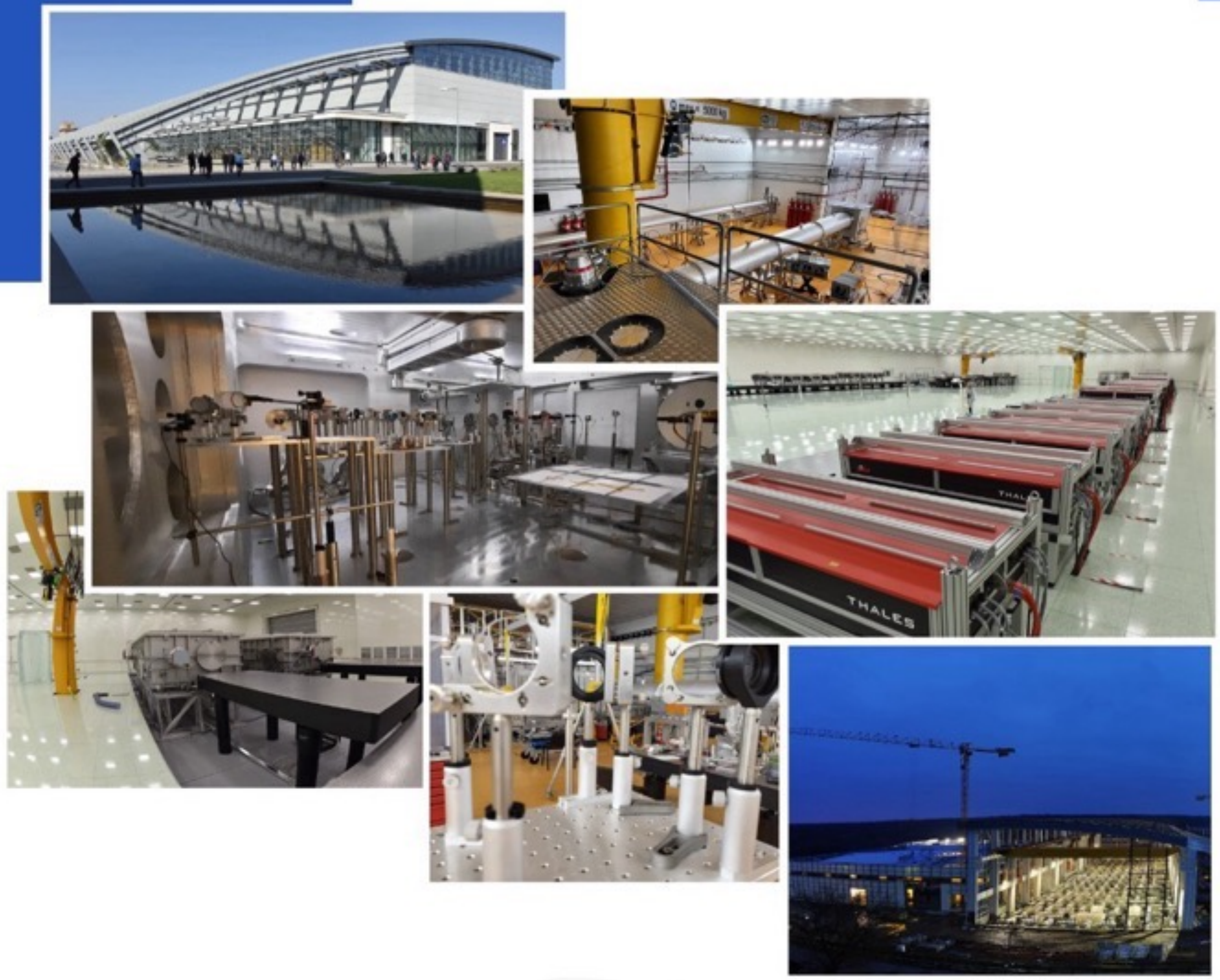



# FROM BASIC RESEARCH TO APPLICATIONS AT EXTREME LIGHT INFRASTRUCTURE – NUCLEAR PHYSICS

CĂLIN A. UR
ELI-NP / IFIN-HH

eli nuclear physics

IFIN-HH

April 16, 2026
IUPAP WG9/C12
Nuclear Science Symposium 2026

Cofinanțat de Uniunea Europeană

Program Sănătate

Structural Instruments 2014-2020

# Extreme Light Infrastructure – Nuclear Physics @ ELI

**ELI-NP – has established a major world-class research infrastructure in Romania as part of the pan–European project ELI**

dedicated to research in the emerging field of **Nuclear Photonics** with extreme electromagnetic radiation

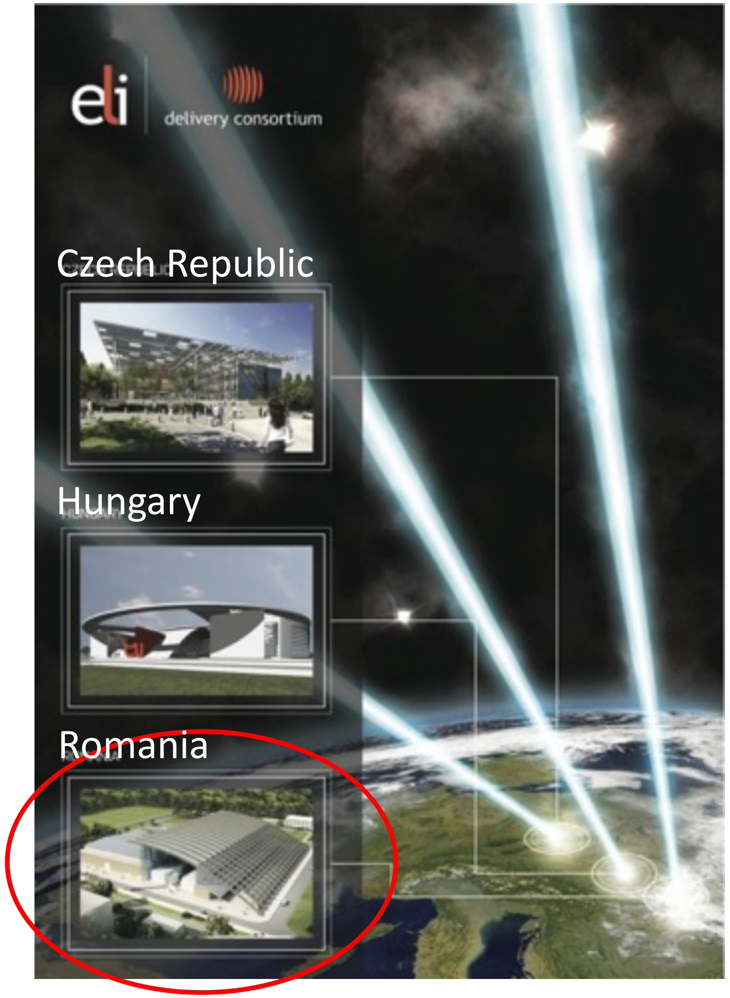
**High-level exploratory and interdisciplinary basic research ...**

- Laser–matter interaction
- Laser–driven particle acceleration
- Nuclear reactions in plasma
- Nuclear astrophysics
- Quantum electrodynamics

**... leading to innovative applied research of societal interest**

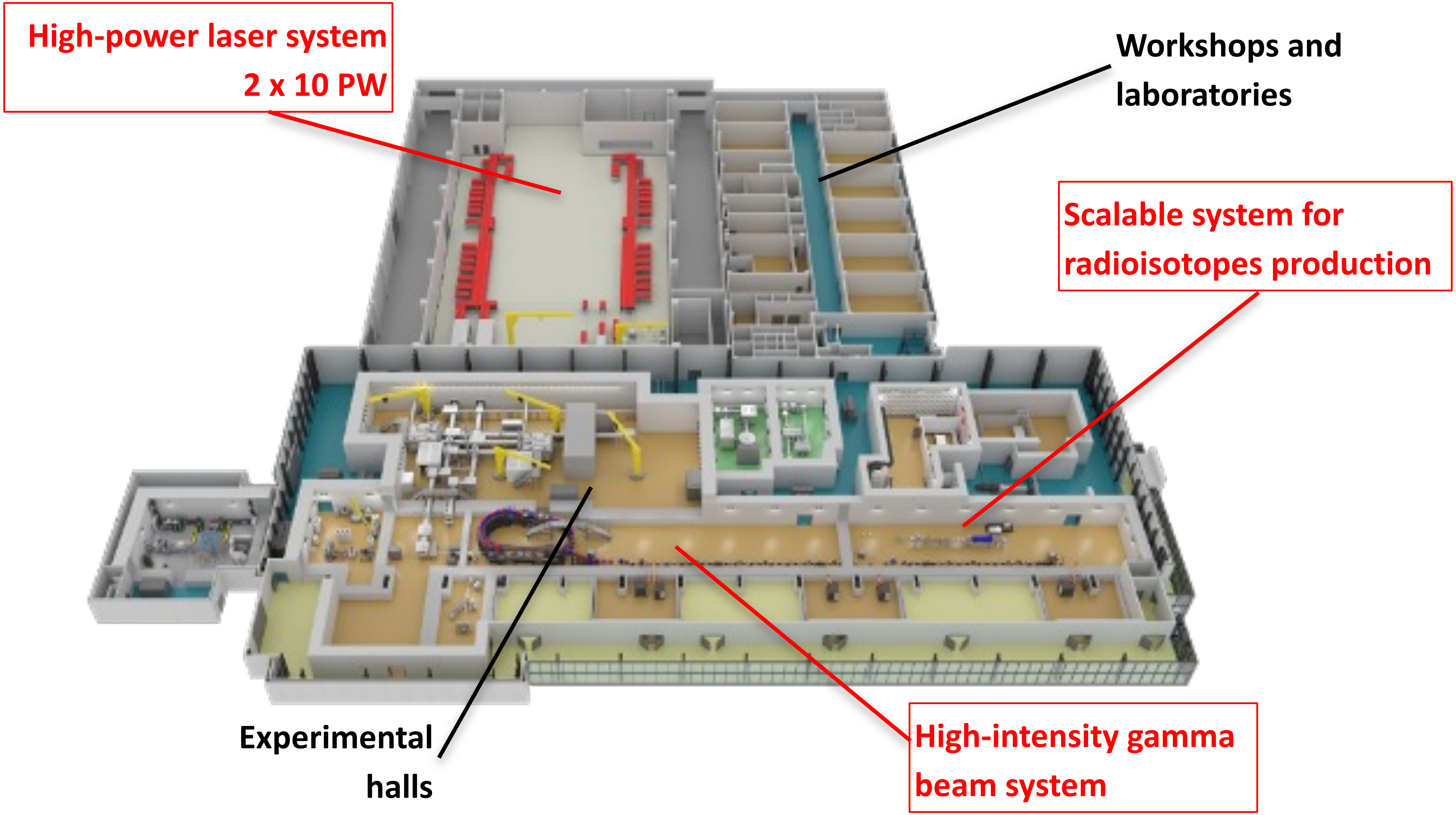
- Medical applications (radiotherapy, imaging)
- Industrial applications (radioscopy, tomography)
- Material studies for space industry

**Extreme Light Infrastructure (ELI)**



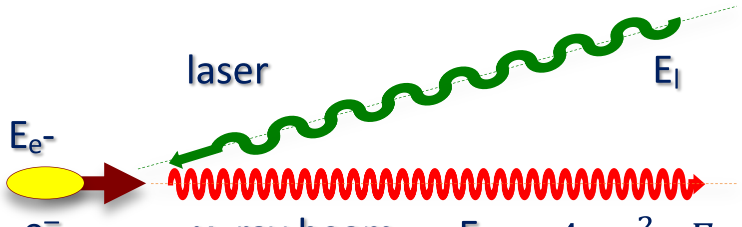

🎯 **ELI** - the largest laser research center worldwide distributed in three countries (RO, HU, CZ)

# Extreme Light Infrastructure – Nuclear Physics @ Infrastructure



# The ELI-NP Gamma Beam System

**Laser Compton Backscattering off relativistic electrons**

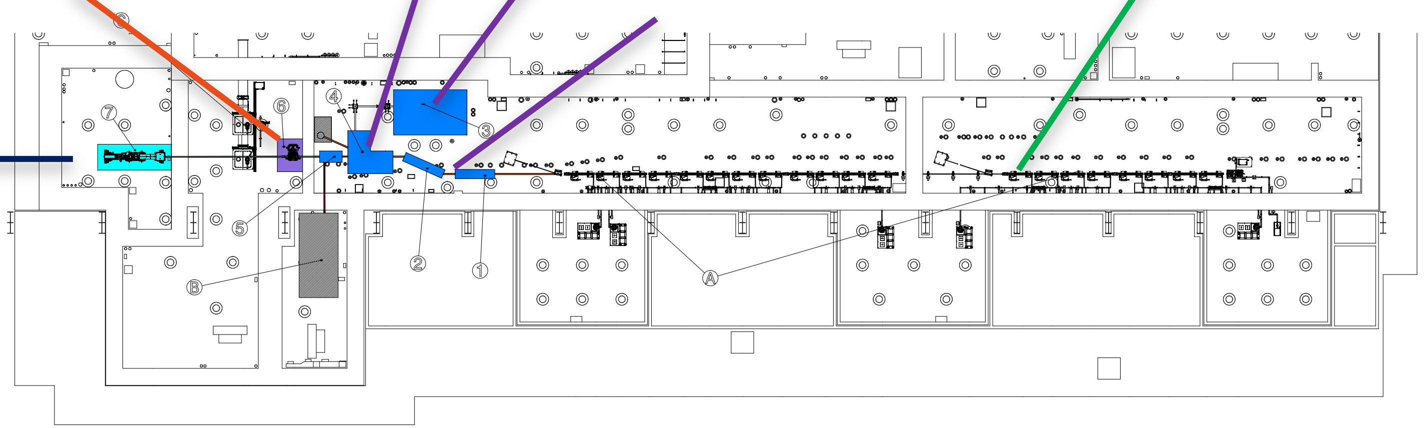



$E_\gamma \approx 4 \cdot \gamma^2 \cdot E_l$

**Solution**
*RF electron linear accelerator and optical cavity*

**HL Collider**
$L \sim 10^{35}\ cm^{-2}\ s^{-1}$

Energy up to: **19.5 MeV**
Quasi-monochromatic: **< 0.5% rel. bandwidth**
High spectral density: **> 5000 photons/eV/s**
High-degree of linear polarization: **> 95%**




**Configuration I – low intensity**
- 50 Hz
- Eγ = 19.5 MeV
- ΔEγ/Eγ = 0.5 %
- Spectral density = 10-20 photons/eV/s

plus components for upgrade to high intensity →

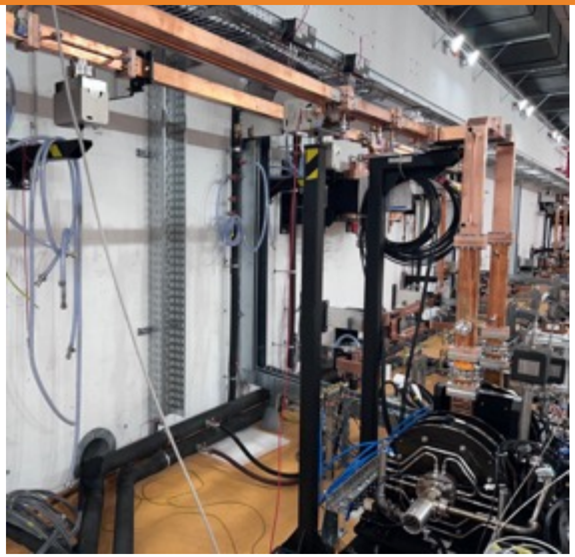
**Configuration II – high intensity**
- about 10 kHz
- Eγ = 19.5 MeV
- ΔEγ/Eγ = 0.5 %
- Spectral density = 5000 photons/eV/s

**To be completed in 2026**

**To be implemented in 2027-2028**

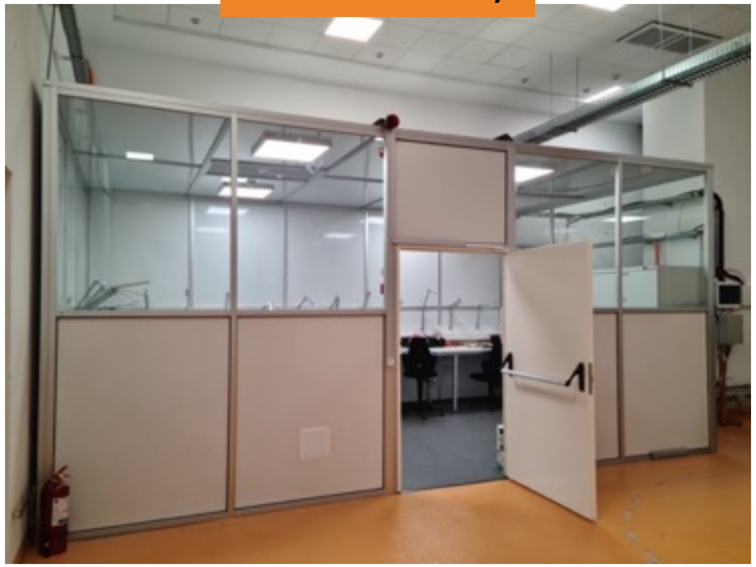
# The ELI-NP Gamma Beam System

Photogun in Accelerator Bay 1



Accelerating structures in Accelerator Bay 2

RF Laboratory



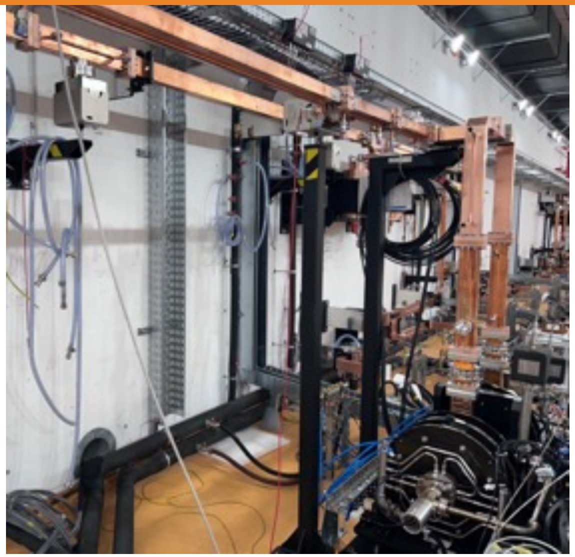
RF Modulators – all operational

HPRF on module M5 5/2/2026

Synchronized PG laser with LLRF 6/4/2026

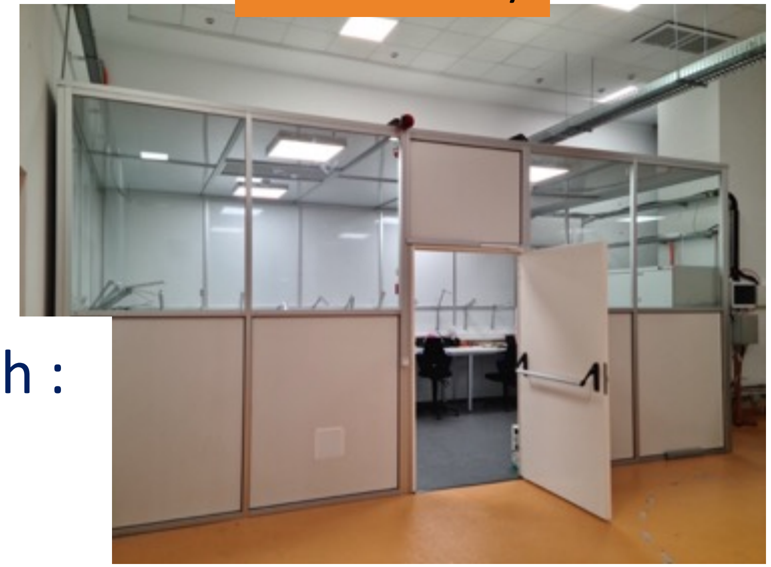
# The ELI-NP Gamma Beam System

Photogun in Accelerator Bay 1



Accelerating structures in Accelerator Bay 2

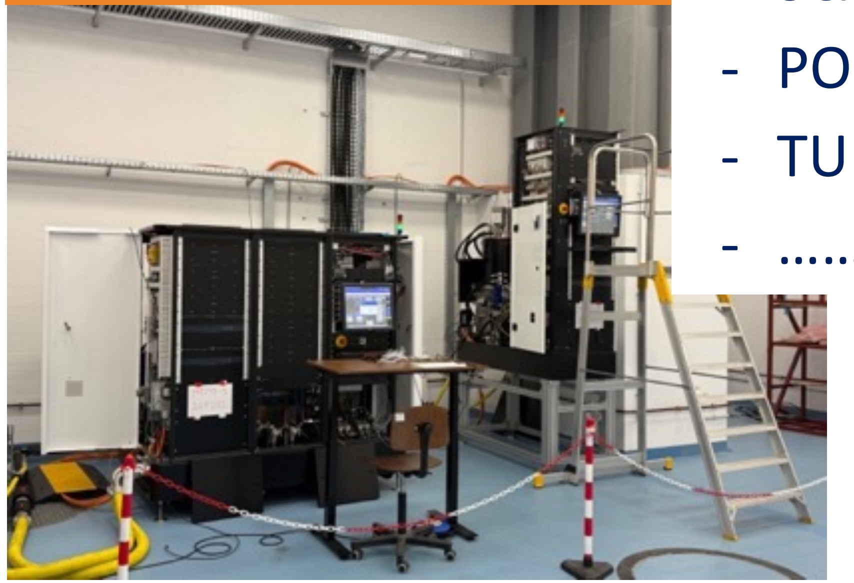
RF Laboratory



Activities done in collaboration with :

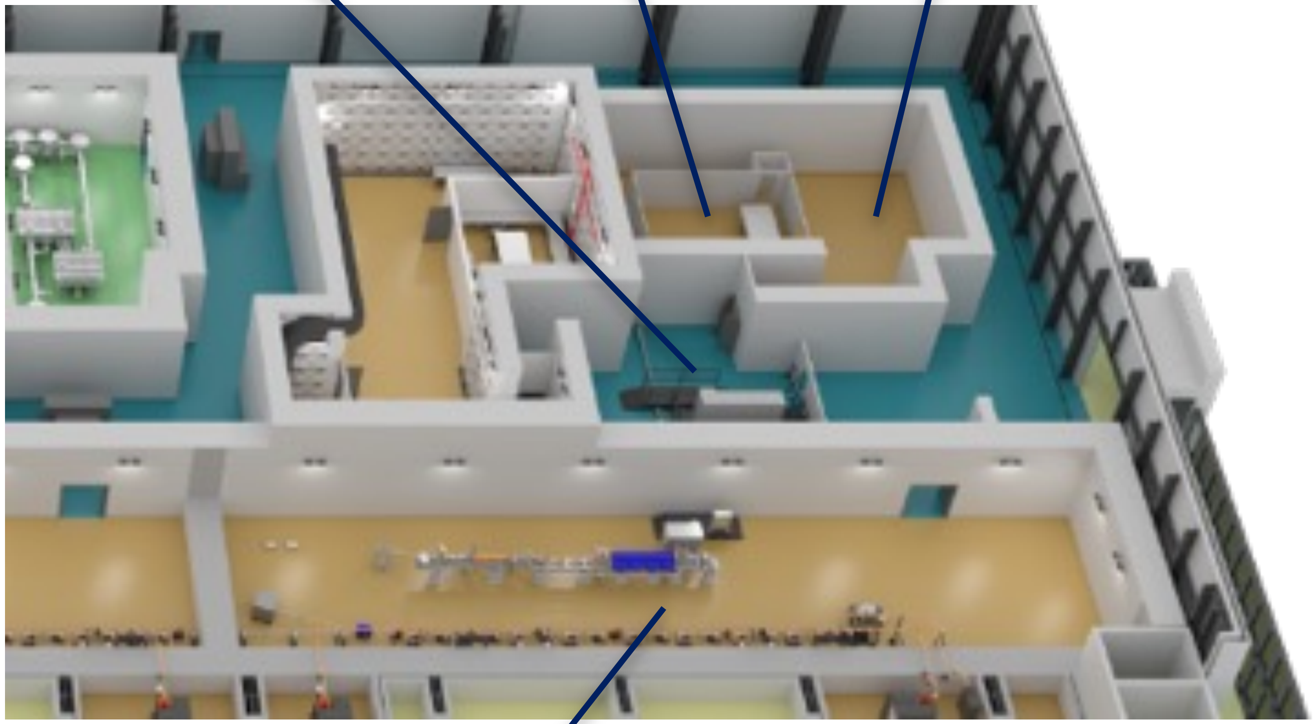
- CERN – Accelerator Division
- Research Instruments GmbH
- SCANDINOVA SYSTEMS
- POLITEHNICA Bucharest
- TU Munchen
- …….

RF Modulators – all operational



nized PG laser with LLRF 6/4/2026

# Scalable System for Radioisotopes Production

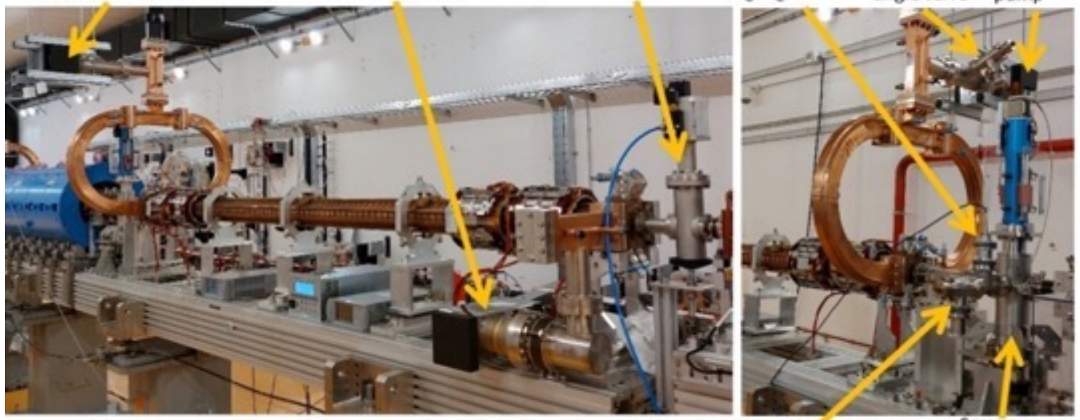



Components delivered within the **Stage I** of the contract with EuroGammaS Association for GBS – existing on ELI-NP site

- In collaboration with INFN and CNRS

First Stage – RF Electron linear accelerator

- Photogun S-band + 2 S-band + 1 C-band
- Max. Energy ≥ 100 MeV
- Average Current ≈ 1 nA → 50 nA → ~ 1 μA



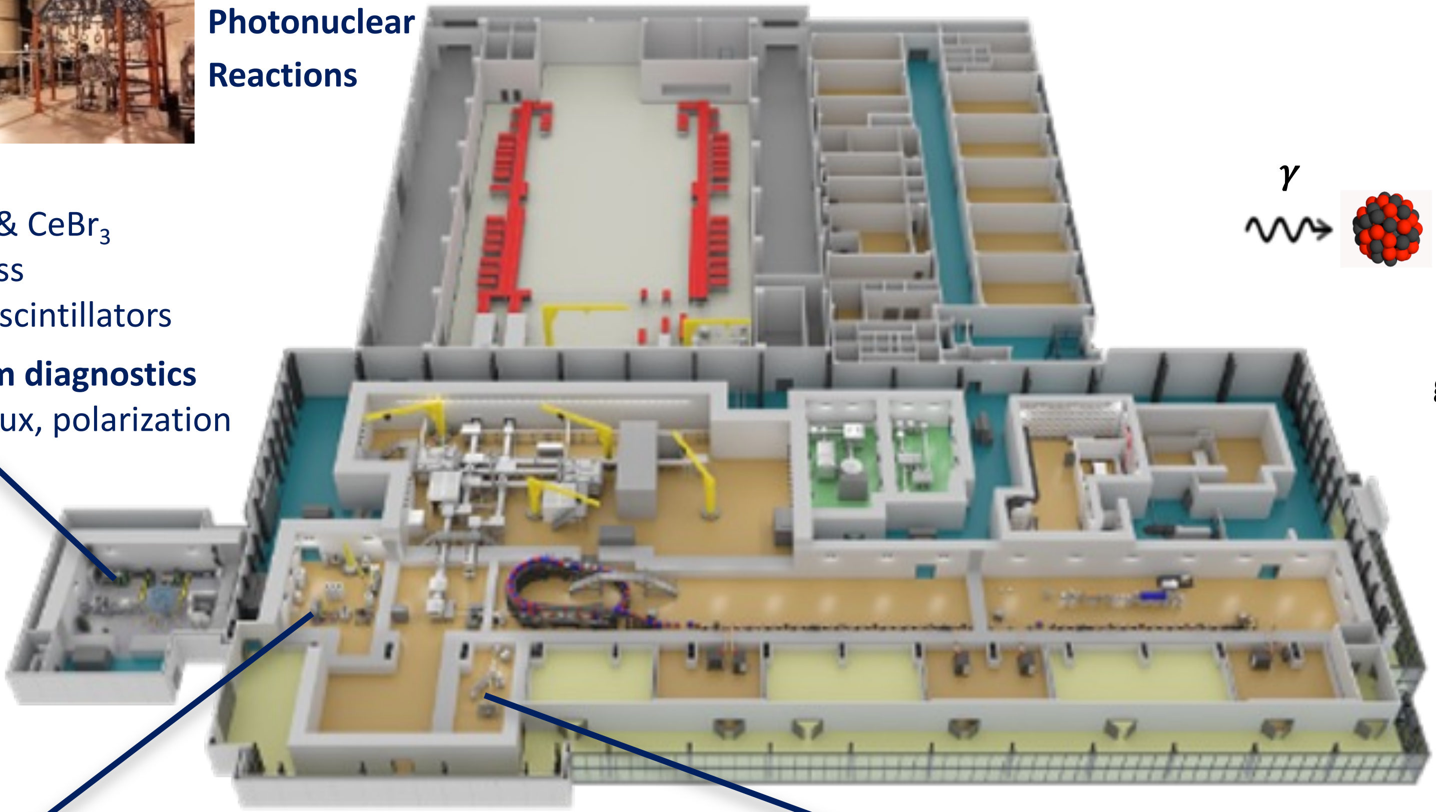

**Currently: accelerating structures conditioning**

# Gamma-driven experimental setups – all operational

**E9: $\gamma$ beams**
**Photonuclear Reactions**

**ELIGANT-GN**
- 34 $LaBr_3$ & $CeBr_3$
- 25 $^7$Li glass
- 36 liquid scintillators

**Gamma beam diagnostics**
- energy, flux, polarization



**E8: $\gamma$ beams**
**Photonuclear Reactions**

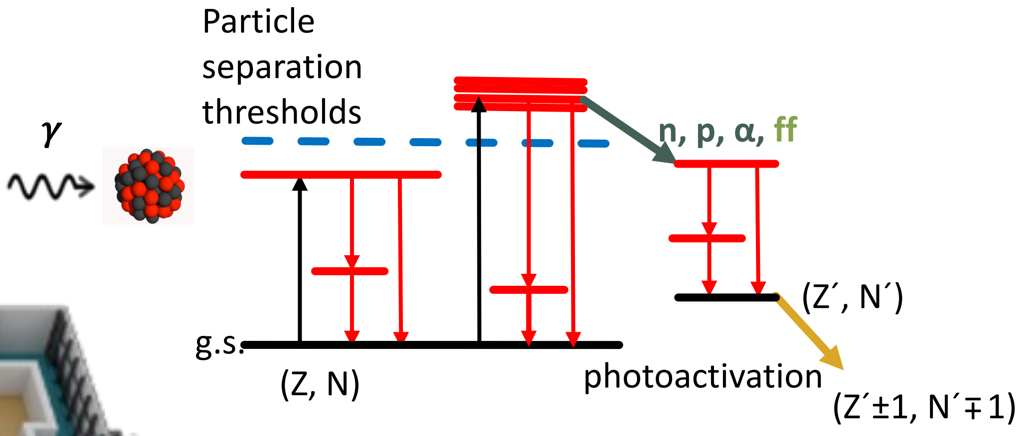
**ELIADE**
- 8 HPGe segmented clover
- 4 $LaBr_3$(Ce)

**Gamma-Ray Imaging**

**ELISSA**
- DSSSD

**ERA: positrons**
**Material Studies**

## Physics Case: photonuclear reactions




**Nuclear physics**
- e.m. dipole response of nuclei
- Nuclear structure
- Pygmy and Giant Dipole Resonances
- Photonuclear reactions cross sections
- Nuclear astrophysics
- Photofission and exotic nuclei

**Applications**
- Industrial imaging
- Radioisotopes generation
- Material studies with positrons

# Most powerful laser system operational in the world @ ELI-NP

**Unique system in the world:**

power, intensity, number of beams, versatility and flexibility

- Demonstrated **power level 10 PW**
- combination of **2 high-power laser arms**
- each arm has three output power levels:

**100 TW@10 Hz  1 PW@1 Hz  10 PW@1/minute**



Virtual tour of the ELI-NP laser system
https://www.eli-np.ro/thales_eli-np.php

High Power Laser Science and Engineering, (2020), Vol. 8, e43, 15 pages.
doi:10.1017/hpl.2020.41
HIGH POWER LASER SCIENCE AND ENGINEERING

RESEARCH ARTICLE

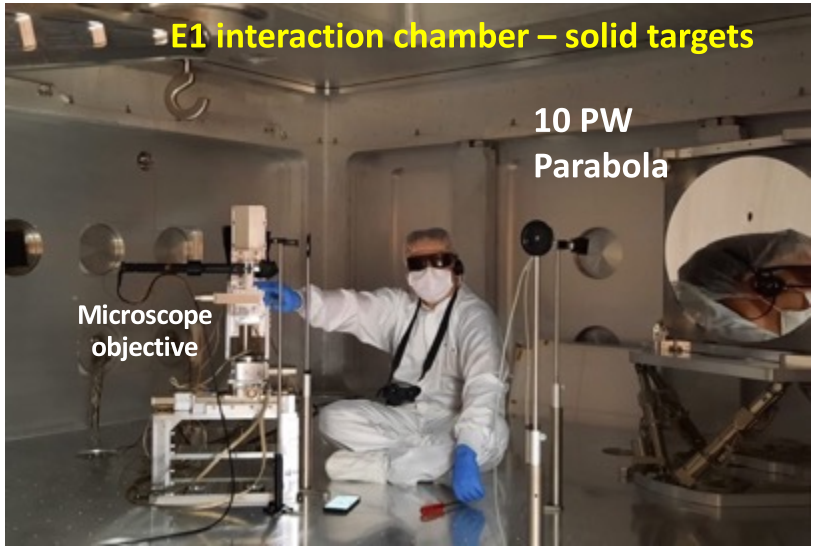
**High-energy hybrid femtosecond laser system demonstrating 2 × 10 PW capability**

François Lureau[1], Guillaume Matras[1], Olivier Chalus[1], Christophe Derycke[1], Thomas Morbieu[1], Christophe Radier[1], Olivier Casagrande[1], Sébastien Laux[1], Sandrine Ricaud[1], Gilles Rey[1], Alain Pellegrina[1], Caroline Richard[1], Laurent Boudjemaa[1], Christophe Simon-Boisson[1], Andrei Baleanu[2], Romeo Banici[2], Andrei Gradinariu[2], Constantin Caldararu[2], Bertrand De Boisdeffre[2], Petru Ghenuche[3], Andrei Naziru[3,4], Georgios Kolliopoulos[3], Liviu Neagu[3], Razvan Dabu[3], Ioan Dancus[3], and Daniel Ursescu[3]

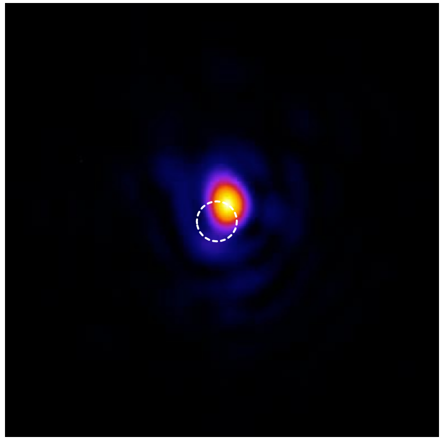
[1]Thales LAS France, 78990 Élancourt, France
[2]Thales Systems Romania, 060071 Bucureşti, Romania
[3]Extreme Light Infrastructure – Nuclear Physics, 'Horia Hulubei' National Institute for Physics and Nuclear Engineering, 077125 Bucharest Magurele, Romania
[4]University of Bucharest, Faculty of Physics, 077125 Bucharest Magurele, Romania

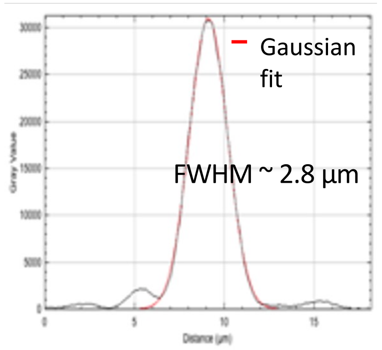
(Received 1 August 2020; revised 22 October 2020; accepted 26 October 2020)

# April 13th 2023 – a landmark in the history of plasma physics




*First time focusing 10 PW below **3 µm***






I = $10^{23}$ W/cm$^2$

→ E = 0.86 x $10^{15}$ V/m
B = 3 x $10^6$ T

Extreme light intensity (10 PW ⟹ $10^{23}$ W/cm$^2$)

*Extreme electric fields ($10^{15}$ V/m)*

***Strong-field QED***

**10 PW laser + solid target**

↓

**PW $\gamma$-source**

**10 PW laser + GeV LWFA electrons**

↓

**Radiation reaction**
**Breit-Wheeler pairs**
**QED vacuum**

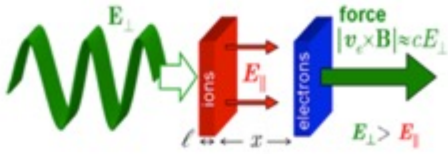
*Extreme light pressures (Tbar)*

***Nuclear Physics with Lasers***

**10 PW radiation pressure acceleration of *dense* ion beams**

**Nuclear reactions in plasma**

**Ultra-intense neutron source**



# Laser-driven experimental setups – all operational – available for users

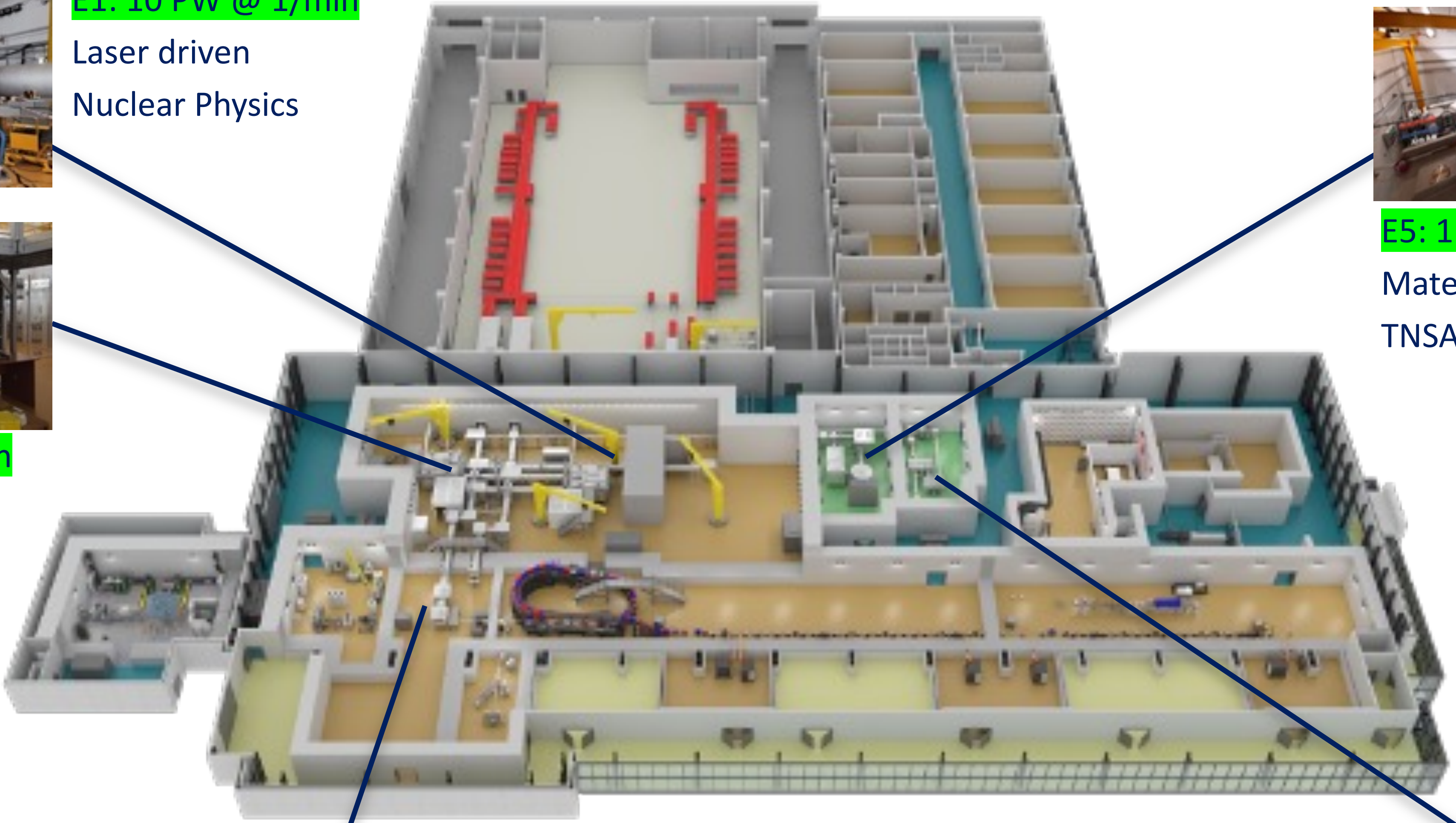
E1: 10 PW @ 1/min

Laser driven

Nuclear Physics

E6: 10 PW @ 1/min

Strong Field QED



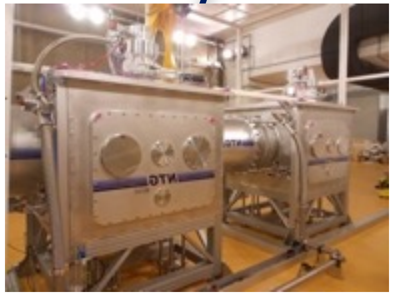
E5: 1 PW @ 1 Hz

Material Studies, LWFA,

TNSA, RPA

E7: 1 PW @ 1 Hz

Strong Field QED



E4: 0.1PW@10 Hz

Photon-photon int.,

LWFA, X-ray imaging

# HPLS OPERATION 2021–2025 – USER FACILITY SINCE 2022

**2021 – Delivered beamtime – 36 weeks**
16 weeks @ 100 TW
20 weeks @ 1 PW

**2022 – Delivered beamtime – 59 weeks**
20 weeks @ 100 TW
28 weeks @ 1 PW
11 weeks @ 10 PW

**2023 – Delivered beamtime – 52 weeks**
7.5 weeks @ 100 TW
20 weeks @ 1 PW
24.5 weeks @ 10 PW

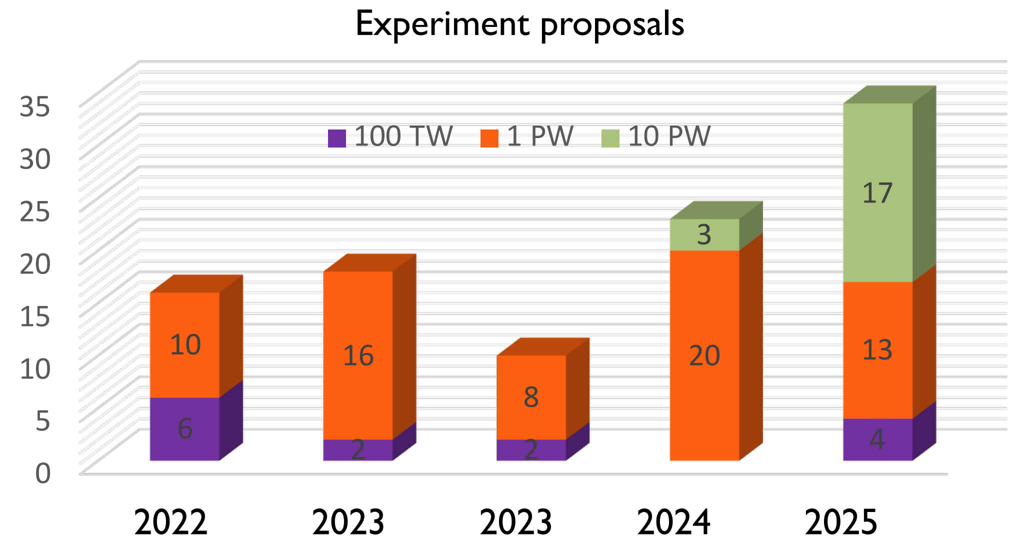
**2024 – Delivered beamtime – 67 weeks**
7 weeks @ 100 TW
30 weeks @ 1 PW
30 weeks @ 10 PW

**2025 – Delivered beamtime – 58 weeks**
29 weeks @ 1 PW
29 weeks @ 10 PW

**Attraction pole for users**
- **In the period 2022–2025 over 200 users (130 in 2025)**
- **Interest has increased since offering access to 10 PW laser beams in 2024**

**Access based on scientific excellence – user calls launched in common with ELI ERIC**

**ELI-NP Program Advisory Committee (PAC) – international experts**



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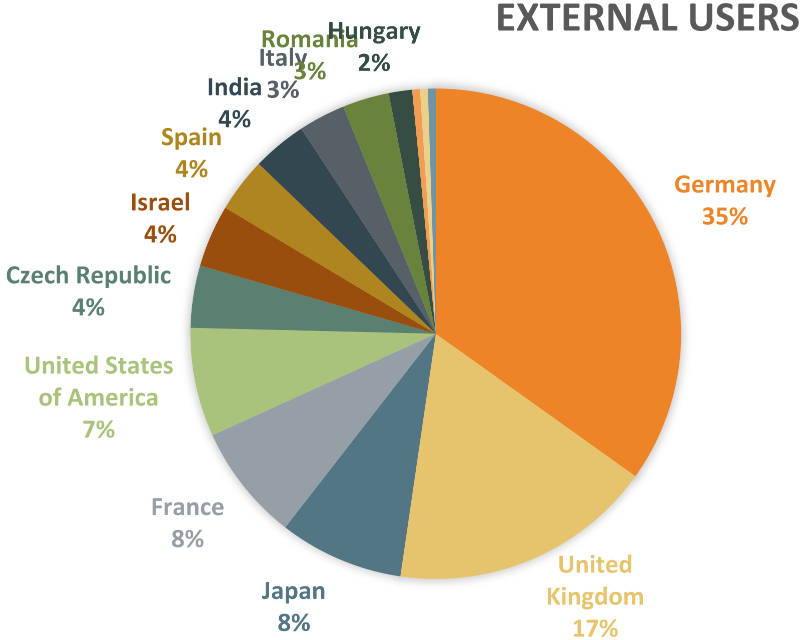
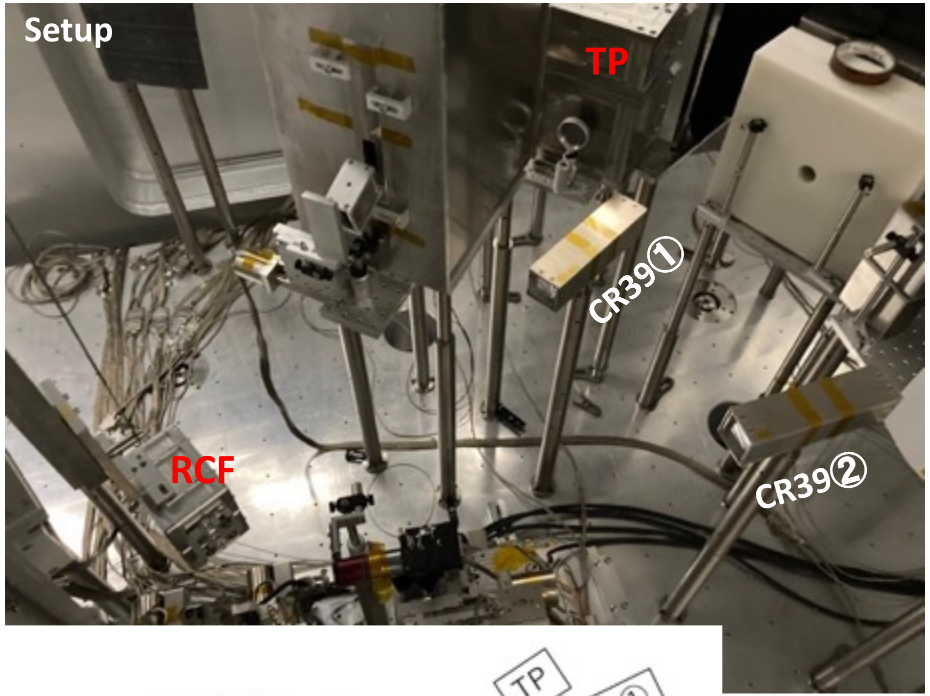
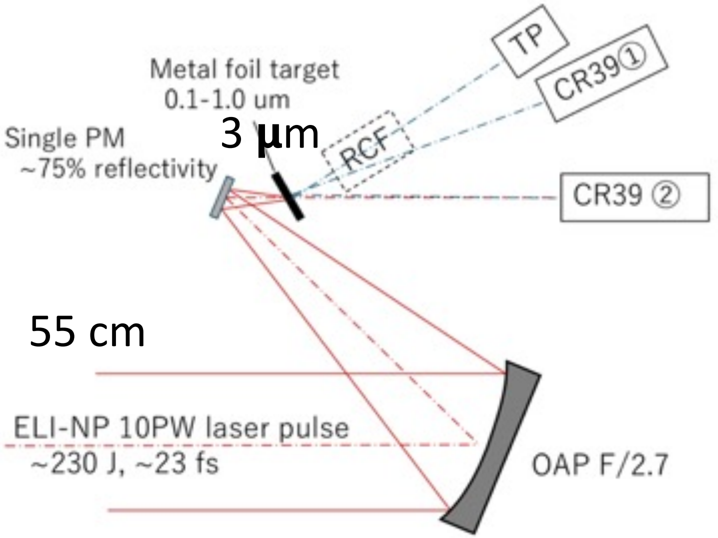
**EXTERNAL USERS**



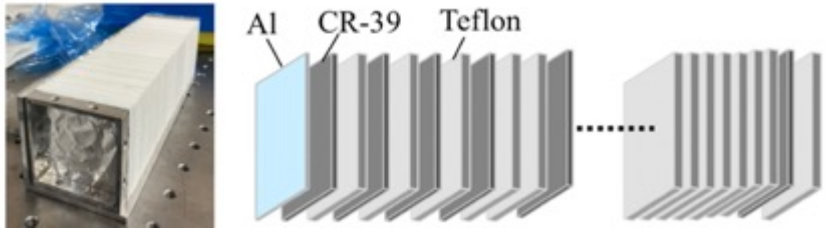
# 10 PW Highlights – Carbon ions acceleration

**Analysis by Ozaki, Kanasaki (Kobe U.), Fukuda (KPSI)**



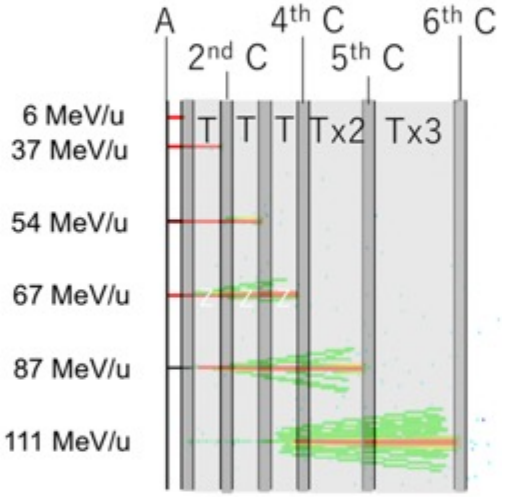




**Schematic of the CR-39 Stack**[1]



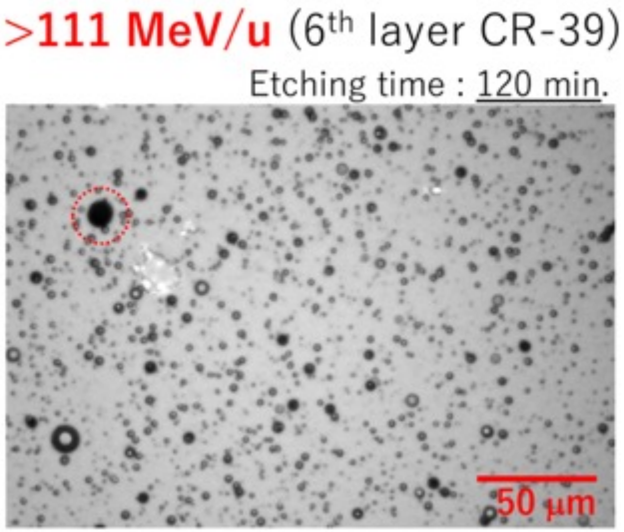

[1] M. Kanasaki et al., in preparation.

[2] T. Sato et al., J. Nucl. Sci. Technol. **55**, 68 (2018).

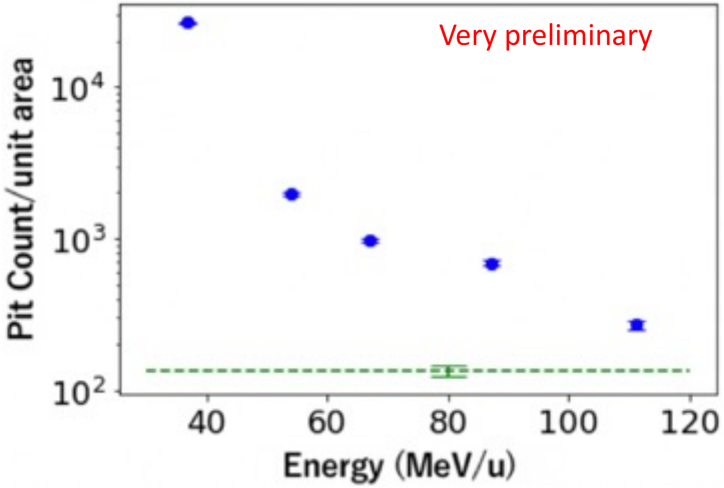



A: Aluminum (13 um)
C: CR-39 (0.9 mm)
T: Teflon (1.8 mm)

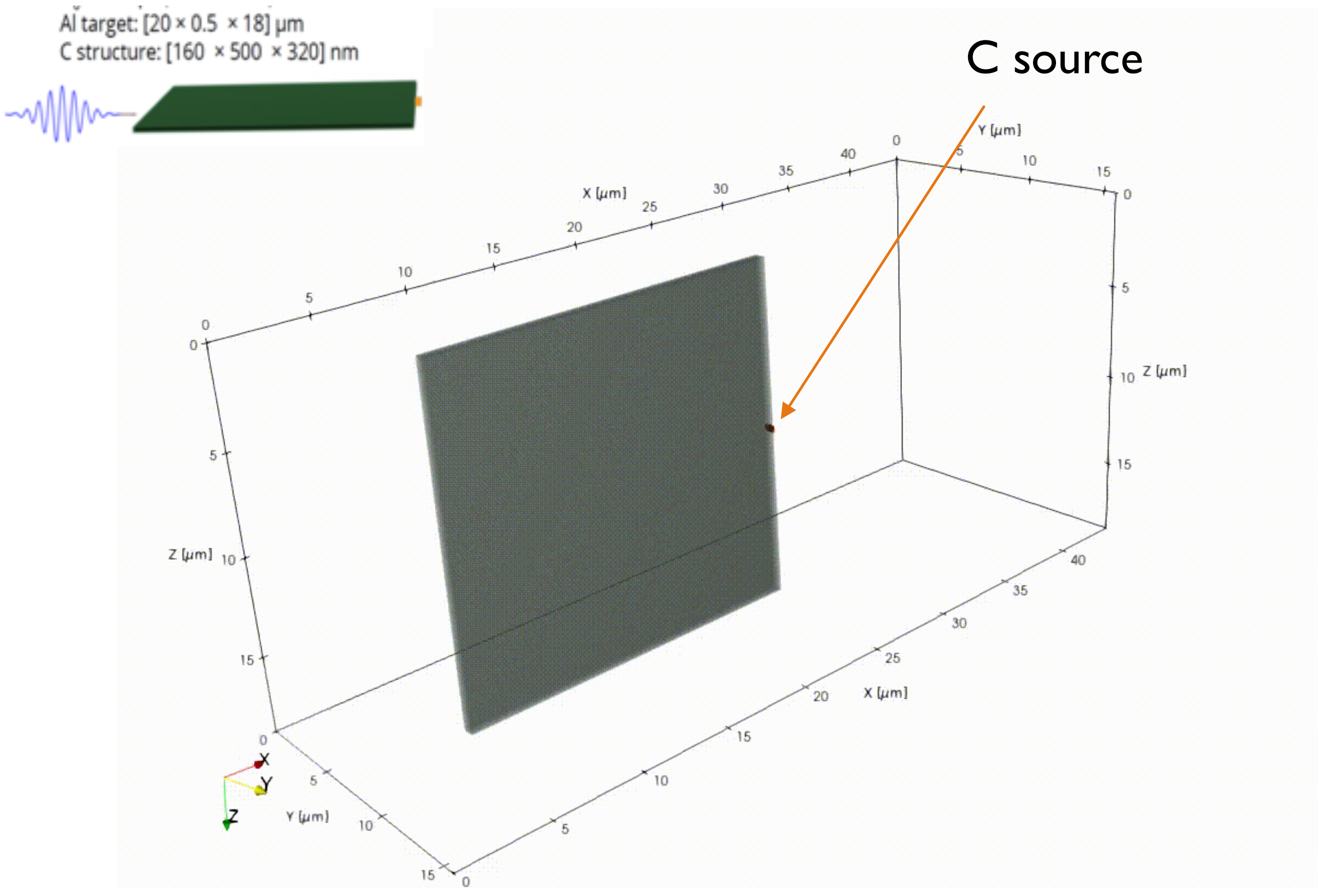
**Microscope Image of Etch Pits**




**Carbon ion spectrum**

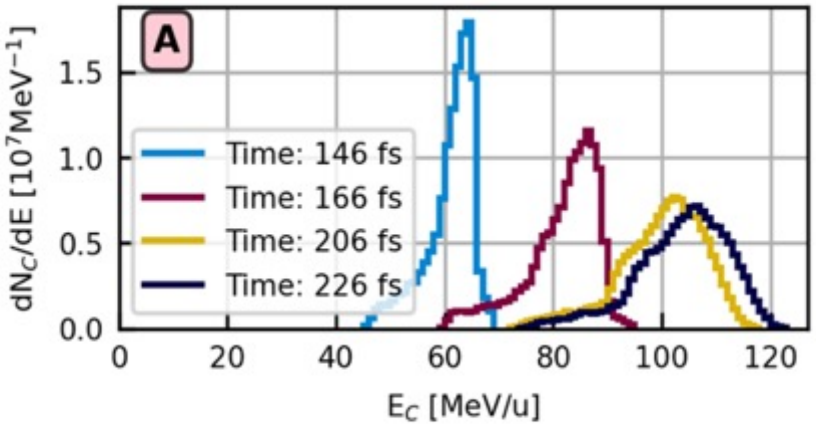


# 10 PW – Carbon ion acceleration – 3D PIC Simulations (‘Peeler’ scheme)

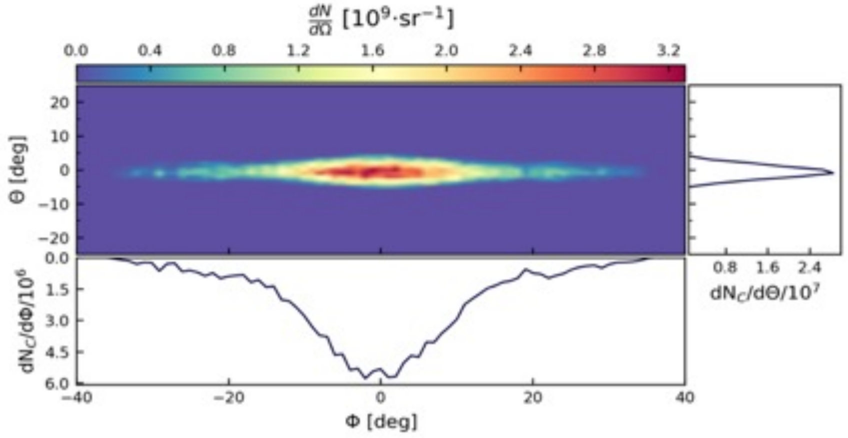



*B. Corobean et al., MRE 2025*

**$C^{6+}$ energy spectrum evolution**



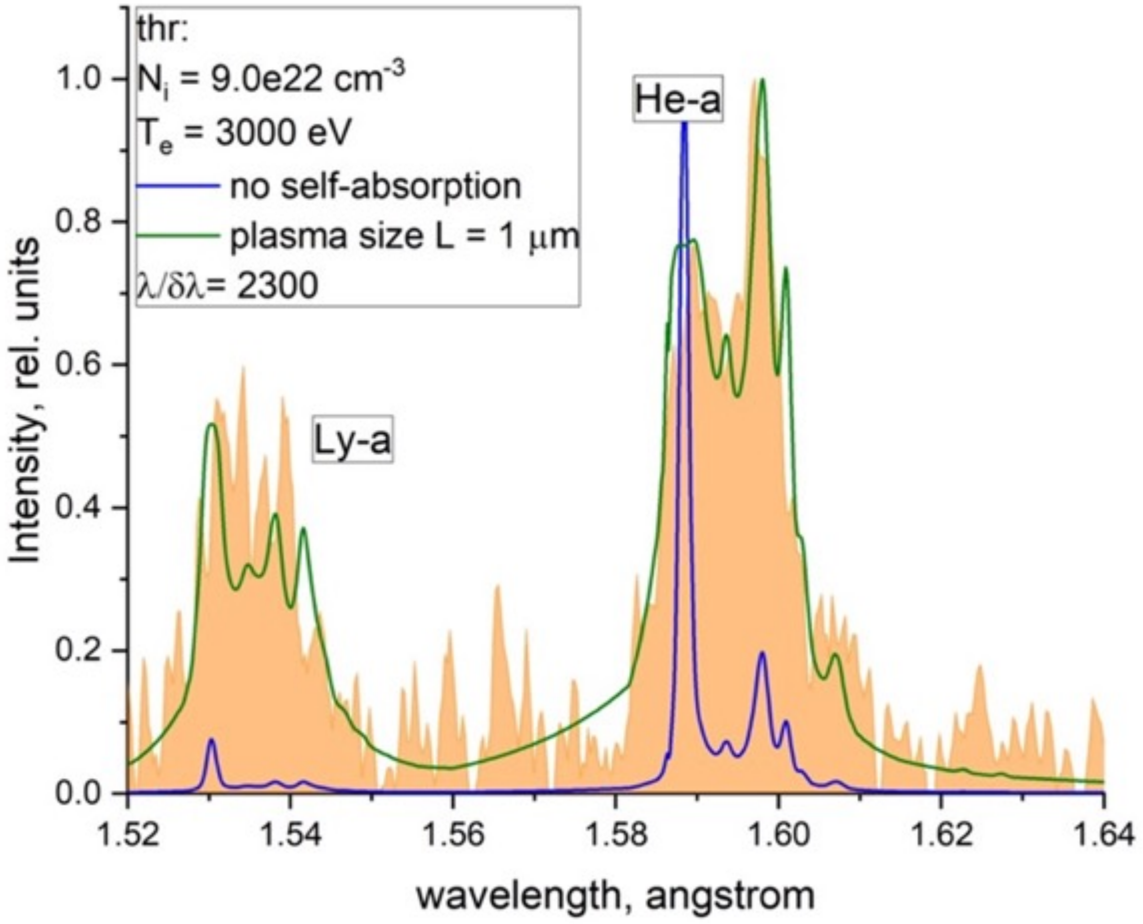

**$C^{6+}$ angular distribution**




**⇨ ‘Quasi monochromatic’ C-ion source having yield of $>10^8$ C-ion/shot can be obtained**

# 10 PW Highlights – Plasma of fully ionized ions

**Experiment at high intensity in E1 interaction chamber**



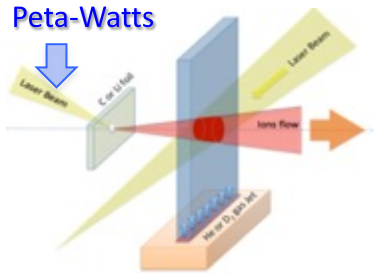

Courtesy of T. Pikuz , collaboration with U. Osaka and KPSI, Japan

**First observation of H-like $Ly_{\alpha}$ of Ni (Z=28) in laser produced plasma (Collab. with Osaka University)**

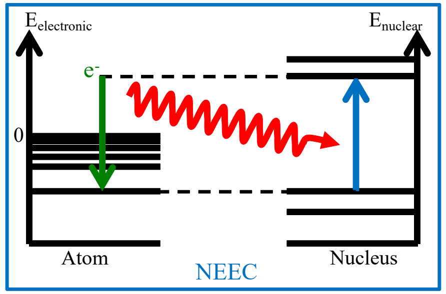
For **the first time a fully ionised plasma of Nickel atoms at solid density has been created** and fully characterised through the measurement of $Ly_{\alpha}$ line indicating a temperature of 3 keV at a density close to $10^{23}$ $e^{-}/cm^{3}$

High ionization states at solid density are a paramount in plasma physics since it opens **the possibility to investigate states of matter that are similar to those existing in stellar environment**.

**Study of electron screening factor in nuclear reactions of astrophysical interest**




**Nuclear de-excitations in plasma**



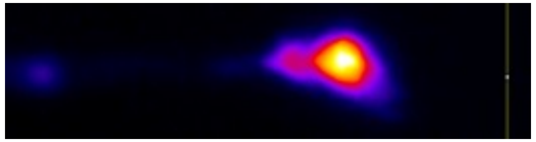
# 10 PW Highlights – High energy electrons and gamma rays

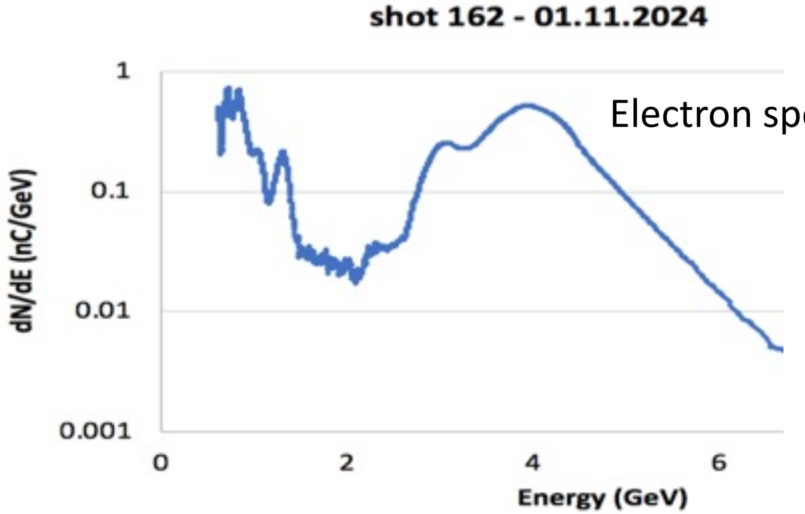
### Interaction chamber E6 – gas targets

### LWFA Electron acceleration using 60 mm gas length , He+N2 2% gas

*ELI50069 – P.I. S. Corde, LOA/ K. TA-PHUOC, CELIA /V. Malka, WIS/ P. Ghenuche, ELI-NP*

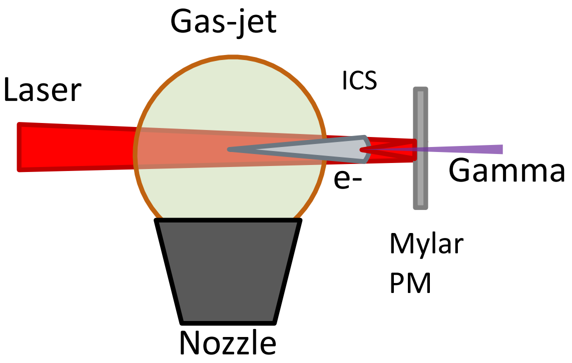
RAW image of the Lanex scintillator screen



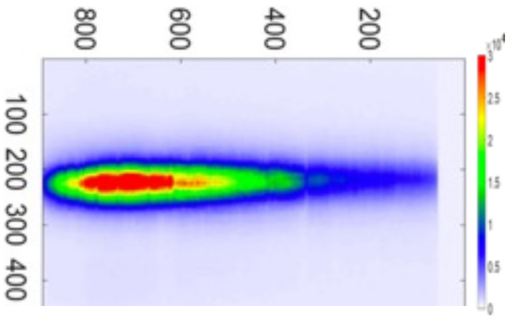




### High-energy gamma rays following Inverse Compton Scattering

Sketch of the ICS setup




Gamma from Inverse Compton Scattering – LYSO matrix detector

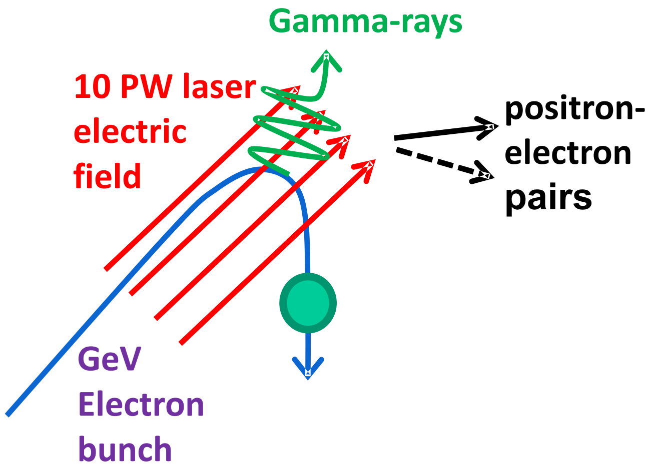



A. Matheron et al., arXiv:2412.19337v1 [physics.plasm-ph]

# 10 PW Highlights – High energy electrons and gamma rays

**Interaction chamber E6 – gas targets**

**Strong–field QED**




**High-energy gamma rays following Inverse Compton Scattering**

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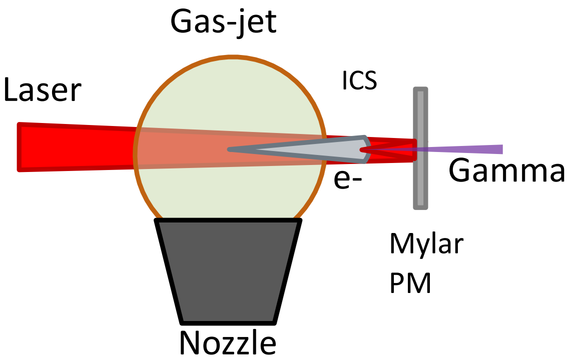
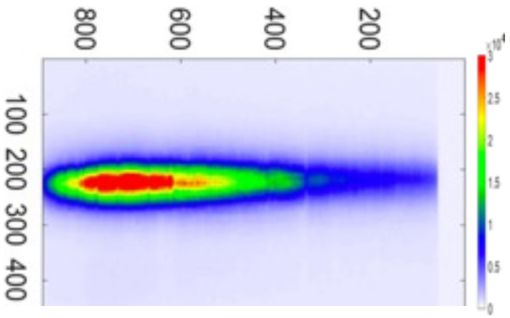



Gamma from Inverse Compton Scattering – LYSO matrix detector




Collision of multi-GeV e-beams with intense laser beams (>$10^{22}$ W/cm$^2$)

- Synchrotron radiation or Nonlinear Compton:
  $e^- + n\gamma_L \rightarrow e^- + \gamma_R$
- Breit-Wheeler pair production:
  $\gamma_R + n\gamma_L \rightarrow e^- + e^+$

A. Matheron et al., arXiv:2412.19337v1 [physics.plasm-ph]

# 10 PW Highlights – Experimental setup for muon generation & detection

**Preliminary experimental results**

**Muon generation via the Bethe-Heitler process by LWFA electrons interacting with a Lead converter**

*ELI50138 – P.I. D. Doria*

10 PW laser long focal (~ 30m) fired into a gas jet (He +2%$N_2$) 60mm long

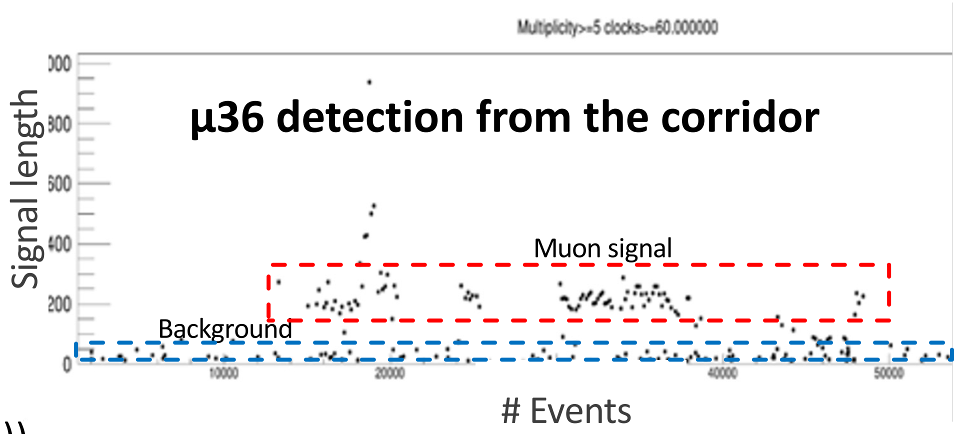
**Detection setup**

**Inside experimental area**

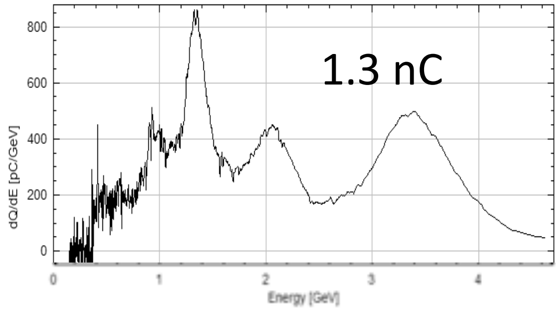
- 2 x Scintillator PMT probes
- Neutron monitor **(n)**
- Electron spectrometer (**Lanex, magnet (M)**)
- Lead Converter electrons to muons **(C)**

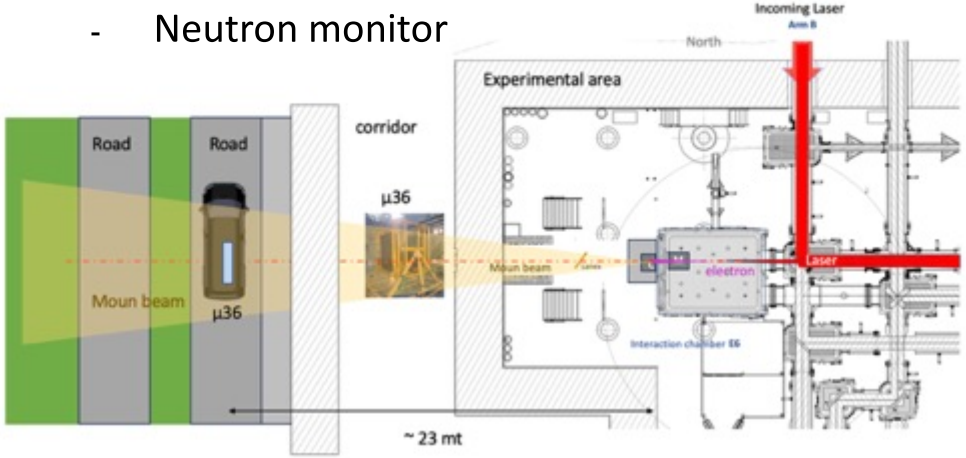
**In the corridor**

- **µ36** detector 3 m away
- Gamma monitors
- Neutron monitor



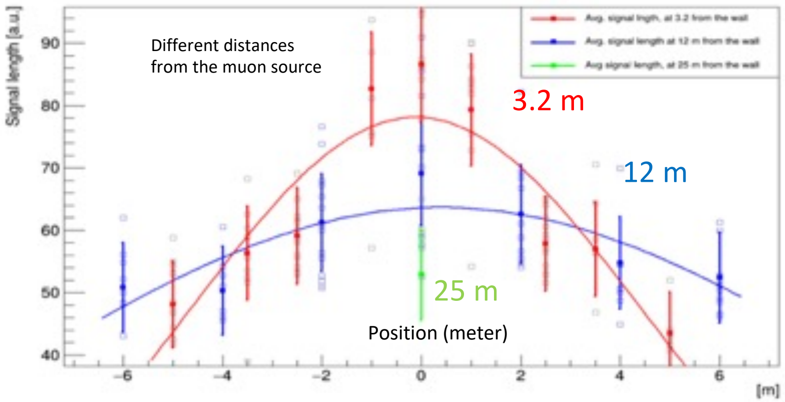

**Typical electron beam**




**Detection of beam size using the van**

Map of the Muon beam obtained by moving the van and taking several shots per position




Assuming a 1 nC electron charge we obtain a total of **400 ± 60 muons for a 2 GeV electron beam** and **(1.16 ± 0.06) x $10^4$ muons for a 5 GeV electron beam**

# Laser–Driven Medical Applications Research

Dr. LASER

## Project Dr. LASER – Included in the Romanian Health Program

- in collaboration with UMFCD Bucharest, POLITEHNICA Bucharest, IOCN Cluj Napoca, IRO Iasi and 2 SMEs
- Contract signed on February 2025
- Co-funded by EU and Romanian Government

### Laser-driven C-ions for hadron therapy

- 10 PW-class lasers have potential to accelerate heavy-ions to therapeutic energy and dose, at ultrahigh dose rate, in few mm
- laser-driven ultra-high dose rate heavy-ion irradiation can enable the FLASH effect (healthy tissue sparring) ($10^{10}$ Gy/s)

### Interferometric phase contrast X–ray imaging

- Conventional, absorption-contrast X-ray imaging has poor visibility of soft tissue tumors
- Method requires intense, directional, short–pulse and spatially coherent X–ray source: 100 TW class lasers can do this

### Medical interest radioisotopes production

- High power lasers offer the possibility for producing medical radioisotopes due to their ability to accelerate different types of particles
- "*on-site*" production of medically short-lived radioisotopes with 100 TW-class high repetition rate lasers

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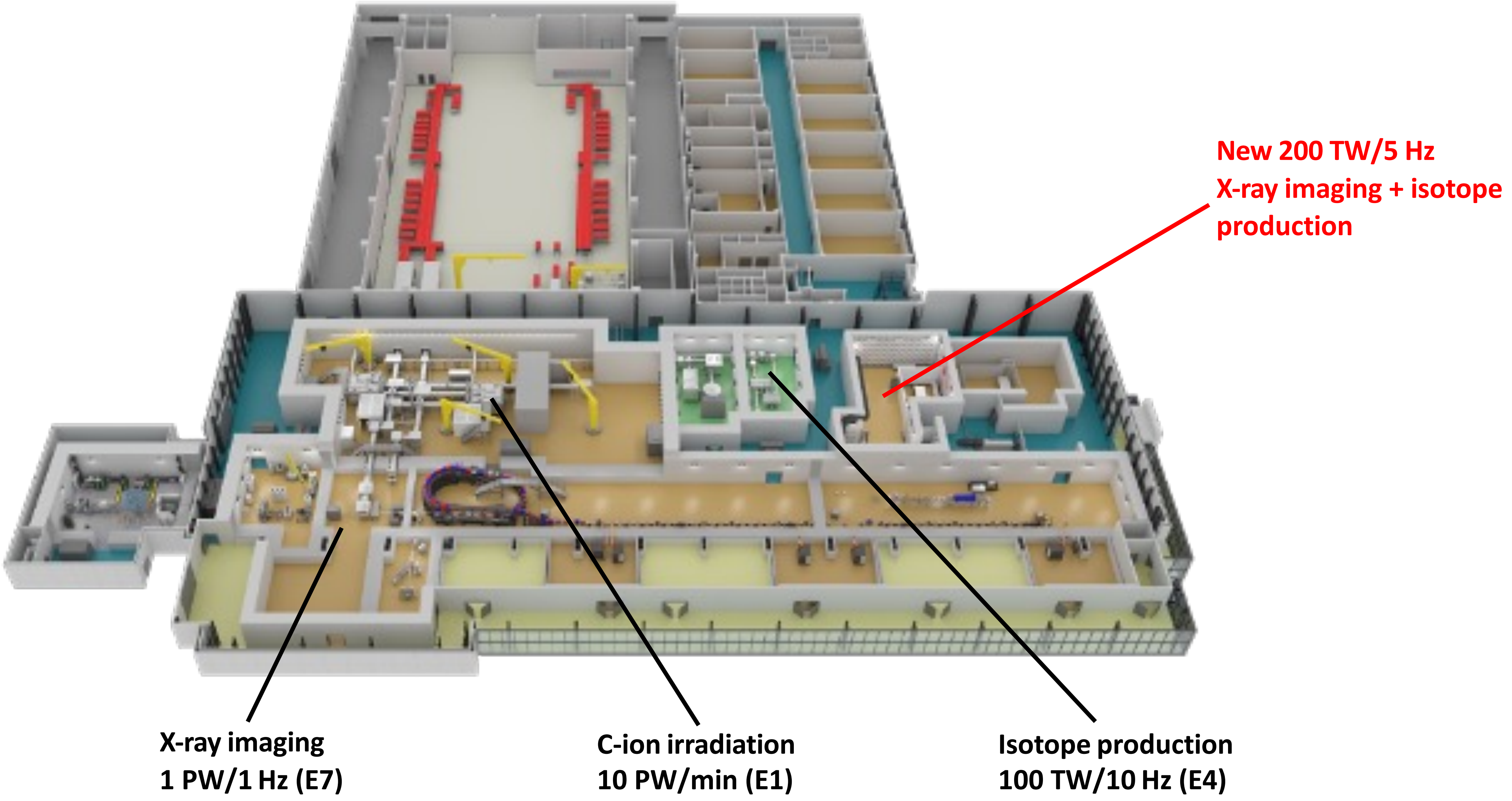
# Laser–Driven Medical Applications Research

Dr. LASER

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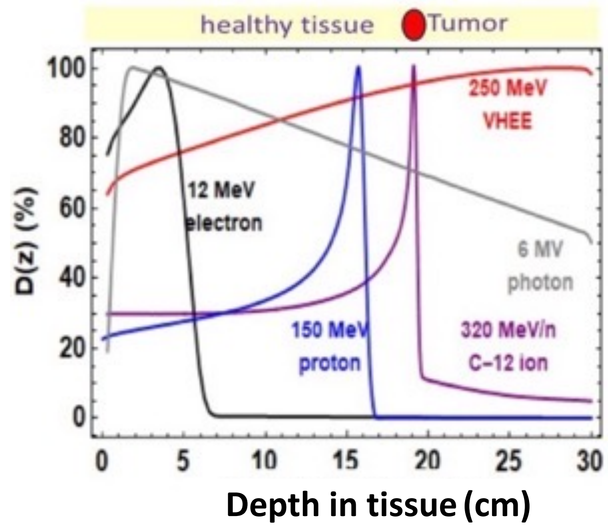
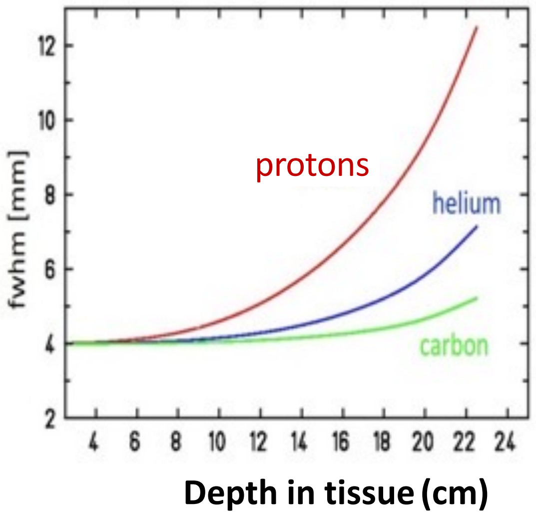
# Radiotherapy with Ultra-High Dose Rate C-ion beams

Dr. LASER

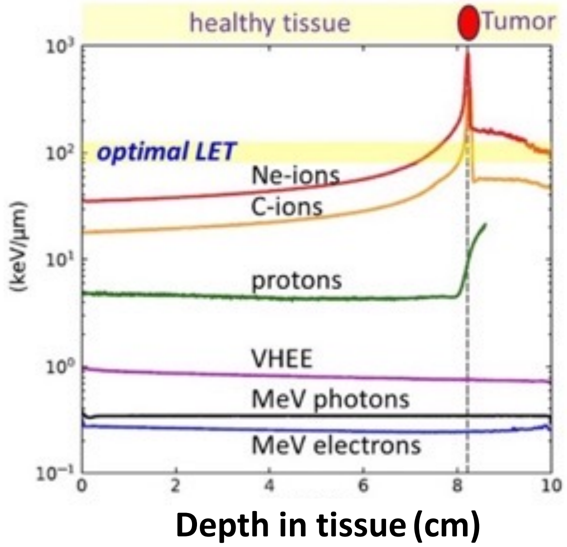
## Sharp dose depth localization




## Sharp dose lateral localization

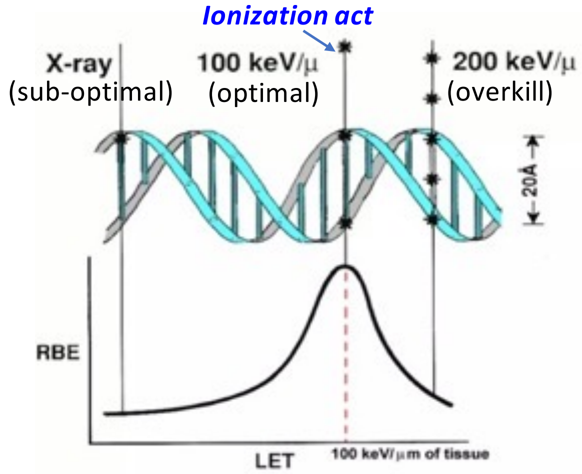



## Optimal LET for maximal RBE




Delorme et al Sci Rep 2021

- **laser-driven ultra-high dose rate** (UHDR) heavy-ion irradiation can enable the FLASH effect (healthy tissue sparring) (**$10^{10}$ Gy/s**)
- **C-ions kill better cancer stem cells**, synergy with immunotherapy
- Proposed medical focus on long term: **start from skin-level cancer, progressing to HNC and breast cancer** (#1 cause of cancer mortality for women)




*RBE = biological effectiveness relative to X-rays*

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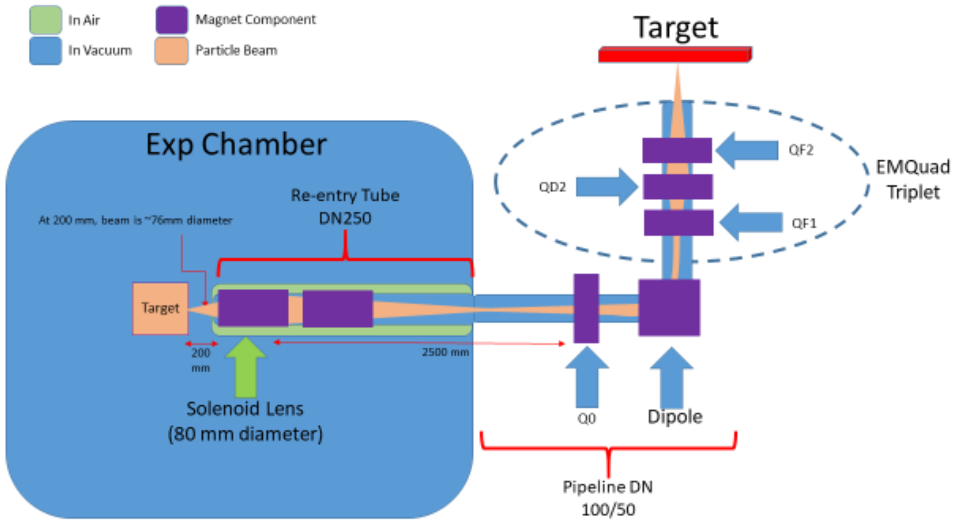
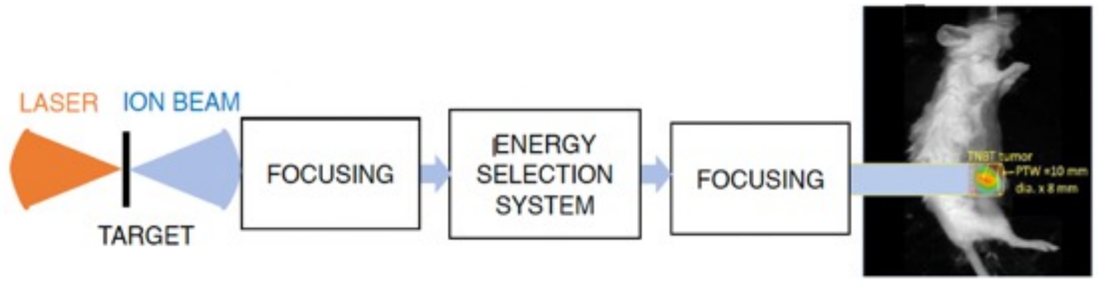
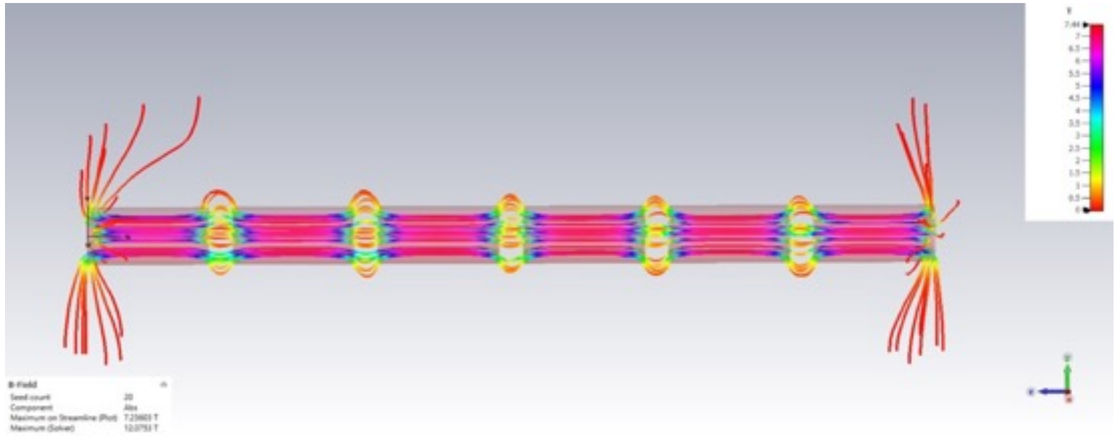
# C-ion transport systems for radiobiology on cells and later small-animals



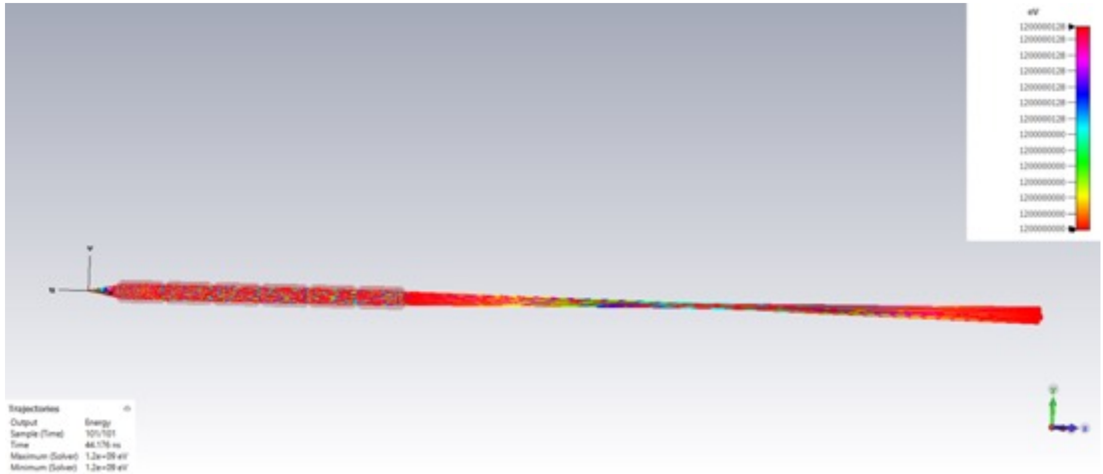




Courtesy of M. Patrascoiu

## High Temperature Superconducting Solenoids (7 T)



## TNSA, 100 MeV/u C-ions, Divergence 20 degrees

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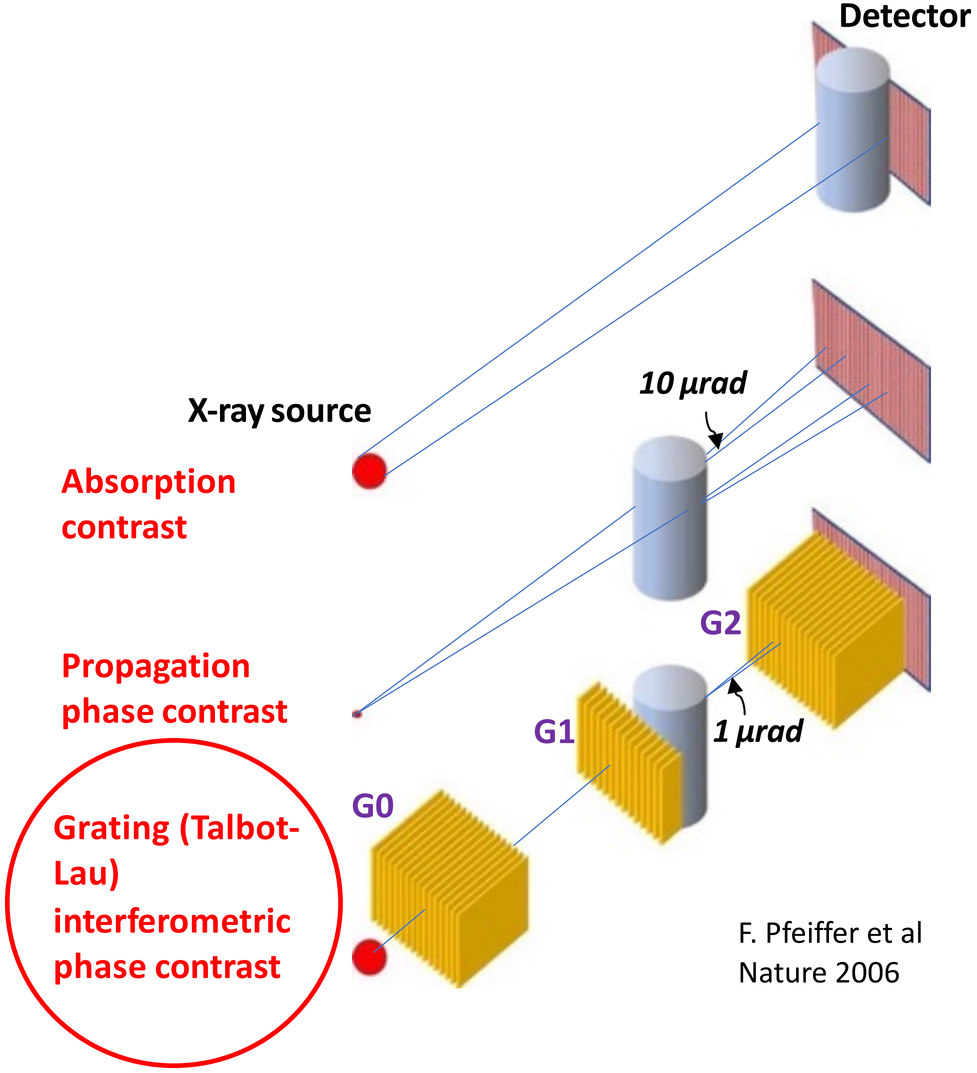
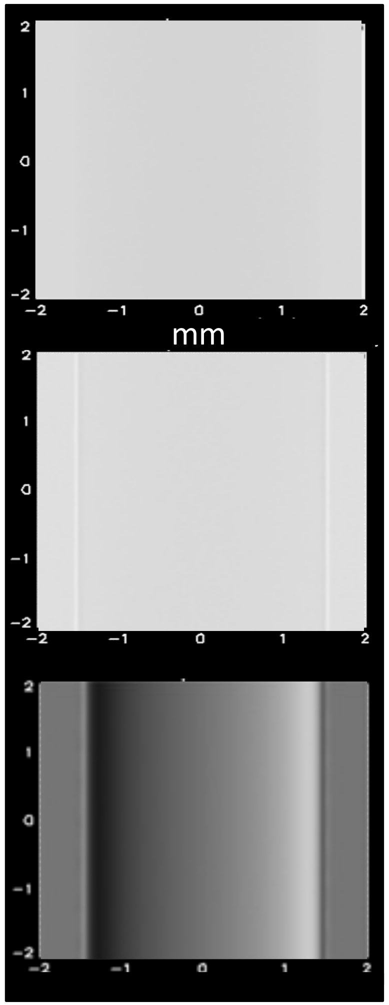
# Grating interferometry most sensitive phase contrast X-ray imaging method

Dr. LASER

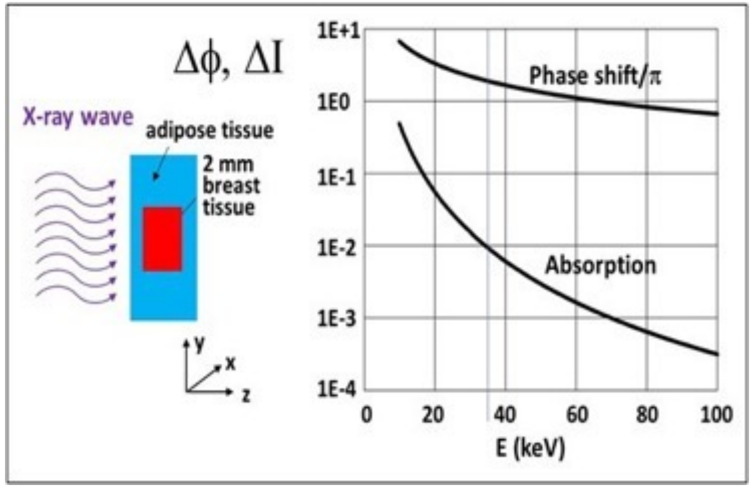



F. Pfeiffer et al
Nature 2006

breast tissue fibril in adipose tissue 30 keV




## X-ray phase shift vs. absorption in breast tissue fibril




- Grating interferometer measures X-ray refraction angles
  - < 1 µrad angles in soft tissues
  - Feasible grating periods > few µm

=> multi-meter long interferometers for high angular sensitivity at low dose

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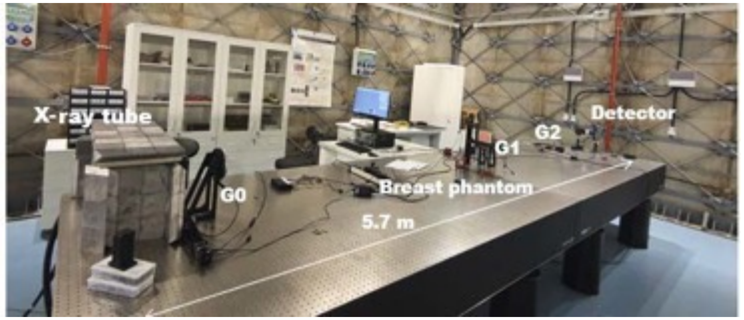
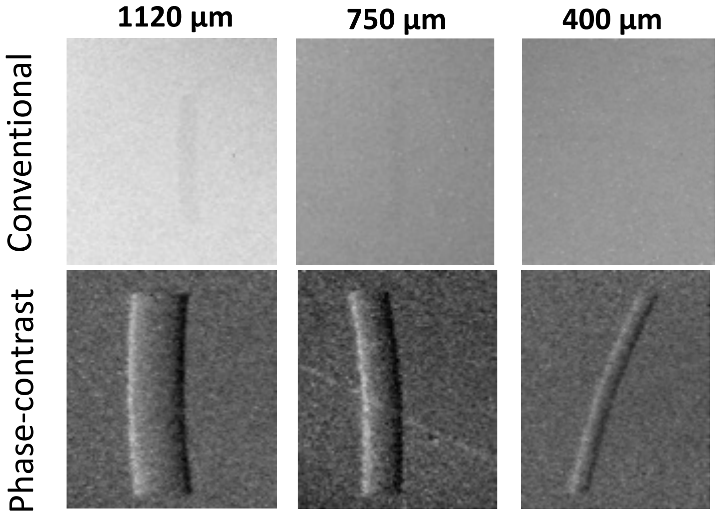
# Interferometric phase contrast mammography



**6 m length 2.4 µm period grid interferometer at ELI-NP**



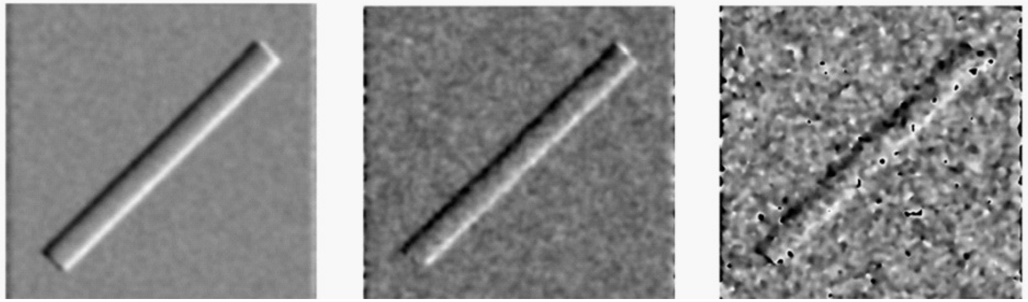

**Predictions confirmed by experiments with conventional X-ray tube – 2 mGy**



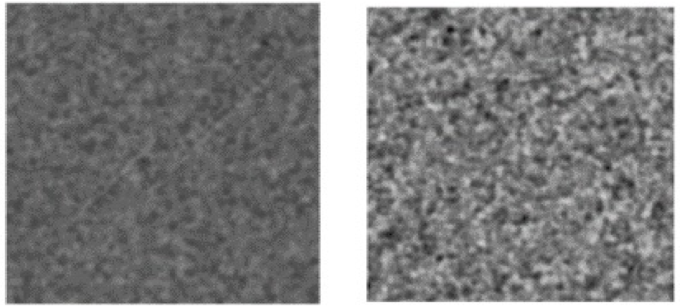

N Safca et al Phys Med Bio 2022

**Predicted interferometric images of 400 µm breast glandular tissue in adipose tissue, with 6 m length 2.4 µm period interferometer at 33 keV**

2 mGy ($3x10^{10}$ photons/shot) | 0.2 mGy ($3x10^{9}$ photons/shot) | 0.02 mGy ($3x10^{8}$ photons/shot)



**Conventional images**



**Potential for ultrasensitive, low dose mammography**

**Interferometry with directional and intense laser-based X-ray sources to be developed towards clinical mammography (<1 s exposure)**

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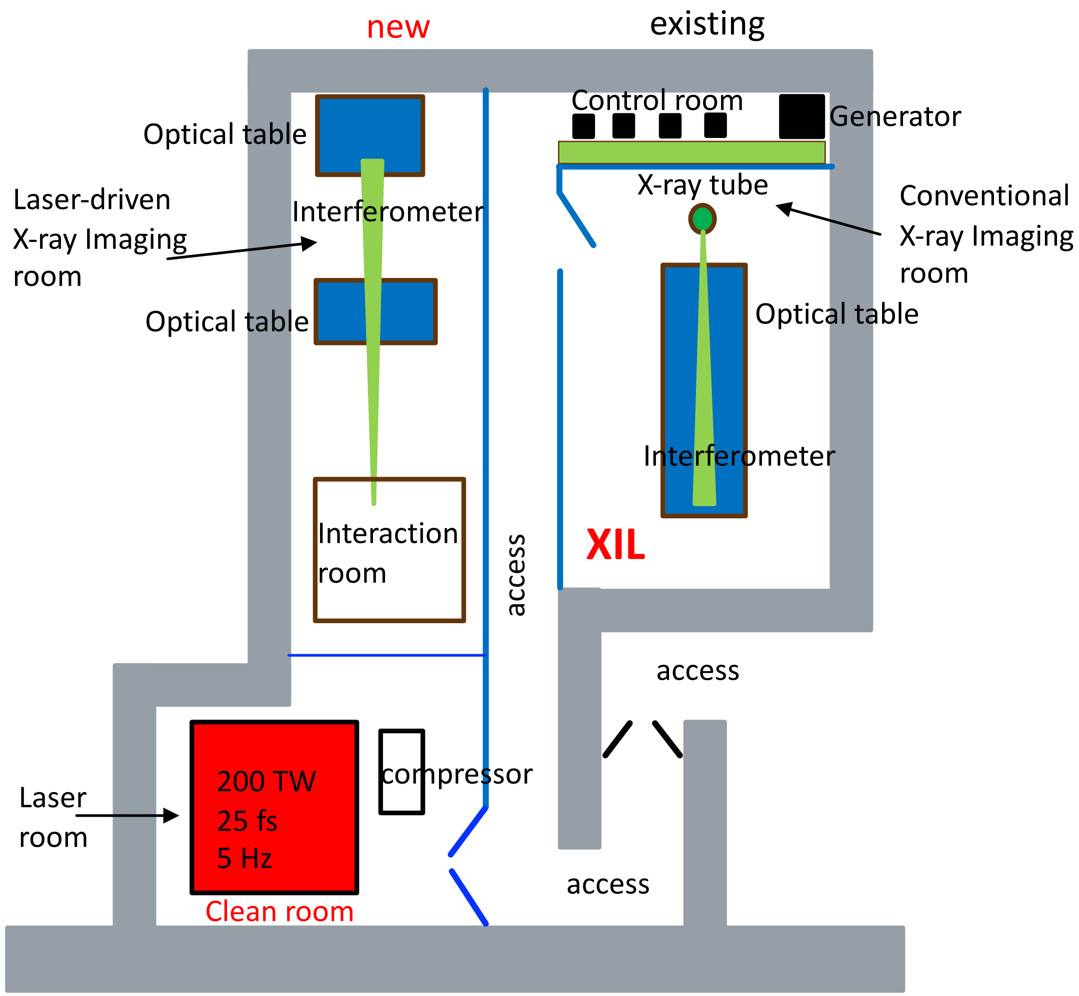
# Interferometric phase contrast X-ray imaging systems

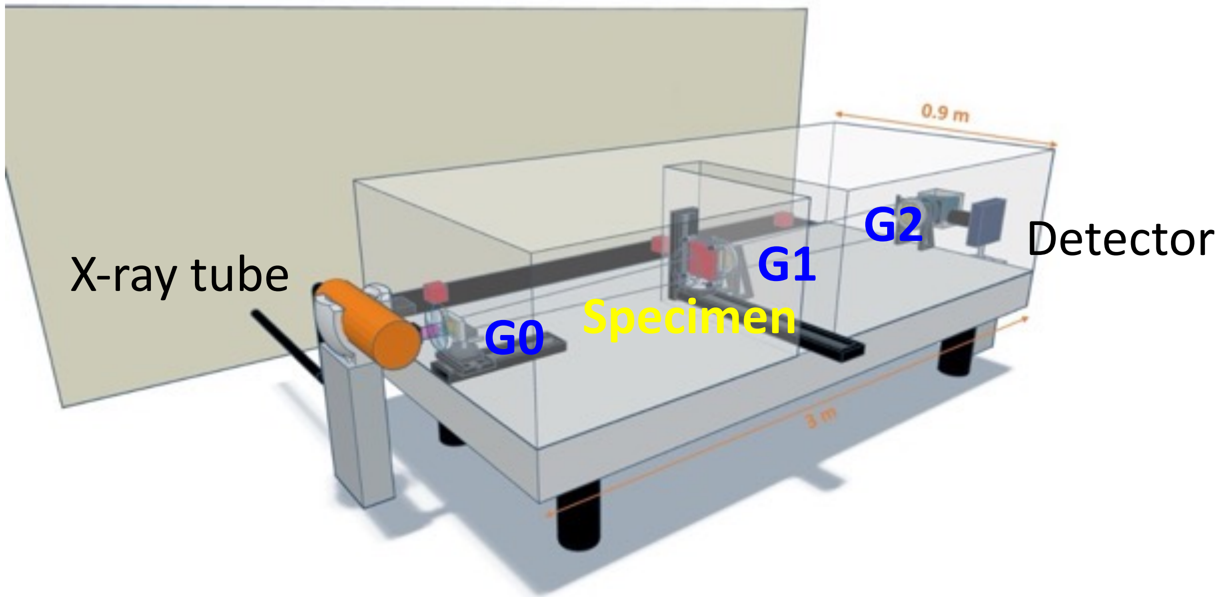
Dr. LASER

## Laser-based system
## E3 Experimental area




## System based on classical X-ray source

- to be tested in hospital for tumor specimen testing
- all components already contracted

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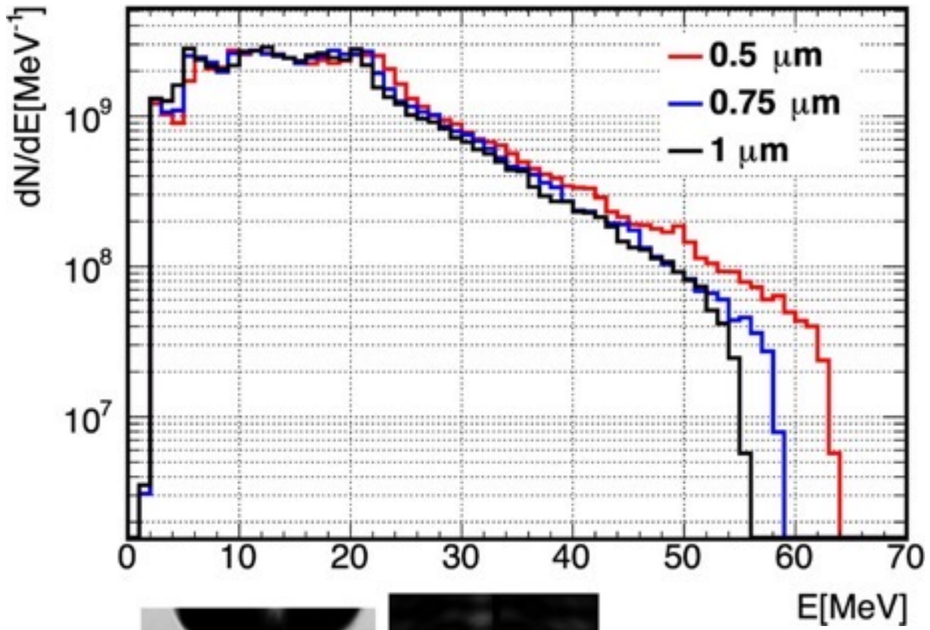
# Laser–Driven Radioisotopes Production



## Predicted proton spectra with water leaf target (P. Tomassini ELI-NP)





Water leaf target
(D. Ursescu ELI-NP)

## Predicted isotope production (A. Cucoanes ELI-NP)

| Isotope | $t_{1/2}$ [min] | Reaction | Cross-section | Isotopic conc. in nat.tg. | Activ 30m [MBq] | Activ 60m [MBq] |
|---|---|---|---|---|---|---|
| $^{11}C$ | 20 | $^{14}N(p,\alpha)^{11}C$ | TENDL 2021 | 99.6% | | 59.7 |
| | | $^{11}B(p,n)^{11}C$ | TENDL 2021 | 80.4% | | 111.6 |
| $^{13}N$ | 10 | $^{16}O(p,\alpha)^{13}N$ | TENDL 2021 | 99.8% | 11.2 | 12.6 |
| | | $^{13}C(p,n)^{13}N$ | Firouzbakht et al. Radiochim. Act. 55,1 - 5 (1991) | 1.06% | 42.2 | 48.2 |
| $^{15}O$ | 2 | $^{15}N(p,n)^{15}O$ | TENDL 2021 | 0.4% | 43.9 | |

- Water leaf target for high rep rate, debris free operation over long times
- Proton beam focusing for high specific activity and for spectral filtering
- Experiments to start with 100 TW/10 Hz
- Heavy water leaf target for deuteron acceleration $^{14}N(d,n)^{15}O$

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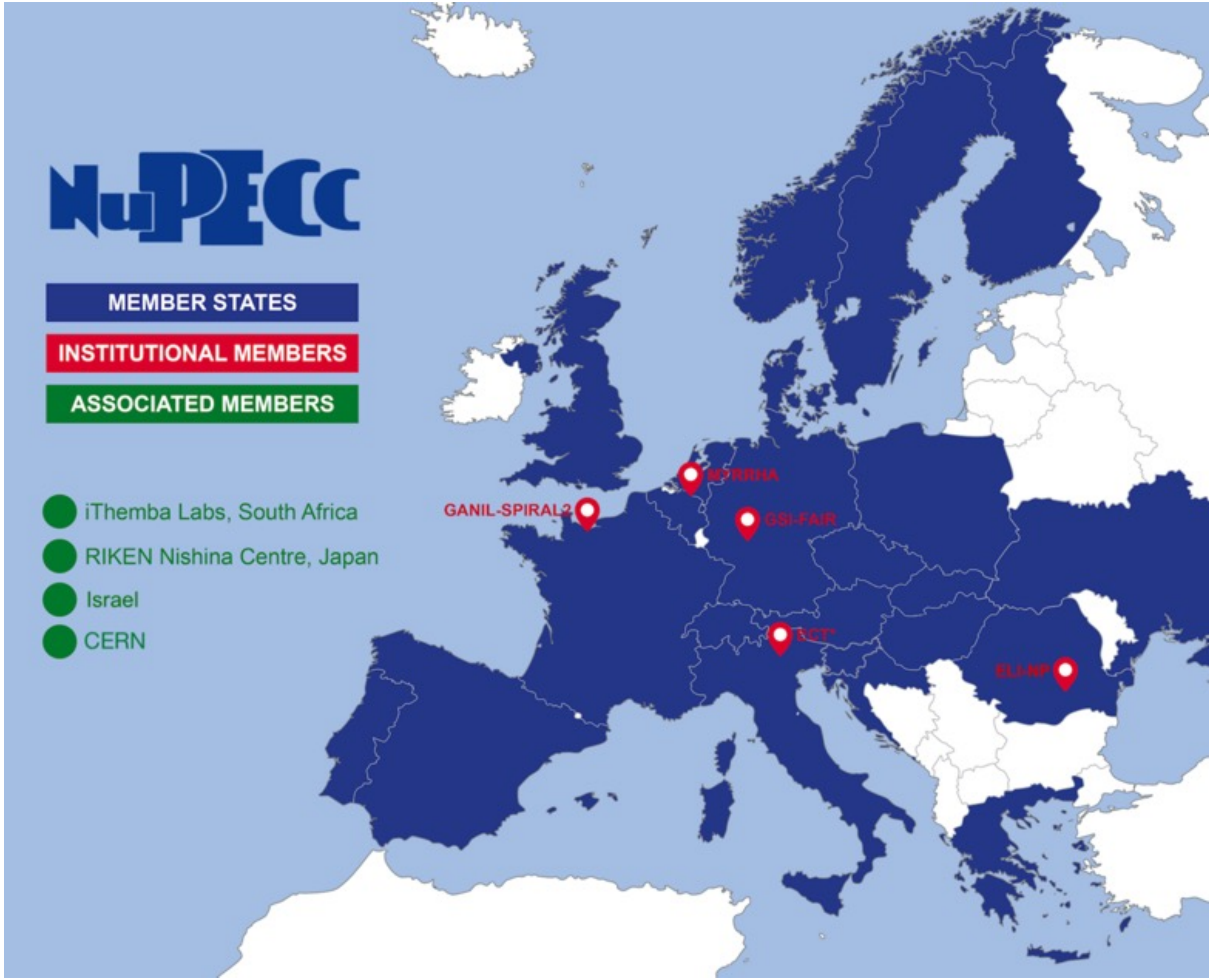
# ELI-NP IS INSTITUTIONAL MEMBER OF NUPECC SINCE NOV. 2023



# Summary

- ELI-NP is an international research center – institutional member of NuPECC since 2023
- 10 PW laser system is operational at nominal parameters – user facility since 2022
- Demonstrated $10^{23}$ $W/cm^2$ laser intensity at 10 PW
- Demonstration of electron and ion acceleration – physics cases nuclear and SF QED
- Project on Medical applications of high-power lasers
- Gamma beam system – under implementation – first experiments in 2027

# Thank you !

EUROPEAN UNION

GOVERNMENT OF ROMANIA

Structural Instruments 2014-2020

Project co-financed by the European Regional Development Fund through the Competitiveness Operational Programme
"Investing in Sustainable Development"

Extreme Light Infrastructure-Nuclear Physics (ELI-NP) - Phase II

eli nuclear physics

www.eli-np.ro



Dr. LASER

*"Medical applications of high-power lasers - Dr. Laser"*

*www.eli-np.ro/projects/drlaser/*

*SMIS Code: 326475*

*Project co-financed by the European Union and the Romanian Government within the Romanian Health Program*



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