

LASER WAKEFIELD ACCELERATION IN CARBON NANOTUBE BUNDLES*

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Abstract

Laser wakefield acceleration (LWFA) can produce accelerating fields of several hundred GV/m, greatly reducing accelerator size and cost. Carbon nanotube (CNT) bundle-based targets, featuring high plasma density ($>10^{19} \text{ cm}^{-3}$), tunable effective density, excellent thermal properties, and hollow channels that enable laser propagation in overcritical-density targets, have attracted interest as solid-state plasma sources. Previous studies suggested that CNT-based structures can increase the acceleration field to the TV/m range, making them promising for compact radiation sources and radiotherapy. However, the insufficient beam quality still limits their broad application. In this work, we model a hollow solid-state plasma channel composed of CNT bundles. A 2 PW laser pulse based on the parameters of the ELI-ALPS High-Field Laser facility is injected into the channel, generating self-injected electron bunches that are trapped and accelerated by a TV/m-scale accelerating field, as demonstrated by WarpX particle-in-cell simulations. Compared with previous LWFA results using solid-state targets, this work produces a quasi-monoenergetic electron bunch with a charge of 2.8 nC, a mean energy of 198 MeV, and an energy spread of 2.8% over an acceleration length of 104 μm , demonstrating the potential of CNT bundle-based targets for compact TV/m-scale acceleration.

INTRODUCTION

Laser wakefield acceleration (LWFA) was first proposed by Tajima and Dawson in 1979 [1]. Since then, LWFA has developed from proof-of-principle demonstrations to GeV-scale electron acceleration. An early proof-of-principle experiment demonstrated an accelerating field of $\sim 1.7 \text{ GV/m}$ [2], while later experiments at Berkeley Lab using capillary-discharge-guided gaseous plasmas achieved multi-GeV electron beams with an average accelerating field of $\sim 47 \text{ GV/m}$ [3]. Since the plasma wave breaking field increases with plasma density, crystals and solid-state plasmas have been proposed as potential media for ultra-high-gradient acceleration [4, 5]. Among these solid-state plasma candidates, carbon-based nanostructures such as graphene and carbon nanotubes (CNTs) have attracted particular interest because of their high electron density, structural tunability, and potential to guide intense laser pulses through hollow channels. Recently, graphene structures have been reported to

support an acceleration field up to 4.79 TV/m in simulations [6], while ultrahigh-density carbon nanotubes (CNTs) have been predicted to achieve fields on the order of 100 – 400 TV/m [7]. In addition, a new acceleration mechanism has been identified in CNT-based structures, where sub-TeV/m acceleration is achieved in the leaky surface plasmon polariton (SPP) regime [8]. These advances suggest that nanostructured carbon-based plasmas provide a promising route toward compact, ultra-high-gradient laser-driven accelerators.

However, previous studies of CNT targets at plasma densities of 10^{21} – 10^{22} cm^{-3} have reported relatively low beam quality, particularly with large energy spread [9]. One critical reason is the laser-plasma instabilities caused by the mismatch between the laser pulse duration, τ , and the plasma wavelength, λ_p , when $c\tau > \lambda_p$ [10–12], where c denotes the speed of light.

In full three-dimensional particle-in-cell (PIC) simulations, the spatial resolution must be sufficiently high to resolve the nanostructured CNT units accurately, making such simulations computationally expensive. To reduce this cost, the effective density approach (EDA), which represents nanostructured CNT targets using a volume-averaged plasma density, was proposed in Ref. [13]. This approach enables analytical expressions originally derived for uniform plasmas to estimate the wakefield properties.

In this work, we investigate LWFA in CNT-bundle targets at relatively low plasma densities of 10^{19} – 10^{20} cm^{-3} , where the laser pulse length can be better matched to the plasma wavelength than in ultrahigh-density CNT regimes. We first perform parameter scans over the effective plasma density, laser waist, and inner radius of uniform CNT targets to optimise the beam quality. The optimal parameter set is then applied to CNT-bundle targets, where the geometry is further optimised to reduce the energy spread.

TARGET GEOMETRY

Figure 1 shows a schematic of the CNT bundle-based target, which consists of several tens of concentric shells of CNT bundles surrounding a central hollow channel. Each bundle is composed of nanoscale single-walled CNTs. Applying the effective density approach, the periodically non-uniform CNT bundle distribution is approximated as an equivalent homogeneous plasma, defined as [7]:

$$n_{\text{eff}} = n_b \frac{Nf}{1 + (N-1)(1+\kappa)}. \quad (1)$$

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where f denotes the filling factor, which determines the fraction of CNT bundles occupied on each concentric shell and satisfies $0 < f < 1$. κ is the normalised radial gap between two adjacent bundle shells, defined as g/d , where g is the radial gap between neighbouring shells and d is the bundle diameter. N denotes the total number of concentric shells in the CNT target, given by

$$N = \frac{r_{\text{out}} - r_{\text{in}} - d}{d + g} + 1. \quad (2)$$

where the r_{out} and r_{in} represent the inner and outer edges of the bundles, respectively. Accordingly, the radius of the j -th concentric shell is given by

$$r_j = r_{\text{in}} + \frac{d}{2} + (j-1)(d+g), \quad j = 1, 2, \dots, N. \quad (3)$$

The azimuthal angle of the i -th CNT bundle on the j -th shell is given by:

$$\theta_{j,i} = \theta_{j,0} + \frac{2\pi(i-1)}{M_j}, \quad i = 1, 2, \dots, M_j. \quad (4)$$

where the optional azimuthal offset for all bundle shells is $\theta_{j,0} = 0$. M_j is the number of bundles placed on the j -th shell, given by:

$$M_j = \lfloor f M_{j,\text{max}} \rfloor, \quad j = 1, 2, \dots, N. \quad (5)$$

where $M_{j,\text{max}}$ denotes the maximum number of CNT bundles that can be accommodated along the circumference of the j -th shell, given by:

$$M_{j,\text{max}} = \left\lfloor \frac{2\pi r_j}{d} \right\rfloor. \quad (6)$$

The floor operation is applied in the definition of $M_{j,\text{max}}$ to ensure that the number of bundles does not exceed the available circumference, thereby avoiding overlap between neighbouring CNT bundles on the same shell. The transverse carbon density distribution is given by

$$n_C(x, y) = \begin{cases} n_b, & \text{if } (x - x_{j,i})^2 + (y - y_{j,i})^2 \leq (d/2)^2, \\ 0, & \text{otherwise.} \end{cases} \quad (7)$$

where $(x_{j,i}, y_{j,i})$ gives the transverse centre position of the i -th CNT bundle on the j -th shell, given by

$$x_{j,i} = r_j \cos \theta_{j,i}, \quad y_{j,i} = r_j \sin \theta_{j,i}. \quad (8)$$

The main geometric and density parameters used to model the nanostructured CNT target are summarised in Table 1. The effective target density and inner radius are determined from parameter scans performed using a uniform plasma target, following the principle of the effective density approach (EDA). After applying the optimal parameter set, the bundle diameter, shell gap, and filling factor are further optimised through additional parameter scans. For simplicity and as a computational trade-off, $d = g = 200$ nm is adopted here.

Table 1: Parameters of the nanostructured CNT bundles

Parameters	Symbols (Units)	Values
Effective target density	n_{eff} (cm ⁻³)	1.8×10^{19}
Bundle density	n_b (cm ⁻³)	3.5×10^{20}
Bundle diameter	d (nm)	200
Shell gap	g (nm)	200
Inner radius	r_{in} (μm)	1.7
Outer radius	r_{out} (μm)	9.9
Filling factor	f (%)	10

LASER AND SIMULATION SETUPS

The ELI-ALPS 2 PW high-field laser parameters are used in this study [14], which represents one of the state-of-the-art facilities for ultra-intense laser-plasma interaction experiments. The laser pulse is modelled as a linearly polarised Gaussian beam with a central wavelength of 800 nm and a peak power of 2 PW, as schematically illustrated in Fig. 1. The focal spot size is determined to $w_0 = 3.7$ μm based on the parameter scan within uniform targets, corresponding to a peak intensity of 4.65×10^{21} W/cm² and a normalised vector potential of $a_0 = 46.4$. The full-width at half-maximum (FWHM) pulse duration is 17 fs. The laser is focused at the entrance of the plasma target ($z_f = 0$), with a Rayleigh length of $z_R = 53.8$ μm. These parameters place the interaction firmly in the highly nonlinear regime relevant for LWFA.

Table 2 summarises the main numerical parameters used in full 3D WarpX simulations [15]. The computational domain has a size of $x \times y \times z = 20 \mu\text{m} \times 20 \mu\text{m} \times 25 \mu\text{m}$, discretised with $N_x \times N_y \times N_z = 320 \times 320 \times 512$ grid cells. This corresponds to spatial resolutions of $\Delta z = 0.095 k_p^{-1} = 48.8$ nm and $\Delta x = \Delta y = 0.122 k_p^{-1} = 62.5$ nm. Each cell is initialised with $4 \times 4 \times 4$ macroparticles to ensure sufficient sampling of the phase space while maintaining computational efficiency. The time step is set to 0.11 fs, satisfying the Courant–Friedrichs–Lewy (CFL) condition.

Field ionisation is modelled using the ADK (Ammosov-Delone-Krainov) model to capture the strong-field ionisation dynamics of the target [16, 17]. The electromagnetic fields are advanced using the Yee solver, and absorbing boundary conditions are applied in all directions to minimise unphysical reflections at the domain boundaries. In addition, ions are assumed to remain stationary on the ultrashort acceleration timescale, so that electron acceleration is completed before the target damage [18].

SIMULATION RESULTS

Wakefield and electron profile

Figure 2 shows a clear nonlinear wakefield structure formed behind the laser driver. The ponderomotive force of the laser expels plasma electrons outward, generating an ion cavity in the wake, indicating that the interaction is operating in the blowout regime.

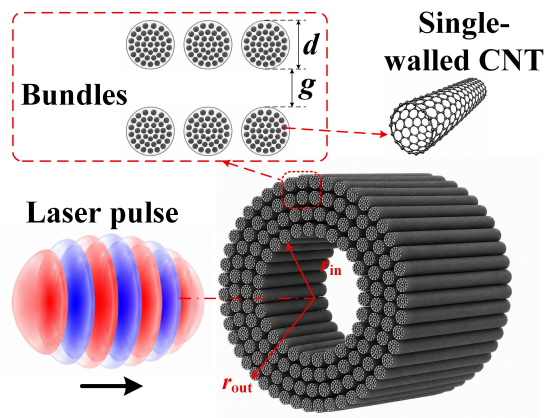


Figure 1: Schematic diagram of LWFA using a nanostructured CNT target.

Table 2: Numerical parameters in this study

Parameters	Values
Window size	$20\text{ }\mu\text{m} \times 20\text{ }\mu\text{m} \times 25\text{ }\mu\text{m}$
Number of grids	$320 \times 320 \times 512$
Macroparticles per cell	$4 \times 4 \times 4$
Time step	0.11 fs
Field ionisation	ADK model
Field solver	Yee
Boundary conditions	Absorbing

Near the rear of the bubble, ionised electrons from the CNT target satisfy the trapping condition, i.e., phase velocity of the bubble is smaller than the electron velocity, and background electrons are therefore trapped by the wakefield. These self-injected electrons form a compact, high-density bunch inside the accelerating phase. A notable feature is that the trapped electrons exhibit a quasi-rectangular spatial profile in the (x, z) plane. This suggests that the injection process is spatially localised and may be influenced by the structured geometry of the CNT bundle target.

The on-axis accelerating field E_z reaches multi-TV/m and shows a pronounced modification in the region occupied by the trapped bunch. In particular, the profile of E_z is flattened around the trapped electrons, referred to as the beam-loading effect. The flattening effect of the wakefield allows electrons at different longitudinal positions within the bunch to experience a uniform accelerating field, thereby decreasing the energy spread.

Beam quality

Figure 3 shows the energy spectrum of the accelerated electrons after a propagation distance of $104\text{ }\mu\text{m}$. A narrow energy peak is observed at 195 MeV . To mitigate the energy-spread growth caused by continual trapping [10], an optimised energy cut of $E > 190\text{ MeV}$ is applied. The mean energy reaches 198 MeV , with a total charge of 2.8 nC . The root-mean-square (rms) energy spread is 2.7% , indicating the generation of a quasi-monoenergetic electron bunch. The normalised emittance is 12.0 mm mrad . Based

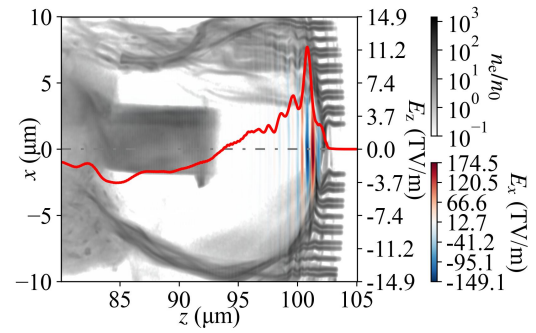


Figure 2: Electron density, laser field and longitudinal wake-field near the interaction region. The grayscale map shows n_e/n_0 , the coloured structure shows E_x , and the red curve represents the on-axis longitudinal field E_z .

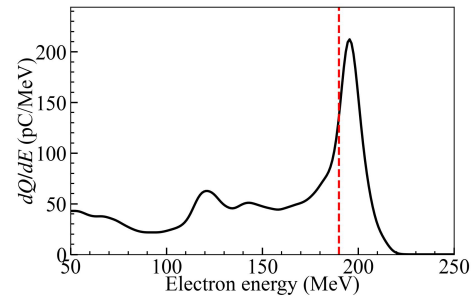


Figure 3: Electron energy spectrum of the accelerated bunch. The red dashed line indicates the electron energy cut.

on the acceleration length, the mean acceleration field is 1.9 TV/m . These results suggest that the CNT-bundle target can support efficient electron acceleration, producing a low energy-spread bunch over an ultrashort acceleration length.

CONCLUSIONS AND OUTLOOK

We studied LWFA in low-density CNT-bundle targets with effective plasma densities of $10^{19} - 10^{20}\text{ cm}^{-3}$ using the WarpX code, aiming to improve the laser-plasma matching condition. Parameter scans of the effective target density, inner radius, and laser waist were performed to guide the parameter selection for CNT-bundle targets. With further optimised bundle target we produce a quasi-monoenergetic electron bunch with a mean energy of 198 MeV , 2.8 nC charge, 2.7% rms energy spread, and a mean acceleration field of 1.9 TV/m over $104\text{ }\mu\text{m}$. These results suggest that low-density CNT-bundle targets can provide a promising route toward compact TV/m-scale acceleration with low energy spread. Future work will extend the optimisation by using machine-learning-based approaches and perform proof-of-principle experiments at existing high-power laser facilities.

REFERENCES

- [1] T. Tajima and J. M. Dawson, "Laser Electron Accelerator", *Phys. Rev. Lett.*, vol. 43, no. 4, p. 267, 1979.
doi:10.1103/PhysRevLett.43.267

- [2] K. Nakajima *et al.*, “A proof-of-principle experiment of laser wakefield acceleration”, *Phys. Scr.*, vol. 1994, no. T52, pp. 61–64, 1994. doi:10.1088/0031-8949/1994/T52/009
- [3] W. Leemans *et al.*, “Multi-GeV electron beams from capillary-discharge-guided subpetawatt laser pulses in the self-trapping regime”, *Phys. Rev. Lett.*, vol. 113, no. 24, p. 245002, 2014. doi:10.1103/PhysRevLett.113.245002
- [4] T. Tajima and M. Cavenago, “Crystal x-ray accelerator”, *Phys. Rev. Lett.*, vol. 59, no. 13, p. 1440, 1987. doi:10.1103/PhysRevLett.59.1440
- [5] M. F. Gilljohann *et al.*, “Channeling acceleration in crystals and nanostructures and studies of solid plasmas: new opportunities”, *J. Instrum.*, vol. 18, no. 11, P11008, 2023. doi:10.1088/1748-0221/18/11/P11008
- [6] C. Bontoiu *et al.*, “TeV/m catapult acceleration of electrons in graphene layers”, *Sci. Rep.*, vol. 13, no. 1, p. 1330, 2023. doi:10.1038/s41598-023-28617-w
- [7] B. Lei *et al.*, “100 s TeV/m-level particle accelerators driven by high-density electron beams in micro structured carbon nanotube forest channel”, *New J. Phys.*, vol. 27, no. 8, p. 084301, 2025. doi:10.1088/1367-2630/adf87d
- [8] B. Lei *et al.*, “Leaky surface plasmon-based wakefield acceleration in nanostructured carbon nanotubes”, *Plasma Phys. Control. Fusion*, vol. 67, no. 6, p. 065036, 2025. doi:10.1088/1361-6587/ade00a
- [9] C. Bontoiu *et al.*, “Numerical study of self-injected electron acceleration in CNT structured targets driven by an 800 nm laser”, *Sci. Rep.*, 2025. doi:10.1038/s41598-025-29386-4
- [10] E. Esarey, C. B. Schroeder, and W. P. Leemans, “Physics of laser-driven plasma-based electron accelerators”, *Rev. Mod. Phys.*, vol. 81, no. 3, pp. 1229–1285, 2009. doi:10.1103/RevModPhys.81.1229
- [11] J. Krall, A. Ting, E. Esarey, and P. Sprangle, “Enhanced acceleration in a self-modulated-laser wake-field accelerator”, *Phys. Rev. E*, vol. 48, no. 3, p. 2157, 1993. doi:10.1103/PhysRevE.48.2157
- [12] A.J.W. Reitsma, R.A. Cairns, R. Bingham, and D.A. Jaroszynski, “Efficiency and Energy Spread in Laser-Wakefield Acceleration”, *Phys. Rev. Lett.*, vol. 94, no. 8, p. 085004, 2005. doi:10.1103/PhysRevLett.94.085004
- [13] A. Bonatto *et al.*, “Exploring ultra-high-intensity wakefields in carbon nanotube arrays: An effective plasma-density approach”, *Phys. Plasmas*, vol. 30, no. 3, 2023. doi:10.1063/5.0134960
- [14] R. S. Nagymihály *et al.*, “First operation phase of the 10 Hz 2 PW laser of ELI ALPS”, in *Proc. 2023 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC)*, p. 1, 2023. doi:10.1109/CLEO/Europe-EQEC57999.2023.10231672
- [15] J.-L. Vay *et al.*, “Warp-X: A new exascale computing platform for beam-plasma simulations”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 909, pp. 476–479, 2018. doi:10.1016/j.nima.2018.01.035
- [16] M. V. Ammosov, N. B. Delone, and V. P. Krainov, “Tunnel ionization of complex atoms and atomic ions in electromagnetic field”, in *Proc. SPIE 0664, High Intensity Laser Processes*, vol. 664, pp. 138–141, 1986. doi:10.1117/12.938695
- [17] M. Chen *et al.*, “Numerical modeling of laser tunneling ionization in explicit particle-in-cell codes”, *J. Comput. Phys.*, vol. 236, pp. 220–228, 2013. doi:10.1016/j.jcp.2012.11.029
- [18] S. Hakimi *et al.*, “Wakefield in solid state plasma with the ionic lattice force”, *Phys. Plasmas*, vol. 25, no. 2, 2018. doi:10.1063/1.5016445