Laser-Plasma Wakefield Acceleration with Higher Order Laser Modes

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Abstract. Laser-plasma collider designs point to staging of multiple accelerator stages at the 10 GeV level, which are to be developed on the upcoming BELLA laser, while Thomson Gamma source designs use GeV stages, both requiring efficiency and low emittance. Design and scaling of stages operating in the quasi-linear regime to address these needs are presented using simulations in the VORPAL framework. In addition to allowing symmetric acceleration of electrons and positrons, which is important for colliders, this regime has the property that the plasma wakefield is proportional to the transverse gradient of the laser intensity profile. We demonstrate use of higher order laser modes to tailor the laser pulse and hence the transverse focusing forces in the plasma. In particular, we show that by using higher order laser modes, we can reduce the focusing fields and hence increase the matched electron beam radius, which is important to increased charge and efficiency, while keeping the low bunch emittance required for applications.

Keywords: Laser Plasma Wakefield Acceleration, High order laser modes, Particle in Cell Simulation
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INTRODUCTION

Laser-plasma wakefield accelerators [1] achieve accelerating electric fields thousands of times those of conventional accelerators by using the radiation pressure of an intense laser to drive a plasma wave (review: [2]). Such accelerators have recently demonstrated quasi-monoenergetic electron beams [3-5] at up to GeV energies [6, 7] and with good stability [6, 7], and are being developed to support applications such as future high energy physics colliders [8], and efficient high quality accelerators near 0.5 GeV for Thomson gamma sources in nuclear security [9] and as drivers for free electron lasers [10]. For such applications, a key requirement is accelerator stages that accomplish efficient transfer of the laser energy into low-emittance electron (and, in the case of colliders, positron) beams.

Recent work has demonstrated design of stages that efficiently transfer laser energy into a particle bunch in the nonlinear [11, 12] and quasi-linear [13, 14] regimes. In the highly nonlinear 'blow-out' regime the plasma electrons are completely evacuated, and the remaining ion column provides a fixed, linear focusing for electrons [15]. Positron focusing is present only over a small phase range and is not linear. On the other hand, driving the wake at lower amplitude produces symmetric acceleration and focusing for electrons and positrons. By driving the wake at the largest amplitude where it remains nearly sinusoidal, typically near $a_0 \sim 1$, with a_0 the dimensionless laser amplitude [16], accelerating gradients can be large while retaining nearly symmetric positron behavior [13]. In addition, in the linear and quasilinear regimes the transverse mode shape of the laser can be used to control the focusing forces on the particle bunch, which can be important for emittance matching of the bunch to the structure [17, 18]).

Here we show that high order laser modes can be used in quasilinear stages to control the focusing forces, and therefore the transverse beam dynamics, and the importance of such control for improving beam loading of the accelerator and efficiency. We describe design studies which have characterized regimes of operation for quasilinear stages with Gaussian lasers, and show that these results indicate the desirability of controlling the focusing forces on the bunch for beam loading of low emittance beams. Simulations in conjunction with theory are then used to demonstrate control over focusing by selecting the ratios of the modes, their delay and other parameters, and to show how this control can enable efficient stages for low emittance beams, including compensation for the effects of the plasma channel required to guide the laser driver and for mild nonlinearity (for further detail see [17, 18]).

QUASILINEAR STAGE DESIGN AND REGIME

Scalable stage designs in the quasilinear regime have been developed which predict performance at any density and hence stage energy (so long as the plasma period remains much longer than the laser wavelength) using a single simulation. This allows prediction of performance over a wide parameter range including GeV light source stages and 1-10 GeV collider relevant stages among others. Laser and electron beam dimensions are scaled by the plasma wavelength, and the simulations, conducted in VORPAL [19], have been shown to accurately represent beam loading, quasilinear field structure, laser depletion and guiding, and energy gain [13, 14], and have been confirmed by envelope and Lorentz boosted simulations [20, 21]. The simulation may be conducted at relatively high density, making computation inexpensive, and the technique has been used to tune stage parameters to achieve efficient acceleration of low energy spread bunches.

Scalable stage designs [14] show that the optimal spot size for a quasilinear stage is in the range of roughly $4 < k_p w_0 < 6$, where w_0 is the laser spotsize and k_p the plasma wave number, and show that in this regime the transverse focusing fields are of approximately the same strength as the longitudinal accelerating field. The laser pulse is guided in these stages by a plasma channel scaled to guide the spot, with a density rise reduced to compensate for self focusing [22], producing propagation at a constant spot radius. Linear fluid theory and simulations of the $k_p L = 1$ stage design from [14] (Fig. 1) illustrate the tradeoffs governing choice of spot size. At small $k_p w_0$, transverse fields become stronger, absorbing an increasing fraction of laser energy, reducing efficiency. Also at small $k_p w_0$, channel dispersion reduces laser group velocity, reducing the dephasing length and hence stage energy. Using larger spot sizes in principle reduces the focusing field, but if $a_0 \sim 1$ is chosen, to give the largest gradient achievable while retaining a nearly sinusoidal wake, power then exceeds the critical power for relativistic self focusing, causing the pulse to self-focus and enter the blow-out regime even with no channel. These results indicate that focusing forces in the quasilinear regime using Gaussian lasers, like those in the nonlinear regime, will likely be of the order of the accelerating field.

The high focusing fields (of the order of GV/m for 10 GeV stages) of efficient high gradient stage designs mean that the emittance-matched bunch radius σ_r will be much less than the plasma period [15, 23]: $\sigma_r^2 = \varepsilon_n/(\gamma k_\beta)$. Here, ε_n is the normalized emittance , γ is the relativistic factor of the electron bunch, and k_β is the wavenumber of the betatron oscillations associated with the focusing fields. In the linear regime $k_\beta^2 \propto \nabla E_\perp$, and for a typical 10 GeV stage using a Gaussian laser with $k_p w_0 = 5$, and $\gamma = 20,000$ (10 GeV) at $n_0 = 10^{17} cm^{-3}$, the matched e- beam radius is < 1 micron ($<< \lambda_p \sim 100 \mu m$) at ε_n = 1 mm mrad. This radius will be even smaller for collider emittances.

Small beam radius and high focusing forces limit charge in the quasilinear regime, and may cause ion motion and alignment issues in all regimes. Charge is limited because a small-radius particle bunch causes blow-out of the plasma electrons even for low charge, as illustrated in Fig. 2, while a larger-radius bunch of the same charge creates a linear wake allowing more efficient utilization of the accelerating field of a quasilinear wake [13]. Blow-out stages do not suffer from this limitation, but the very strong focusing forces can create beams so small they cause ion motion, affecting emittance [24]. Strong focusing forces also complicate alignment tolerances for staged or collider

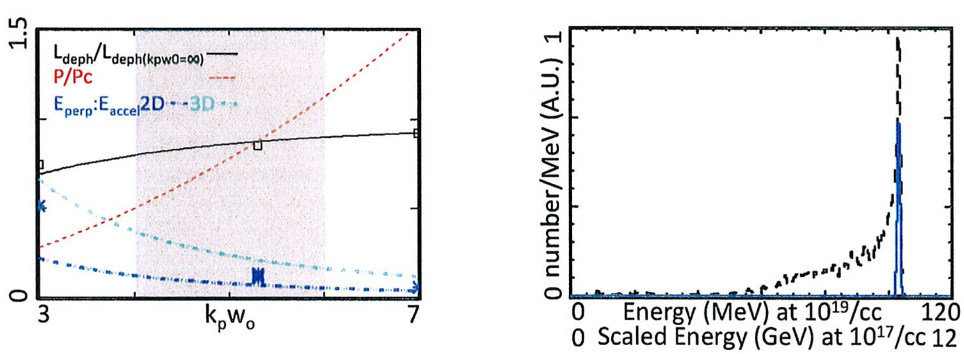

FIGURE 1. Spot size dependence of the linear dephasing length L_{deph}, energy ratio of the focusing to accelerating field, and power normalized to critical power for self focusing (P/P_c) at $a_0 = 1$ (lines) plotted with simulated quasilinear field ratios (*) and normalized dephasing lengths (boxes) (left). In this regime, at $a_0 = 1.4$, $k_p L = 1$, $k_p w_0 = 5.3$, a properly matched electron beam can be efficiently accelerated showing 1.5% integrated and sub-percent slice energy spread (right) .

systems [25]. For these reasons, control over the focusing forces and beam radius is important.

The beam radius scales as $1/E_{\perp}^{-1/4}$, indicating that focusing fields must be decreased by orders of magnitude to achieve the desired beam sizes. This in turn indicates that scaling of laser spot size or positioning the beam near the zero-crossing of the transverse fields are not practical approaches. To decrease transverse field by two orders of magnitude, enough to increase beam size three-fold, by changing laser spot size would require reduction of a_0 to ~ 0.2, reducing accelerating gradient twenty-fold, even in the best case where power is kept at the same fraction of the critical power for self guiding. On the other hand, positioning the beam near the zero-crossing of the transverse field requires, to meet the same criteria, that the beam be much shorter than the plasma period, which does not allow loading of high-charge beams for efficient beam loading [26]. Additionally it would require very precise control of plasma taper to keep the bunch at the zero-crossing. If the beam is not matched, it will undergo strong spot size, or betatron, oscillations degrading the emittance of the beam. Hence alternative techniques are needed to control the focusing forces.

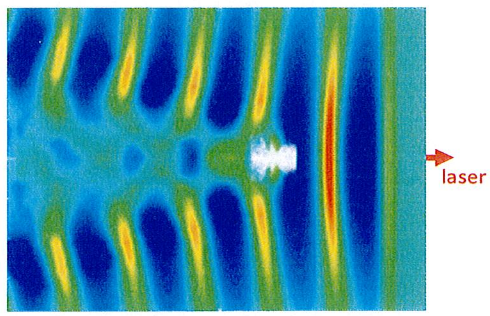

FIGURE 2. A small-radius electron bunch (white, propagating from left to right) loads the wake (blue-red) only near the center, reducing efficiency and potentially leading to blow-out of the wake.

HIGH ORDER MODE ADJUSTMENT OF FOCUSING

In the linear regime, the focusing force can be reduced by tailoring the transverse intensity profile of the laser pulse [17, 18]. In particular, for a flat top profile where $a^2 = a_0^2$ out to a given radius, $F_{\perp} \sim \nabla_{\perp} a^2 = 0$, demonstrating that very low focusing forces are obtainable to allow matching of low emittance bunches. Such a flat top laser mode can be constructed from a series of high order modes. Hence in principle, combinations of modes can be used to shape the transverse fields, as shown in Fig. 3 for a combination of a Gaussian and first order Hermite-Gaussian (HG) mode in 2D. It can further be shown in the low-power limit that the condition on the plasma channel for the matched laser spot size is the same for all HG (2D) or Laguerre-Gaussian (3D) modes, i.e., $\Delta n = \Delta n_c = 1/\pi r_e r_0^2$ [27], such that these modes will propagate in the same plasma channel at constant spot radius, allowing acceleration over the dephasing distance.

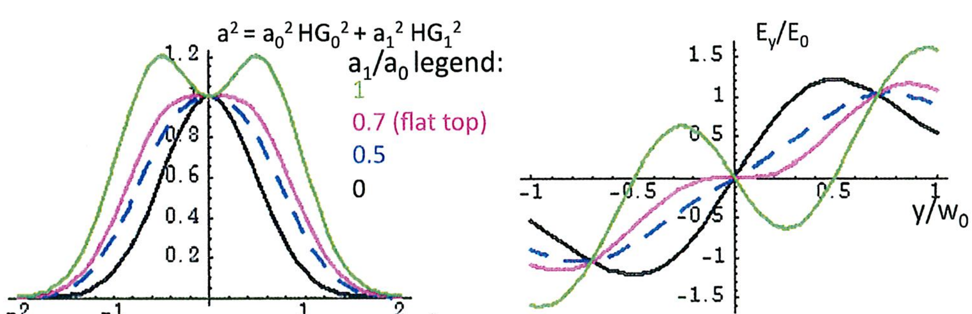

FIGURE 3. Combination of gaussian and first order Hermite-Gaussian modes with the appropriate ratio of amplitudes a1/a0=0.7 produces a flat top laser mode (left) and a flat region in the focusing field transversely in the linear regime in a uniform plasma (right).

Simultaneous co-propagation of multiple modes in the same plasma channel may induce intensity modulations and hence wake modulations. This is because the phase shift of the mode depends on the mode numbers (m,p) as do the group and phase velocities, with higher order modes having larger phase velocity, leading to beating of the modes which varies with propagation distance. Several techniques are available to avoid undesirable modulation of the wake which could steer the beam. Modulation can be prevented by using crossed polarizations for the two modes in 2D. In 3D the first-order Laguerre-Gaussian mode has radial polarization, so that overlap of polarization with the linearly polarized Gaussian will occur in one plane. Different frequencies can be used for the two modes which causes the beat to average to zero, or the modes can be delayed by $n\lambda_p$ (that is, sit in different wake buckets) to avoid beating. The wakes linearly add to give the same effect in either case. Additionally, at high beam energies where the electron betatron period is much longer than the beat period, the modulation may be tolerable. These techniques have been verified using PIC simulation, showing that it is possible to co-propagate multiple modes in a plasma channel without modulation to create an accelerating structure with controllable focusing fields.

The plasma channel (used to guide the drive laser pulse) induces curvature in the wake [28], which must be taken into account to create the desired shaping of the focusing field. Channel-induced wake curvature creates a nonzero $E_\perp$ for a flat top laser mode, and the field structure is different for each bucket behind the drive laser pulse, as shown in Fig. 4(center). Contrary to the case with a flat plasma density profile, there is no condition on a_1/a_0 for which the transverse electric field is null near axis for all phases ζ. The location of the zero crossing of $E_\perp$ is set by the ratio a_1/a_0. To create an extended region longitudinally where the field is near-zero, as desired to control focusing, the high order mode can be delayed slightly with respect to the Gaussian mode as shown in Fig. 4(right) (for detailed calculations see [17, 18]). Using the mode amplitude ratio and delay, the location and longitudinal slope of the near-zero region of $E_\perp$ can be controlled. This allows the focusing field phase to be controlled for optimal overlap with the accelerating field, and its longitudinal and transverse slope to be controlled to control focusing and to compensate beam loading.

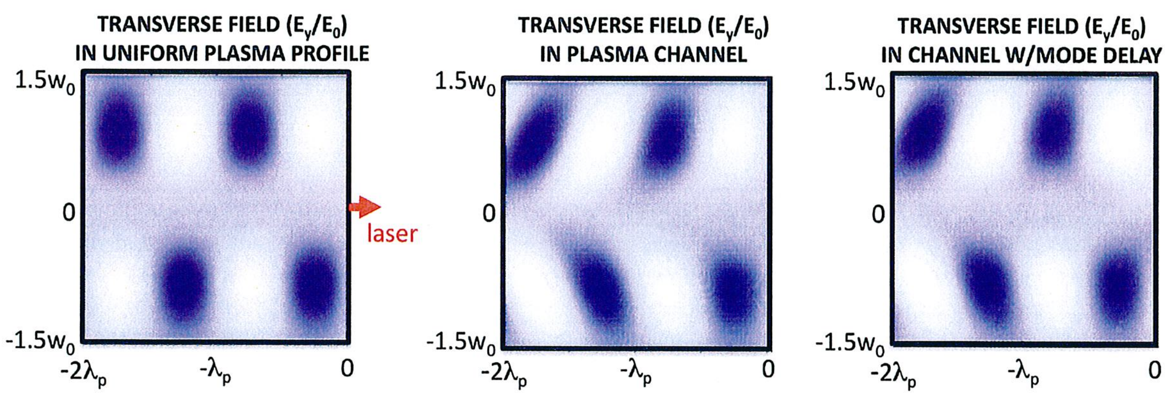

FIGURE 4. The transverse wakefields of a flat top laser mode generated by combination of a Gaussian and HG01 mode in a uniform plasma show a region of near-zero field near axis (left). Curvature of the wake in a plasma channel removes this region (center), but a near-zero region can be restored, and its location and slope controlled, by adjusting the ratio and delay between the modes (right).

SIMULATIONS OF HIGH ORDER MODE AND E-BEAM PROPAGATION

Simulations were used to confirm the linear theory predictions, to extend their validity to the quasilinear regime, and to evaluate the propagation and emittance matching of electron beams in the resulting wakes. The simulations were conducted in 2D using the VORPAL framework, using parameters close to the 10 GeV scaled stage designs outlined above, where $a \sim 1$, $k_p w_0 = 5.3$, and the laser pulse is efficiently depleted over the dephasing length of the electrons. Fig. 5 shows the intensity profile of cross-polarized Gaussian and HG01 modes with $a_0 = 0.7$ and $a_1 = 0.5$. To compensate for self focusing, the channel depth is adjusted such that $\Delta n = 0.7\Delta n_c$. The modes propagate over many Rayleigh lengths, maintaining a flat top profile even as the laser depletes its energy into the wake, visible as a reduction in intensity. This demonstrates the applicability of the technique to deeply depleted, efficient quasilinear stages. These simulations have also been used to evaluate slippage of the modes with respect to one another due

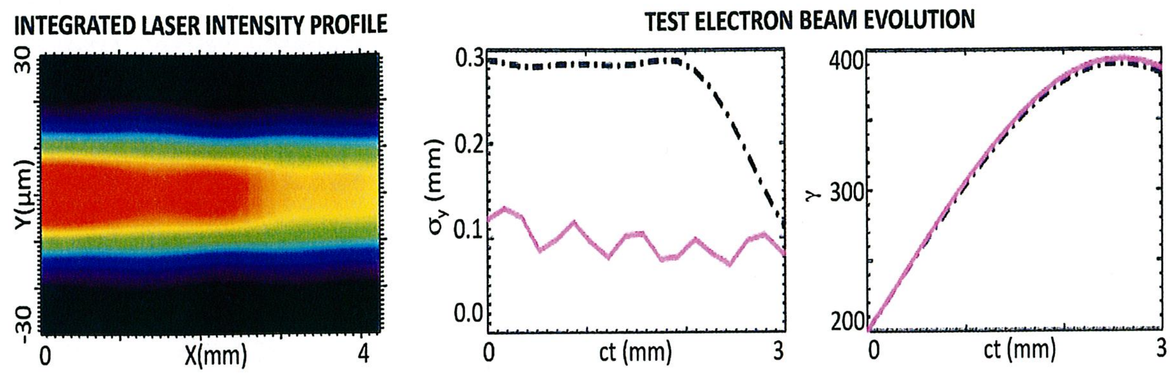

FIGURE 5. Quasilinear simulation shows the intensity profile of a flat top laser mode is maintained as the pulse propagates to the dephasing length (left). Use of such a high order mode increases emittance-matched beam radius three-fold (center) while maintaining acceleration gradient (right).

to group velocity difference, showing that the focusing field remains reduced over a dephasing length. The linear calculations of mode ratio and delay are approximately valid in this regime, and ten-percent-level adjustments are made based on the simulations.

Propagation of a test electron beam was next modeled to demonstrate the effectiveness of appropriately shaped laser modes in increasing the matched beam radius. The simulated stage was based on the stage design of [26, 14], using $a_0 = 1$, $k_pL = 1$, $k_pw_0 = 5.3$. By using Gaussian plus HG01 modes, with $a_1 = 0.69a_0$, and a delay of $k_p\zeta_s = 0.2$, between the two modes, the matched beam radius is increased almost a factor of 3 and variation in radius is decreased to 1.5% as shown in Fig. 5 center. Beam energy gain and gradient are unaffected. A beam with this radius would be highly mismatched (130% variation) in a wakefield driven by a Gaussian pulse, causing emittance degradation due to the fact that the transverse tails of the electron beam distribution reach the non-linear part of the focusing field. The increased beam radius should, according the results of [13], allow the charge of the beam to be increased by a factor of 9, for a gain of 4.5 in efficiency given that the high order mode uses twice the energy, for a given emittance. To increase beam radius further, additional higher order modes may be used to extend the flattop region of the laser pulse; using the first and second order Hermite-Gaussian modes with the fundamental yields an additional factor of 2.5 in gain.

CONCLUSION

In this paper, we have examined efficient laser-plasma wakefield accelerator stage designs in the quasilinear regime, showing that potential limitations in beam loading for low-emittance bunches can be overcome by using high order laser modes to shape the transverse wake field. For high gradient stages and high beam loading, desired for applications, this approach offers advantages over alternatives that use change in spot size or the zero-crossing of the field. In addition to allowing efficient beam loading, it mitigates other issues such as ion motion and alignment tolerances which have been raised for such accelerators. Additional details of this work are presented in [17, 18]. Plasma density taper and beam loading will allow additional control, to keep the bunch in the flattened phase of the wake, and are the subject of ongoing work.

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