Stable monoenergetic ion acceleration by a two color laser tweezer

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Abstract

In the past decades, the phenomenal progress in the development of ultraintense lasers has opened up many exciting new frontiers in laser matter physics, including laser plasma ion acceleration. Currently a major challenge in this frontier is to find simple methods to stably produce monoenergetic ion beams with sufficient charge for real applications. Here, we propose a novel scheme using a two color laser tweezer to fulfill this goal. In this scheme, two circularly polarized lasers with different wavelengths collide right on a thin nano-foil target containing mixed ion species. The radiation pressure of this laser pair acts like a tweezer to pinch and fully drag the electrons out, forming a stable uniform accelerating field for the ions. Scaling laws and three-dimensional particle-in-cell simulations confirm that high energy (10-1000 MeV) high charge (∼1010) proton beams with narrow energy spread (∼4% – 20%) can be obtained by commercially available lasers. Such a scheme may open up a new route for compact high quality ion sources for various applications.

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With the rapid development of ultraintense lasers in the past decades, many exciting new frontiers in the field of laser matter physics have been opened up, such as fast ignition of inertial confinement fusion \[1\], laboratory astrophysics \[2, 3\], compact particle accelerators \[4–11\] and light sources \[12–14\]. Among these topics, laser driven ion acceleration has attracted much attention worldwide for its potential to generate compact ultrafast high quality ion sources \[15, 16\]. For many applications, ion beams that are quasi-monoenergetic and have a sufficient charge are desired. Furthermore, such beams need to be produced stably \[17–19\]. Developing schemes to meet these requirements is the current focus of research in the field of laser ion acceleration. During more than a decade of intense research, several acceleration schemes have been proposed, such as target normal sheath acceleration (TNSA) \[20–22\], collisionless shock acceleration (CSA) \[10, 23, 24\], radiation pressure acceleration (RPA) \[25–30\], breakout afterburner acceleration (BOA) \[31, 32\], magnetic vortex acceleration (MVA) \[33–35\], chirped standing wave acceleration (CSWA) \[36\] etc. However, none of the above schemes provides a simple stable mechanism to produce a monoenergetic ion beam with sufficient charge.

In this paper, we propose a new scheme using a two color laser tweezer, which provides a possible solution to meet these demands. In this scheme, two circularly polarized (CP) intense laser pulses with different frequencies (\(\omega_0\) and \(\omega_1\), \(\omega_0 > \omega_1\)) but nearly equal normalized vector potential (\(a_0\)) collide on a nanometer thick foil (nano-foil) with mixed atomic species (as shown in Fig.1(a) and (b)). The electrons in the foil quickly get squeezed into a thin sheet by the radiation pressure of this beat wave, i.e., the slowly moving ponderomotive potential well, and then are fully dragged out of the foil as a whole, as if they were grabbed and pulled out by a laser “tweezer”. This creates a nearly constant longitudinal electric field between these electrons and the heavy ions that lag behind (see Fig.1(c)). If the target contains a minority species of protons (or light ions), they then can be accelerated by such field to high energy in a very short distance. It is noted that these electrons are spatially separated from the ions. Therefore, instabilities caused by electron-ion streaming couplings \[37\], a frustrating problem for the RPA scheme, are fully avoided, thus the acceleration structure is much more stable. In this paper, we develop a simple theoretical model for this scheme and a scaling law for the dependence of the beam energy on the laser energy. Two and three dimensional Particle-in-Cell (PIC) simulations using OSIRIS \[38\] are systematically used to verify the theory and scaling formulas, and good agreement has been obtained. Based
on these formulas and simulations, we predict that 10 MeV-GeV level proton beams with sufficient charge ($\sim 10^{10}$ protons) and narrow energy spread ($\sim 4\% - 20\%$) may be realizable using laser pulses containing 1-80 J energy through OPA or OPCPA technique in the near future\[39, 40\]. Since the moving ponderomotive bucket of the laser beat wave acts like a “light tweezer”, we call this scheme “Bi-Color Laser Tweezer Acceleration” (BCTA). Such a scheme may open up a new route for compact high quality laser based ion source for various applications.

FIG. 1. The basic schematic model of Bi-Color Laser Tweezer Acceleration (BCTA).
RESULTS AND DISCUSSIONS

Basic concept and formulation

This scheme can be most easily understood in a moving frame with the velocity $v_d = c \beta_d \equiv c (1 - \omega_1 / \omega_0) / (1 + \omega_1 / \omega_0)$. In this frame, the two counter-propagating laser pulses have the same frequency of $\omega_d = \sqrt{\omega_0 \omega_1}$ and a standing wave is formed as they overlap if they have nearly equal vector potentials ($a_0$). An electron can be trapped in the ponderomotive potential well of the standing wave under proper conditions, and this condition can be obtained by examining the one dimensional (1D) single electron dynamics in a circularly polarized standing wave as follows. To simplify the derivation, we adopt the standard normalization in laser plasma physics, where $k_d = 1$, $m_e = 1$, $c = 1$ and $e = 1$ are the laser wave number in the moving frame, electron rest mass, light speed in vacuum and electron charge respectively. In reality the lasers each have finite longitudinal extent (a spectrum of frequencies). When the peaks of the lasers overlap and they are sufficiently long compared to the dominant wavelength, we can approximate the vector potential of CP standing wave as $\vec{A} = 2a_0 \sin t \sin z \hat{y} - 2a_0 \cos t \sin z \hat{x}$, where $z$ represents the propagation axis of the laser pulse, $\hat{y}$ and $\hat{x}$ are the unit vectors of transverse directions. We assume the electrons initial transverse momentum was zero and that they started in a region where the vector potential also vanished, i.e., $(\vec{P}_\perp = \vec{A}_0 = 0)$. The equations of motion for an electron can be written as:

\begin{align}
\vec{P}_\perp &= \vec{A} \\
\frac{d\gamma}{dt} &= -\vec{E} \cdot \vec{v} = 0 \\
\frac{dv_z}{dt} &= -\frac{2a_0^2}{\gamma^2} \sin 2z
\end{align}

where $\gamma$ and $v_z$ are the Lorentz factor and longitudinal velocity of the electrons respectively. Eq. 1c indicates that the electron experiences a spatially periodic ponderomotive force $f_p = -\frac{2a_0^2}{\gamma^2} \sin 2z$. This force is focusing in the $\hat{z}$ direction at nodes and de-focusing at antinodes of the standing wave, making it possible to trap electrons at nodes. We can obtain a relation...
between $v_z$ and $z$ by integrating Eq. 1c, leading to

$$v_z^2 - \frac{2a_0^2}{\gamma_0^2} \cos 2z = v_{z0}^2 - \frac{2a_0^2}{\gamma_0^2} \cos 2z_0$$

(2)

where $v_{z0}$, $\gamma_0$, $z_0$ are the initial longitudinal velocity, Lorentz factor and phase position, respectively. From the assumption of $A_0 = 0$ and Eq. 1b, one gets $z_0 = N\pi$ (N=0,1,2,3,...) and $\gamma = \gamma_0$. For what follows we assume $z_0 = 0$ without loss of generality. It is then straightforward to obtain $P_z^2 = P_{z0}^2 - 4a_0^2 \sin^2 z$. If electrons are trapped, their trajectories in $z - P_z$ phase space should be closed in this standing wave frame which implies there must have at least two intersections with $P_z = 0$ axis. This leads to a trapping condition of $P_{z0}^2 \leq 4a_0^2$. Combined with initial conditions in the moving frame ($v_{z0} = \beta_d$ and $z_0 = 0$), one can get

$$\frac{4a_0^2}{1 + 4a_0^2} \geq \beta_d^2$$

(3)

The above analysis is simply based on single electron dynamics in one-dimension. For the standing wave to be formed in the first place, the laser pulses need to penetrate through the thin foil. For cases of interest the foil has a thickness greater than the the non-relativistic collisionless skin depth, $c/\omega_p$. Therefore, it is necessary that the self-induced relativistic transparency $I > I_{th} = \pi c (en_0l_0)^2$ condition be satisfied\[41, 42\], where $I$, $n_0$ and $l_0$ are the intensities for both lasers, the foil’s initial density and thickness, respectively.

Upon reexamining the trapped electron dynamics in the lab frame, one finds that essentially all the electrons are first quickly squeezed into a very thin sheet, then this sheet is trapped in the moving ponderomotive potential well with a phase velocity of $\beta_d$, and eventually gets dragged out as a whole from the ion background. A nearly constant capacitor-like large electric field ($E_z = 4\pi en_0l_0$) is induced between this stable electron sheet and the heavy ions left behind, and such a constant field then can be used to accelerate minority protons embedded in the foil to generate a quasi-monoenergetic beam in a very short distance.

The maximum energy gain of the protons $\epsilon_{max}$ will be reached when they move beyond the trapped electron sheet, where the accelerating field nearly vanishes. The maximum acceleration time $t_m$ for the protons can be easily estimated as:

$$\int_0^{t_m} \frac{\alpha t}{\sqrt{1 + \alpha^2 t^2}} dt = \beta_d t_m \Rightarrow t_m = \frac{2\beta_d \gamma_d^2}{\alpha}$$

(4)
where $\alpha = eEz/m_p$ is acceleration rate of the protons, $m_p$ is the proton rest mass and $\gamma_d = 1/\sqrt{1-\beta_d^2}$ is the Lorentz factor of the moving frame. By simply integrating the accelerating field over distance, one can get the expression of $\epsilon_{\text{max}}$:

$$\epsilon_{\text{max}} = 2\beta_d^2\gamma_d^2[m_pc^2]$$ (5)

**PIC simulation verification for BCTA scheme**

FIG. 2. 3D PIC simulation verification for BCTA scheme. (a)-(c) The $z-y$ slices (at $x=0$) of the electron density, the electric field ($E_y$) and the proton momentum ($P_z$) at three different times. (d)-(f) The lineouts of the electron density (green line), the transverse field $E_y$ (red line) and the longitudinal field $E_z$ (purple line) along the central axis ($y=0$) of (a)-(c). The laminar structures in proton momentum ($P_z$) are due to numerical discrete cells in PIC simulations.

To verify the validity and stability of the BCTA scheme, 3D PIC simulations have been systematically performed, and very good agreement between simulation and the idealized theoretical model has been achieved. In Fig. 2 we show the results from a typical 3D simulation. In this simulation, a flattop temporal envelope with equal rise and fall time of 2 fs and a super-gaussian transverse profile ($a_0 \exp(-r^4/w_0^4)$, $a_0 = 16$, $w_0 = 8\mu m$) are used for the laser pulses to make direct comparison with the theoretical prediction. A 27fs 800nm CP laser pulse and a 54fs 1.6$\mu$m CP laser pulse are initialized to counter-propagate towards a 45nm thick target located at $z = 100c/\omega_0$, and reach the front and
back surface at the time $t_0 = 100\omega_0^{-1}$. The target has a uniform density profile, and it is composed of electrons ($n_0 = 45 \ n_c$), immobile ions ($n_i = 40.5 \ n_c$) and small fraction of protons ($n_H = 4.5 \ n_c$), where $n_c = 1.74 \times 10^{21} \text{cm}^{-3}$ is the critical plasma density for a 800nm laser. Sufficiently small cell sizes ($\Delta z \times \Delta x \times \Delta y = 3 \times 6 \times 6 \ \text{nm}^3$) and sufficient large particle numbers ($4 \times 2 \times 2 \ \text{particles per species per cell}$) are used to ensure the fidelity of the simulations, where $z$ represents the longitudinal direction and $x$, $y$ represent the transverse directions.

Fig. 2(a)-(c) show the $z-y$ slices (at $x = 0$) of the electron density, the electric field ($E_y$) and the proton momentum ($P_z$) at three different times, and (d)-(f) give lineouts of the electron density (green line), the transverse field $E_y$ (red line) and the longitudinal field $E_z$ (purple line) along the central axis ($y = 0$) of (a)-(c).

At a time slightly before the lasers reach and overlap each other on the target ($t_1 = 95\omega_0^{-1}$), as shown in Fig. 2(a) and (d), the target has not been perturbed by the lasers. Soon after the laser collides ($t_2 = 120\omega_0^{-1}$), a high density electron sheet is formed by the ponderomotive potential well of the laser beat wave (a “laser tweezer”) and moving towards the $+z$ direction, as can be clearly seen in Fig. 2(b) and (c). The sheet moves at a speed of $0.34c$, in very good agreement with the estimated value of $1/3c$ ($v_d = c\beta_d \equiv c(1-\omega_1/\omega_0)/(1+\omega_1/\omega_0)$). A nearly constant longitudinal electric field of 64 TV/m ($16 m_e c\omega_0/e$) is formed between the electron sheet and the immobile ion background. Due to the fact that electrons and ions are spatially separated, there are no transverse ripples growing up in the central region of the electron density as shown in Fig. 2(b) and (c), and therefore the longitudinal electric field $E_z$ is not perturbed and proceeds almost unchanged during the whole process (see Fig. 2(e) and (f)). Meanwhile, Protons with a doped rate of 10% almost have no influence on this constant field, and are accelerated together to high energy in only 40fs (see Fig. 2(b)(c)).

Fig. 3(a) gives the proton ($P_z - P_y$) phase space at the time $t = 210\omega_0^{-1}$. One can see protons that obtain the maximum energy show good 1D acceleration feature with very low transverse momentum. For simplicity, here we take the angle $\theta_{x,y} = 15 \text{ mrad}$ as a critical point to check the proton energy spectra of different divergence angles in Fig. 3(b). It is shown that protons with small divergence angles $\theta_{x,y} \leq 15 \text{ mrad}$ (blue curve) eventually reach the energy around 214 MeV with a narrow energy spread (FWHM) 4.5%, in good agreement with the estimated value of 230 MeV from 1D theory (Eq. 5). The total
particle number of this bunch is $1.3 \times 10^{10}$, which is already sufficient for many applications. Interestingly, protons of relatively large angles $\theta_{x,y} > 15$ mrad (orange curve) have a nearly flattop spectra profile in the range of 30-200 MeV with a charge number of $4 \times 10^{11}$. These two beams can be easily separated by using a narrow-size aperture at a proper distance behind the foil. We note that the proton charge can be further increased for wider laser focal spot (e.g., 16 $\mu$m) or by increasing the proton doping fraction (e.g., 20%) for the scheme.

![Figure 3](image)

**FIG. 3.** The phase space and energy spectra of accelerated protons. (a) The proton $(P_z - P_y)$ phase space at the time $t = 210\omega_0^{-1}$. (b) The energy spectra of protons with energy larger than 15 MeV. The blue and orange curves in the figures correspond the protons with divergence angles less than 15 mrad and more than 15 mrad, respectively.

**Proton energy scaling**

It is of great interest to derive a scaling law for the proton energy of the BCTA scheme. For simplicity, we adopt $k_0 = 1$ instead of $k_d = 1$ in the following derivations, where $k_0$ is the laser wave number of shorter wavelength. As mentioned above, idealized 1D theory indicates that the acceleration time $t_m$ (Eq. [4]) does not depend on the transverse profile of the laser. However, in a real multi-dimensional geometry, laser pulses with finite transverse width lead to trapped electron sheets whose widths decrease with propagation distance, as can be seen from previous 3D simulation in Fig. 2(b) and (c). This phenomenon caused by the diffraction of the electron sheet and of the lasers cause the sheet to dissipate even before $t_m$ for tightly focused lasers, leading to a termination of the BCTA process. This process is difficult to incorporate into the scaling law so we rely on simulations to find the effective acceleration time $t_{eff} \approx 1.3 w_0$ ($t_{eff} \leq t_m$). Note that this will depend on the transverse
Combining the relativistic transparency condition \(a_0 \approx l_0 n_0 / n_c = E_z\) and the expression of \(t_{eff} \approx 1.3w_0\) leads to the following formula for the maximum energy of the proton beam:

\[
\epsilon_{max} \simeq \left( \sqrt{1 + 1.69 \frac{a_0^2 w_0}{m_p^2 c^2}} - 1 \right) [m_p c^2]
\]

(6)

It is also important to estimate required laser energy needed to obtain \(\epsilon_{max}\). Firstly, the minimal pulse duration \(\tau\) of the laser with shorter/longer wavelength is \(\tau \approx (1 \mp \beta_d) t_{eff}\). Then, for a gaussian temporal envelope and super-gaussian transverse profile \((a_0 \exp(-t^2/4\tau_0^2) \exp(-r^4/w_0^4))\) with a FWHM intensity duration \(\tau \approx 2.36\tau_0\), only laser energy within the FWHM region will effectively take part in the “laser tweezer” process, and thus the required energy can be roughly estimated as \(W_{\text{laser}} \simeq 1.63(a_0 w_0)^2 \tau \pi\).

If an 800nm laser is chosen as the one with shorter wavelength, the total energy of the laser pair can be written as:

\[
W_{\text{total}} \simeq 1.46 \times 10^{-6} \frac{1 - \beta_d}{1 + \beta_d} a_0^2 w_0^3 [J]
\]

(7)

In order to verify the above predictions of Eq. 6 and 7, five different 2D PIC simulations have been performed using realistic parameters. Laser pulses in all cases had a gaussian temporal envelope and super-gaussian transverse profile with \(w_0 = 4\mu m\). The target was composed of carbon and hydrogen with a thickness of 45 nm. All the simulation parameters and their results are presented in Table 1, and the spectra of protons with \(\theta_{x,y} \leq 15\) mrad are plotted in Fig. 4(a).

As shown in Table 1 and Fig. 4(a), \(\sim 10^{10}\) proton beams with the energy \(\sim 20\) MeV to \(\sim 1\) GeV and narrow spread (4% to 20%) are obtained for a laser energy in the range of 1-80 J. The charge in the proton beam is estimated by using the proton density per unit length and then assuming a round beam for cylindrical symmetry.

Two useful conclusions also can be obtained in Fig. 4(a). First, a laser pulse with a gaussian temporal envelope (the purple solid curve) is able to capture the monoenergetic feature of BCTA, although \(\epsilon_{max}\) is slightly lower than that obtained from a reference simulation which used ideal flattop profile (the black dashed curve); second, the averaged energy of proton beam in the 3D simulation (the pink dashed curve) is very close to that from 2D
TABLE I. 2D PIC simulation parameters and results of five different cases.

| Parameter and Results | A      | B      | C      | D      | E      |
|-----------------------|--------|--------|--------|--------|--------|
| Laser wavelength [µm]: | λ_1, λ_2 | 0.8, 1.6 | 0.8, 1.6 | 0.8, 1.6 | 0.8, 2.4 | 0.8, 3 |
| Laser pulse duration (FWHM) [fs]: | τ_1, τ_2 | 9, 18 | 9, 18 | 9, 18 | 7, 21 | 6, 22.5 |
| Laser energy [J]: | W_1, W_2 | 0.82, 0.41 | 6.0, 3.0 | 13.1, 6.6 | 32.1, 10.7 | 65.5, 17.5 |
| Plasma density [n_c = 1.74 × 10^{21} cm^{-3}]: n_0 | 21 | 52 | 77 | 112 | 175 |
| Proton density [n_c = 1.74 × 10^{21} cm^{-3}]: n_H | 2 | 5 | 7 | 10 | 17 |
| Proton final peak energy [MeV]: ϵ_{max} | 18 | 110 | 190 | 490 | 820 |
| Particle number: N [10^{10}] | 0.3 | 0.5 | 0.8 | 1.3 | 2.0 |

a Laser pulses adopted in all cases have a gaussian temporal envelop and super-gaussian transverse profile with the expression of \( a_0 \exp(-t^2/4\tau_0^2) \exp(-r^4/w_0^4) \). The spot size \( w_0 \) is chosen as 4µm.

b These are demanded minimal pulse durations for effective acceleration time \( t_{eff} \). Lasers with longer pulses can still work, only wasting the redundant parts.

(only 5% lower). Both these two observations indicate the validity and robustness of BCTA for real experiments.

Fig. 4(b) gives the relation between proton maximum energy and laser energy, and one can see that the scaling from simulations has good agreements with the earlier estimations. From the scaling laws and the PIC simulations it is predicted that less than 20 J laser energy is required to produce a 200 MeV proton beam. Furthermore, if the laser energy is increased to \( \sim 100 \) J, the scaling laws predict that a 1 GeV monoenergetic proton beam can be obtained, indicating BCTA is very promising for generating 100-1000 MeV high quality ion beams with commercially available lasers.

Conclusions

In summary, we propose a simple new scheme named Bi-Color Laser Tweezer Acceleration (BCTA) that has the potential to generate a stable proton beam with a narrow energy spread and a significant charge. In this scheme, the ponderomotive force of the beat wave (laser tweezer) formed by two CP colliding laser pulses with different wavelengths can fully drag the electrons out of a thin nano-target with mixed species, creating a stable uniform longitudinal electric field for the monoenergetic acceleration of doped protons (or any light ion species). Scaling laws and companying PIC simulations show that 10-1000 MeV level proton beams with sufficient particles (\( \sim 10^{10} \)) and narrow energy spread (\( \sim 4\% - 20\% \)) may be obtained by using a bi-color femtosecond laser with 1 – 80 J energy, making BCTA
FIG. 4. The proton energy spectra and related scaling law. (a) Spectrum of proton beams with divergence angle less than 15 mrad for different laser energies corresponding to case A (blue solid), B (orange solid), C (green solid), D (red solid) and E (purple solid). The pink dashed curve is from a 3D simulation with the same parameters as case E and the black dashed curve is related to the case of a laser pulse with temporally flattop profile and the same energy as case E. (b) Scaling of proton peak energy against laser energy. The obtained scaling agrees well with Eq. 6 and 7.

METHODS

Particle-in-cell simulation

The mechanism for BCTA is explored using the fully relativistic particle-in-cell code OSIRIS in two and three dimensional Cartesian coordinates with a fixed window. For all simulations, sufficiently small cell sizes ($\Delta z \times \Delta y = 2 \times 6 \text{ nm}^2$ for 2D, $\Delta z \times \Delta x \times \Delta y = 3 \times 6 \times 6 \text{ nm}^3$ for 3D) and sufficiently large particle numbers ($4 \times 4$ particles per species per cell for 2D, $4 \times 2 \times 2$ particles per species per cell for 3D) are used to ensure fidelity, where $z$ represents the longitudinal direction and $x$, $y$ represent the transverse directions. The simulation parameters and relevant results are presented in the section of results and discussions.

[1] R. Kodama, P. A. Norreys, K. Mima, A. E. Dangor, R. G. Evans, H. Fujita, Y. Kitagawa, K. Krushelnick, T. Miyakoshi, N. Miyanaga, T. Norimitsu, S. J. Rose, T. Shozaki, K. Shigemori, A. Sunahara, M. Tampo, K. A. Tanaka, Y. Toyama, Y. Yamanaka, and M. Zepf.
Fast heating of ultrahigh-density plasma as a step towards laser fusion ignition. *Nature*, 412(6849):798–802, 2001.

[2] B. A. Remington, D. Arnett, R. P. Drake, and H. Takabe. Experimental astrophysics - modeling astrophysical phenomena in the laboratory with intense lasers. *Science*, 284(5419):1488–1493, 1999.

[3] Jiayong Zhong, Yutong Li, Xiaogang Wang, Jiaqi Wang, Quanli Dong, Chijie Xiao, Shoujun Wang, Xun Liu, Lei Zhang, Lin An, Feilu Wang, Jianqiang Zhu, Yuan Gu, Xiantu He, Gang Zhao, and Jie Zhang. Modelling loop-top x-ray source and reconnection outflows in solar flares with intense lasers. *Nature Physics*, 6(12):984–987, 2010.

[4] S. P. D. Mangles, C. D. Murphy, Z. Najmudin, A. G. R. Thomas, J. L. Collier, A. E. Dangor, E. J. Divall, P. S. Foster, J. G. Gallacher, C. J. Hooker, D. A. Jaroszynski, A. J. Langley, W. B. Mori, P. A. Norreys, F. S. Tsung, R. Viskup, B. R. Walton, and K. Krushelnick. Monoenergetic beams of relativistic electrons from intense laser-plasma interactions. *Nature*, 431(7008):535–538, 2004.

[5] C. G. R. Geddes, C. Toth, J. van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W. P. Leemans. High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding. *Nature*, 431(7008):538–541, 2004.

[6] J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J. P. Rousseau, F. Burgy, and V. Malka. A laser-plasma accelerator producing monoenergetic electron beams. *Nature*, 431(7008):541–544, 2004.

[7] B. M. Hegelich, B. J. Albright, J. Cobble, K. Flippo, S. Letzring, M. Paffett, H. Ruhl, J. Schreiber, R. K. Schulze, and J. C. Fernandez. Laser acceleration of quasi-monoenergetic mev ion beams. *Nature*, 439(7075):441–444, 2006.

[8] H. Schwoerer, S. Pfotenhauer, O. Jackel, K. U. Amthor, B. Liesfeld, W. Ziegler, R. Sauerbrey, K. W. D. Ledingham, and T. Esirkepov. Laser-plasma acceleration of quasi-monoenergetic protons from microstructured targets. *Nature*, 439(7075):445–448, 2006.

[9] T. Toncian, M. Borghesi, J. Fuchs, E. d’Humieres, P. Antici, P. Audebert, E. Brambrink, C. A. Cecchetti, A. Pipahl, L. Romagnani, and O. Willi. Ultrafast laser-driven microlens to focus and energy-select mega-electron volt protons. *Science*, 312(5772):410–413, 2006.

[10] D. Haberberger, S. Tochitsky, F. Fiuza, C. Gong, R. A. Fonseca, L. O. Silva, W. B. Mori, and C. Joshi. Collisionless shocks in laser-produced plasma generate monoenergetic high-energy...
proton beams. *Nature Physics*, 8(1):95–99, 2012.

[11] Sasi Palaniyappan, Chengkun Huang, Donald C. Gautier, Christopher E. Hamilton, Miguel A. Santiago, Christian Kreuzer, Adam B. Sefkow, Rahul C. Shah, and Juan C. Fernandez. Efficient quasi-monoenergetic ion beams from laser-driven relativistic plasmas. *Nature Communications*, 6, 2015.

[12] S. Y. Chen, A. Maksimchuk, and D. Umstadter. Experimental observation of relativistic nonlinear thomson scattering. *Nature*, 396(6712):653–655, 1998.

[13] B. Dromey, M. Zepf, A. Gopal, K. Lancaster, M. S. Wei, K. Krushelnick, M. Tatarakis, N. Vakakis, S. Moustaizis, R. Kodama, M. Tampo, C. Stoekl, R. Clarke, H. Habara, D. Neely, S. Karsch, and P. Norreys. High harmonic generation in the relativistic limit. *Nature Physics*, 2(7):456–459, 2006.

[14] H. P. Schlenvoigt, K. Haupt, A. Debus, F. Budde, O. Jaeckel, S. Pfotenhauer, H. Schwoerer, E. Rohwer, J. G. Gallacher, E. Brunetti, R. P. Shanks, S. M. Wiggins, and D. A. Jaroszynski. A compact synchrotron radiation source driven by a laser-plasma wakefield accelerator. *Nature Physics*, 4(2):130–133, 2008.

[15] H. Daido, M. Nishiuchi, and A. S. Pirozhkov. Review of laser-driven ion sources and their applications. *Reports on Progress in Physics*, 75(5), 2012.

[16] Andrea Macchi, Marco Borghesi, and Matteo Passoni. Ion acceleration by superintense laser-plasma interaction. *Reviews of Modern Physics*, 85(2):751–793, 2013.

[17] T. E. Cowan, J. Fuchs, H. Ruhl, A. Kemp, P. Audebert, M. Roth, R. Stephens, I. Barton, A. Blazevic, E. Brambrink, J. Cobble, J. Fernandez, J. C. Gauthier, M. Geissel, M. Hegelich, J. Kaae, S. Karsch, G. P. Le Sage, S. Letzring, M. Manclossi, S. Meyroneinc, A. Newkirk, H. Pepin, and N. Renard-LeGalloudec. Ultralow emittance, multi-mev proton beams from a laser virtual-cathode plasma accelerator. *Physical Review Letters*, 92(20), 2004.

[18] S. V. Bulanov, T. Z. Esirkepov, V. S. Khoroshkov, A. V. Kunetsov, and F. Pegoraro. Oncological hadrontherapy with laser ion accelerators. *Physics Letters A*, 299(23):240–247, 2002.

[19] V. Malka, S. Fritzler, E. Lefebvre, E. d’Humieres, R. Ferrand, G. Grillon, C. Albaret, S. Meyroneinc, J. P. Chambaret, A. Antonetti, and D. Hulin. Practicability of protontherapy using compact laser systems. *Medical Physics*, 31(6):1587–1592, 2004.

[20] R. A. Snavely, M. H. Key, S. P. Hatchett, T. E. Cowan, M. Roth, T. W. Phillips, M. A. Stoyer, E. A. Henry, T. C. Sangster, M. S. Singh, S. C. Wilks, A. MacKinnon, A. Offenberger,
D. M. Pennington, K. Yasuike, A. B. Langdon, B. F. Lasinski, J. Johnson, M. D. Perry, and E. M. Campbell. Intense high-energy proton beams from petawatt-laser irradiation of solids. *Physical Review Letters*, 85(14):2945–2948, 2000.

[21] S. C. Wilks, A. B. Langdon, T. E. Cowan, M. Roth, M. Singh, S. Hatchett, M. H. Key, D. Pennington, A. MacKinnon, and R. A. Snavely. Energetic proton generation in ultra-intense laser-solid interactions. *Physics of Plasmas*, 8(2):542–549, 2001.

[22] P. Mora. Plasma expansion into a vacuum. *Physical Review Letters*, 90(18), 2003.

[23] L. O. Silva, M. Marti, J. R. Davies, R. A. Fonseca, C. Ren, F. S. Tsung, and W. B. Mori. Proton shock acceleration in laser-plasma interactions. *Physical Review Letters*, 92(1), 2004.

[24] F. Fiuza, A. Stockem, E. Boella, R. A. Fonseca, L. O. Silva, D. Haberberger, S. Tochitsky, C. Gong, W. B. Mori, and C. Joshi. Laser-driven shock acceleration of monoenergetic ion beams. *Physical Review Letters*, 109(21), 2012.

[25] T. Esirkepov, M. Borghesi, S. V. Bulanov, G. Mourou, and T. Tajima. Highly efficient relativistic-ion generation in the laser-piston regime. *Physical Review Letters*, 92(17), 2004.

[26] A. Macchi, F. Cattani, T. V. Liseykina, and F. Cornolti. Laser acceleration of ion bunches at the front surface of overdense plasmas. *Physical Review Letters*, 94(16), 2005.

[27] X. M. Zhang, B. F. Shen, X. M. Li, Z. Y. Jin, and F. C. Wang. Multistaged acceleration of ions by circularly polarized laser pulse: Monoenergetic ion beam generation. *Physics of Plasmas*, 14(7), 2007.

[28] A. P. L. Robinson, M. Zepf, S. Kar, R. G. Evans, and C. Bellei. Radiation pressure acceleration of thin foils with circularly polarized laser pulses. *New Journal of Physics*, 10, 2008.

[29] O. Klimo, J. Psikal, J. Limpouch, and V. T. Tikhonchuk. Monoenergetic ion beams from ultrathin foils irradiated by ultrahigh-contrast circularly polarized laser pulses. *Physical Review Special Topics-Accelerators and Beams*, 11(3), 2008.

[30] X. Q. Yan, C. Lin, Z. M. Sheng, Z. Y. Guo, B. C. Liu, Y. R. Lu, J. X. Fang, and J. E. Chen. Generating high-current monoenergetic proton beams by a circularly polarized laser pulse in the phase-stable acceleration regime. *Physical Review Letters*, 100(13):135003, 2008.

[31] L. Yin, B. J. Albright, B. M. Hegelich, K. J. Bowers, K. A. Flippo, T. J. T. Kwan, and J. C. Fernandez. Monoenergetic and gev ion acceleration from the laser breakout afterburner using ultrathin targets. *Physics of Plasmas*, 14(5), 2007.
[32] L. Yin, B. J. Albright, K. J. Bowers, D. Jung, J. C. Fernandez, and B. M. Hegelich. Three-dimensional dynamics of breakout afterburner ion acceleration using high-contrast short-pulse laser and nanoscale targets. *Physical Review Letters*, 107(4), 2011.

[33] A. V. Kuznetsov, T. Z. Esirkepov, F. F. Kamenets, and S. V. Bulanov. Efficiency of ion acceleration by a relativistically strong laser pulse in an underdense plasma. *Plasma Physics Reports*, 27(3):211–220, 2001.

[34] S. V. Bulanov, D. V. Dylov, T. Z. Esirkepov, F. F. Kamenets, and D. V. Sokolov. Ion acceleration in a dipole vortex in a laser plasma corona. *Plasma Physics Reports*, 31(5):369–381, 2005.

[35] Tatsufumi Nakamura, Sergei V. Bulanov, Timur Zh Esirkepov, and Masaki Kando. High-energy ions from near-critical density plasmas via magnetic vortex acceleration. *Physical Review Letters*, 105(13), 2010.

[36] F. Mackenroth, A. Gonoskov, and M. Marklund. Chirped-standing-wave acceleration of ions with intense lasers. *Physical Review Letters*, 117(10), 2016.

[37] Y. Wan, C. H. Pai, C. J. Zhang, F. Li, Y. P. Wu, J. F. Hua, W. Lu, Y. Q. Gu, L. O. Silva, C. Joshi, and W. B. Mori. Physical mechanism of the transverse instability in radiation pressure ion acceleration. *Physical Review Letters*, 117(23):234801, 2016.

[38] R. A. Fonseca, L. O. Silva, F. S. Tsung, V. K. Decyk, W. Lu, C. Ren, W. B. Mori, S. Deng, S. Lee, T. Katsouleas, and J. C. Adam. Osiris: A three-dimensional, fully relativistic particle in cell code for modeling plasma based accelerators. *Lecture Notes in Computer Science*, 2331:342–351, 2002.

[39] I. N. Ross, P. Matousek, M. Towrie, A. J. Langley, and J. L. Collier. The prospects for ultra-short pulse duration and ultrahigh intensity using optical parametric chirped pulse amplifiers. *Optics Communications*, 144(13):125–133, 1997.

[40] G. Cerullo and S. De Silvestri. Ultrafast optical parametric amplifiers. *Review of Scientific Instruments*, 74(1):1–18, 2003.

[41] A. A. Gonoskov, A. V. Korzhimanov, V. I. Eremin, A. V. Kim, and A. M. Sergeev. Multicascade proton acceleration by a superintense laser pulse in the regime of relativistically induced slab transparency. *Physical Review Letters*, 102(18), 2009.

[42] Andrea Macchi, Silvia Vehgini, and Francesco Pegoraro. Light sail acceleration reexamined. *Physical Review Letters*, 103(8), 2009.
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AUTHOR CONTRIBUTIONS

Y.W. and W.L. proposed the concept. Y.W. developed the theoretical model and performed the simulations. Y.W. and W.L. wrote the paper. C.J.Z., J.F.H., F.L., C.H.P., Y.P.W., Y.Q.G, W.B.M., and C.J., contributed to refining the details of the paper. All authors reviewed the manuscript.