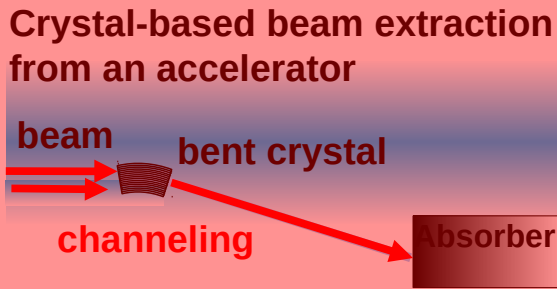
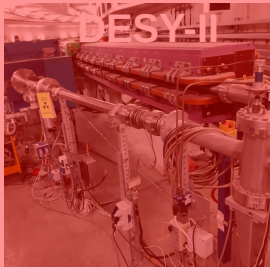


Ultra-high acceleration gradient using structured nanomaterials

Alexei Sytov and J. Resta-López
on behalf of the NanoAcc collaboration

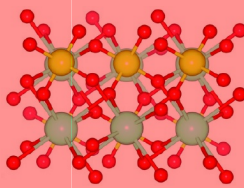

Applications

Crystal-based beam extraction from an accelerator

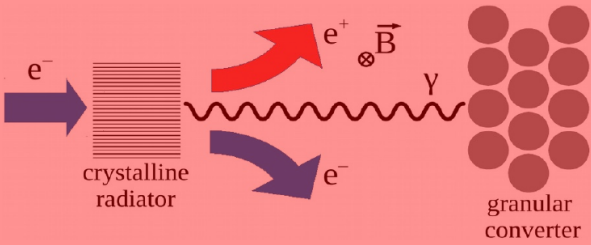
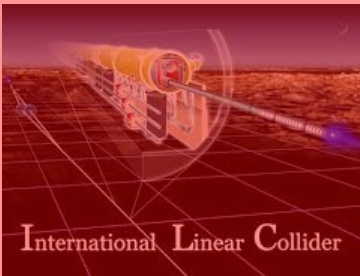
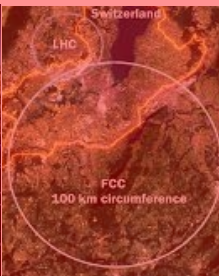



Gamma-ray Space Telescope

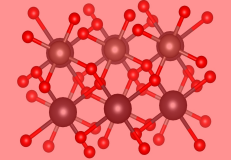
Ultrashort crystalline calorimeter

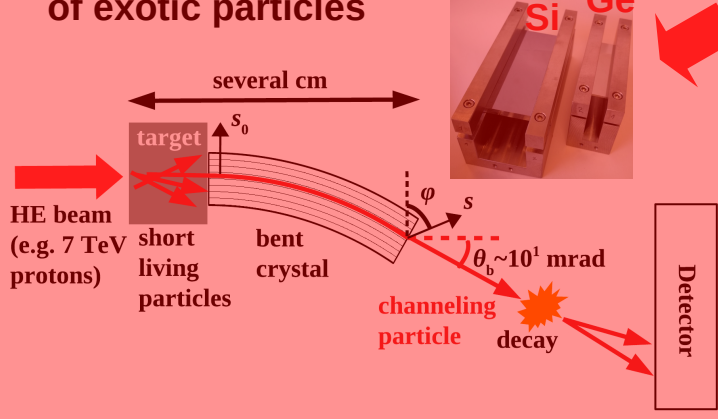

Positron source for future e+/e- and muon colliders

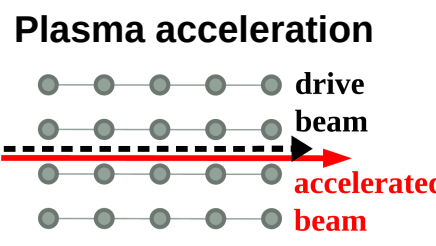
Oriented crystals



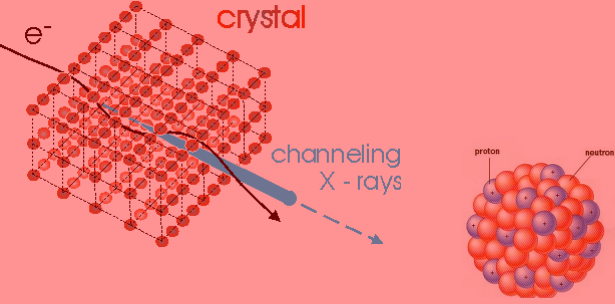
Measurement of dipole magnetic and electric moments of exotic particles

Plasma acceleration



X and gamma-ray source for nuclear and medical physics



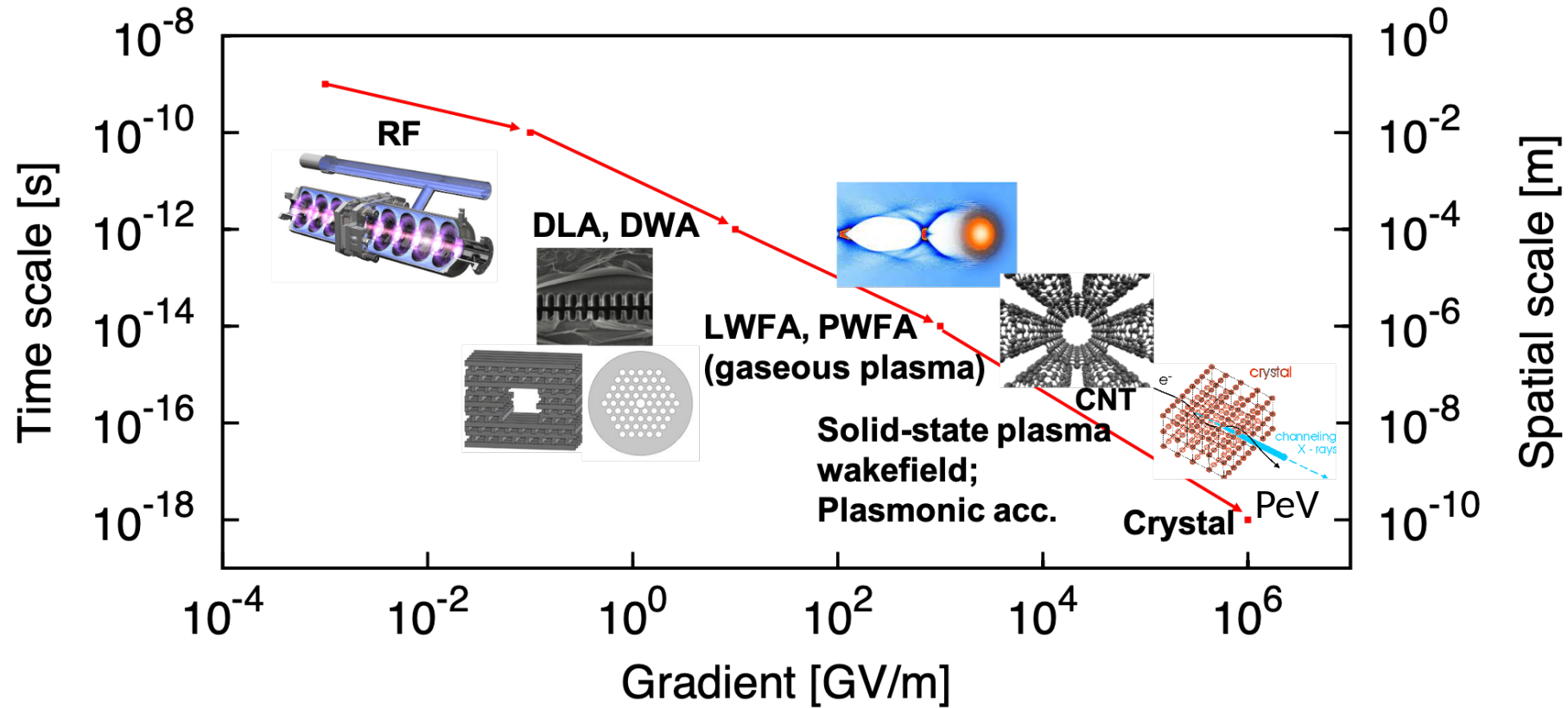
High-acceleration gradient. Novel concepts

- Towards more compact and sustainable accelerators

Acceleration gradient*

$$E[\text{GV/m}] \approx 100 \sqrt{n_0 [10^{18} \text{cm}^{-3}]}$$

Scale of the oscillations, dimension of drivers



Challenges and solutions of WFA in solids

stability

drive beam size vs
plasma wavelength λ_p

multiple scattering

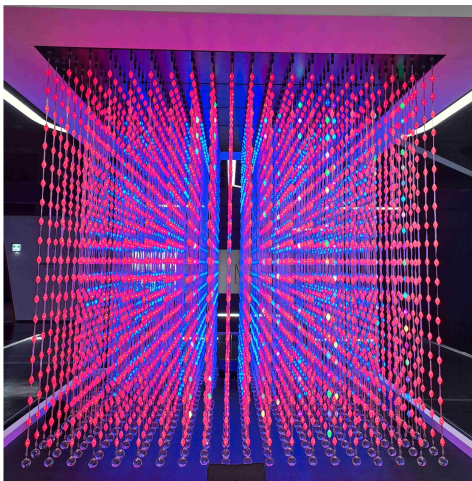
energy distribution

radiation damage of
the target

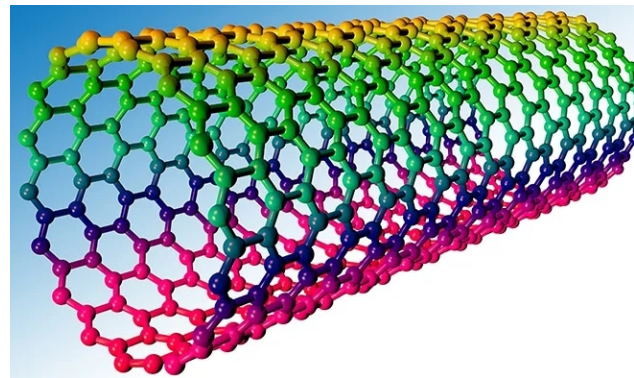
beam emittance

Potential **solution** of most of problems:
non-constant density of the solid

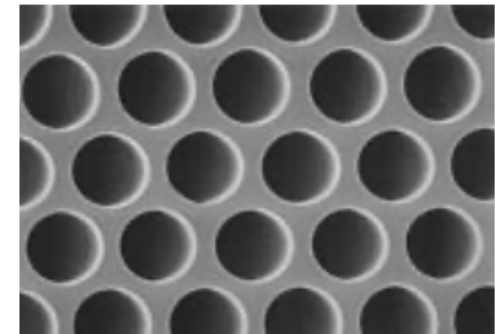
Oriented crystals



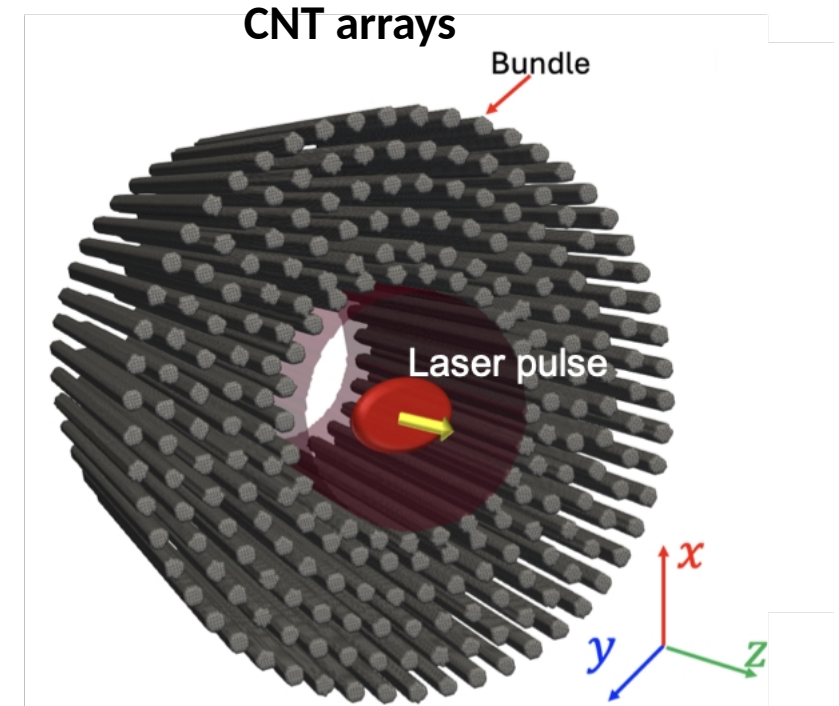
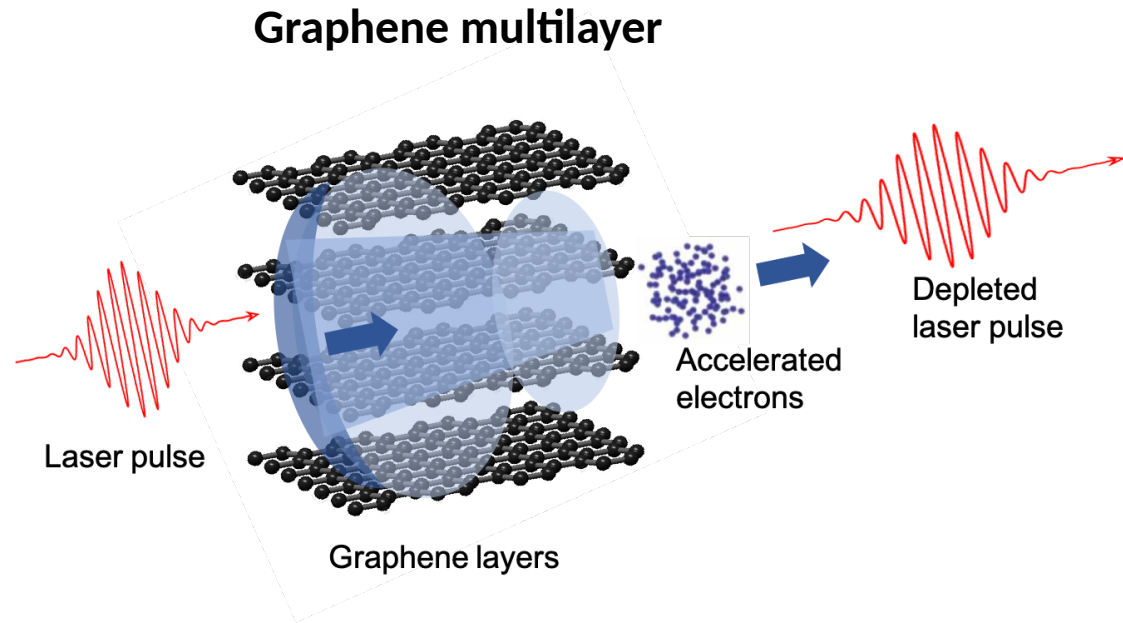
Nanotubes



Structured solids



LWFA in graphene and CNT based structures

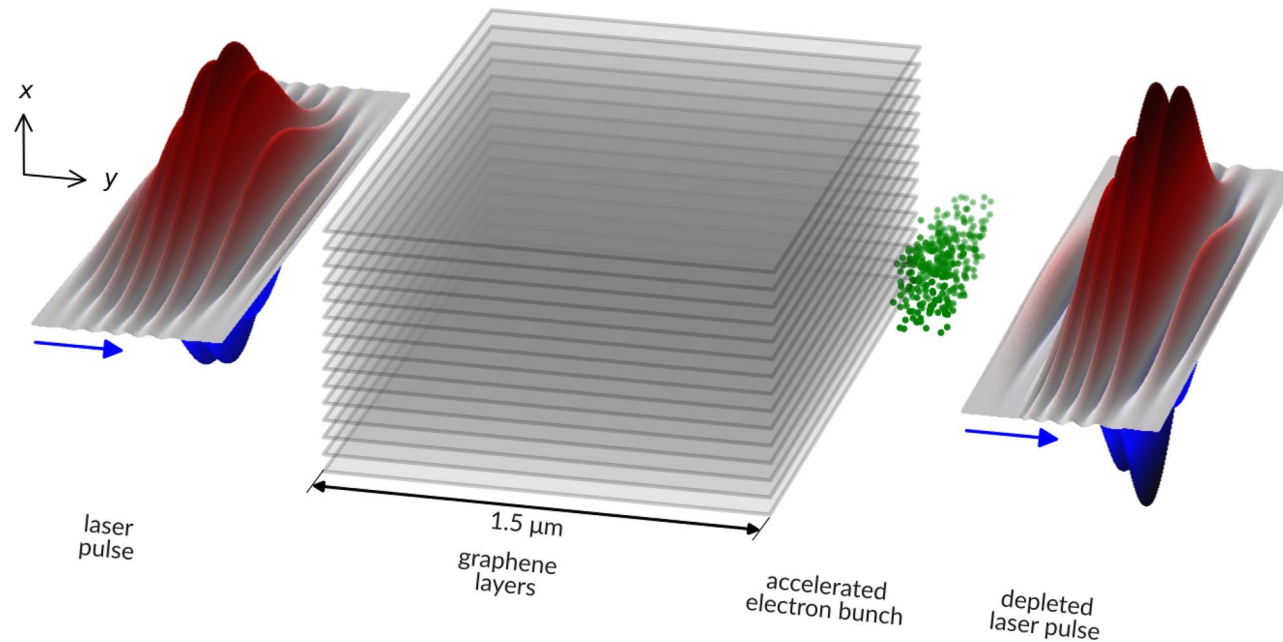


Why graphene and CNTs?

- Special thermo-mechanical and optoelectronic properties.
- Relatively easy ionization of conduction electrons to generate a high density plasma ($n_e \sim 10^{20} - 10^{22} \text{ cm}^{-3}$).
- Advances in nanofabrication techniques. Flexibility to fabricate interesting geometries.
- High thermal and mechanical robustness
 - Melting point of a freestanding single-tip CNT $\sim 3000 - 4000 \text{ K}$.
 - Tensile strength $> 100 \text{ GPa}$ (100 x Stainless steel).
- Hollow structures that allow good laser transmission.

LWFA in graphene

TeV/m “Catapult” (ballistic) accelerator with graphene layers

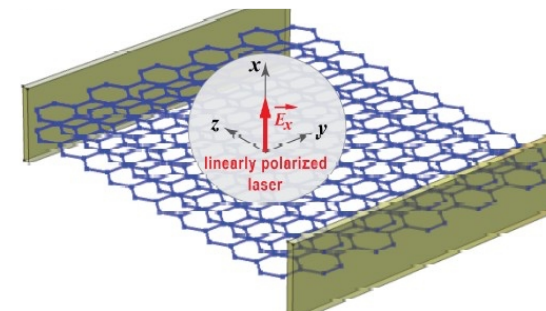


Laser parameters. UV range

Quantity	Value	Unit
Wavelength, λ	100	nm
Period, T	0.334	fs
Peak intensity, I_0	10^{21}	W/cm ²
Spot size (FWHM), w_0	0.4	μm
Focal point, y_f	0.25	μm
Pulse energy, E	8	mJ
Pulse length (9 cycles), Δt	3	fs
Potential vector, a_0	2.7	–

Challenging parameters

Lithographic and etching techniques

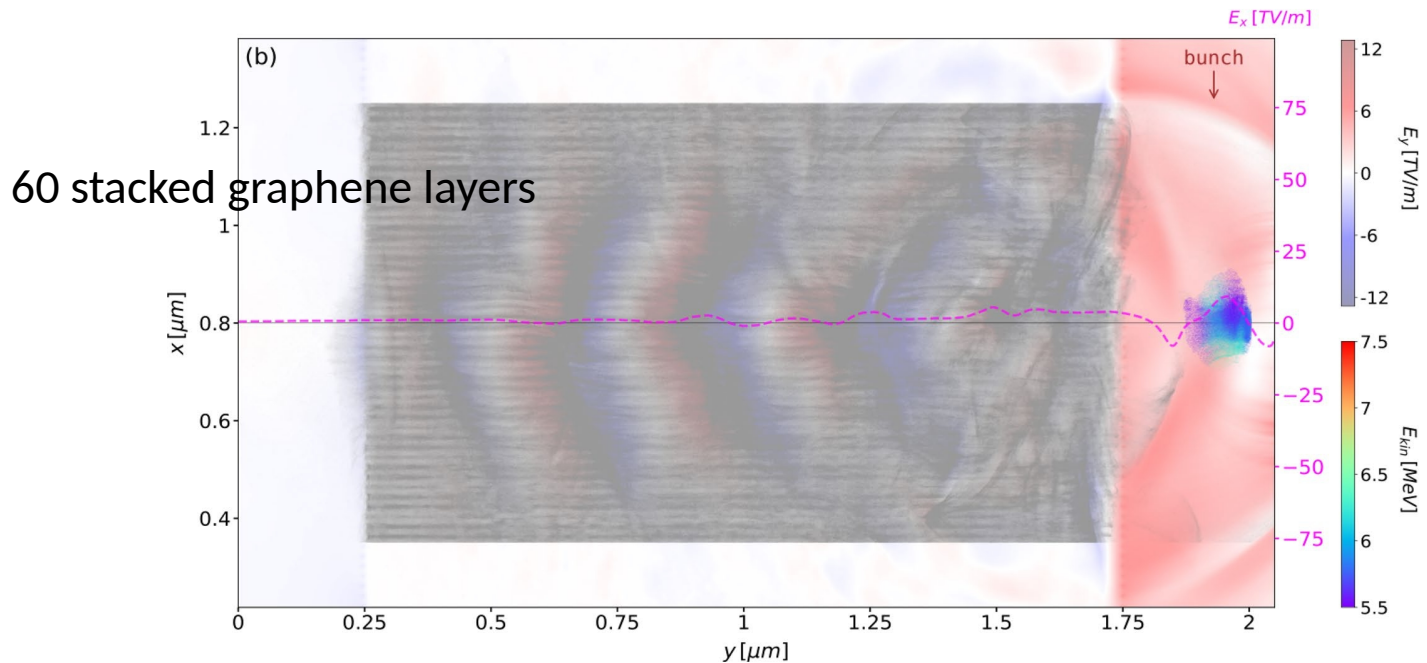


C. Bontoiu et al., Sci. Rep. **13** (2023) 1330

C. Bontoiu et al., Proc. of IPAC 2022

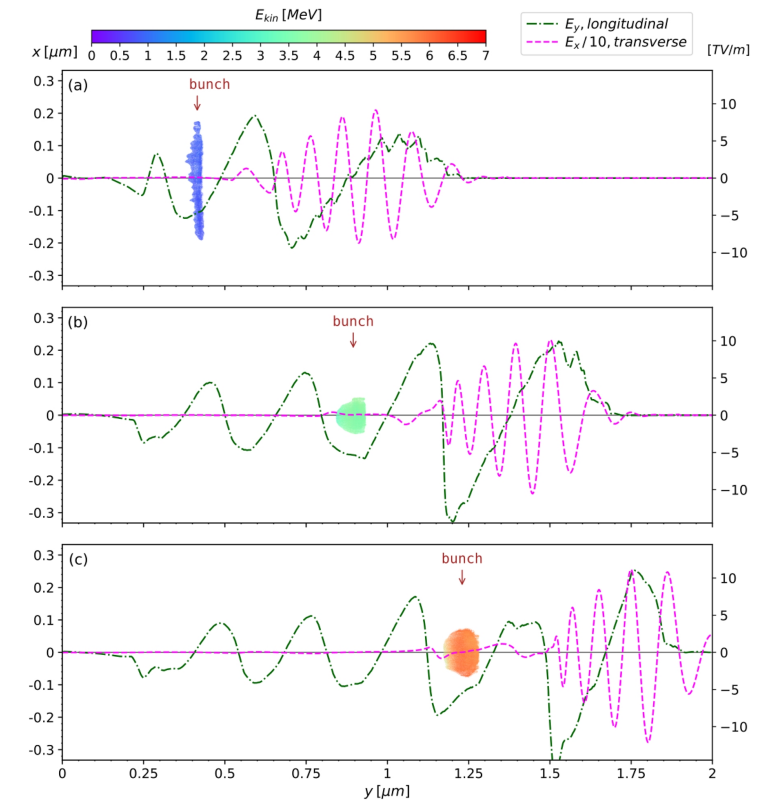
LWFA in graphene

TeV/m “Catapult” (ballistic) accelerator with graphene layers. PIC Simulations



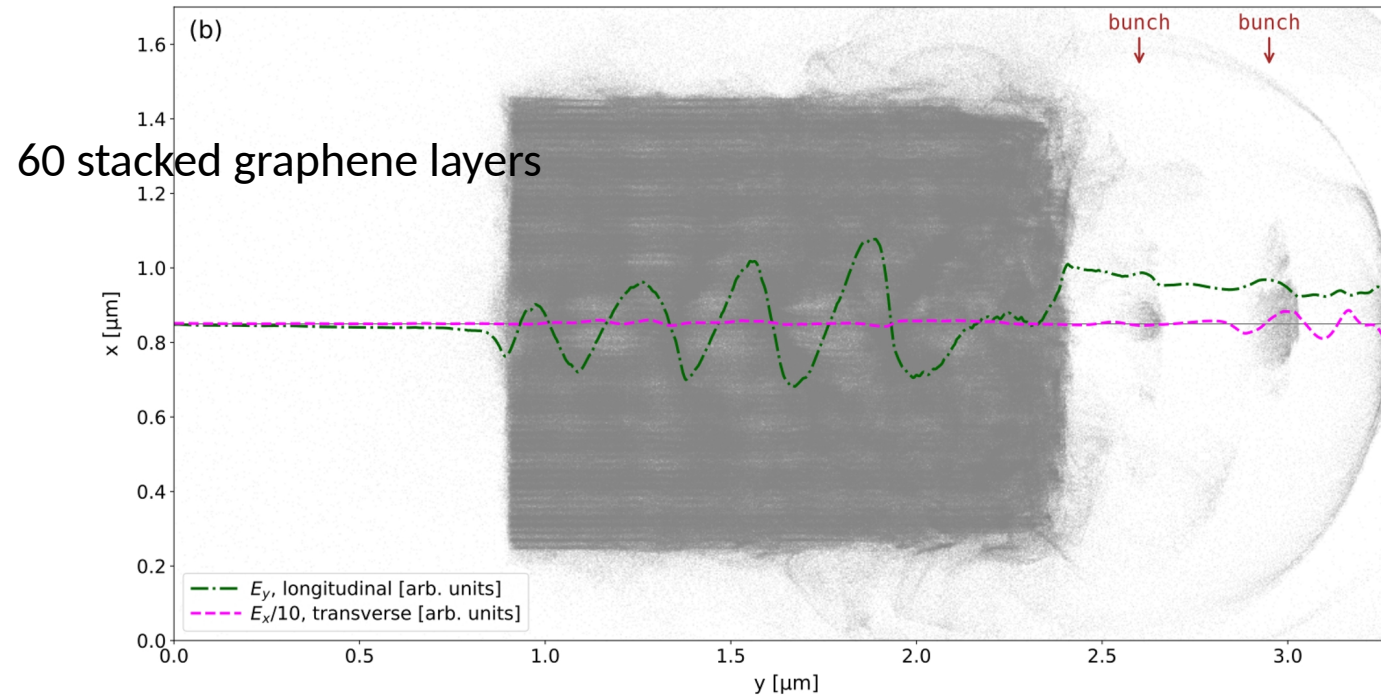
Ultra-short e-pulses, $\Delta t=0.21$ fs (FWHM)
 $\langle E_{kin} \rangle = 6$ MeV gain in $\sim 1 \mu\text{m}$
 $Q=2.55$ pC
RMS transverse emittance: 300 pm-rad

Wakefields, self-injected and accelerated bunch



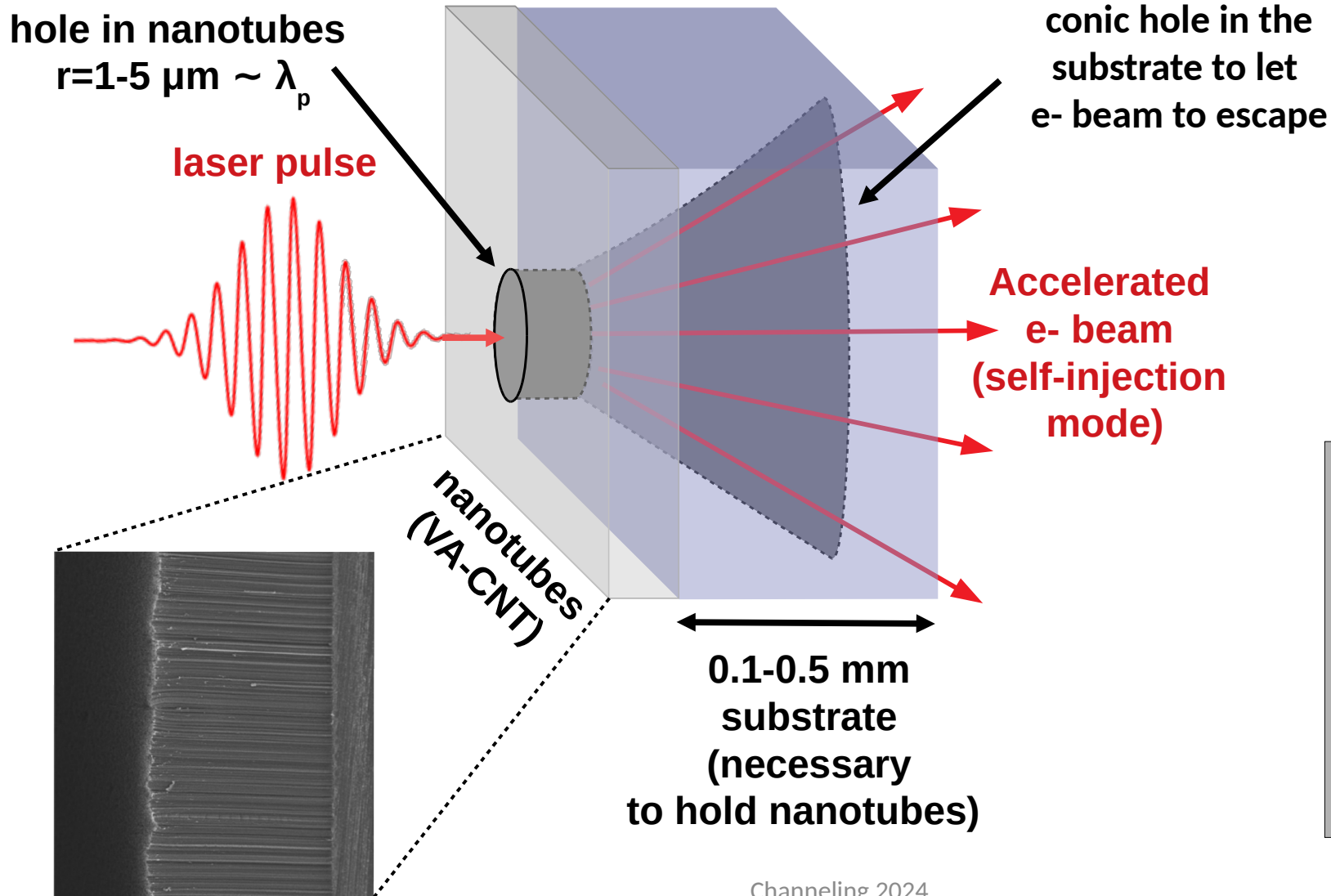
LWFA in graphene

TeV/m “Catapult” (ballistic) accelerator with graphene layers. PIC Simulations



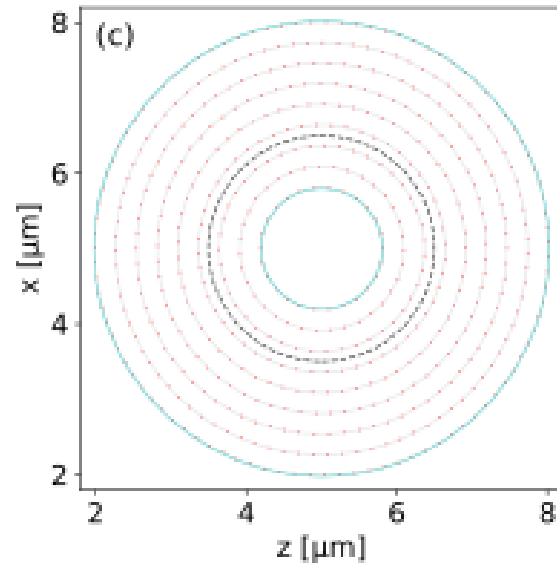
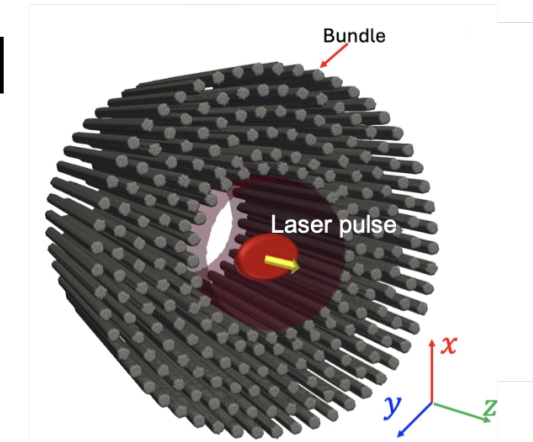
- Method to generate 1-10 MeV sub-femtosecond e-bunches
- Several bunches generated before the full damage of the structure (~ 100 fs)
- Potential application: injector in a staged accelerator or FEL?

Plasma acceleration in hollow vertically aligned carbon nanotubes: idea of a setup

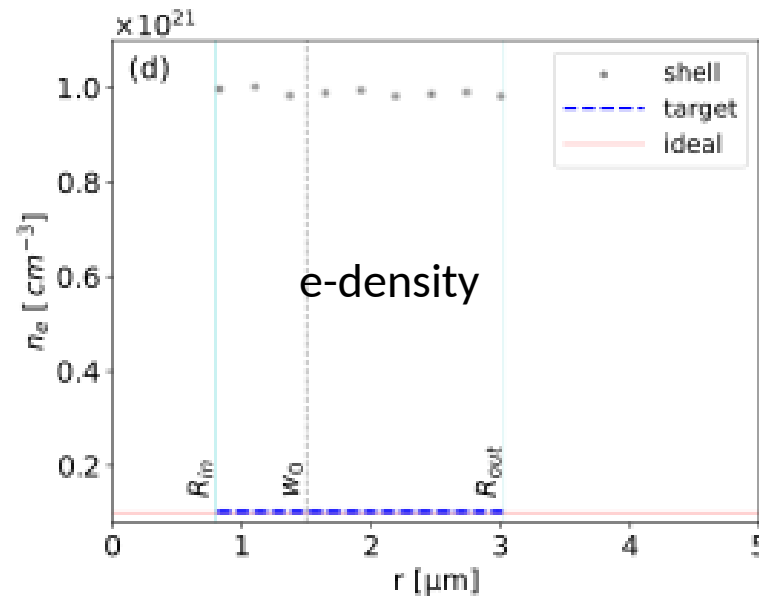


LWFA acceleration in CNT based

Aligned CNT bundles



9 shells with 546 CNT bundles (red points) concentrically aligned. Each red point contains 25 CNTs



Laser parameters (IR range)

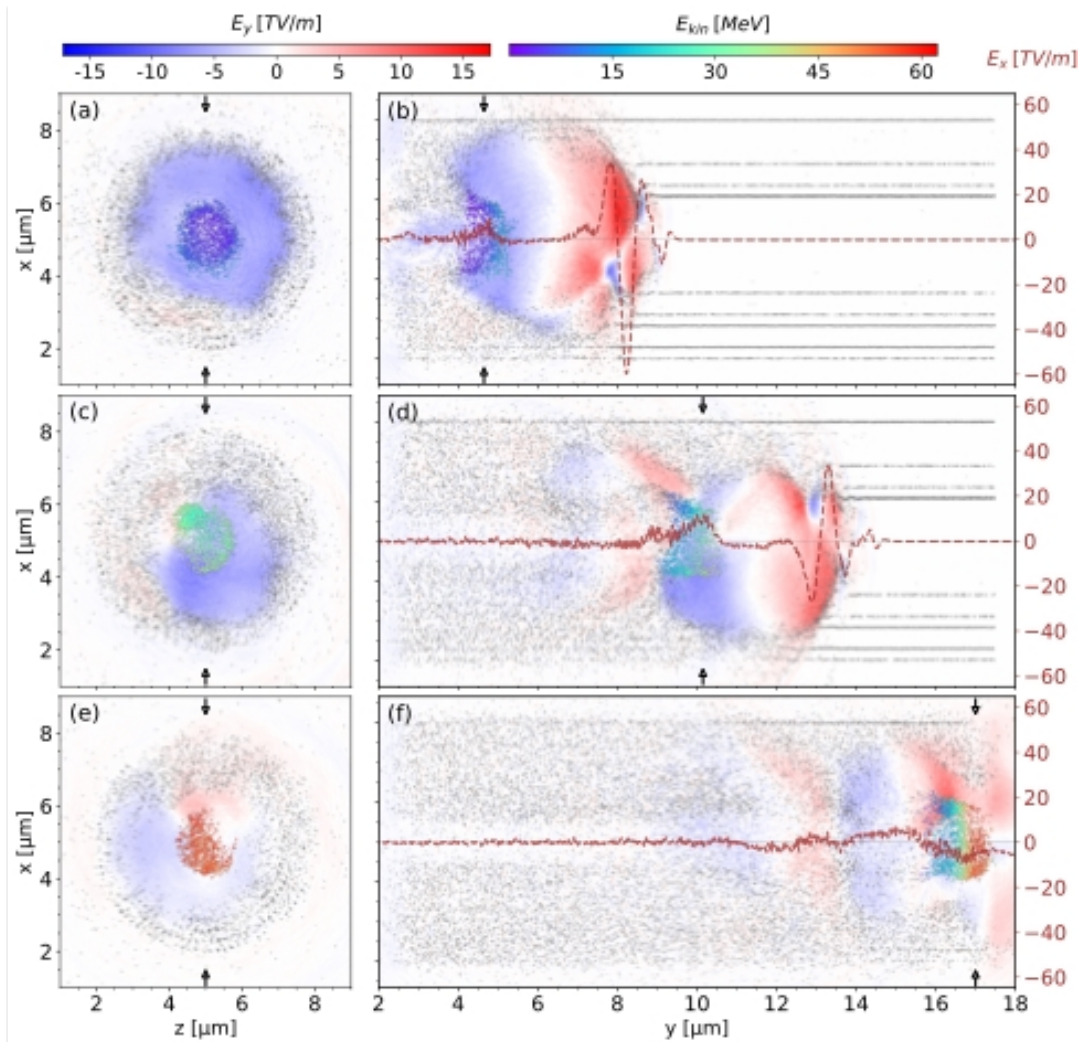
Parameter	Value	Unit
Wavelength, λ	800	nm
Period, T	2.66	fs
Energy, E	301	mJ
Peak Intensity, I_0	10^{21}	W/cm ²
Potential vector, a_0	21.6	-
Pulse Length, Δt	8	fs
Spot Size, w_0	1.5	μm

Parameters more relaxed than in the graphene multilayer case and **technologically feasible**

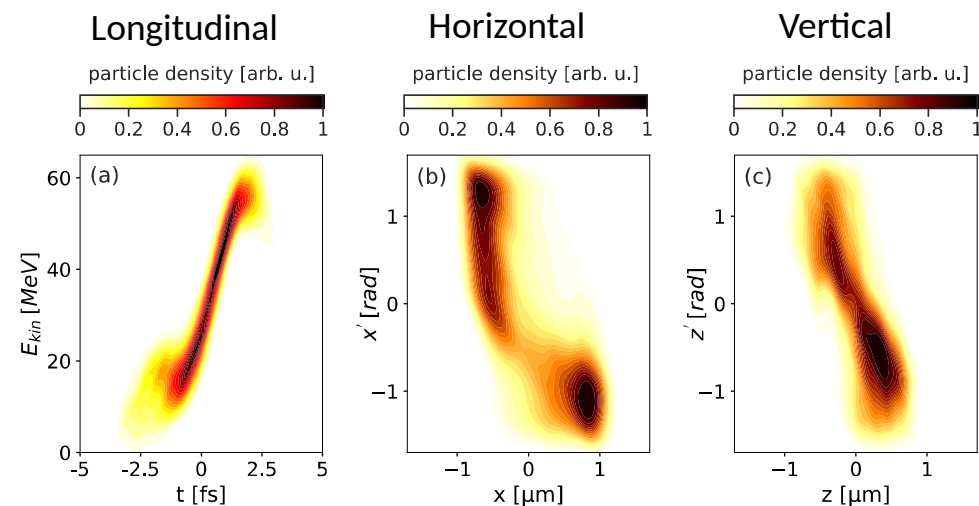
Cristian Bontoiu, PhD Thesis

LWFA acceleration in CNT based targets

Aligned CNT bundles. PConGPU simulations



Bunch phase space at extraction



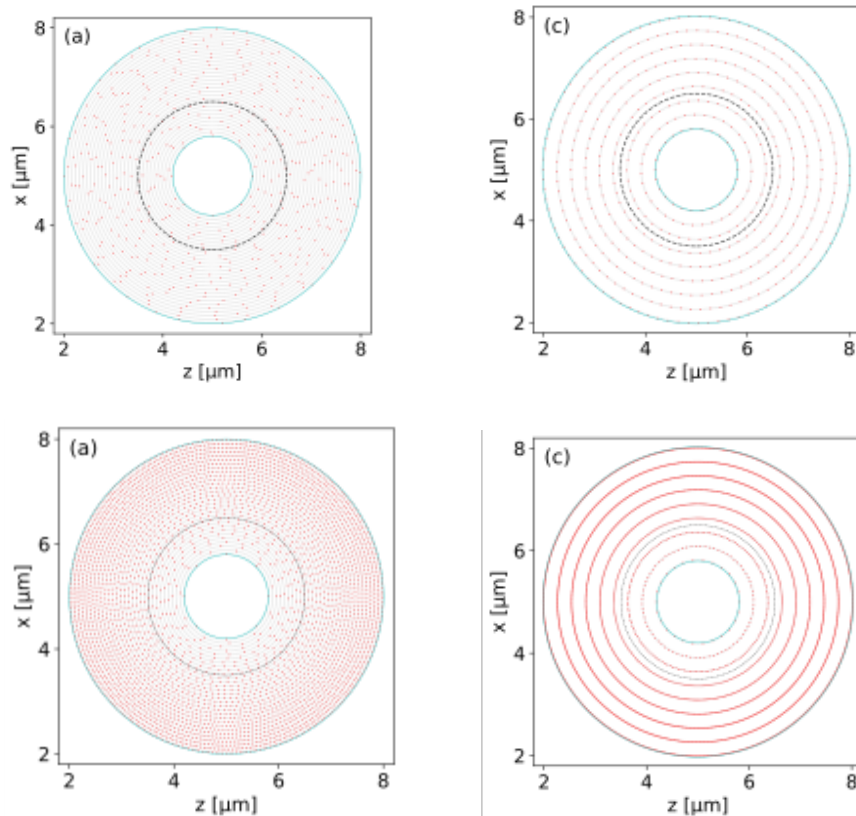
After 3 cycles ($\Delta t=8$ fs)

Ultra-short e-pulses, $\Delta t=3.8$ fs (FWHM)
 $\langle E_{kin} \rangle=31$ MeV gain in $\sim 17 \mu\text{m}$
 $Q=0.8$ nC
RMS vertical emittance: $0.4 \mu\text{m-rad}$
RMS horizontal emittance: $0.3 \mu\text{m-rad}$

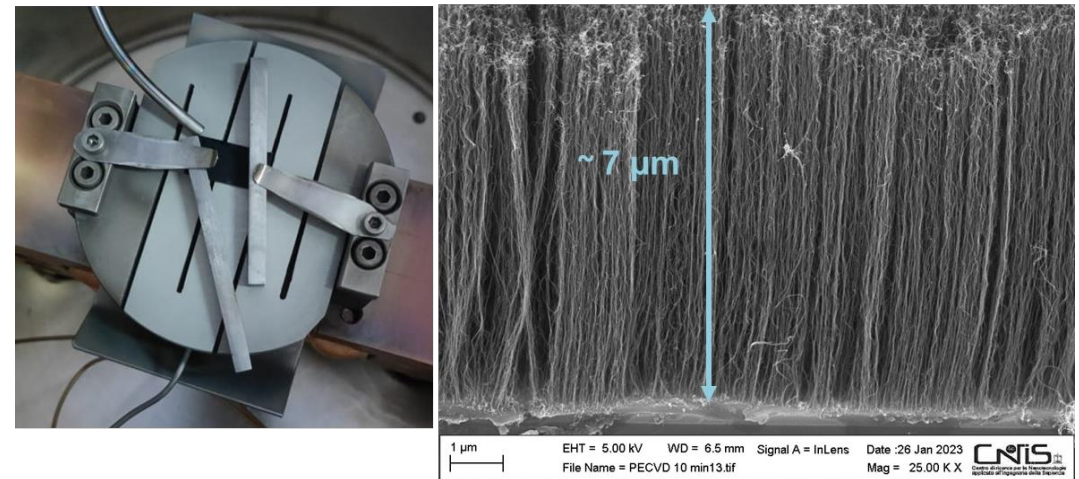
Nanotubes

The collaboration is currently preparing optimal targets for proof-of-principle experiment, investigating manufacturing techniques.

Investigation of different configurations



Example of Chemical Vapor Deposition (CVD) growth of CNT forest in the TITAN Lab at the INFN



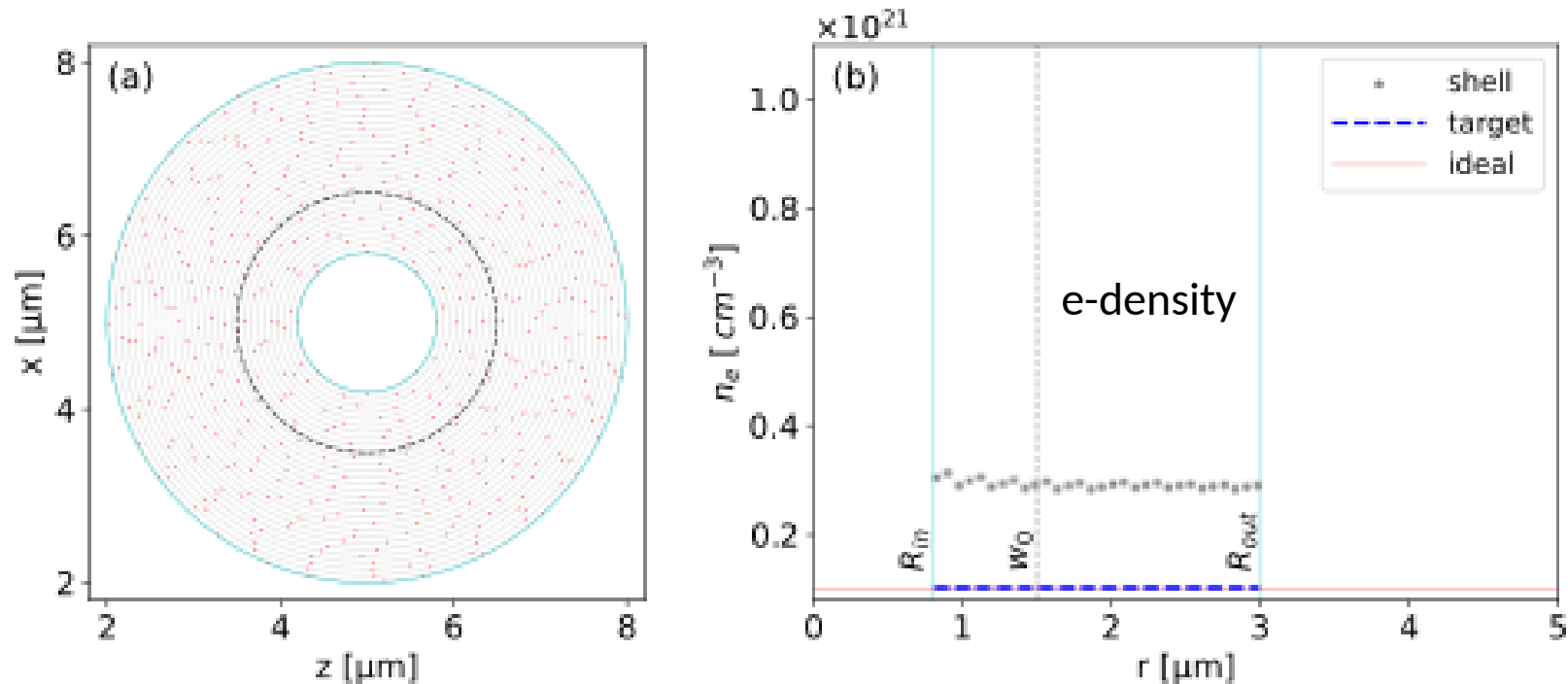
Ilaria Rago, Gianluca Cavoto et al.

*R.P. Yadav,..., G. Cavoto NIM A 1060, 169081 (2024)

LWFA acceleration in CNT based targets

Non-aligned CNT bundles

We found similar results with uniformly distributed targets of effective density $n_e \sim 10^{20} \text{ cm}^{-3}$

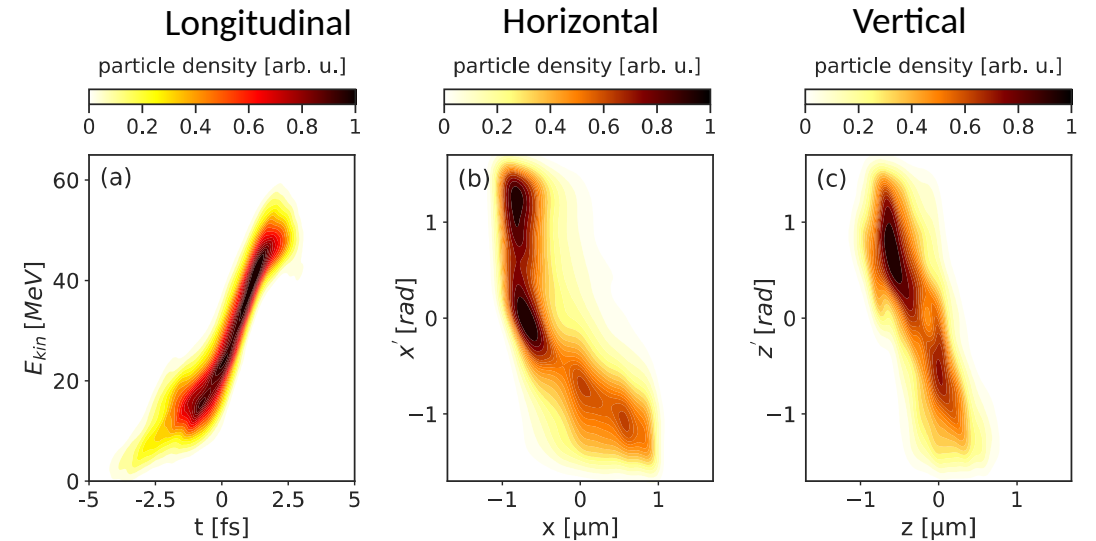
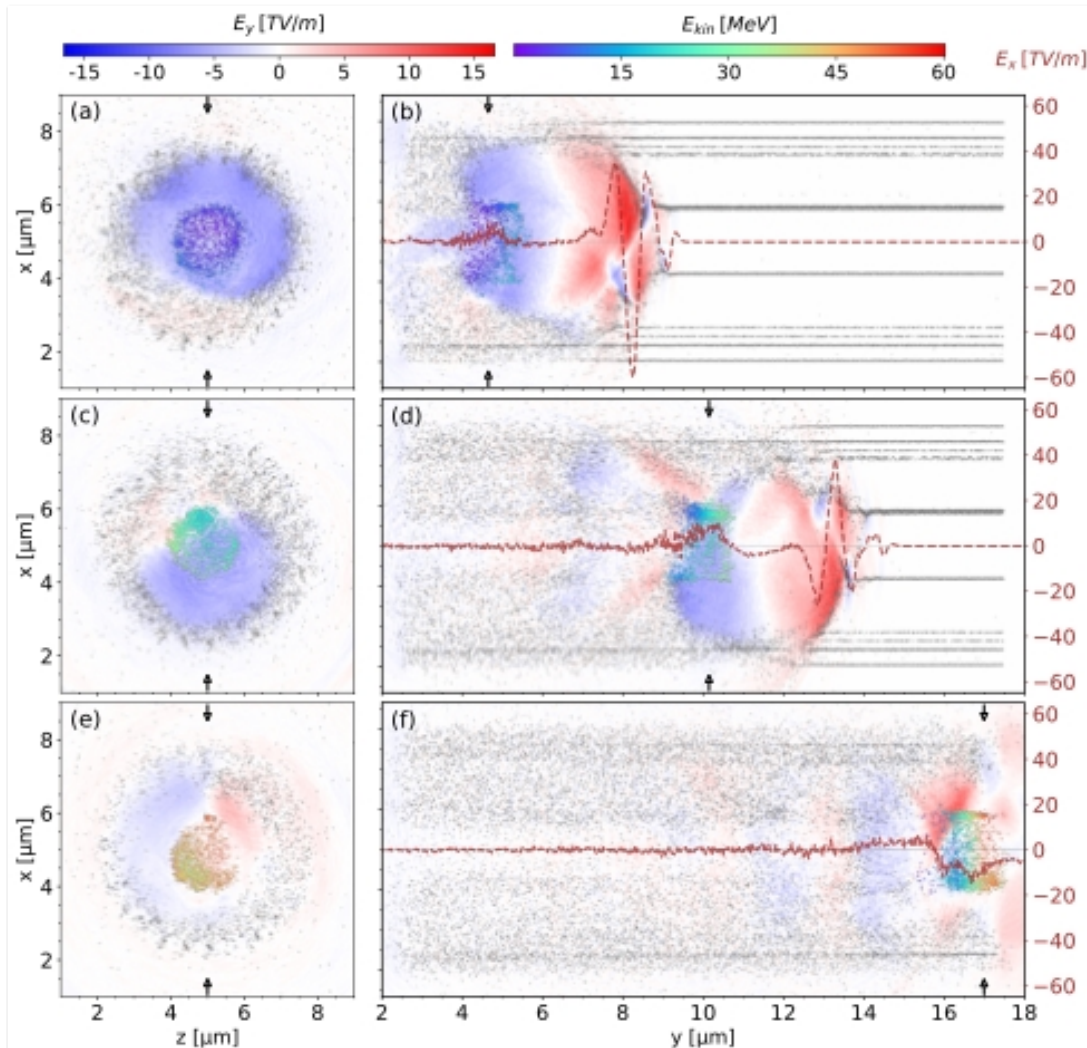


30 shells with 535 CNT bundles (red points) distributed uniformly

LWFA acceleration in CNT based targets

Non-aligned CNT bundles. PIconGPU simulations

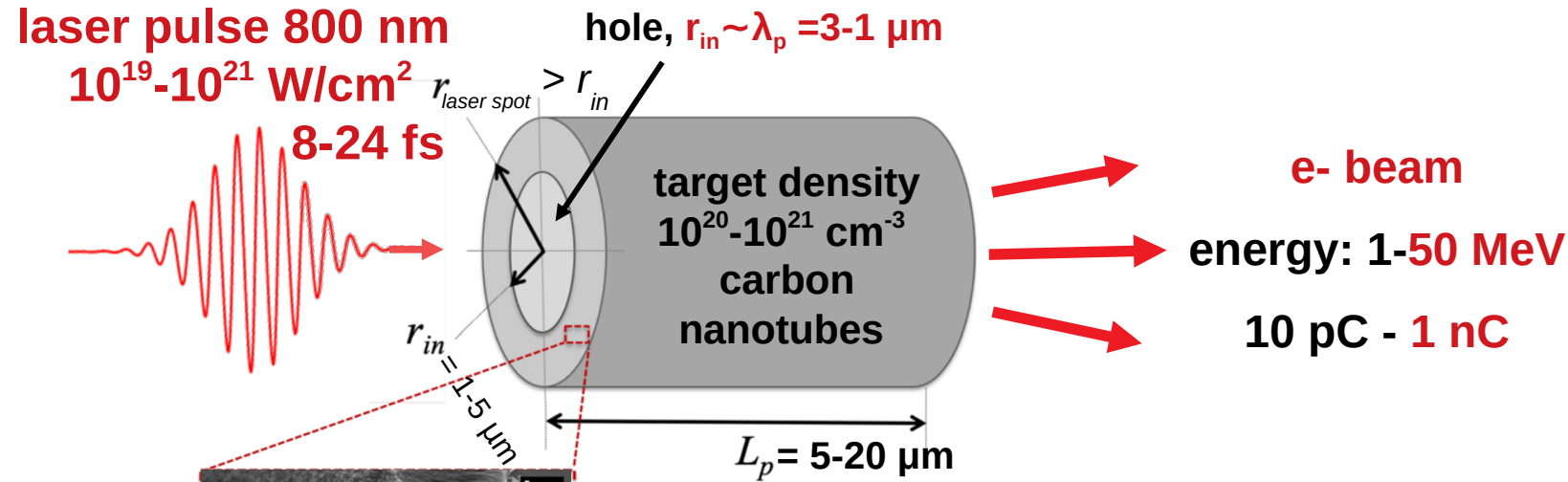
Bunch phase space at extraction



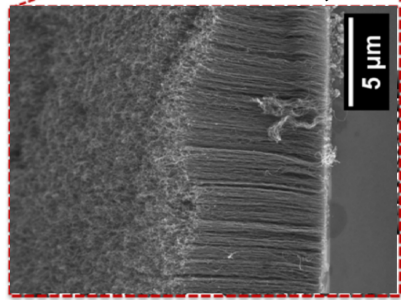
After 3 cycles ($\Delta t=8$ fs)

Ultra-short e-pulses, $\Delta t=3.8$ fs (FWHM)
 $\langle E_{kin} \rangle = 27.7$ MeV gain in $\sim 17 \mu\text{m}$
 $Q=0.8$ nC
 RMS vertical emittance: $0.4 \mu\text{m-rad}$
 RMS horizontal emittance: $0.25 \mu\text{m-rad}$

Idea of experimental setup



e- self-injection
 from the target



carbon nanotubes

acceleration
 gradient up to 2
 TeV/m

observables

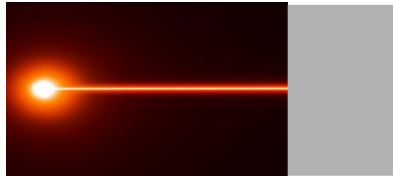
- e- beam
- betatron radiation

Laser facility list:

- FLAME (Frascati) 10^{20} W/cm^2
- I-LUCE (INFN LNS, to be installed) 10^{21} W/cm^2
- Alternatively:
- ELIMAIA-ELIMED (ELI) $3 \cdot 10^{21} \text{ W/cm}^2$

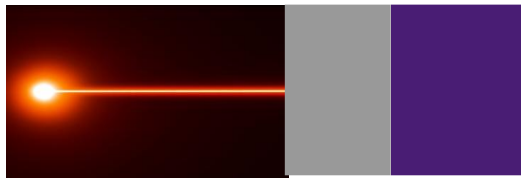
Potential applications

Laser target



1 nC, peak energy 20 MeV
e- beam source

Accelerators &
light sources



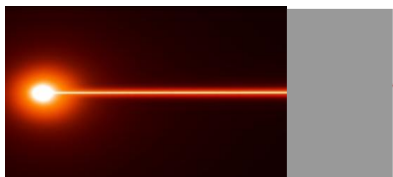
X-, γ -rays (bremsstrahlung);
positron source

W
target

Radiation
damage

mirror

Compton
scattering



Radiation
therapy

Imaging

NanoAcc collaboration

Towards an experimental test of LWFA in CNT based structures

University of Valencia, Spain: Javier Resta-López, Pablo Martín-Luna, Juan Rodríguez-Pérez

Centro de Láseres Pulsados (CLPU), Salamanca, Spain: Giancarlo Gatti

Federal University of Health Sciences of Porto alegre, Brazil: Alexandre Bonatto

CI and University of Manchester, UK: Oznur Apsimon, Guoxing Xia, Jiaqi Zhang

CI and University of Liverpool, UK: Bifeng Lei, Carsten P. Welsch

INFN, Ferrara: Laura Bandiera, Alexei Sytov

INFN, Milano: Illya Drebot

INFN, Roma: Ilaria Rago

Sapienza University of Rome, Italy: Gianluca Cavoto, Ravi Prakash Yadav

National Technical University of Athens, Greece: Konstantinos Valagiannopoulos

CERN, Switzerland: Volodymyr Rodin

Still open to new collaborators

NanoAc 2024

Second workshop focused on
“Application of Nanostructures in the
field of Accelerator Physics”

Invited speakers:

Sultan Dabagov (INFN, Italy)

Giancarlo Gatti (CLPU, Spain)

Jorge Vieira (IST, Portugal)

Frank Zimmermann (CERN, CH)

Now open for registration and
contributions

<https://forum.icmuv.uv.es/event/3/>



The poster for NanoAc 2024 features a black background with white and yellow text. At the top left is the NOVAS logo (a cluster of six circles) and the text 'NOVAS'. At the top right is the 'Gen=I' logo. The main title 'NanoAc 2024' is in large white font. Below it, the subtitle 'Second Workshop on Application of Nanostructures in Accelerator Physics' is in smaller white font. The dates 'Dates: 17 – 18 September 2024' and the venue 'Venue: ICMUV – University of Valencia, Parc Científic, Valencia, Spain' are listed. A central image shows a 3D molecular structure of a nanostar. To its right is a list of topics with checkboxes. Below the topics is the 'Co-chairs' section with names and affiliations. At the bottom, there is a photograph of the ICMUV building at night, a URL, and logos for ICMUV, the University of Valencia, and the Generalitat Valenciana.

NOVAS

NanoAc 2024 **Gen=I**

Second Workshop on Application of Nanostructures in Accelerator Physics

Dates: 17 – 18 September 2024

Venue: ICMUV – University of Valencia, Parc Científic, Valencia, Spain

Topics

- Plasmonic particle acceleration
- Solid-state wakefield plasma acceleration
- Particle channelling in CNTs and crystals
- CNT-based cathodes
- Beam diagnostics based on nanomaterials
- X-ray sources based on nanomaterials
- Simulations of nanostructured plasmas

Co-chairs

Laura Bandiera (INFN, Sezione di Ferrara, Italy)
Alexandre Bonatto (UFCSPA, Porto Alegre, Brazil)
Cristian Bontoiu (Cockcroft Institute, University of Liverpool, UK)
Pablo Martín-Luna (IFIC, University of Valencia-CSIC, Spain)
Javier Resta-López (ICMUV-University of Valencia, Spain)
Guoxing Xia (Cockcroft Institute, University of Manchester, UK)

<https://forum.icmuv.uv.es/event/3/>

ICMUV
INSTITUT DE CIÈNCIA
DELS MATERIALS de la
Universitat de València

**VNIVERSITAT
D' VALÈNCIA**

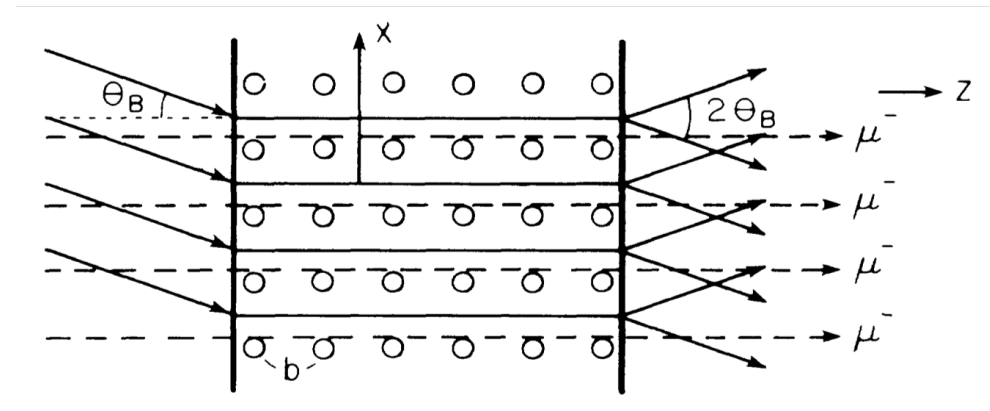
**GENERALITAT
VALENCIANA**
Conselleria de Educació,
Universitats y Empleo



Thank you for attention!

Acceleration in solid-state structures. The beginning

Crystal channeling acceleration



T. Tajima and M. Cavenago, PRL 59 (1987) 1440

- Accelerating fields $\sim 1-100$ TV/m
- Channelled particles confined to the rows of atoms by electric fields of the order of $10-100$ GV/m
- Crystals excited by ultra-short X-ray pulses. Laser power \sim TW or PW
- Crystals have been used in accelerators as collimators and bending elements

Very challenging!