GA 101032975

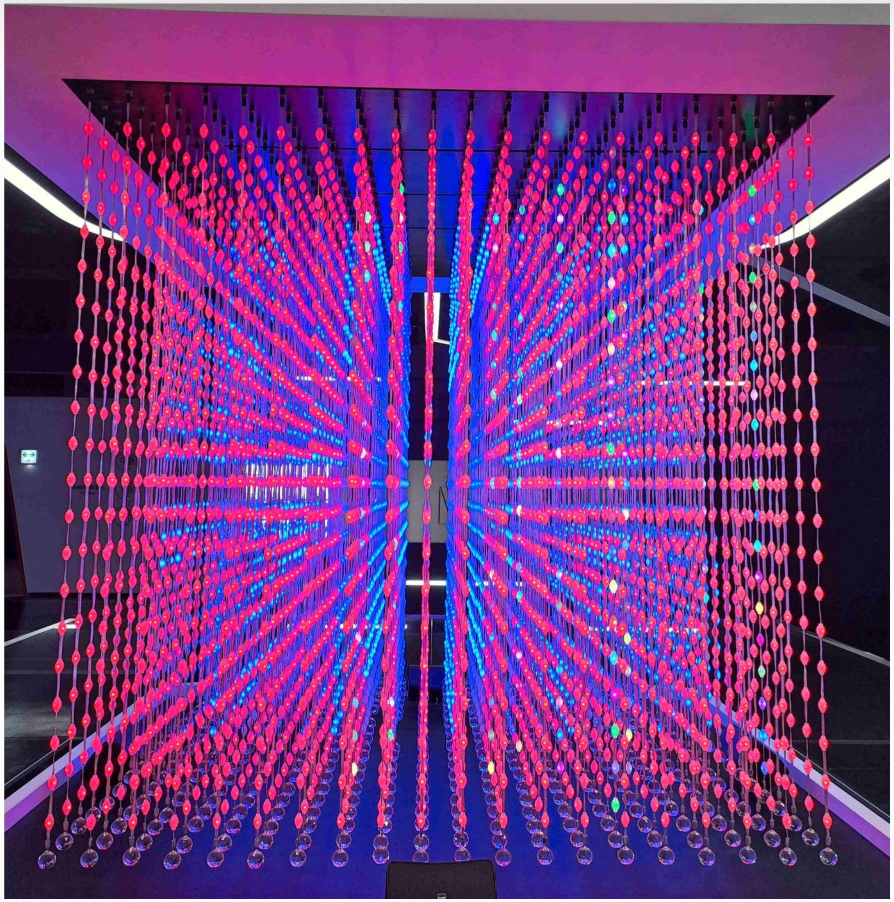
(is finished)

Oriented crystals and nanostructures and their applications

Dr. Alexei Sytov

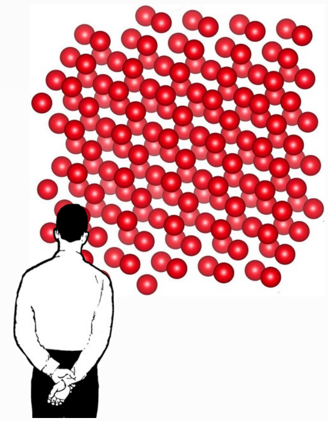
NanoAc Workshop 2025

How an oriented crystal looks like

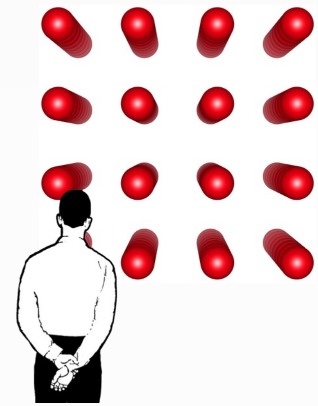


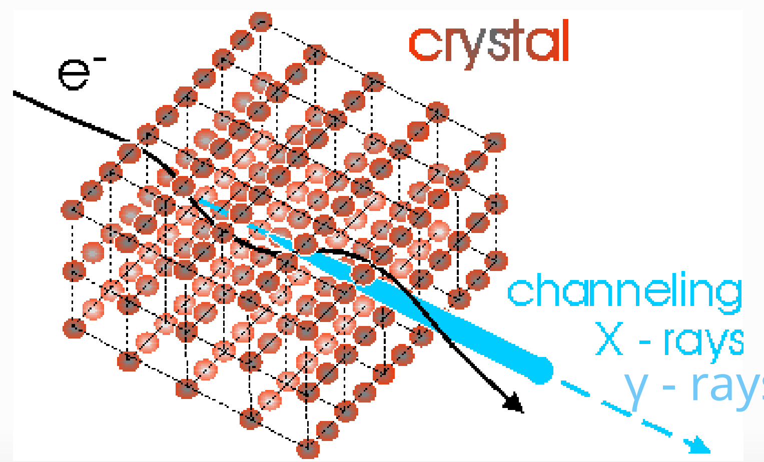
from National Science Museum, Daejeon, Korea

Non-oriented crystal

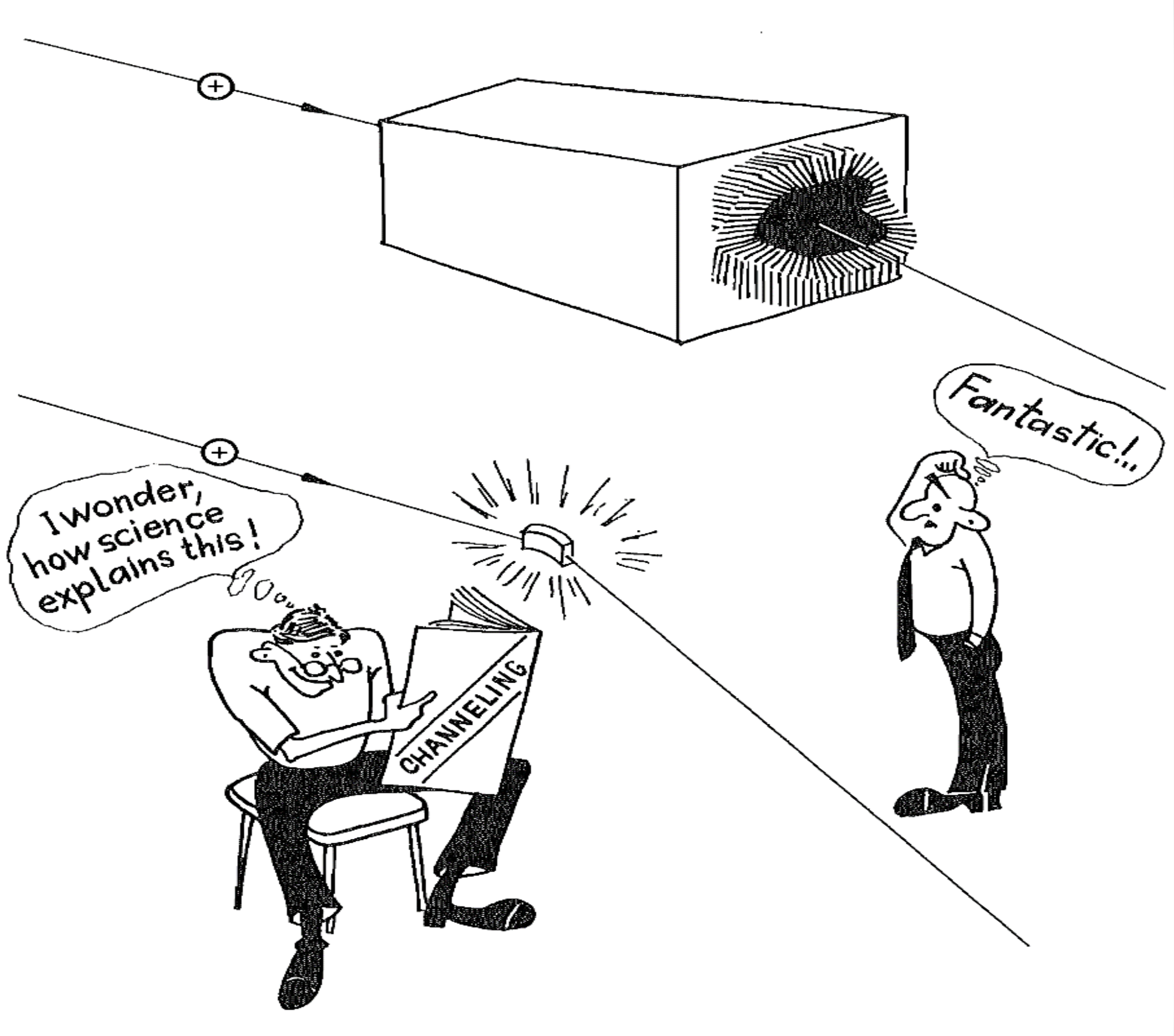


Oriented crystal



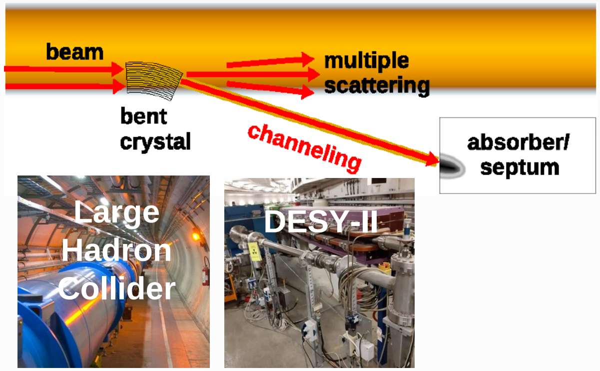


The world of the channeling effect

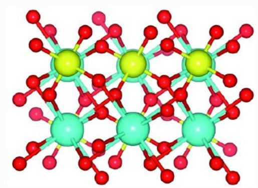


Applications*

Crystal-based collimation or beam extraction from an accelerator

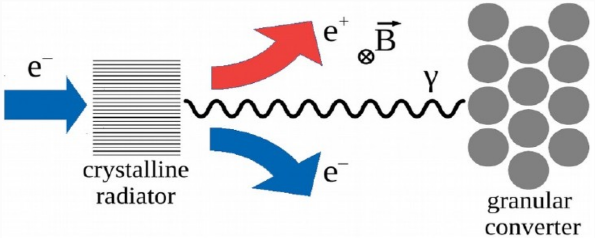


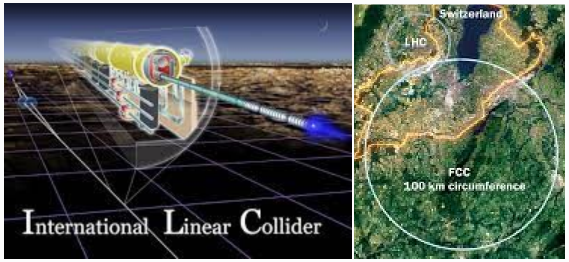
Ultrashort crystalline calorimeter



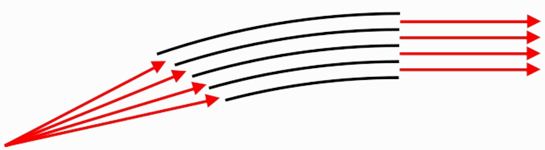
Gamma-ray Space Telescope

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

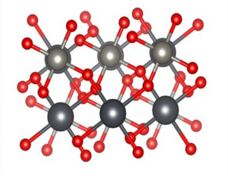




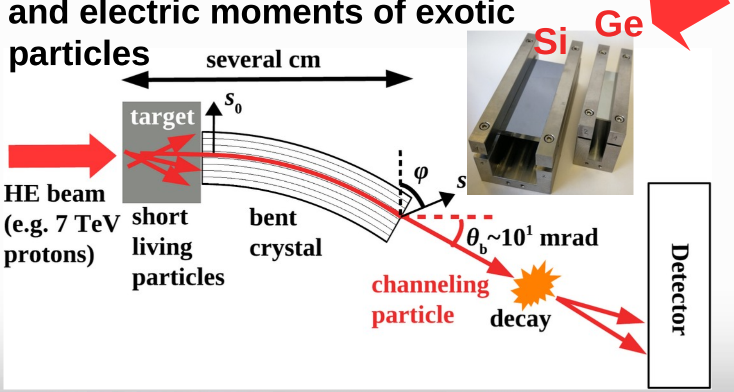
Beam focusing



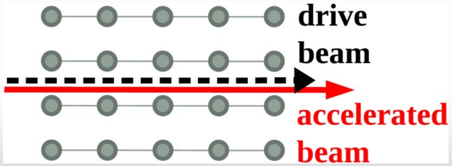
Oriented crystals



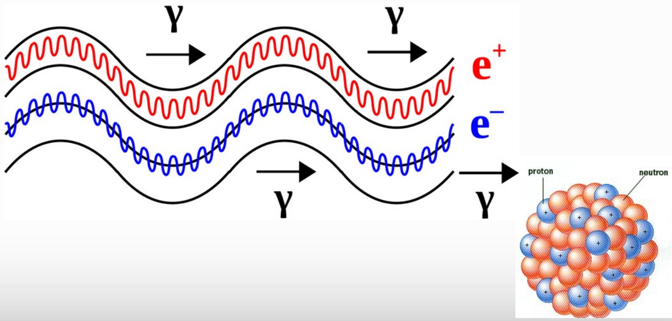
Measurement of dipole magnetic and electric moments of exotic particles



Plasma acceleration



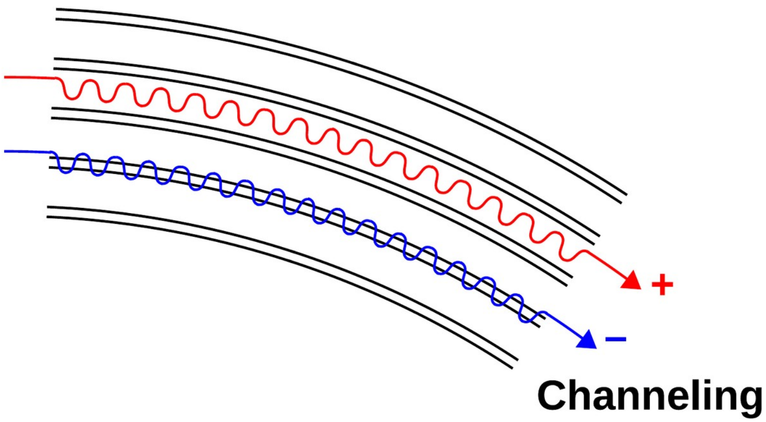
X and γ-ray source for nuclear and medical physics



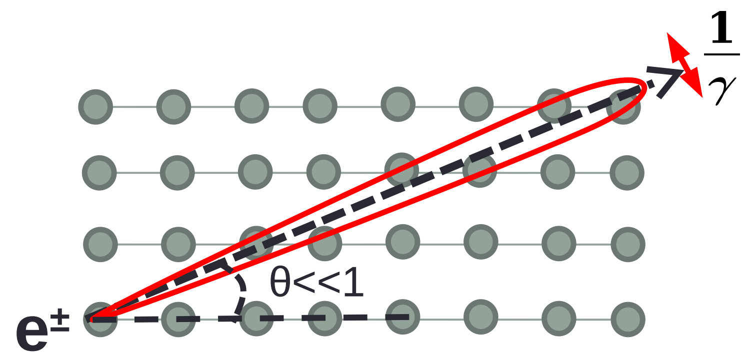
*A. Sytov et al. Journal of the Korean Physical Society 83, 132-139, (2023)

The idea: MC simulations of coherent effects in a crystal

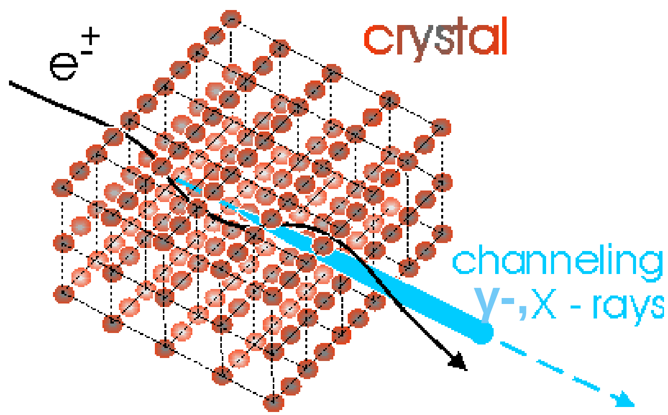
Channeling*



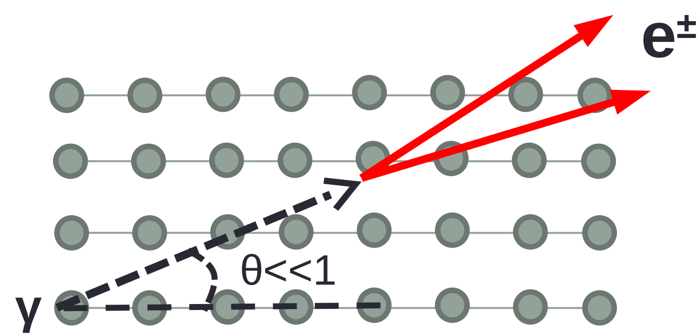
Coherent bremsstrahlung***



Channeling radiation**



Coherent pair production****

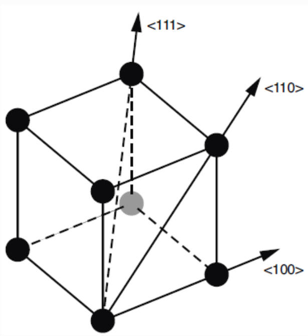


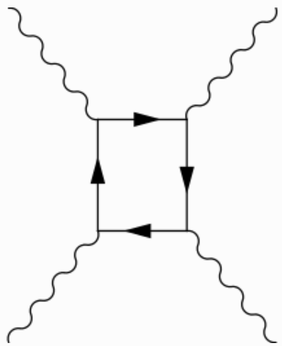
*J. Stark, Zs. Phys. 13, 973–977 (1912); J. A. Davies, J. Friesen, J. D. McIntyre, Can J. Chem. 38, 1526–1534 (1960)
**M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)
***B. Ferretti, Nuovo Cimento 7, 118 (1950); M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).
**** H. Überall, Phys. Rev. 103, 1055 (1956).

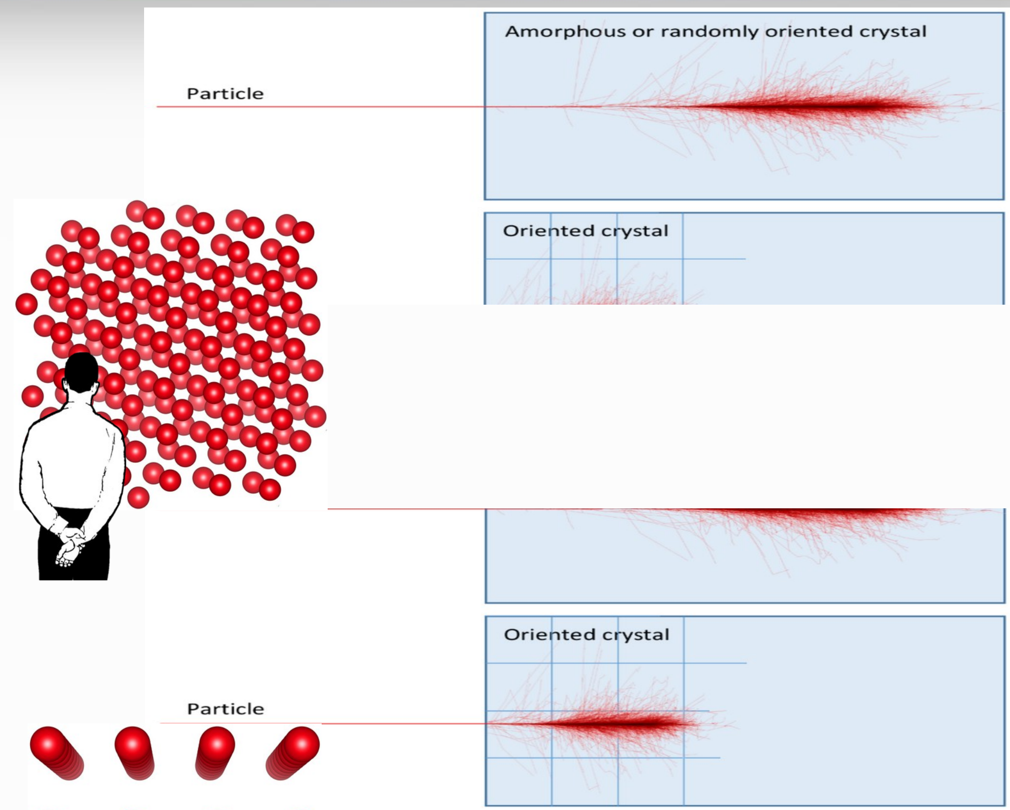
Electromagnetic shower acceleration

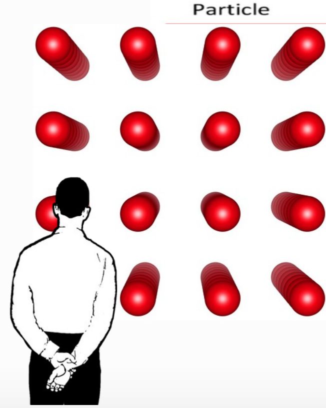
Axial field
10^{11} V/cm

Approaching the **Schwinger limit** starting from few **GeV** for **e+/e-**









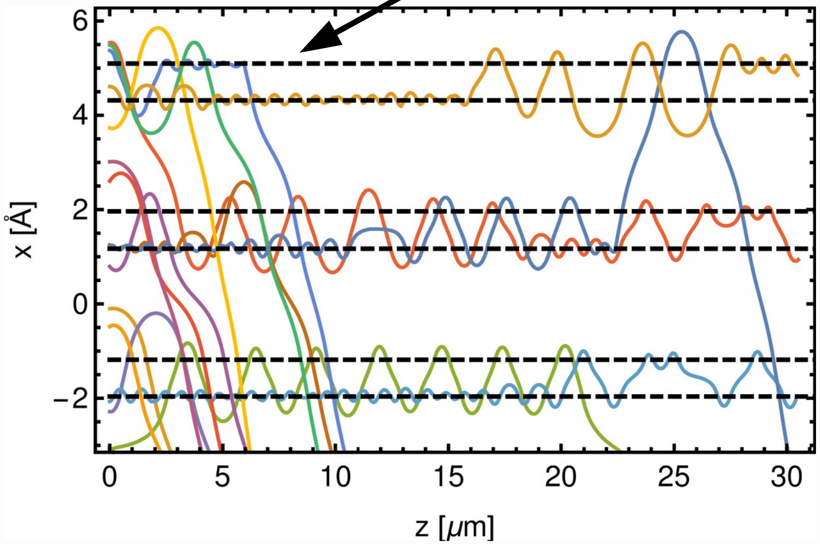
The **radiation** intensity and the **pair production** cross-section **drastically increase** in **oriented crystals!**

Shower development in the field of axes is **accelerated**. The radiation length is considerably reduced.

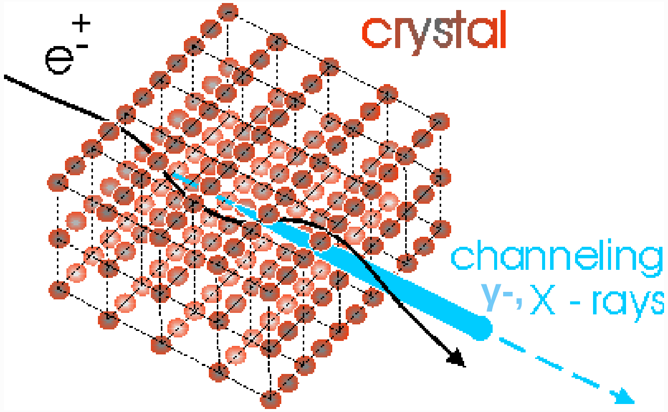
Geant4 G4ChannelingFastSimModel

Main conception – simulation of classical trajectories of charged particles in a crystal in averaged atomic potential of planes or axes. Multiple and single **scattering simulation** at every step

Crystal planes



channeling*



Baier-Katkov formula:
integration is made over the classical trajectory

$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{\left[(E^2+E'^2)(v_1 v_2 - 1) + \omega^2/\gamma^2\right]}{2E'^2} e^{-ik'(x_1 - x_2)}$$

A.I. Sytov, V.V. Tikhomirov. NIM B 355 (2015) 383–386.
L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res., Sect. B 355, 44 (2015)
***A. Sytov et al. Journal of the Korean Physical Society 83, 132–139 (2023)**
A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

Channeling, radiation and coherent pair production models (2022-2024)

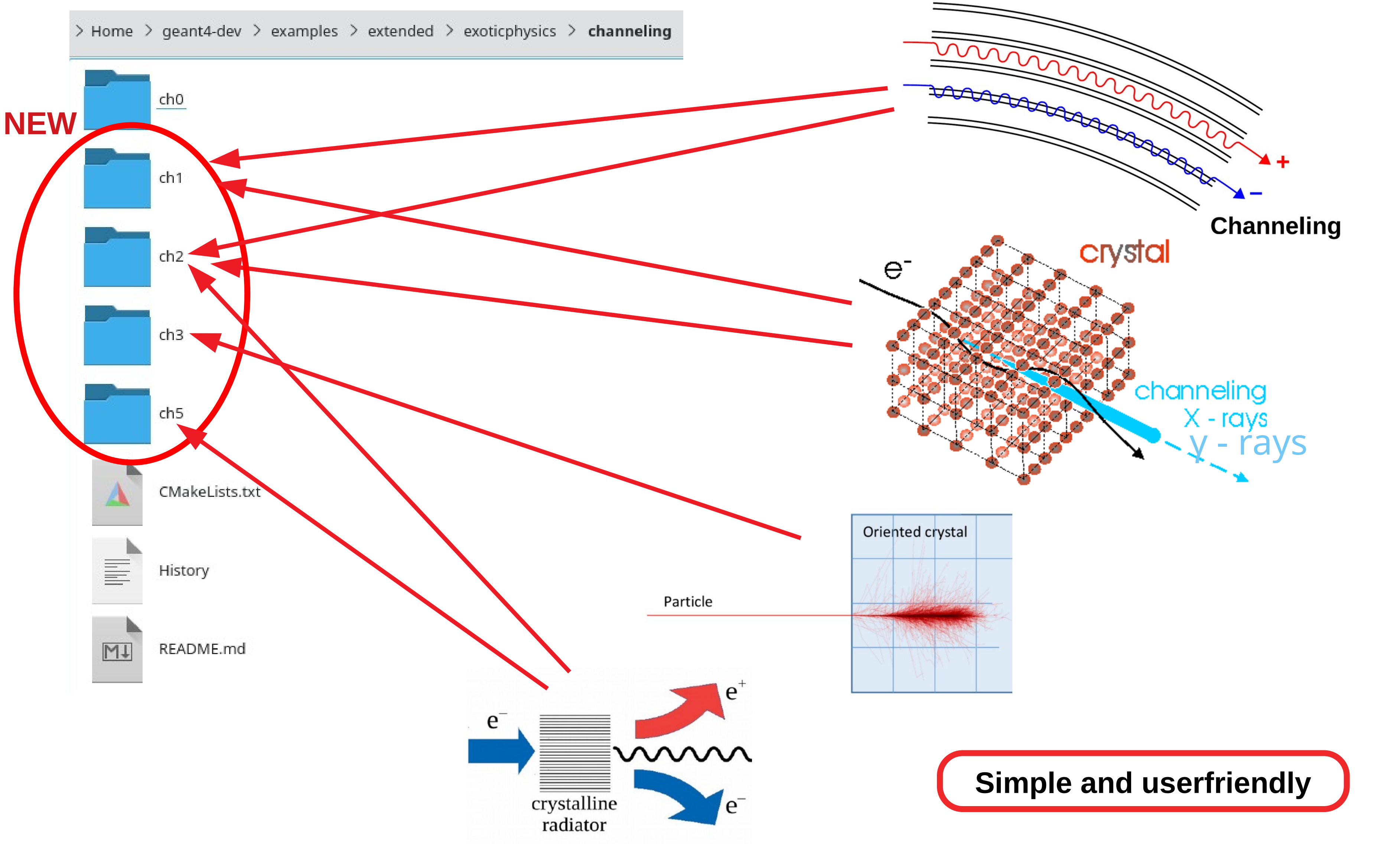
Home > Geant4 > geant4-v11.3.0 > source > parameterisations > channeling > src

- G4BaierKatkov.cc ← **Radiation** spectrum, generation of secondary photons (Baier-Katkov method)
- G4ChannelingFastSimCrystalData.cc ← Crystal structure input&crystal geometry
- G4ChannelingFastSimInterpolation.cc ← Interpolation of **G4CHANNELINGDATA**
- G4ChannelingFastSimModel.cc ← **Channeling** model
- G4CoherentPairProduction.cc ← **NEW: Coherent pair production** model
- G4VChannelingFastSimCrystalData.cc ← Coulomb scattering and ionization losses models in a crystal

Home > Geant4 > geant4-v11.3.0 > source > physics_lists > constructors > gamma_lepto_nuclear > src

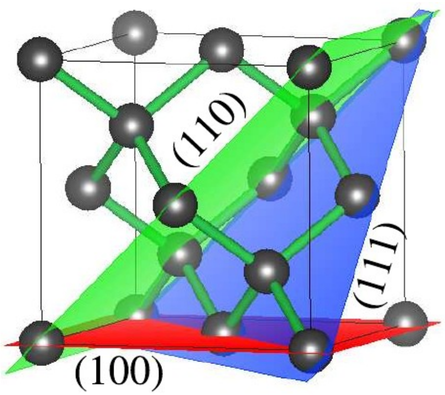
- G4CoherentPairProductionPhysics.cc ← **NEW: Coherent** pair production physics

List of channeling Geant4 examples successfully implemented in 2024-2025



G4CHANNELINGDATA 2.0

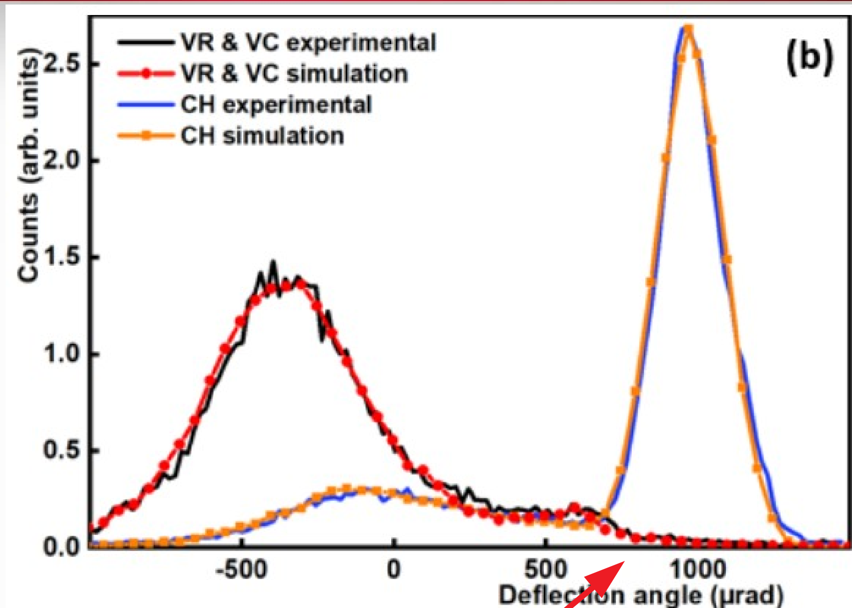
- Diamond_axes_100.dat
- Diamond_axes_110.dat
- Diamond_axes_111.dat
- Diamond_planes_100.dat
- Diamond_planes_110.dat
- Diamond_planes_111.dat
- Ge_axes_100.dat
- Ge_axes_110.dat
- Ge_axes_111.dat
- Ge_planes_100.dat
- Ge_planes_110.dat
- Ge_planes_111.dat
- History
- README
- Si_axes_100.dat
- Si_axes_110.dat
- Si_axes_111.dat
- Si_planes_100.dat
- Si_planes_110.dat
- Si_planes_111.dat
- W_axes_111.dat

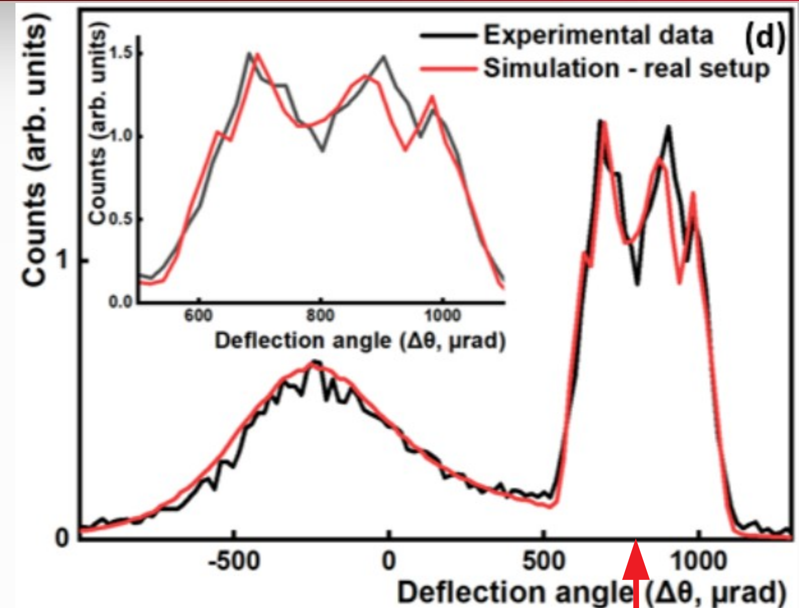


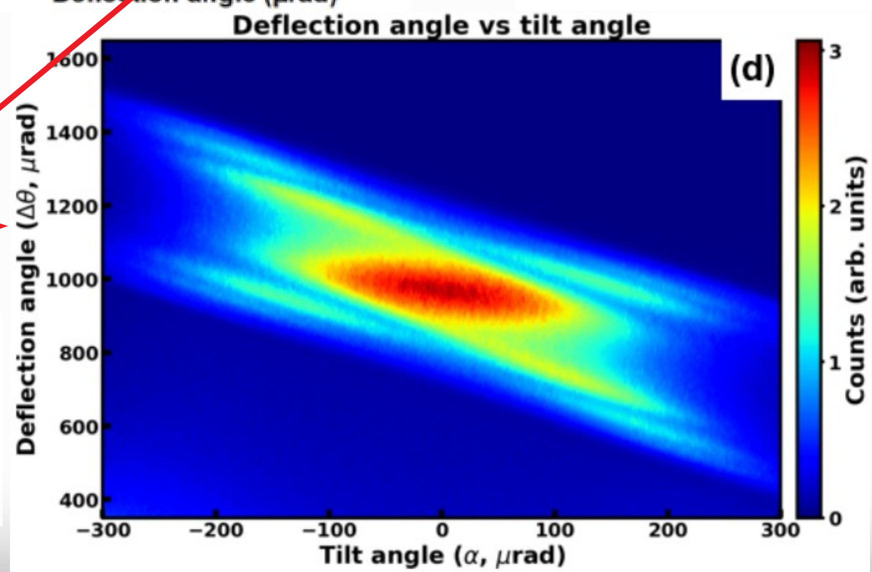
Diamond, Si and Ge: (100), (110), (111), <100>, <110>, <111>
W: <111>

To be extended the next year!

Superfresh experimental validation – channeling of positrons at Mainz Mikrotron MAMI. PRL accepted*

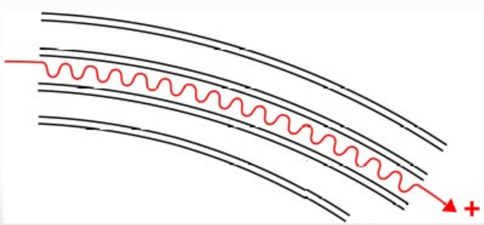






Channeling e+

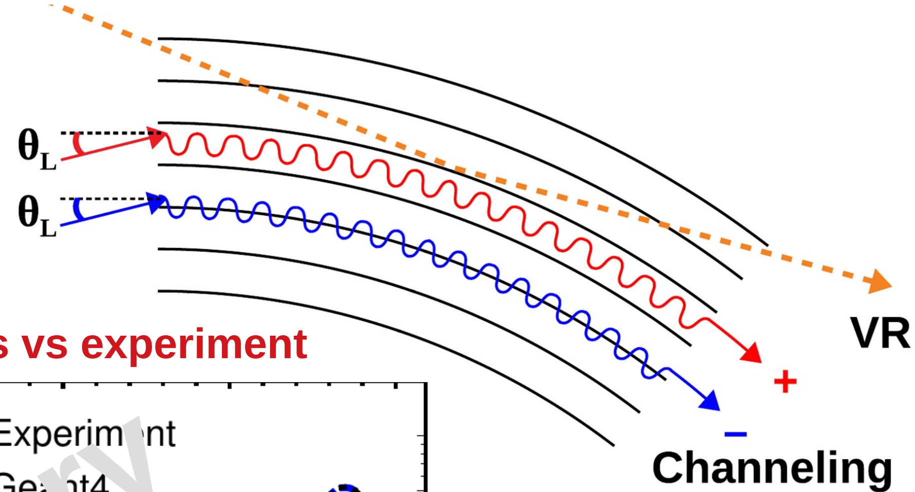
Channeling e+



More Geant4 channeling model validation: quasichanneling oscillations* at SLAC FACET Facility

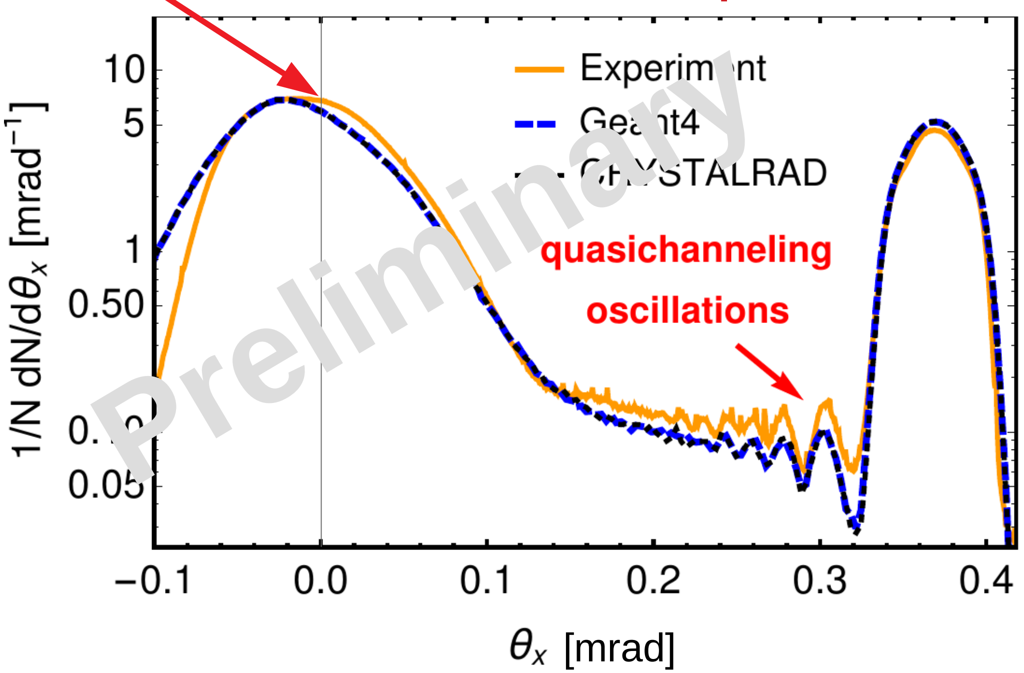
20.35 GeV positrons

60 µm thick bent crystal



volume reflection (VR)

Geant simulations vs experiment



quasichanneling oscillations

channeling

To be submitted for publication soon

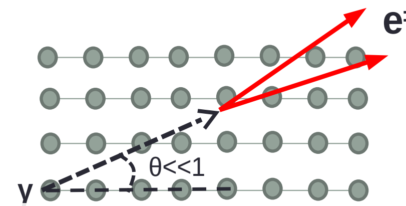
*T. N. Wistisen, ..., and A. Sytov, Phys. Rev. Lett. 119, 024801 (2017)

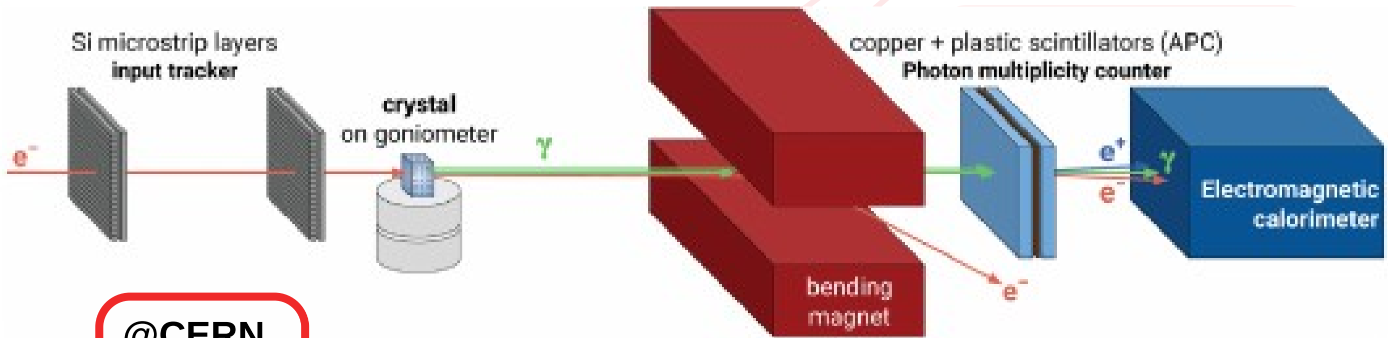
Fresh experimental validation of the radiation model*

Home > Geant4 > geant4-v11.3.0 > source > parameterisations > channeling > src

G4BaierKatkov.cc

Further experimental validation



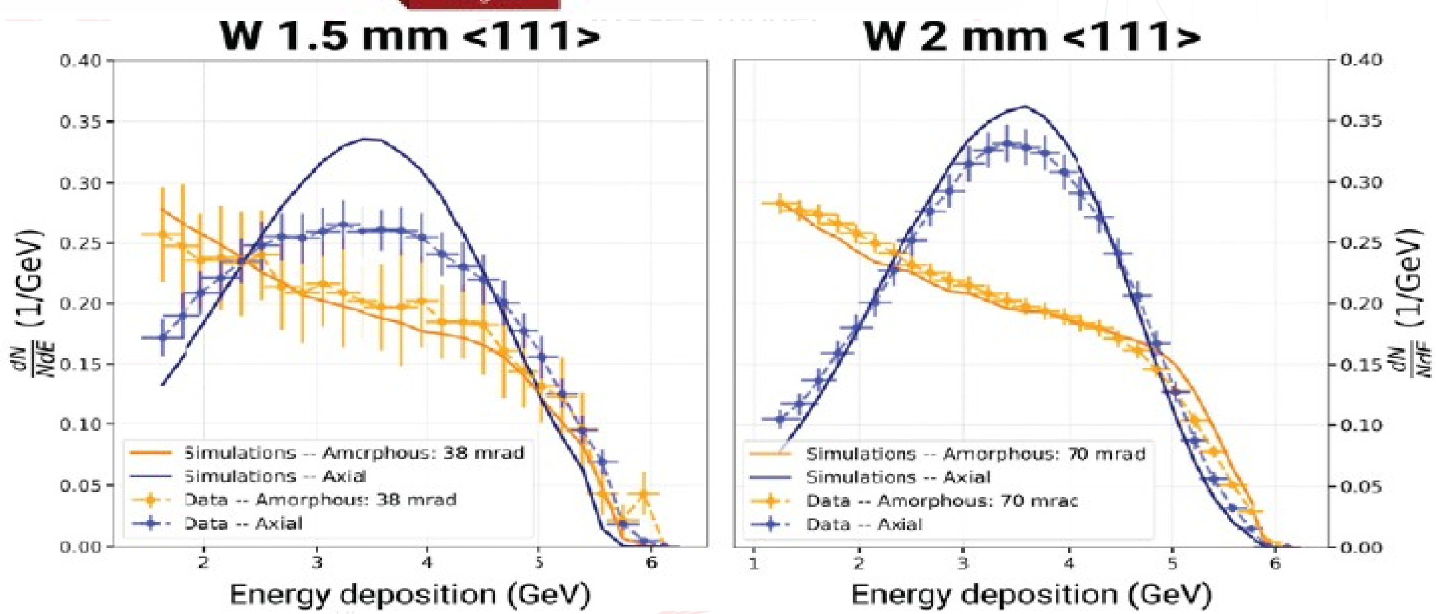


@CERN

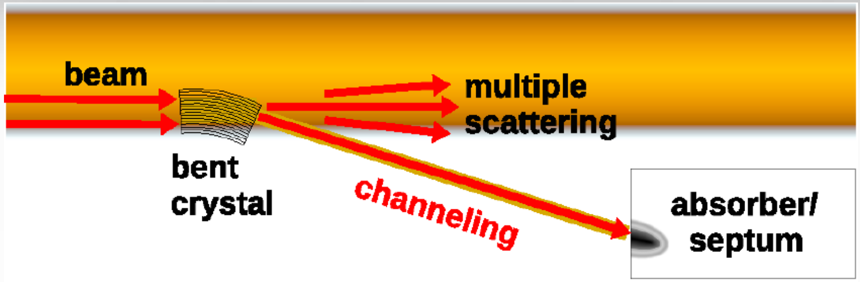
G4CoherentPairProduction.cc

G4VChannelingFastSimCrystalDa

NEW crystal materials and crystallographic directions into **G4CHANNELINGDATA**

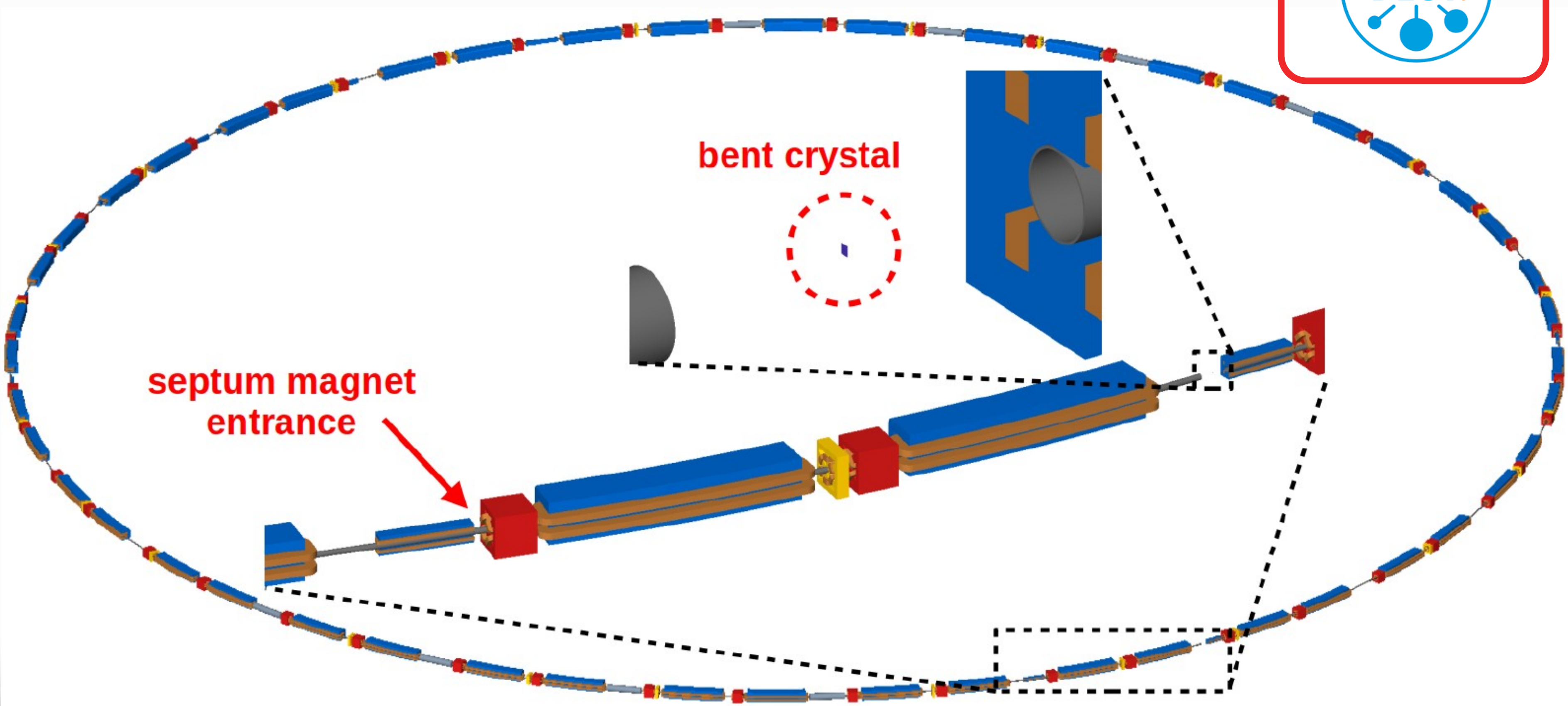


Progress with BDSim: model for crystal-based extraction of electrons from DESY II Booster Synchrotron



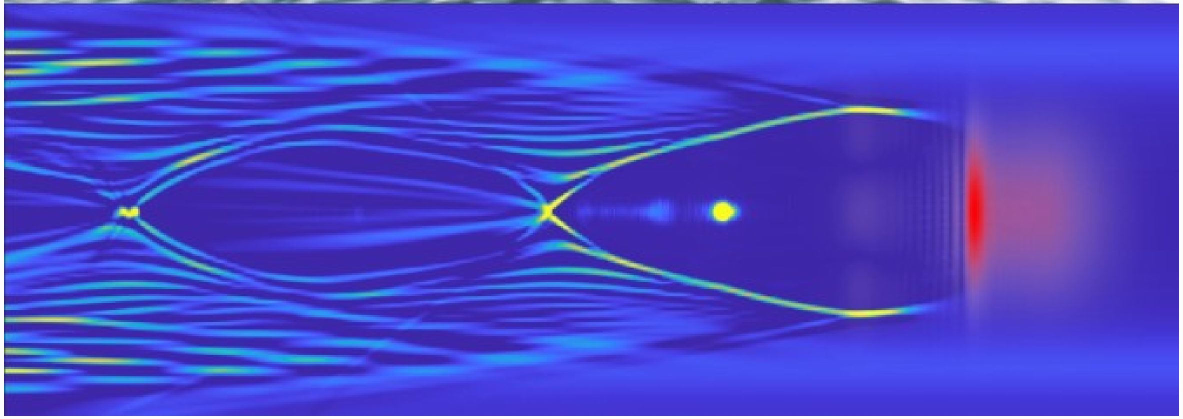
In close collaboration with

DESY.

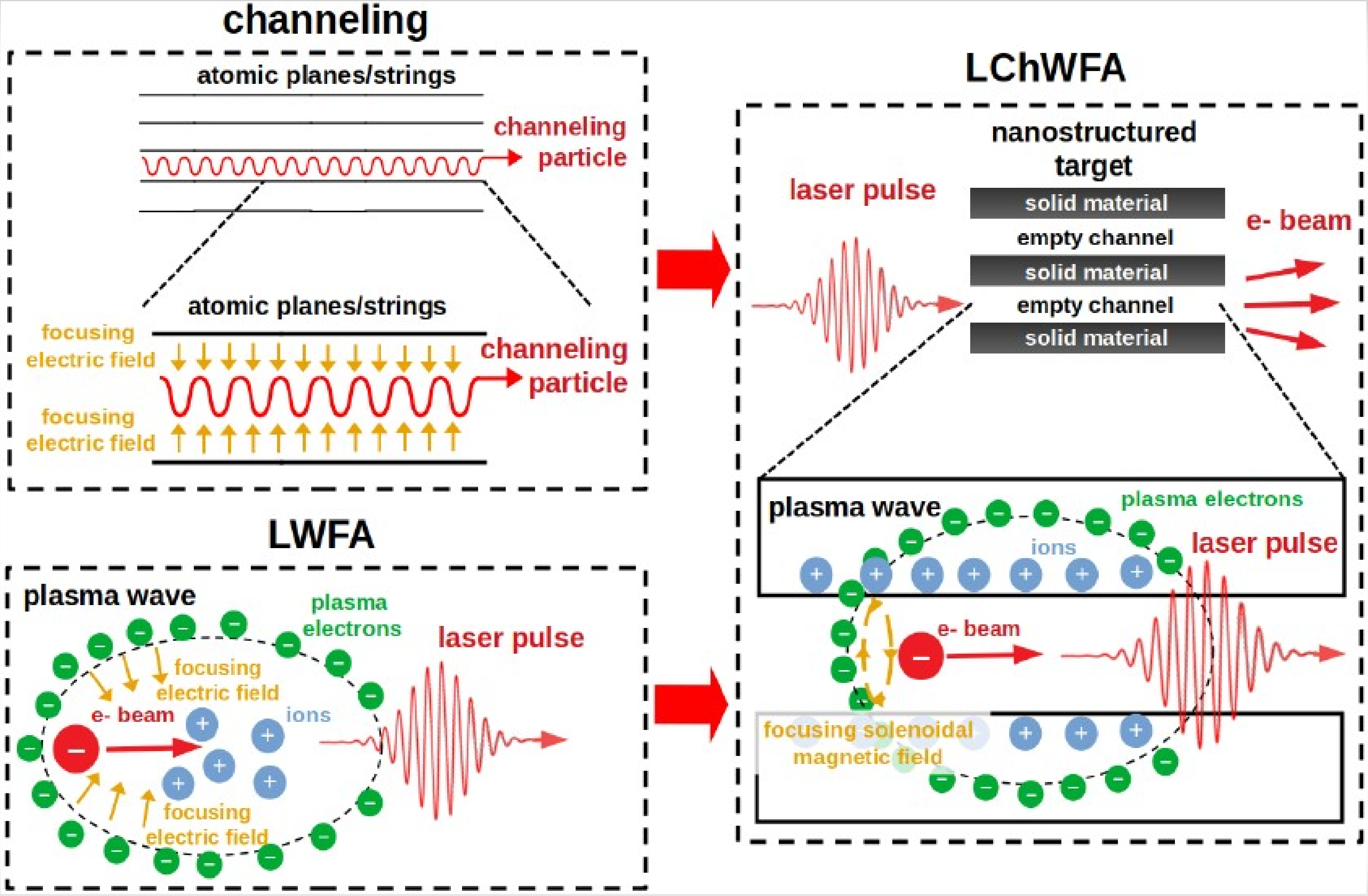


A. Sytov et al. arXiv2412.10715v2 (2024)

Channeling& Geant4 for plasma wakefield acceleration

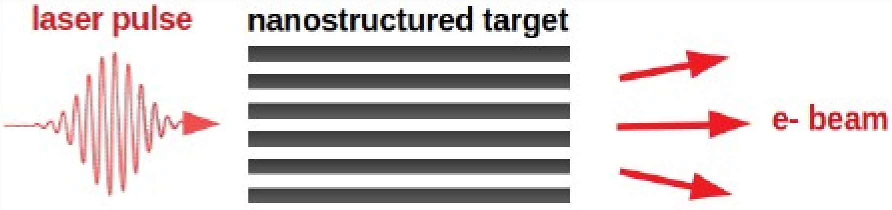


Channeling + LWFA = channeling LWFA



Project NEPTUNE-G4 submitted as Italian FIS Consolidator Grant (waiting for the results)

Neural-network Enhanced Plasma acceleraTion in NanostructurEs:
a Geant4-based simulation platform for modern applications



The **project goal** is to develop a **novel simulation platform** that integrates Machine Learning (**ML**), trained on Particle-In-Cell (**PIC**) simulations of **LWFA** and **channeling LWFA** within the **Geant4** simulation toolkit.

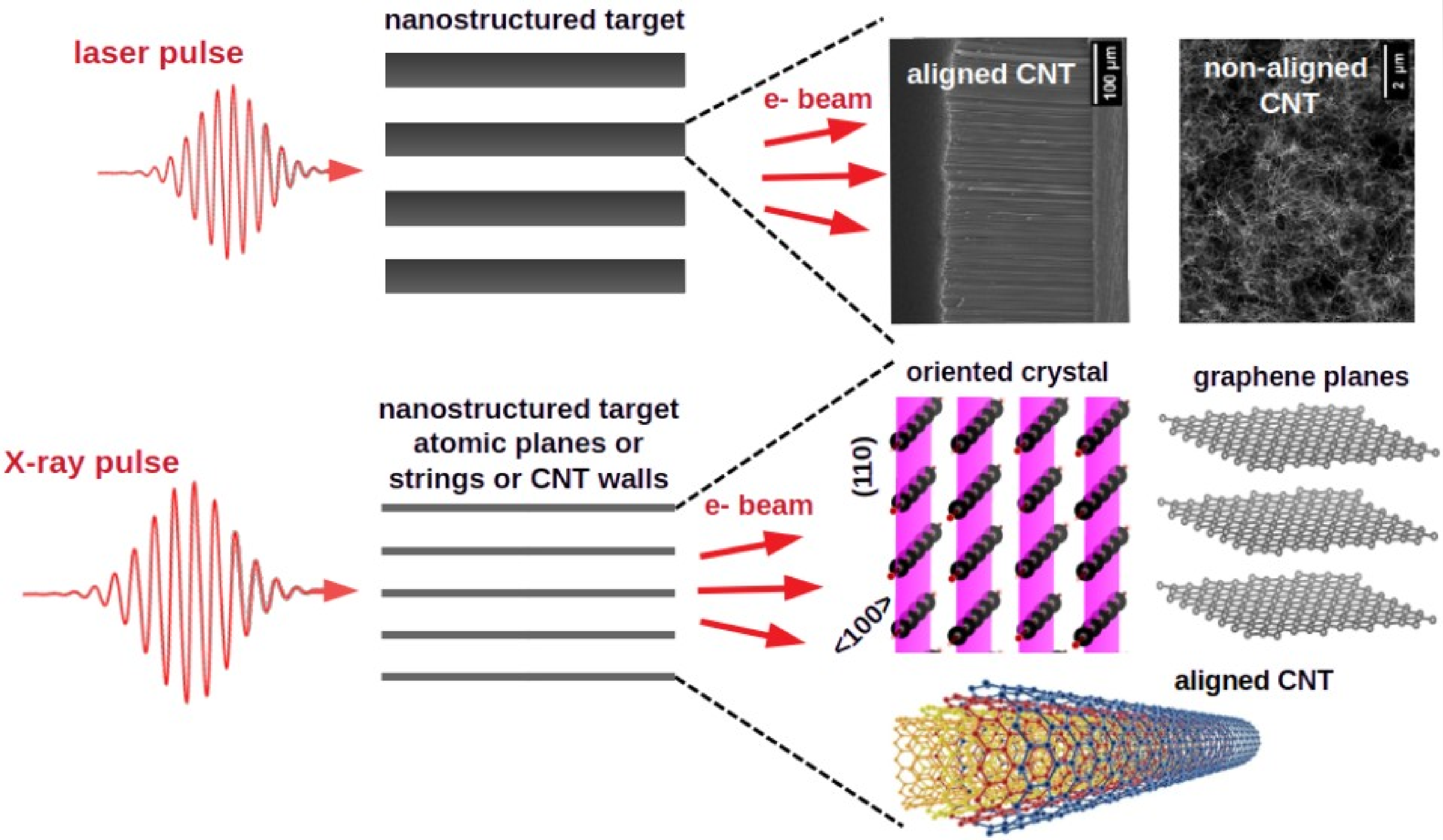
Host institution:

INFN
Istituto Nazionale di Fisica Nucleare

Collaborators

- **NanoAc** Collaboration
- **Sapienza** Università di Roma
- **Pallas** Experiment @IJCLab (France)
- Prof. **Toshiki Tajima** @UCI (US)
- Prof. **Inhyuk Nam** @UNIST (Korea)
- Dr. **Alberto Ribon**, spokesperson Geant4 Collaboration

Channeling LWFA in nanostructures and crystals



T. Tajima, M. Cavenago. PRL 59, 1440 (1987); X. Zhang, T. Tajima et al. PRAB 19, 101004 (2016);
E. Barraza-Valdez, T. Tajima Photonics 9(7), 476 (2022); M.F. Gilljohann et al. JINST 18 P11008
C. Bonţoiu et al. Sci. Reports 13, 1330 (2023); C. Bonţoiu et al.arXiv:2502.00183. Subm. to Sci. Reports.

ML Learning to implement plasma acceleration into Geant4

Implementation of **ML surrogate** model of **laser-driven plasma wakefield acceleration** trained with PIC simulations into Geant4

PIC simulations to generate the dataset

↓

ML surrogate model training

↓

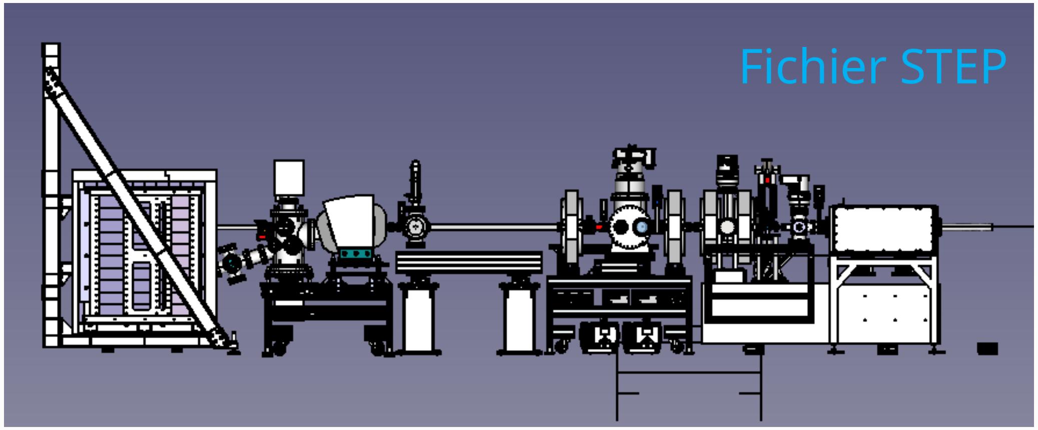
Implementation of the model into Geant4 particle source

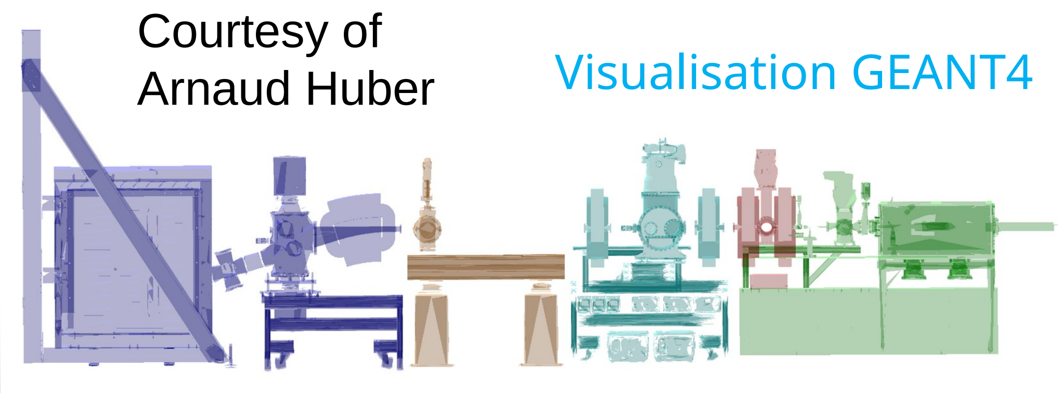
↓

Linking of the model to Gean4 applications

PALLAS Project: **Test facility for laser-plasma injector Partner of EuPRAXIA**

LP2i Bordeaux · université de BORDEAUX · INFN Istituto Nazionale di Fisica Nucleare · cnrs · NUCLÉAIRE & PARTICULES · PALLAS





INFN&Uniroma Sapienza contribution into NanoAc project

Our group within NanoAc project

- **Ferrara** Division **(INFN leader)**. **A. Sytov – national responsible.**
- **LNS** – Laboratori Nazionali del Sud (host of I-LUCE Facility)
- **INFN Roma 1** & **Sapienza** Università di Roma (host of TITAN lab for Nanotubes production)
- **INFN Milano** (expertise in radiation, Compton backscattering).

Our contribution to NanoAc

Leadership in WPs:

- WP5 Nanostructured target fabrication and characterization. **WP Leader I. Rago**.
- WP6 Application studies and prototyping. **WP Leader G. Petringa**.

Contribution to other WPs:

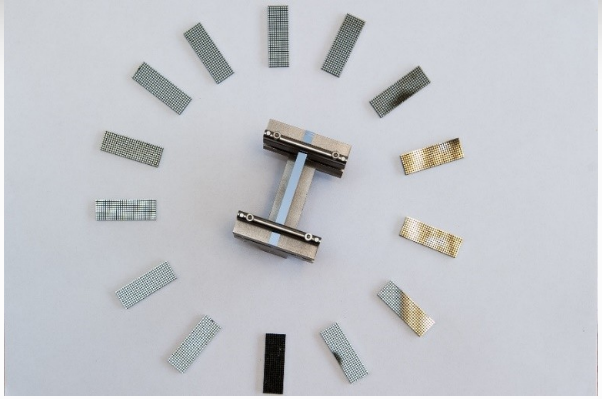
- WP1 Coordination and project management (dissemination, communication)
- WP3 Computational models (optimization and model validation vs experiment)
- WP4 Proof-of-principle experiment

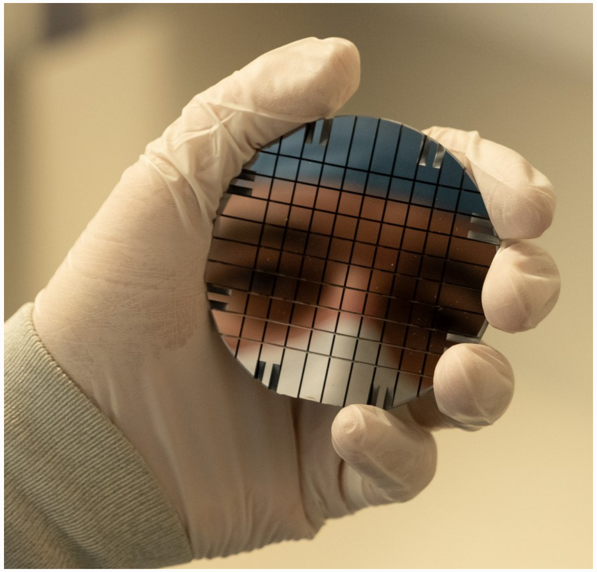
INFN Ferrara Division

Experts in

- Channeling
- Crystal production & characterization
- Channeling experiments
- Application developments
- Computer simulations

- Our laboratory fully equipped: **clean room** (130 m2)





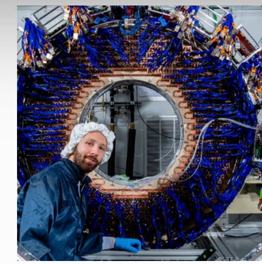
https://crystalab.unife.it/

INFN Ferrara Division

Laura Bandiera
INFN senior researcher

Nicola Canale
INFN Post-Doc

Vincenzo Guidi
UNIFE full professor

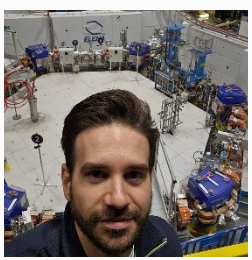


Pierluigi Fedeli
PhD student

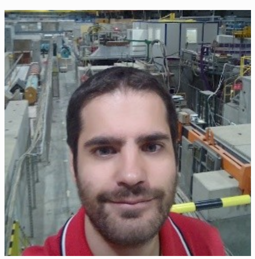
Jeniffer Reyes Garrido
PhD student

Andrea Mazzolari
UNIFE associate professor

Alexei Sytov
INFN senior fellow



Lorenzo Malagutti
INFN research engineer



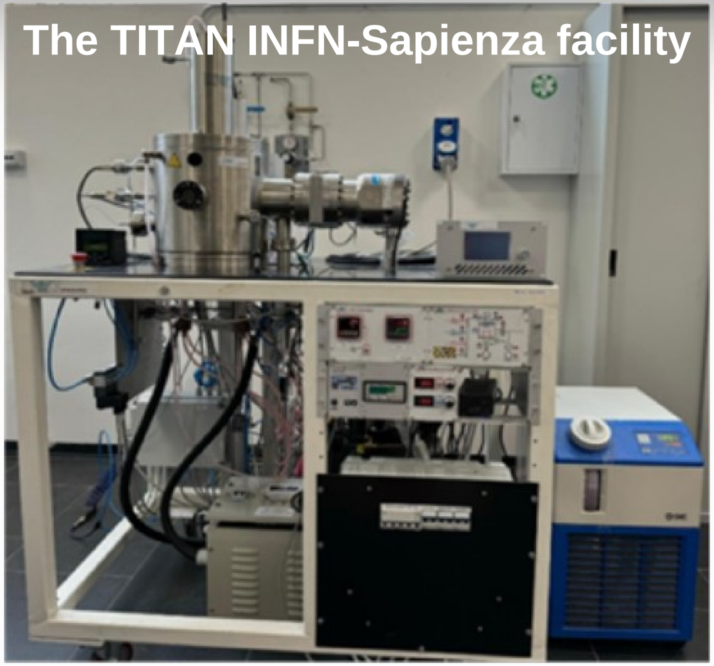
Marco Romagnoni
UNIFE researcher

Gianfranco Paternò
INFN research engineer

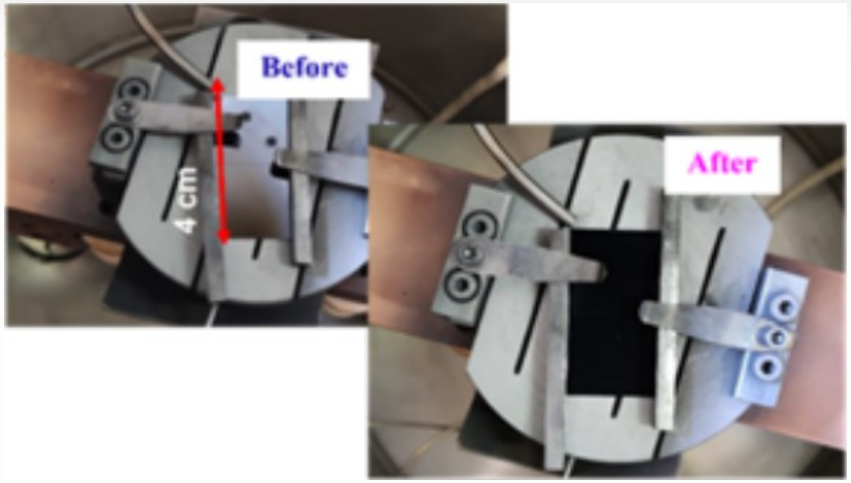
Riccardo Negrello
PhD student

Francesco Cescato
PhD student

The TITAN INFN-Sapienza facility at Sapienza University of Rome



VA-CNTs synthesis

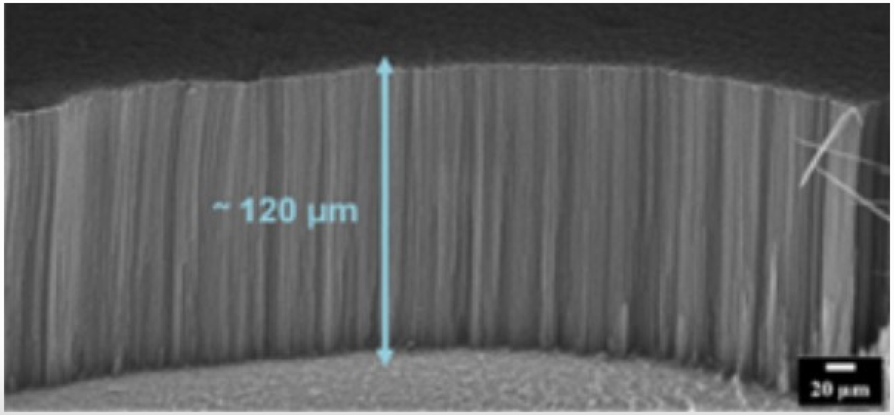


Gianluca Cavoto

Ilaria Rago

Francesco Pandolfi

SEM image of a typical VA-CNT



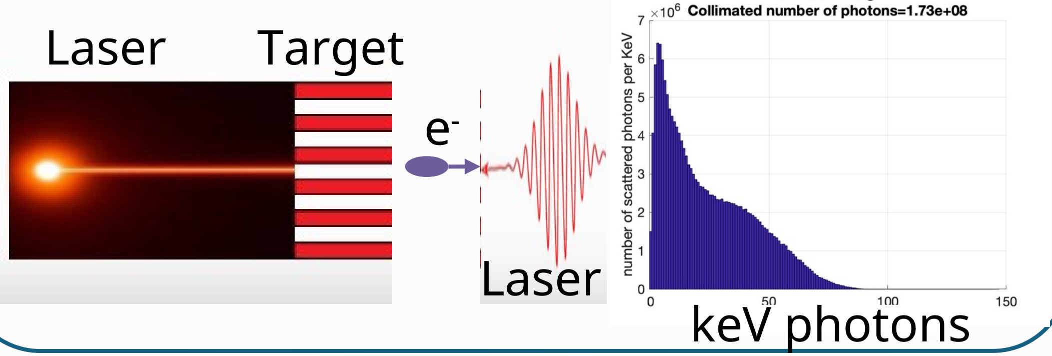
INFN Milano Division: experts in radiation

Ultra-compact radiation sources

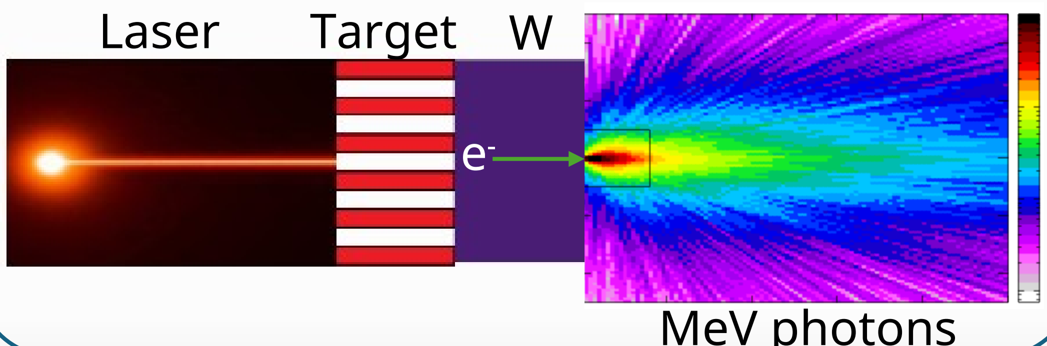
- **keV X-Ray Source** from Laser Compton backscattering
- **γ-Ray Source** in the **MeV** range based on bremsstrahlung radiation

Illya Drebot

Compton Backscattering X-ray Source



Bremsstrahlung radiation source



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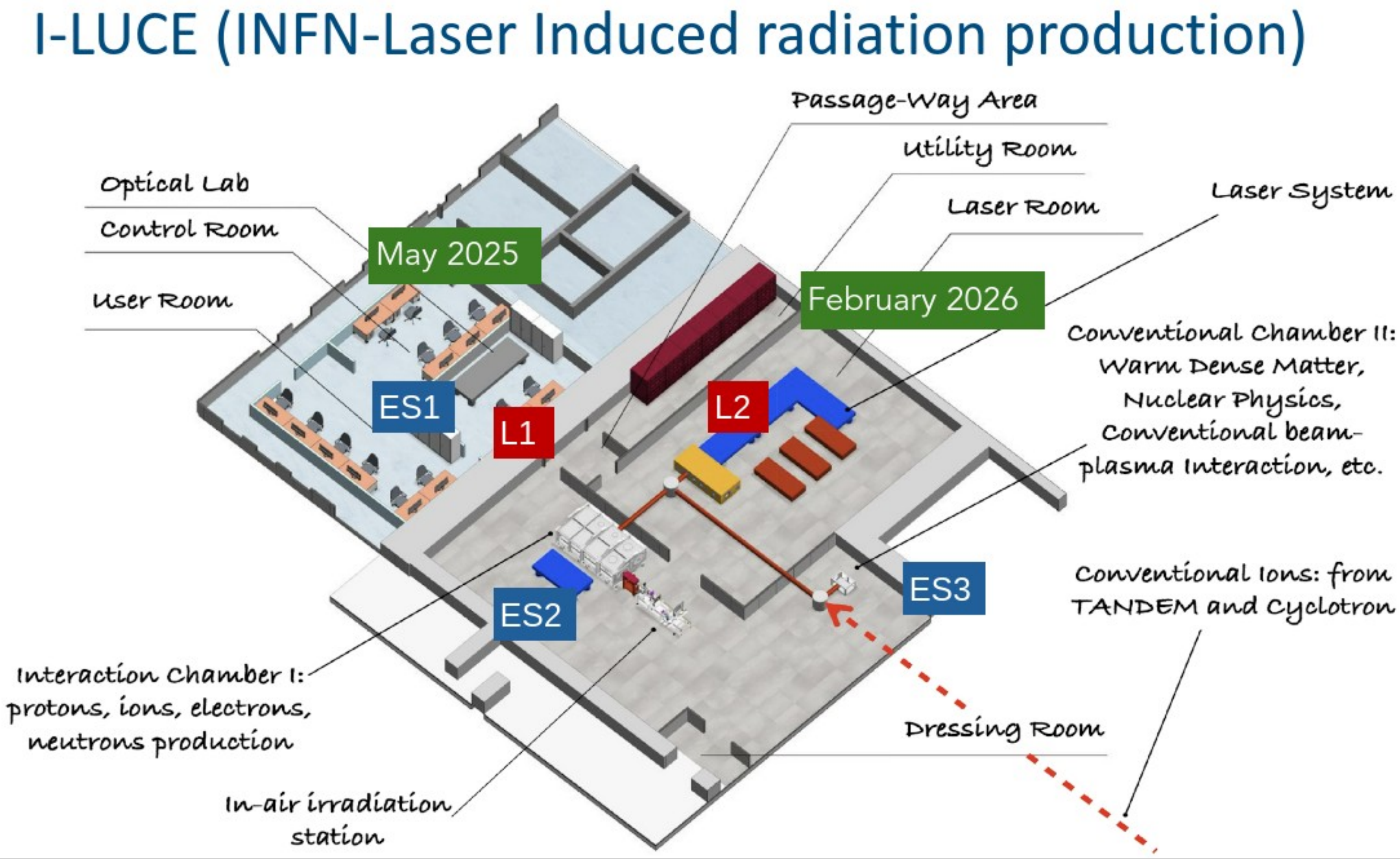
Experts in

- **Plasma acceleration**: experiment & simulations (PIC code & Geant4) & ML
- **Medical physics**/radiotherapy



Anthem

EuAPS

SAMOTHRACE

Available laser systems @I-LUCE facility

COHERENT L1

Laser Power	< 260 GW
Laser Energy per Pulse	5 – 9 mJ
Laser Pulse Duration	> 35 fs
Laser Intensity	–
Repetition Rate	1 kHz
Plasma Density	–

THALES L2

Laser Power	45 – 320 TW
Laser Energy per Pulse	1.5 – 8 J
Laser Pulse Duration	23 – 25 fs
Laser Intensity	–
Repetition Rate	2.5 – 10 Hz
Plasma Density	–
Strehl Ratio	>80% with Deformable Mirror

Quark 320 system

Experimental area

Control and Users room

Available laser systems @I-LUCE facility: Two modalities for the L2 laser

Laser Power		≥ 50 TW
Energy per pulse		≥ 1 J
Pulse duration		≤ 23 fs
Focusing surface		36 μm²
Max power density (at the target)		$1.21 \cdot 10^{20}$
Contrast ratio @100 ps (ASE)		$> 10^{10}$
Repetition rate		≥ 10 Hz
Protons Ions	Max energy	4 MeV
	Particle per pulse (at 2 MeV)	10^{11} MeV^{-1} Sr^{-1}
	Energy spread	100%
	Beam divergency (max)	±20°
Eletrons	Max energy	0.1 GeV
	Particles per pulse	10^{9}
	Beam divergency (max)	± 20 mad
Neutrons	Max energy	TBD
Gamma X-beams	Synchrotron radiation of the e- inside the plasma or breemsstrahlung	
	Energy	up to 20 MeV

Laser Power		350 TW
Energy per pulse		≥ 7 J
Pulse duration		≤ 23 fs
Focusing surface		36 μm²
Max power density (at the target)		$8.82 \cdot 10^{20}$
Contrast ratio @100 ps (ASE)		$> 10^{10}$
Repetition rate		1 Hz
Protons Ions	Max energy	50 MeV
	Particle per pulse (at 2 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
Gamma X-beams	Synchrotron radiation of the e- inside the plasma or breemsstrahlung	
	Energy	up to 80 MeV

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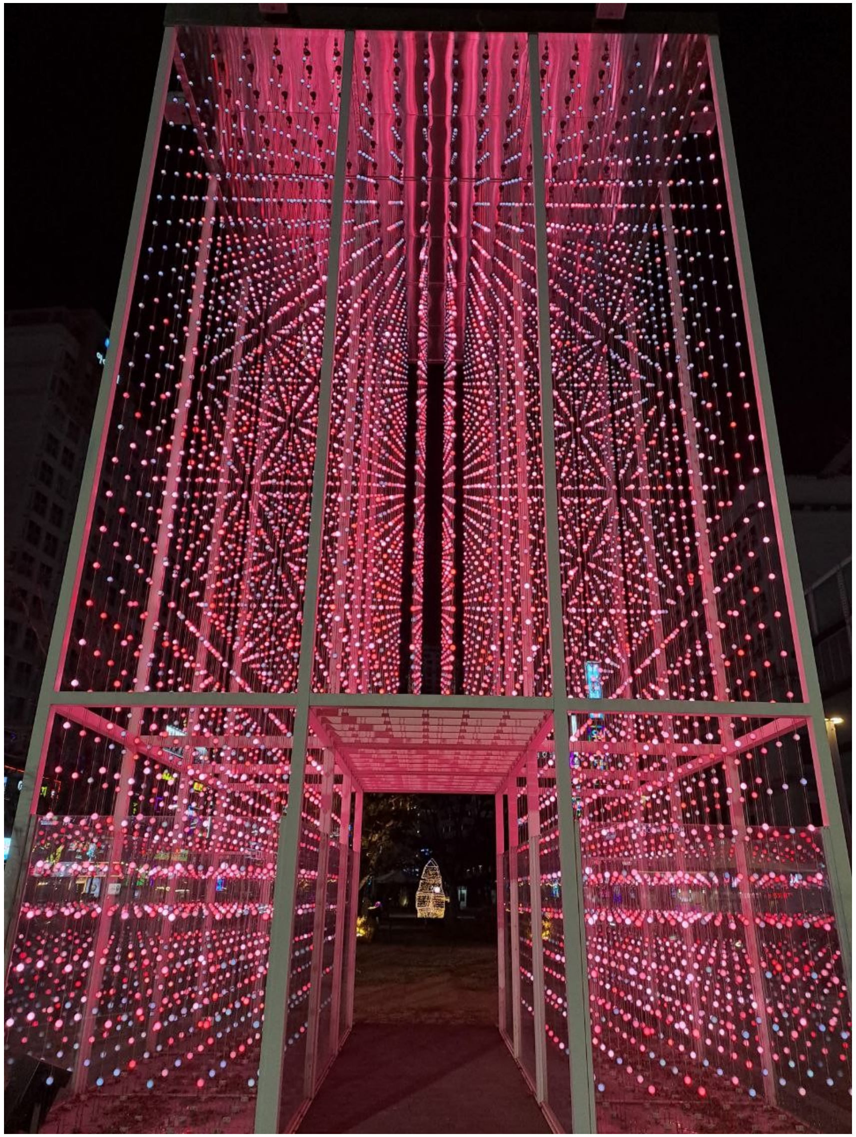

Thank you for attention!