The NanoAc Collaboration: Toward a Proof-of-Principle for Laser Wakefield Acceleration in Nanostructured Solid-State Plasma

NOVAS

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Abstract

Solid-state plasma wakefield acceleration has recently garnered attention as a viable alternative for achieving unprecedented ultra-high acceleration gradients on the order of 1 TV/m or beyond. In this context, recent advancements in nanofabrication techniques have opened up the possibility of creating structured plasmas with tailored properties. For instance, the utilization of carbon nanotube (CNT) bundles holds great potential for generating stable plasmas with electron densities reaching as high as 10^{24} cm^{-3}, i.e., orders of magnitude higher than conventional gaseous plasmas. As part of a new collaborative effort called NanoAc, we have conducted Particle-In-Cell (PIC) simulations to investigate laser wakefield acceleration in nanostructured solid-state plasmas based on CNT arrays. Our results confirm the attainment of wakefields at the TV/m scale. Additionally, we observed self-injection, sub-femtosecond bunch formation, and electron acceleration in micrometre-scale targets, yielding kinetic energies of ~10 MeV. These findings open up promising possibilities to design novel ultra-compact accelerators and radiation sources. In this contribution, we present a summary of the work carried out by the NanoAc collaboration to date and discuss the preparation of future experimental tests in existing laser facilities.

INTRODUCTION

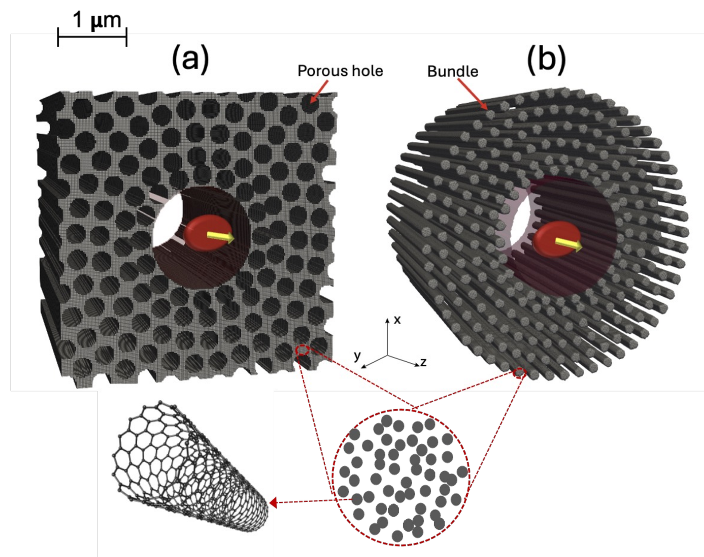
Feasibility study of **resonant LWFA** in **solid-state targets** composed of CNT bundles.

Self-injection and acceleration (**gradient > TV/m**) of electrons.

By arranging CNT bundles in an alternating pattern with voids or low-density regions, the effective density of the target can be tuned. As the driver propagates through the voids, it ionizes the adjacent solid walls. The ionized electrons fill the gaps, forming a **high-density plasma.**

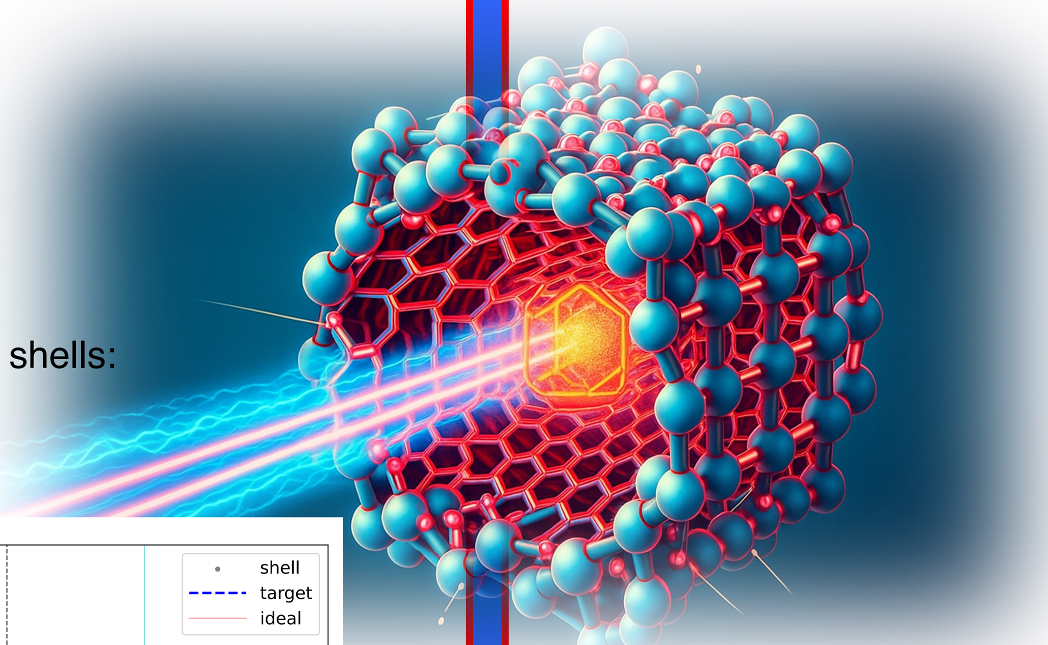
The primary objective of NanoAc is to conduct an **experimental proof-of-principle for resonant LWFA in solid-state targets based on CNT arrays**. This novel beam acceleration and manipulation technique has the potential to unlock multi-TV/m field regimes, generate **ultra-high-brightness electron beams**, and enable a new generation of **chip-scale accelerators** with transformative implications for ultrafast science

Target configurations



(a) porous target with walls composed of CNT bundles, and (b) nanowired target, where each wire consists of vertically aligned CNT bundles.

Wide topological flexibility to tune the effective energy



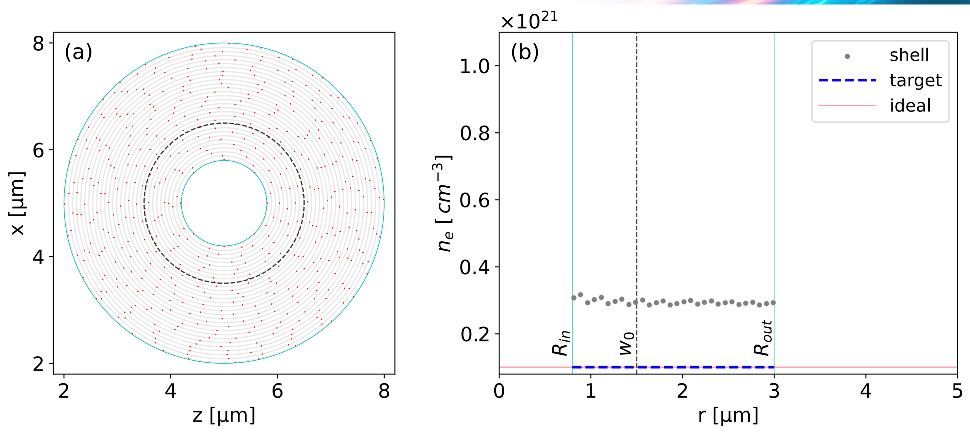
NUMERICAL CALCULATIONS

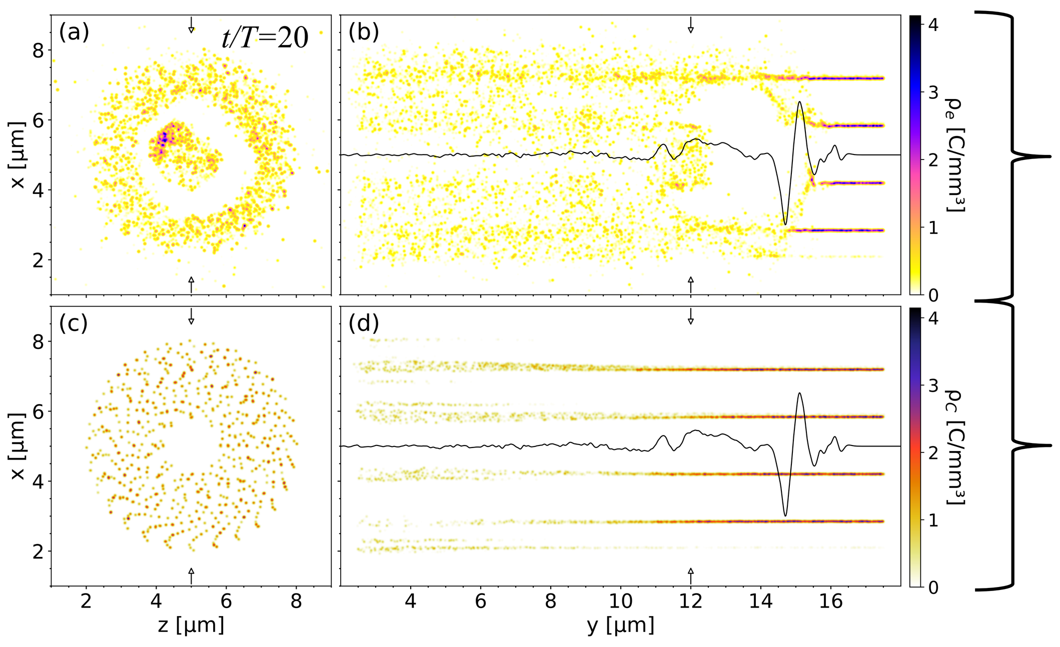
3D PIC simulations using the PIConGPU code

- 535 CNT bundles distributed in 30 shells with gap of 50 nm between shells: 25 CNT per bundle
- Effective plasma density: $n_e \approx 10^{20}\ \mathrm{cm}^{-3}$

Laser parameters

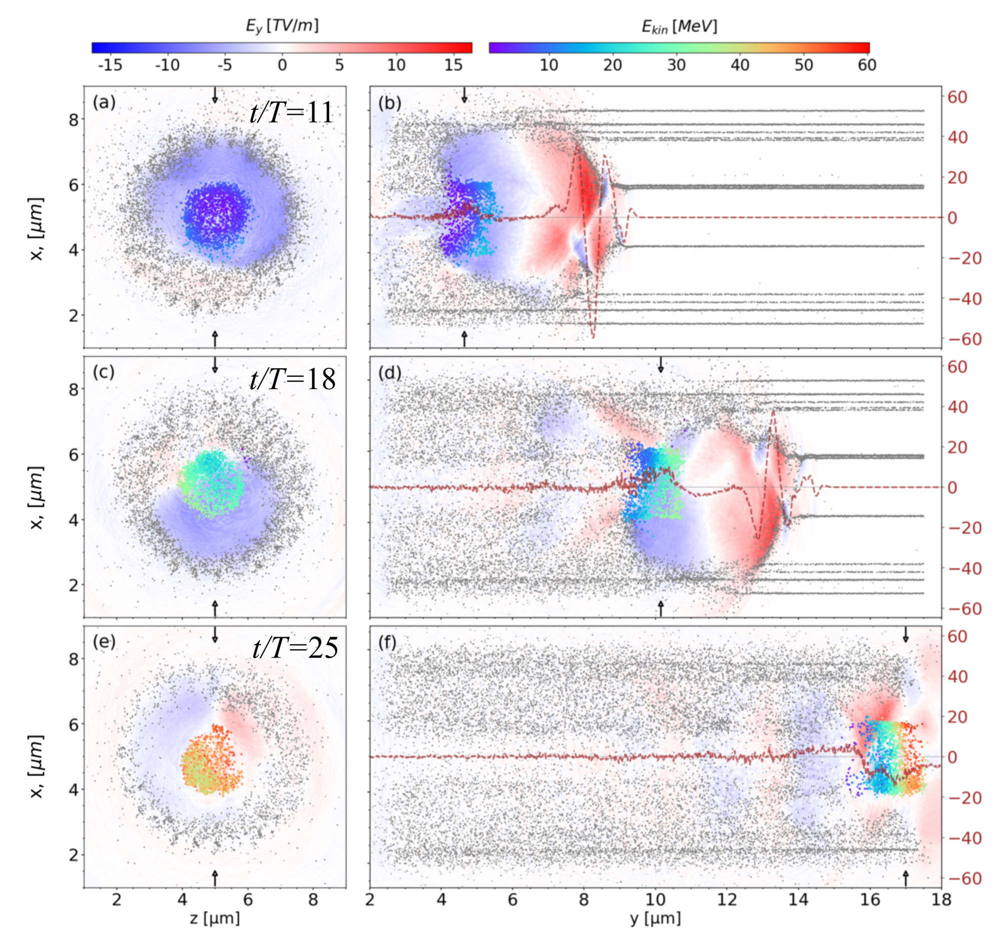
Parameter	Value		Unit
Wavelength, λ	800		nm
Period, T	2.67		fs
FWHM pulse duration, Δt	2.67		fs
Spot size, w_0	1.5		µm
Peak intensity, I_0	10^{20}	10^{21}	W/cm^2
Potential vector, a_0	6.8	21.6	-
Pulse energy, E	10	100	mJ





Transverse and axial view of the electron charge density

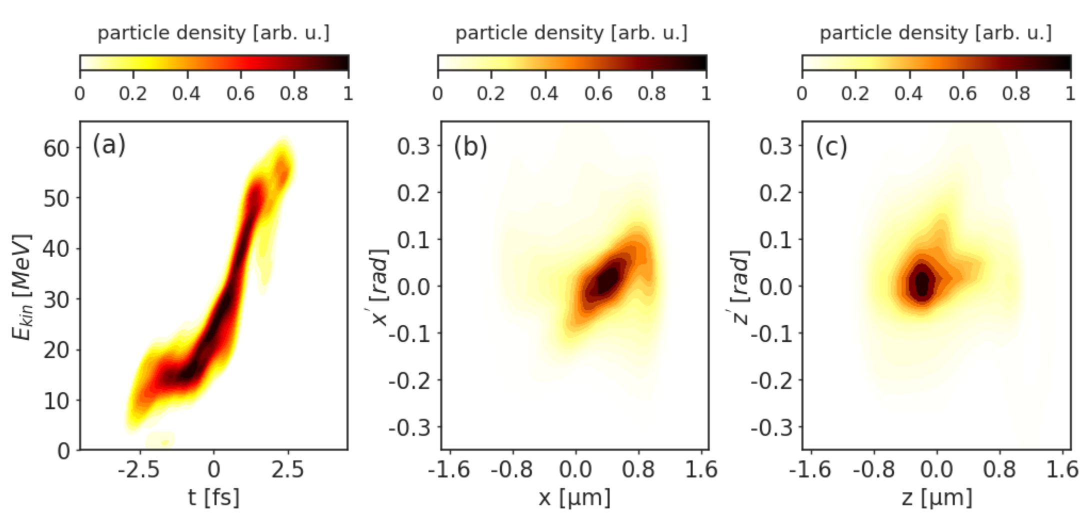
Transverse and axial view of the carbon charge density



- The laser pulse ionizes the interaction region, repelling electrons towards the outer shells, generating a moving **wakefield bubble**.
- Electrons are then **self-injected** at the back of the bubble and experience **TV/m** longitudinal electric fields.
- In this example an electron bunch of **867 pC** charge is resonantly accelerated to about 28 MeV in 15 µm. The acceleration gradient is **1.86 TV/m**

Further details: *C. Bontoiu, et al., preprint: arXiv:2502.00183v2 [physics.acc-ph] 11 Feb 2025*

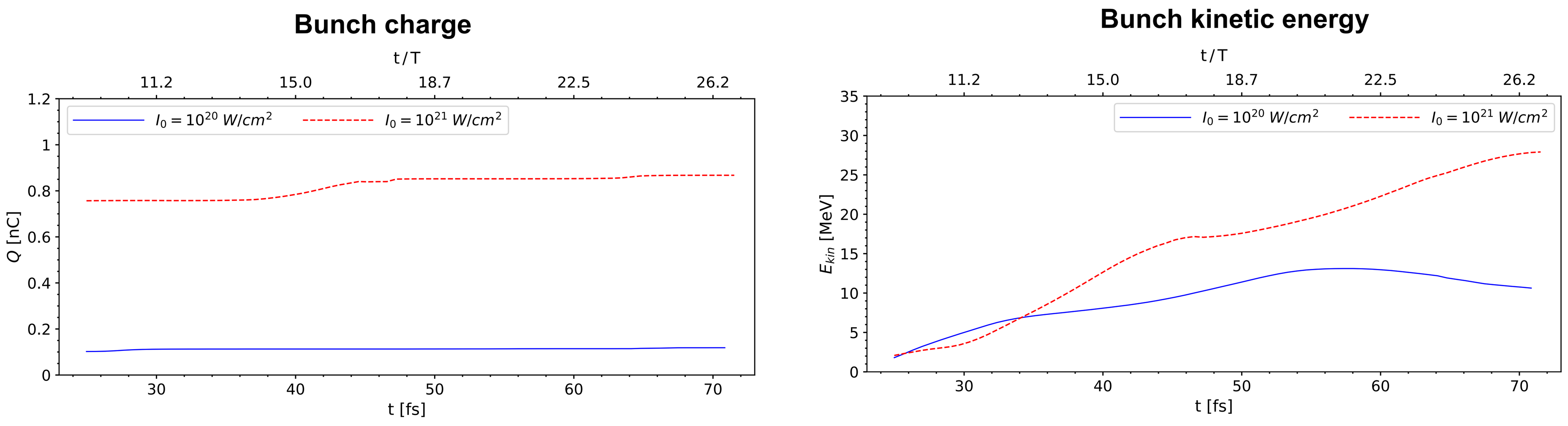
Phase space at extraction



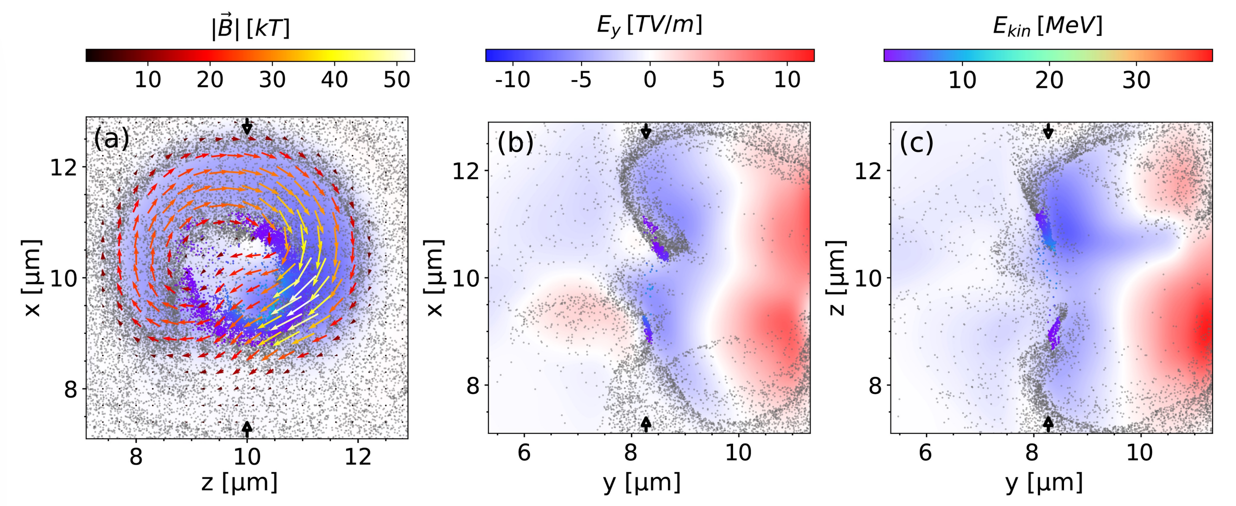
Bunch parameters at extraction

Parameter	Value at $I_0 = 10^{20}$	Value at $I_0 = 10^{21}$	Unit W/cm^2
Charge, Q	0.12	0.87	nC
Average kinetic energy, E_{kin}	10.63	27.91	MeV
Average acceleration gradient, E_{kin}/L	0.71	1.86	TeV/m
FWHM bunch length, Δt_b	1.72	3.98	fs
FWHM energy spread, ΔE	115	105	%
Normalized RMS longitudinal emittance, $\bar{\varepsilon}_{\parallel}$	0.06	0.52	fs – MeV
FWHM vertical size, Δx	1.43	1.17	µm
FWHM vertical divergence, $\Delta x'$	0.22	0.13	rad
Normalized RMS vertical emittance, $\bar{\varepsilon}_x$	1.16	2.16	π mm – mrad
FWHM horizontal size, Δz	1.24	0.82	µm
FWHM horizontal divergence, $\Delta z'$	0.19	0.13	rad
Normalized RMS horizontal emittance, $\bar{\varepsilon}_z$	1.30	2.19	π mm – mrad

Parametric time evolution



Induced magnetic field and focusing

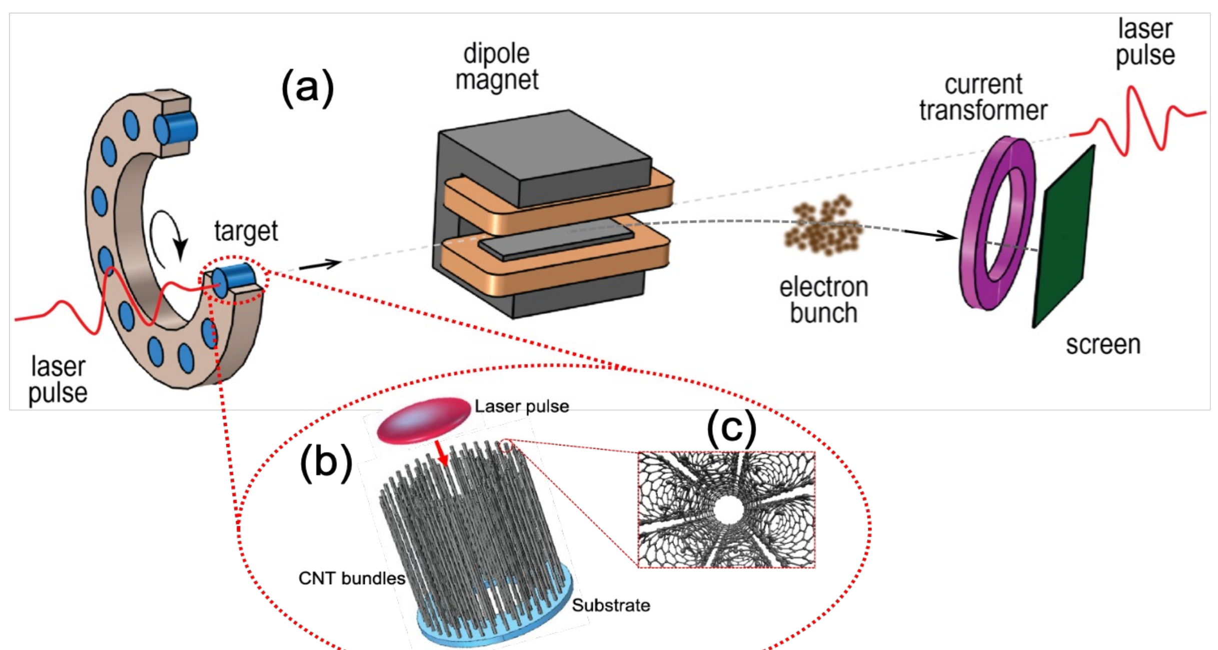


Azimuthal magnetic field peak **~ 50 kT** (monitored at t/T=10)

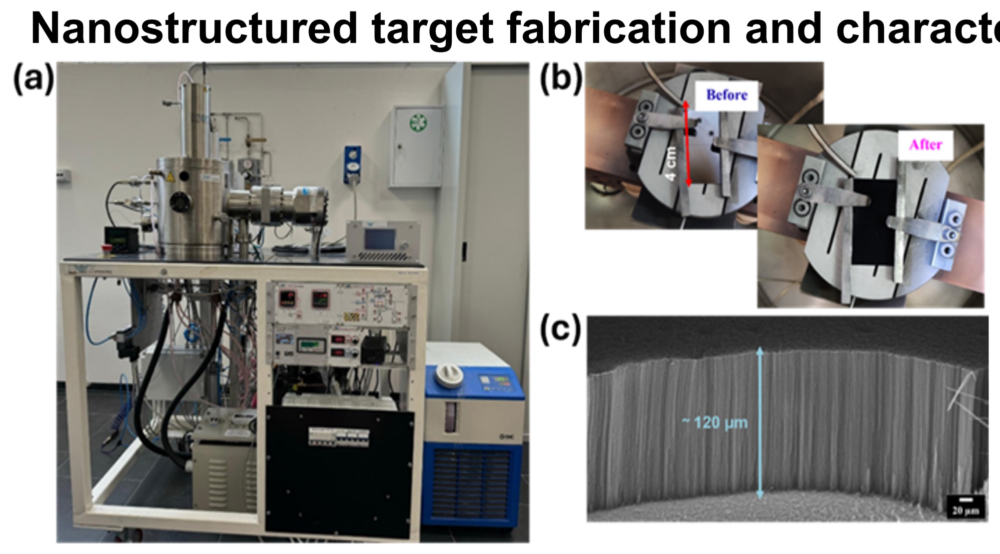
PRELIMINARY EXPERIMENTAL LAYOUT

Laser facility

G. Gatti, et al.



Nanostructured target fabrication and characterisation



(a) The TITAN INFN-Sapienza facility at Sapienza University of Rome; (b) silicon substrate mounted on the heating element inside the CVD chamber before (left) and after (right) VA-CNTs synthesis; (c) SEM image of a typical VA-CNT array growth. *G. Cavoto, et al.*

Outlook

Numerical results demonstrate the feasibility of achieving LWFA in a solid-state plasma with an 800 nm (infrared) laser pulse. Using PIConGPU simulations, we demonstrate that this laser can accelerate an electron pulse with a charge of 867 pC to an average energy of 27.9 MeV within a 15 µm-long carbon nanotube bundle target, achieving acceleration gradients in the TV/m range. Furthermore, the obtained ultra-short pulse length ($\lesssim$ 10 fs) and relatively low transverse emittance ($\approx 2\pi$ mm – mrad), could make this acceleration technique suitable for interesting applications in the field of ultrafast science, e.g., for single-shot MeV ultrafast electron diffraction. Our future research plan includes the further optimisation of results to improve the beam energy, charge, and quality (divergence, energy spread), thereby enhancing its overall applicability. Currently, the collaboration is preparing optimised targets for a proof-of-principle experiment,

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Work supported by the Generalitat Valenciana (CIDEGENT/2019/058)