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A Mesoscopic Linear Accelerator Driven by Superintense Subpicosecond Laser Pulses

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A MESOSCOPIC LINEAR ACCELERATOR DRIVEN BY SUPER-INTENSE SUBPICOSECOND LASER PULSES

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ABSTRACT

We reconsider the idea of a solid-state laser-driven linac in view of the latest developments in the creation of super-intense subpicosecond laser pulses and studying their interaction with surfaces. We suggest that by guiding such pulses in a disposable mesoscopic (several hundred nm diameter) hollow metal waveguide it will be possible to avoid deleterious effects of the breakdown and provide very high acceleration gradients.

I. INTRODUCTION

The use of high-power lasers for high-gradient particle acceleration was first proposed by Shimoda[1] in 1962 and has been considered at intervals over the past years. The main physical requirements for the continuous particle acceleration in a linac, scaled down to the laser frequencies, consist basically of (a) creating an appreciable longitudinal electric field of the accelerating wave, (b) velocity matching between the wave and accelerated particles, (c) maintaining the strong focused and coherent wave in the process of acceleration, (d) providing the focussing of the high energy particle beam on a tiny spot for high luminosity low current operations and (e) overcoming the breakdown problems. A number of promising acceleration schemes, where some of these requirements can be met, was discussed during the last decade[2-4]. The plasma beat-wave[5] and laser wake-field[5,6] schemes, the laser-driven grating linac scheme[7], the plasma wake-field scheme[8] and the X-ray-driven crystal accelerator scheme[9] have received much attention recently. However, until now, no scheme proposed would seem to meet *all* the requirements.

The most direct method of using the intense laser beam for the purpose of acceleration would employ a guided propagation of the laser beam (in the form of a TM-mode) in a periodically loaded structure. The existing approach to the conceptual design of a possible solid-state laser-driven accelerator microstructure, based on hollow dielectric or metal waveguides, employs relatively long (picosecond) laser pulses[10,11]. In this case, the breakdown of the wall material puts a comparatively modest upper limit (several GeV/m) on the acceleration gradient. The aim of this communication is to reconsider this approach in view of the latest developments in the creation of super-intense and ultra-short (subpicosecond) laser pulses and to study their interaction with surfaces. We suggest that by guiding such pulses in a disposable mesoscopic (several hundred nm radius) hollow metal waveguide, it will be possible to avoid deleterious effects of the breakdown and yield much higher acceleration gradients, up to several TeV/m, provided that no additional nonlinear process enters that would hinder formation of accelerating fields. In the present communication, we shall briefly discuss the main physical aspects of the proposed scheme. Many of our considerations will necessarily have a qualitative character at this stage. We hope to elaborate on some of them in the future.

II. MESOSCALE STRUCTURE AND LASERS

The best choice of the laser source used for the acceleration would be that which provides the maximum intensity achievable (and thus maximum electric field amplitude) under conditions of ultra-short pulses. Table 1 gives values of the electric field amplitude E for several existing and planned sources of ultra-short pulses of super-intense laser radiation in the optical, UV- and IR-ranges. Femtosecond sources based on solid state gain media (e.g. Nd: glass, alexandrite, Ti: sapphire) appear to offer the most promise for achieving extremely high light intensities, combined with short pulse duration and good background suppression. Terawatt peak powers have been achieved in picosecond pulses[12,13]. The principal technical problems remaining are development of pulse compression to 100 fs. or less at high light intensity, and improvement of the background suppression. Dye systems[14] achieve excellent background suppression using common saturable absorber dyes, and short pulses, but provide limited total energy ($\sim 10^{-3}$ J) because of the relatively small energy storage capacity. Excimer based systems[15-19] are currently limited by the lack of good saturable absorbers in the UV, resulting in large, nanosecond duration background radiation accompanying the short pulse.

When the radiation source is specified, we have to prescribe the loaded waveguide parameters. A large amount of work was done on the calculation of the dispersion characteristics and electromagnetic field structures in various periodically loaded waveguides, with applications mainly to the microwave range[20,21]. Many of those results can be scaled down to the optical wavelengths. The main constraints on the wave-guide parameters are the following. First, the wave phase velocity must be equal to the speed of light c for an untapered waveguide, or must start with a smaller value and then approach c in a tapered one in order to achieve the phase-locking and autoresonance acceleration. Second, the wave group velocity must be close to c. Otherwise, an efficient energy transfer from the laser to the particle beam would be impossible, and also the time of establishing the accelerating wave structure in the wave-guide would be too large to overcome the breakdown problems. Third, the laser frequency must be larger than the waveguide cutoff frequency (although not *much* larger, to avoid overcrowding of the waveguide). It means that the waveguide diameter has to be not too much larger than the laser wavelength, i.e., several hundred nm. Finally, the loading structures necessary for the fulfillment of the second condition, must not be too protruding in order not to increase significantly the laser-beam induced damage of the waveguide walls.

The most serious limitations on both laser intensity and laser pulse duration are set by the interaction between the laser pulse and the waveguide walls. Optical damage in the traditional sense–formation of pits and cracks in the solid, or transient ablative clouds above the surface–need not concern us because the required ionic motion takes place on a time scale much longer than a femtosecond pulse, even at the high light intensities being considered here. This fact is the principal advantage of the current scheme over earlier proposals involving picosecond laser pulses. Nevertheless, recent experiments have shown that an intense laser pulse can drastically alter the optical properties of an intact metal surface even on a femtosecond time scale. The important mechanisms are electron heating (which changes the electron collisionality)[22-29], pressure ionization (which increases the free electron density)[30], and the expansion of a short scale length plasma gradient at the surface (which introduces resonance absorption)[25,27].

Electron heating and pressure ionization[23] occur essentially instantaneously with absorption of light within the skin depth of the metal. Because of the small heat capacity of a Fermi gas, electron temperature T_{el} is easily driven transiently above the Fermi temperature (several tens of eV) by excitation of free electron metal surfaces with obliquely incident, p-polarized femtosecond pulses of moderate intensity (10^{15} W/cm^2). Experiments[22-27] have shown that resistivity (i.e., electron-ion collision frequency ν) increases approximately linearly with T_{el} up to several tens of eV, resulting in an angle-dependent drop in optical reflectivity. For example, in aluminum[24], resistivity increases from 2.5 to 200 μohm-cm., corresponding to ν increasing from 10^{14} s^{-1} to 10^{16} s^{-1}. The resulting reflectivity drops from nearly unity to as low as 0.4 at some incident angles. Pressure ionizaiton is relatively unimportant in this electron temperature range.

The final mechanism which can degrade optical reflectivity of a metal surface on a femtosecond time scale is expansion of the surface plasma gradient. Unlike the previous mechanisms, this expansion requires a short, but finite, time delay before reflectivity is influenced. Calculations[25] show that resonance absorption is maximized at plasma gradient scale lengths of approximately 0.2λ. Time-resolved pump-probe experiments[27] with obliquely incident femtosecond pulses show that the reflectivity drop attributable to hydrodynamic expansion is delayed by several hundred femtoseconds from the excitation. Thus during a pulse of 100 fs. duration, electron heating is the dominant effect. The same remarks as above apply to angle-dependence of resonance absorption.

Also, at very high intensities of the laser beam we will have to take into account the radiation pressure of the beam, which will tend to drive the electrons, initially located around the ion sited in the vicinity of the wall, radially outward. This effect was studied earlier in the plasma physics context[31]. The radiation pressure must be balanced by the Coulomb force arising due to the charge separation (recall that the ions remain immobile on the short time scales involved). This strongly nonlinear effect can significantly increase the skin depth and reduce optical attenuation of the beam, otherwise too strong.

III. PHASE STABILITY

Now let us discuss the problem of the longitudinal phase stability of the accelerated particles in untapered and tapered waveguides. A similar problem has been considered recently[32] for the simple case of a sinusoidal longitudinal plasma wave. The results of Ref. 32 will remain applicable to the near-axis acceleration of electrons by the main TM-mode in the mesoscopic waveguide, although for a realistic (non-sinusoidal) form of the wave field in the periodically loaded waveguide, the simple criteria obtained in Ref. 32 should be modifed.

The necessary condition for the continuous acceleration is the phase locking of the accelerated particles. For a given particle, this condition can be written as[32]

$$2\varepsilon > N(1+P_0^2)^{1/2} - P_0 - (N^2-1)^{1/2}, \tag{1}$$

where $\varepsilon = qE_z/mc\omega$, q and m are the particle charge and mass, respectively, E_z is the longitudinal electric field amplitude of the wave, $P_0 = P(\xi = 0)$, $P = p/mc$ is the scaled relativistic momentum of the particle, $\xi = kz - \omega t - \xi_0$ is the phase of the particle with respect to the wave, k is the wave number in the z-direction, $N = ck/\omega$ is the refractive index of the wave. Note that the Lorentz factor γ of a particle is simply $\gamma = (1 + P^2)^{1/2}$. When N=1 (the wave phase velocity is equal to c), the phase-locking condition takes the form

$$2\,\varepsilon > (1 + P_0^2)^{1/2} - P_0, \tag{2}$$

It follows that the phase locking requires sufficiently large injection energy: $P_0 > (4\varepsilon)^{-1} - \varepsilon$ at relatively small wave fields, $\varepsilon < 0.5$, and does not impose any constraint on the injection energy at larger fields, $\varepsilon > 0.5$. Now, if a particle finds itself phase-locked with a wave, whose phase velocity is exactly equal to c, the particle acceleration is unlimited. The several TeV/m values of the acceleration gradient achievable in the optical wavelength range correspond to the values of ε of the order of 1. Fig. 1 gives an example of the continuous electron acceleration by a laser wave (TM mode) with $\varepsilon = 0.25$ (the distance is expressed in the units of $c/\omega = \lambda/2\pi$). This translates to TeV energies in this case in a 1.5 meter long hollow fiber. Calculations with different initial phases give similar results. Even if the initial phase is "inappropriate" and causes an initial deceleration, at a later stage the electron (or positron) enters the regime of a continuous and unlimited acceleration. Note that criteria (1) and (2) are written in terms of the particle momenta at $\xi = 0$, so the injection of particles with other initial phases requires a larger injection energy (for details see Ref. 32).

It is also of interest to develop a compact laser-driven *ion* linac. In this case we must necessarily start with low energy ions, for which the criterion of the phase-locking with the relativistic wave is not fulfilled. Therefore, we have to employ an initially non-relativistic (or mildly relativistic) accelerating wave to phase-lock the particles. Then, by gradually increasing the wave phase velocity with the distance z (corresponding criteria are discussed in Ref. 32, see also Ref. 33; it is important, that these criteria are wave-amplitude dependent), we can keep the particles phase-locked and, on the average, accelerated. The necessary phase-velocity increase can be realized in a tapered waveguide. Fig. 2 gives an example of this regime of the ion acceleration. We numerically integrated the equation of motion of a relativistic ion in the longitudinal electric field of a wave with a slowly varying phase velocity. For simplicity, parameter ε was chosen to be constant: $\varepsilon = 5\cdot10^{-4}$. The (dimensionless) ion injection momentum was chosen to be 1.0. In this case we are starting with the refraction coefficient $N_0 = 1.41$, which means that initial phase velocity of the wave is 0.71c. The spatial profile of the refraction coefficient in this example is the following: $N(z) = (N_0 + \alpha z)/(1 + \alpha z)$. Numerical calculations show that the optimal value of α is close to $7.5\cdot10^{-4}$; this is the value used in Fig. 2. At larger values of α the phase unlocking occurs, while at smaller α the acceleration rate drops. One can see from this example that we are starting with GeV protons to reach much higher energy on the same one-meter scale.

It should be noted that no special form of the N(z)-profile is necessary: calculations with other forms of N(z) give similar results. Of importance is the rate of change in N(z). The tapering of the waveguide necessary for the ion acceleration can be achieved through a controlled variation of the loading structures.

Very short laser pulses involved in this acceleration scheme necessarily have a finite spectral bandwidth, so that parameter $\Delta\omega/\omega$ is not less than $1\text{-}2\cdot 10^{-2}$. This means that the wave phase velocity will be weakly changing in the process of propagation. One may wonder how this affects the acceleration efficiency. In a simplified example, presented in Fig. 3, we have modeled the changes of ω by a simple frequency modulation formula $\omega(t) = \omega_0 + \Delta\omega \sin(\Delta\omega t)$ with the same amplitude and frequency of the frequency modulation. The carrier frequency ω_0 has been chosen to satisfy condition $\omega_0/k = c$, while $\Delta\omega/\omega_0$ has been taken 0.02. It is seen from Fig. 3 that the relatively small frequency variations have no deleterious effect on the acceleration.

IV. CONCLUSION

In summary, we propose a new realization of the laser-driven linac based on the guided propagation of strong subpicosecond laser pulses in (disposable) hollow metal fibers, containing a periodic loading structure, tapered if necessary. We have discussed the basic aspects of the scheme and some relevant limitations. Experiments on prototype waveguides containing the loading structures are needed to check the viability of the scheme. It is important to emphasize the need to carry out research to understand if and what this process of the accelerating field formation is deleteriously affected by. A simple, yet useful, experiment would measure the transmission coefficient of a prototype waveguide as a function of pulse duration and intensity.

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REFERENCES

1. K. Shimoda, Applied Optics **1**, 33 (1962).
2. *Laser Acceleration of Particles*, edited by P.J. Channell (AIP, New York, 1982).
3. *Laser Acceleration of Particles*, edited by C. Joshi and T. Katsouleas (AIP, New York, 1985).
4. *Advanced Accelerator Concepts*, edited by C. Joshi (AIP, New York, 1989).
5. T. Tajima and J.M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).
6. S. Sprangle, E. Esarey, A. Ting and G. Joyce, Appl. Phys. Lett. **53**, 2146 (1988).
7. R.B. Palmer, Part. Accel. **11**, 81 (1980).
8. P. Chen, J.M. Dawson, R.W. Huff, and T.Katsouleas, Phys. Rev. Lett. **54**, 693 (1985).
9. T. Tajima and M. Cavenago, Phys. Rev. Lett. **59**, 1440 (1987); P. Chen and R.J. Noble, in *Relativistic Channeling*, edited by R.A. Carrigan, Jr. and J.A. Ellison (Plenum, New York, 1987), p. 517.
10. S. Humphries, Jr., *Principles of Charged Particle Acceleration* (John Wiley & Sons, New York, 1986), p.441.
11. R.L. Byer, see ref. 4, p. 4.
12. P. Maine, D. Stricland, P. Bado, M. Pessot, and G. Mourou, IEEE J. Quant. Electron. **24** , 398 (1988).
13. P. Bado, J. Squier, F. Salin, J. S. Coe, C.Y. Chien, J.L. Tapié, and G.A.Mourou, in *Ultrafast Phenomena VII*, eds. C.B. Harris, E.P. Ippen, G.A. Mourou, and A. Zewail (Springer-Verlag, Heidelberg 1990).
14. W.M. Wood, G. Focht, and M.C. Downer, Opt. Lett. **13**, 984 (1988).
15. S. Szatmari, F.P. Schäfer, E. Müller-Horsche, and W. Mückenheim, Opt. Commun. **63**, 305 (1987).
16. Tighe, C.H. Nam, J. Robinson, and S. Suckewer, Rev. Sci. Inst. 59, 2235 (1988).
17. S. Szatmari, G. Kühnle, J. Jasny, and F.P. Schäfer, Appl. Phys. **B49**, 239 (1989).
18. J.H. Glownia, G. Arjavalingham, P.P. Sorokin, and J.E. Rothenberg, Opt. Lett. **11**, 79 (1986).
19. S. Watanabe, A. Endoh, M. Watanabe, and N. Surakura, Opt. Lett. 13, 580 (1988).
20. R.E. Collin, *Foundations for Microwave Engineering* (McGraw- Hill, Auckland, 1966).
21. *Linear Accelerators*, edited by P. Lapostolle and A. Septier (1970).

22. J.C. Kieffer, P. Audebert, M. Chaker, J.P. Matte, H. Pépin, T. W. Johnston, P.Maine, D. Meyerhofer, J. Delettrez, D. Strickland, P. Bado, and G. Mourou, Phys.Rev. Lett. **62** , 760 (1989).

23. R. Fedosejevs, R. Ottmann, R. Sigel, G. Kühnle, S. Szatmari, and F.P. Schäfer, Phys. Rev. Lett. **64** , 1250 (1990).

24. H.M. Milchberg, R.R. Freeman, S.C. Davey, and R.M. More, Phys. Rev. Lett. **61,** 2364 (1988).

25. H.M. Milchberg and R.R. Freeman, J. Opt. Soc. Am. **B6,** 1351 (1989).

26. W.C. Banyai, D.C. Anacker, X.Y. Wang, D.H. Reitze, G.B. Focht, M.C. Downer, and J.L. Erskine, in *Ultrafast Phenomena VII* (Springer-Verlag, Heidelberg 1990), in press.

27. X.Y. Wang, W.C. Banyai, D. H. Reitze, and M.C. Downer, Opt. Let., submitted for publication.

28. R.M. More, Z. Zinamon, K.H. Warren, R. Falcone, and M. Murnane, J. de Phys. **49**, 43 (1988).

29. Y.T. Lee and R. M. More, Phys. Fluids **27** , 1273 (1984).

30. R.M. More, Adv. At. Mol. Phys. **21,** 305 (1985).

31. D.C. Barnes, T. Kurki-Suonio, and T. Tajima, IEEE Trans. Plasma Sci. **15**, 154 (1987).

32. B. Meerson, Phys. Lett. **A150**, 290 (1990).

33. G.A. Loew and R. Talman, in *Physics of High Energy Particle Accelerators*, edited by M. Month (AIP, New York, 1983), p.21.

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FIGURE CAPTIONS

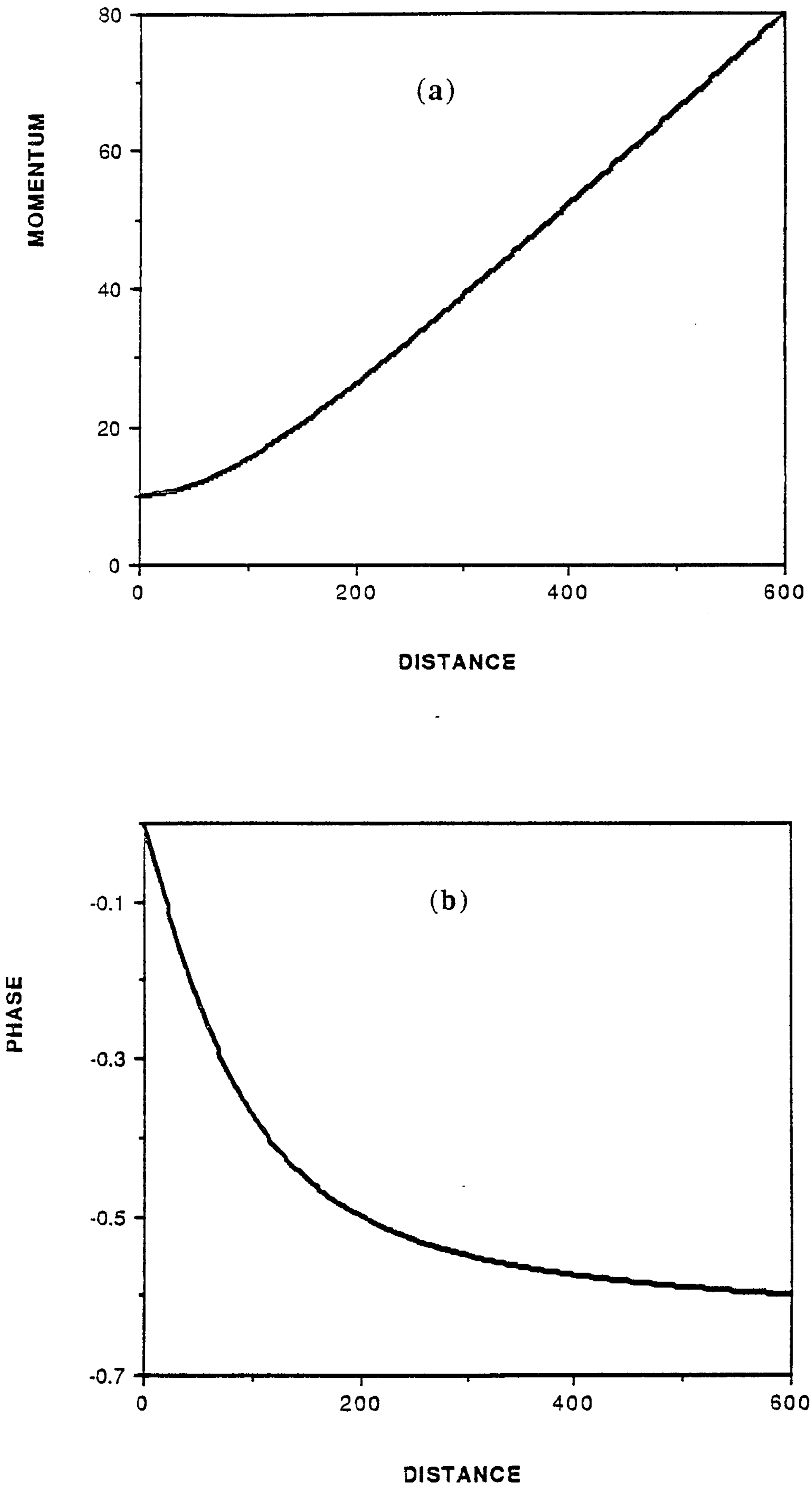
Fig.1. An example of continuous electron acceleration in the field of a sinusoidal TM-mode in an untapered waveguide. Shown are the scaled momentum P (a) and relative phase x (b) as functions of the scaled distance $z\omega/c$. The wave refraction index $N = 1$, parameter $\varepsilon = 0.25$.

Fig. 2. An example of continuous ion acceleration in the field of a sinusoidal TM-mode in a tapered waveguide. Shown are the scaled momentum P (a) and relative phase x (b) as functions of the scaled distance $z\omega/c$. Parameter $\varepsilon = -5.0\ 10^{-4}$ = const. The spatial profile of the refraction index is $N(z) = (N_0 + a\,z)/(1 + a\,z)$ with $N_0 = 1.41$ and $a = 7.5\ 10^{-4}$.

Fig. 3. The same as in Fig. 1, but the wave refraction index is modulated according to $N(t) = 1 + 0.02 \sin(0.02t)$.

TABLE 1

Fs. Source	λRange	Peak Intensity (W/cm^2)	Peak E (V/cm)	Pulse Width	Comments	References
solid state	IR	10^{18} (current)	3×10^{10}	1 ps.		12,13
		10^{21} (estimated future potential)[12,13]	1×10^{12}	100 fs.		
dye	visible	10^{16}	3×10^{9}	100 fs.	good pre-pulse suppression	14
excimer	UV	10^{18}	3×10^{10}	100 fs.	significant pre-pulse at higher intensities	15-19



(a)
MOMENTUM
80
60
40
20
0
0
200
400
600
DISTANCE
(b)
PHASE
-0.1
-0.3
-0.5
-0.7
0
200
400
600
DISTANCE

Fig. 1

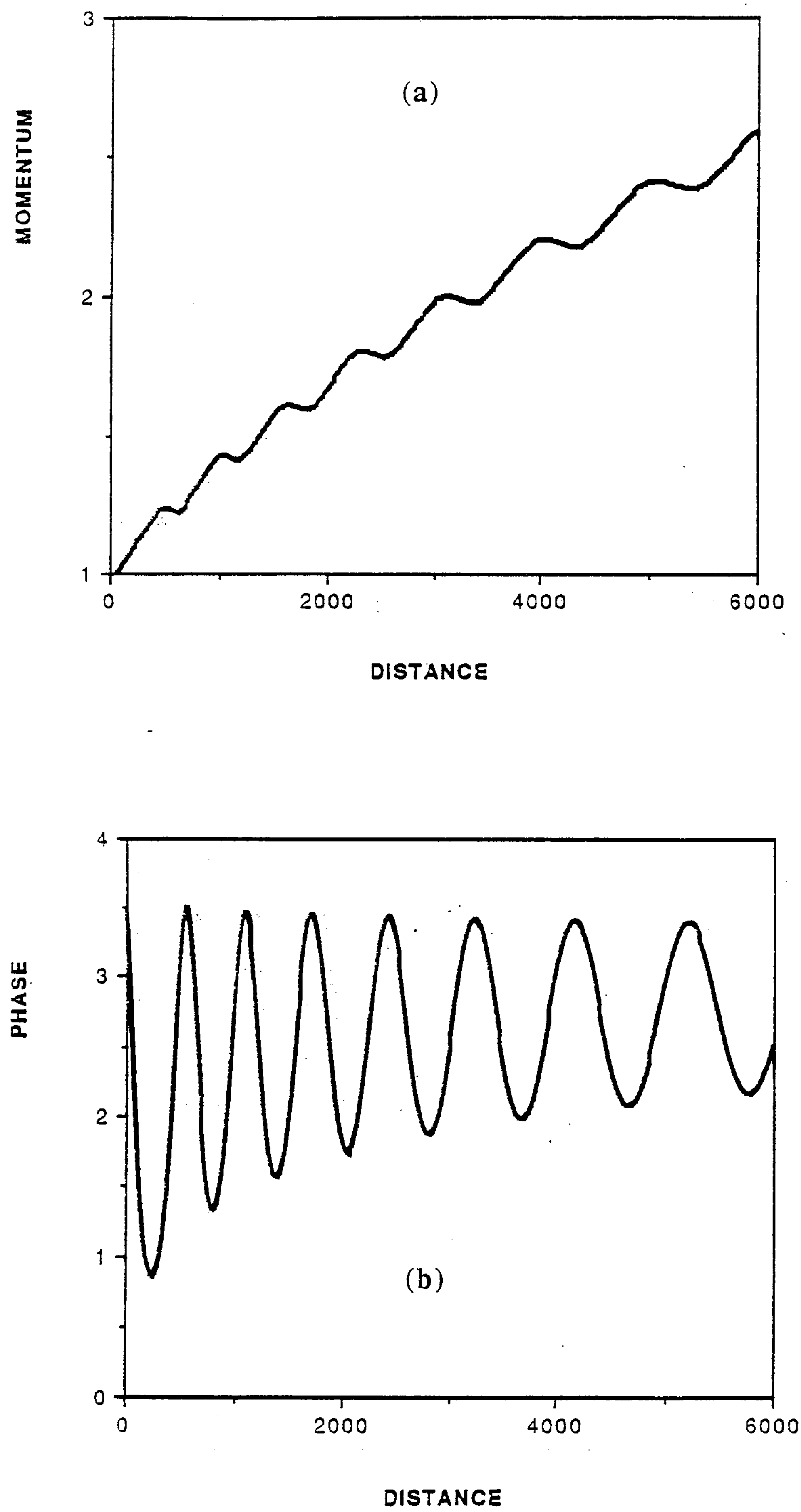
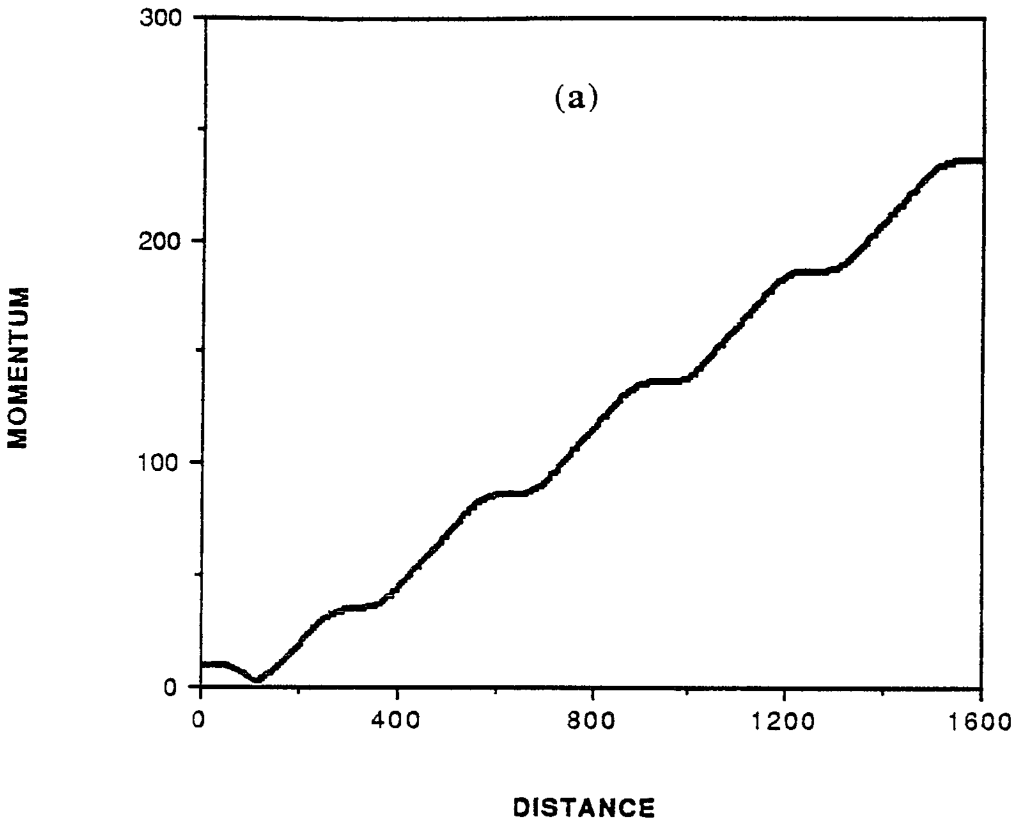

(a)
MOMENTUM
3
2
1
0
2000
4000
6000
DISTANCE
(b)
PHASE
4
3
2
1
0
0
2000
4000
6000
DISTANCE

Fig. 2


(a)
MOMENTUM
DISTANCE
300
200
100
0
0
400
800
1200
1600

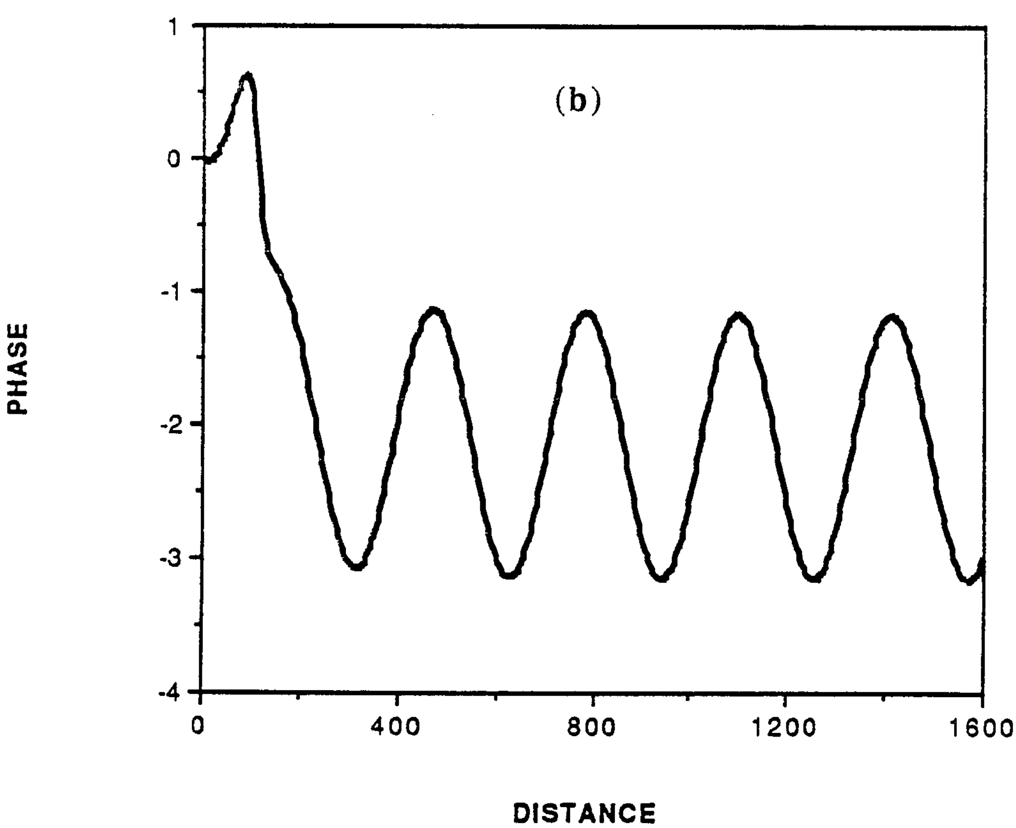

(b)
PHASE
DISTANCE
1
0
-1
-2
-3
-4
0
400
800
1200
1600

Fig. 3