Transversely Pumped Laser Driven Particle Accelerator

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Abstract / Concept Overview

We present a novel acceleration scheme capable of accelerating electrons and ions in an underdense plasma. Transversely Pumped Acceleration (TPA) uses multiple arrays of counter-propagating laser beamlets that focus onto a central acceleration axis. Tuning the injection timing and the spacing between the adjacent beamlets allows for precise control over the position and velocity of the intersection point of the counter-propagating beam arrays. This results in an accelerating structure that propagates orthogonal to the direction of laser propagation. We present the theory that sets the injection timing of the incoming pulses to accelerate electrons and ions with a tunable phase velocity plasma wave. Simulation results are presented which demonstrate 1.12 GeV proton beams accelerated in 3.6 mm of plasma and electron acceleration gradients on the order of 1 TeV/m in a scheme that circumvents dephasing. This work has potential applications as a compact accelerator for medical physics and high energy physics colliders.

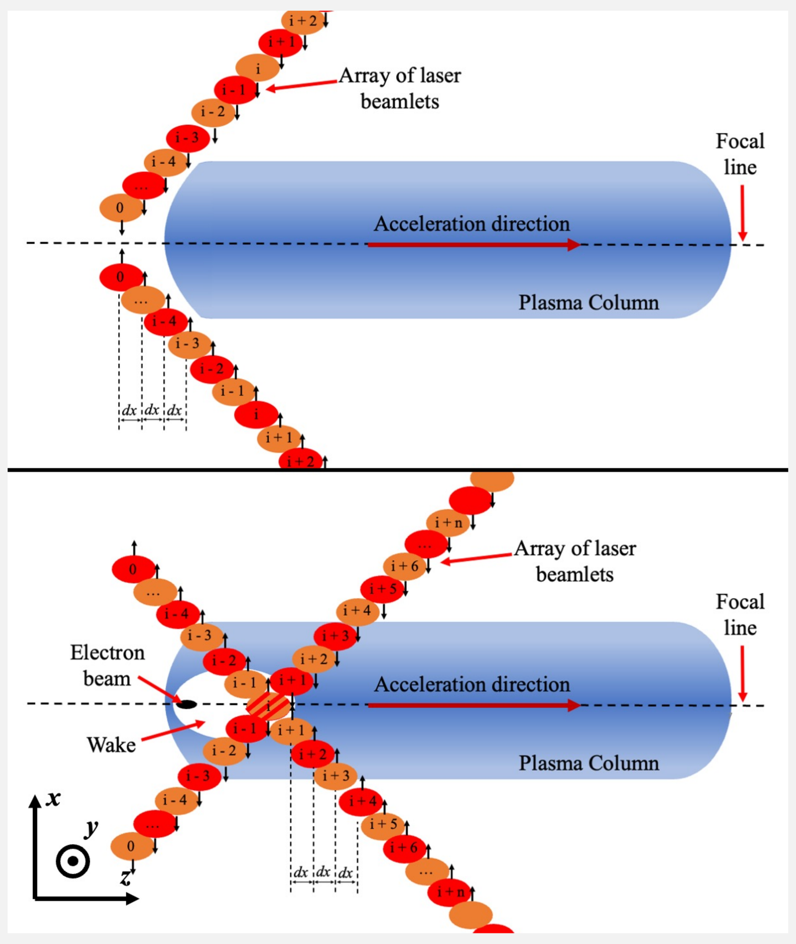

Figure 1. Multiple laser beamlet arrays are injected symmetrically onto a line focus in the center of the plasma column. The direction of particle acceleration is transverse to the direction of laser beamlet propagation. Laser propagation directions are denoted with black arrows. The top figure shows the scheme prior to the crossing of the beamlet arrays and the bottom figure shows the scheme after the beamlet arrays cross and a wake has been produced in the plasma column.

Phase Matching

To accelerate electrons and ions in an underdense plasma, it is necessary to match the phase velocity of the produced plasma wave to the velocity of the particles being accelerated.

Consider a coordinate system with $\hat{z}$ being the acceleration direction. A train of pulses, each labeled i, propagate in the direction $\hat{k}$ with $\hat{k}\cdot\hat{z}=0$. The position of the intensity maximum is $s(t)$ with the resulting intensity pulse designed to move with an axial group velocity function $V = ds/dt$ and with axial intensity profile $I(\zeta, t)$, where $\zeta = z - s(t)$.

For a particle accelerated along the z axis starting at $z = 0$ in a wake with electric field, $E_z(z)$, from the equation of motion the differential of the particle momentum is $dp_z = (qE_z/v_z)dz$. We may then write:

$$\rightarrow s^{-1}(z) = \int_0^{p_z(z)} \frac{v_z}{V}\frac{dp_z'}{qE_z}$$

Phase matching requires $V(z) = v_z$ and a time averaged constant driver produces a time averaged constant accelerating field, $E_z = E^*$, which gives:

$$\rightarrow s^{-1}(z) = \frac{p_z(z) - p_0}{qE^*}$$

p_0 is the initial momentum and $p_z(z) = mc\sqrt{\gamma^2-1}$ can be found by integrating the equation for the particle kinetic energy, $\gamma(z)mc^2 = \gamma_0 mc^2 + qE^*z$. This gives the injection timing t_i of the i^{th} pulse as:

$$\rightarrow t_i = \frac{mc}{qE^*}\left(\sqrt{\left(\gamma_0 + \frac{qE^*z_i}{mc^2}\right)^2 - 1} - \frac{p_0}{mc}\right)$$

Consider two cases of interest:

Ultrarelativistic electron:

$\left(\gamma_0 + \frac{qE^*z_i}{mc^2}\right)^2 \gg 1$ and $\frac{p_0}{mc} \simeq \gamma_0$

i.e., the group velocity is constant and equal to the speed of light

$$t_i \simeq \frac{z_i}{c}$$

Proton accelerated from rest:

$\gamma_0 = 1$ and $p_0 = 0$

$$t_i = \frac{z_i}{c}\sqrt{1 + \frac{2mc^2}{qE^*z_i}}$$

Ion Acceleration

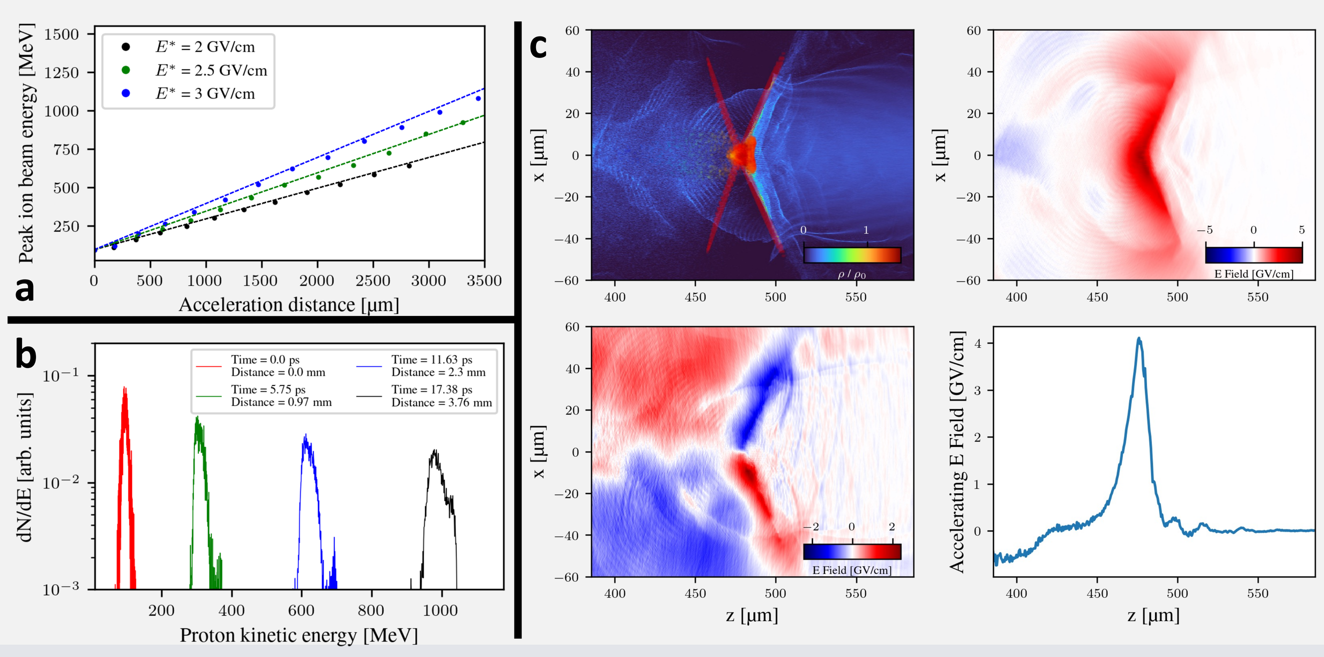

Figure 2. a, Peak ion energy as a function of acceleration distance for different values of E*. A maximum proton energy of 1.12 GeV was obtained in 3.6 mm for E* = 2.5 GV/cm. **b,** Ion energy spectrum at different times for E* = 2.5 GV/cm. **c,** (Top left) Ion beam in red, shown in accelerating structure. The electron density is shown in blue and the laser pulses are shown as red contours. (Top Right) Accelerating field structure. (Bottom left) Focusing field structure. (Bottom right) Line-out of accelerating field structure along the central axis of the simulation.

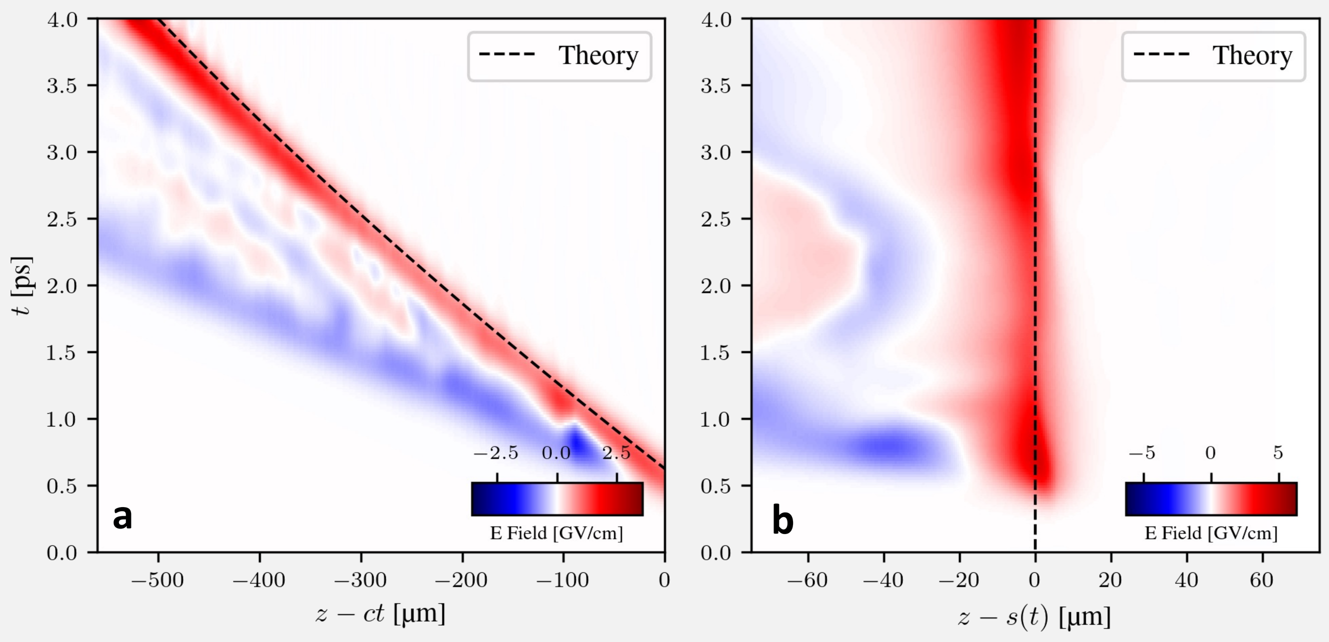

Figure 3. a, Streak plot of the on axis accelerating fields for ions in the speed of light frame. **b,** Streak plot of the same accelerating fields in the frame co-moving with the ion beam that is being accelerated. The theoretical predictions for both streak plots are shown as a dashed black line.

Plasma Density	a_0 per pulse (energy)	Pulse Spacing	Pulse Duration	Laser w_0	Initial energy of Injected beam	Ion beam density
0.0017 n_{cr} (1.7 $\times 10^{18}$cm^{-3})	8 (290 mJ)	3 µm	25 fs	3 µm	95 MeV (20 MeV FWHM spread)	1.5 $\times 10^{16}$cm^{-3} (4 µm FWHM)

Dephasingless Electron Acceleration

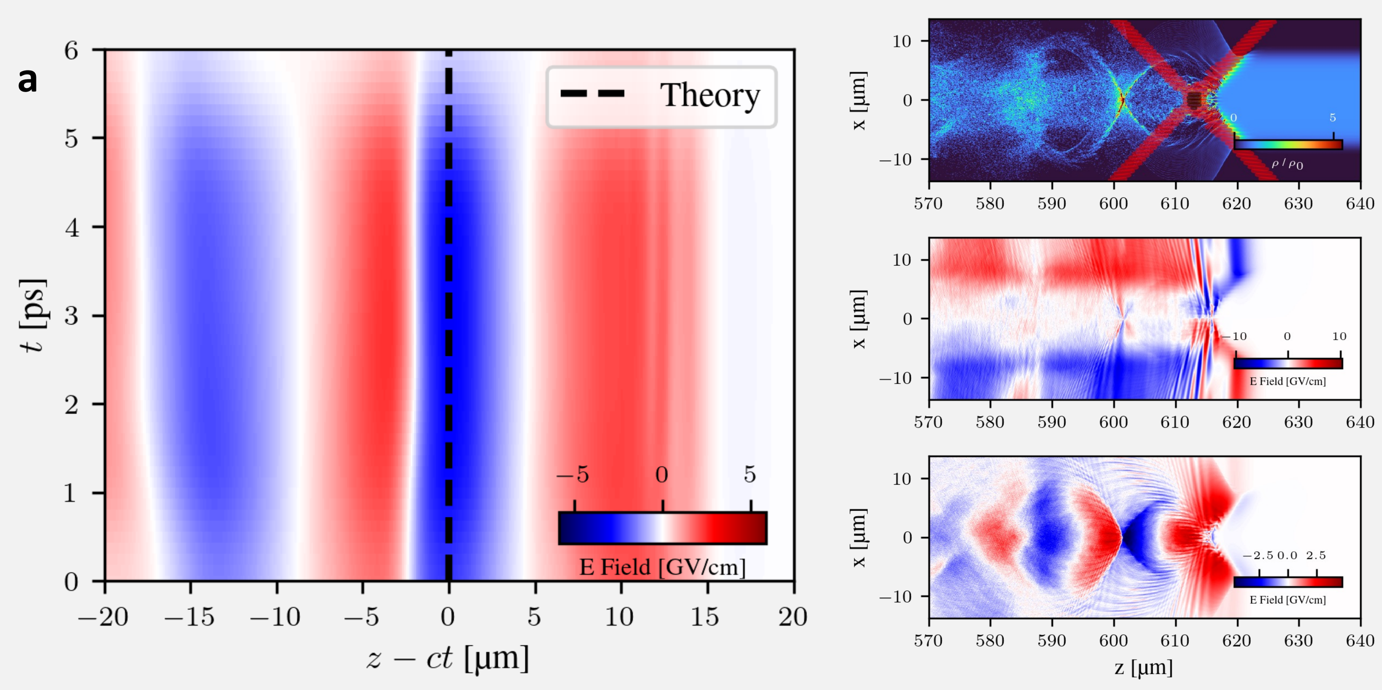

Figure 4. a, Streak plot showing a phase velocity of *c*. The on axis accelerating fields are shown as a function of time and space. The black dashed line denotes a perturbation with a velocity of *c*, showing agreement of simulation with theory. **b,** (Top) Electron density of accelerating structure. Laser contours are shown in red. The energy per laser pulse is 7 mJ. (Middle) Focusing fields. (Bottom) Accelerating fields.

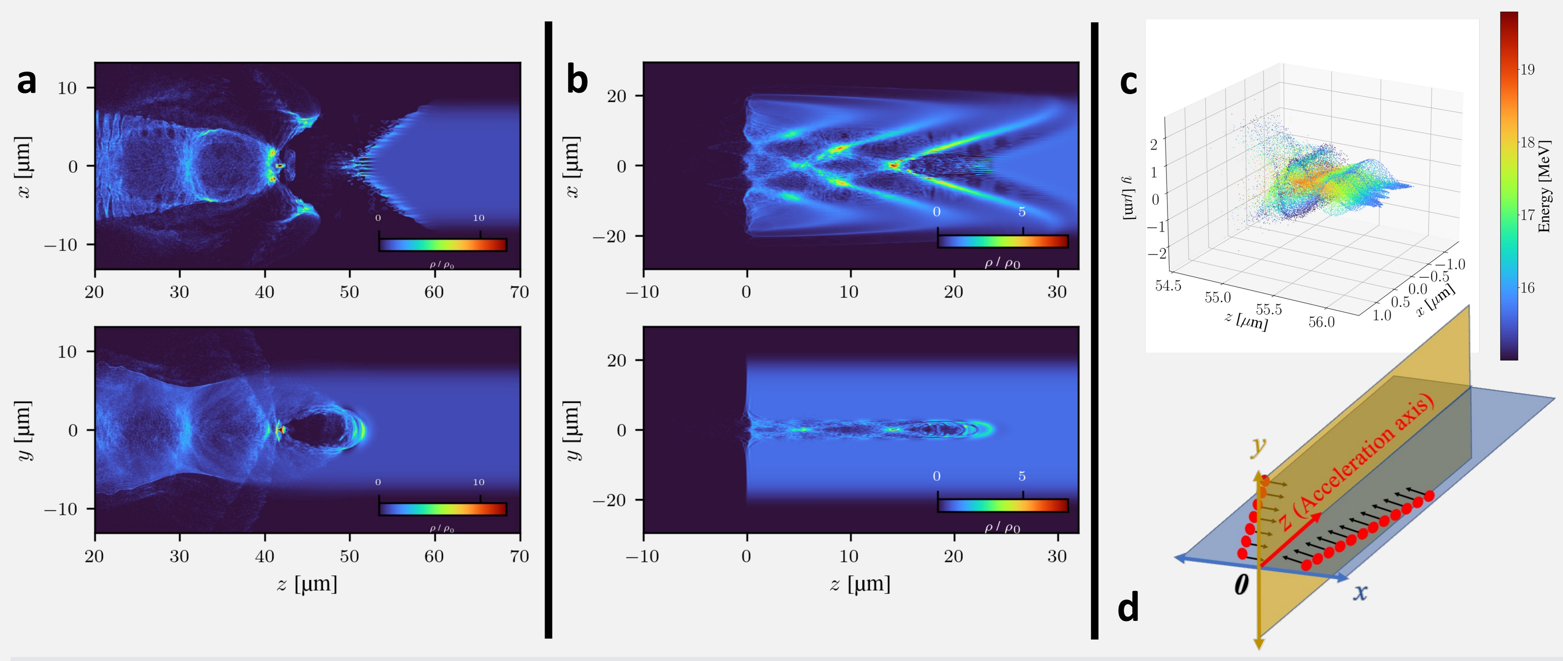

Figure 5. a, (b) Cross sections of the electron density profiles for 3D simulations demonstrating the accelerating structure in a 16 (40) µm FWHM plasma column. The top plots show the cross section of the y=0 plane, while the bottom plots show the cross section of the x=0 plane. **c,** Scatter plot of 3D electron beam. Energies of particles are given in the color bar. Note that this scatter plot shows electrons with energies > 15 MeV, accelerated over 50 µm. **d,** Geometry of the 3D simulations in this study.

Spacing	Laser w_0	Pulse duration	a_0 per pulse (energy)	Laser λ	Plasma density
1.3 µm	1.64 µm	20 fs	2.5 (7 mJ)	1 µm	0.012 n_{cr} (1.2 $\times 10^{19}$cm^{-3})

Discussion

- TPA is a novel acceleration scheme that offers many advantages over existing acceleration concepts in terms of scalability, versatility, and the usage of many relatively low power lasers.
- TPA can produce tunable phase velocity plasma waves, which can be used to accelerate ions in an underdense plasma by matching the phase velocity of the plasma wave to the velocity of the accelerating ion bunch.
- A plasma wave with a constant phase velocity of *c* can be produced to accelerate electrons without the limitation of dephasing, allowing for higher density operation and larger acceleration gradients.
- TPA could allow for an increase in average power of laser generated particle sources, while simultaneously making them more compact.

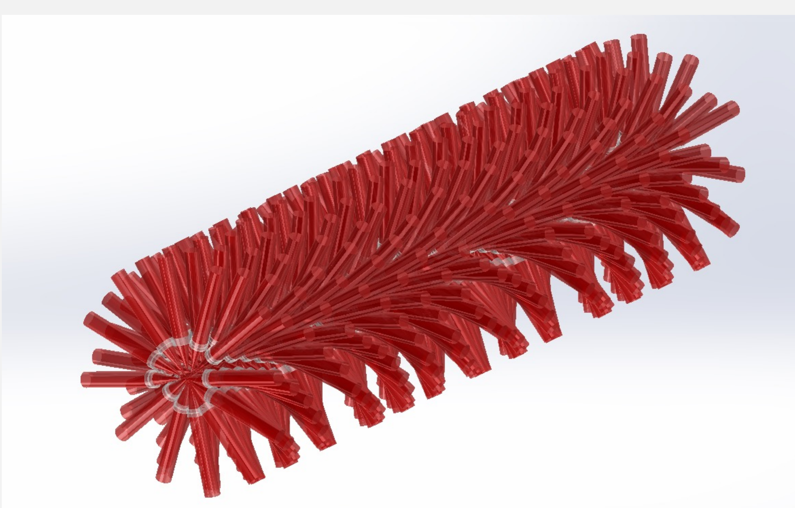

Figure 6. Helical extension to three dimensions. The paths of the beamlets are shown in red and spiral around the central acceleration axis. The focusing optics are gray. Pairs of transversely injected pulses that meet at focus in the middle of the plasma can be arranged in a helix to allow for closer spacing between the adjacent foci. Other arrangements are possible and could offer custom electron beam properties.

References and Acknowledgments

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EUROPEAN NETWORK FOR NOVEL ACCELERATORS

EuroNNAc4

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