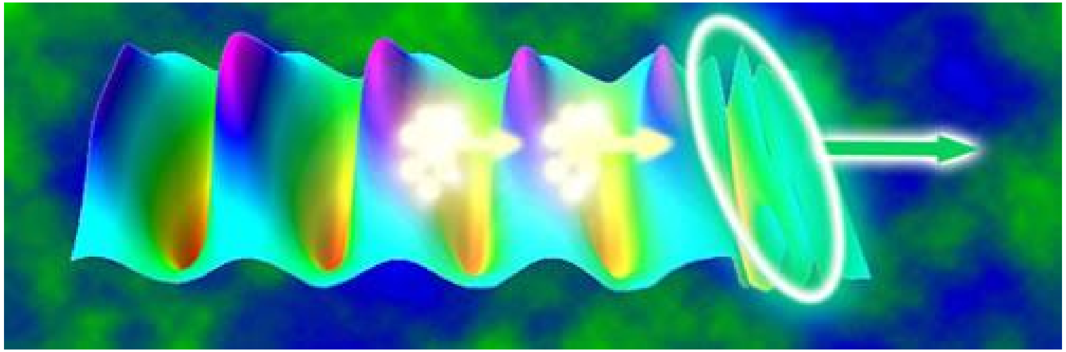


Dr. Alexei Sytov

INFN Sezione di Ferrara

Applications of laser-driven radiation: current activities at INFN

XXI Seminar on Software for Nuclear, Subnuclear and Applied Physics

Alghero 14/06/2024

World of particle accelerators

CERN
Large Hadron Collider:
Construction
$5 billion (collider only)
Operation: $1 billion/year

Germany
DESY 4th gen
Synchrotron Light
Source PETRA-IV:
€1.54 billion

Pohang 4th gen X-FEL:
$390 million

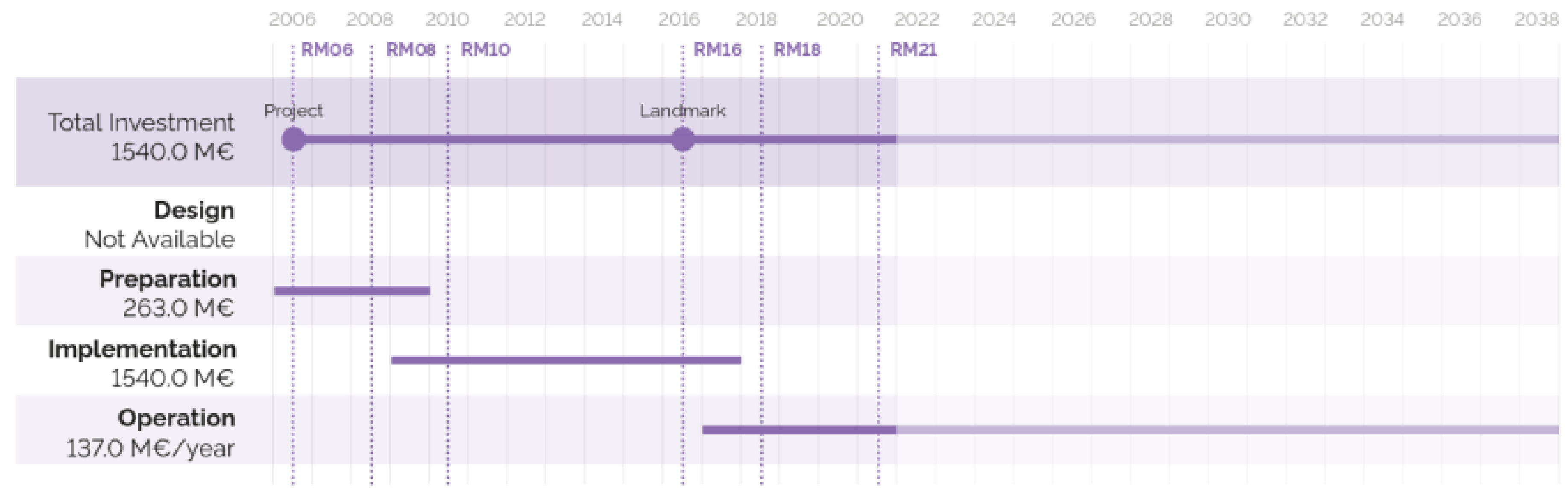
World of particle accelerators: European X-FEL, DESY

A huge «micro»scope

Recording chemical reactions on video using X-Rays

To perform R&D in

- **Material science**
- **Nanotechnologies**
- **Genetics**
- **Viruses and vaccines**



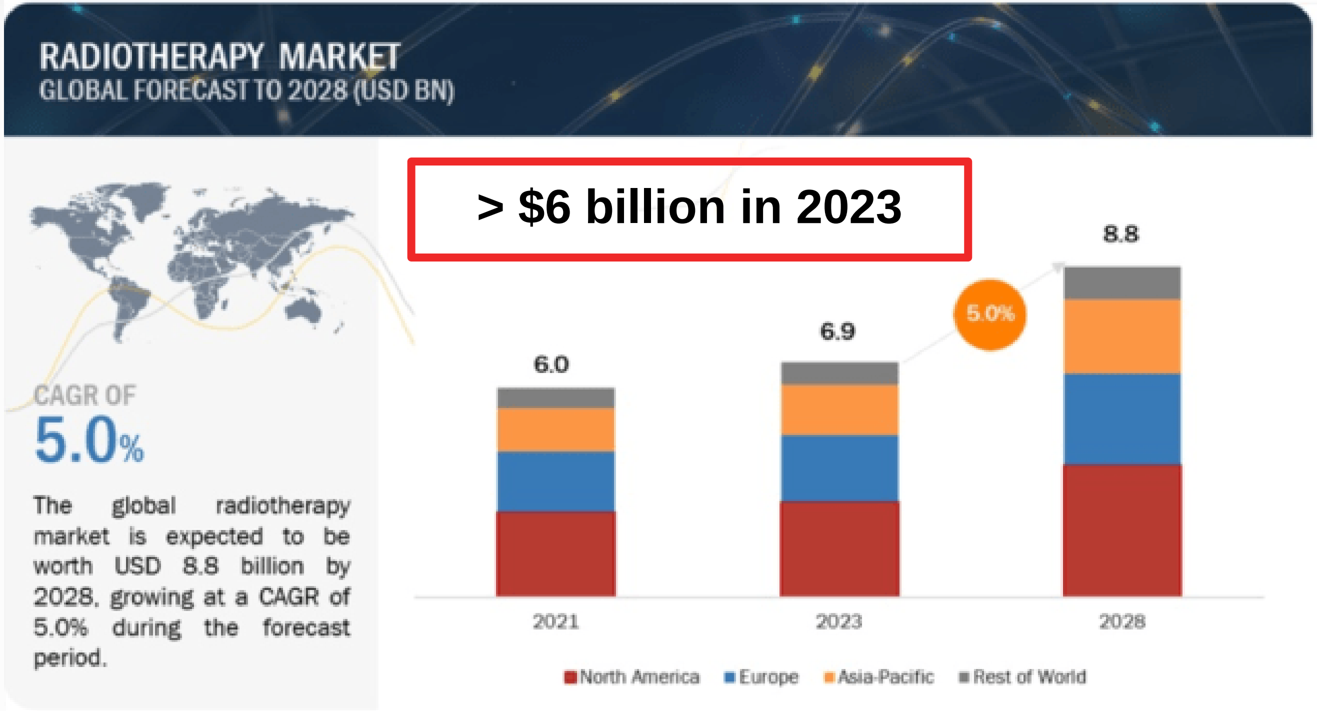
https://roadmap2021.esfri.eu/projects-and-landmarks/browse-the-catalogue/european-xfel/

World of particle accelerators: cancer radiotherapy

7 million patients in 2023

5-year relative survival rate > 90 %

Procedure cost $ 5000-50000

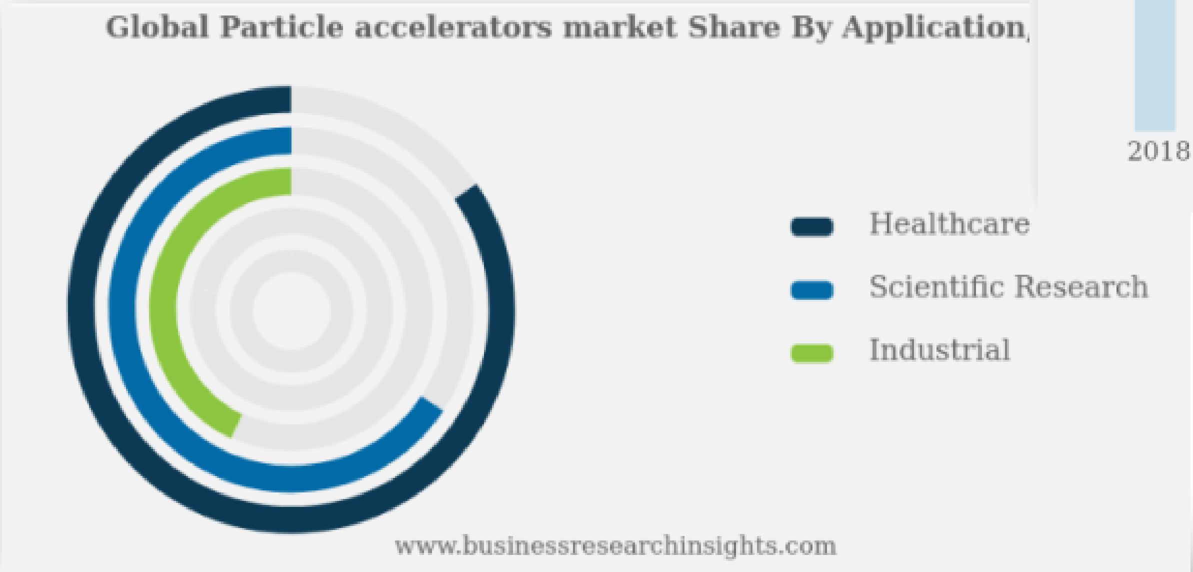


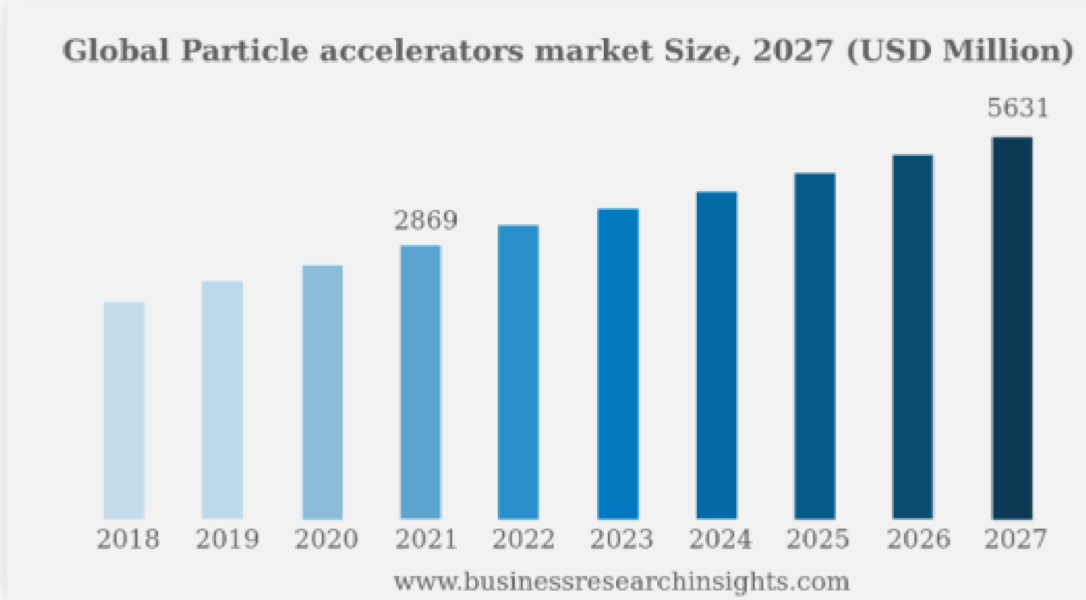
> $6 billion in 2023

Cyclotron facility cost $10 million
X-ray facility cost $3 million

World market of particle accelerators

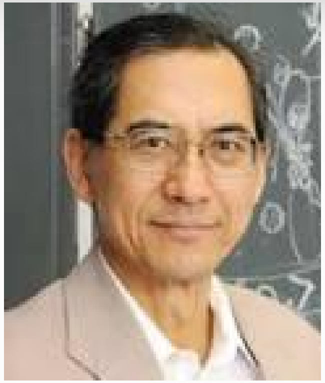
> $3 billion in 2023





Idea of plasma wakefield acceleration

Particle accelerators are huge and dramatically expensive!



Prof. **Toshiki Tajima**

Prof. **John W. Dawson**

**Idea:
to shrink the accelerators to the table-top size**

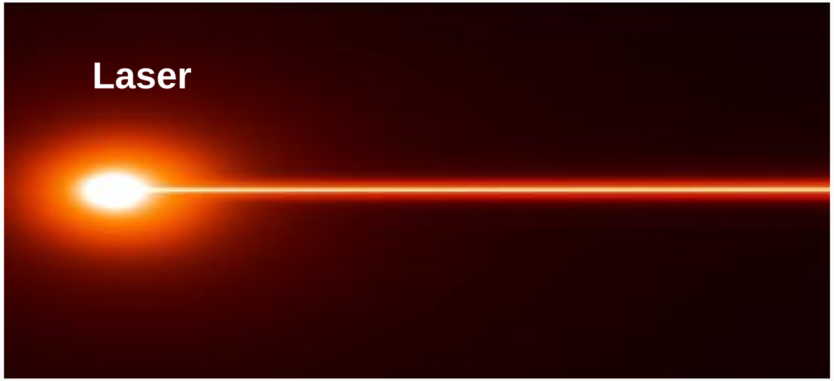
We can use **plasma** to **accelerate charge particles**

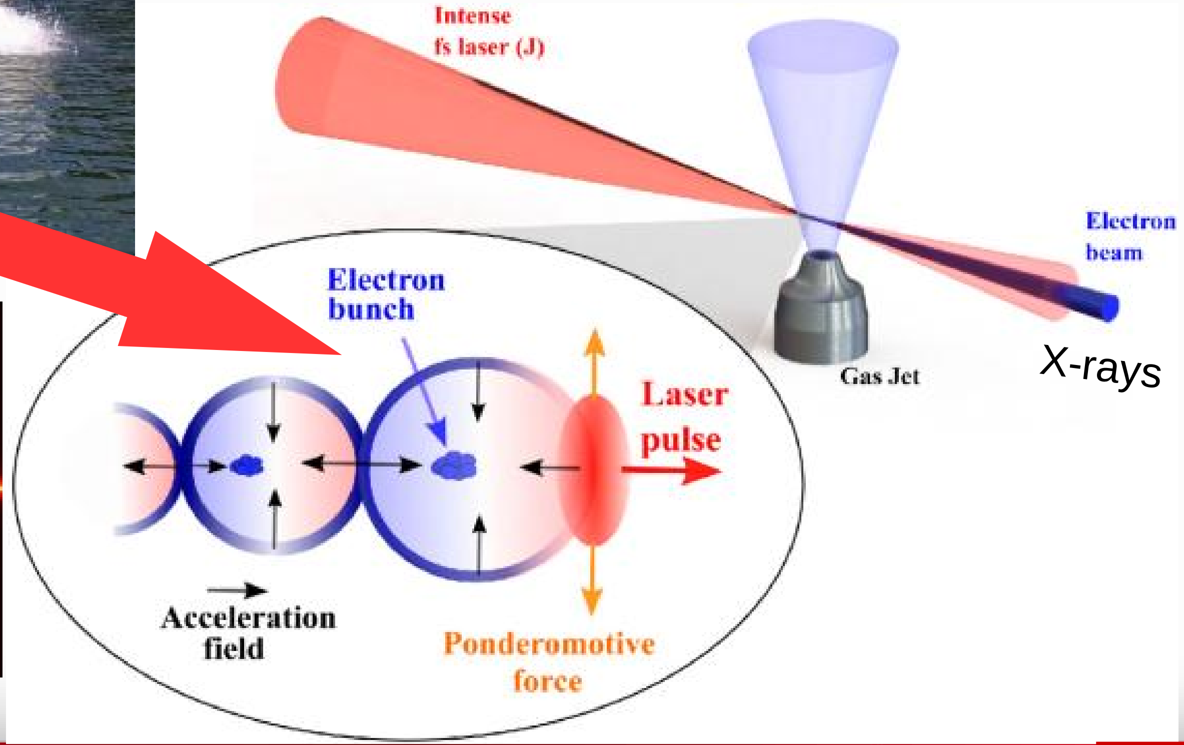
But:
we need a very **powerful laser**

T. Tajima and J. M. Dawson. Laser Electron Accelerator Phys. Rev. Lett. 43, 267 (1979)

Physics of plasma acceleration: just like wakesurfing!

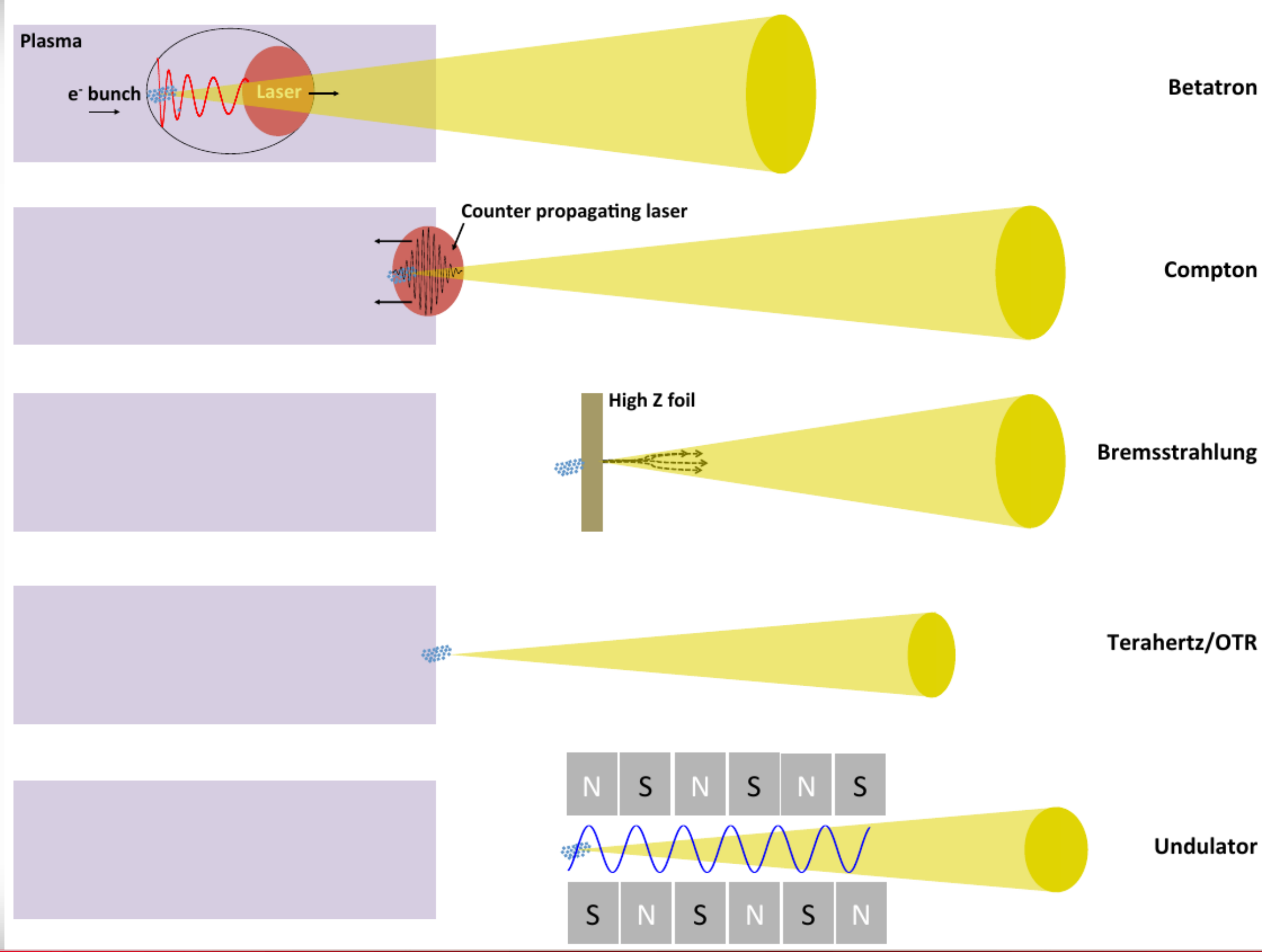
Electron beam energy: MeV — tens of GeV





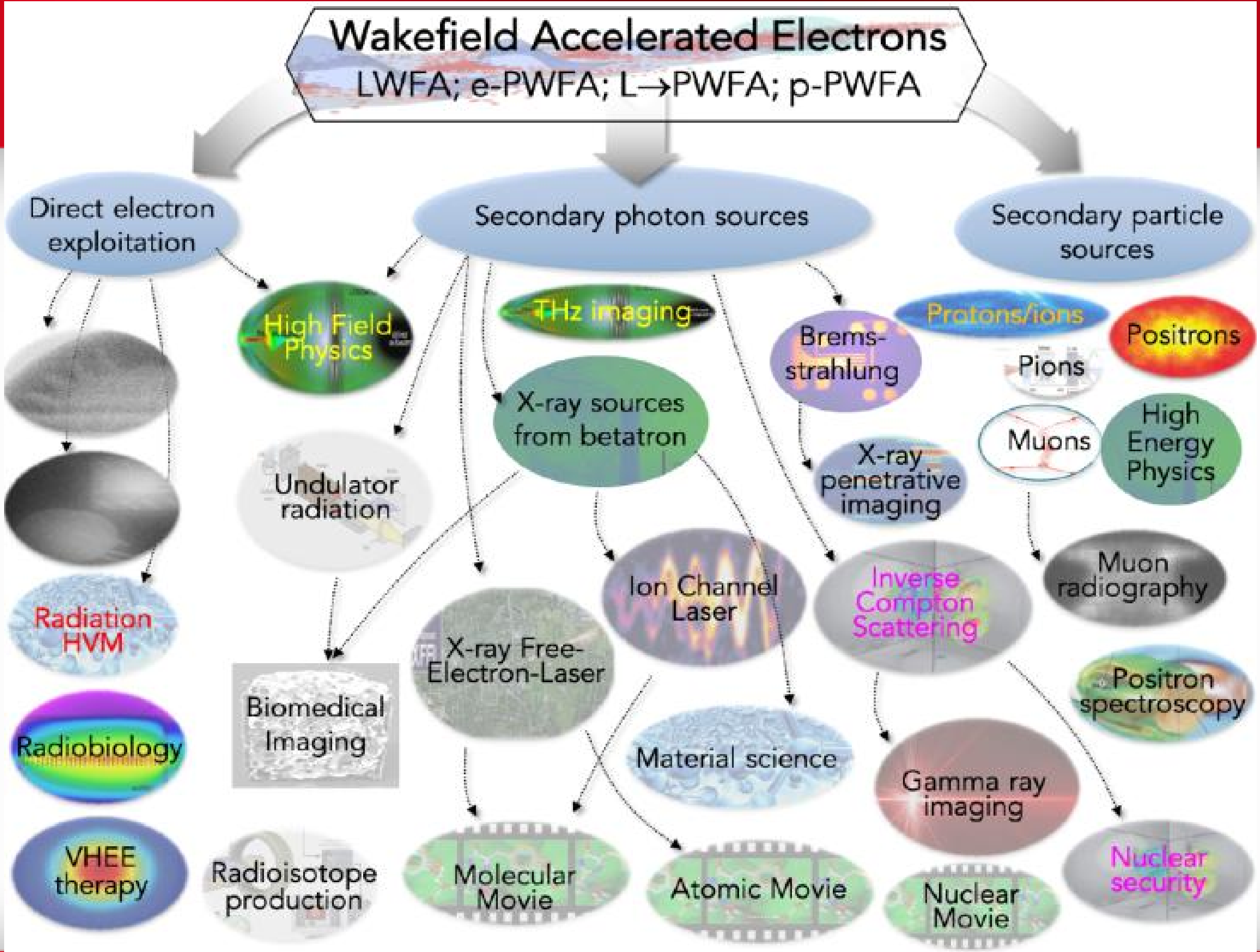
Picture: H.T. Kim et al. Multi-GeV Laser Wakefield Electron Acceleration with PW Lasers Appl. Sci. 2021, 11, 5831.

Radiation source based on plasma acceleration of electrons

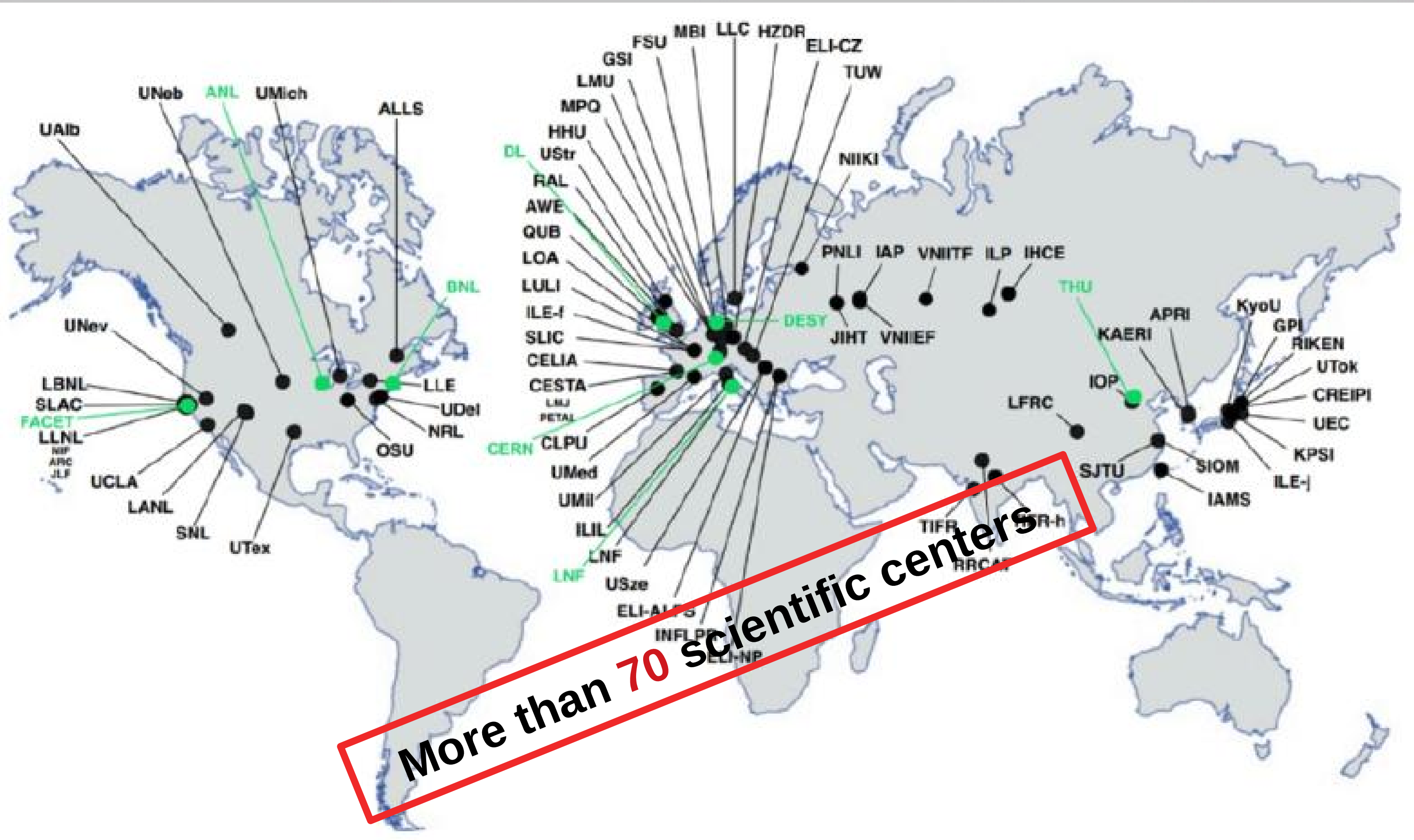


X-rays

γ-rays


Wakefield Accelerated Electrons
LWFA; e-PWFA; L→PWFA; p-PWFA
Direct electron exploitation
Secondary photon sources
Secondary particle sources
High Field Physics
THz imaging
Brems-strahlung
Protons/ions
Positrons
Pions
X-ray sources from betatron
Undulator radiation
X-ray penetrative imaging
Muons
High Energy Physics
Radiation HVM
Ion Channel Laser
Inverse Compton Scattering
Muon radiography
X-ray Free-Electron-Laser
Biomedical Imaging
Radiobiology
Positron spectroscopy
Material science
Gamma ray imaging
VHEE therapy
Radioisotope production
Molecular Movie
Atomic Movie
Nuclear Movie
Nuclear security

Scientific centers working on plasma wakefield acceleration

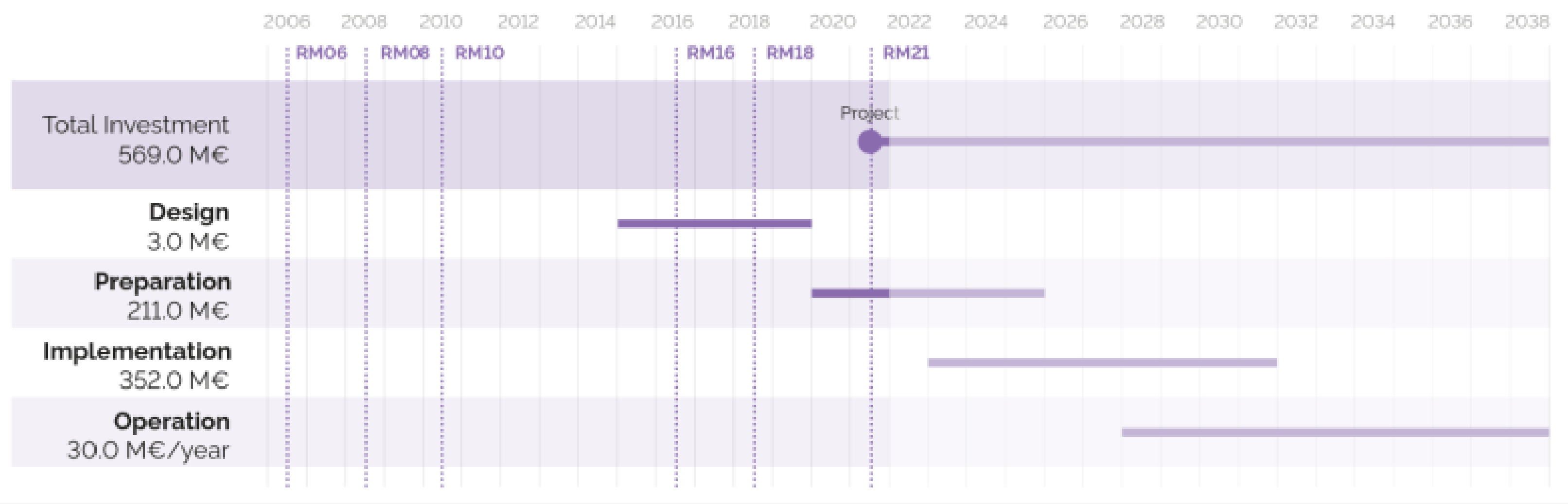


Example of a big project in plasma acceleration: EuPRAXIA

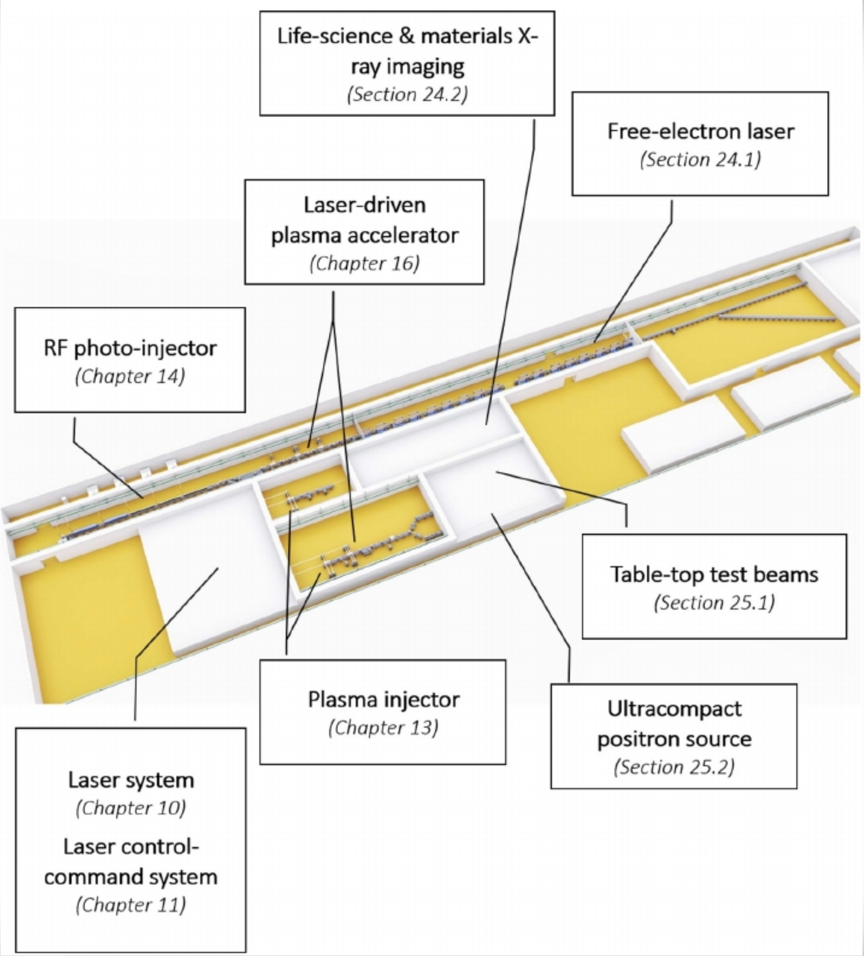
December 2020, EuPRAXIA consortium: 40 members; 11 observers.

Hosted by INFN, Italy

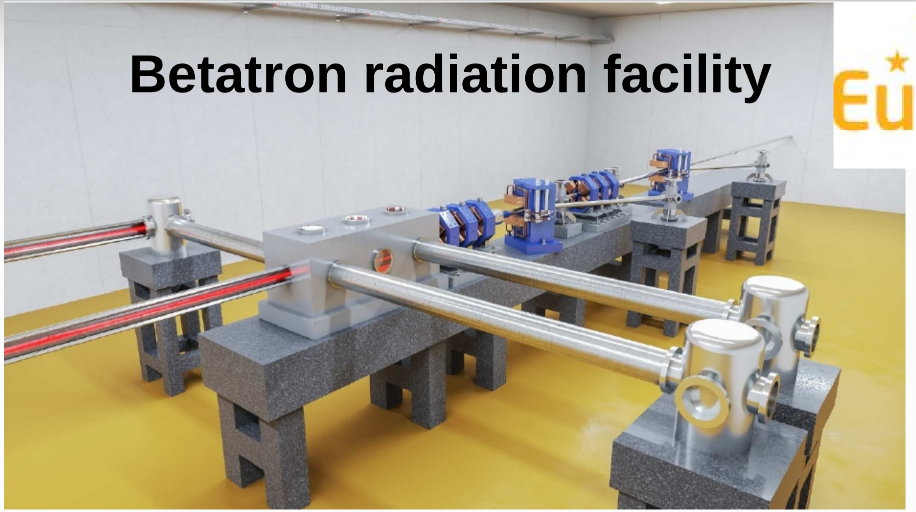
Operation until 2062



Laser-driven plasma acceleration @EuPRAXIA

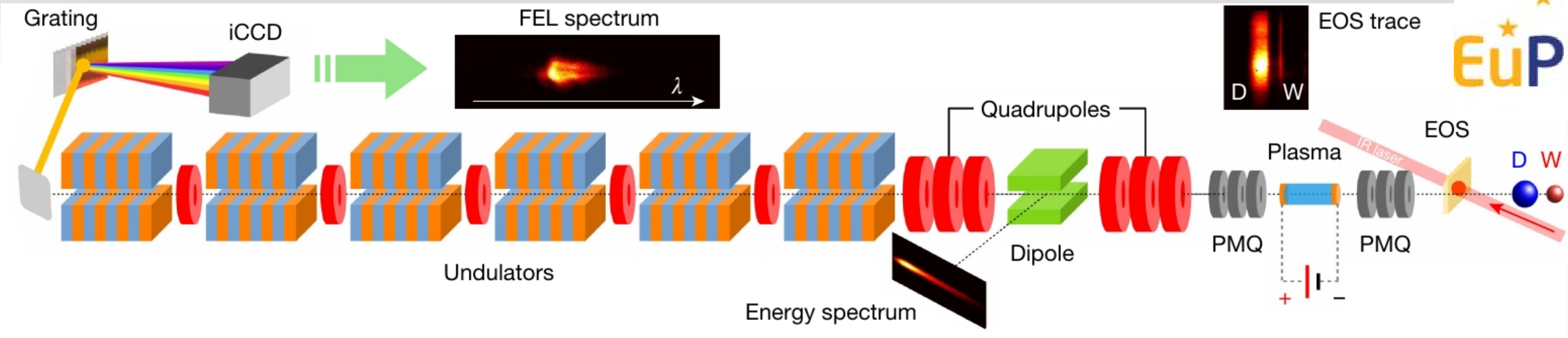


Betatron radiation facility



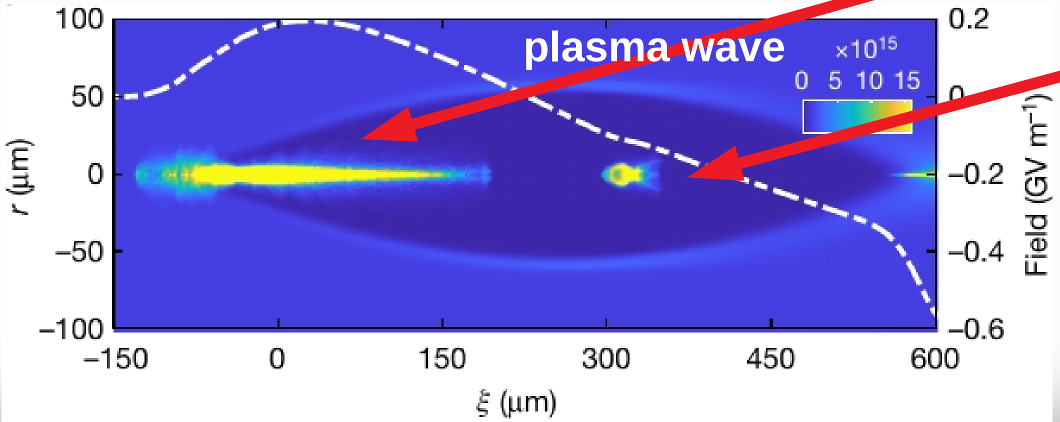
Quantity	Baseline Goal	Range of Exploration
Energy	5 GeV	≥1 GeV
Charge	30 pC	5–100 pC
Bunch length (FWHM)	10 fs	≤30 fs
Peak current	3 kA	2–5 kA
Energy spread	1 %	<1 %
Normalised emittance in x,y	1 mm mrad	<1 mm mrad
Slice energy spread	0.1 %	<0.1 %
Normalised slice emittance in x,y	<1 mm mrad	≪1 mm mrad

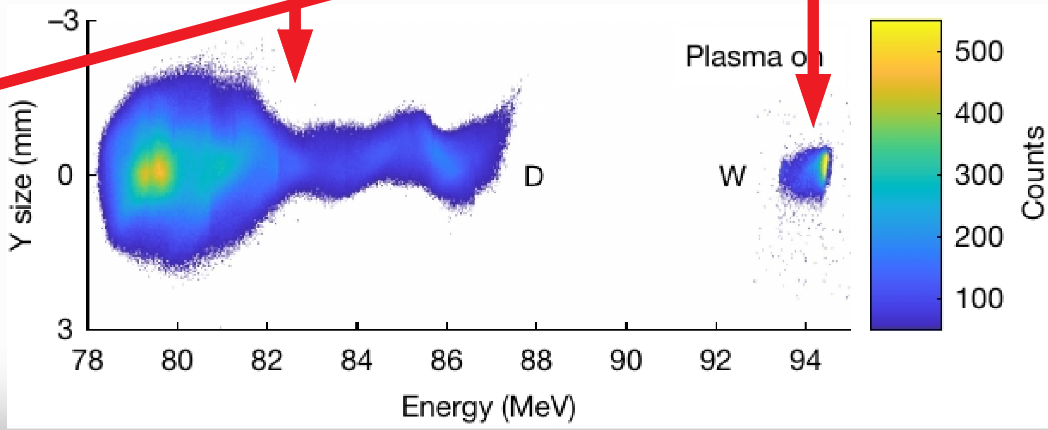
Beam-driven plasma acceleration @EuPRAXIA



drive e- beam

accelerated e- beam





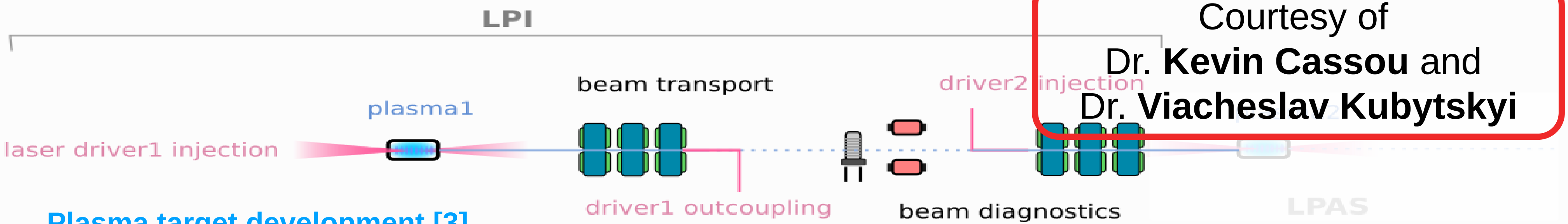
R. Pompili et al. Nature 605, 659 (2022)

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);
```

Examples of investment in plasma acceleration: ELI

lead country
CZ, HU, RO
members countries
DE, FR, IT, UK

ELI

Extreme Light Infrastructure

The world's fastest and most intense advanced lasers to unravel the fundamental secrets of the Universe and materials

TIMELINE

Roadmap Entry
2006
Preparation Phase
2007-2010
Implementation/Construction Phase
2011-2017
Operation Start
2018

ESTIMATED COSTS

capital value
850 M€
design
Not Available
preparation
6 M€
construction
850 M€
operation
80 M€/year

This is where the most power lasers are!

This is where plasma borns!

http://roadmap2018.esfri.eu/projects-and-landmarks/browse-the-catalogue/eli/

Startups in plasma acceleration are coming!

TAU Systems, US

Created in 2022

Attracted $15 million from a business angel

Reached world record particle energy by plasma acceleration

Claim to built first commercial X-FEL based on plasma acceleration by 2027

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

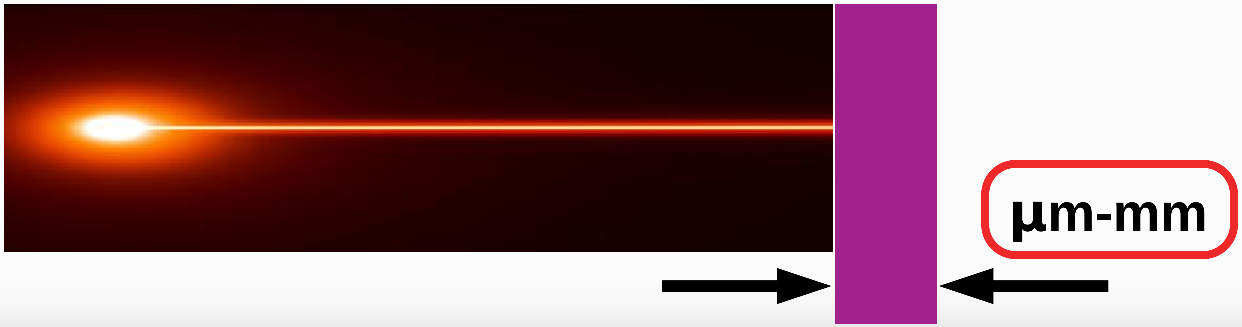
Acceleration gradient*

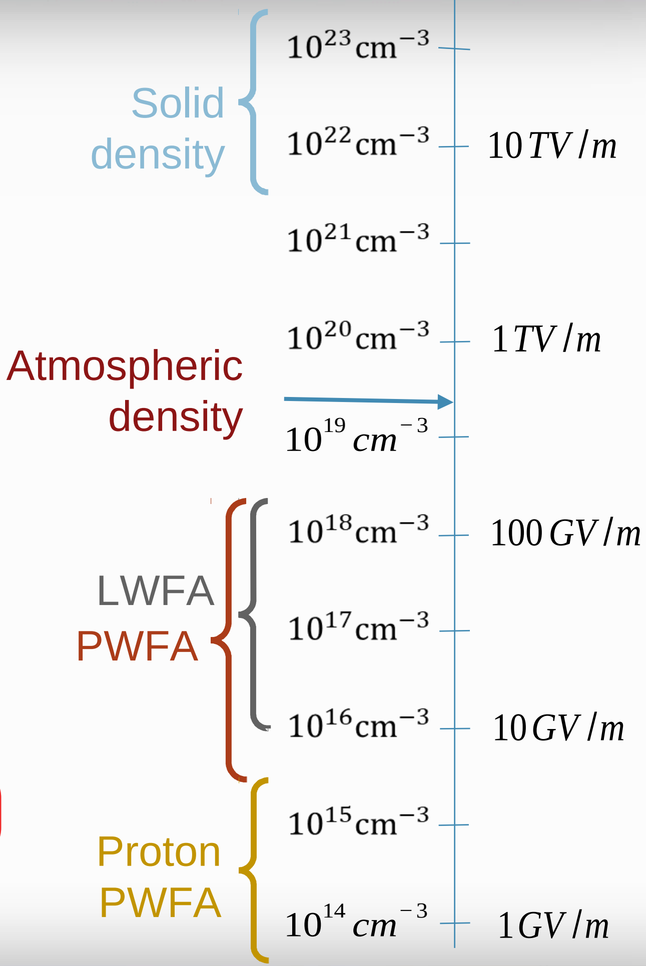
$$E[\mathrm{GV/m}] = m_e \omega_p c/e \approx 100\sqrt{n_0[10^{18}\mathrm{cm}^{-3}]}$$

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

All you need:

laser **target**





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

Challenges and solutions

stability

multiple scattering

radiation damage of the target

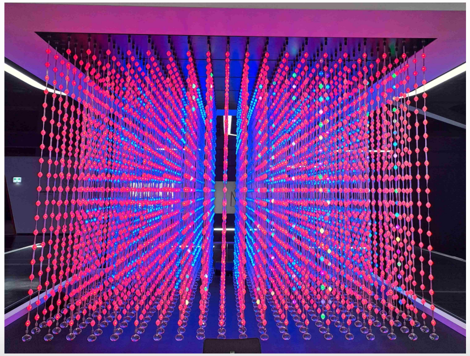
drive beam size vs plasma wavelength λ_p

energy distribution

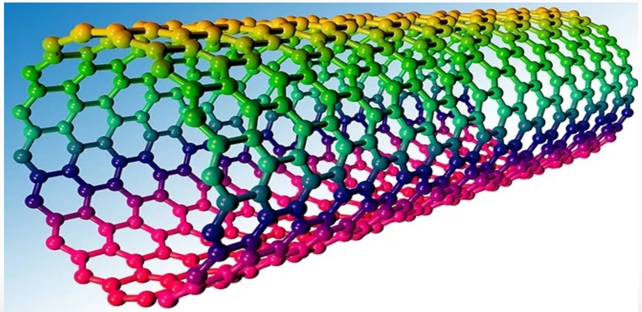
beam emittance

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

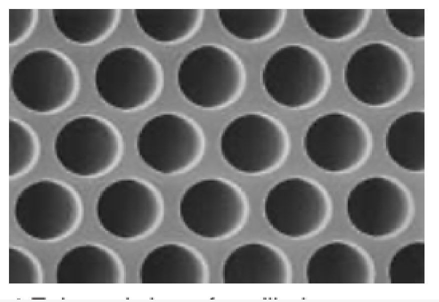
Oriented crystals



Nanotubes



Structured solids



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

Keypoint quantities of plasma wave formation

$$E\,[\mathrm{GV\,m^{-1}}] = m_e \omega_p c/e \approx 100\sqrt{n_0\,[10^{18}\,\mathrm{cm^{-3}}]}$$

$\sigma_{\text{laser } x,y,z} < \lambda_p \sim 1/\sqrt{n_0}$

Plasma wave length should be bigger than the size of the drive beam/laser pulse in 3D

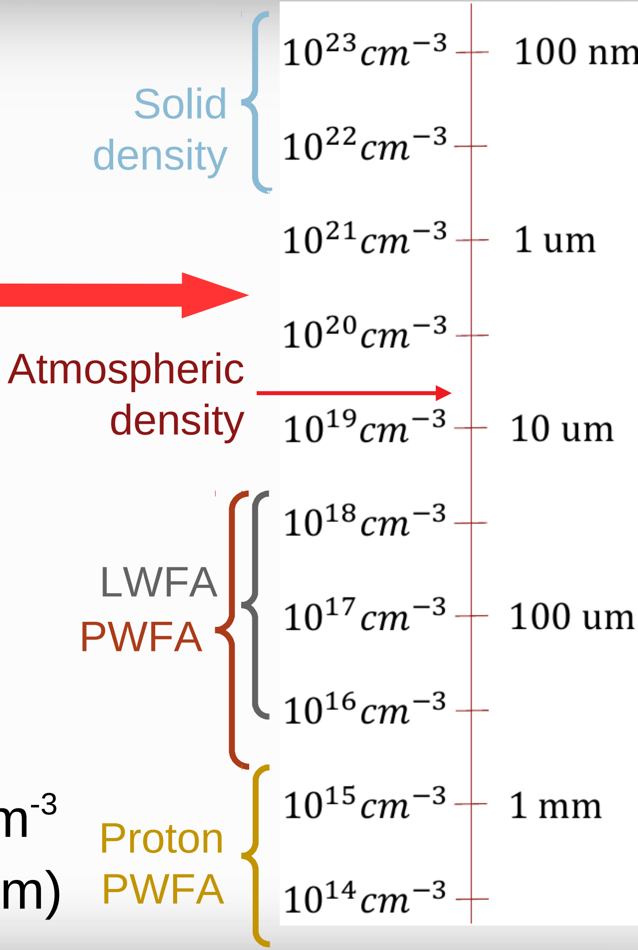
Carbon nanotubes

$\lambda_p \sim 3$ μm ($n_0 = 10^{20}$ cm^{-3}) (our case)

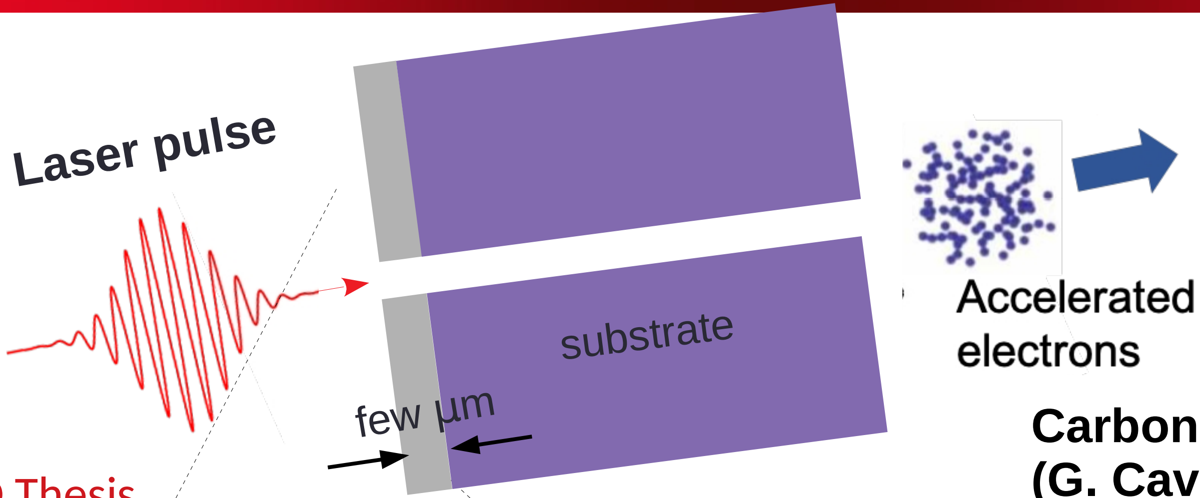
Critical target density
(max density the laser is able to penetrate)

$$n_c(\lambda_L) = \frac{\pi m_e c^2}{e^2 \lambda_L^2} \approx (1.1 \times 10^{21}\ [\mathrm{cm^{-3}}])/\lambda_L^2\,[\mu\mathrm{m}]$$

$n_c \sim 2 \cdot 10^{21}$ cm^{-3} ($\lambda_{laser} \sim 800$ nm)

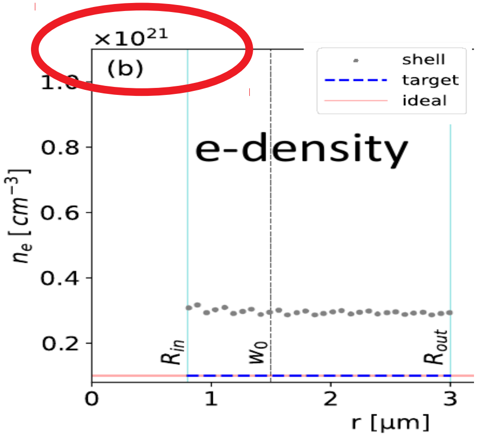


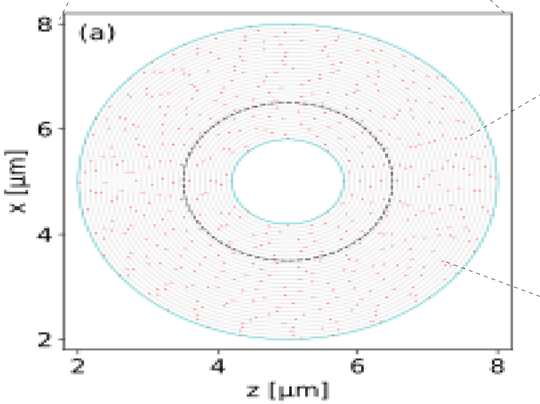
LWFA acceleration in CNTs based targets: the idea

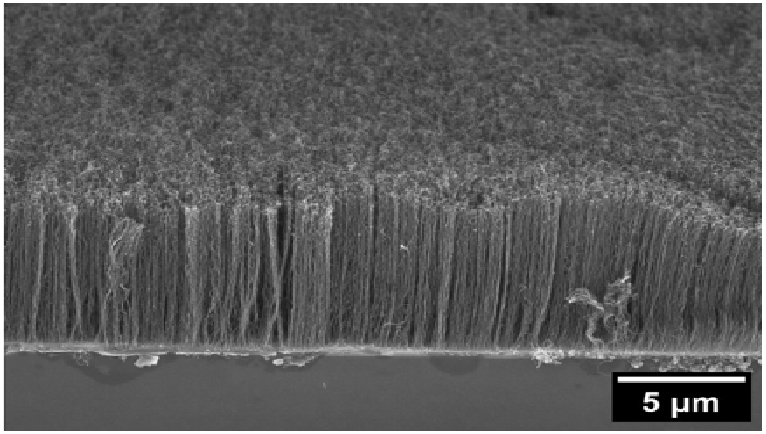


Cristian Bontoiu, PhD Thesis

Carbon nanotubes (G. Cavoto group)*







LWFA acceleration in CNTs based targets in self-injection mode: simulations

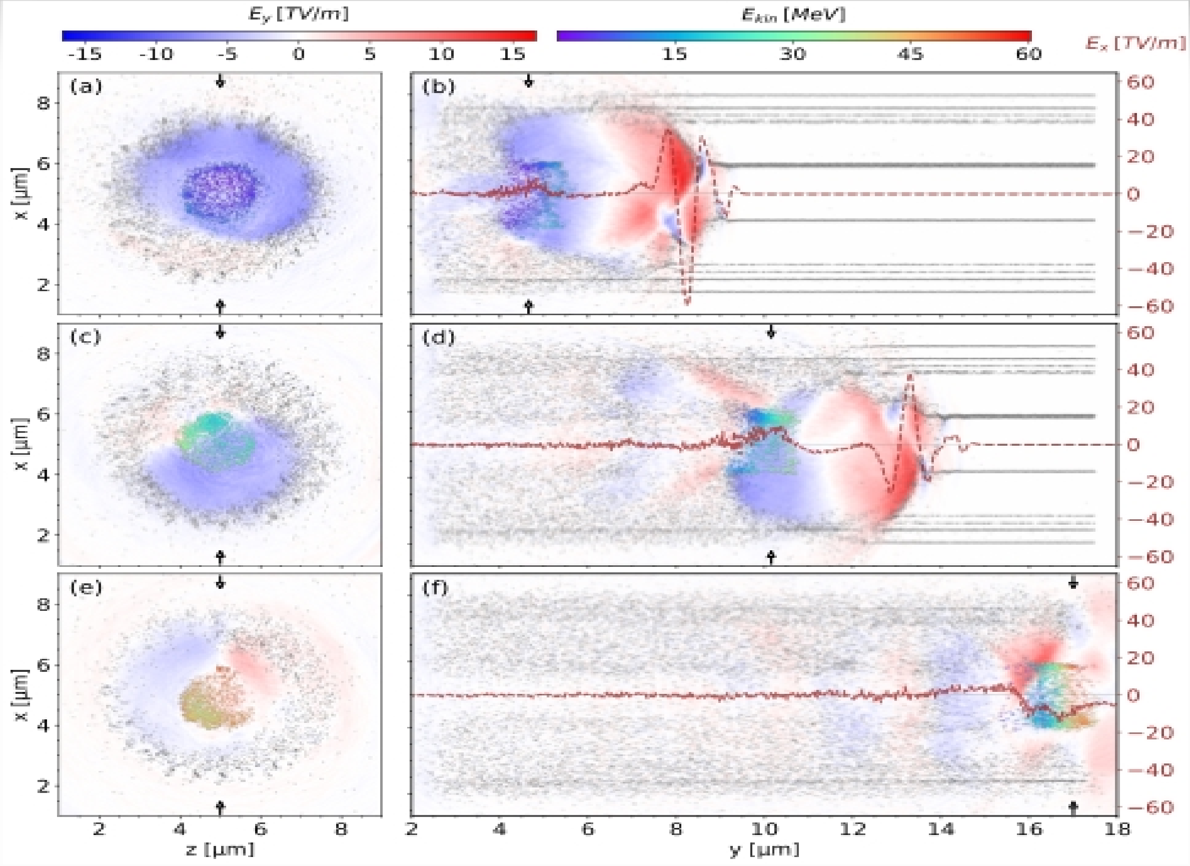
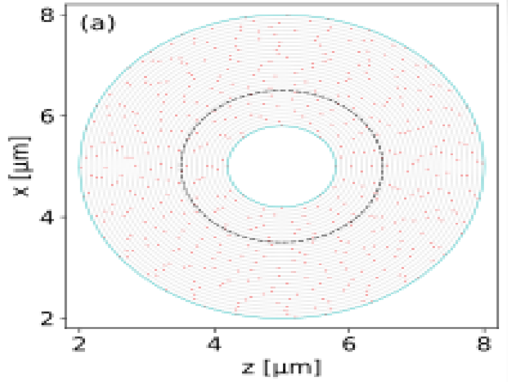


Figure 28: Electron macroparticles shown as grey dots and the longitudinal electric field shown as a colour density plot for model *A constant* with Δt = 8 fs (3 cycles), $I_0 = 10^{21}$ W/cm²: (a-b) t/T = 11; (c-d) t/T = 18; (e-f) t/T = 25.

Target

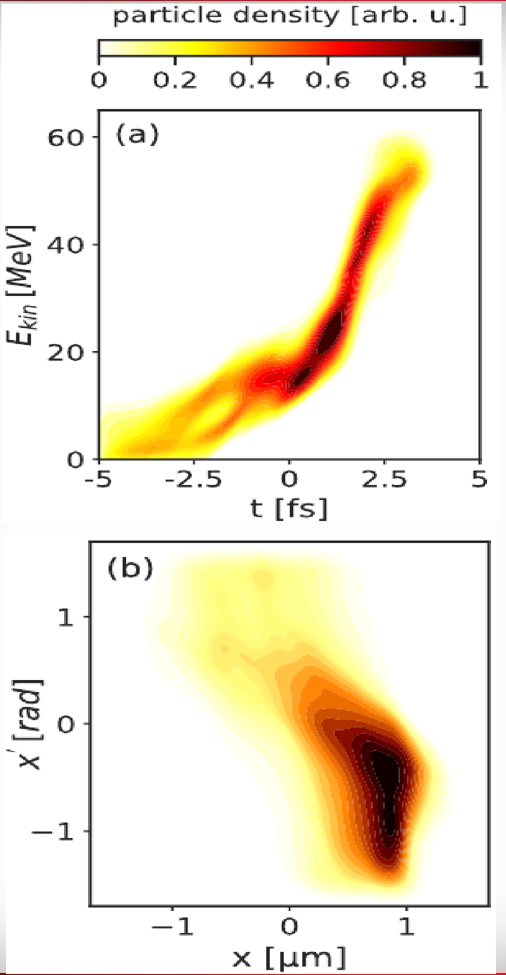


30 shells with 535 CNT bundles (red points) distributed uniformly

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, $\varepsilon_{\parallel}$	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

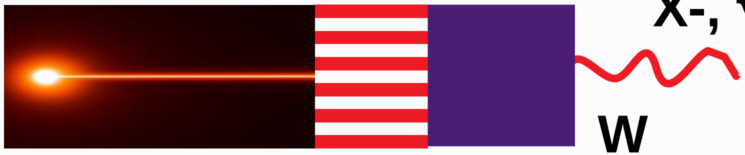
Let's dream about applications

Laser target

1 nC; 20-40 MeV
e- beam source

Accelerators & light sources

Radiation damage



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

W target

Radiation therapy

Compton scattering

Imaging

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

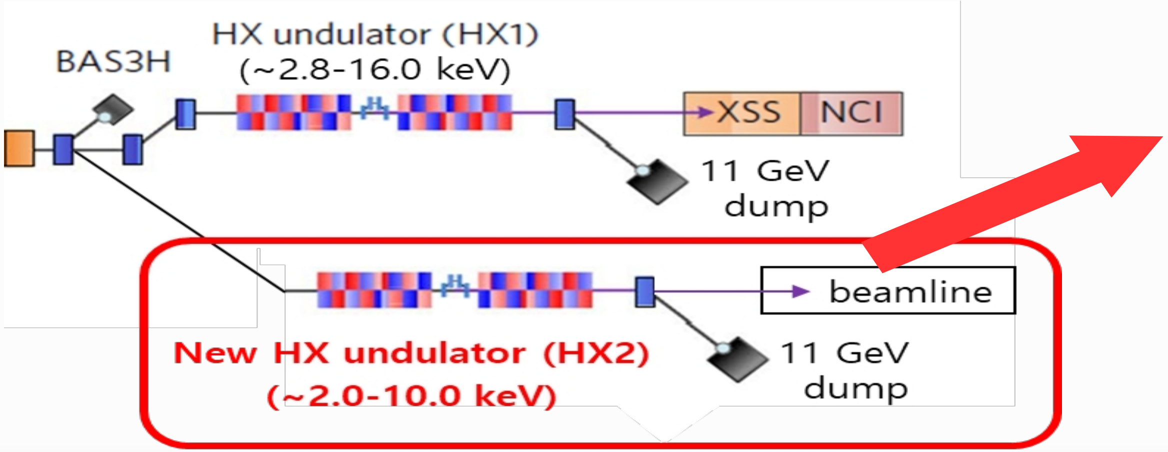
A probable laser facility for the first proof-of-concept experiment

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

4^{th} generation XFEL, Pohang Accelerator Laboratory

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

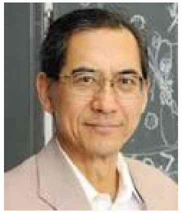
Parameters of future undulator:

Peak power = 2 TW,

X-ray energy = 10 mJ

Pulse duration = 5 fs

Focal spot size = **10 nm**



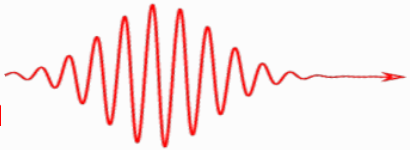
Idea of
Prof. **Toshiki Tajima**

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

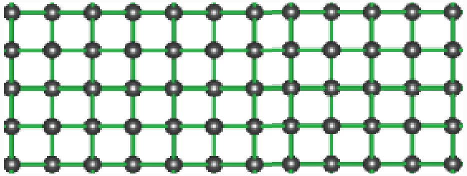
Idea: plasma acceleration by X-rays

$$n_c(\lambda_L) = \frac{\pi m_e c^2}{e^2 \lambda_L^2} \approx (1.1 \times 10^{21}\ [\mathrm{cm}^{-3}])/\lambda_L^2[\mu\mathrm{m}]$$

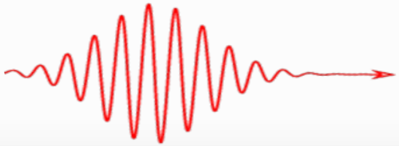
X-ray pulse



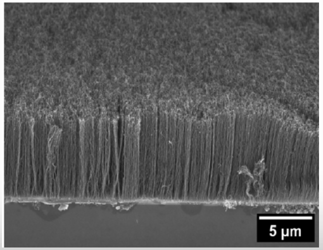
Oriented crystal

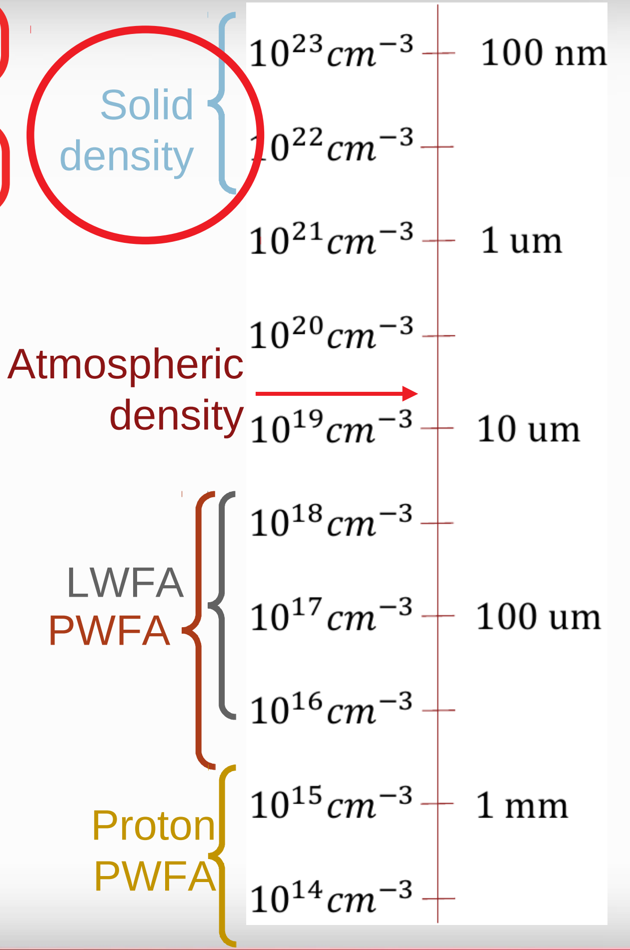


X-ray pulse

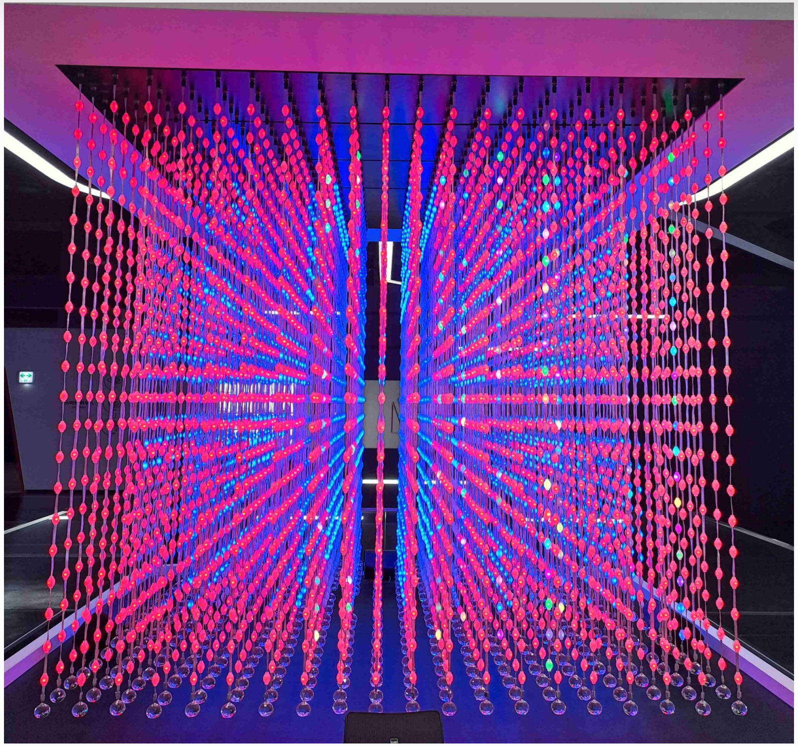


Nanotubes

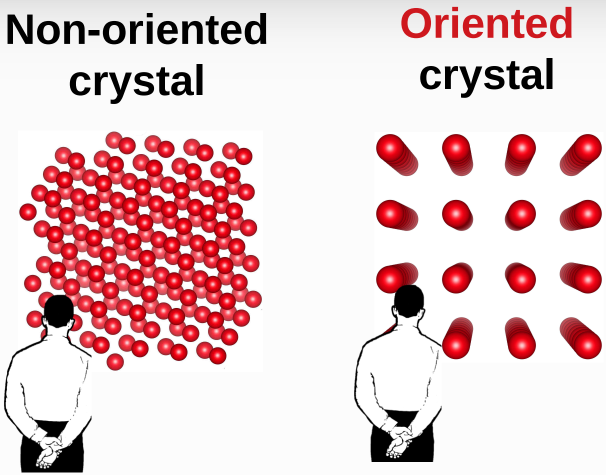


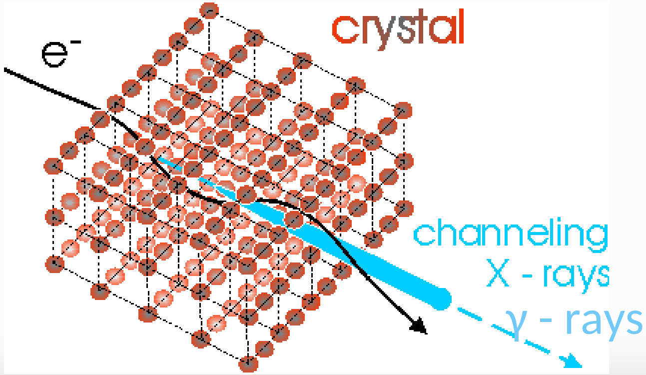


How an oriented crystal looks like



from National Science Museum, Daejeon, Korea



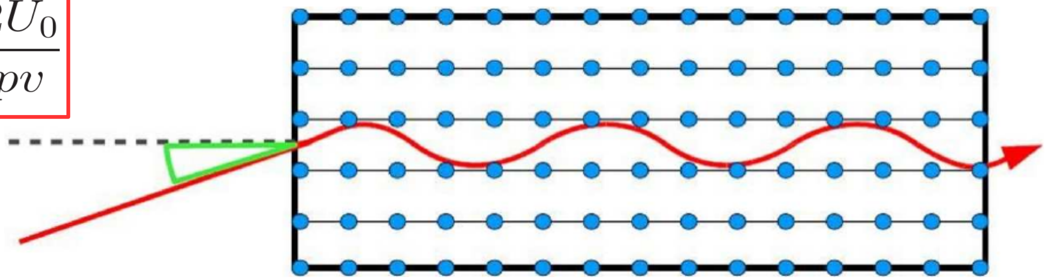


Channeling effect*

Lindhard angle:

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

channeling



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**

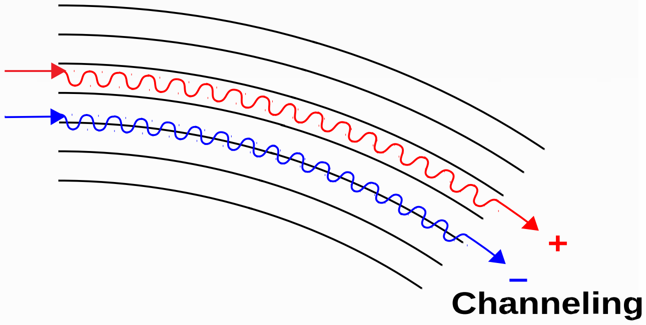
Strong focusing at Angstrom scale => small beam emittance

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

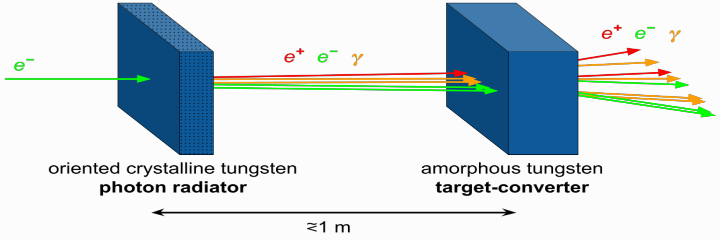
*J. Stark, Zs. Phys. 13, 973–977 (1912)
J. A. Davies, J. Friesen, J. D. McIntyre, Can J. Chem. 38, 1526–1534 (1960)
M. T. Robinson, O. S. Oen, Appl. Phys. Lett. 2, 30–32 (1963)
J. Lindhard, Kgl. Dan. Vid. Selsk. Mat.-Fys. Medd. 34 No 4, 2821–2836 (1965)

Let’s dream about future lepton colliders!

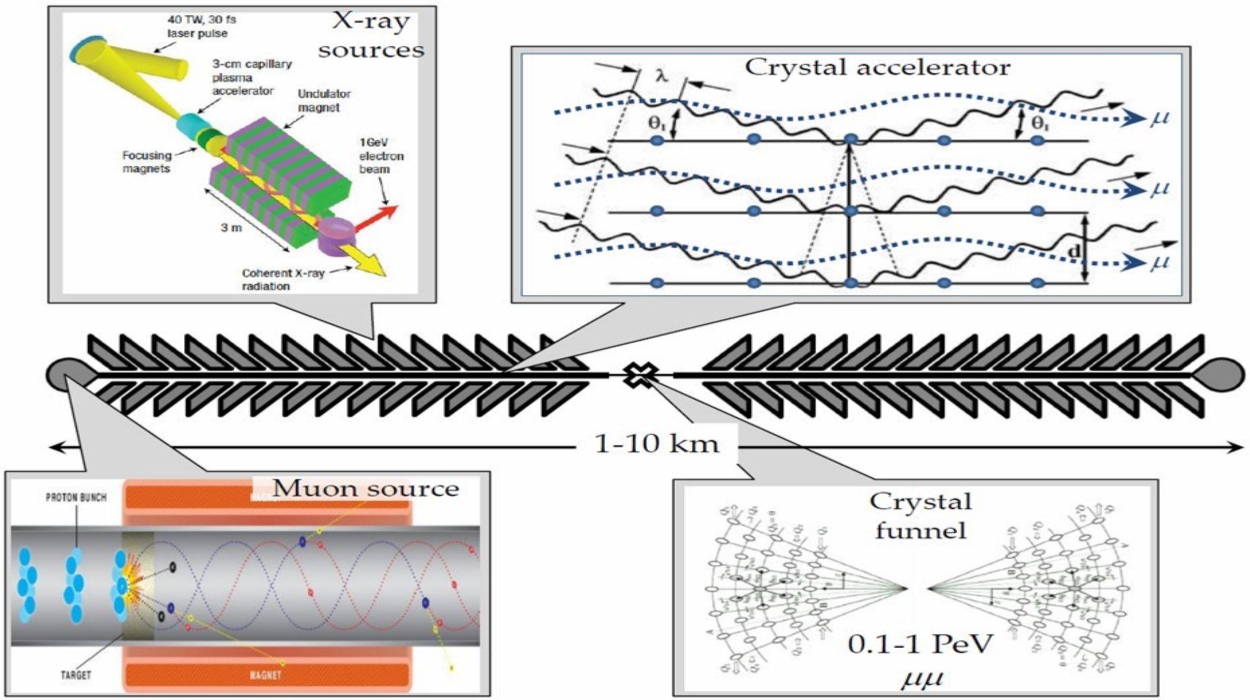
Channeling in a bent crystal



Hybrid crystal-based positron source***



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



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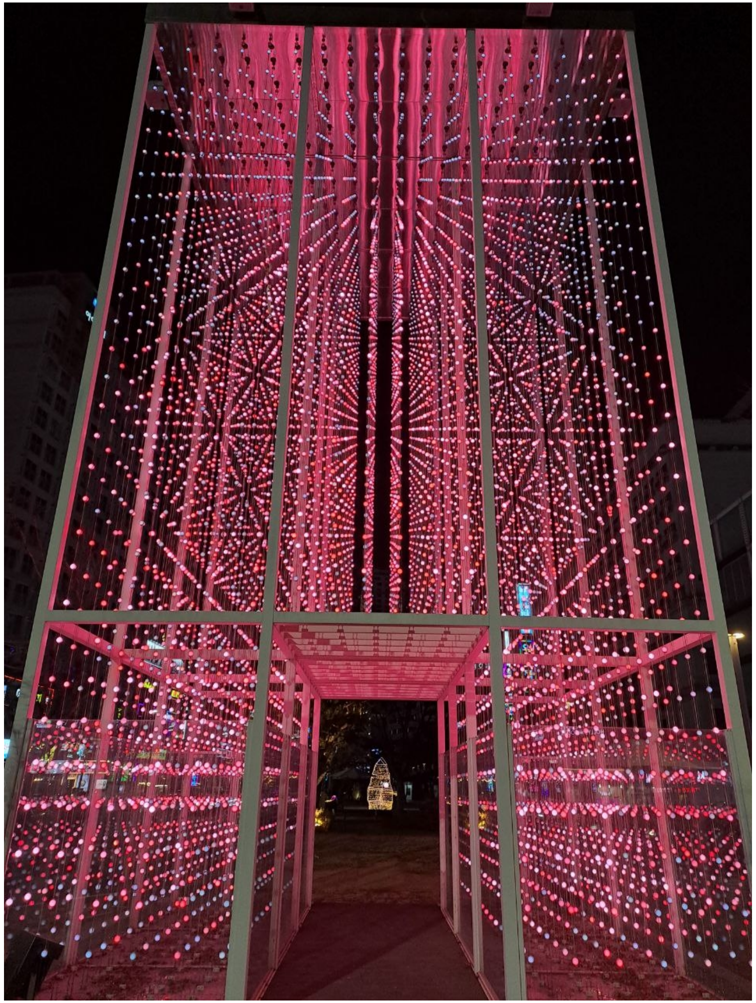
**V. Shiltsev, Physics-Uspekhi 55, (10), 965 (2012)

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



Thank you for attention!