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# Ultrahigh-charge electron beams from laser-irradiated solid surface

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**Compact acceleration of a tightly collimated relativistic electron beam with high charge from a laser–plasma interaction has many unique applications. However, currently the well-known schemes, including laser wakefield acceleration from gases and vacuum laser acceleration from solids, often produce electron beams either with low charge or with large divergence angles. In this work, we report the generation of highly collimated electron beams with a divergence angle of a few degrees, nonthermal spectra peaked at the megaelectronvolt level, and extremely high charge (~100 nC) via a powerful subpicosecond laser pulse interacting with a solid target in grazing incidence. Particle-in-cell simulations illustrate a direct laser acceleration scenario, in which the self-filamentation is triggered in a large-scale near-critical-density plasma and electron bunches are accelerated periodically and collimated by the ultraintense electromagnetic field. The energy density of such electron beams in high-Z materials reaches to  $\sim 10^{12}$  J/m<sup>3</sup>, making it a promising tool to drive warm or even hot dense matter states.**

laser–plasma interaction | direct laser acceleration | ultrahigh-charge beam | high energy density | near-critical-density plasma

In studies of laser–plasma acceleration (LPA), several laser wakefield accelerator (LWFA) (1) concepts have been proposed in the last few decades, including the plasma beat wave accelerator (1, 2), the self-modulated laser wakefield accelerator (SM-LWFA) (3), the cross-modulated laser wakefield accelerator (XM-LWFA) (4), and LWFA in the bubble regime (5, 6). The successful generation of high-quality electron beams at the gigaelectronvolt scale with quasi-monoenergetic spectra has stimulated the study of LPAs worldwide (7–14). However, almost all LPA experiments and theoretical models are based on interactions between lasers and gases, limiting the beam charge to typically a few tens of picocoulombs. While the charge of the electron bunch could reach a few nanocoulombs in laser–solid interactions due to higher absorption efficiency and attempts have been made to optimize beam collimation (15–23), the beam quality still needs to be greatly improved due to large divergence angles and quasi-thermal broad energy spectra. Such electrons are usually generated via several heating mechanisms such as resonant absorption (24, 25), vacuum heating (25–27),  $\mathbf{J} \times \mathbf{B}$  heating (28), and stochastic heating (29). Directional electron beams with nanocoulomb charge have been produced via vacuum laser acceleration (VLA) with a plasma mirror injector (30). Unfortunately, the beam collimation also suffers from the ponderomotive force of the laser pulse in vacuum during acceleration, which results in a large divergence angle (hundreds of milliradians) and a halo in the electron beam profile. Recently, a few megaelectronvolts of quasi-monoenergetic electron acceleration have been observed in femtosecond laser–solid interaction with beam divergence angles of  $1^\circ$ – $2^\circ$  (31). However, the beam charge is still limited to hundreds of

picocoulombs, and the underlying physics of such acceleration remain unclear.

In this work, electron beams with extremely high beam charge of approximately 100 nC are generated in 200-TW, subpicosecond laser–solid interactions with deliberately induced preplasma. The electron beams are highly collimated with an average divergence angle  $< 3^\circ$  and the energy spectra are nonthermal with peaks at several megaelectronvolts. Particle-in-cell (PIC) simulations illustrate a scenario of electron acceleration in which the acceleration and confinement regimes are combined in a unique way. It is shown that electron beams are mainly produced via direct laser acceleration (DLA) (32–38) in plasma channels (39, 40) driven by the long laser pulse in a large-scale near-critical preplasma. The strong electromagnetic field inside the plasma channel confines the electron beams tightly. The significant improvement of the beam charge benefits from the persistent DLA process.

## Experimental Results

The experiment was performed on Titan at the Jupiter Laser Facility at Lawrence Livermore National Laboratory (LLNL). The setup of the experiment is shown in Fig. 1. Copper block targets were irradiated by a 200-TW, subpicosecond laser at an incident angle of  $72^\circ$  in P polarization. The laser pedestal 3 ns

## Significance

**In the last three decades, the laser–plasma accelerator (LPA) has shown a rapid development owing to its super-high-accelerate gradients, which makes it a very promising compact accelerator and light source. Acceleration of a high-quality electron beam with divergence angle as small as possible and beam charge as high as possible has been a long-term goal ever since the inception of the LPA concept. However, until now the most popular acceleration scenario has failed to achieve both goals. We solved this problem and obtained tightly collimated electron beams with small divergence angle and extremely high beam charge (~100 nC) via the powerful ps laser pulse interacting with a solid target.**

Author contributions: L.C. and J. Zhang designed research; Yong Ma, J. Zhao, Y.L., D.L., and L.C. performed research; Yong Ma, J.L., S.J.D.D., Yanyun Ma, X.Y., and Z.G. contributed new reagents/analytic tools; Yong Ma, J. Zhao, Y.L., and L.C. analyzed data; Yong Ma, L.C., and Z.S. wrote the paper; and J. Zhang facilitated the experiment and led the whole project.

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The authors declare no conflict of interest.

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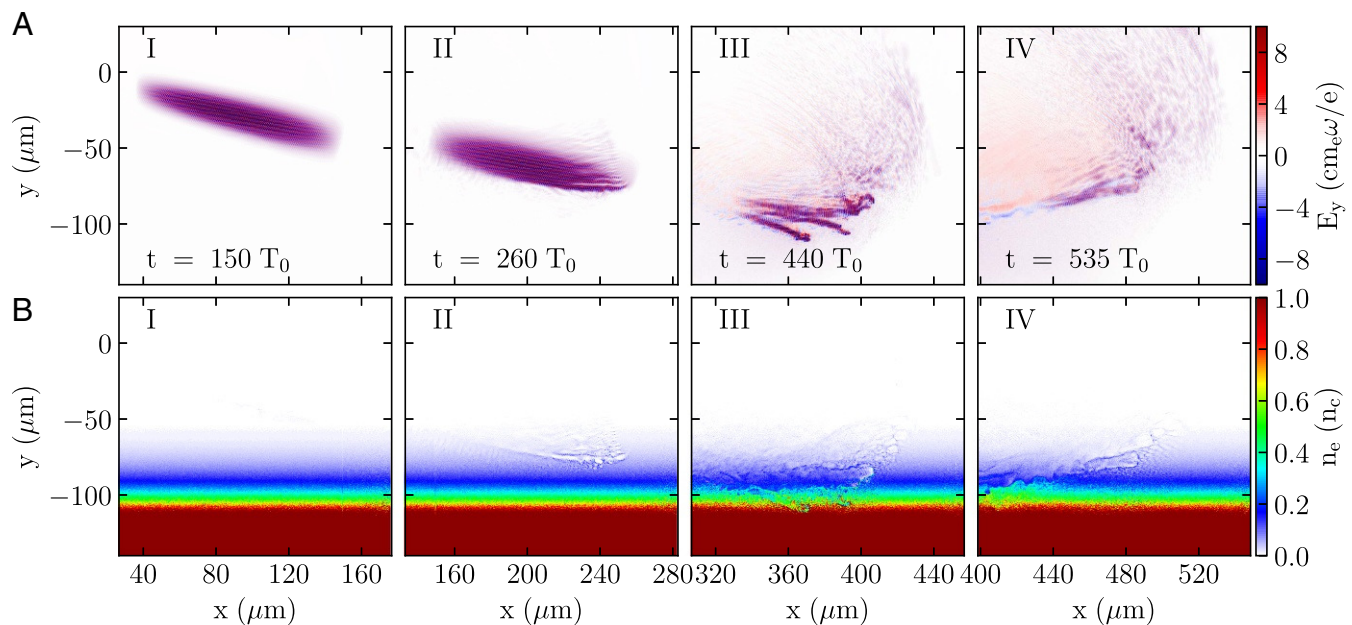
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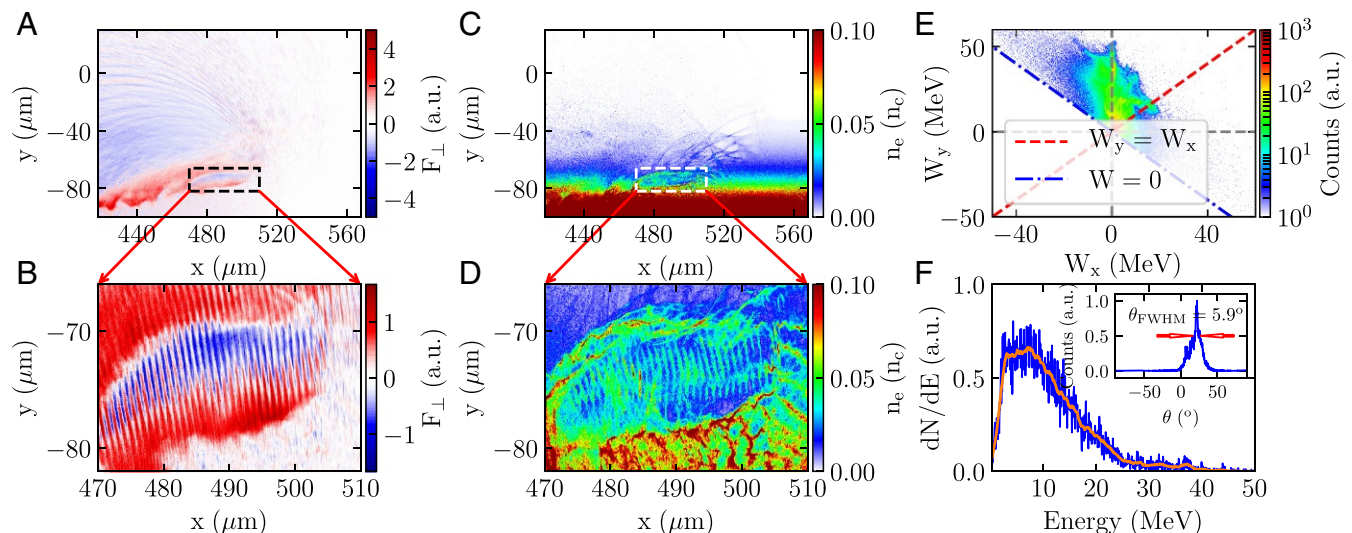
**Fig. 5.** Snapshots of laser fields and plasma electron density distributions at four time steps in PIC simulation. (A, I–IV) Laser field distributions. (B, I–IV) Plasma electron density distributions.

at a later stage. In Fig. 7, the vertical dashed line separates the electron trajectories into two parts. The right-hand side represents the DLA, while the left-hand side represents the stochastic heating. The stochastic motion of electrons in the laser field appears as abrupt “jumps” in electron trajectories (similar phenomena can be found in ref. 34), which act as a trigger to make the DLA happen. As deeply studied in ref. 29, efficient DLA can be triggered by stochastic motion of electrons when the laser fields exceed some threshold amplitudes, using two counterpropagating laser pulses. While in our work, the interference of the incident and reflected laser pulses results in

high-amplitude field and the enhanced stochastic motion eventually leads to the efficient DLA.

As a consequence of the collimation and acceleration inside the plasma channel, the electron spectrum agrees with that of the experiment, as shown in Fig. 6F. The simulated electron beam propagates along  $22.1^\circ$  from the  $x$  axis, close to the laser specular, with a FWHM divergence angle of  $5.9^\circ$ .

Our experimental observation can exclude another electron acceleration mechanism, VLA, in laser–solid interaction. In VLA, during the direct interaction with the laser field, electrons will escape the focal volume transversely after gaining



**Fig. 6.** (A and C) The transverse force and plasma density distribution at  $t = 555 T_0$ . (B and D) The transverse focusing force and the fine structure of the electron beam distribution inside a plasma channel. (E) The energy gain components distribution in  $(W_x, W_y)$  space at  $t = 555 T_0$ . The red dashed line divides the space into two regions: DLA-dominated region in the upper left and the wakefield acceleration-dominated region in the lower right. Electrons above the horizontal gray dashed line gain energy in the laser field while those below lose energy. Electrons to the right of the vertical dashed line gain energy from the wakefield while those to the left lose energy. (F) The energy spectrum of electrons escaping from the plasma at a slightly later time at  $t = 585 T_0$ . Inset shows the corresponding angular distribution of the electron beam.



**Simulations.** The simulations were performed using the PIC code EPOCH (53). The pulse duration of the incident laser is 270 fs (FWHM) with a spot size of 7  $\mu\text{m}$ . The wavelength, incident angle, and polarization of the laser are the same as those in the experiment. The peak intensity of the laser is  $2.8 \times 10^{20} \text{ W/cm}^2$ .

The simulation box is initially located in  $y \in (-140, 30) \mu\text{m}$  and  $x \in (0, 150) \mu\text{m}$  with a moving window in  $x$ . The target plasma is located in  $y \in (-140, -10) \mu\text{m}$  with density profile of  $n_e = 10^{-(y+110)/25} n_c$  in  $y$ . The grid size is  $\lambda_i/40$  in both directions and each cell contains 42 numerical macroparticles. The density profile is given by the radiation hydrodynamic code MULTI (54) by assuming the laser contrast is  $10^{-6}$ .

The work done by the electric field can be split into  $x$ ,  $y$ , and  $z$ :

$$W = -\frac{e}{m_e c^2} \int_0^t (E_x v_x) + (E_y v_y) + (E_z v_z) dt'. \quad [1]$$

The EPOCH code was modified to track these components (55):

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