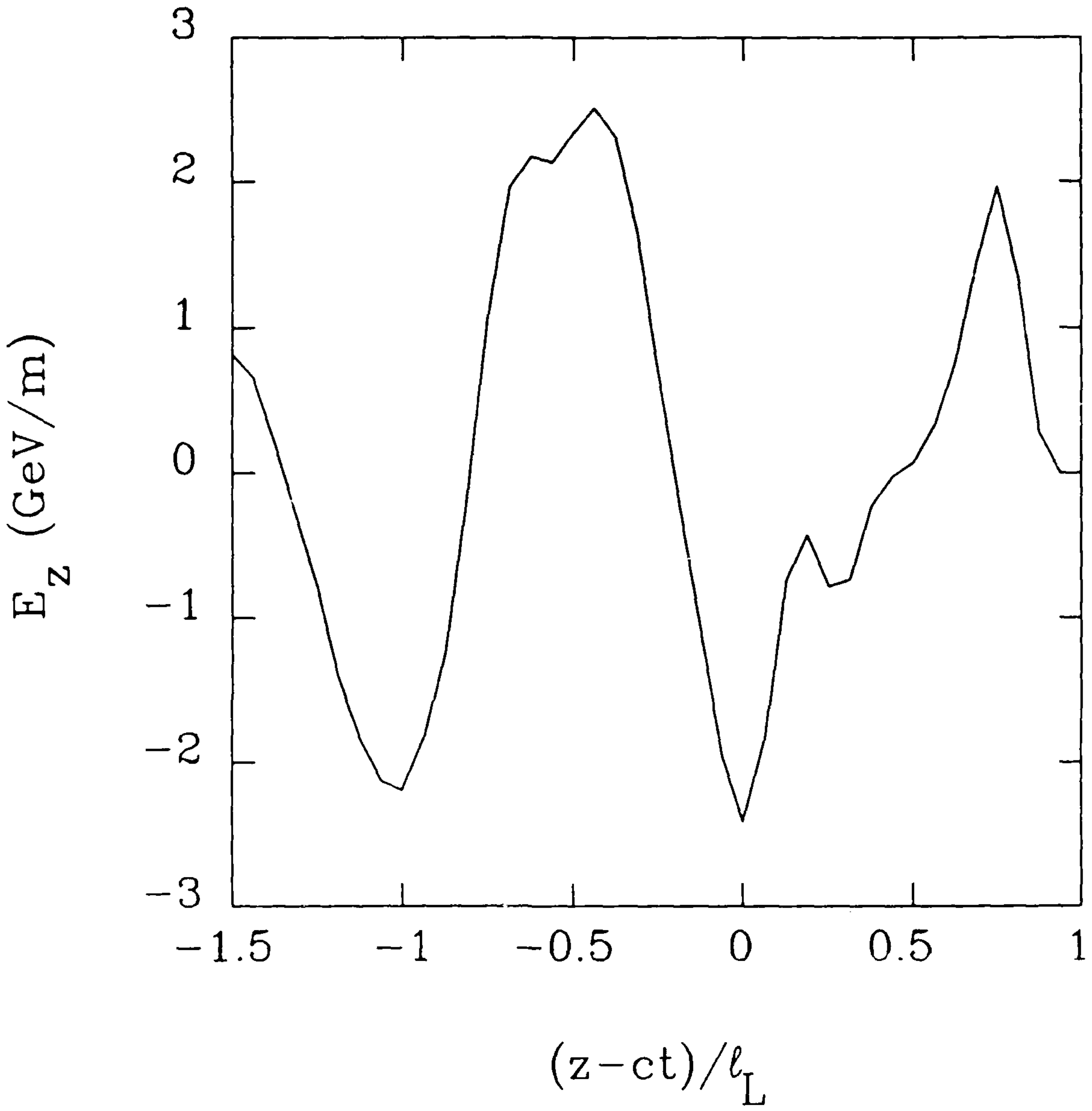


Fig. 3 The axial wakefield obtained from the particle code FRIEZR for the same parameters as in Fig. 2. The laser pulse is modeled by a fixed ponderomotive force which extends over the region $0 \leq (z-ct)/\ell_L \leq 1$.

DISTRIBUTION LIST*

Naval Research Laboratory
4555 Overlook Avenue, S.W.
Washington, DC 20375-5000

Attn: Code 1000 - CAPT W. G. Clautice
1001 - Dr. T. Coffey
1005 - Head, Office of Management & Admin.
2000 - Director of Technical Services
2604 - NRL Historian
4603 - Dr. W.W. Zachary
4700 - Dr. S. Ossakow (26 copies)
4710 - Dr. C.A. Kapetanakos
4730 - Dr. R. Elton
4740 - Dr. W.M. Manheimer
4740 - Dr. S. Gold
4790 - Dr. P. Sprangle
4790 - Dr. C.M. Tang
4790 - Dr. M. Lampe
4790 - Dr. Y.Y. Lau
4790A- W. Brizzi
6652 - Dr. N. Seeman
6840 - Dr. S.Y. Ahn
6840 - Dr. A. Ganguly
6840 - Dr. R.K. Parker
6850 - Dr. L.R. Whicker
6875 - Dr. R. Wagner
2628 - Documents (22 copies)
2634 - D. Wilbanks
1220 - 1 copy
Cindy Sims (Code 2634) 1 copy)

Records 1 copy

* Every name listed on distribution gets one copy except for those where extra copies are noted.

Dr. R. E. Aamodt
Science Applications Intl. Corp.
1515 Walnut Street
Boulder, CO 80302

Dr. B. Amini
1763 B. H.
U. C. L. A.
Los Angeles, CA 90024

Dr. D. Bach
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. D. C. Barnes
Science Applications Intl. Corp.
Austin, TX 78746

Dr. L. R. Barnett
3053 Merrill Eng. Bldg.
University of Utah
Salt Lake City, UT 84112

Dr. S. H. Batha
Lab. for Laser Energetics &
Dept. of Mech. Eng.
Univ. of Rochester
Rochester, NY 14627

Dr. F. Bauer
Courant Inst. of Math. Sciences
New York University
New York, NY 10012

Dr. Peter Baum
General Research Corp.
P. O. Box 6770
Santa Barbara, CA 93160

Prof. George Bekefi
Rm. 36-213
M.I.T.
Cambridge, MA 02139

Dr. Russ Berger
FL-10
University of Washington
Seattle, WA 98185

Dr. O. Betancourt
Courant Inst. of Math. Sciences
New York University
New York, NY 10012

Dr. B. Bezzerides
MS-E531
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Leroy N. Blumberg
U.S. Dept. of Energy
Division of High Energy Physics
ER-224/Germantown
Wash., DC 20545

Dr. Howard E. Brandt
Department of the Army
Harry Diamond Laboratory
2800 Powder Mill Road
Adelphi, MD 20783

Dr. Richard J. Briggs
Lawrence Livermore National Laboratory
P. O. Box 808, L-626
Livermore, CA 91550

Dr. Bob Brooks
FL-10
University of Washington
Seattle, WA 98195

Prof. William Case
Dept. of Physics
Grinnell College
Grinnell, Iowa 50221

Mr. Charles Cason
Commander, U. S. Army
Strategic Defense Command
Attn: CSSD-H-D
P. O. Box 1500
Huntsville, AL 34807-3801

Dr. Paul J. Channell
AT-6, MS-H818
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. A. W. Chao
Stanford Linear Accelerator Center
Stanford University
Stanford, CA 94305

Dr. Francis F. Chen
UCLA, 7731 Boelter Hall
Electrical Engineering Dept.
Los Angeles, CA 90024

Dr. K. Wendell Chen
Center for Accel. Tech.
University of Texas
P.O. Box 19363
Arlington, TX 76019

Dr. Pisin Chen
SLAC, Bin 26
P.O. Box 4349
Stanford, CA 94305

Dr. Marvin Chodorow
Stanford University
Dept. of Applied Physics
Stanford, CA 94305

Major Bart Clare
USASDC
P. O. Box 15280
Arlington, VA 22215-0500

Dr. Christopher Clayton
UCLA, 1538 Boelter Hall
Electrical Engineering Dept.
Los Angeles, CA 90024

Dr. Bruce I. Cohen
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. B. Cohn
L-630
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. B. Cole
Univ. of Wisconsin
Madison, WI 53706

Dr. Francis T. Cole
Fermi National Accelerator Laboratory
Physics Section
P. O. Box 500
Batavia, IL 60510

Dr. Richard Cooper
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Ernest D. Courant
Brookhaven National Laboratory
Upton, NY 11973

Dr. Paul L. Csonka
Institute of Theoretical Sciences
and Department of Physics
University of Oregon
Eugene, Oregon 97403

Dr. Chris Darrow
UCLA
1-130 Knudsen Hall
Los Angeles, CA 90024

Dr. J. M. Dawson
Department of Physics
University of California, Los Angeles
Los Angeles, CA 90024

Dr. Adam Drobot
Science Applications Intl. Corp.
1710 Goodridge Dr.
Mail Stop G-8-1
McLean, VA 22102

Dr. D. F. DuBois, T-DOT
Los Alamos National Laboratory
Los Alamos, NM 87545

Dr. J. J. Ewing
Spectra Technology
2755 Northup Way
Bellevue, WA 98004

Dr. Frank S. Felber
11011 Torreyana Road
San Diego, CA 92121

Dr. Richard C. Fernow
Brookhaven National Laboratory
Upton, NY 11973

Dr. H. Figueroa
1-130 Knudsen Hall
U. C. L. A.
Los Angeles, CA 90024

Dr. Jorge Fontana
Elec. and Computer Eng. Dept.
Univ. of Calif. at Santa Barbara
Santa Barbara, CA 93106

Dr. David Forslund
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. P. Garabedian
Courant Inst. of Math. Sciences
New York University
New York, NY 10012

Dr. Walter Gekelman
UCLA - Dept. of Physics
1-130 Knudsen Hall
Los Angeles, CA 90024

Dr. Dennis Gill
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. B. B. Godfrey
Mission Research Corporation
1720 Randolph Road, SE
Albuquerque, NM 87106

Dr. P. Goldston
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Prof. Louis Hand
Dept. of Physics
Cornell University
Ithaca, NY 14853

Dr. J. Hays
TRW
One Space Park
Redondo Beach, CA 90278

Dr. Wendell Horton
University of Texas
Physics Dept., RLM 11.320
Austin, TX 78712

Dr. J. Y. Hsu
General Atomic
San Diego, CA 92138

Dr. H. Huey
Varian Associates
B-118
611 Hansen Way
Palo Alto, CA 95014

Dr. Robert A. Jameson
Los Alamos National Laboratory
AT-Division, MS H811
P.O. Box 1663
Los Alamos, NM 87545

Dr. G. L. Johnston
NW16-232
M. I. T.
Cambridge, MA 02139

Dr. Shayne Johnston
Physics Department
Jackson State University
Jackson, MS 39217

Dr. Mike Jones
MS B259
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. C. Joshi
7620 Boelter Hall
Electrical Engineering Department
University of California, Los Angeles
Los Angeles, CA 90024

Dr. E. L. Kane
Science Applications Intl. Corp.
McLean, VA 22102

Dr. Tom Katsouleas
UCLA, 1-130 Knudsen Hall
Department of Physics
Los Angeles, CA 90024

Dr. Rhon Keinigs MS-259
Los Alamos National Labortory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Kwang-Je Kim
Lawrence Berkeley Laboratory
University of California, Berkeley
Berkeley, CA 94720

Dr. S. H. Kim
Center for Accelerator Technology
University of Texas
P.O. Box 19363
Arlington, TX 76019

Dr. Joe Kindel
Los Alamos National Laboratory
P. O. Box 1663, MS E531
Los Alamos, NM 87545

Dr. Ed Knapp
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Peter Kneisel
Cornell University
F. R. Newman Lab. of Nucl. Studies
Ithaca, NY 14853

Dr. Norman M. Kroll
University of California, San Diego
San Diego, CA 92093

Dr. Michael Lavan
Commander, U. S. Army
Strategic Defense Command
Attn: CSSD-H-D
P. O. Box 1500
Huntsville, AL 35807-3801

Dr. Kenneth Lee
Los Alamos National Laboratory
P.O. Box 1663, MS E531
Los Alamos, NM 87545

Dr. Baruch Levush
Dept. of Physics & Astronomy
University of Maryland
College Park, MD 20742

Dr. Chuan S. Liu
Dept. of Physics & Astronomy
University of Maryland
College Park, MD 20742

Dr. N. C. Luhmann, Jr.
7702 Boelter Hall
U. C. L. A.
Los Angeles, CA 90024

Dr. Clare Max
Institute of Geophysics
& Planetary Physics
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. B. D. McDaniel
Cornell University
Ithaca, NY 14853

Dr. Colin McKinstrie
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Prof. Kim Molvig
Plasma Fusion Center
Room NW16-240
M.I.T.
Cambridge, MA 02139

Dr. A. Mondelli
Science Applications Intl. Corp.
1710 Goodridge Drive
McLean, VA 22101

Dr. Warren Mori
1-130 Knudsen Hall
U. C. L. A.
Los Angeles, CA 90024

Dr. P. L. Morton
Stanford Linear Accelerator Center
P. O. Box 4349
Stanford, CA 94305

Dr. John A. Nation
Laboratory of Plasma Studies
369 Upson Hall
Cornell University
Ithaca, NY 14853

Dr. K. C. Ng
Courant Inst. of Math. Sciences
New York University
New York, NY 10012

Dr. Robert J. Noble
S.L.A.C., Bin 26
Stanford University
P.O. Box 4349
Stanford, CA 94305

Dr. J. Norem
Argonne National Laboratory
Argonne, IL 60439

Dr. Craig L. Olson
Sandia National Laboratories
Plasma Theory Division 1241
P.O. Box 5800
Albuquerque, NM 87185

Dr. H. Oona
MS-E554
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Robert B. Palmer
Brookhaven National Laboratory
Upton, NY 11973

Dr. Richard Pantell
Stanford University
308 McCullough Bldg.
Stanford, CA 94305

Dr. John Pasour
Mission Research Corporation
8560 Cinderbed Rd.
Suite 700
Newington, VA 22122

Dr. Samual Penner
Center for Radiation Research
National Bureau of Standards
Gaithersburg, MD 20899

Dr. Claudio Pellegrini
National Synchrotron Light Source
Brookhaven National Laboratory
Upton, NY 11973

Dr. Melvin A. Piestrup
Adelphi Technology
13800 Skyline Blvd. No. 2
Woodside, CA 94062

Dr. Z. Pietrzyk
FL-10
University of Washington
Seattle, WA 98185

Dr. Don Prosnitz
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. R. Ratowsky
Physics Department
University of California at Berkeley
Berkeley, CA 94720

Dr. Charles W. Roberson
Office of Naval Research
Detachment Arlington
800 North Quincy St., BCT # 1
Arlington, VA 22217-5000

Dr. Stephen Rockwood
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Harvey A. Rose, T-DOT
Los Alamos National Laboratory
Los Alamos, NM 87545

Dr. James B. Rosenzweig
Dept. of Physics
University of Wisconsin
Madison, WI 53706

Dr. Alessandro G. Ruggiero
Argonne National Laboratory
Argonne, IL 60439

Dr. R. D. Ruth
SLAC, Bin 26
P. O. Box 4349
Stanford, CA 94305

Dr. Jack Sandweiss
Gibbs Physics Laboratory
Yale University
260 Whitney Avenue
P. O. Box 6666
New Haven, CT 06511

Dr. Al Saxman
Los Alamos National Laboratory
P.O. Box 1663, MS E523
Los Alamos, NM 87545

Prof. John Scharer
Electrical & Computer Engineering Dept.
University of Wisconsin
Madison, WI 53706

Dr. George Schmidt
Stevens Institute of Technology
Department of Physics
Hoboken, NJ 07030

Dr. N. C. Schoen
TRW
One Space Park
Redondo Beach, CA 90278

Dr. Frank Selph
U. S. Department of Energy
Division of High Energy Physics, ER-224
Washington, DC 20545

Dr. Andrew M. Sessler
Lawrence Berkeley Laboratory
University of California, Berkeley
Berkeley, CA 94720

Dr. Richard L. Sheffield
Los Alamos National Laboratory
P.O. Box 1663, MS H825
Los Alamos, NM 87545

Dr. John Siambis
Lockheed Palo Alto Research Laboratory
3251 Hanover Street
Palo Alto, CA 94304

Dr. Robert Siemann
Dept. of Physics
Cornell University
Ithaca, NY 14853

Dr. J. D. Simpson
Argonne National Laboratory
Argonne, IL 60439

Dr. Charles K. Sinclair
Stanford University
P. O. Box 4349
Stanford, CA 94305

Dr. Sidney Singer
MS-E530
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. R. Siusher
AT&T Bell Laboratories
Murray Hill, NJ 07974

Dr. Jack Slater
Mathematical Sciences, NW
2755 Northup Way
Bellevue, WA 98009

Dr. Todd Smith
Hansen Laboratory
Stanford University
Stanford, CA 94305

Dr. Richard Spitzer
Stanford Linear Accelerator Center
P. O. Box 4347
Stanford, CA 94305

Mr. J. J. Su
UCLA
1-130 Knudsen Hall
Los Angeles, CA 90024

Prof. Ravi Sudan
Electrical Engineering Department
Cornell University
Ithaca, NY 14853

Dr. Don J. Sullivan
Mission Research Corporation
1720 Randolph Road, SE
Albuquerque, NM 87106

Dr. David F. Sutter
U. S. Department of Energy
Division of High Energy Physics, ER-224
Washington, DC 20545

Dr. T. Tajima
Department of Physics
and Institute for Fusion Studies
University of Texas
Austin, TX 78712

Dr. Lee Teng, Chairman
Fermilab
P.O. Box 500
Batavis, IL 60510

Dr. H. S. Uhm
Naval Surface Warfare Center
White Oak Laboratory
Silver Spring, MD 20903-5000

U. S. Naval Academy (2 copies)
Director of Research
Annapolis, MD 21402

Dr. William A. Wallenmeyer
U. S. Dept. of Energy
High Energy Physics Div., ER-22
Washington, DC 20545

Dr. John E. Walsh
Department of Physics
Dartmouth College
Hanover, NH 03755

Dr. Tom Wangler
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. S. Wilks
Physics Dept.
1-130 Knudsen Hall
UCLA
Los Angles, CA 90024

Dr. Perry B. Wilson
Stanford Linear Accelerator Center
Stanford University
P.O. Box 4349
Stanford, CA 94305

Dr. W. Woo
Applied Science Department
University of California at Davis
Davis, CA 95616

Dr. Jonathan Wurtele
M.I.T.
NW 16-234
Plasma Fusion Center
Cambridge, MA 02139

Dr. Yi-Ton Yan
Los Alamos National Laboratory
MS-K764
Los Alamos, NM 87545

Dr. M. Yates
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Ken Yoshioka
Laboratory for Plasma and Fusion
University of Maryland
College Park, MD [illegible]742

Dr. R. W. Ziolkowski, L-156
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

END
DATE
FILMED
12-88
DTIC