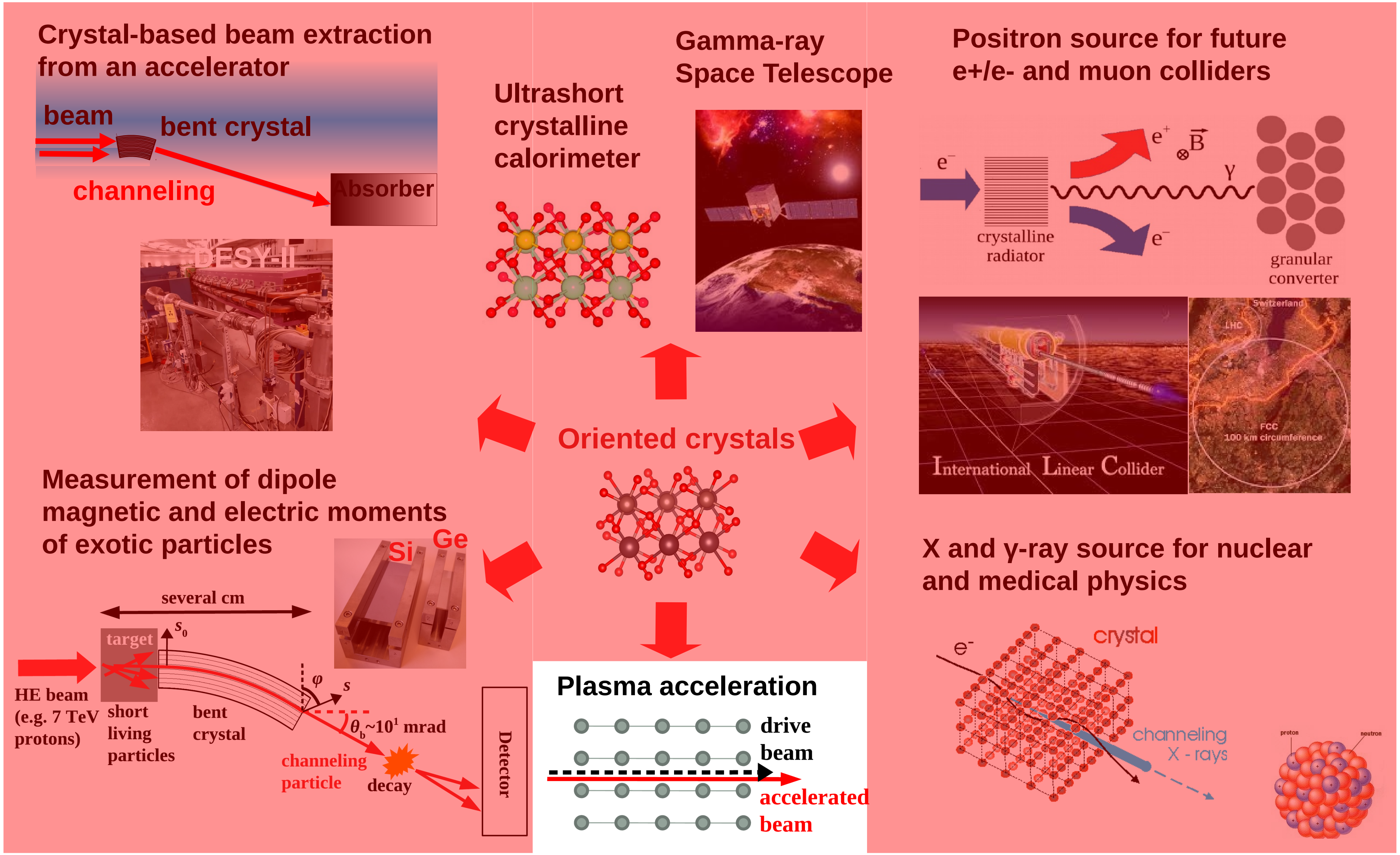
Ultra-high acceleration gradient using structured nanomaterials

Alexei Sytov and J. Resta-López

on behalf of the NanoAcc collaboration

Channeling 2024
8-13 September 2024

Applications



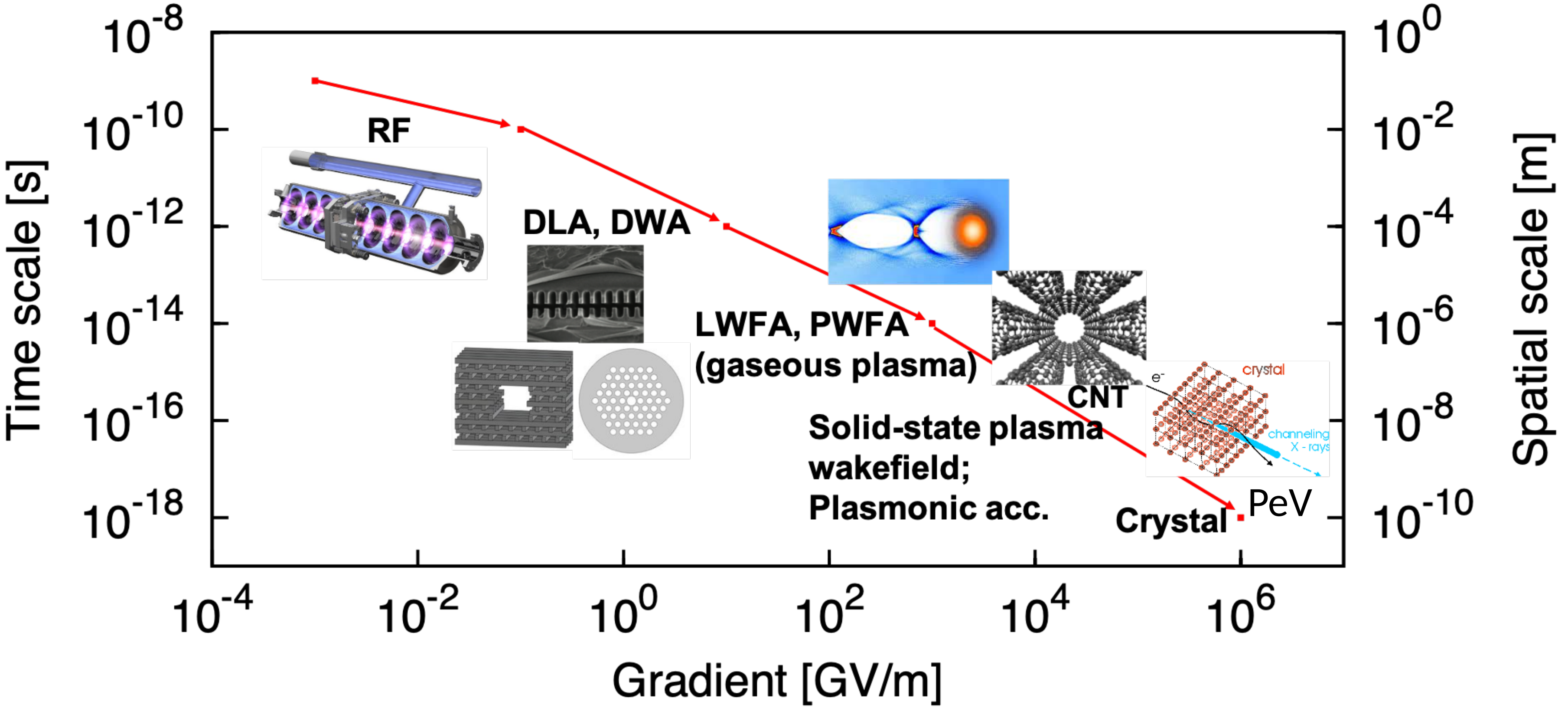
High-acceleration gradient. Novel concepts

- Towards more compact and sustainable accelerators

Acceleration gradient*

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

Scale of the oscillations, dimension of drivers



Challenges and solutions of WFA in solids

stability

multiple scattering

radiation damage of the target

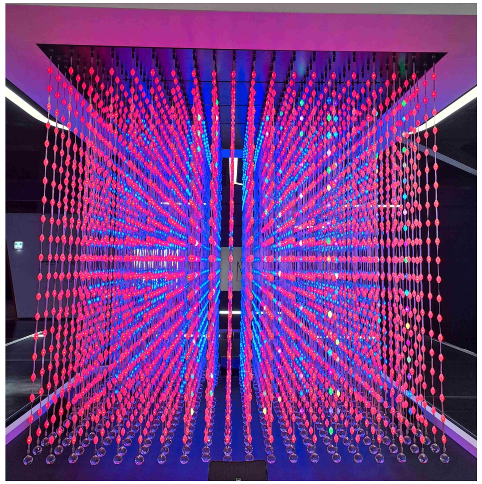
drive beam size vs plasma wavelength λ_p

energy distribution

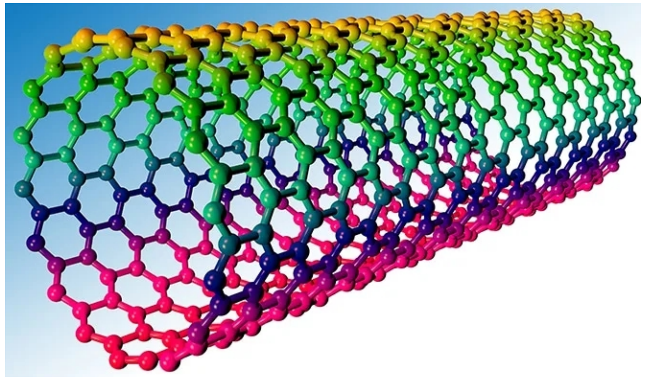
beam emittance

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

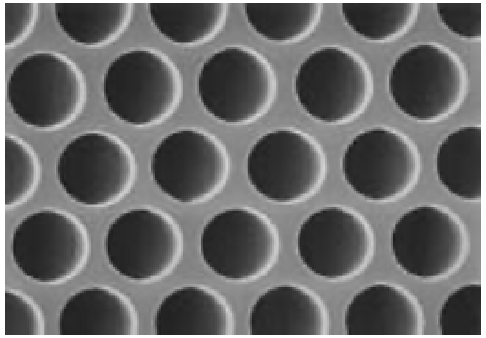
Oriented crystals



Nanotubes

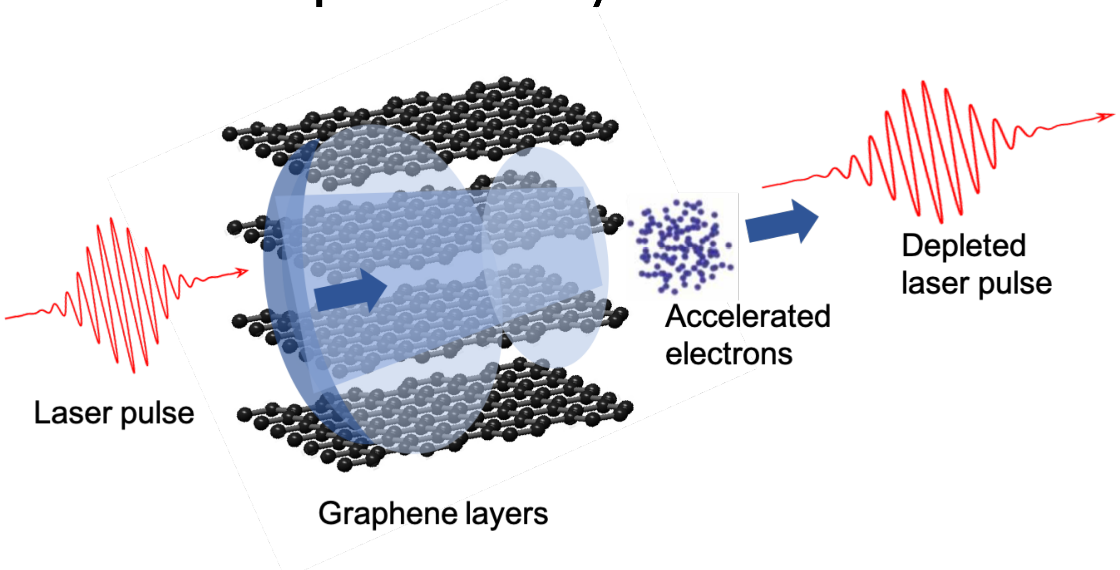


Structured solids

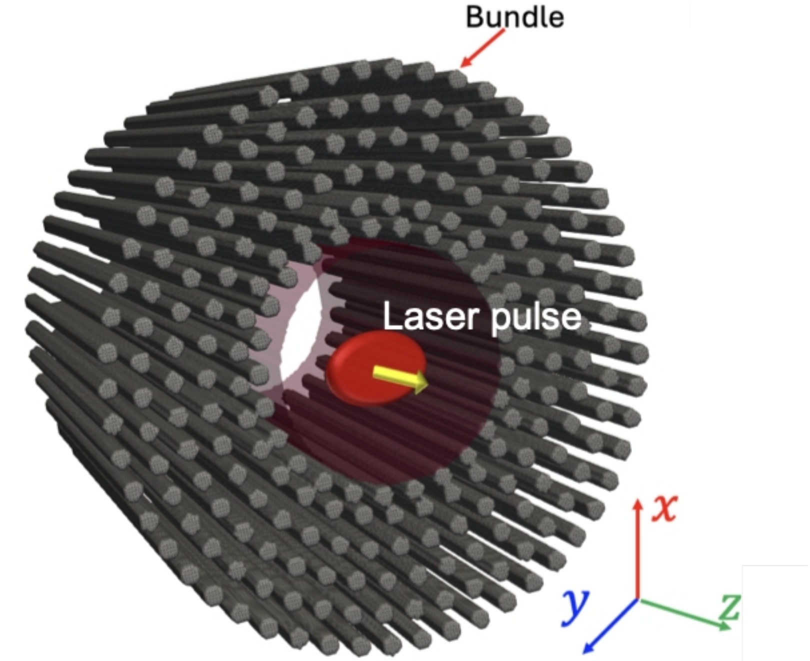


LWFA in graphene and CNT based structures

Graphene multilayer



CNT arrays

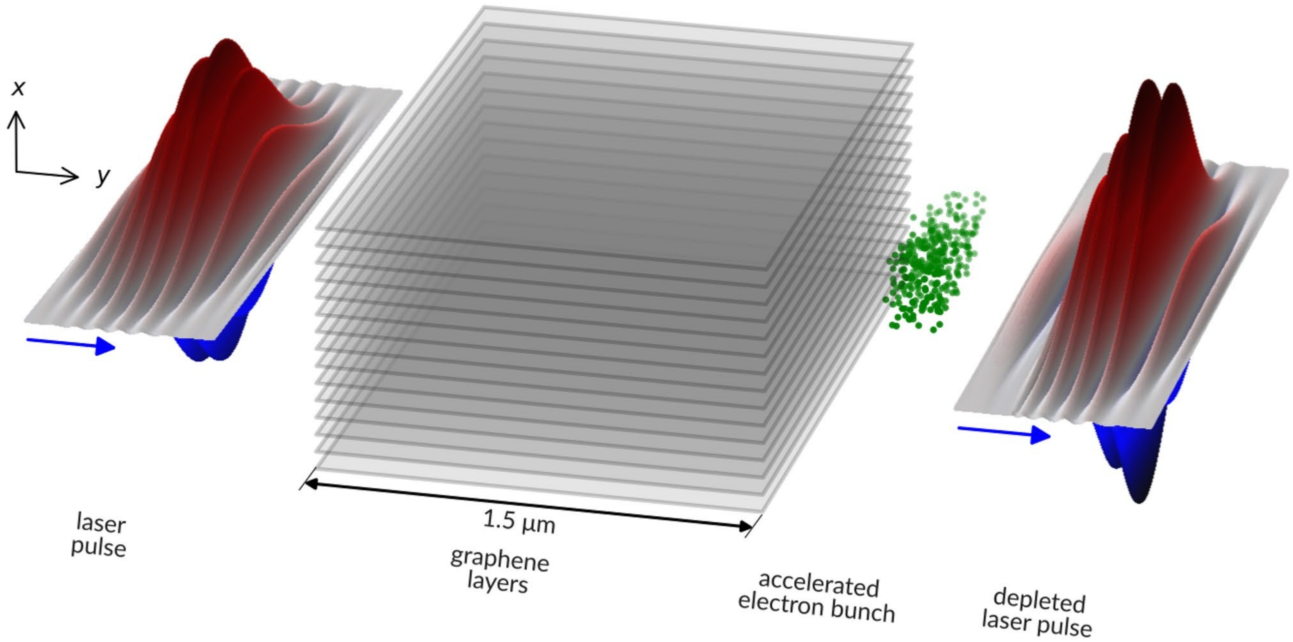


Why graphene and CNTs?

- 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} cm^{-3}).
- Advances in nanofabrication techniques. Flexibility to fabricate interesting geometries.
- High thermal and mechanical robustness
  - Melting point of a freestanding single-tip CNT ~ 3000 – 4000 K.
  - Tensile strength > 100 GPa (100 x Stainless steel).
- Hollow structures that allow good laser transmission.

LWFA in graphene

TeV/m "Catapult" (ballistic) accelerator with graphene layers

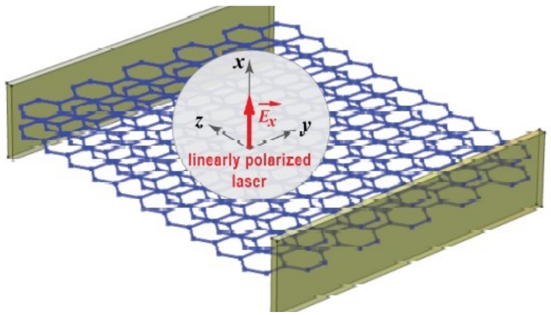


Laser parameters. UV range

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

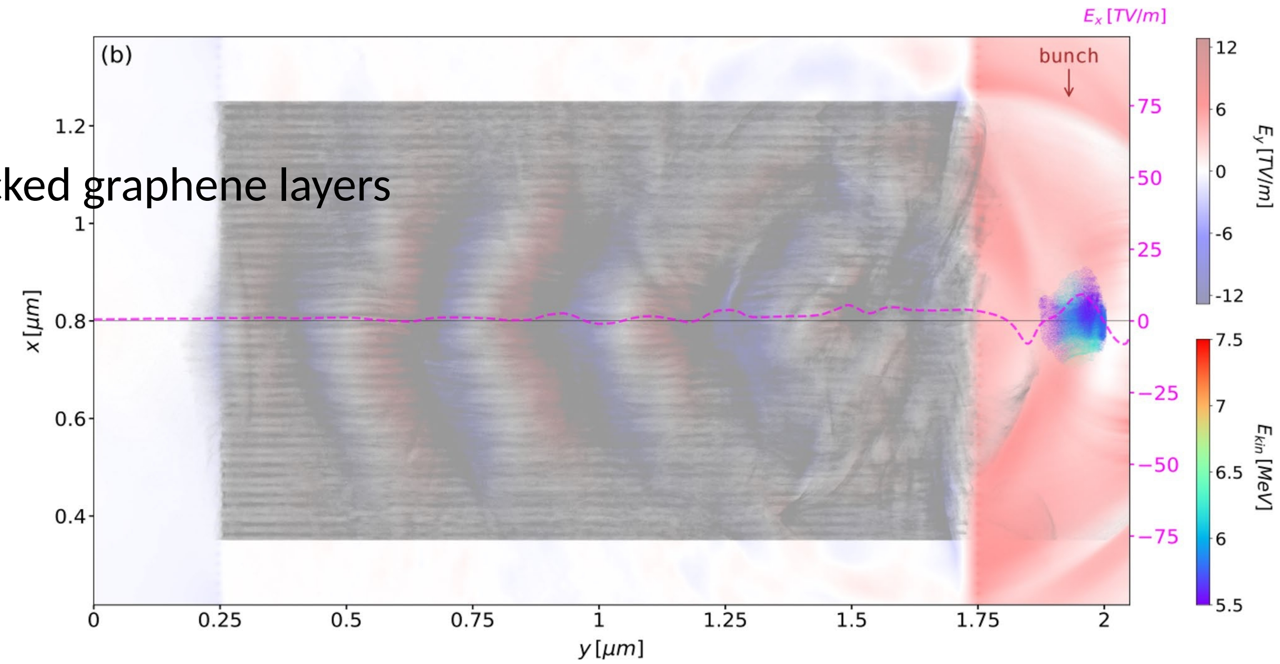


C. Bontoiu et al., Sci. Rep. **13** (2023) 1330
C. Bontoiu et al., Proc. of IPAC 2022

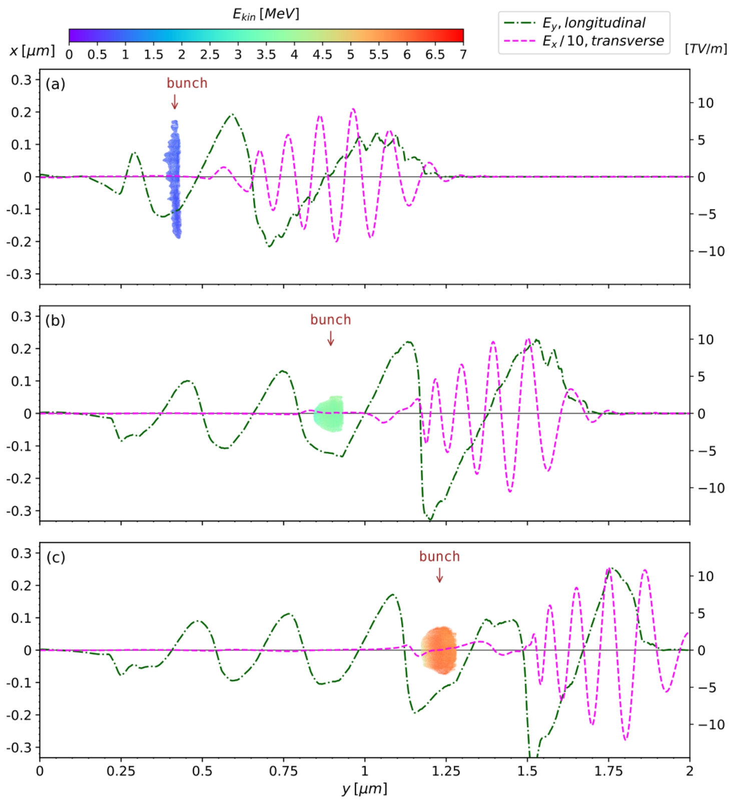
LWFA in graphene

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

60 stacked graphene layers



Wakefields, self-injected and accelerated bunch

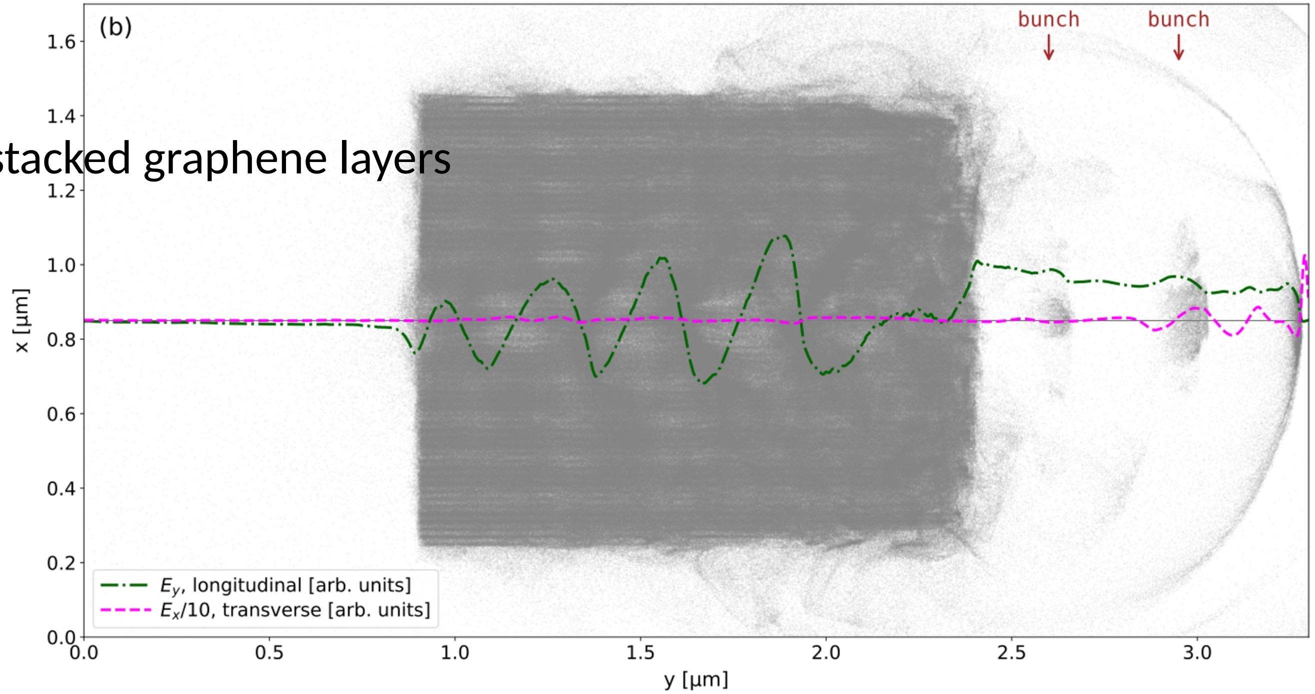


Ultra-short e-pulses, Δt=0.21 fs (FWHM)
<E_{kin}>=6 MeV gain in ~ 1 μm
Q=2.55 pC
RMS transverse emittance: 300 pm-rad

LWFA in graphene

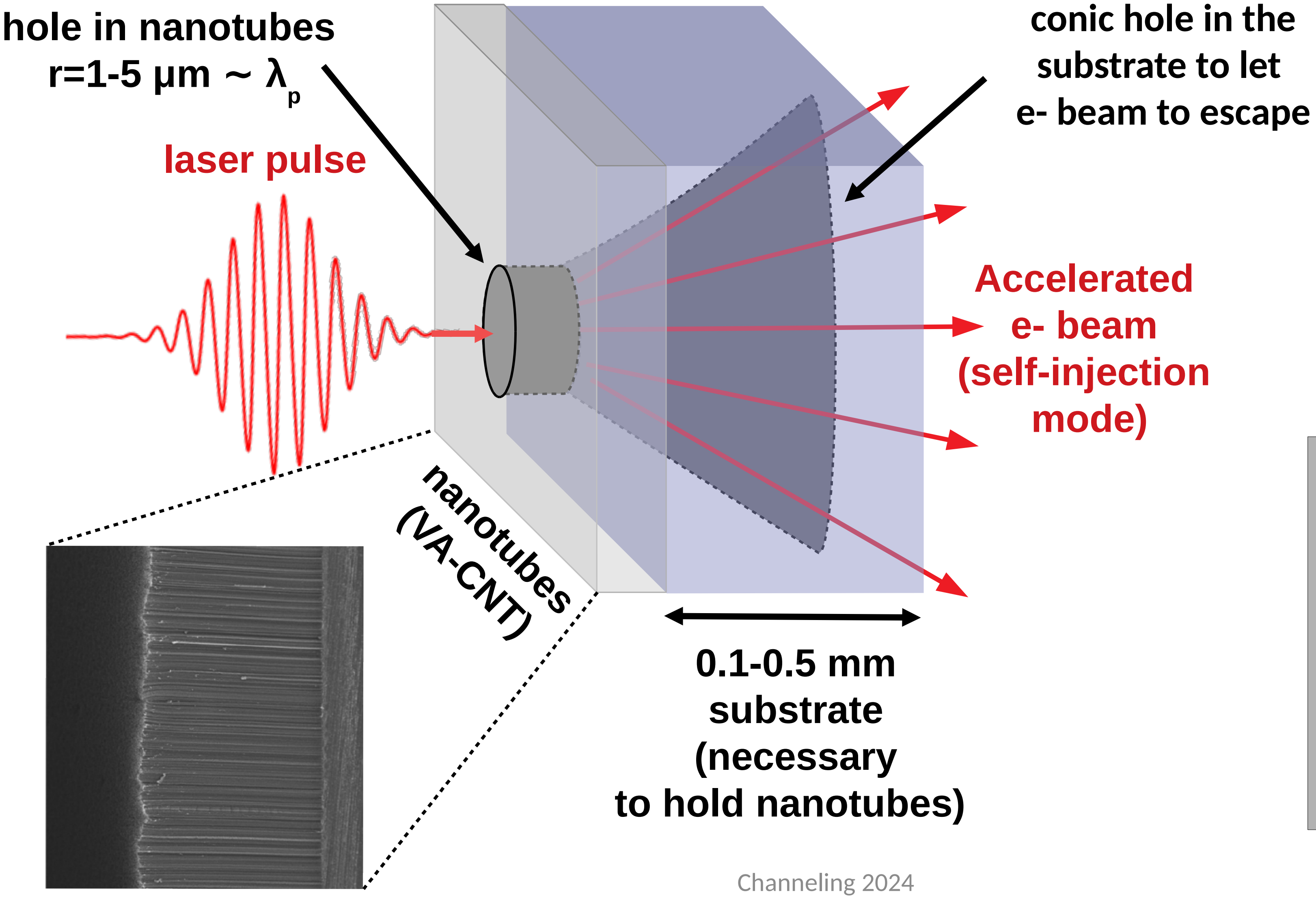
TeV/m "Catapult" (ballistic) accelerator with graphene layers. PIC Simulations

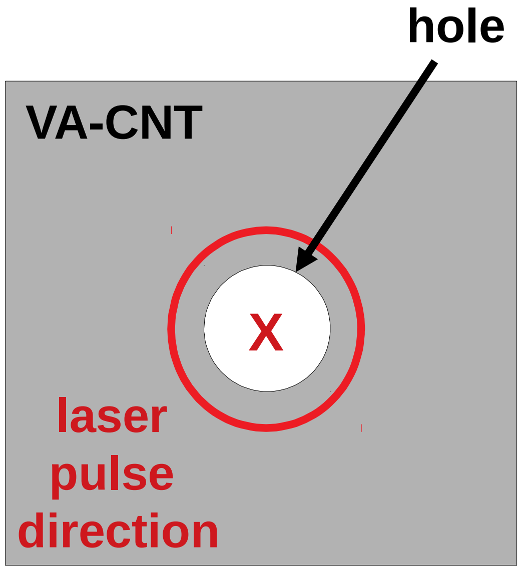
60 stacked graphene layers



- 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?

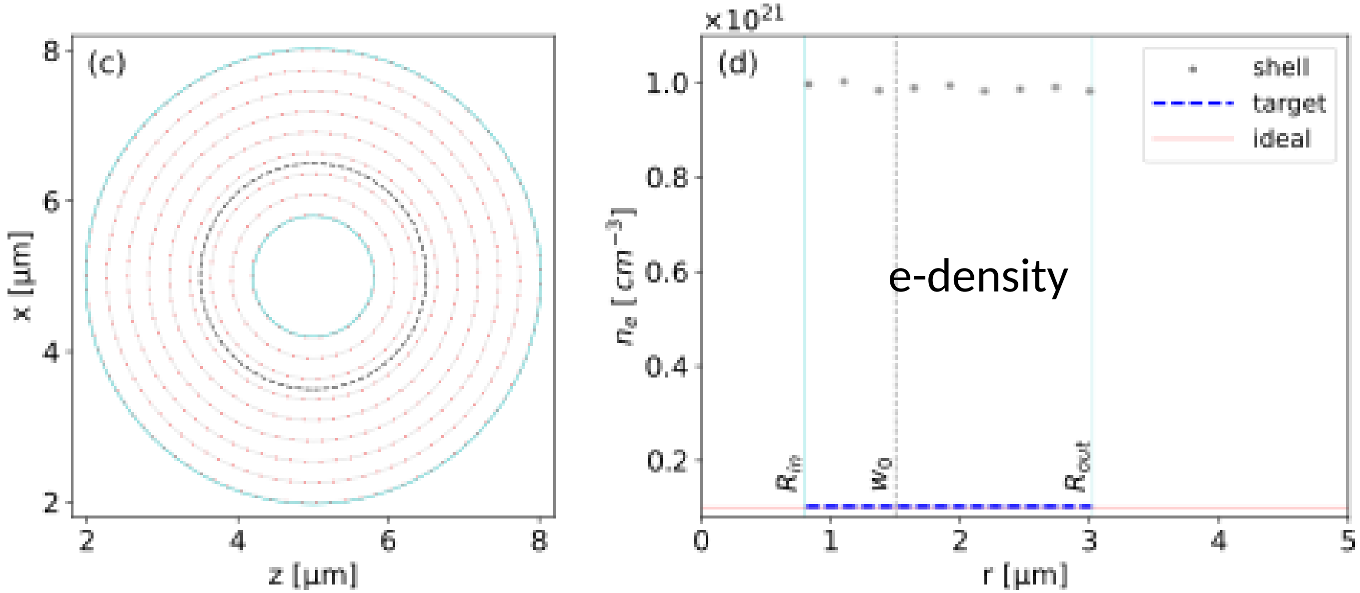
Plasma acceleration in hollow vertically aligned carbon nanotubes: idea of a setup

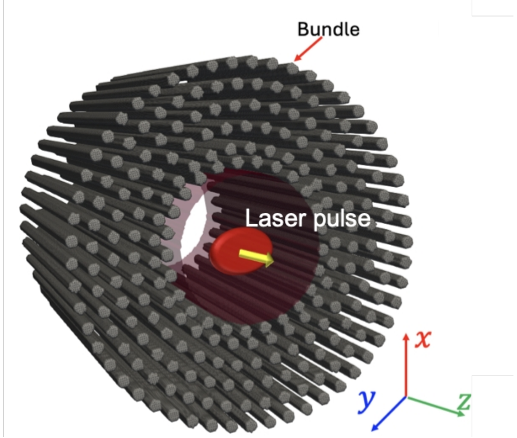




LWFA acceleration in CNT based

Aligned CNT bundles





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

Laser parameters (IR range)

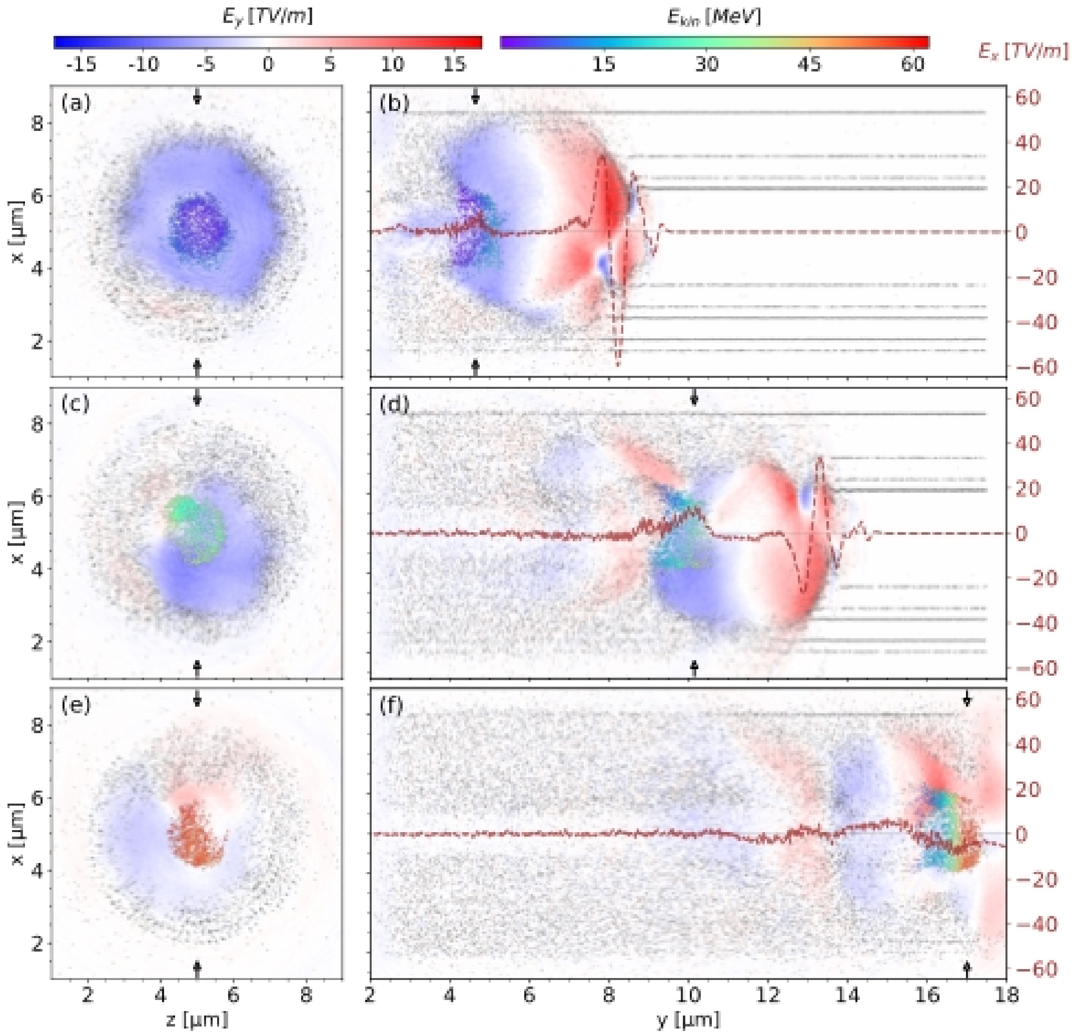
Parameter	Value	Unit
Wavelength, λ	800	nm
Period, T	2.66	fs
Energy, E	301	mJ
Peak Intensity, I_0	10^{21}	W/cm^2
Potential vector, a_0	21.6	-
Pulse Length, Δt	8	fs
Spot Size, w_0	1.5	μm

Cristian Bontoiu, PhD Thesis

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

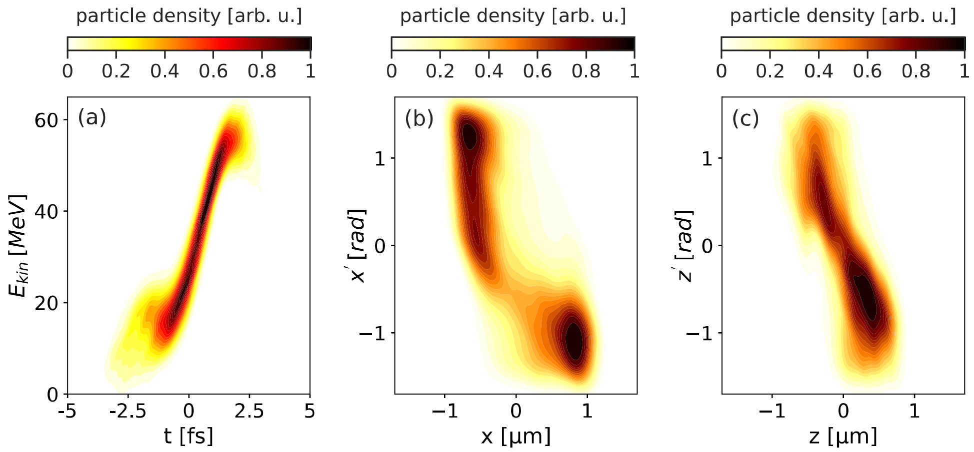
LWFA acceleration in CNT based targets

Aligned CNT bundles. PIConGPU simulations



Bunch phase space at extraction

Longitudinal | Horizontal | Vertical



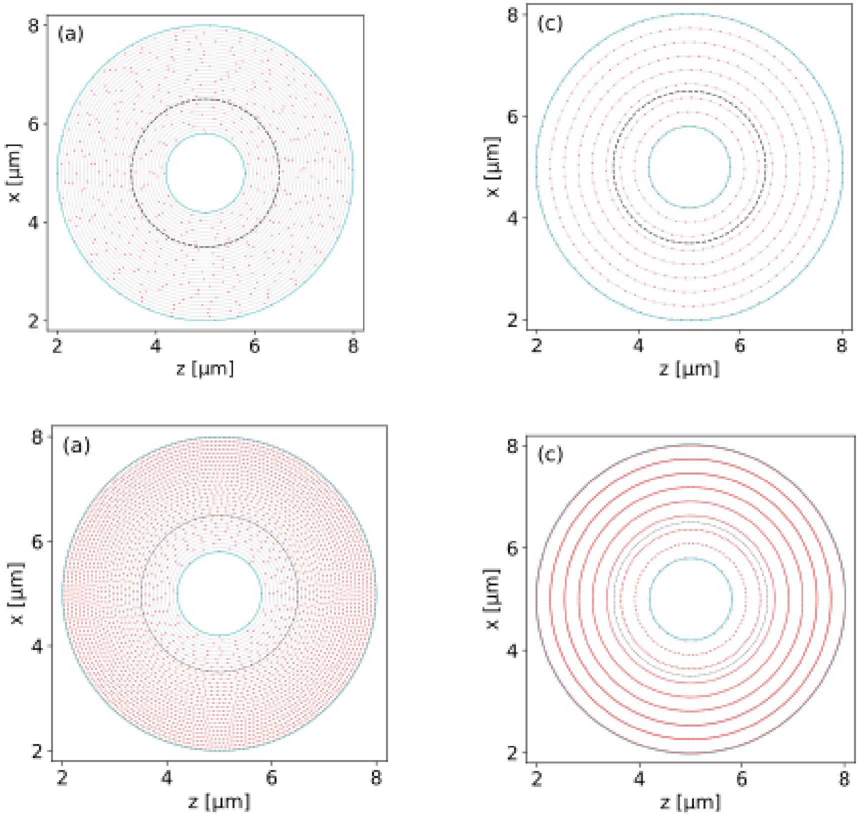
After 3 cycles (Δt=8 fs)

Ultra-short e-pulses, Δt=3.8 fs (FWHM)
<E_{kin} >=31 MeV gain in ~ 17 μm
Q=0.8 nC
RMS vertical emittance: 0.4 μm-rad
RMS horizontal emittance: 0.3 μm-rad

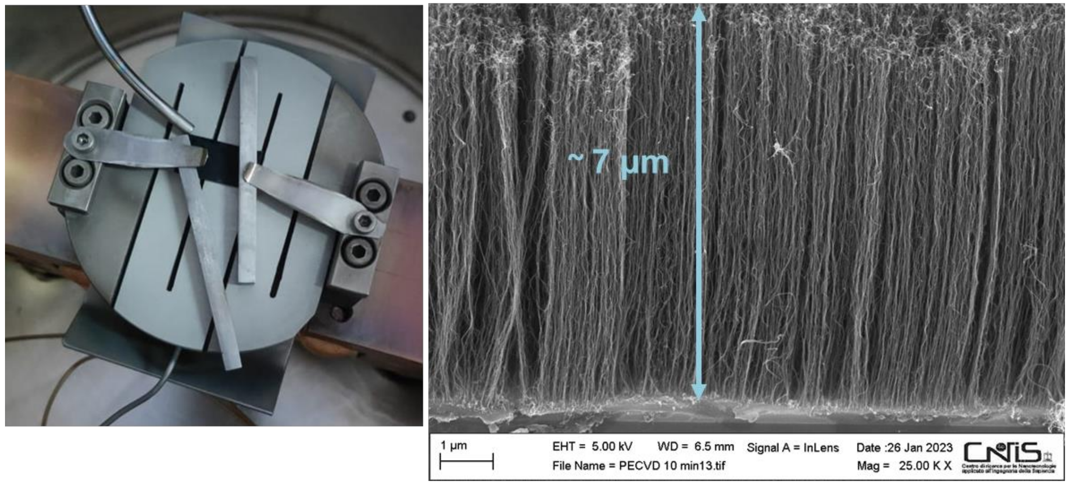
Nanotubes

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



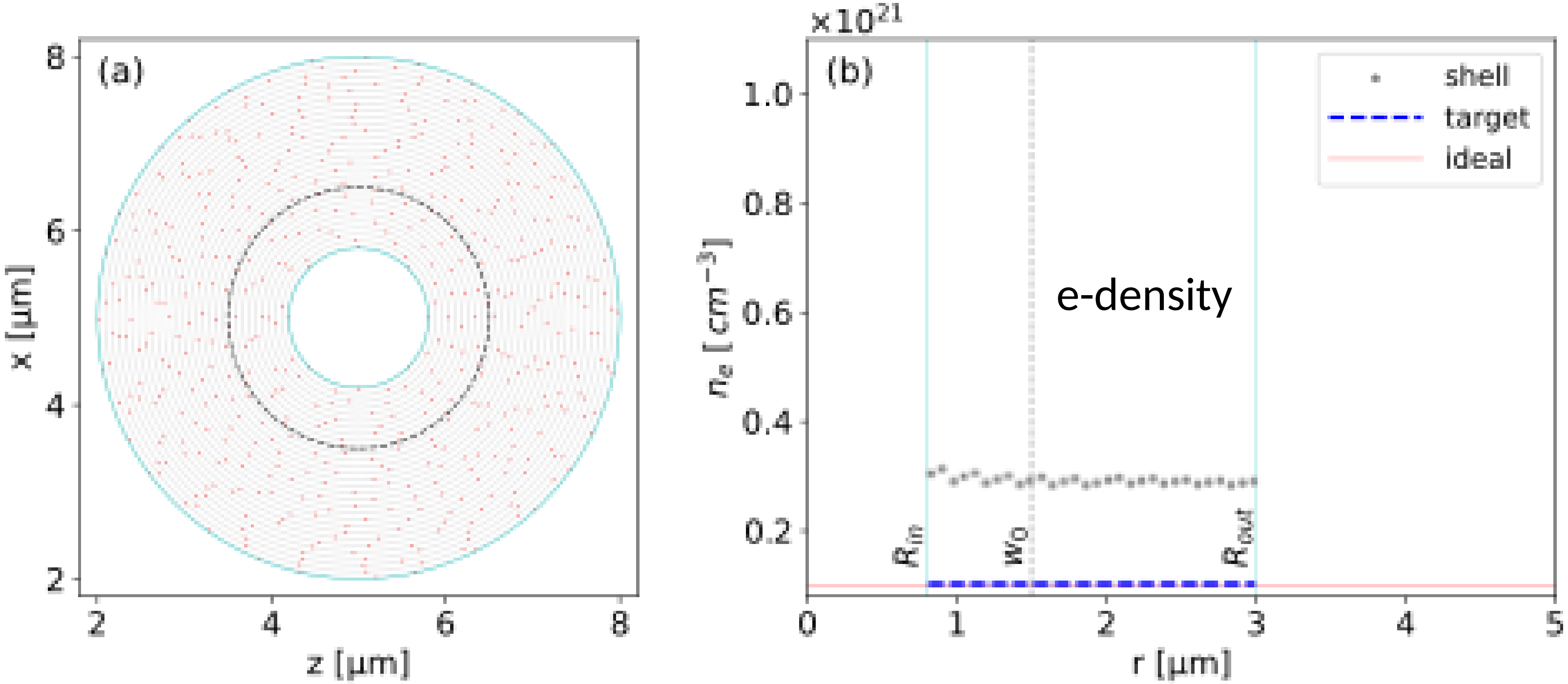
Ilaria Rago, Gianluca Cavoto et al.

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

LWFA acceleration in CNT based targets

Non-aligned CNT bundles

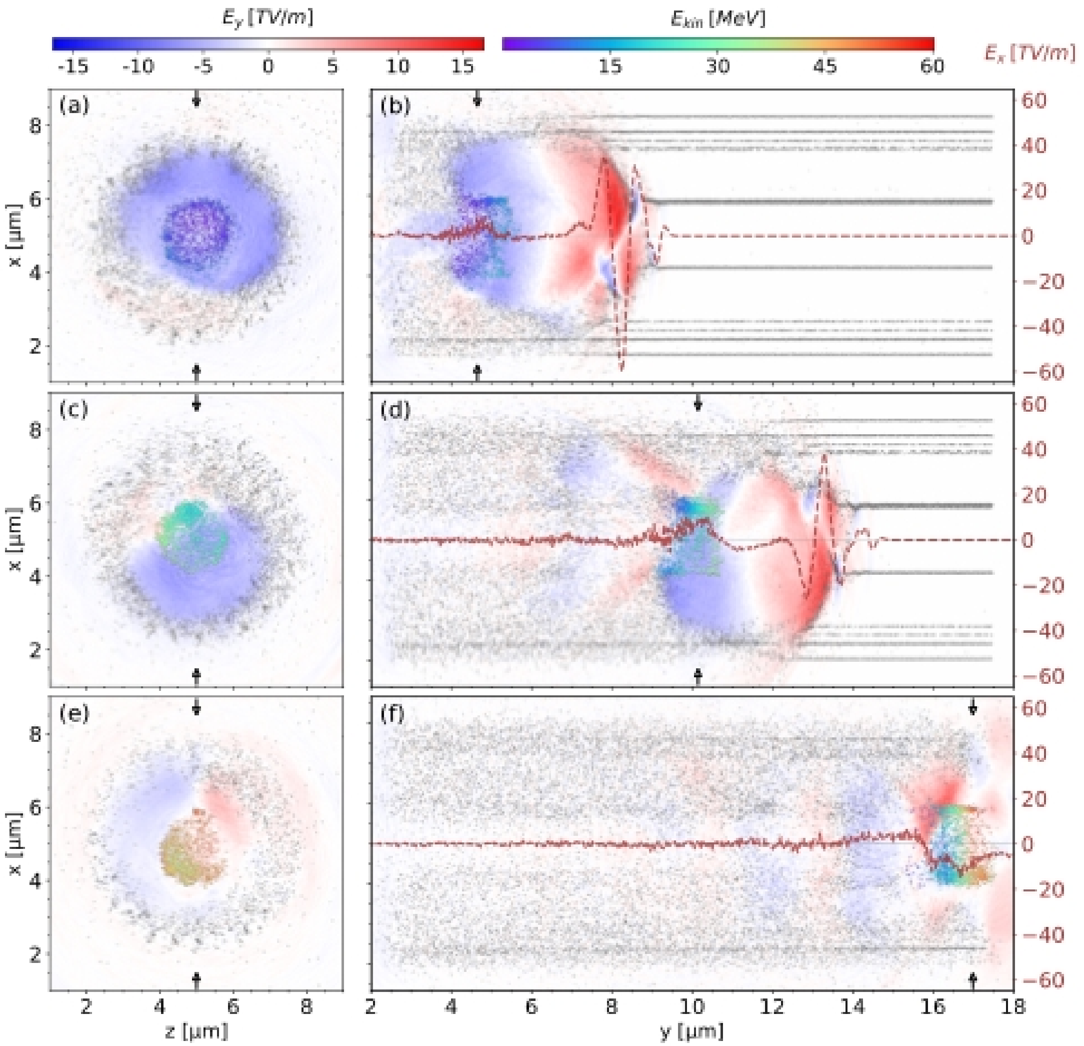
We found similar results with uniformly distributed targets of effective density $n_e \sim 10^{20}$ cm^{-3}



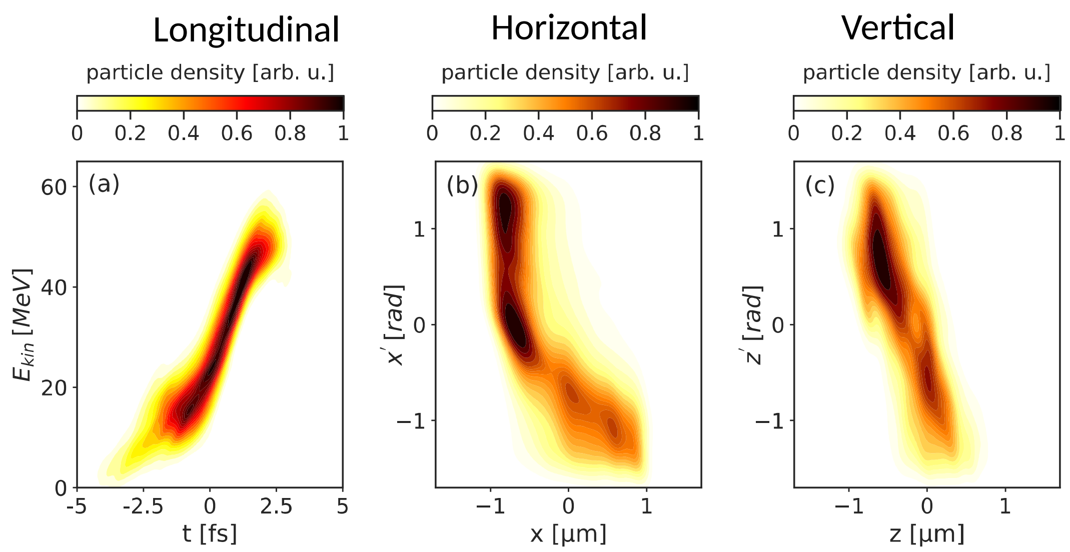
30 shells with 535 CNT bundles (red points) distributed uniformly

LWFA acceleration in CNT based targets

Non-aligned CNT bundles. PIConGPU simulations



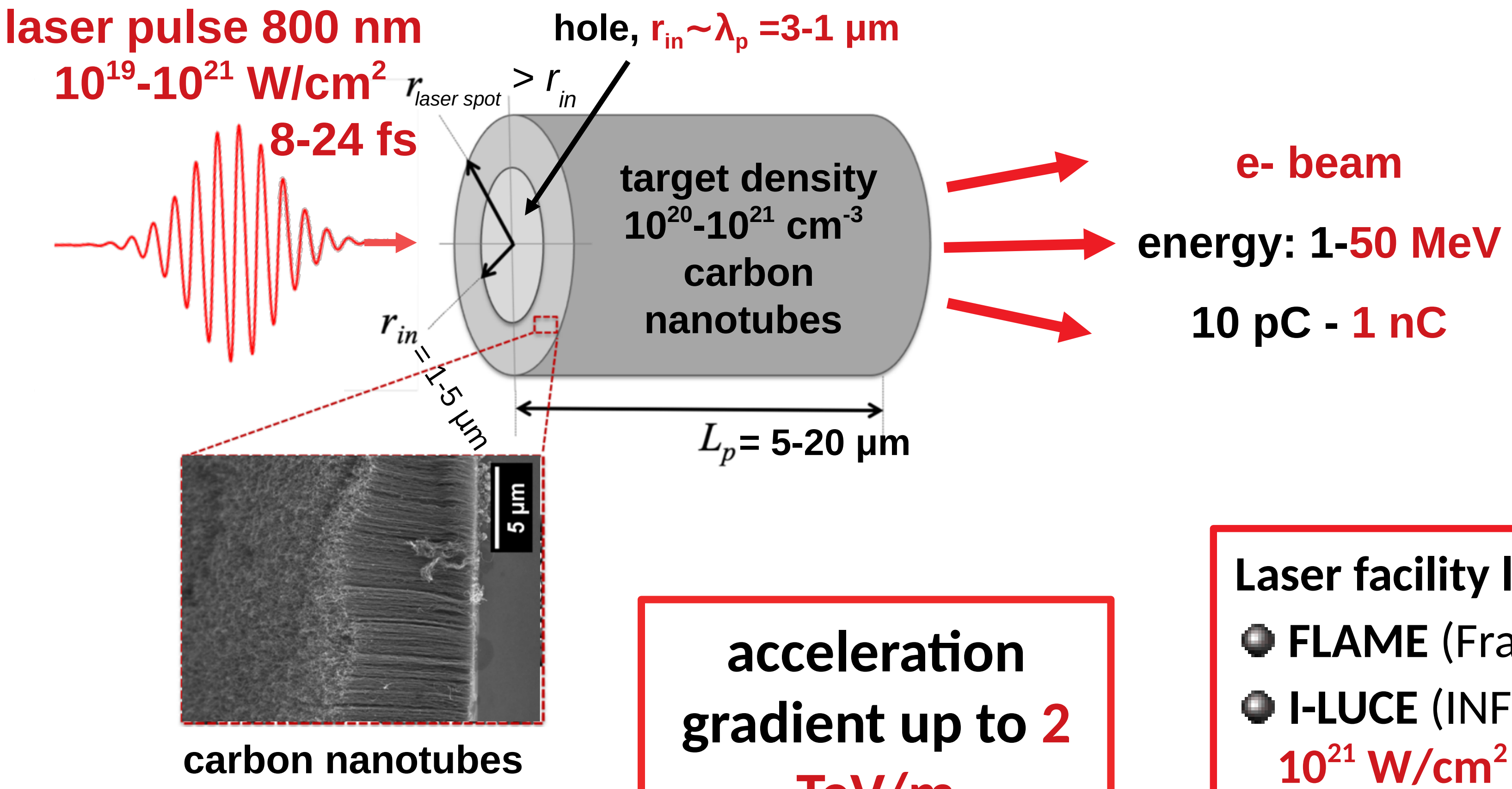
Bunch phase space at extraction



After 3 cycles (Δt=8 fs)

Ultra-short e-pulses, Δt=3.8 fs (FWHM)
<E_{kin} >=27.7 MeV gain in ~ 17 μm
Q=0.8 nC
RMS vertical emittance: 0.4 μm-rad
RMS horizontal emittance: 0.25 μm-rad

Idea of experimental setup



e- self-injection from the target

acceleration gradient up to 2 TeV/m

Laser facility list:

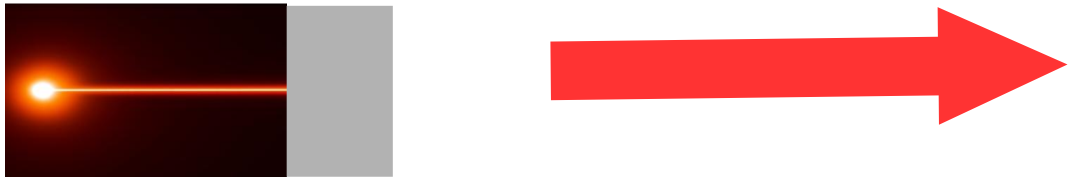
- **FLAME** (Frascati) **10^{20} W/cm^2**
- **I-LUCE** (INFN LNS, to be installed) **10^{21} W/cm^2**
- Alternatively:
- **ELIMAIA-ELIMED** (ELI) **$3 \cdot 10^{21}$ W/cm^2**

observables

- **e- beam**
- **betatron radiation**

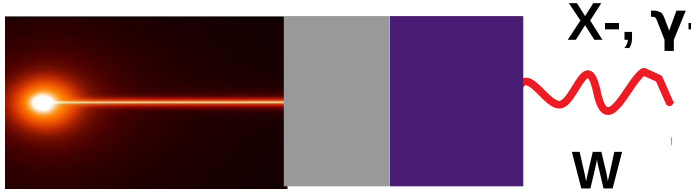
Potential applications

Laser target



1 nC, peak energy 20 MeV
e- beam source

Accelerators & light sources



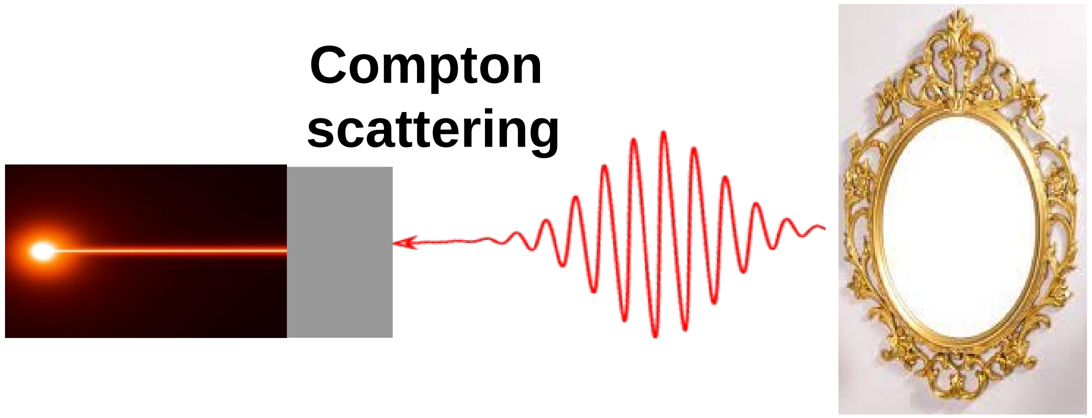
X-, γ-rays (bremsstrahlung);
positron source

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)

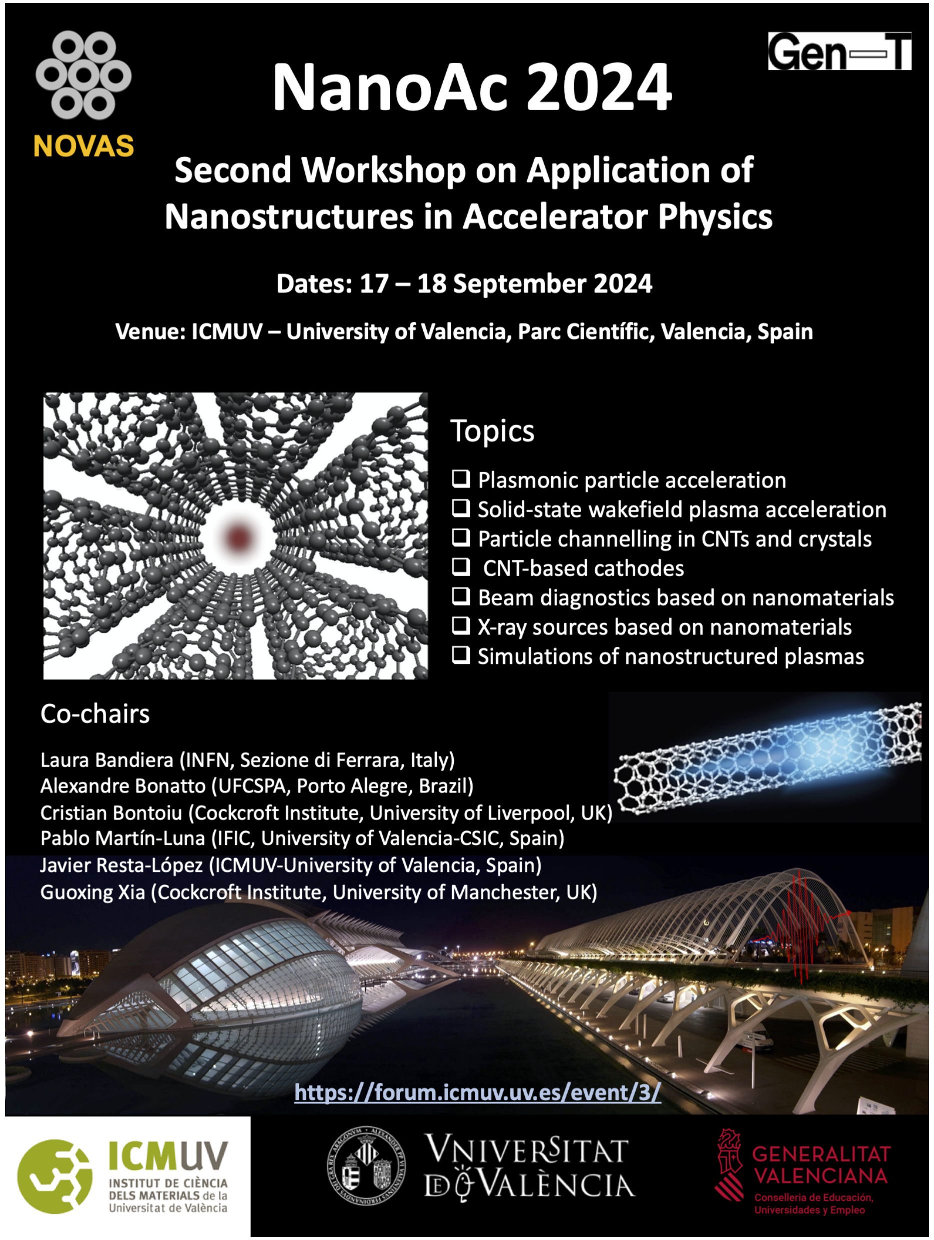
Giancarlo Gatti (CLPU, Spain)

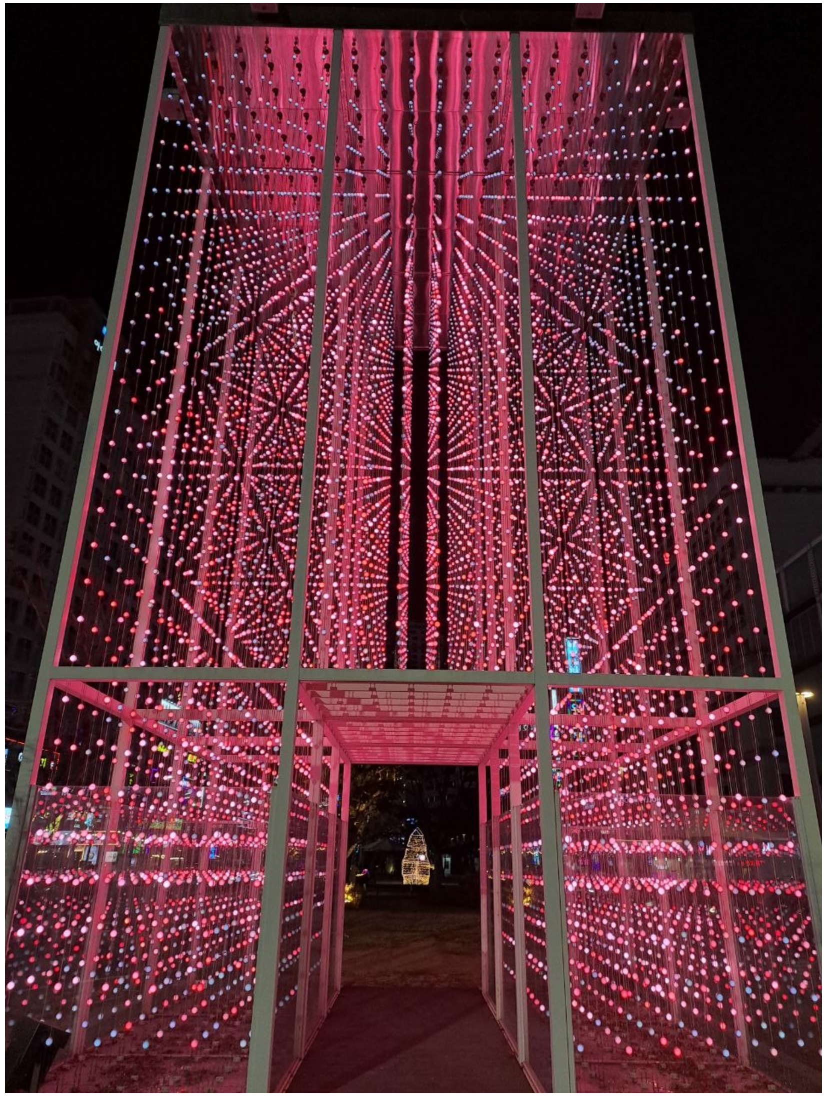
Jorge Vieira (IST, Portugal)

Frank Zimmermann (CERN, CH)

Now open for registration and contributions

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

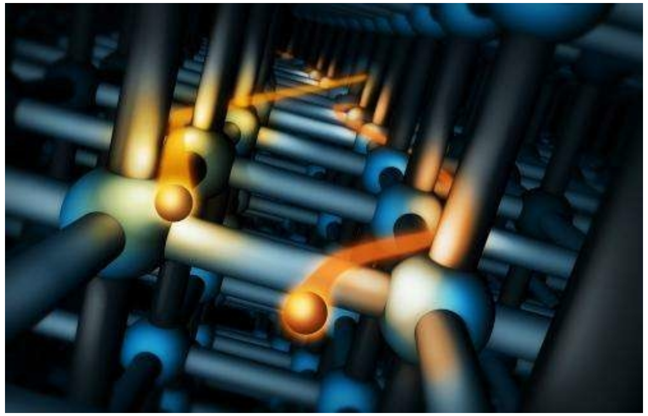


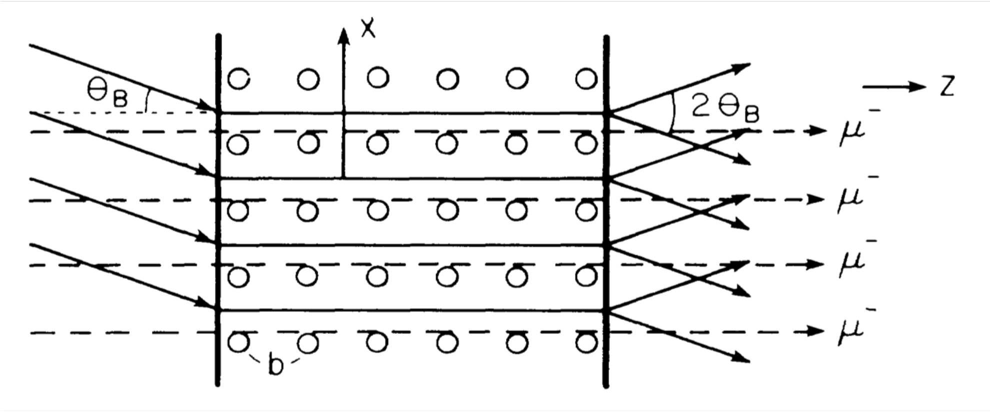


Thank you for attention!

Acceleration in solid-state structures. The beginning

Crystal channeling acceleration





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

- Accelerating fields ~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 ~ TW or PW
- Crystal have been used in accelerators as collimators and bending elements

Very challenging!