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TeV/m ACCELERATION IN LASER-GRAPHENE INTERACTIONS

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Abstract

Electron acceleration in solid-state plasmas is of interest within the Laser Wakefield Acceleration (LWFA) research. Layered nanostructures such as graphene nanoribbons can be used as targets for intense UV lasers to generate and accelerate electron bunches. We present numerical Particle in Cell (PIC) simulations of a novel sub-femtosecond self-injection scheme which relies on edge-plasma oscillations in a layered graphene target. The scheme delivers 0.4 fs-long electron bunches of 2.5 pC total charge with an energy gain rate of 4.8 TeV/m. These parameters are unprecedented and, if confirmed experimentally, may have an impact on fundamental femtosecond research.

INTRODUCTION

Graphene targets can be grown in the form of many 2D layers of Carbon atoms stacked together [1]. Each layer is 0.34 nm-thick and, when completely ionized delivers a plasma density of 10^{23} cm^{-3}. Ionization with a sufficiently intense laser pulse, ensures that electrons leave the layers to form a virtually homogeneous cloud, with a density of 10^{22} cm^{-3}. With the electron mass m_e and charge e, and vacuum electric permittivity ε_0, the plasma angular frequency defined as $\omega_p = \sqrt{n_e\, e^2/m_e\, \varepsilon_0}$ can be used to assess the viability of a laser pulse of 100 nm wavelength. Key plasma and laser parameters listed in Table 1, show that the interaction falls in the overdense regime ($\omega_p > \omega_0$) for the layer plasma and in the underdense regime ($\omega_p < \omega_0$) for the cloud plasma, where ω_p and ω_0 are the angular frequencies for the plasma and laser, respectively. Through

Table 1: Plasma and laser parameters

	Layer	Cloud	Laser	Unit
n_e	6.84×10^{23}	1.16×10^{22}	-	
ω	46.66	6.08	18.84	$\times 10^3$ rad THz
λ	40	310	100	nm

PIC simulations carried out with PIConGPU [2], we show that electron self-injection is possible from the edge of the multilayer graphene plasma, provided that the laser pulse is sufficiently intense and energetic. Accelerated electron bunches can be extracted at the other edge of the target [3].

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SIMULATION SETUP

The graphene target is made of 60 layers stacked with an inter-layer gap of 20 nm. The interaction is modelled using a linearly polarized Gaussian laser pulse whose parameters are shown in Table 2. The simulations were performed in a

Table 2: Laser parameters

Quantity	Value	Unit
wavelength: λ	100	nm
period: T_{laser}	0.334	fs
peak intensity: I_0	10^{21}	W/cm^2
spot size*: w_0	0.4	µm
focal point: y_0	0.25	µm
pulse energy: ΔE	8	mJ
pulse length§: Δt	3	fs

*FWHM, §9 cycles

box of 2 µm × 1.6 µm with a rectangular mesh cell of 0.135 nm × 0.135 nm, which corresponds to 2.51 cells per layer thickness, and 10 macroparticles per cell, as these were the limitations of the available hardware. The target length along the y-axis is set to 1.5 µm as a realistic dimension of the graphene layers available in the near future. Three ionization mechanisms were enabled: tunneling, barrier suppression, and collision. It is worth mentioning that unlike with the LWFA in low-Z gases, ionization through collision is significant for this scenario. The PIConGPU code was chosen due to its capability to scale performance with the number of available graphics cards, but also due to the rich variety of technical features such as macroparticle initialization, ionization mechanisms, field solvers etc. Simulations were carried out using Carbon atoms in the 3rd ionization state (C^{3+}), to account for rather weaker first ionization potentials of graphene as compared with those of the Carbon atom [4].

RESULTS

With the laser pulse advancing along the target, electrons collapse towards its left edge, by this point nearly void of electrons. One of the outcomes is the appearance of a thick wall of electrons, just behind the laser pulse, as shown in Fig. 1(a); another one, is that while most of the wall follows the laser pulse, being continuously replenished, its left extremities are attracted leftwards by the ions, initiating a damped oscillation which lasts for about 36 laser cycles. This split between the electrons in the wall and those

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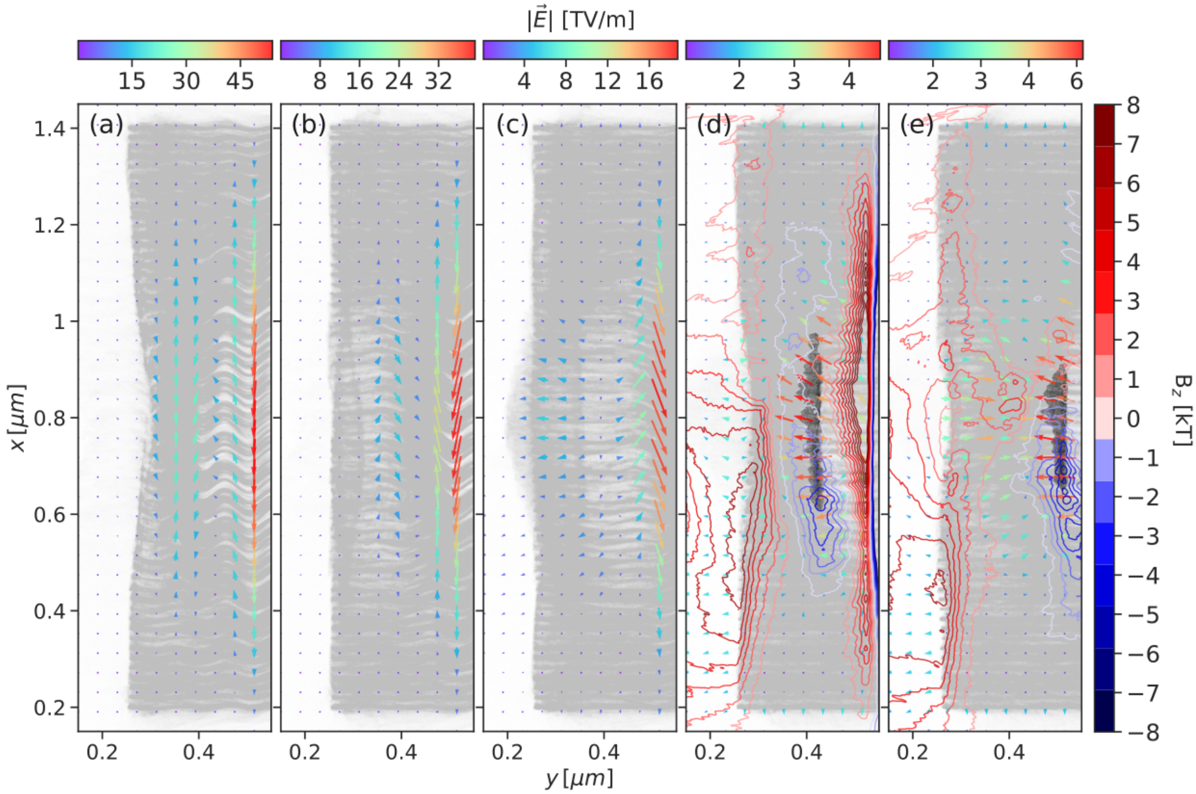

Figure 1: Longitudinal plasma oscillations at the target left-edge shown as electron macroparticles, in gray for the background and in black for the injected bunch. The arrows indicate the electric field vectors in the yx-plane while the contours indicate the magnetic field perpendicular to the yx-plane. The second half of the laser pulse can be seen in (a), (b) and (c) through its intense transverse electric field and wiggled layers of macroparticles. Electron self-injection is visible starting with (b). The ion bubble is closed starting with (d). In (e) the background plasma recedes leftwards, while the injected bunch undergoes acceleration rightwards.

moving leftwards gradually builds up a bubble of ions. From the electrons moving leftwards, a 10 nm-thick ribbon shown in Fig. 1(b) is catapulted into the left half of the bubble due to the favourable longitudinal electric field E_y just being formed. This behaviour is shown in Fig. 1(b–e). Longitudinal oscillations at the left edge can be modelled as $y(t) = A\ exp(-\xi\omega_e t)\ cos(\omega_e t + \varphi_0)$ where t denotes time in s, $A = 45 \times 10^{-9}$ m, $\omega_e = 2\pi c/\lambda_e$, $\lambda_e = 320.9 \times 10^{-9}$ m, $\xi = 2.05 \times 10^{-2}$ rad^{-1}, and $\varphi_0 = 0.98\,\pi$. This ribbon is transformed into a bunch, which is focused from an initial transverse FWHM size of 265 nm to a minimum transverse FWHM size of 65 nm during about 5 laser cycles. Thereafter, the bunch is slightly defocused, and leaves the target with a kinetic energy of about 6 MeV as it can be seen from the longitudinal phase space shown in Fig. 2. At this point the bunch length is slightly longer than 0.3 fs. The longitudinal unnormalized rms emittance is about 32 fs keV with a FWHM energy spread of about 12 %. After extraction, the bunch diverges under the action of its own space charge, as transverse focusing provided by the wakefield bubble disappears. The transverse phase space can be seen in Fig. 3 where the FWHM divergence is about 300 mrad. The transverse unnormalized rms emittance is about 3×10^{-3} mm mrad. Kinetic energy and bunch charge are smaller than those obtained in the most recent LWFA experiments [5] by a factor of 1×10^3 and 2 respectively. However, the acceleration gradient is 10 times larger.

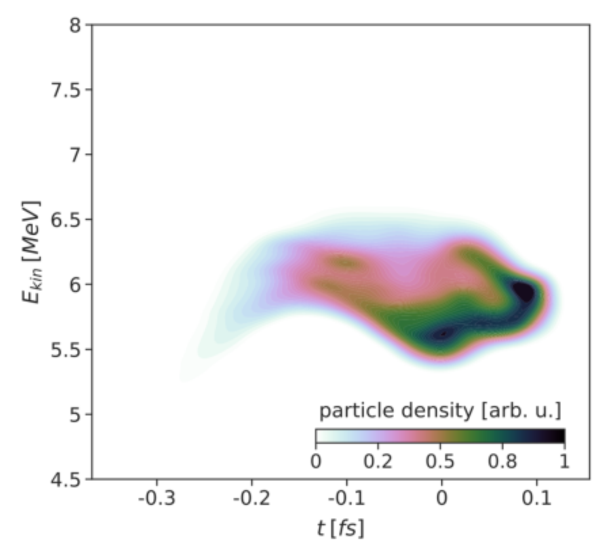

Figure 2: Bunch longitudinal phase space after extraction.

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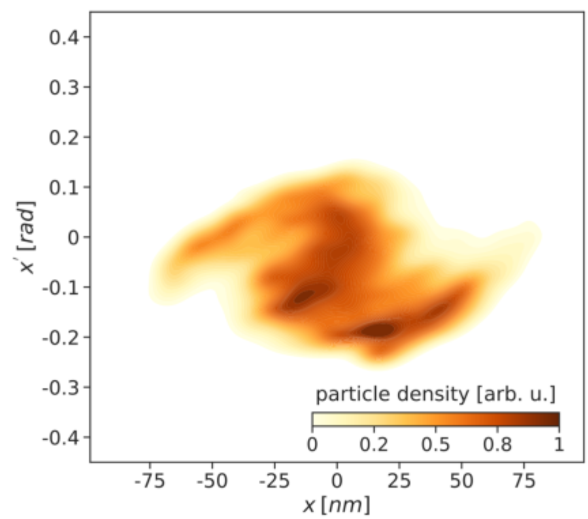

Figure 3: Bunch transverse phase space after extraction.

CONCLUSIONS

We have shown that multilayer graphene can sustain TV/m longitudinal electric fields. With the advent of UV laser sources and the development of Thin Film Compression techniques for UV lasers, following a similar approach used for IR lasers, the phenomenon described in this article offers a promising path towards the generation of sub-femtosecond-long electron bunches with a mean kinetic energy of several MeV. This shows exciting prospects for delivering the shortest electron bunches ever produced in laboratory with excellent potential to advance ultra-fast electron diffraction techniques beyond the current limits [6]. Another potential application is the generation of THz magnetic impulses with the current techniques aiming for time resolutions in the order of tens of fs [7]. Overall, this work demonstrates that LWFA in solid state plasma can be achieved without the need of X-ray lasers as previously thought [8], and therefore has the potential to direct current research on novel acceleration techniques towards using UV laser pulses and layered nanomaterials.

ACKNOWLEDGEMENTS

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