Generation of periodic accelerating structures in plasma by colliding laser pulses

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A mechanism for generating large (>1 GeV/m) accelerating wakes in a plasma is proposed. Two slightly detuned counterpropagating laser beams, an ultrashort timing pulse and a long pump, exchange photons and deposit the recoil momentum in plasma electrons. This produces a localized region of electron current, which acts as a virtual electron beam, inducing intense plasma wakes with phase velocity equal to the group velocity of the short pulse. Modulating the pumping beam generates periodic accelerating structures in the plasma (''plasma linac'') which can be used for particle acceleration unlimited by the dephasing between the particles and the wake. An important difference between this type of plasma accelerator and the conventional wakefield accelerators is that this type can be achieved with laser intensities $I \ll 10^{18}$ W/cm^2. [S1063-651X(99)15708-8]

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I. INTRODUCTION

Plasma was suggested as an attractive medium for particle acceleration [1] because of the high electric field it can sustain. In a plasma-based accelerator [2], particles gain energy from a longitudinal plasma wave. To accelerate particles to relativistic energies, the plasma wave needs to be sufficiently intense, with a phase velocity close to the speed of light. To satisfy the latter requirement, laser pulses [1] and relativistic particle beams [3] are used to excite plasma waves. To satisfy the former requirement, the fractional density perturbation of the plasma by the wave $\hat{n}=\delta n/n_0$ should be substantial, since the accelerating gradient, $E_0=\hat{n}E_{wb}$, is directly proportional to $\hat{n}$, where $E_{WB}=mc\omega_p/e$ is the cold wave-breaking field, $-e$ and m are the electron charge and mass, and $\omega_p=\sqrt{4\pi e^2 n_0/m}$ is the plasma frequency. For example, a laser wake field accelerator (LWFA) requires ultrashort pulses of about $1/\omega_p$ duration and an intensity of order $I \sim 10^{18}$ W/cm^2 because $\hat{n}\approx a_0^2/2$, where a_0 is the normalized vector potential, related to the laser intensity I_0 through $a_0^2 = 0.37\lambda_0^2[\mu\mathrm{m}]I_0/10^{18}$ W/cm^2, where λ_0 is the laser wavelength. Producing large plasma wakes in a plasma wake field accelerator (PWA) requires equally short electron bunches of very high density n_b (since $\hat{n}\sim n_b/n_0$).

In this paper we suggest an approach to generating accelerating wakes in plasma, which we call a colliding-beam accelerator (CBA). This method requires neither ultrahigh intensity lasers, nor high-current electron beams. Rather, by colliding two counterpropagating laser beams of subrelativistic intensities, a short timing beam (TB) a_0 and a long pumping beam (PB) a_1, a plasma wave with phase velocity v_{ph} equal to the group velocity of the short pulse $v_g\approx c$ is generated. This wave induces a fractional density perturbation of the plasma, $\hat{n}\approx\omega_p/\omega_0$, where ω_0 and $\omega_1\approx\omega_0$ are the laser frequencies. In order to induce a density perturbation of this magnitude, laser intensities should satisfy $a_0 a_1 \geqslant \omega_p^2/\omega_0^2$. This condition implies nonrelativistic laser intensities $I_{0,1}\ll 10^{18}$ W/cm^2, because $\omega_p^2/\omega_0^2 \ll 1$ for tenuous plasmas.

The counterpropagating geometry intensifies the energy-momentum exchange between laser pulses when cold plasma is chosen as the nonlinear medium for the interaction. This is because plasma electrons are driven by the ponderomotive potential $\Phi_p=mc^2|a^2|/2$, created by the interference of the two laser pulses. When laser beams counterpropagate, an interference pattern with periodicity $\approx\lambda_0/2$ is generated. The rapidly-varying-in-space ponderomotive potential exerts a much larger ponderomotive force $\vec{F}=-\vec{\nabla}\Phi_p$ than it would in the case of co-propagating laser pulses. Moreover, the effect of the laser beams on each other depends on the fractional density perturbation of the plasma, which is, roughly, the ratio of the particle speed to the phase velocity of the excitation. Since the velocity of the interference pattern of two counterpropagating beams detuned by $\Delta\omega$ is $v_{\mathrm{ph}}/c = \Delta\omega/2k_0 \ll 1$, it follows that plasma electrons have to be accelerated to a fairly small velocity $v_z/c\approx\Delta\omega/2k_0$ in order to generate a large fractional bunching of the plasma.

Differently put, if one were to calculate the intensity of copropagating or counterpropagating laser pulses, required to produce the same density perturbation, it would turn out that a much smaller intensity would be needed in the counterpropagating geometry. This property of the colliding laser beams was used in the earlier work on electromagnetically induced guiding in plasma [4], where it was shown that a long laser beam of subrelativistic intensity can be used to guide a short counterpropagating pulse in the plasma. Moreover, by making the appropriate choice of frequency detuning between the lasers, an ultrashort pulse can be amplified by a counterpropagating pumping beam [5,6] to a very high intensity, which may exceed the intensity of the pump by several orders of magnitude. The focus of this paper is, however, on the momentum exchange between laser beams. It was long recognized [7] that the interaction between laser beams in the plasma results in the momentum transfer to plasma electrons and ions. Most calculations, however, assumed long laser beams, in which case most of the momentum was transferred to the ions. In this paper we demonstrate that if one of the two counterpropagating beams is shorter

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than the plasma period, significant momentum can be transferred to plasma electrons, thereby generating a plasma wave that has a phase velocity equal to the group velocity of the short pulse, i.e., close to the speed of light. Such a wave can be used for particle acceleration.

The remainder of the paper is organized as follows. In Sec. II we illustrate the concept of a colliding-beam accelerator through a numerical simulation, which emphasizes two important aspects of the CBA: (a) subrelativistic laser pulses are needed to produce large wakes, and (b) a sequence of acceleration/drift sections can be produced in plasma by modulating the frequency and amplitude of the long pumping beam, mimicking sections of a conventional rf accelerator in the plasma medium. In Sec. III we consider the basic physics of the enhanced wake excitation: interference of two counterpropagating laser beams generates a spatially periodic (with period $\lambda_0/2$) ponderomotive potential, which can impart an overall momentum to the plasma. Two regimes are considered: when the electron motion in this ponderomotive potential is linear, and when it is strongly nonlinear. Comparisons between the laser wakefield and colliding-beam accelerators are presented in Sec. IV. Section V concludes and outlines additional applications of CBA.

II. NUMERICAL ILLUSTRATION OF CBA

When two laser pulses collide in plasma, they may exchange photons [5,6,8]. The direction of the energy flow between the pulses is governed by the Manley-Rowe relation: the higher-frequency photons backscatter into the lower-frequency photons. The recoil momentum is deposited into the plasma electrons. For example, when the pump frequency is higher, $\Delta\omega=\omega_0-\omega_1<0$, plasma electrons, on average, acquire a negative momentum and produce an electron current. It is the essential point of this paper that this current can generate a plasma wave substantially larger in amplitude (the enhanced wake) than the conventional plasma wake produced by mere forward scattering. Since the sign of the current is controlled by the frequency detuning $\Delta\omega$, so is the phase of the plasma wave $\phi=\omega_p(t-z/v_{\rm ph})$. The ability to control ϕ is important, since it may solve the dephasing problem of wake-field acceleration. Dephasing between the plasma wave and the accelerated relativistic electrons occurs after a distance $L_d=\lambda_p^3/\lambda_0^2$. Generating a series of wake sections with tailored relative phases and magnitudes may result in a new type of plasma linac, in which the injected electrons experience acceleration over distances much exceeding L_d. In order to demonstrate the control over the phase and amplitude of the wake in a CBA, we present in Fig. 1(b) the results of a numerical simulation, where two wake sections of 1 mm total length and the relative phase difference of π are shown. The full dephasing distance of $L_d=1$ cm would involve a much larger plasma volume and considerably more computational effort.

Collision of a short TB of duration $\tau_L=\omega_p^{-1}$ and normalized vector potential $a_0=0.08$ with a long pump $a_1=0.012$ is modeled using a one-dimensional (1D) version of the particle-in-cell (PIC) simulation code VLPL [9]. Figure 1(a) illustrates the temporal profile of the PB, which moves to the left; Figs. 1(b) and 1(c) are the snapshots of the generated plasma wake and the phase space of accelerated electrons,

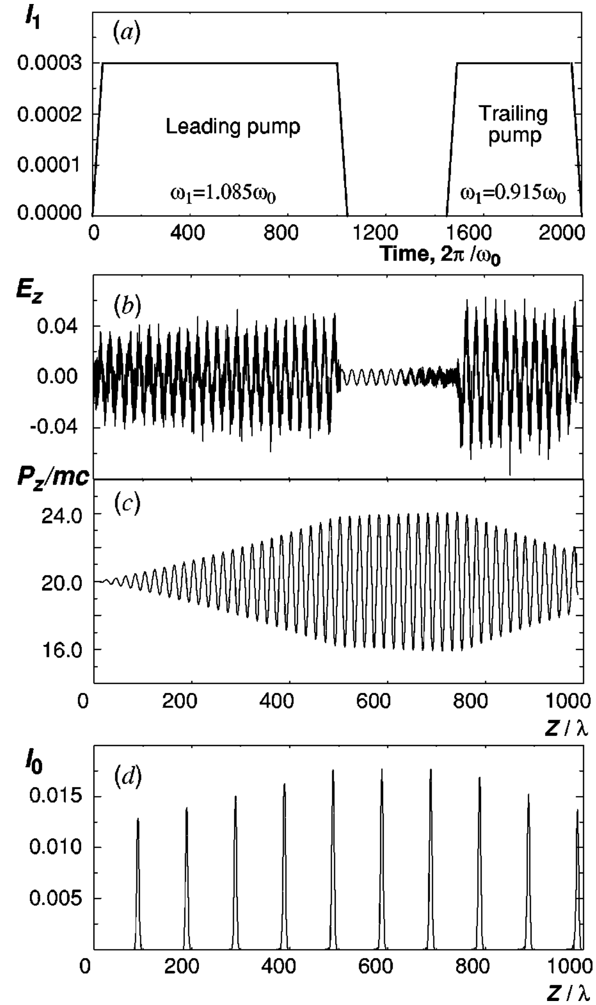

FIG. 1. Collision between a short timing beam ($a_0=0.08$, $\tau_L=\omega_p^{-1}$) and an intermittent pump ($a_1=0.012$) in $n_0=2.5\times10^{18}\,{\rm cm}^{-3}$ plasma ($\omega_0/\omega_p=20$). 10 MeV electrons are continuously injected into the plasma. (a) Time dependence of the pumping beam intensity $I_1=2a_1^2$; (b) longitudinal electric field $eE_z/mc\omega_p$; (c) propagation of the TB through the plasma, $I_0=2a_0^2$; (d) phase space of injected electrons.

which are continuously injected with an initial energy of 10 MeV; Fig. 1(d) shows the evolution of the TB as it moves through the plasma. To show how one can control the phase and the magnitude of the resulting plasma wake, we split the PB into two sections: the leading section of duration $\Delta t_1=500\times2\pi/\omega_0$, where $\Delta\omega=-1.7\omega_p$, and the trailing section $\Delta t_3=250\times2\pi/\omega_0$, where $\Delta\omega=1.7\omega_p$. These two pump beam sections are separated by the middle section of duration $\Delta t_2=\Delta t_3$, where the pump is switched out.

As Figs. 1(a) and 1(b) show, the three pump sections map into three spatial acceleration regions, which are different from each other in TB dynamics, magnitude, and phase of the plasma wake. In the leading region the pump beam has higher frequency and energy flows into the TB, amplifying it. A strong plasma wake with the peak accelerating gradient of 8 GeV/m is induced. The middle region is void of the pump. Here the TB interacts with the plasma through the usual LWFA mechanism only, producing a weak, <1 GeV/m, accelerating wake. In this region the energy of the injected electrons does not significantly change, as seen from

Fig. 1(d). When the trailing (low-frequency) part of the pump collides with the TB, the energy flows from the TB into the PB [Fig. 1(c)]. Again, a strong plasma wake is induced [Fig. 1(b)]. This wake, however, is shifted in phase by $\Delta\phi=\pi$ with respect to the leading region. As a result, the particles that gained energy in the leading region are decelerated in the trailing region [Fig. 1(d)]. This shows that both the amplitude and the phase of the enhanced plasma wake can be controlled by shaping the long low-intensity pump beam.

III. BASIC FORMALISM

To proceed, we develop a one-dimensional theory of the enhanced wake generation by colliding laser pulses. We consider the interaction between the electron plasma and two planar circularly polarized laser pulses $\vec{a}_0$ and $\vec{a}_1$, where $\vec{a}_{0,1}=a_{0,1}(\vec{e}_x \pm i\vec{e}_y)/2$, $\theta_0=(k_0 z-\omega_0 t)$, and $\theta_1=(k_1 z+\omega_1 t)$. We assume laser pulses close in frequency $|\Delta\omega| \ll \omega_0$, and tenuous plasma $\omega_p \ll \omega_{0,1}$, so that $k_0 \approx k_1 \approx \omega_0/c$. We further assume very low laser intensities, $a<0.1$, so that the injection of the background electrons into the accelerating wake [10,11] does not occur. The dynamics of the plasma is almost one dimensional if the transverse size of each of the lasers is much larger than c/ω_p.

Plasma electrons experience the longitudinal ponderomotive force of the laser beatwave $F=-mc^2\partial_z \vec{a}_0\cdot\vec{a}_1 \approx 2k_0 a_0(\zeta,z)a_1\cos(2k_0 z-\Delta\omega t)$, where $\zeta=t-z/v_g$. The motion of an arbitrary plasma electron (labeled by index j) is determined by its ponderomotive phase $\psi_j=2k_0 z_j-\Delta\omega t_j$, where z_j and t_j are the electron position and time, respectively. The equation of motion for the jth electron can be expressed as

$$\frac{\partial^2\psi_j}{\partial\zeta^2}+\omega_B^2\sin\psi_j=-\omega_p^2\sum_{l=1}^{\infty}\hat{n}_l e^{il\psi_j}-\frac{2\omega_0 e E_z}{mc}+\text{c.c.}, \quad (1)$$

where $\omega_B^2(\zeta,z)=4\omega_0^2 a_0 a_1$ is the bounce frequency [11] of an electron in the ponderomotive potential. The duration of the ponderomotive potential coincides with the duration of the TB. It turns out that two plasma waves are excited by the collision of a short pulse with a long pump: a slow wave with the wavelength $\lambda_0/2$, and a fast wave (enhanced wake) with the wavelength λ_p. This is reflected in Eq. (1): $\hat{n}_l=\langle e^{-il\psi_j}/l\rangle_{\lambda_0/2}$ is the lth harmonic of the slow wave, and E_z, the enhanced wake, is the electric field of the fast wave. The average of E_z over $\lambda_0/2$ does not vanish, so it may be viewed as the zeroth harmonic of the slow plasma wave. In deriving Eq. (1) we assumed that the TB evolves slowly on a ω_p^{-1} time scale, and that the electron velocities $v_j \ll c$.

The nonlinear origin of the enhanced wake E_z can be understood as follows [12]. As the photons are exchanged between the counterpropagating beams, electrons, on average, acquire the recoil momentum and produce a current. However, the current in 1D must be balanced by the displacement current [7]. An electric field E_z is produced, satisfying Faraday's law $\partial E_z/\partial t=-4\pi\langle J_z\rangle$, where $\langle J_z\rangle$ is the current averaged over the period of the slow wave. Two flows contribute to $\langle J_z\rangle$: the linear plasma flow in the field of the enhanced wake $J_f=-en_0 v_f$, and the nonlinear (space-averaged) flow $-e\langle nv\rangle$. Taking the time derivative of Faraday's law, we obtain

$$\left(\frac{\partial^2}{\partial\zeta^2}+\omega_p^2\right)E_z=-4\pi e\frac{\partial\langle nv\rangle}{\partial\zeta}. \quad (2)$$

As Eq. (2) indicates, the magnitude of the fast plasma wave is maximized when the transfer of the laser momentum to the plasma (via radiation recoil) occurs over a period of time shorter than the plasma period. Since the transfer time is equal to the duration of the short pulse, the latter has to be of order ω_p^{-1}. The general idea of generating fast accelerating wakes through backscattering was originally expressed in Ref. [12], where the duration of the laser pulse was taken to be much longer than ω_p^{-1}. A more effective approach, which utilizes an ultrashort pulse, is described here for the first time.

Two regimes of the fast wave excitation are considered below: (a) linear slow wave, which implies $\langle e^{-i\psi_j}\rangle \ll 1$, and (b) nonlinear particle-trapping regime.

A. Linear slow plasma wave

If the slow wave remains linear, its higher harmonics can be neglected, and $\langle nv\rangle=n_0(n_1 v_1^*+n_1^* v_1)$, where, as defined earlier, $\hat{n}_1=\langle e^{-i\psi_j}\rangle$ is the plasma density perturbation, and v_1 is the associated velocity perturbation. Using the continuity equation, it can be shown that $\langle nv/c\rangle=(\Delta\omega/\omega_0)|\hat{n}_1|^2$.

Integrating Eq. (2), find that, behind the timing beam, the accelerating electric field oscillates as $E_z(\zeta)=\tilde{e}(mc\omega_p/e)\sin\omega_p\zeta$, where

$$\tilde{e}=\frac{\omega_0\Delta\omega}{\omega_p}\int_{-\infty}^{+\infty}d\zeta\sin\omega_p\zeta|\hat{n}_1|^2. \quad (3)$$

For $|\hat{n}_1|<1/2$ a linearized equation for the density perturbation $(\partial^2/\partial\zeta^2+\omega_p^2)\hat{n}_1=c^2\nabla^2|a|^2/2$ is valid [13]. Substituting $|\hat{n}_1|^2$ into Eq. (3) and assuming that the TB is Gaussian, $a_0(\zeta)=a_0\exp(-\zeta^2/2\tau_L^2)$, we obtain

$$\tilde{e}=\frac{\pi\Delta\omega}{8\omega_0}\left(4a_1 a_0\frac{\omega_0^2}{\omega_p^2}\right)^2\omega_p^2\tau_L^2 e^{-\omega_p^2\tau_L^2/4}\left[e^{-(\omega_p-\Delta\omega)^2\tau_L^2}+e^{-(\omega_p+\Delta\omega)^2\tau_L^2}+\frac{2}{3}e^{-\Delta\omega^2\tau_L^2}\right]. \quad (4)$$

The most efficient excitation of the accelerating wake requires $\tau_L \approx 2.0\omega_p^{-1}$ and $\Delta\omega=\pm 1.1\omega_p$. For these parameters $|\tilde{e}|\approx 0.6\omega_p/\omega_0\ (4a_0 a_1\omega_0^2/\omega_p^2)^2$. The enhanced wake exceeds the regular wake from forward scattering whenever $a_1>(\omega_p/\omega_0)^{3/2}/4$. For $n_0=10^{18}\,\mathrm{cm}^{-3}$, this corresponds to the pump intensity $I_1>2\times10^{14}\,\mathrm{W/cm}^2$.

Interaction between the slow and fast plasma waves was studied earlier [14] in the regime of long laser pulses. It was found that the fast wave suppressed the growth of the slow wave while the slow wave did not significantly affect the evolution of the fast wave. Interestingly, in the short-pulse regime considered here, the slow wave can nonlinearly generate the fast wave as described by Eq. (3).

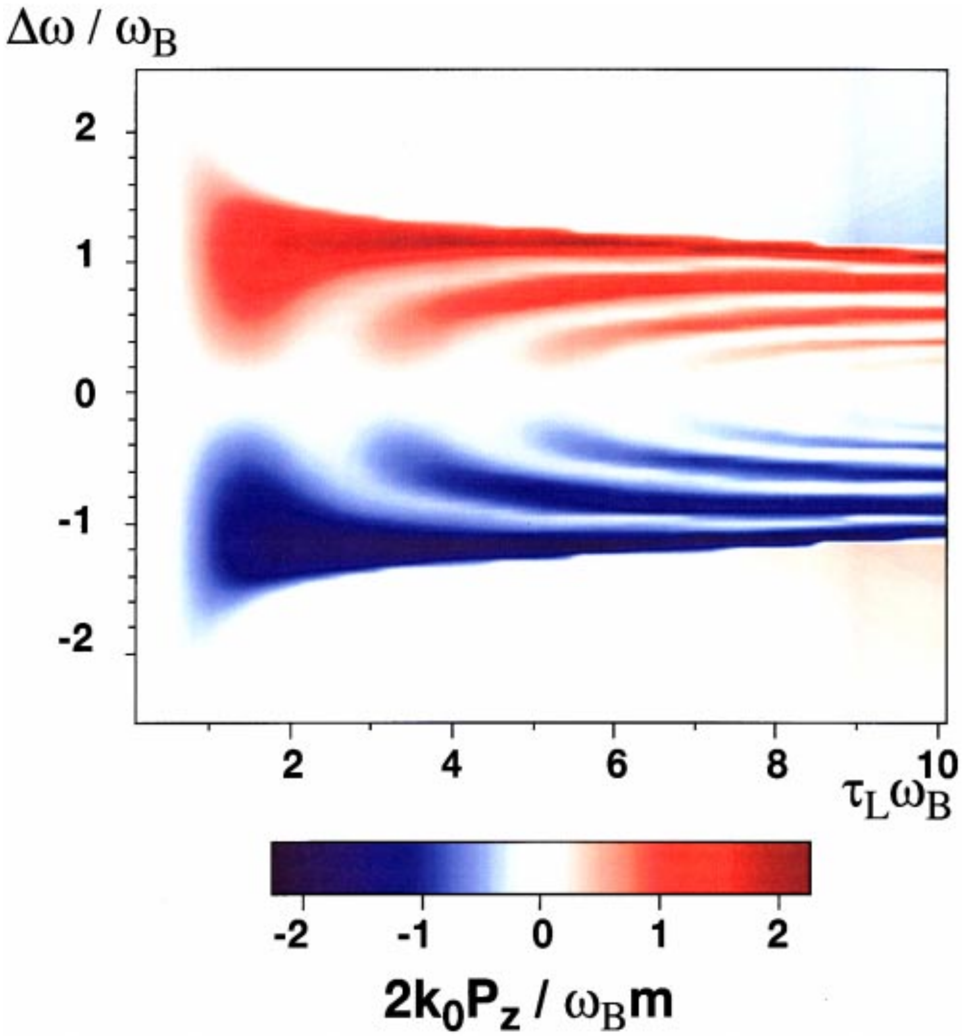

FIG. 2. (Color) Average momentum P_z gained by plasma electrons in the ponderomotive bucket as a function of the normalized TB duration $\omega_B \tau_L$ and the frequency detuning $\Delta\omega/\omega_B$.

B. Particle-trapping regime

Equation (4) is valid if the slow plasma wave is linear. To find the maximum magnitude of the enhanced wake, consider the nonlinear regime of Eq. (1) when $\omega_B^2 > \omega_p^2$. In this regime, all the terms on the right-hand side of Eq. (1) become smaller than the ponderomotive term on the left-hand side. One may neglect the electrostatic forces acting on plasma electrons during the short period of TB interaction. Hence, the particle motion is qualitatively described by the nonlinear pendulum equation

$$\ddot{\psi}_j + \omega_B^2(\zeta)\sin\psi_j = 0. \qquad (5)$$

Plasma electrons, initially stationary in the laboratory frame, enter the time-dependent ponderomotive bucket with the initial ''speed'' $\dot{\psi} = -\Delta\omega$. If this speed is smaller than the bucket height $\dot{\psi}_{\max} = 2\omega_B$, some electrons (with the appropriate initial ponderomotive phase) become trapped and execute a synchrotron oscillation in the bucket. It turns out that, by appropriately choosing the pulse duration and frequency detuning, a substantial average momentum can be imparted to plasma electrons.

To demonstrate this, we assume that the TB has a Gaussian temporal profile and $\omega_B^2(\zeta) \equiv \omega_B^2 \exp(-\zeta^2/2\tau_L^2)$. We solve the nonlinear pendulum equation (5) for an ensemble of test electrons. Before the arrival of the TB (at $\zeta = -\infty$) the electrons are uniformly distributed in phase $0 < \psi_j < 2\pi$ and have identical $\dot{\psi}_j = -\Delta\omega$. The average momentum P_z, gained by the electrons after the interaction, is calculated as $P_z = (m/2k_0)\Sigma_j \Delta\dot{\psi}_j$, where $\Delta\dot{\psi}_j = \dot{\psi}_j(\zeta = +\infty) - \dot{\psi}_j(\zeta = -\infty)$. In the color plot of Fig. 2, P_z is shown as the function of the normalized pulse duration $\omega_B \tau_L$ and frequency detuning $\Delta\omega/\omega_B$. From Fig. 2, the average momentum, gained by the electrons, has the same sign as the frequency detuning.

The largest average momentum gain $P_z \approx mc\Delta\omega/\omega_0$ is realized for $\Delta\omega \approx \omega_B$ and $\tau_L \approx 2/\omega_B$. For these parameters, most of the electrons execute half of a bounce in the ponderomotive bucket. Other bright color streaks in Fig. 2 correspond to the electrons executing 3/2, 5/2, etc. bounces. For those higher-order resonances, P_z is maximized for longer pulse durations τ_L. If the pulse duration is longer than ω_p^{-1}, the neglected space-charge terms are likely to reduce P_z.

The amplitude of the enhanced wake can be estimated in the strongly nonlinear regime, $\omega_B^2 \gg \omega_p^2$. The short TB has a duration $\tau_L \sim 2\omega_B^{-1}$, small in comparison with the plasma period. Behind the TB electrons are left with an average momentum P_z, generating an enhanced wake with the electric field

$$\frac{eE_z}{mc\omega_p} = \frac{\langle P_z \rangle}{mc} \sin\omega_p\zeta \approx \mathrm{sign}(\Delta\omega)\left(\frac{\omega_B}{\omega_0}\right)\sin\omega_p\zeta. \qquad (6)$$

Since the bounce frequency $\omega_B \sim I_0^{1/4}$ increases slowly with the intensity of the TB, it is realistic to assume that $\omega_B \sim \omega_p$, so that $\hat{n} \sim \omega_p/\omega_0$. Note that the phase of the enhanced wake is controlled by the sign of the frequency detuning $\Delta\omega$, as observed in the PIC simulation. This is true when the slow plasma wave is either linear, or nonlinear, as predicted by Eqs. (4) and (6), respectively.

IV. COMPARISON BETWEEN CBA AND LWFA

We are now in the position of comparing the CBA with the more conventional LWFA and PWA. In the CBA laser recoil can generate an accelerating plasma wake with amplitude which, for small laser intensities $a_0 < (2\omega_p/\omega_0)^{1/2}$, exceeds the wake generated by the forward scattering in a LWFA. For example, colliding a 30 fs $I_0 = 3\times10^{15}$ W/cm^2 pulse with an equal intensity pump in a $n_0 = 10^{18}$ cm^{-3} plasma yields a 3 GeV/m accelerating gradient. In a LWFA, producing an electric field of the same magnitude in the same density plasma would require a 1.8×10^{17} W/cm^2 intensity of the short pulse. A 30 fs long electron beam with density $n_b = 3\times10^{16}$ cm^{-3} is required to drive the accelerating field of such magnitude in a PWA. Since CBA requires neither high laser intensity nor large beam current, it can be viewed as an attractive alternative to conventional plasma accelerators.

To compare the energy requirements of the CBA and LWFA, we've calculated the laser energies U_{CBA} and U_{LWFA}, needed to accelerate the electrons by a fixed amount ΔW. The ratio $R = U_{\mathrm{CBA}}/U_{\mathrm{LWFA}}$ can be shown to be $R \approx |a_1|^2(\omega_0/\omega_p)^3$. For the simulation parameters of Fig. 1 we find $R = 1.25$. Therefore, roughly the same laser energy is needed to accelerate electrons to a given energy using either of the two accelerating schemes. To avoid the instabilities of the pumping beam, it may be necessary to focus different sections of the pump on different locations in the plasma.

A useful property of the CBA is that for $\Delta\omega < 0$ the energy of the wake is provided by the long low-intensity pump. This is in contrast with the traditional LWFA, where the energy of the laser wake comes from the ultrashort pulse. This may be advantageous because long low-intensity laser beams are easier to generate and recycle. A disadvantage is the limited efficiency of the CBA, since most of the energy flows from the pump into the short pulse. Defining the efficiency η as the ratio of the wake energy to the depleted energy of the pump, we obtain

$$\eta = \eta_{\mathrm{depl}}^{-1} \frac{\omega_p}{\omega_0} \frac{1}{4a_1^2(\omega_0/\omega_p)^3}, \tag{7}$$

where η_{depl} is the coefficient of pump depletion. This definition of efficiency is only meaningful if the remaining energy of the low-intensity pump can be recovered. For the example considered, the pump depletion is about 15%, so that $\eta = 10\%$. The remaining 90% of the depleted energy flows into the short pulse.

Another advantage of using the long low-intensity beam as the energy source is that its properties can be tailored to circumvent particle dephasing by generating periodic accelerating structure (plasma linacs). By repeating the time sequence for the pump, shown in Fig. 1, with the appropriately chosen durations of the pump sections $\Delta t_1 = 2L_d/c$ and $\Delta t_2 = \Delta t_3 = L_d/c$, one can achieve limitless particle acceleration, not encumbered by dephasing. The convenience of this particular sequence is that the particle is accelerated for 3/4 of the time. Also, since $\Delta t_1 > \Delta t_2$, there is a net energy flow from the pump into the beam which can compensate for the diffractive losses.

V. CONCLUSIONS

CBA can also be used as a combined accelerator/x-ray source. For instance, 15 cm of plasma is sufficient to accelerate electrons to 1 GeV using the laser-plasma parameters of the PIC simulation shown in Fig. 1. Assuming that the cross section of the pump is determined by Gaussian diffraction, it appears that a 1 ns 0.5 kJ laser pulse [15–17] can be used as a PB. In the course of their acceleration, electrons Compton backscatter the pump photons, producing a broadband spectrum of x rays, $\hbar\omega \leqslant 10$ MeV.

In conclusion, we identified and analyzed a method for generating ultrahigh-gradient accelerating wakes in plasma by colliding a short laser pulse with a long counterpropagating pump. This method requires modest laser intensities $\leqslant 10^{18}$ W/cm^2 and provides a straightforward way of generating periodic accelerating structures in the plasma (plasma linacs) to deal with the dephasing of the ultrarelativistic particles. It appears that this colliding beam accelerator could be one of the possible approaches to multistaging a particle accelerator.

ACKNOWLEDGMENTS

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