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Plasma-based Accelerator with Magnetic Compression

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Electron dephasing is a major gain-inhibiting effect in plasma-based accelerators. A novel method is proposed to overcome dephasing, in which the modulation of a modest ($\sim \mathcal{O}(10$ kG$)$), axial, uniform magnetic field in the acceleration channel leads to densification of the plasma through magnetic compression, enabling direct, time-resolved control of the plasma wave properties. The methodology is broadly applicable and can be optimized to improve the leading acceleration approaches, including plasma beat-wave, plasma wakefield, and laser wakefield acceleration. The advantages of magnetic compression compared to other proposed schemes to overcome dephasing are identified.

PACS numbers:

Introduction.— Charged-particle acceleration in plasma employs short, intense laser pulses or high energy electron bunches to excite longitudinal plasma waves to high amplitudes at phase velocities near the speed of light, thereby accelerating relativistic particles to high energies over very short distances [1–6]. One major factor limiting energy gain in plasma-based accelerators is *phase slippage*, in which a particle eventually outruns the segment of the wave providing a positive accelerating force (see, e.g., Ref. [3]). The maximum achievable energy gain for a particle trapped in a plasma wave is limited by the wave amplitude and phase velocity, v_{ph}. Methods to improve gain require that particles remain in phase with the forward accelerating component of a plasma wave for an extended period of time. The *surfatron* employs a static, transverse applied magnetic field to control the axial phase of an accelerating particle in a beat-wave accelerator [7, 8], while a stationary, axial plasma density gradient can be used to synchronize the advance of a wakefield and an accelerating ultrarelativistic electron [9–13]. The use of active media to modulate the wake phase velocity has also been proposed [14].

In this Letter, we propose a new method to modulate precisely the phase velocity of an accelerating plasma wave by imposing a time-varying, uniform axial magnetic field throughout the plasma. Within a bounded parameter regime, uniform transverse magnetic compression of the plasma column is possible on experimentally relevant timescales. Thus, a tunable, time-varying density profile can be realized. With magnetic compression, the plasma wave phase velocity can be increased beyond the subluminal driver group velocity, in the case of laser wakefield (LWFA) and plasma beat-wave (PBWA) acceleration, or the driver beam velocity, in the case of plasma wakefield (PWFA) acceleration (up to and even beyond c). Static, axial magnetic fields have been shown to enhance electron injection, trapping, beam stability, and energy gain in LWFA [15, 16] and PBWA [17]; however, this is the first time a time-varying field has been proposed as a control mechanism for the wave dynamics.

For PBWA, only a small fractional density increase through magnetic compression is needed to increase the electron dephasing length to arbitrarily long distances, without inducing transverse motion of the accelerating electrons across the plasma wave, unlike the surfatron method [7]. For wakefield acceleration, generating a propagating luminal phase front in the wake via magnetic compression requires much smaller shifts in density than the axial density gradient method [9–13], and no density singularity arises in the optimized density profile as the accelerating electron bunch approaches the driver. Additionally, in PWFA, proportional densification of the driving beam and background plasma causes the wakefield amplitude to increase with propagation distance, rather than decrease, as occurs with the axial gradient method [9]. Also, generating a time-varying, but axially uniform, density profile in the acceleration channel using a time-varying, uniform magnetic field should be technologically considerably easier than generating a stationary axial density gradient, which, in equilibrium, requires pressure balance as well.

Plasma beat-wave acceleration with compression.— In PBWA, two co-propagating lasers combine to form a traveling ponderomotive beat-wave. Here, the laser frequencies $\omega_{1,2} = \omega_d \pm \Delta\omega/2$ and wavenumbers $k_{1,2} = k_0 \pm \Delta k/2$, with $\Delta\omega \approx \omega_p$, $\Delta k \approx \omega_p/c \equiv k_p$, and $\omega_d \gg \omega_p$, where ω_p is the electron plasma frequency. For simplicity, we consider the 1D limit, i.e., $r_{\mathrm{d}} \gg k_p^{-1}$, where r_{d} is the characteristic transverse dimension of the driver, such that the focus will be primarily on the axial dynamics of accelerating electrons. The beat-wave resonantly drives a long (many k_p^{-1}) plasma wavetrain of frequency ω_p and wavenumber k_p to high amplitude over several plasma periods. Subsequently, the approximately uniform wavetrain is used as an accelerating structure for externally injected electrons. For PBWA, autoresonant phase-locking of resonantly driven plasma waves to frequency chirped laser beat-waves has been proposed as a way to drive plasma waves to high amplitudes [18, 19], but the dephasing problem is not addressed. Here, we propose a method to modulate both ω_p and v_{ph}.

Consider homogeneous, uniformly magnetized plasma, i.e., $\mathbf{B} = B(t)\hat{\mathbf{z}}$, where $B(t)$ changes with time. For example, this could be realized within a plasma column confined inside a solenoid carrying a time-varying current. Magnetization implies that the plasma density, n, varies with $|\mathbf{B}|$. For slow variation of plasma parameters, a plasma wave with wavevector $\mathbf{k} \parallel \mathbf{B}$ obeys the eikonal equation [20]: $\omega^2 = \omega_p^2 + 3k^2 v_{\mathrm{T}\|}^2$, where $v_{\mathrm{T}\|}$ is the electron thermal velocity parallel to the magnetic field. In the case of an ultrarelativistic plasma wave, i.e., $v_{\mathrm{ph}} = \omega/k \simeq c$, the cold plasma eikonal equation suffices, $\omega = \omega_p$. Since $\omega_p^2 \propto n \propto B$, we have $\omega_p = \omega_p(t)$, while k remains constant (neglecting nonlinear effects [3]), since the compression is perpendicular to the wavevector. In the neighborhood of $\omega/k = c$, changes in n result in large changes in ω/k, so that minimal compression is needed to retain proper phasing of relativistic particles.

The axial dynamics of a relativistic electron interacting with a sinusoidal potential exhibiting a dynamically changing $v_{\mathrm{ph}}(t)$ are captured by the equations [21]:

$$\frac{d\gamma}{dt} = \left(1 - \frac{1}{\gamma^2}\right)^{1/2} \left(\frac{eE_0}{m_e c}\right) \cos\xi, \tag{1}$$

$$\frac{d\xi}{dt} = ck\left(1 - \frac{1}{\gamma^2}\right)^{1/2} - \dot{\Psi}, \tag{2}$$

where $\xi = kx - \Psi(t)$, $\gamma m_e c^2$ is the electron energy in the laboratory frame, e is the elementary charge, and $\Psi(t) = \int_0^t \omega(k;t')\, dt'$. Because minimal compression is anticipated to correct the wave phase velocity, the electric field amplitude $E_0 \approx$ const.

The compression profile required to overcome phase slippage in PBWA can be calculated from Eqs. (1) and (2). Suppose $\Psi(t)$ is configured such that a stable fixed point arises in the phase space associated with the rest frame of the accelerating plasma wave. Then, combining Eqs. (1) and (2) by eliminating the square root gives $\dot{\gamma} = \Phi_0(\dot{\xi} + \dot{\Psi})\cos\xi$, with $\Phi_0 \equiv eE_0/km_e c^2$. If $\xi = \xi_0$, corresponding to the fixed point, there exists an energy-like integral of motion: $d/dt(\gamma - \Phi_0\Psi\cos\xi_0) = 0$. Equation (2) yields the necessary plasma compression profile. Noting that $\dot{\Psi} = \omega_p(t)$, and that the distance traversed by a phase-locked particle $D(t) = (\Psi - \Psi_0)/k$, the required normalized density profile, $\tilde{n} = \omega_p^2/\omega_{p0}^2$, is:

$$\tilde{n}[D(t)] = \frac{\gamma_0^2\left[(\gamma_0 + \Phi_0 kD\cos\xi_0)^2 - 1\right]}{(\gamma_0^2 - 1)\,(\gamma_0 + \Phi_0 kD\cos\xi_0)^2}, \tag{3}$$

where $\gamma_0 = \gamma_{\mathrm{ph},0} \equiv (1 - v_{\mathrm{ph},0}^2/c^2)^{-1/2}$ implies exact initial wave-particle resonance. This expression for $\tilde{n}$ is monotonic in D, asymptotically approaching $\tilde{n}_{\max} = \gamma_0^2/(\gamma_0^2 - 1)$ as $D \to \infty$ (and, hence, $\gamma \to \infty$). For instance, to accelerate a 2 MeV electron bunch ($\gamma_0 \approx 4$) to arbitrarily high energies requires a peak density shift $\tilde{n}_{\max} \approx 1.07$, demonstrating that only small changes in density are needed to accelerate relativistic electrons to arbitrarily high energies while maintaining the proper wave-particle phase relationship. Physically, the quantity $\tilde{n}_{\max}$ represents the total change in density required for $v_{\mathrm{ph}} \to c$. To express Eq. (3) as an explicit function of time, one integrates $D(t) = \int_0^t v\, dt'$ for a relativistic particle at fixed phase in the accelerating potential:

$$D(t) = \frac{1}{\alpha}\left[\sqrt{\left(\alpha ct + \sqrt{\gamma_0^2 - 1}\right)^2 + 1} - \gamma_0\right], \tag{4}$$

with $\alpha = eE_0\cos\xi_0/m_e c^2$. The fixed point assumes zero transverse momentum, which equates to a compression profile optimized to trap relativistic particles with a narrow transverse energy spread.

Peak acceleration occurs when $\xi_0 = 0$, for which an electron starting at $\xi = 0$ obeys $\gamma - \Phi_0\Psi =$ const. In fact, for a wave of specified E_0 and k, this is the *maximum* achievable acceleration, in which the electron experiences the peak accelerating field as the wave and electron accelerate together. More generally, choosing $\xi_0 : (0, \pi/2)$ in Eq. (3) leads to compression profiles enabling electron trapping over a broader range of initial electron energies, at the cost of slower acceleration. This is because the fixed point in the wave rest frame, ξ_0, lies ahead of the peak accelerating field, at $\xi = 0$, allowing some particles that slip behind ξ_0 to catch up to ξ_0 once again.

Wakefield acceleration with compression.— Mitigating phase slippage through magnetic compression in (linear) wakefield acceleration, including LWFA and PWFA, is a somewhat different process. Here, a time-varying density profile during wake excitation results in an axial gradient in the plasma wake parameters, which was not the case with PBWA. Electron dephasing is often the dominant effect limiting energy gain in wakefield acceleration when the driver amplitude is no more than weakly relativistic, i.e., $eA/m_e c^2 < 1$ for LWFA, where A is the peak vector potential of the laser driver [13], or $n_b/n < 1$ for PWFA, where n_b is the peak driver beam density [3].

In wakefield acceleration, a subluminal wakefield is excited by an ultrarelativistic driver, i.e., $\gamma_d = (1 - \beta_d^2)^{-1/2} \gg 1$, with $\beta_d = v_d/c$, and v_d is the driver pulse velocity. For PWFA, the longitudinal velocity of the electron beam driver, v_b, is unaffected by the perpendicular magnetic compression. Because only modest density changes will be needed, the laser pulse group velocity, v_{gr}, is mostly unaffected as well, since a change in plasma frequency, $\Delta\omega_p$, leads to a change in wave phase velocity $\Delta v_{\mathrm{ph}}/v_{\mathrm{ph}} \sim \Delta\omega_p/\omega_p$, which is large compared to the change in laser group velocity, $\Delta v_{\mathrm{gr}}/v_{\mathrm{gr}} \sim (\omega_p/\omega_d)^2\Delta\omega_p/\omega_p$, where ω_d is the characteristic laser frequency, and $\omega_p/\omega_d \ll 1$ in underdense plasma. Thus, both PWFA and LWFA can be treated similarly, where the characteristic driver velocity $v_d =$ const.

We follow the technique of Ref. [9] to derive the required density profile (in the 1D limit) to maintain a luminal phase front in the wakefield initially a distance $w\lambda_{p0}$ behind the lead pulse, with the plasma wavelength $\lambda_p = 2\pi v_d/\omega_p$, and w an arbitrary constant. This luminal front will remain in phase with an accelerating ultrarelativistic bunch of electrons also traveling at velocity $v \simeq c$. First, we review the calculation of the optimal stationary, but inhomogeneous, axial density profile required to perform the same task. The rate of advance of the wake is given by $\Delta z_w/\Delta t = v_d - w\Delta\lambda_p/\Delta t = v_d - wv_d(\partial\lambda_p/\partial n)(dn/dz)$. An ultrarelativistic particle advances at $\Delta z/\Delta t \simeq c$. Setting the two rates of advance equal gives the equation for the optimized density profile:

$$\frac{d\omega_p}{dz} = \frac{\omega_p^2(z)}{2\pi w v_d}\left(\beta_d^{-1} - 1\right), \tag{5}$$

where $(1/n)dn/dz = (2/\omega_p)d\omega_p/dz$ was used. We define the overtaking time, $T \equiv ct_0/(c - v_d)$, and the overtaking length, $L \equiv cT$, where $t_0 = 2\pi w/\omega_{p0}$ is the particle injection time. An ultrarelativistic electron overtakes the slower lead pulse after time T over a total path length L. In dimensionless variables $\tilde{z} \equiv z/L$ and $\tilde{\omega}_p \equiv \omega_p/\omega_{p0}$, Eq. (5) can be expressed as

$$\frac{d\tilde{\omega}_p}{d\tilde{z}} = \beta_d^{-2}\tilde{\omega}_p^2, \tag{6}$$

which has the solution $\tilde{\omega}_p = (1 - \beta_d^{-2}\tilde{z})^{-1}$. This is the well-known optimized axial density profile to sustain the luminous phase front [9], and, since $\beta_d^{-2} > 1$, one observes that the density always becomes singular just prior to the electrons overtaking the driver (at $\tilde{z} = 1$).

For a uniform plasma densifying with time through magnetic compression, $\Delta z_w/\Delta t = v_{\rm ph} - w\Delta\lambda_p/\Delta t$. At each point, the wakefield wavevector initially satisfies $k[z_d(t)] = \omega_p(t)/v_d$ [3], where $z_d(t) = v_d t$ is the axial position of the driver amplitude maximum at time t. The position of the accelerating, ultrarelativistic electron is given by $z \simeq c(t - t_0)$. When an electron moves through a point z within the wake at time t, $k(z)$ has been set by the driver at a previous time, $t' = (t - t_0)/\beta_d$, whereas ω_p has increased through densification since t'. Accordingly, $v_{\rm ph}(t) = v_d\,\omega_p(t)/\omega_p(t')$. Also, $\Delta\lambda_p/\Delta t \to (\partial\lambda_p/\partial n)(dn/dt)$. Setting equal the rates of advance of the wake and the accelerating electron gives

$$\frac{d\omega_p}{dt} = \frac{\omega_p^2(t)}{2\pi w}\left[\beta_d^{-1} - \frac{\omega_p(t)}{\omega_p[(t - t_0)/\beta_d]}\right], \tag{7}$$

in which the required rate of change of ω_p depends on ω_p at a previous time. In dimensionless variables $\tilde{t} \equiv t/T$ and $\tilde{\omega}_p$, Eq. (7) can be expressed as

$$\frac{d\tilde{\omega}_p}{d\tilde{t}} = \frac{\tilde{\omega}_p^2}{\chi}\left[\beta_d^{-1} - \frac{\tilde{\omega}_p(\tilde{t})}{\tilde{\omega}_p[(\tilde{t} - \chi)(1 + \chi\beta_d^{-1})]}\right], \tag{8}$$

where $\chi \equiv 1 - \beta_d \ll 1$. Since $\chi \ll 1$, Eq. (8) can be approximated by expanding the past-time form of $\tilde{\omega}_p$ about $\chi = 0$: $\tilde{\omega}_p[(\tilde{t} - \chi)(1 + \chi\beta_d^{-1})] \approx \tilde{\omega}_p(\tilde{t}) - \chi(1 - \tilde{t}\beta_d^{-1})(d\tilde{\omega}_p/d\tilde{t})$. Plugging this into Eq. (8), expanding the denominator, and rearranging yields

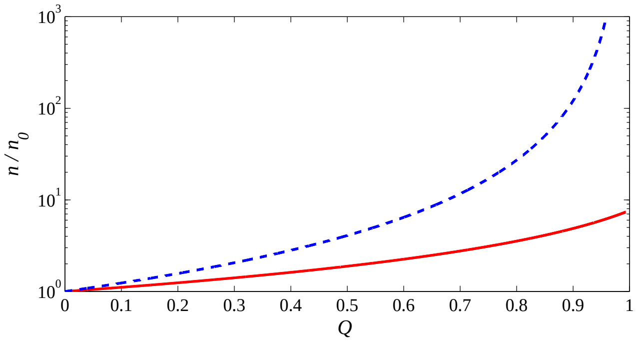

FIG. 1: (color online) Optimized density profiles for: (a) the axial density gradient method (dashed line), with $Q = z/L$ signifying an axially inhomogeneous density profile; and (b) the perpendicular magnetic compression method (solid line), with $Q = t/T$ signifying a time-varying, but axially uniform, density profile. Note that $L = cT$.

$$\frac{d\tilde{\omega}_p}{d\tilde{t}} \approx \frac{\beta_d^{-2}\tilde{\omega}_p^2}{1 + \tilde{\omega}_p(1 - \tilde{t}\beta_d^{-1})}. \tag{9}$$

For an ultrarelativistic driver, $\beta_d \to 1$, and Eq. (9) turns out to be negligibly dependent on the driver velocity.

Comparing Eqs. (6) and (9) reveals that increasing the density in time through magnetic compression, rather than in space through the axial gradient, limits the increase of the plasma density required to maintain a luminal propagating wake front. Figure 1 shows the universal (1D) solutions for $\tilde{\omega}_p^2 = \tilde{n}$ corresponding to both methods, given by Eqs. (6) and (9), in the limit $\beta_d \to 1$. It is clear that perpendicular magnetic compression requires substantially less densification than a stationary, axial density gradient across a wide range of driver energies and plasma densities. Moreover, the density profile for optimized magnetic compression does not exhibit a singularity as the accelerating electron approaches the driver pulse, but remains finite instead, unlike the optimized stationary density gradient profile.

In the special case of PWFA, where a relativistic electron beam with characteristic density n_b drives the plasma wakefield, magnetic compression does not suffer the loss of wakefield amplitude with propagation distance that the stationary density gradient method exhibits [9]. From Eq. (16) of Ref. [9], the peak electric field $E \propto (n_b/n)n^{1/2}$. So, while $E \propto n^{-1/2}$, at fixed n_b, for a wakefield excited in a stationary axial density gradient, magnetic compression causes the background and beam to densify together, i.e., $n_b/n =$ const, meaning $E \propto n^{1/2}$ as the density increases in this case.

Discussion.— In order that variations in $B(t)$ translate to proportional changes in the plasma density, we require that both plasma species be magnetized, i.e., $\omega_{cj}/2\pi\nu_j \gtrsim 1$ for species $j : \{e, i\}$, where $\omega_{cj} = q_j B/m_j c$ is the cyclotron frequency, and ν_j is the collision frequency, assuming electrons and ions are initially in thermal equilibrium and isotropic. The minimum B required is that which marginally magnetizes the ions, or $\omega_{ci}/2\pi\nu_i \approx 1$. For instance, assuming hydrogen plasma, the initial parameters $B = 5\times10^4$ G, $n = 10^{16}$ cm^{-3}, and $T = 20$ eV, where $T = T_e = T_i$ is the plasma temperature, lead to $\omega_{ci}/2\pi\nu_i \approx 1$, and $\omega_{ce}/2\pi\nu_e \approx 30$. As $B(t)$ evolves, the induced azimuthal electric field, $E_\phi(r) = -r\dot{B}/2c$, causes a radial drift of both electrons and ions such that the density $n \propto B$. Since this drift is a gyro-averaged phenomenon, averaging over the continuum of particle gyrophases will lead to uniform densification of the plasma, even on time scales short compared to $1/\omega_{ci}$.

For the choice of parameters leading to plasma magnetization, there still can remain a separation of timescales between that of electron space charge oscillations, ω_p, and that of magnetic gyration, ω_{ce}. The parallel electrostatic plasma response is unaffected by the magnetic field, whereas the perpendicular electrostatic response is characterized by the upper hybrid frequency, $\omega_{\rm uh} = \sqrt{\omega_p^2 + \omega_{ce}^2} \approx \omega_p(1.0 + 0.5\,\omega_{ce}^2/\omega_p^2)$. The example parameters in the previous paragraph give $\omega_{\rm uh} \approx \omega_p$ to within about 1%. Thus, one finds that for the short-pulse ($\sim 1\ \omega_p^{-1}$ duration) wave excitation characteristic of PWFA and LWFA, and even for the somewhat longer (several ω_p^{-1} duration) wave excitation in PBWA, the mechanisms for plasma wave excitation are virtually unaffected by the magnetic field on such short timescales, as Ref. [16] confirmed in simulations under similar conditions. For the ordering $\omega_d \gg \omega_p \gg \omega_{ce}$, where ω_d is the characteristic frequency of any laser driver(s), the effective ponderomotive force of the laser in underdense plasma is also unaffected by the magnetic field [22]. Thus, for a variety of different plasma wave excitation schemes, the (static) magnetic fields needed for marginal plasma magnetization are not expected to change significantly the dynamics of plasma wave formation. On the other hand, a time-varying magnetic field can change the plasma wave structure slowly over time through the associated change in density.

With magnetic compression, there is some perpendicular heating through the adiabatic invariance of the magnetic moment, $\mu_j = m_j v_{\perp j}^2/2B$, on subcollisional timescales. The fastest-growing anisotropy-driven electromagnetic modes, excited by the electron whistler instability when $T_\perp > T_\parallel$, exhibit growth rates Γ scaling like $\Gamma \propto \omega_{ci}$ [23]. For the parameter space considered here, one typically has $\nu_e \gg \omega_{ci}$, and thus, electron temperatures are expected to isotropize well before such instabilities can develop. For the initial parameters $B = 5\times10^4$ G, $n = 10^{16}$ cm^{-3}, and $T = 20$ eV, one finds $2\pi\nu_e/\omega_{ci} \approx 64$.

The primary advantage of magnetic compression is that the optimized solution to the dephasing problem is reduced to the task of shaping variations in the magnetic coil current profile. First, controlling a coil current is much easier technologically than controlling a density profile. Second, shot-to-shot tailoring can be done by reprogramming the current source, requiring no mechanical modification of the system. In contrast, Ref. [13] notes that optimal stationary density profiles may be very difficult to realize experimentally, while shot-to-shot adjustments to the density profile may require significant physical manipulation of the gas injection components. Third, the compression itself increases the wave amplitude [20].

In summary, a new method is proposed to mitigate phase slippage in a wide variety of plasma acceleration concepts, in which the modulation of an axial, homogeneous magnetic field in the accelerating channel leads to densification of the plasma through magnetic compression, enabling direct, time-resolved control of the wave properties. The magnetic field impacts plasma wave formation negligibly on short ($\mathcal{O}(\omega_p^{-1})$) timescales, but does modify the wave dynamics over longer periods of time. In PBWA, only a small amount of compression is needed to increase the dephasing length to arbitrarily long distances. For wakefield accelerators, an optimized compression profile to generate a luminous propagating wake front is derived. Compared to the stationary axial density gradient technique to overcome dephasing in wakefield accelerators, magnetic compression requires a much lower net density variation, and no density singularity arises as the accelerating beam approaches the lead driver pulse. In PWFA, there is the added advantage that the wakefield amplitude increases with propagation distance.

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