Laser-driven and beam-driven plasma acceleration in structured solids

Alexei Sytov, Laura Bandiera, Gianluca Cavoto, Ilaria Rago

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INFN Laboratori Nazionali di Frascati, 16/05/2024

Marie Sklodowska-Curie Action Global Individual Fellowships by A. Sytov in 2021-2025, Project TRILLION GA n. 101032975

Main goal: The **implementation** of both physics of **electromagnetic processes in oriented crystals** and the design of specific applications of crystalline effects into **Geant4** simulation toolkit as Extended Examples to bring them to a large scientific and industrial community and under a free Geant4 license.

Group:

- **A. Sytov** – project coordinator
- **L. Bandiera** – INFN supervisor
- **K. Cho** – KISTI supervisor
- **G. Kube** – DESY supervisor
- **I. Chaikovska** – IJCLab Orsay supervisor

Location:

- 2 years at **KISTI** (partner organization)
- 1 year at **INFN Section of Ferrara** (host organization)
- 1 month of secondment at **DESY** (partner organization)
- 1 month of secondment at **IJCLab Orsay** (partner organization)

Plasma acceleration in solid state targets => towards accelerator on a chip

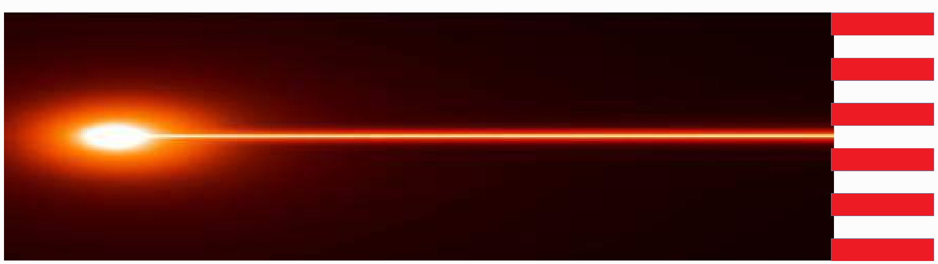
Acceleration gradient*

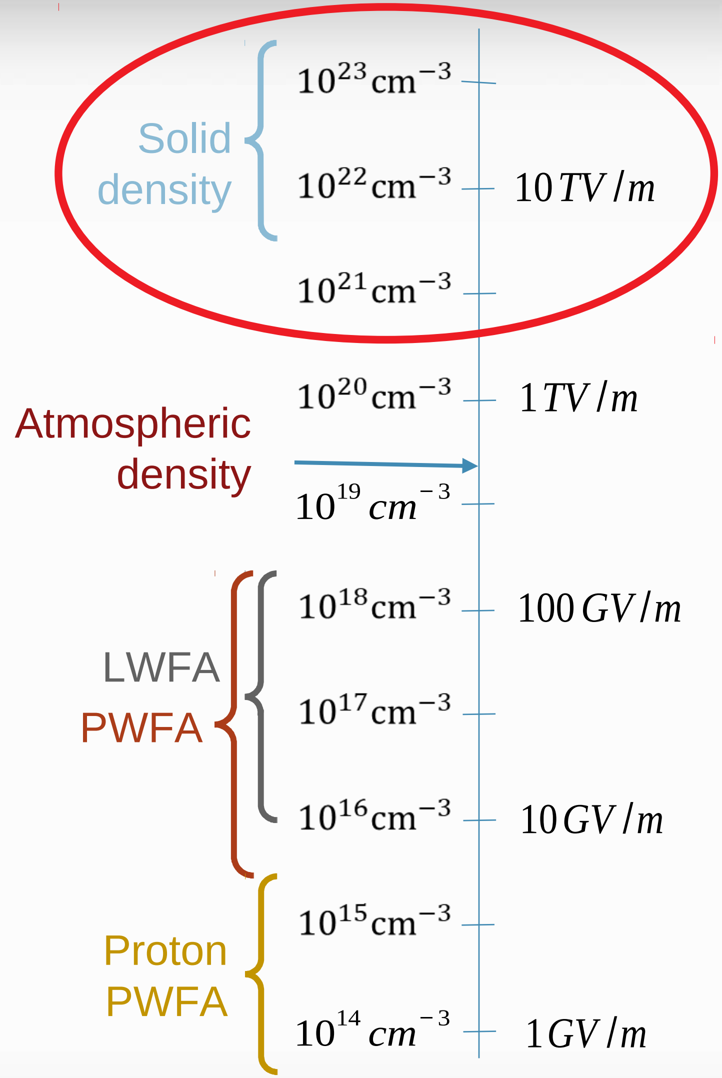
$$E[\mathrm{GV/m}] = m_e \omega_p c/e \approx 100\sqrt{n_0[10^{18}\mathrm{cm}^{-3}]}$$

Solid density plasma accelerators can produce fields of **10 TV/m**

All you need:

drive beam **target**





* Max F. Gilljohann, …, A. Sytov, L. Bandiera, …, T. Tajima, V. Shiltsev and S. Corde JINST 18 P11008 (2023)

Potential applications

Generally the same as for conventional accelerators and plasma accelerators
but very compact

- **Beam source** for accelerator projects
- **X-ray/gamma-ray source** (compton, bremsstrahlung, ...)

All the applications of charged particle/photon beam produced in plasma acceleration

- **Radiotherapy**
- **Imaging**
- **Material Science**
- **Radiation damage**
- **Nuclear physics**
- **...**

All you need:

Challenges and solutions

stability

multiple scattering

radiation damage of the target

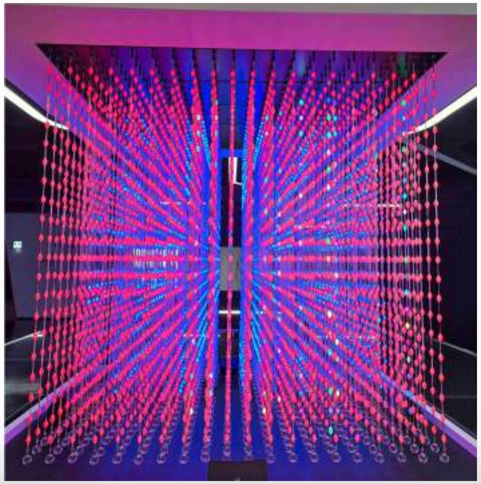
drive beam size vs plasma wavelength λ_p

energy distribution

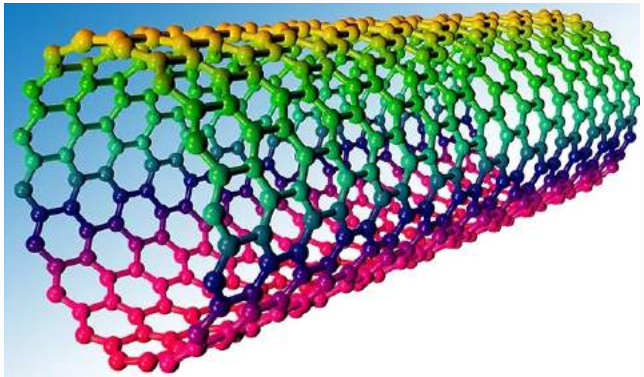
beam emittance

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

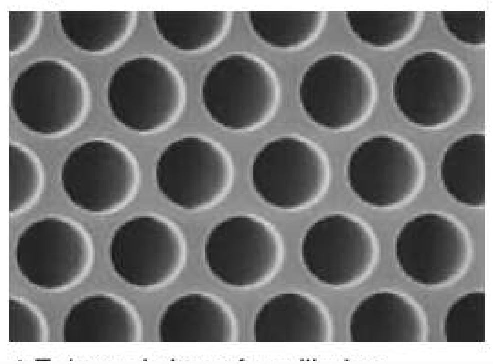
Oriented crystals



Nanotubes



Structured solids



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

This is where we enter in the game!

Laura Bandiera

Alexei Sytov

INFN Ferrara group: **2 decades of experience** of interaction of charged particles with **oriented crystals**, **production** and **characterization** of the crystals, **simulations** (HPC, **Geant4**), application development

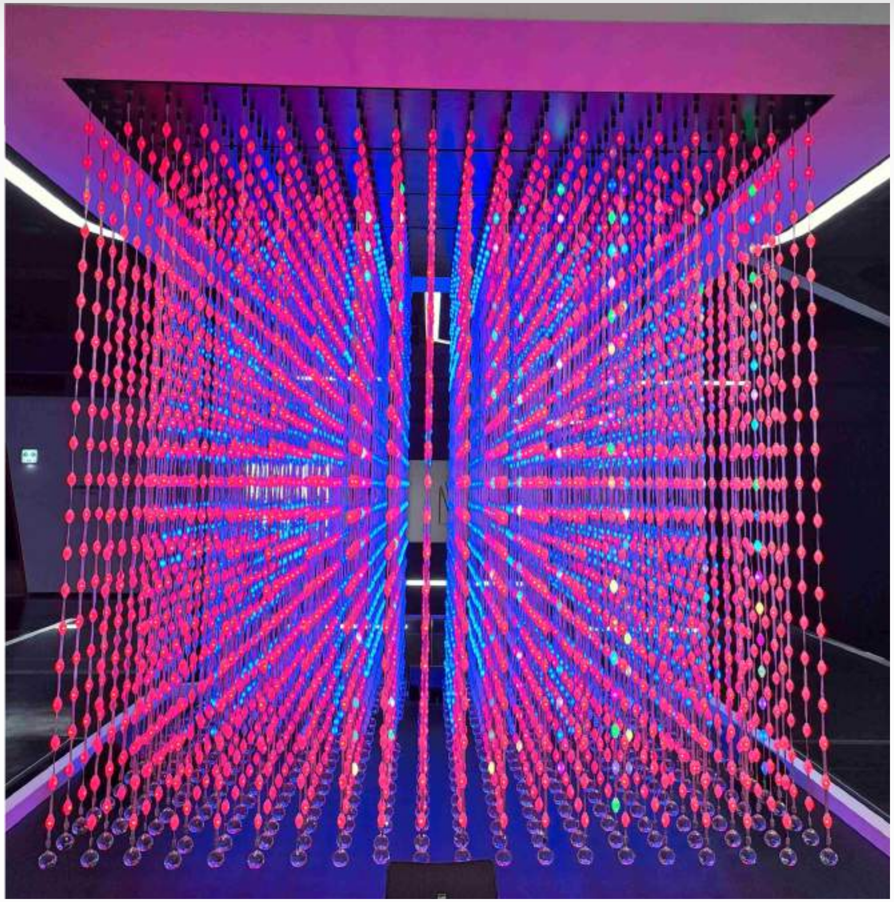
Trillion

Gianluca Cavoto

Ilaria Rago

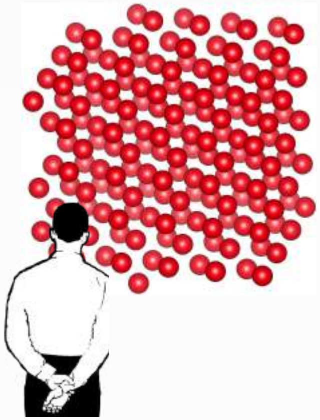
INFN Roma & **Sapienza University of Rome**: experience in: **synthesis** and **characterization** of **carbon nanotubes** and **nanocomposite** materials. In particular: CVD synthesis of CNTs arrays controlling the route in a micro- and nano-fabrication context.

How an oriented crystal looks like

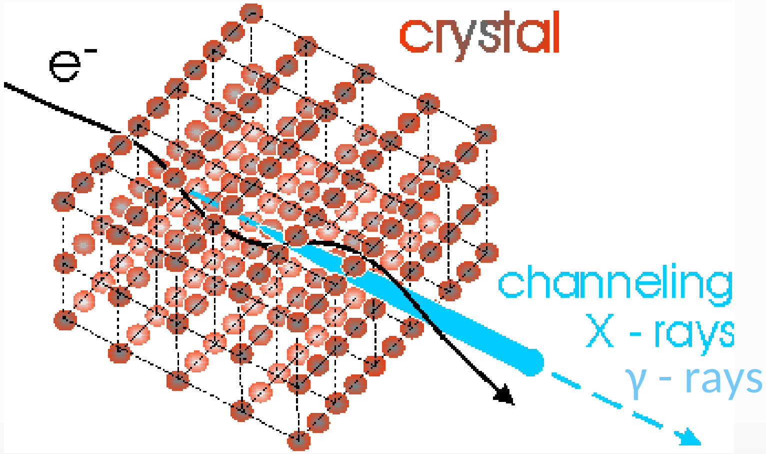


from National Science Museum, Daejeon, Korea

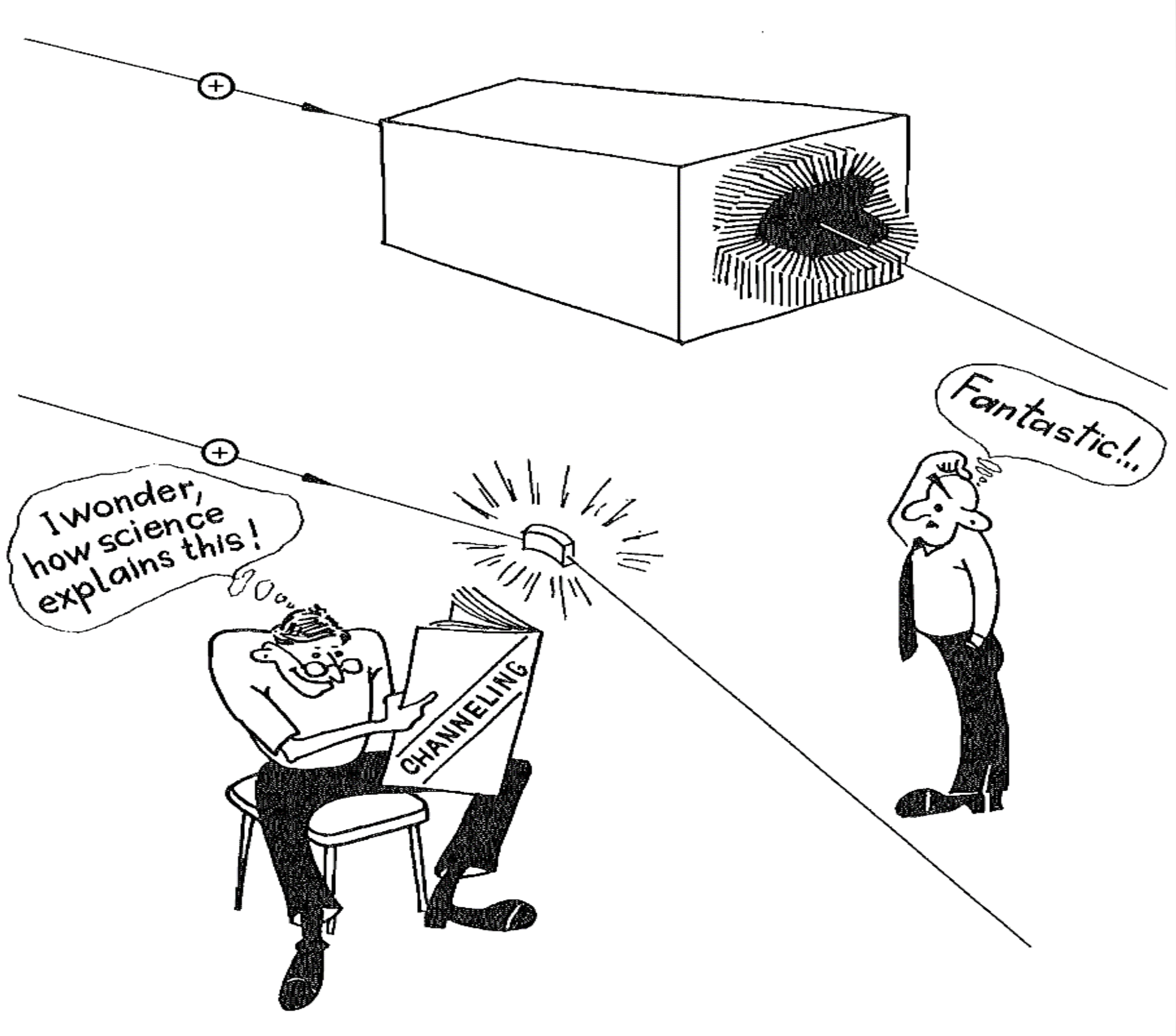
Non-oriented crystal



Oriented crystal



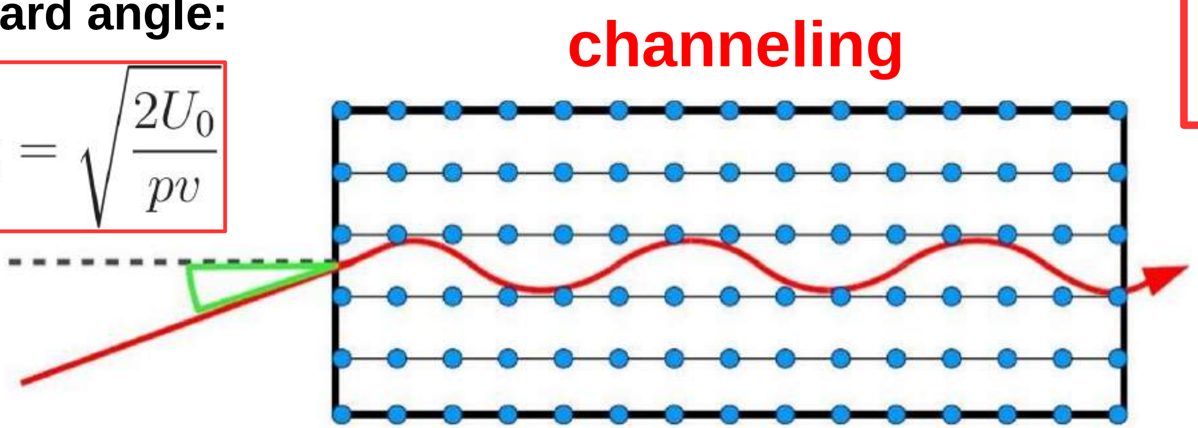
The world of the channeling effect



Channeling effect*

Lindhard angle:

$$\theta < \theta_L = \sqrt{\frac{2U_0}{pv}}$$



Planar/Axial field
$10^9/10^{11}$ V/cm

Channeling* **is the effect of the penetration of charged particles through a monocrystal quasi parallel to its atomic axes or planes.**

Free space for charged particle motion => **reduced scattering**

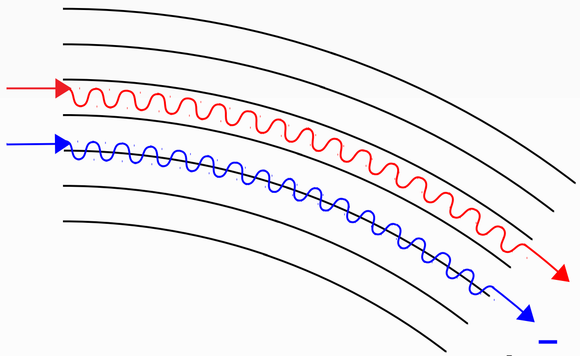
Strong focusing at **Angstrom scale => small beam emittance**

Crystals are **very resistant** to the beam intensities

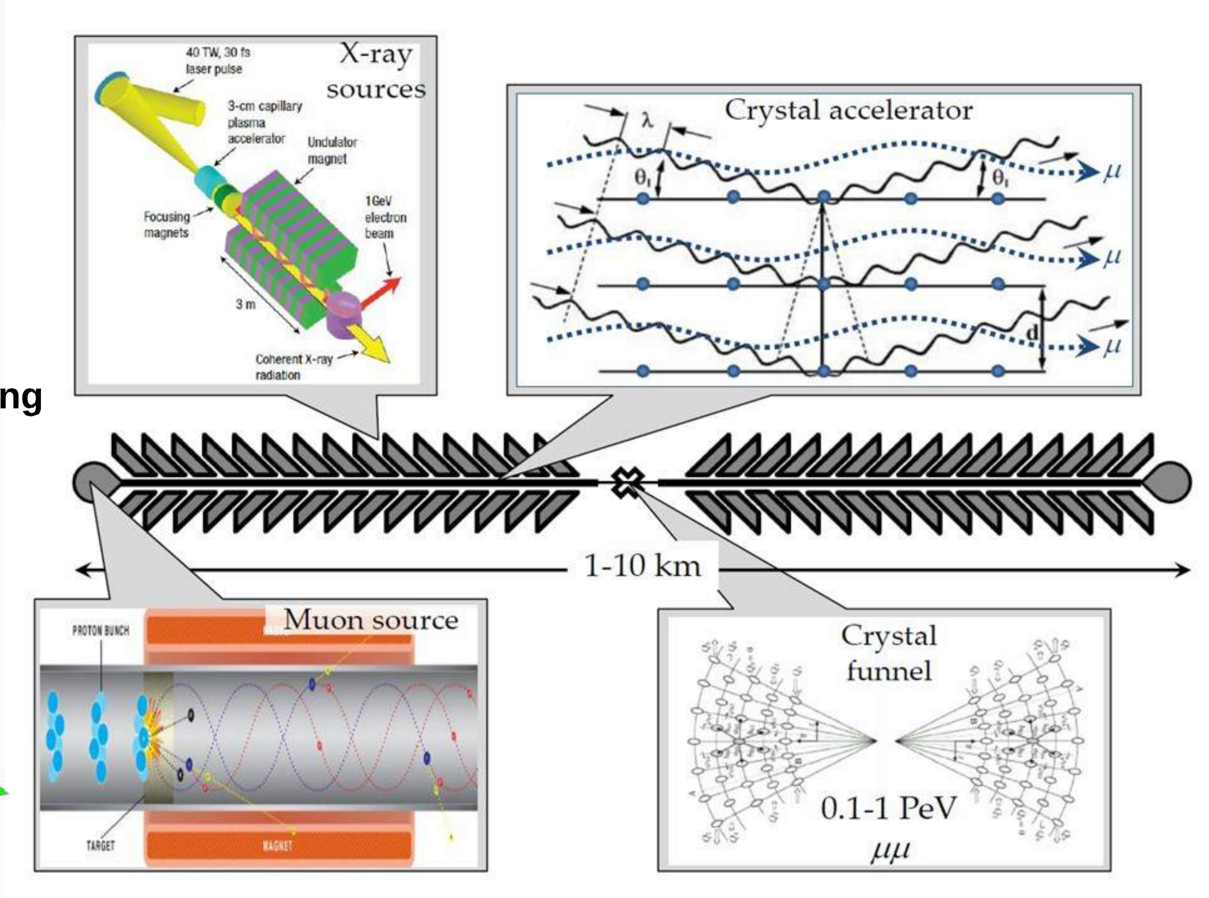
*J. Stark, Zs. Phys. 13, 973–977 (1912)
J. A. Davies, J. Friesen, J. D. McIntyre, Can J. Chem. 38, 1526–1534 (1960)
M. T. Robinson, O. S. Oen, Appl. Phys. Lett. 2, 30–32 (1963)
J. Lindhard, Kgl. Dan. Vid. Selsk. Mat.-Fys. Medd. 34 No 4, 2821–2836 (1965)

Let's dream about future lepton colliders!

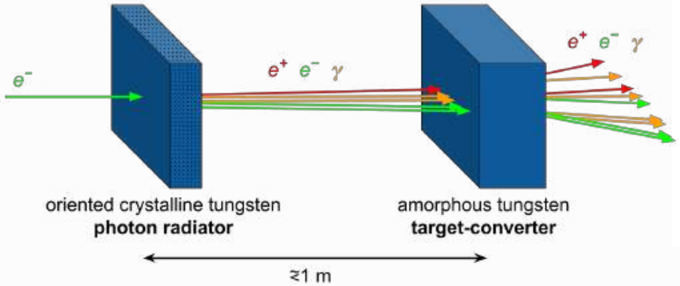
Channeling in a bent crystal



Concept of a linear X-ray crystal muon collider*,**



Hybrid crystal-based positron source***



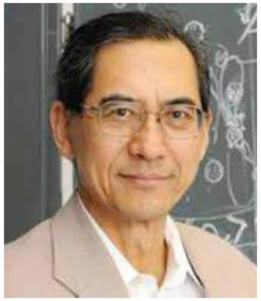
***L. Bandiera et al. Eur. Phys. J. C 82, 699 (2022)

**V. Shiltsev, Physics-Uspekhi 55, (10), 965 (2012)

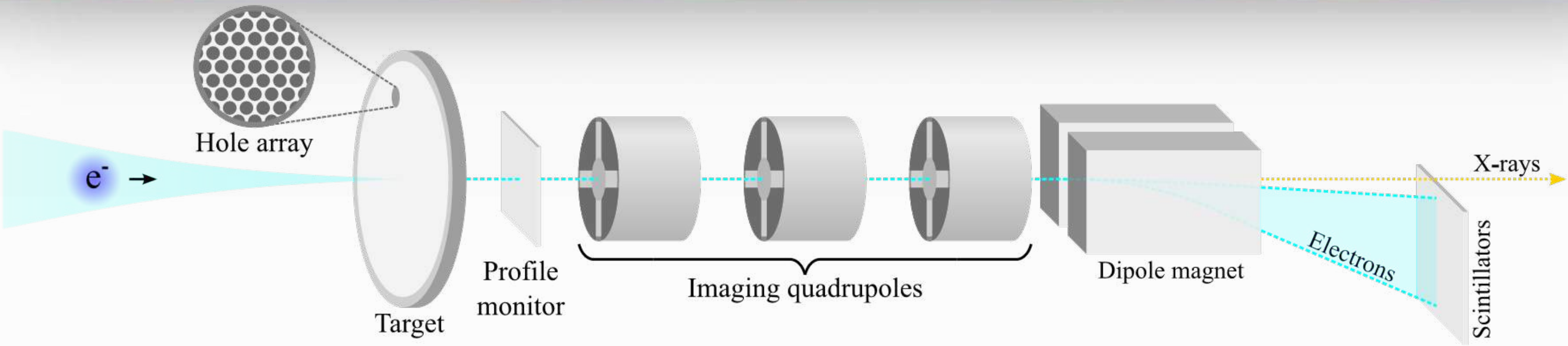
* Max F. Gilljohann, …, A. Sytov, L. Bandiera, …, T. Tajima, V. Shiltsev and S. Corde JINST 18 P11008 (2023)

E-336 Experiment at the SLAC FACET-II Facility
Beam-driven plasma acceleration

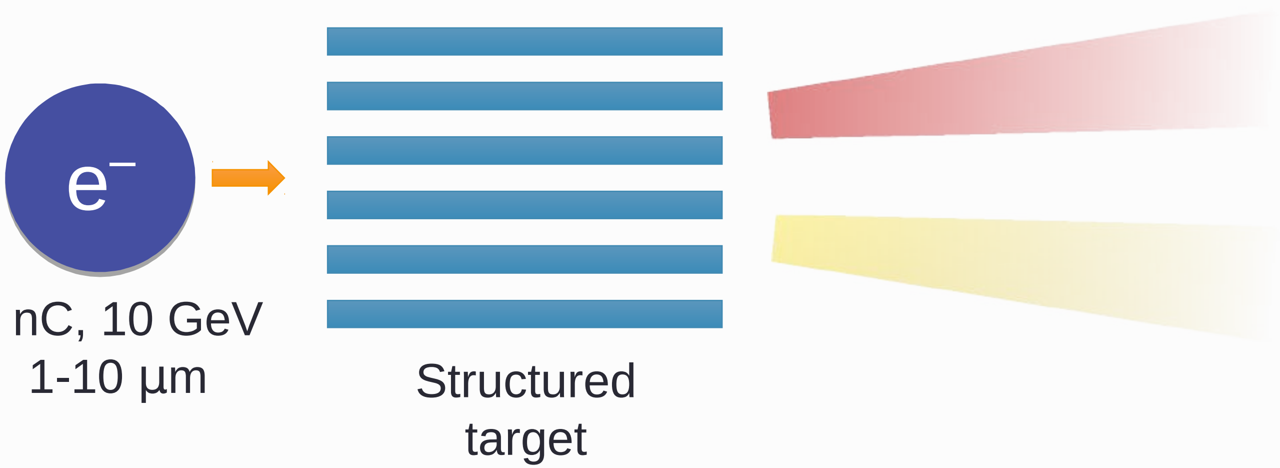
Principal Investigators:
Sébastien Corde and Toshiki Tajima



E336 SLAC FACET-II experimental setup



To measure:



Observation of transverse plasma waves

E336 at SLAC FACET-II
Science goals and definition of success

Science goals

- **Proof-of-principle experiment** - demonstrate feasibility of the study of beam-nanotarget interaction and of beam-induced wakefields in nanotargets
- Observation of electron **beam nano-modulation**
- Observation of **X-ray radiation** due to transverse oscillations in wakefields
- Confirmation of **simulation models**

Definition of success:

- **Evidence** for clearly distinguishable **interaction** of **FACET-II beam with structured solid targets** in comparison to amorphous targets (1.5 years)
- **Systematic parametric study** of beam-nanotarget interaction for various sample thickness, pore diameter, material type, and beam parameters, and comparison/validation against theory, to support signature and **evidence of beam nano-modulation** (3 years - dependent on beam parameters)

*** Max F. Gilljohann, …, A. Sytov, L. Bandiera, …, T. Tajima, V. Shiltsev and S. Corde JINST 18 P11008 (2023)**

E336 at SLAC FACET-II: status

Current state

- **Experimental safety** review carried out.
- “**Nanotargets**” installed and beam damage tested.
- Alignment control installed, alignment diagnostic almost ready.

Next steps:

Phase 1 – FY24-25	• Relative angular alignment diagnostic (on-line). • Absolute angular alignment diagnostic (invasive). • First signature of beam-nanotarget interaction.
Phase 2 – FY25-26	• Improve/upgrade experimental hardware and targets. • Advanced characterization of beam-nanotarget interaction with full set of sample and FACET-II beam parameters.
Phase 3 (conditional)	• Going from transverse wakefields and beam dynamics to longitudinal wakefields.

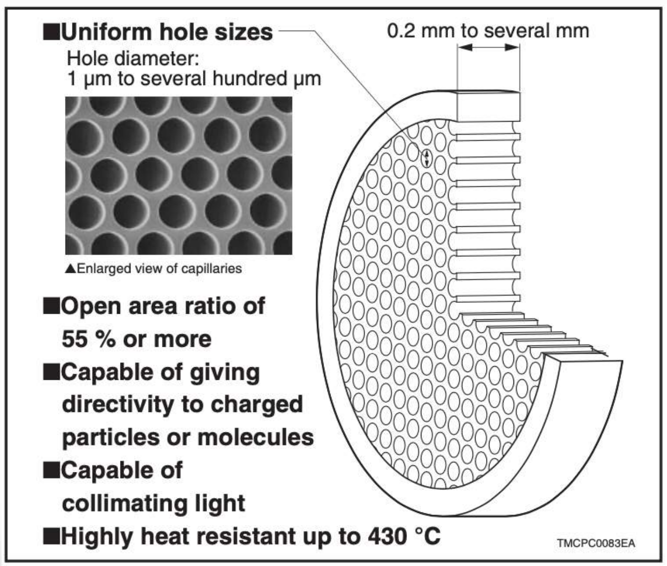
* Max F. Gilljohann, …, A. Sytov, L. Bandiera, …, T. Tajima, V. Shiltsev and S. Corde JINST 18 P11008 (2023)

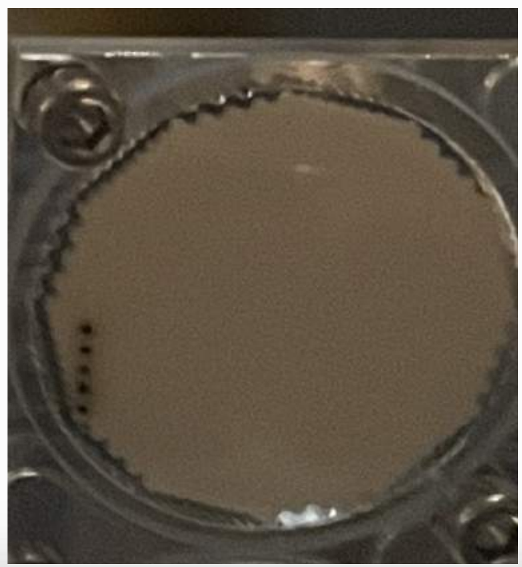
E336 SLAC FACET-II target and initial progress

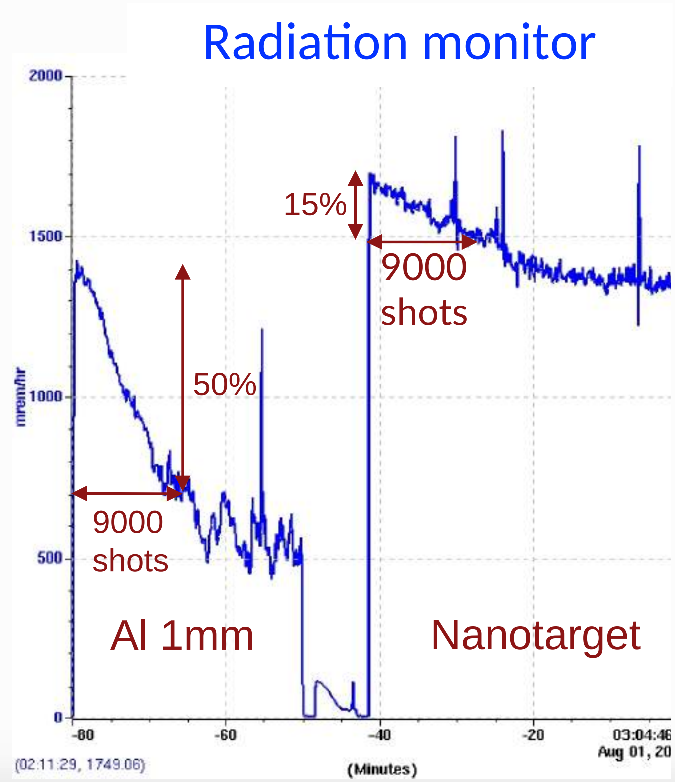
Observables

- 1 mm thick, 6 micron-diameter tubes in lead glass
- Radiation monitor downstream – drop tells how quickly the target is being damaged/drilled
- X-rays and gamma-rays

Damage observed, but targets relatively robust: 15% decrease in radiation in 9000 shots

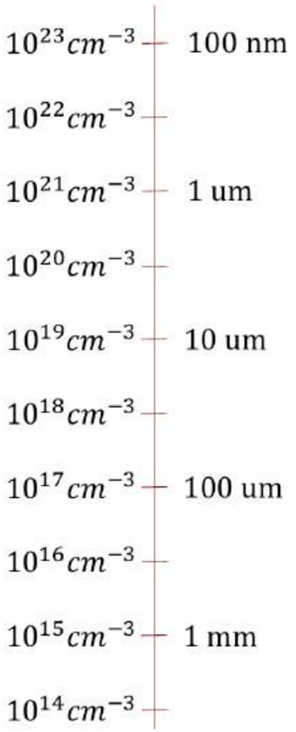


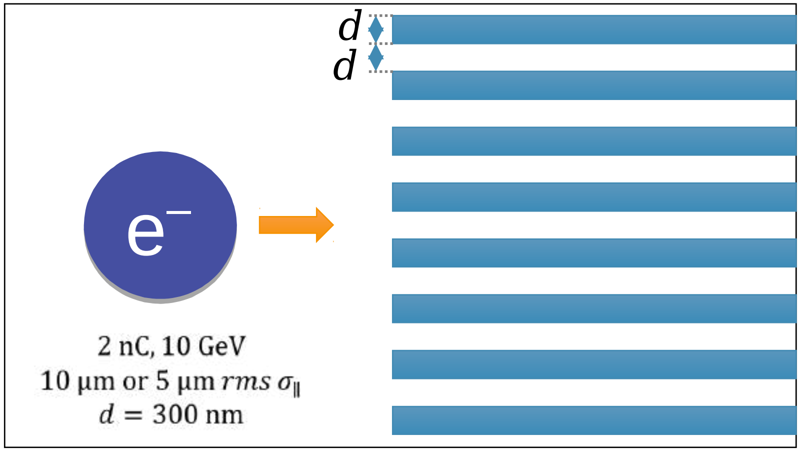




Simulation results: self-modulation of the electron beam

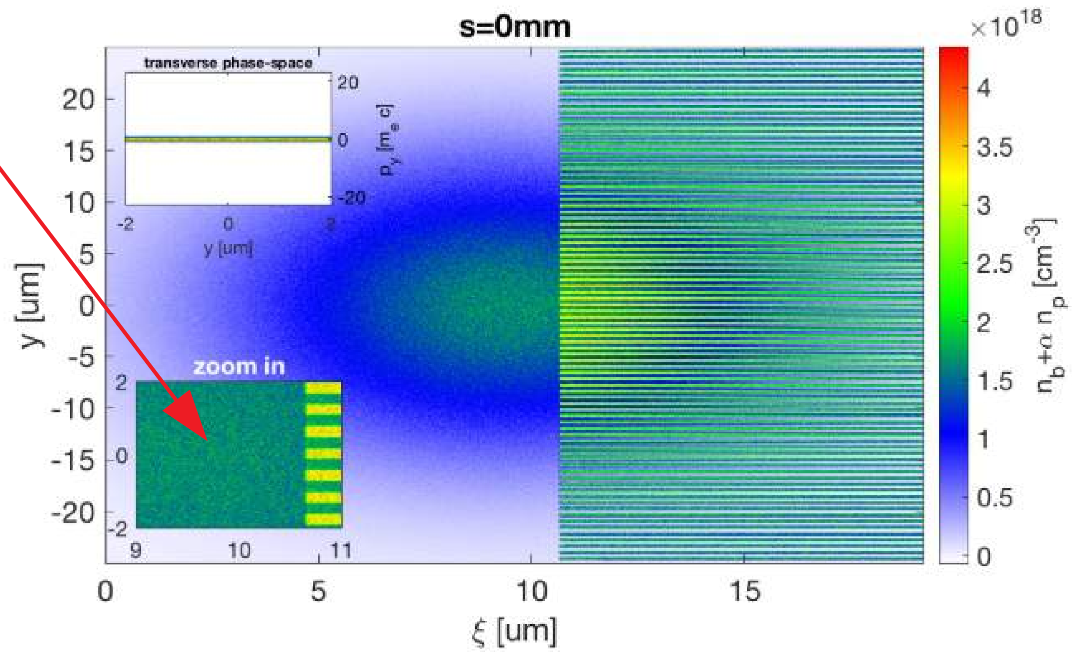
- **Size** of the **wake** scales as $\lambda_p = 2\pi \frac{c}{\omega_p}$
- **Driver** needs to have spatial scale on the order of the **wake scale**
- For solid densities, this is **difficult to achieve** with current facilities





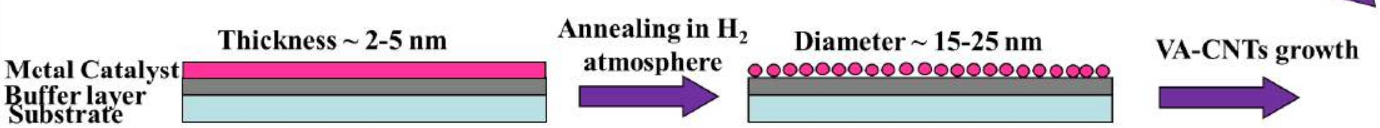
Plasma density has the same structure as the nanotarget

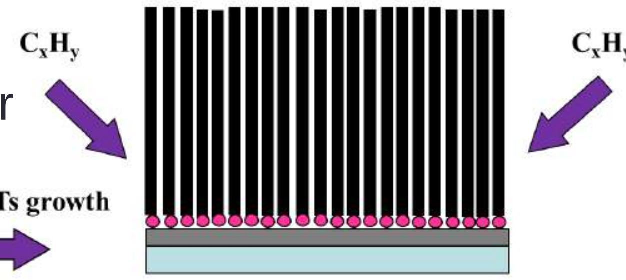
PIC simulations were carried out using the **CALDER** code

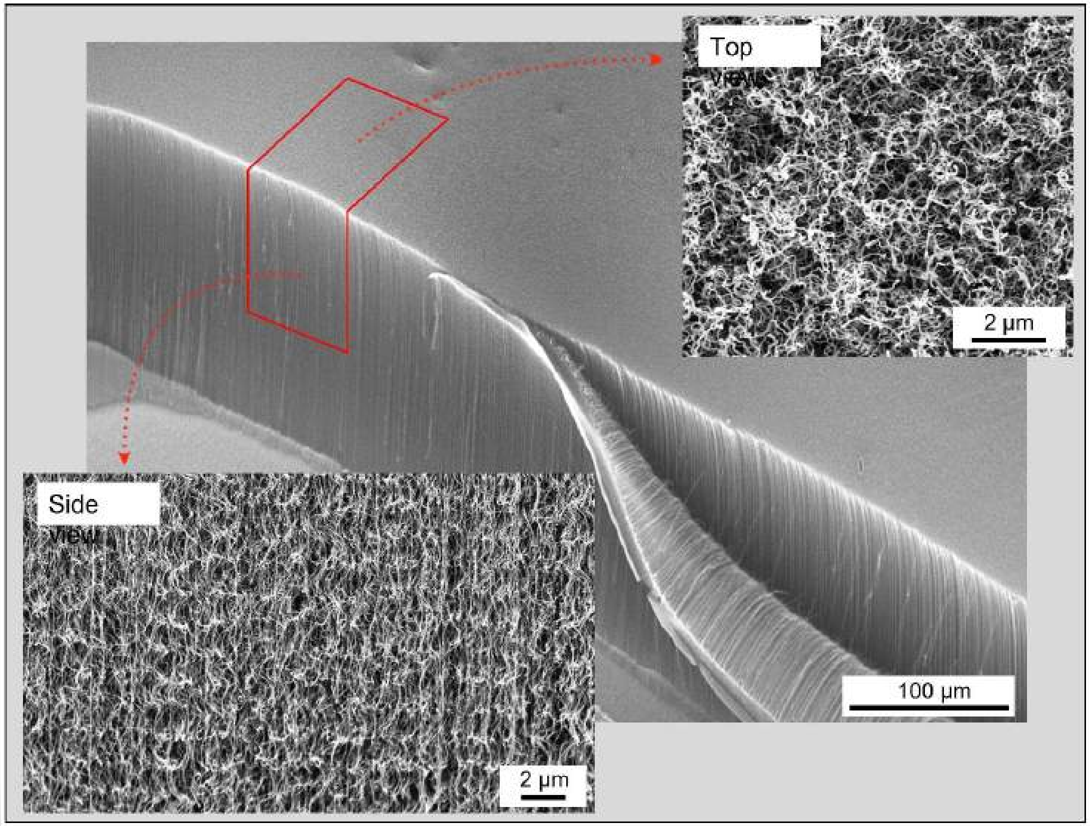


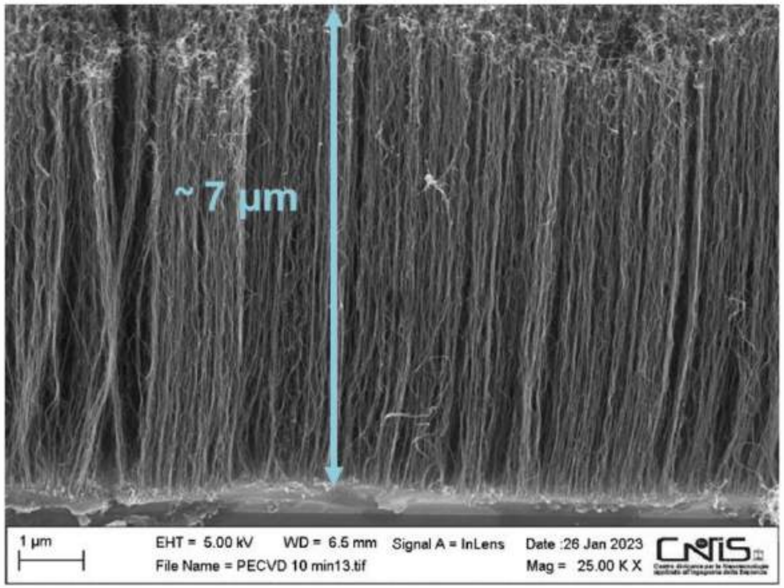
Possible future target: carbon nanotubes

Thermal decomposition of a gaseous precursor on catalytic nanoparticles in a high-vacuum reaction chamber









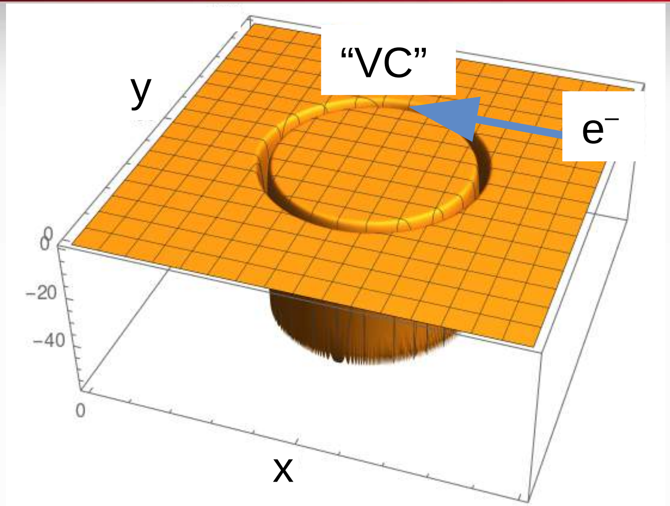
Courtesy of
Prof. Gianluca Cavoto,
Dr. Ilaria Rago

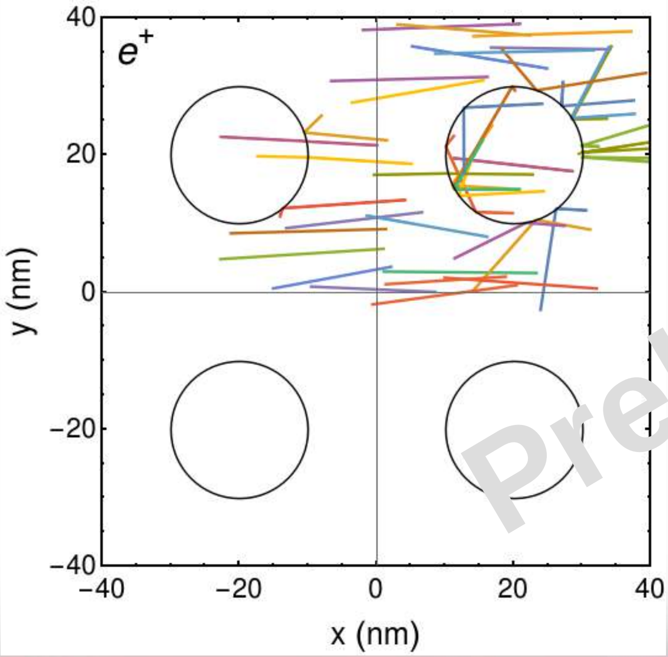
* F. Sarasini et al. Composites Part B 243 (2022) 110136

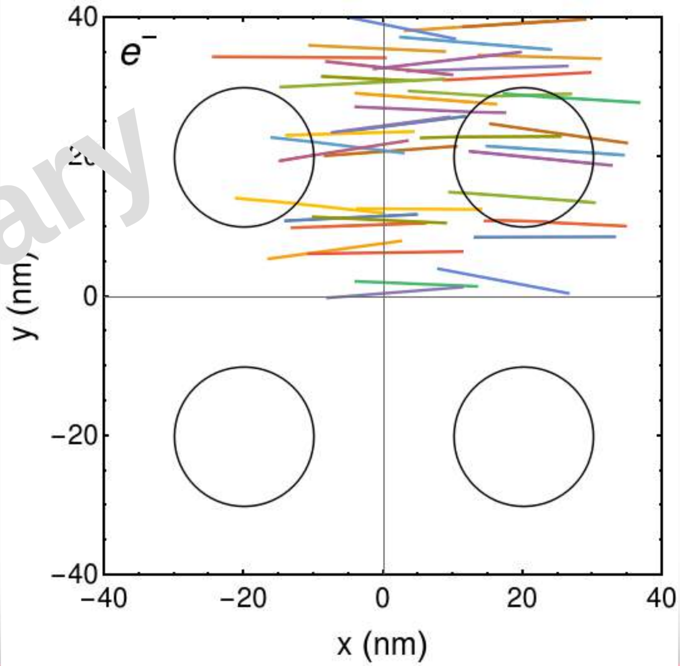
Channeling simulations in CNT: trajectories, ideal case

Simulations with **CRYSTALRAD** simulation code*

Simulation parameters:
Beam: e^-/e^+
Divergence: 10 μrad
CNT diameter: 20 nm
CNT length: 0.2 mm



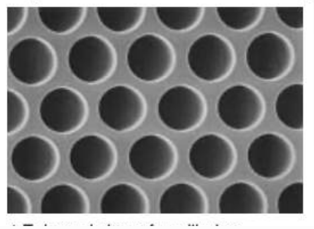




*A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

Our proposal for future E336 stage

Micro (and **smaller**) size **holes** in other materials, nanostructures, crystals



Requires R&D in material science

INFN Roma & INFN Ferrara

Ionization of **crystal media** with the field of FACET II e- beam

→

Channeling of electrons in an oriented crystal inside a plasma wave

New effects to observe

- **Strong focusing in plasma by crystalline electric fields**
- **Channeling** in an ionized oriented crystal **at extreme conditions**
- **Radiation spectra**

Requires nowel simulation techniques: PIC & channeling simulations

INFN Ferrara

The E336 collaboration

Collaboration and institutions:

- **IP Paris/LOA**: Sébastien Corde, Max Gilljohann, Alexander Knetsch, Yuliia Mankovska, Pablo San Miguel Claveria
- **UC Irvine**: Peter Taborek and Toshiki Tajima
- **Fermilab**: Henryk Piekarz and Vladimir Shiltsev
- **SLAC**: Robert Ariniello, Henrik Ekerfelt, F. Fiuza, Mark Hogan, and Doug Storey
- **CEA**: Xavier Davoine and Laurent Gremillet
- **IST**: Bertrand Martinez
- **INFN**: Laura Bandiera, Gianluca Cavoto, Illaria Rago, Alexei Sytov

Publications:

- White paper for Snowmass in AF6 Advanced Accelerator Concepts
arXiv: 2203.07459,
JINST 18 P11008 (2023)
DOI 10.1088/1748-0221/18/11/P11008

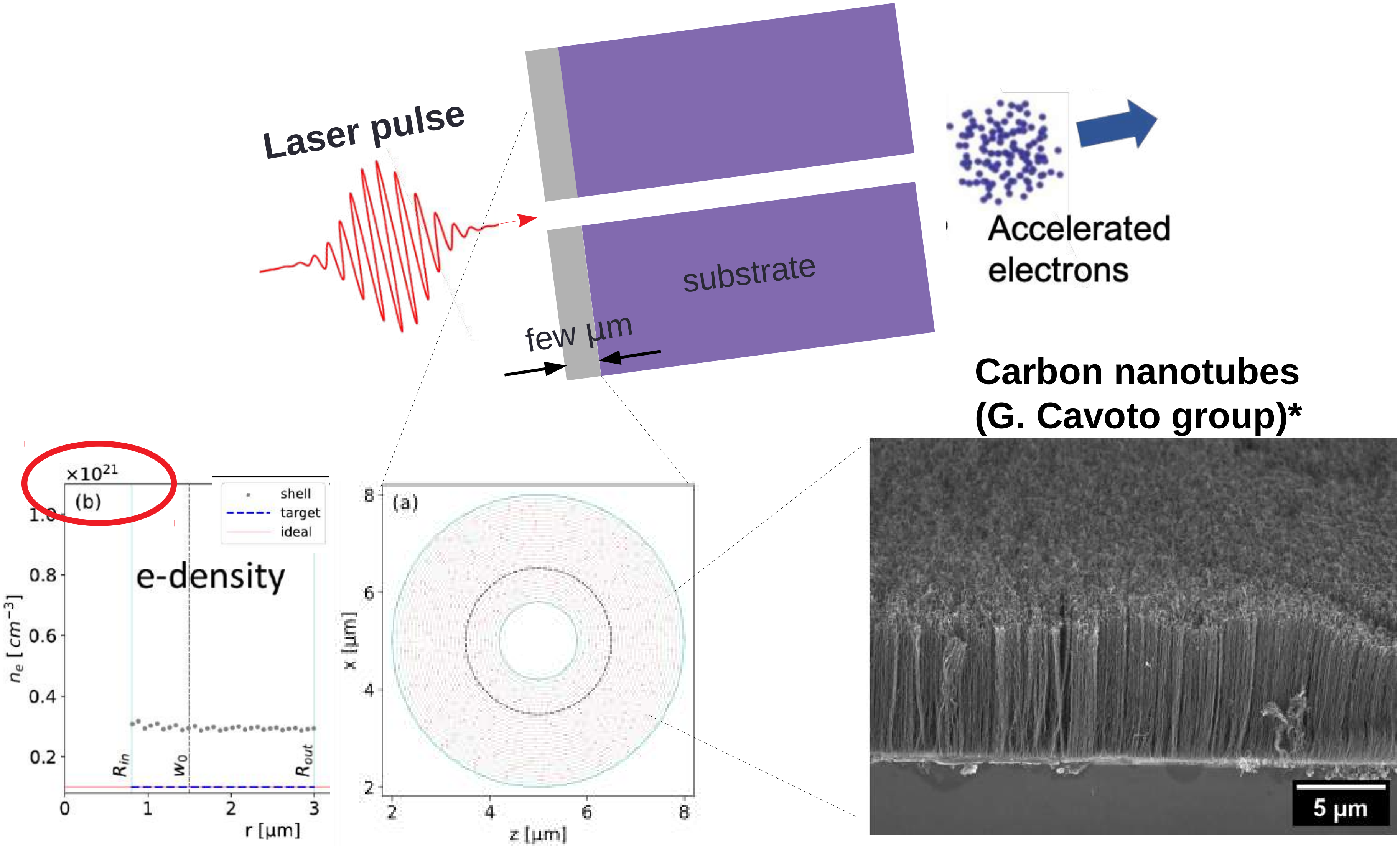
Channeling Acceleration in Crystals and Nanostructures and Studies of Solid Plasmas: New Opportunities

Max F. Gilljohann,[1] Yuliia Mankovska,[1] Pablo San Miguel Claveria,[1] Alexei Sytov,[2,3] Laura Bandiera,[2] Robert Ariniello,[4,5] Xavier Davoine,[6,7] Henrik Ekerfelt,[5] Frederico Fiuza,[5] Laurent Gremillet,[6,7] Alexander Knetsch,[1] Bertrand Martinez,[8] Aimé Matheron,[1] Henryk Piekarz,[9] Doug Storey,[5] Peter Taborek,[10] Toshiki Tajima,[10] Vladimir Shiltsev,[9] Sébastien Corde[1]

Laser-driven plasma acceleration in nanostructures

NanoAcc collaboration
Javier Resta-López et al.

LWFA acceleration in CNTs based targets: the idea



Cristian Bontoiu, PhD Thesis

LWFA acceleration in CNTs based targets: simulations

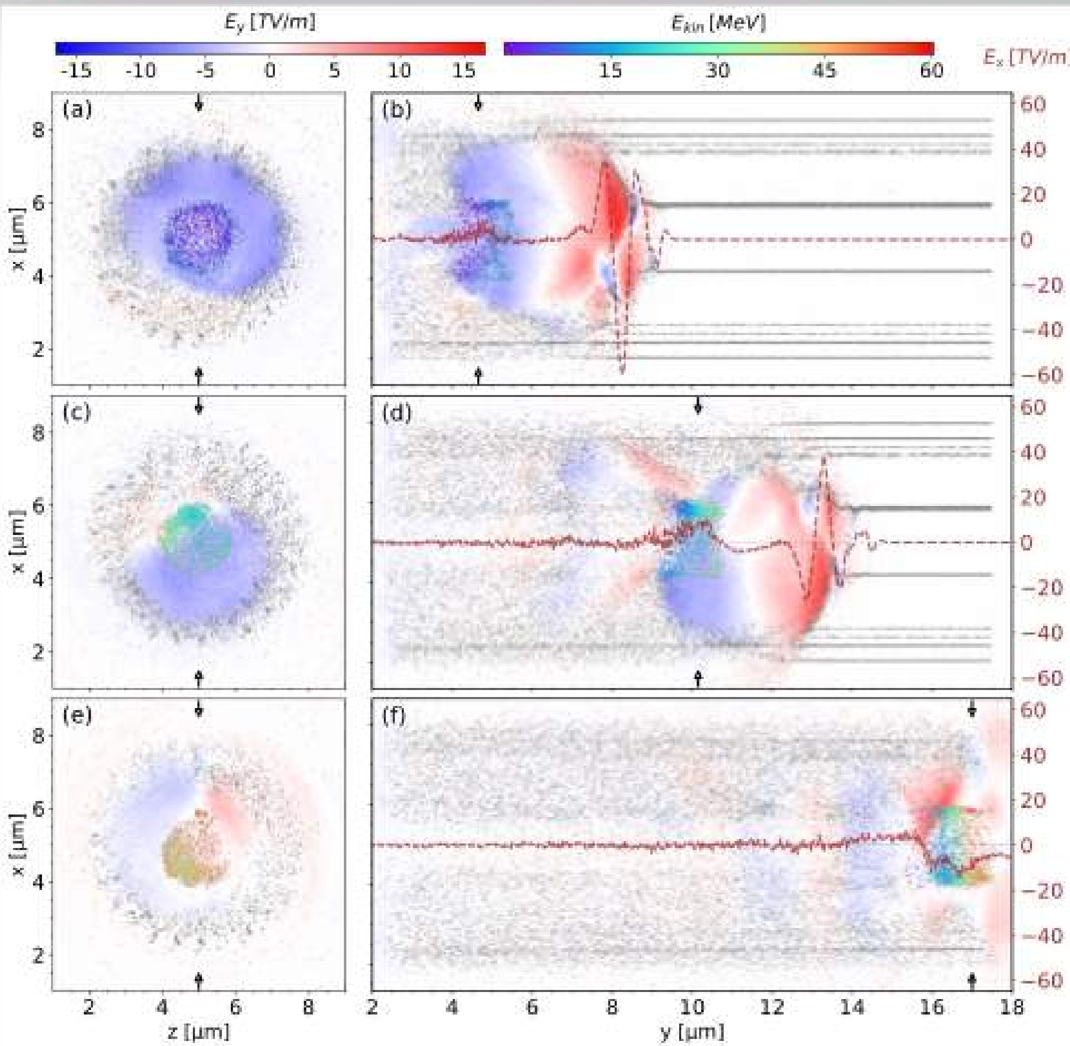
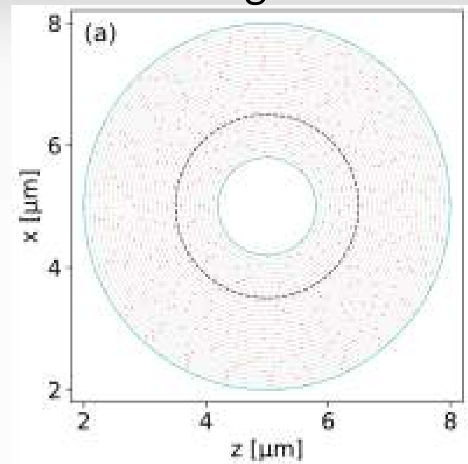


Figure 28: Electron macroparticles shown as grey dots and the longitudinal electric field shown as a colour density plot for model *A constant* with $\Delta t = 8$ fs (3 cycles), $I_0 = 10^{21}$ W/cm²: (a-b) t/T = 11; (c-d) t/T = 18; (e-f) t/T = 25.

Target



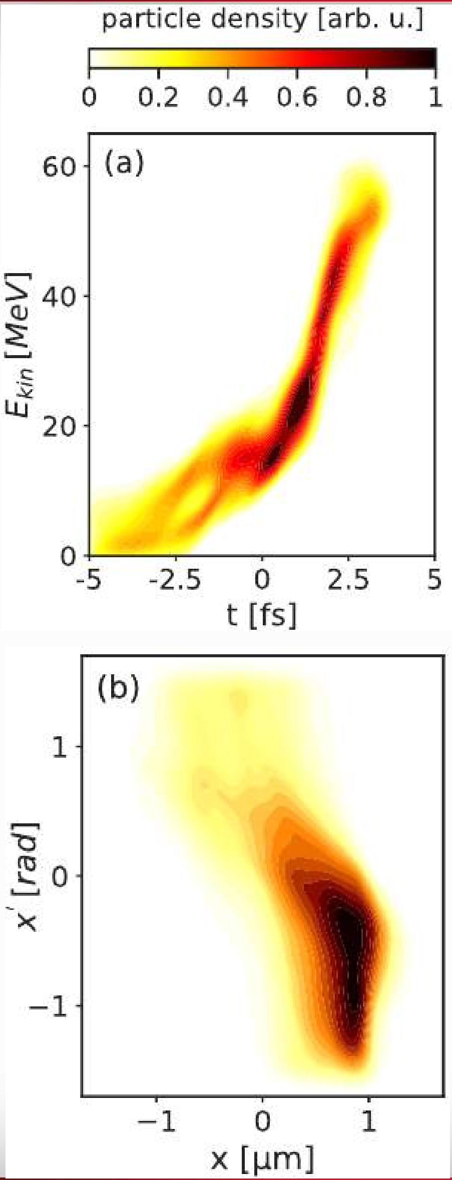
30 shells with 535 CNT bundles (red points) distributed uniformly

Cristian Bontoiu,
PhD Thesis

Simulations with:

PIConGPU

LWFA acceleration in CNTs based targets: e- beam



Parameter	Value			Unit
	Δt = 8 fs	Δt = 16 fs	Δt = 24 fs	
Charge, Q	1.08	1.19	0.79	nC
Average kinetic energy, E_{kin}	23.31	14.50	15.33	MeV
Average acceleration gradient, E_{kin}/L	1.55	0.96	1.02	TeV/m
Average Lorentz factor, γ	46.61	29.38	30.99	-
FWHM bunch length, Δt_b	4.30	6.90	4.07	fs
FWHM energy spread, ΔE	104	63	77	%
RMS longitudinal emittance, $\varepsilon_{\|\|}$	17.01	11.32	9.95	fs-MeV
FWHM vertical size, Δx	1.21	1.11	1.77	μm
FWHM horizontal size, Δz	1.23	1.59	1.82	μm
FWHM vertical divergence, $\Delta x'$	2.92	1.60	3.11	rad
FWHM horizontal divergence, $\Delta z'$	1.85	1.47	3.11	rad
RMS vertical emittance, ε_x	0.84	0.26	0.39	μm-rad
RMS horizontal emittance, ε_z	0.85	0.33	0.38	μm-rad

Cristian Bontoiu, PhD Thesis

A probable laser facility for the first proof-of-concept experiment

ELIMAIA-ELIMED

Max laser energy	10 J
Max Laser intensity @FWHM	Up to 3×10^{21} W/cm^2
Focal spot size	< 3µm diameter
Encircled laser energy	>30% @ FWHM >60% @$1/e^2$
Laser Intensity Contrast (ns-ASE)	$<10^{-10}$
Laser pulse width	<30 fs
Laser repetition rate	single shot; 0.5 Hz in burst mode
Additional features	GDD (Group Delay Dispersion) and TOD (Third Order Dispersion) control
Laser Pointing stability on target	<3 µrad

https://up.eli-laser.eu/equipment/elimaia-elimed-679543007

A probable laser facility for the first proof-of-concept experiment

Laser Power		350 TW
Energy per pulse		>7 J
Pulse duration		≤ 25 fs
Focusing surface		36 μm^2 or better
Max power density (at the target)		$8.82 \cdot 10^{20}$
$I^*\lambda^2$		$5.64 \cdot 10^{20}$
Contrast ratio @100 ps (ASE)		> 10^{10}
Repetition rate		1 Hz
Protons Ions	Max energy	50 MeV
	Particle per pulse (at 30 MeV)	10^{11} MeV^{-1} Sr^{-1}
	Energy spread	100%
	Beam divergency (max)	±20°
Eletrons	Max energy	3 GeV
	Particles per pulse	10^9
	Beam divergency (max)	± 20 mad
Neutrons	Max energy	20 MeV
	Particles per pulse	10^{10}
	Energy spread	100
	Beam divergency	Isotropic
Gamma X-beams	Synchrotron radiation of the electrons inside the plasma or breemsstrahlung	
	Energy	up to 80 MeV

I-LUCE

INFN LNS

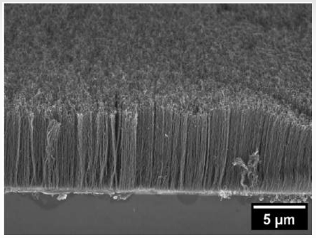
Courtesy of
Prof. **Pablo Cirrone**

We have a collaboration in **Geant4** simulations (Geant4-INFN)

INFN contribution

CNT target R&D

INFN Roma with
INFN Ferrara support



Physics in structured solids & radiation emission

INFN Ferrara & INFN Milano

Application development

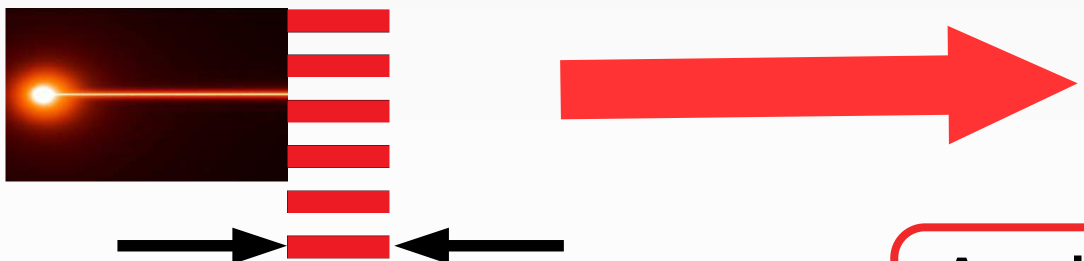
INFN Milano & INFN Ferrara

- Compton scattering
- Bremsstrahlung

Illya Drebot
INFN Milano

Let's dream about applications

Laser **target**



nC 20-40 MeV
e- beam source

0.5 mm with substrate

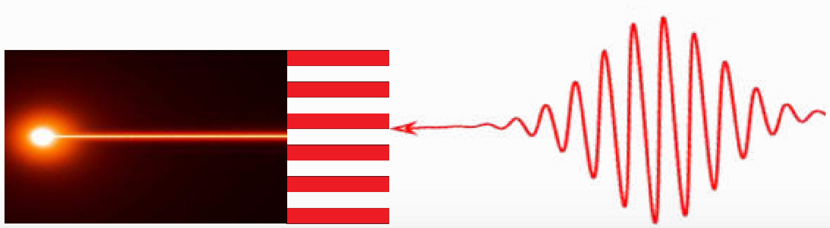
Accelerators & light sources

Radiation damage

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

W target

Radiation therapy



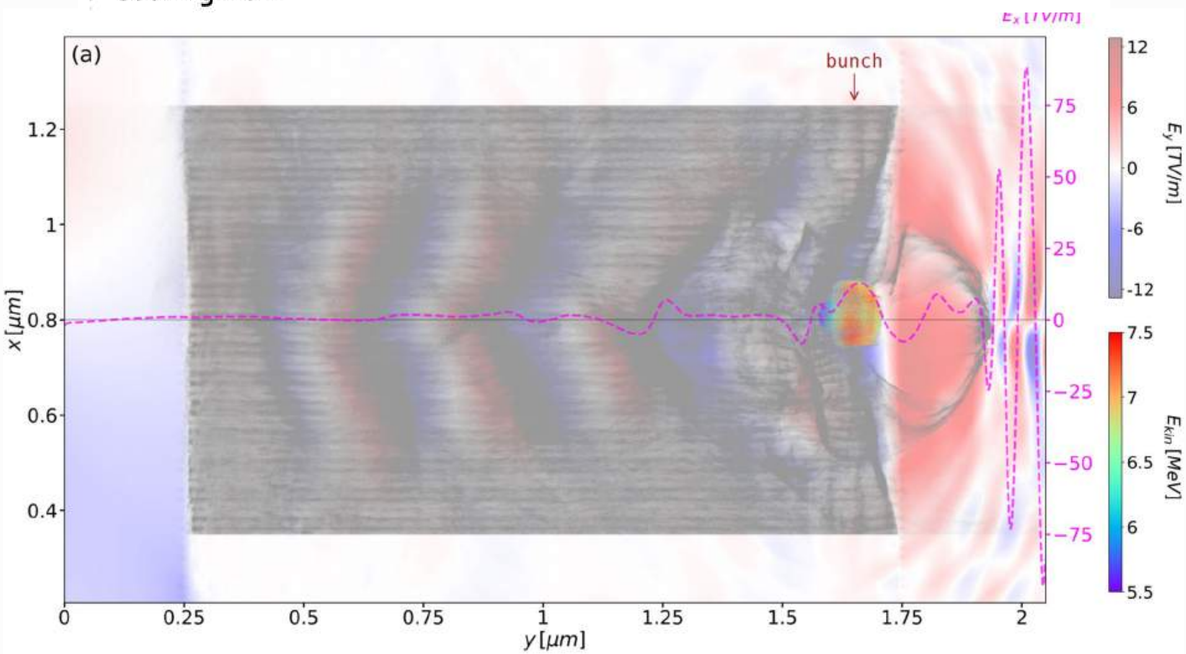
Compton scattering

Imaging

Other activity of NanoAcc: TeV/m “Catapult” (ballistic) accelerator with graphene layers

TeV/m catapult acceleration of electrons in graphene layers

Cristian Bonțoiu[1,2]✉, Öznur Apsimon[2,5], Egidijus Kukstas[1,2], Volodymyr Rodin[1,2], Monika Yadav[1,2], Carsten Welsch[1,2], Javier Resta-López[3], Alexandre Bonatto[4] & Guoxing Xia[2,5]



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	–

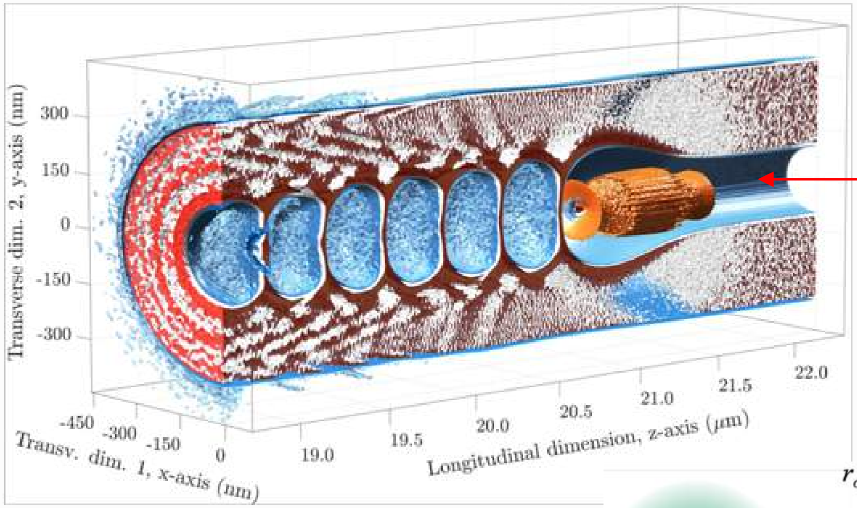
Ultra-short e-pulses, Δt=0.21 fs
E_{kin}=6 MeV gain in ~ 1 μm
Q=2.55 pC
Low emittance: 300 pm-rad

Method to generate few MeV sub-femtosecond e-bunches
Several bunches generated before the full damage of the structure

Other activity of NanoAcc: beam-driven plasma acceleration

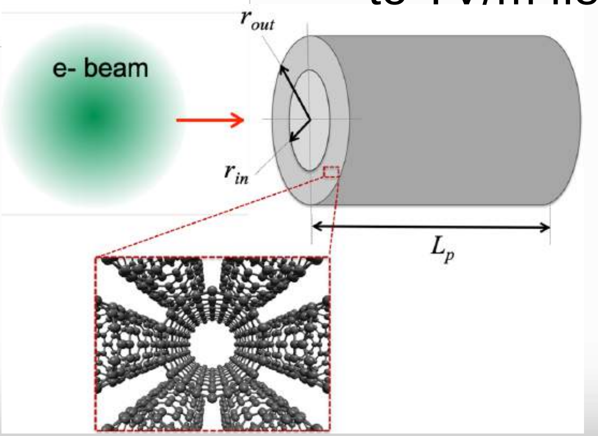
PetaVolts per meter Plasmonics: Snowmass21 White Paper

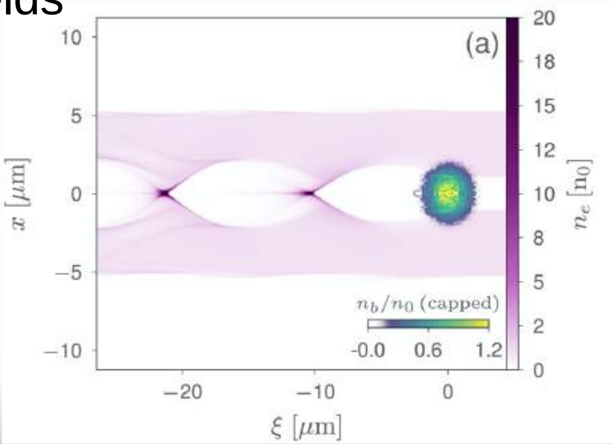
Aakash A. Sahai,[1,*] Mark Golkowski,[1] Stephen Gedney,[1] Thomas Katsouleas,[2]
Gerard Andonian,[3] Glen White,[4] Joachim Stohr,[4] Patric Muggli,[5] Daniele Filipetto,[6]
Frank Zimmermann,[7] Toshiki Tajima,[8] Gerard Mourou,[9] and Javier Resta-Lopez[10]



Driver: ultra-short (< 1 μm), high intensity (>100 kA) electron bunch

Micron- or nano-size hollow channel PIC simulations prediction of 100-GV/m to TV/m fields





A. Bonatto, et al.,
Phys. Plasmas **30**, 033105 (2023)

NanoAc 2024: https://forum.icmuv.uv.es/event/3/

NanoAc 2024

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

Invited speakers:

Sultan Dabagov (INFN, Italy)

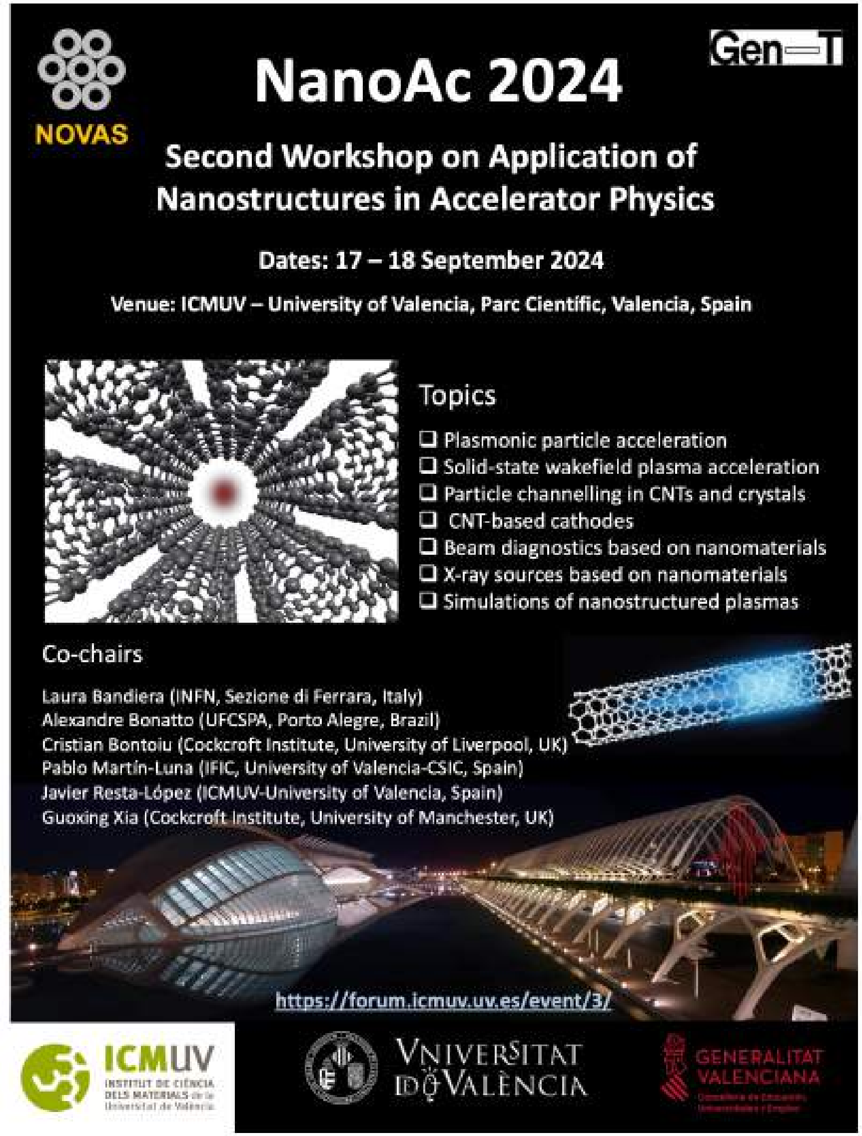
Giancarlo Gatti (CLPU, Spain)

Jorge Vieira (IST, Portugal)

Frank Zimmermann (CERN, CH)

Now open for registration and contributions

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

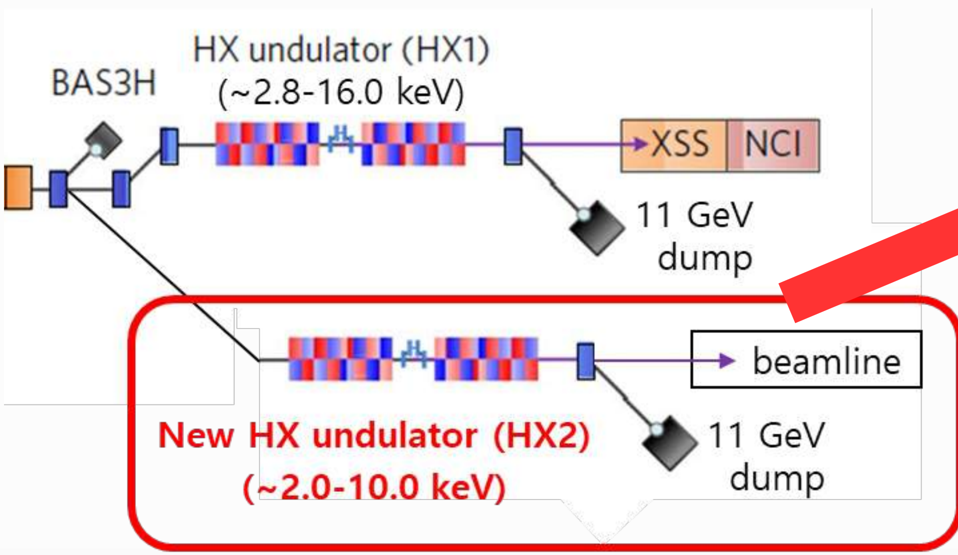


Very recent collaborations

Since November 2023: collaboration with Pohang Acceleration Laboratory, Korea

POHANG ACCELERATOR LABORATORY

HX2 upgrade plan: Attosecond & TW-scale HX FEL



Attosecond & TW- XFEL:
Laser modulation section:
Peak current enhancement by enhanced SASE

Courtesy of
Dr. **Inhyuk Nam**

Extreme X-ray FEL intensity by nano-focusing

POHANG ACCELERATOR LABORATORY

Parameters of future undulator:

Peak power = 2 TW,

X-ray energy = 10 mJ

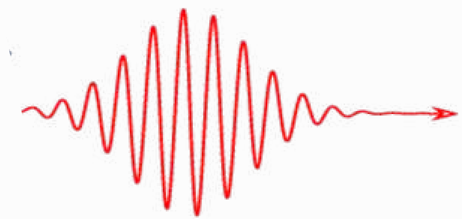
Pulse duration = 5 fs

Focal spot size = **10 nm**

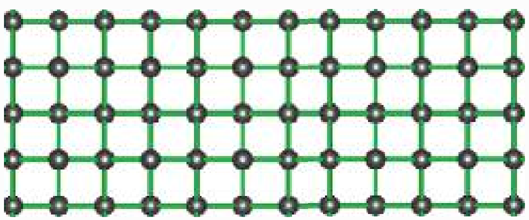
Intensity = ~ 1 x 10^{24} W/cm^2

Idea: plasma acceleration by X-rays

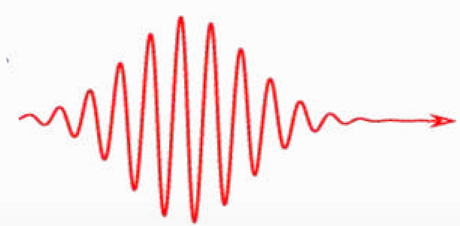
X-ray pulse



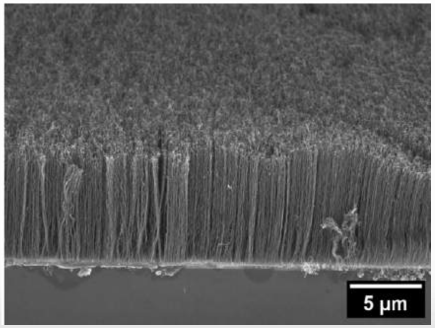
Oriented crystal



X-ray pulse



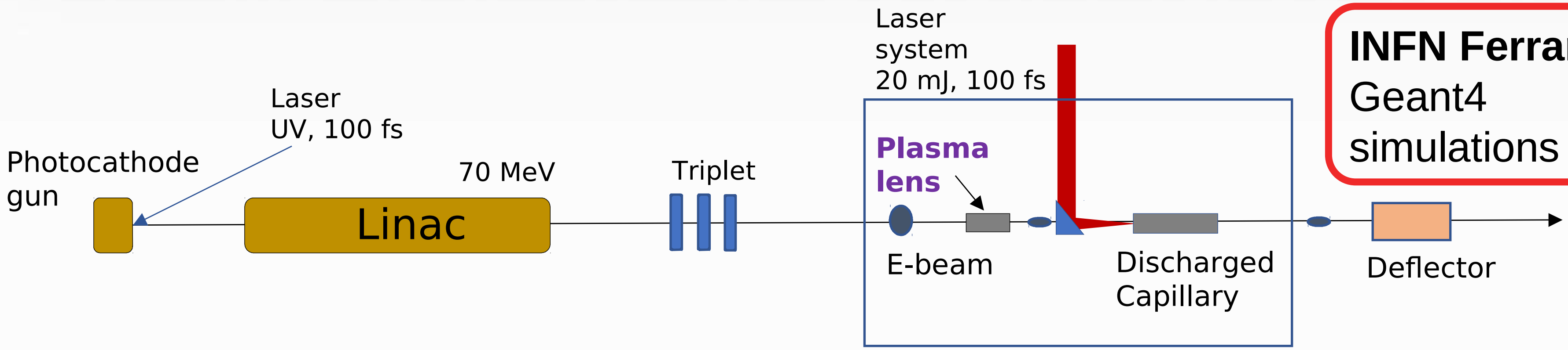
Nanotubes



INFN Ferrara:
physics in crystals
INFN Ferrara & Roma:
targets

Other activity with PAL: PAL-eLABs

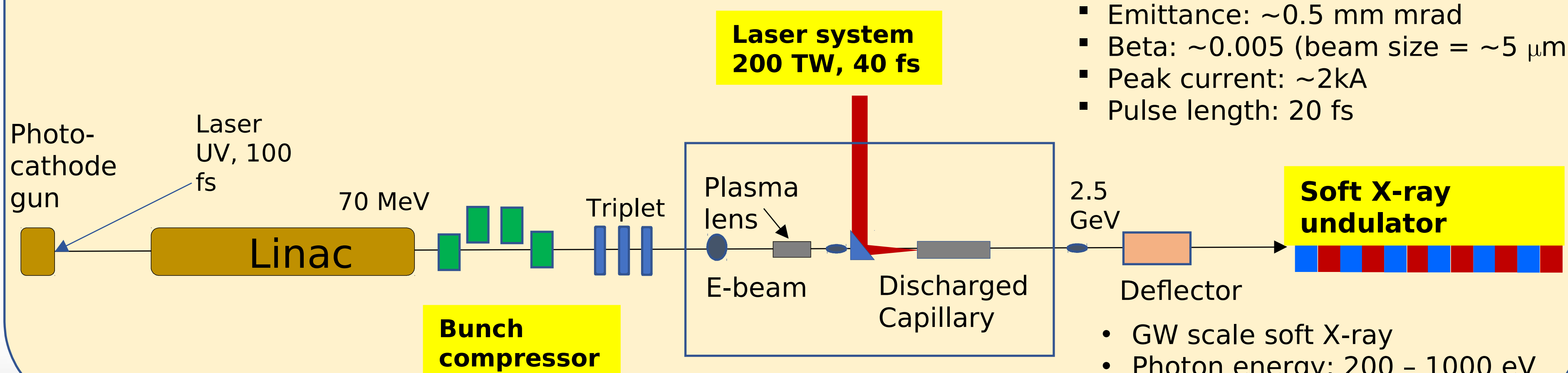
PAL-eLABs Advanced Accelerator R&D beamline (installed, commissioning in 2024)



INFN Ferrara: Geant4 simulations

PAL-eLABs Advanced Accelerator R&D beamline (Future plan)

- E-beam requirement: 50 pC
- Emittance: ~0.5 mm mrad
- Beta: ~0.005 (beam size = ~5 μm)
- Peak current: ~2kA
- Pulse length: 20 fs

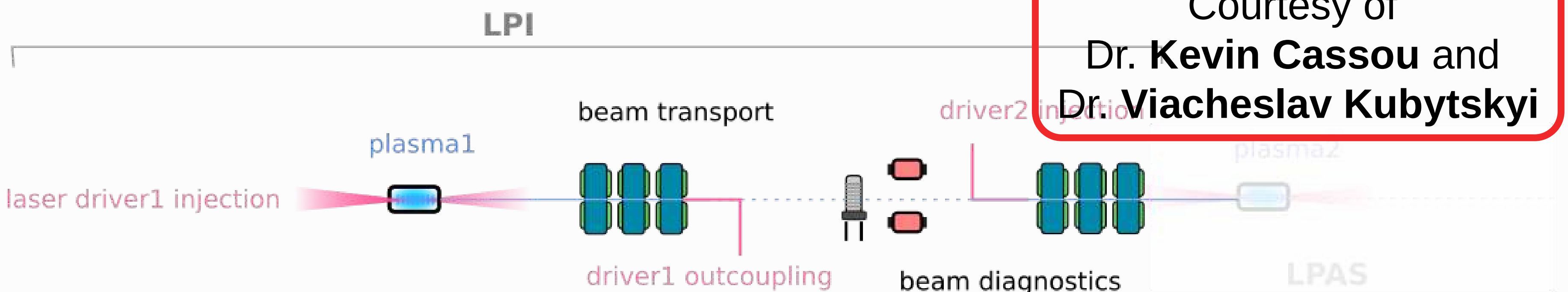


- GW scale soft X-ray
- Photon energy: 200 – 1000 eV

Since March 2024: collaboration with the PALLAS Project

Test facility for laser-plasma injector optimisation towards RF control reliability

In the context of advanced accelerator high quality beam laser plasma injector (LPI) for **EuPRAXIA** [1] preparatory technical design phase and future high gradient accelerator R&D at IJClab [2]: 10 Hz 250MeV LPI test facility to improve **quality and stability of e- beam generated by laser-plasma accelerator**.



Courtesy of Dr. **Kevin Cassou** and Dr. **Viacheslav Kubytskyi**

Plasma target development [3]

- testing various gas cell type
- Continuous flow
- In-lin integration

INFN Ferrara:
Geant4 simulations&ML

[1] : Assmann, R. W. et al. EuPRAXIA Conceptual Design Report. Eur. Phys. J. Spec. Top. 229, 3675–4284 (2020).
[2] pallas.ijclab.in2p3.fr
[3] Drobniak, P. et al. Random scan optimization of a laser-plasma electron injector based on fast particle-in-cell simulations. Phys. Rev. Accel. Beams 26, 091302 (2023), Drobniak, P. et al. Two-chamber gas target for laser-plasma accelerator electron source. Preprint at http://arxiv.org/abs/2309.11921 (2023).

PALLAS Project: Machine Learning

A modeling of the **full beamline** using **Geant4** is **required** for collimator design.

Dataset and **first ML** model generated **by PALLAS**

INFN Ferrara: implementation of plasma acceleration **ML model into Geant4** to create a **Geant4 electron beam source** based on plasma acceleration

```
#ifndef B1PrimaryGeneratorAction_h
#define B1PrimaryGeneratorAction_h 1

#include "G4VUserPrimaryGeneratorAction.hh"
#include "globals.hh"
#include "G4GeneralParticleSource.hh"
#include "G4ParticleGun.hh"
#include <memory>
#include <onnxruntime_c_api.h>
#include <onnxruntime_cxx_api.h>
class G4ParticleGun;
class G4Event;
```

```
PrimaryGeneratorAction::PrimaryGeneratorAction(): G4VUserPrimaryGeneratorAction(),
    fParticleGun(0),
    fEnvelopeBox(0)
{
    G4int n_particle = 1;
    fParticleGun  = new G4ParticleGun(n_particle);

    // default particle kinematic
    fParticleGun->SetParticleDefinition(
        G4ParticleTable::GetParticleTable()->FindParticle("e-"));

    //Neural network: create onnx session
    Ort::Env env(ORT_LOGGING_LEVEL_WARNING, "plasma");
    Ort::SessionOptions session_options;
    session_options.SetIntraOpNumThreads(1);
    auto sessionLocal =
        std::make_unique<Ort::Session>(env, "model2.onnx", session_options);
    fSession = std::move(sessionLocal);

    // Get input node information
    fMemory_info = Ort::MemoryInfo::CreateCpu(
        OrtAllocatorType::OrtArenaAllocator, OrtMemTypeDefault);
```

Conclusions

- **Plasma acceleration** in structured solid has the potential to produce **TV/m fields**. All you need is a drive **beam** and a very compact **target**.

- **INFN** groups **collaborate** with E336 experiment at **SLAC FACET II** Facility (beam-driven plasma acceleration in nanostructures and crystals), **University of Valencia** (laser-driven plasma acceleration in nanostructures), **Pohang Accelerator Laboratory** (X-ray driven plasma acceleration in crystals and nanostructures), **PALLAS** Project (Machine Learning & Geant4) as well as **INFN LNS** (Laser & Geant4).

- **Our Mission**: to develop the **concept of plasma acceleration** in **structured solids** through **simulations** and **target samples** for the **first proof-of-concept experiments**.


GANGNAM STYLE
Thank you! 감사합니다 !