EUROPEAN UNION

GOVERNMENT OF ROMANIA

Structural Instruments 2014-2020

Extreme Light Infrastructure – Nuclear Physics Overview and Perspectives

Călin A. Ur

IFIN-HH

eli nuclear physics

10 Years After

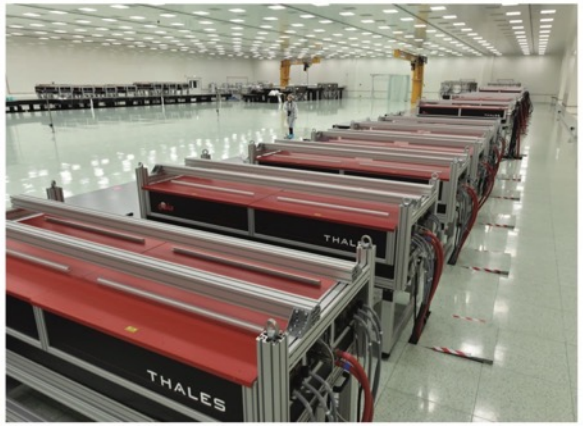
http://www.eli-np.ro

IBWAP 2023

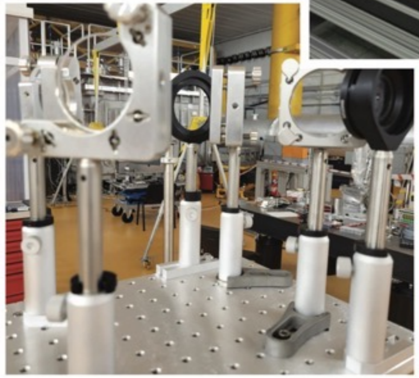
2013 – 2023

After 10 Years with ELI-NP

eli
nuclear physics



10 PW ON TARGET

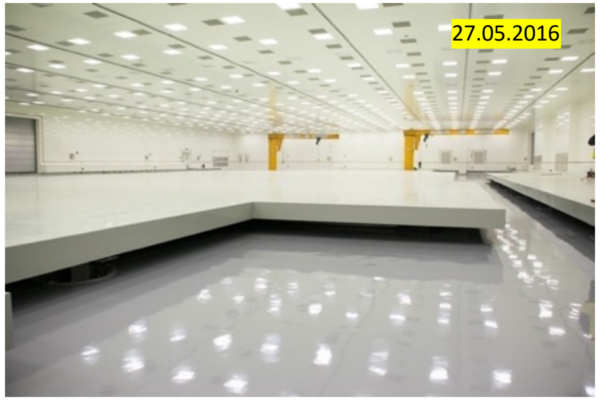


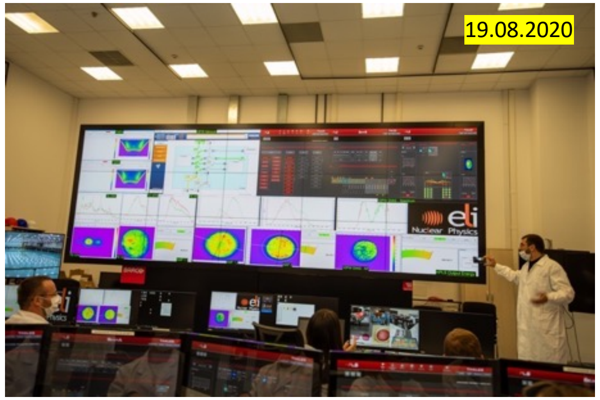
IFIN-HH

July 10, 2023

IFIN-HH / ELI-NP Conference Centre

Some history ....





ELI-NP Physics Case

Advanced studies in basic science ...

- characterization of laser-matter interaction with nuclear physics methods
- particle acceleration with high power lasers
- nuclear reactions in plasma
- photonuclear reactions, nuclear structure, exotic nuclei
- nuclear astrophysics and nucleosynthesis
- quantum electrodynamics

... and applications – developing technologies for:

- medical applications (X-ray imaging, hadron therapy, radioisotopes generation)
- industrial applications (non-destructive studies with γ)
- material studies with positrons
- materials in high radiation fields

Technical Design Reports (TDR)

Rom. Rep. Phys. Vol. 68 (2016)

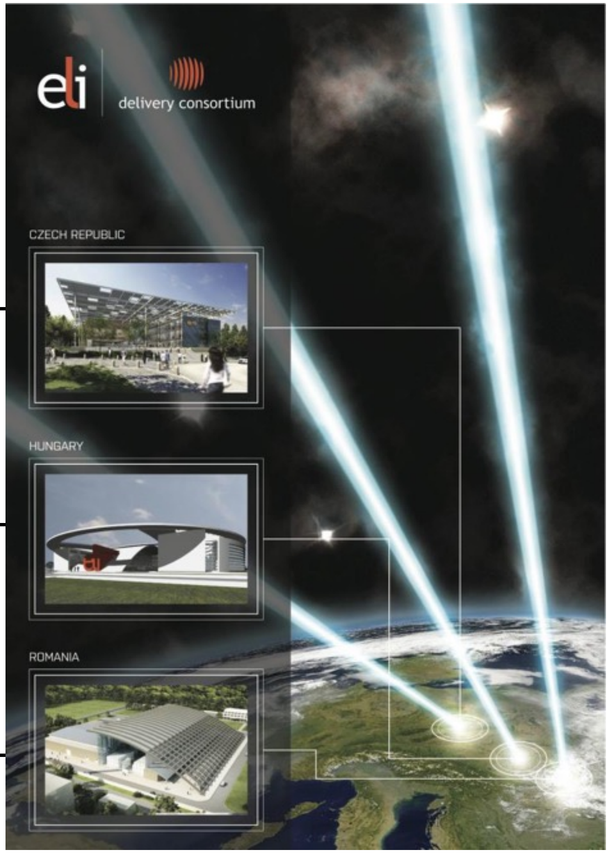
https://rrp.nipne.ro/2016_68_S.html

Extreme Light Infrastructure
Pan-European Research Center

ELI-Beamlines
Prague, CZ

ELI-ALPS
Szeged, HU

ELI-NP
Măgurele, RO
Nuclear Physics Pillar



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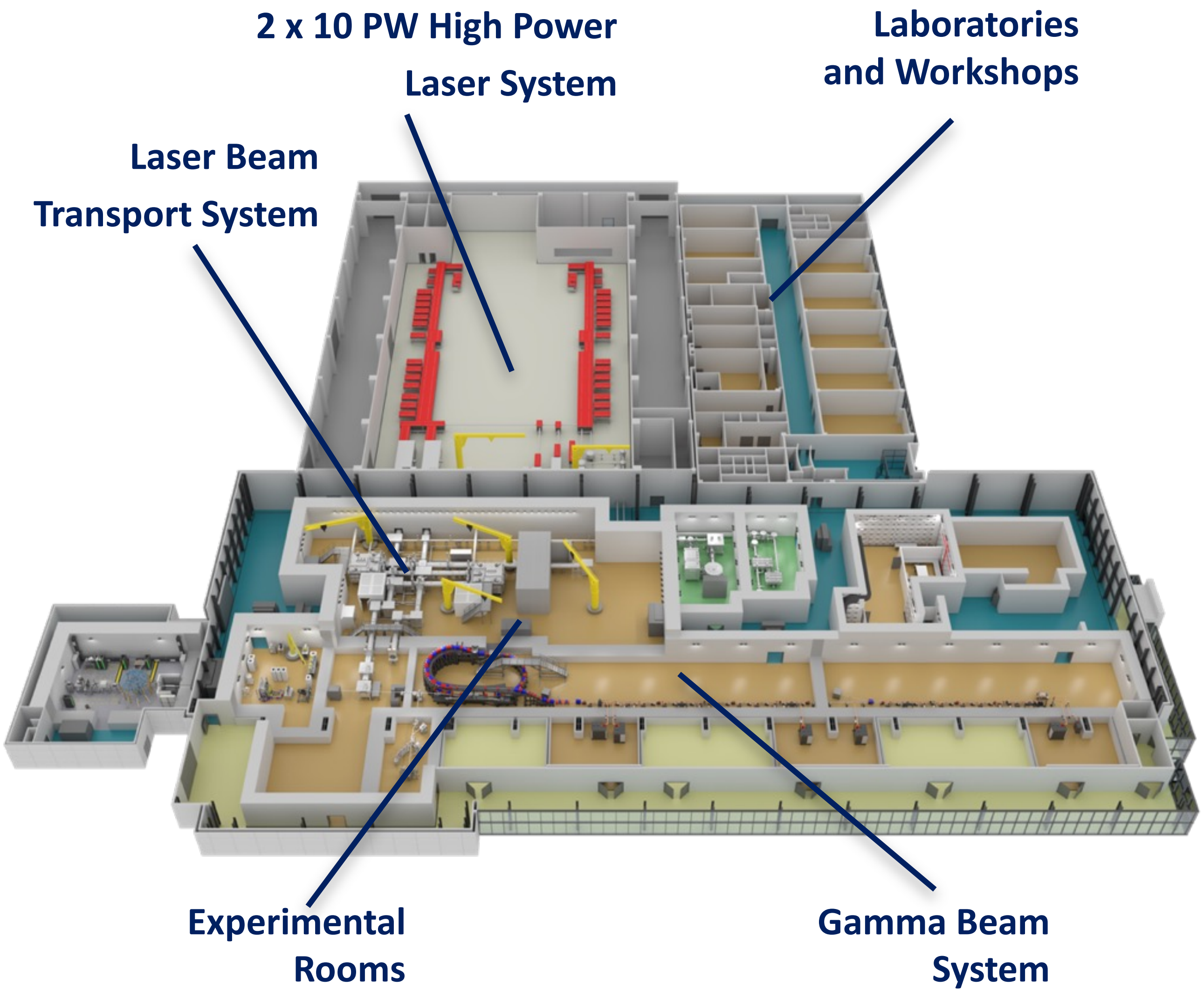
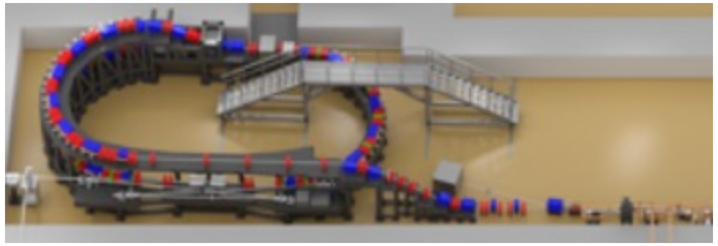


ELI-NP: Implementation Status

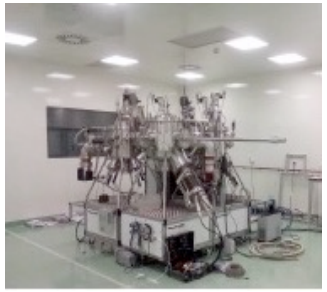
Overall implementation status: more than 85%

Major Components:

- **High power laser system (HPLS) + Laser beam transport system (LBTS)**
  100% – <u>fully implemented and operational</u> (**2019 HPLS, 2020 LBTS**)



- **Gamma beam system**
  45% - completion delayed



- **Experimental setups and laboratories**
  100% – <u>fully implemented</u> – **under final commissioning**

- **Civil constructions**
  100% – <u>fully implemented and operational</u> **(since 2016)**

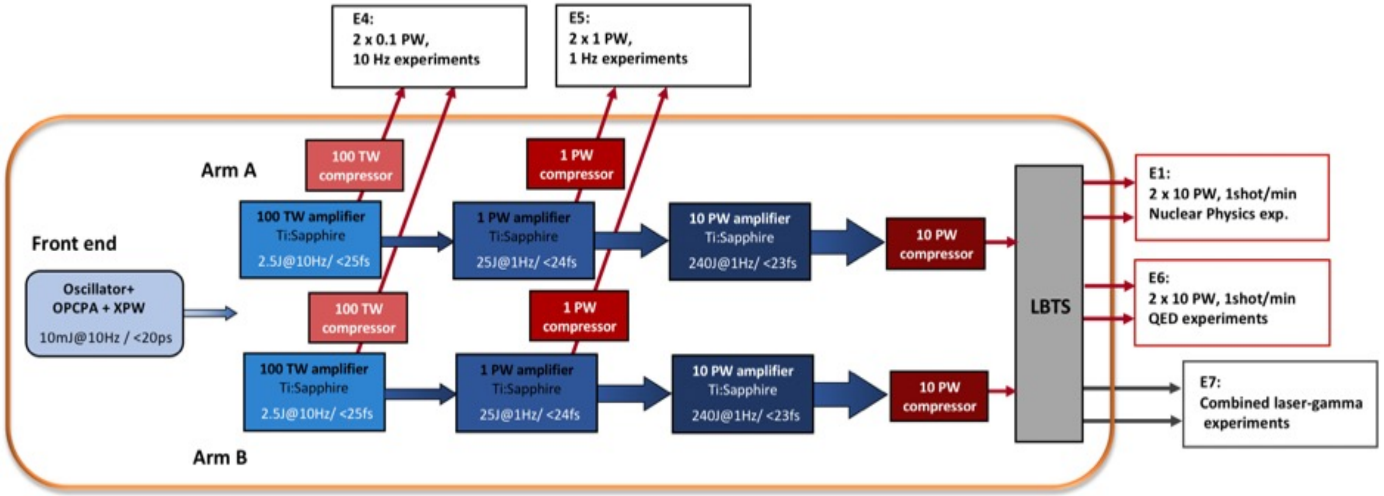
Most Powerful Laser in the World @ ELI–NP

Unique system in the world:
power, intensity, number of beams, versatility and flexibility

- ✓ demonstrated **power level 10 PW**
- ✓ combination of **2 high-power lasers**
- ✓ 100 TW@10 Hz, 1 PW@1 Hz, 10 PW@1/minute

Measured parameters of HPLS

Output type	100 TW	1 PW	10 PW
Pulse energy (J)	2.7	25	242
Pulse duration (fs)	< 25	< 24	<23
Repetition rate (Hz)	10	1	1/60
Calculated Strehl ratio from measured wavefront	> 0.9	> 0.9	> 0.9
Pointing stability (µrad RMS)	< 3.4	< 1.78	< 1.27
Pulse energy stability (rms)	< 2.6 %	< 1.8 %	< 1.8 %



F. Lureau et al., HPLSE 8 (2020) e43
C. Radier et al., HPLSE 10 (2022) e21

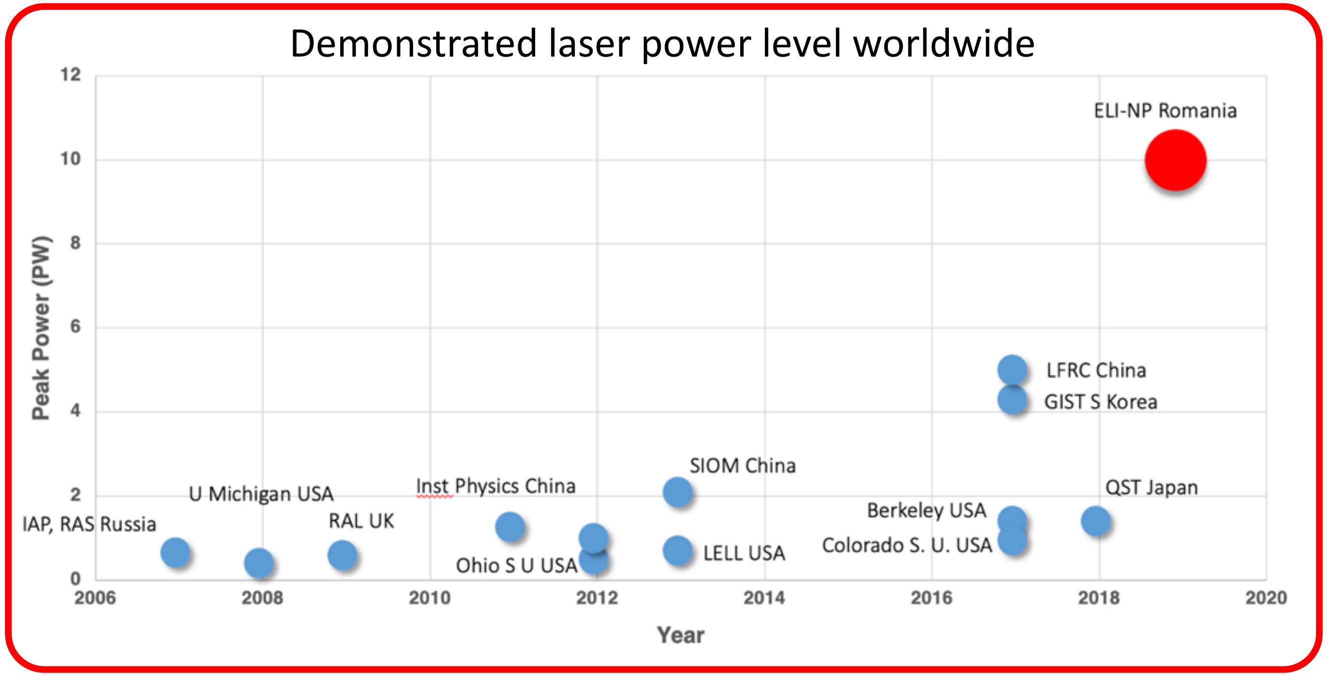
2019 – demonstrated **capability** of the laser system **to deliver 10 PW**

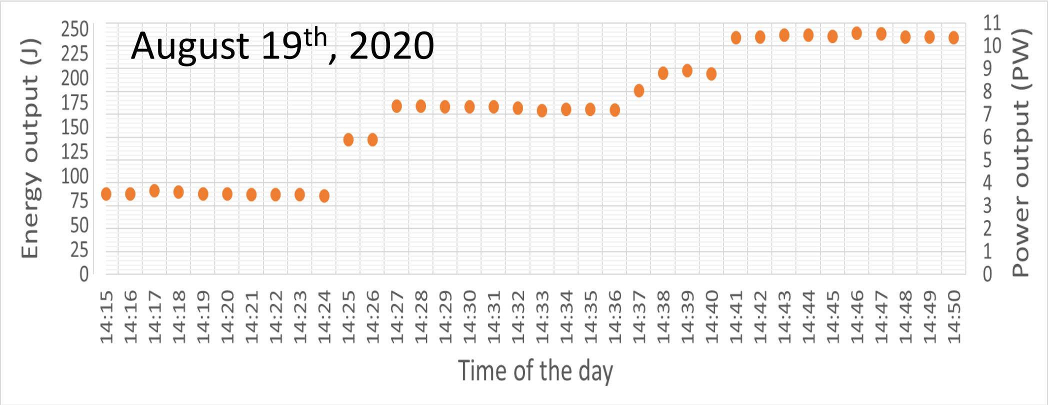
2020 – transport of 10 PW from the laser **to the interaction chamber**

THALES
Building a future we can all trust

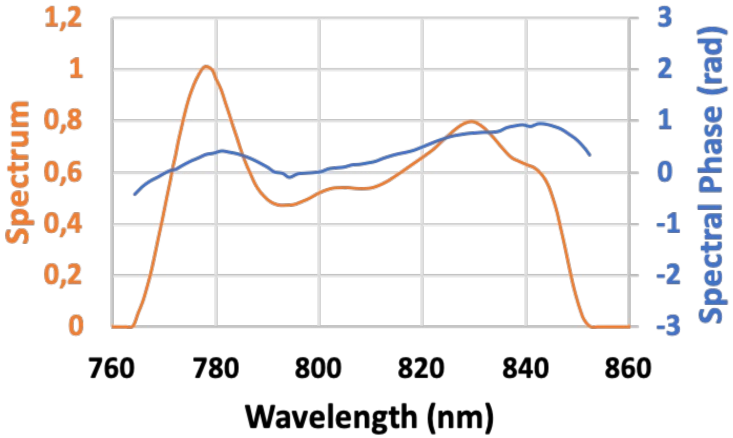
Thales LAS France and Thales Systems Romania
Worldwide premier technology

The Most Powerful Laser operational in the World @ ELI–NP

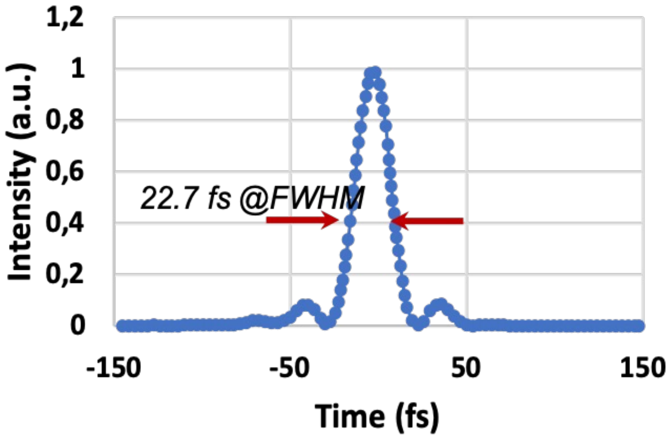




Laser peak power

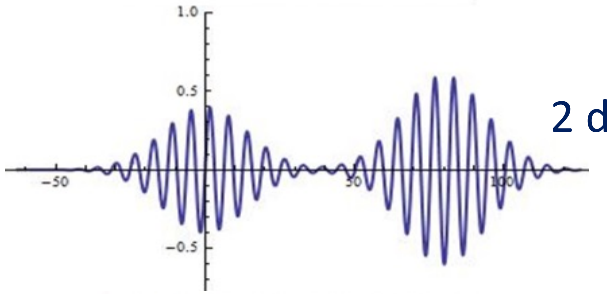


Spectral characteristics

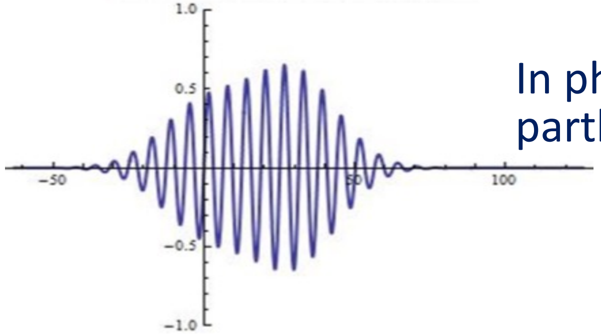


Time characteristics

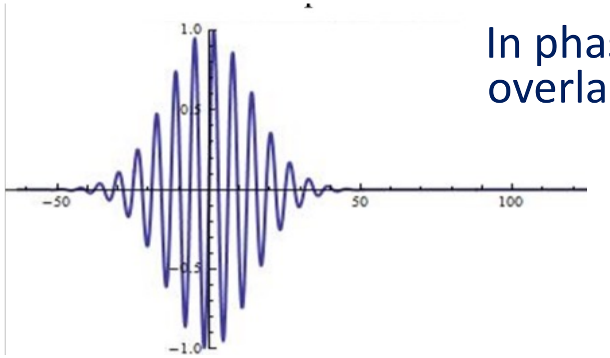
Synchronization of the Two HPLS Arms



2 delayed pulses



In phase
partly overlapped



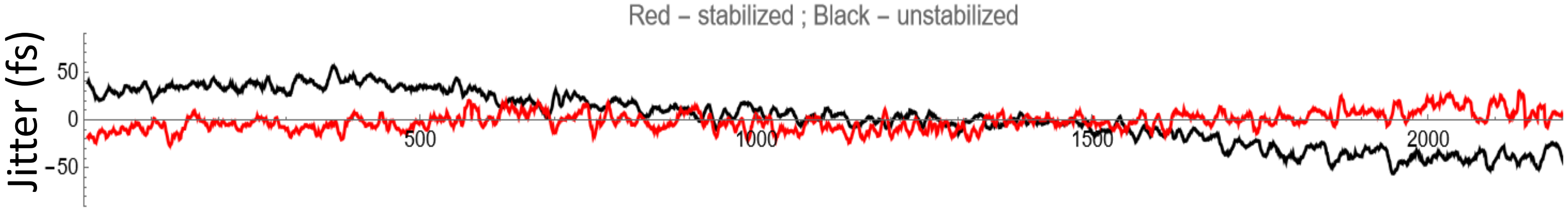
In phase
overlapped

Scalable method towards Exawatt-class laser facility

Enhanced temporal resolution attainable in **pump-probe experiments** driven with PW-class lasers.

HPLS 100TW@10Hz preliminary tests: jitter =23.2 fs RMS over 43 s scan

HPLS 1PW@1Hz preliminary tests: jitter<20fs RMS over 40 minutes scan



Courtesy of D. Ursescu

Laser-Driven Experiments Areas

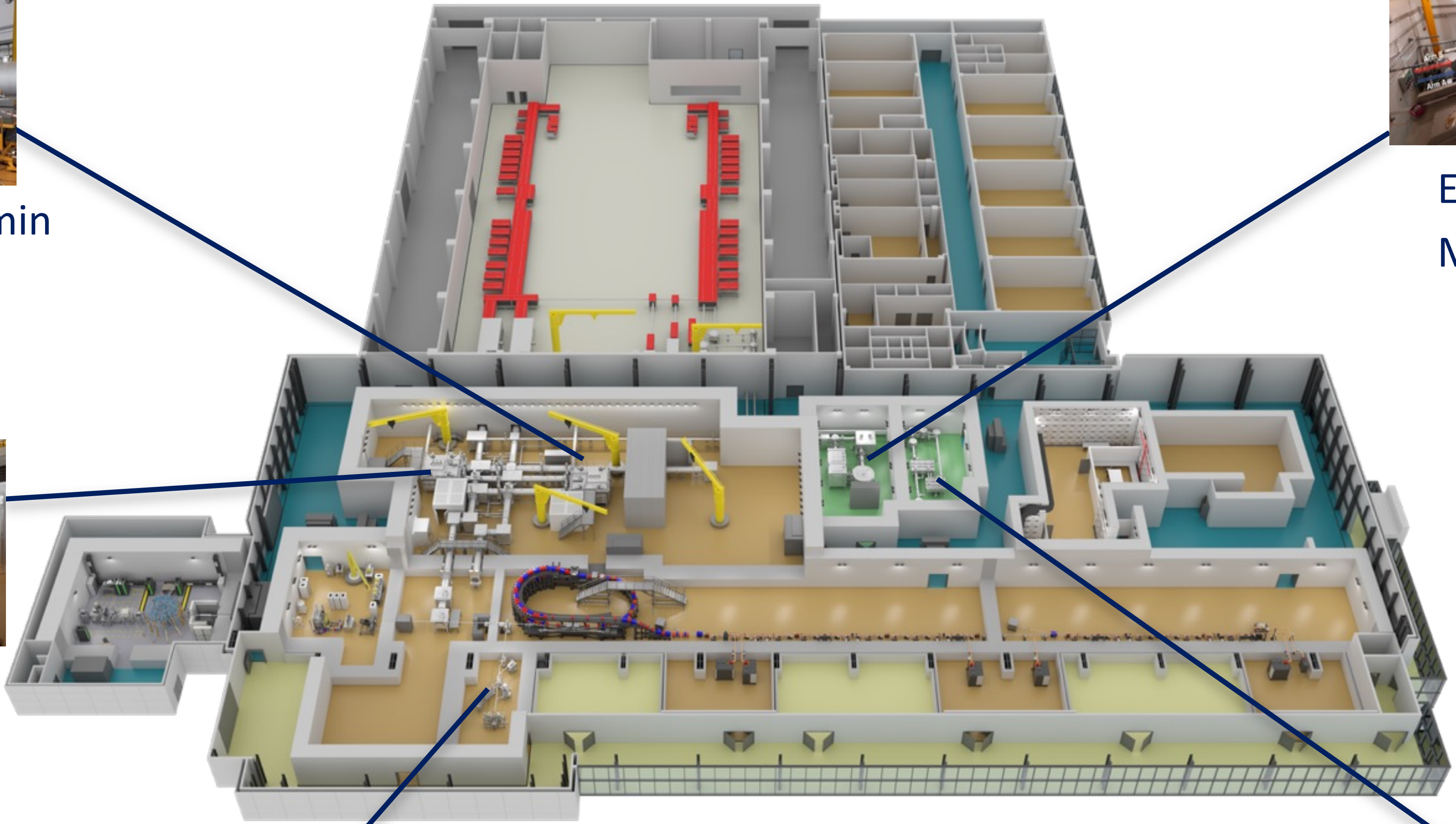
E1: 10 PW @ 1/min

Laser driven

Nuclear Physics

E5: 1 PW @ 1 Hz

Material Studies



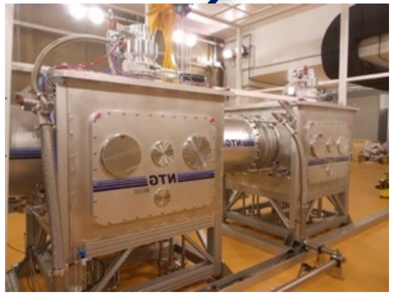
E6:

10 PW @ 1/min

High Field QED

E7: 1 PW @ 1 Hz

High Field QED



E4: 0.1PW@10 Hz

Photon-photon

int., LWFA, X-ray

imaging

Studies under Extreme Conditions @ ELI–NP

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

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

Strong-field QED

10 PW laser + solid target

PW γ-source

10 PW laser + GeV LWFA electrons

Radiation reaction
Breit-Wheeler pairs

Extreme light pressures (Tbar)

Nuclear Physics with Lasers

10 PW radiation pressure acceleration of *dense* ion beams

Nuclear reactions in plasma

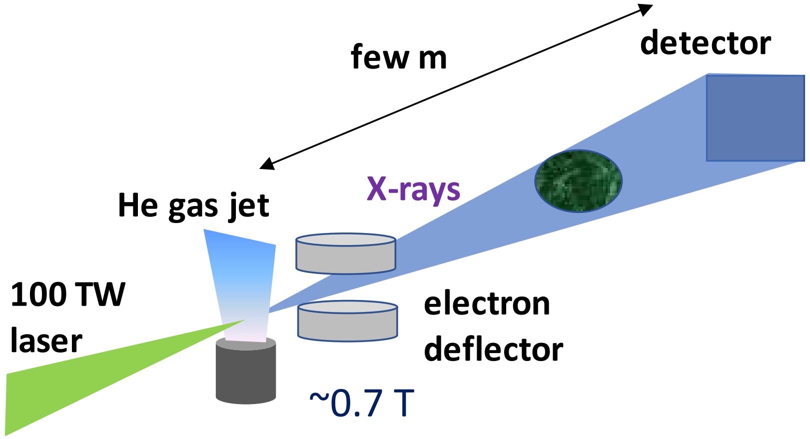
Ultra-intense neutron source

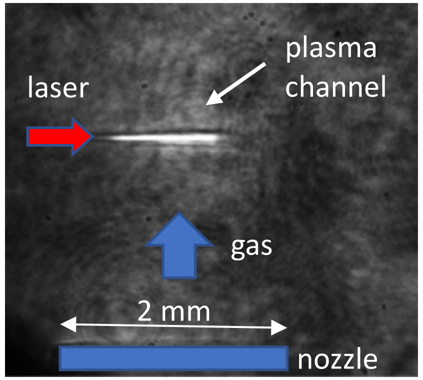
Nuclear lifetimes in plasma

Purpose of **commissioning experiments** 2020 – 2023:

- physics based validation of high-power laser system performance
- develop particle beams for nuclear physics and QED experiments and applications

100 PW Commissioning LWFA results





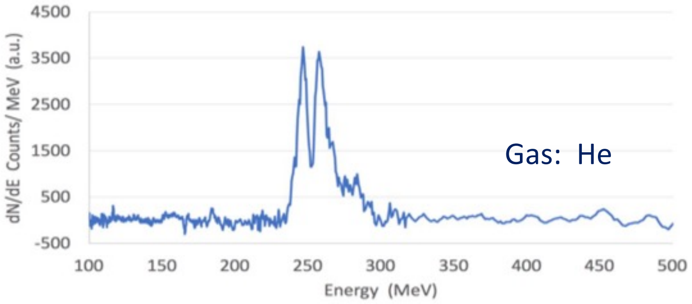
Experimental setup

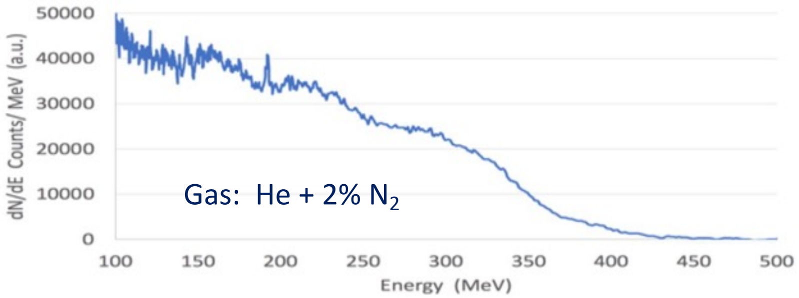
I_0 ~ 10^{19} W/cm^2

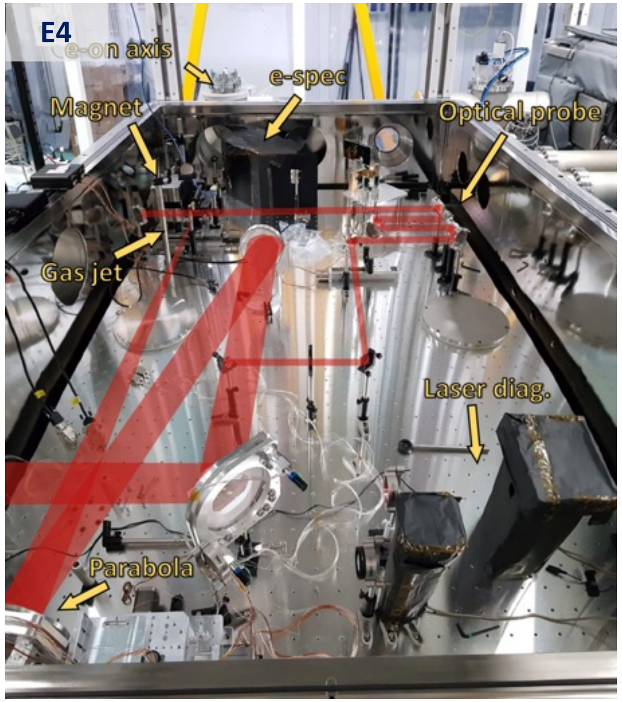
Max Energy: < 2.7 J
Pulse duration: ~ 24 fs
Beam diameter: ~ 54 mm
Repetition rate: 10 Hz
Spot size diameter on target: ~ (22±2) µm at FWHM

Electron diagnostics: spectrometer (up to 500 MeV) – 16 cm long dipole magnet with 3 cm gap and ~0.7 T B-field, and a Lanex screen

Acceleration field of ~ 1 GV/cm

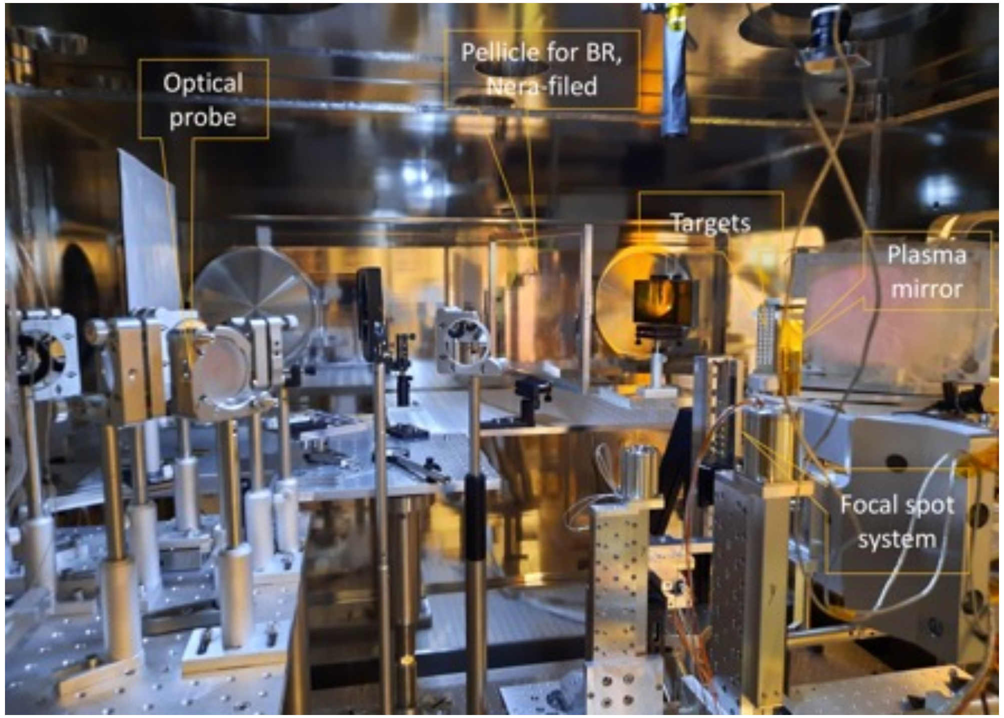






1 PW Commissioning TNSA results

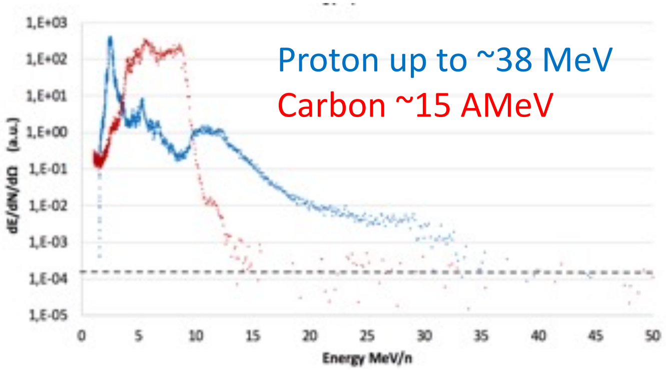
Ion acceleration from solid targets



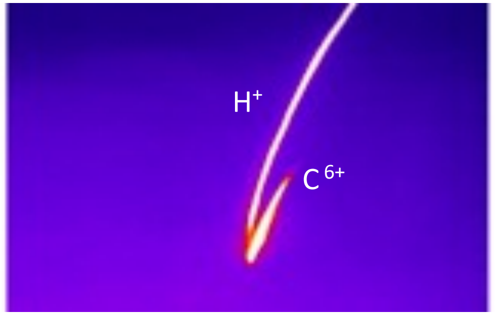
Max Energy: < 24 J
Pulse duration: ~ 24 fs
Beam diameter: ~ 190 mm
Repetition rate: 1 Hz
Spot size diameter on target: ~ (3.6±2) µm at FWHM

Laser beam power: 19 J, ~75 fs ➔ 250 TW
Intensity on target: ~ 1 x10^{21} W/cm^2
Target: 380nm DLC (built in house)

- ✓ Thick and thin foils (e.g., Al, CH, DLC)
- ✓ Plasma mirror
- ✓ Max. proton energy attained of 50 MeV
- ✓ Max. ion energy attained: carbon ion 15 AMeV



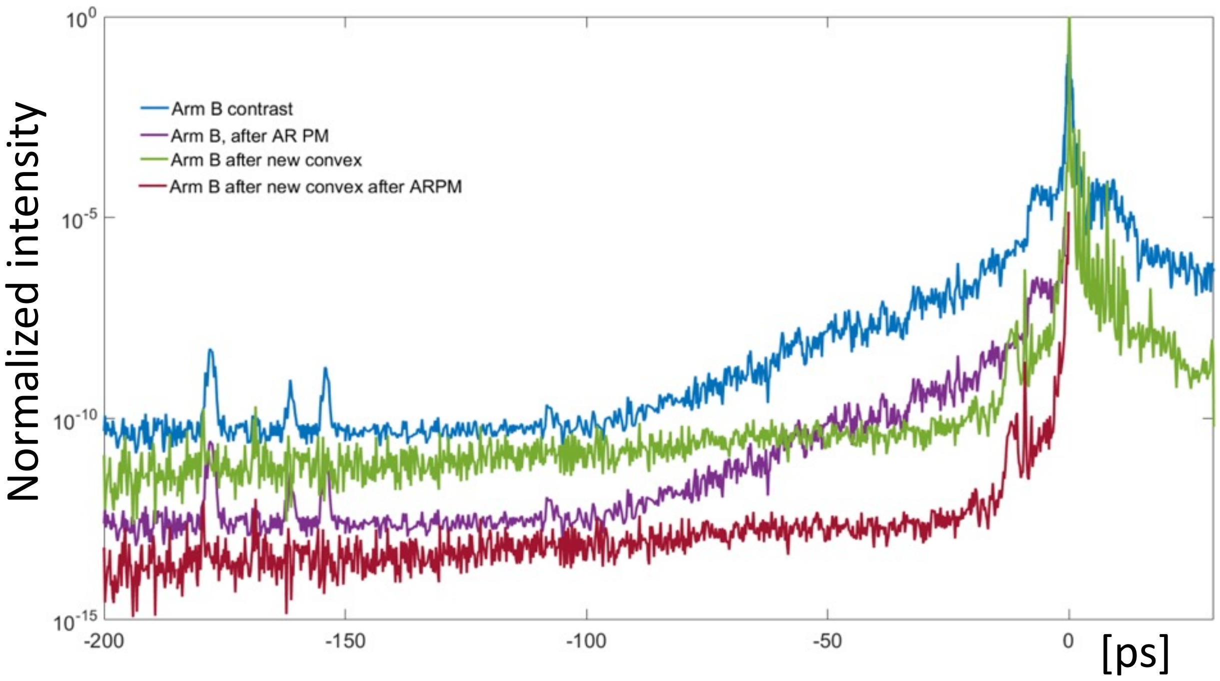
Thomson parabola

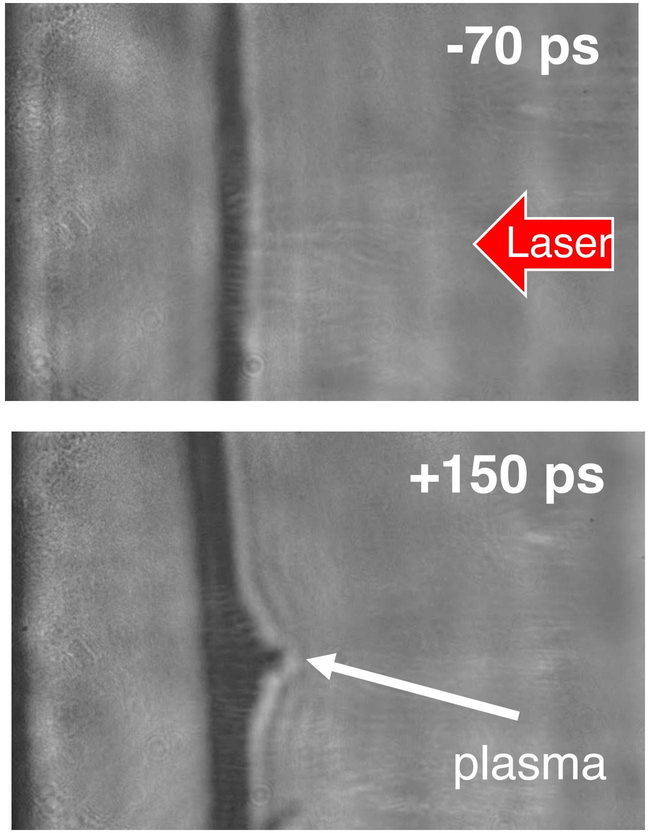


Courtesy of M. Cernăianu

Laser Contrast Improvement

Replacement of the stretcher convex mirror with a low roughness mirror to reduce the spectral phase noise and, consequently, the pedestal in the temporal contrast.





1 PW TNSA experiments with different temporal contrasts and target thicknesses

New temporal contrast allows for the acceleration of protons up to 60 MeV from ultra-thin films

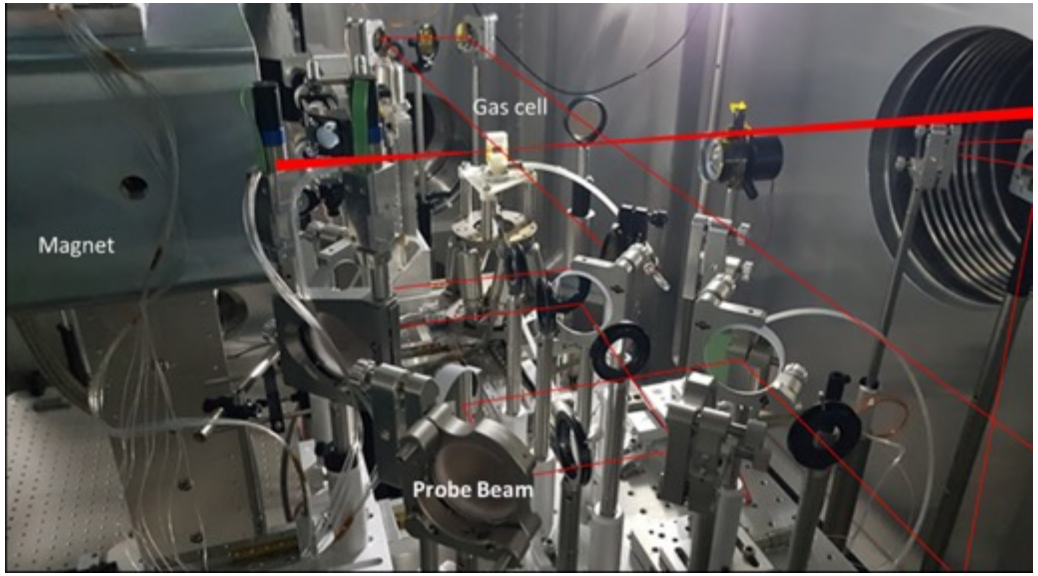
Collaboration with Thales LAS France and Marvel Fusion

1 PW Commissioning LWFA results

Electron acceleration in gas targets

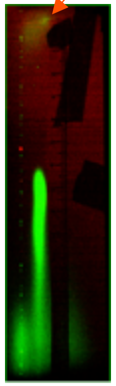
- **Gas jet target** and **gas cell** from **2mm to 2 cm long**
- **Pure He** and **admixture He +2% N_2** were used
- F = 5000 mm parabola
- Max. electron energy attained with both **Helium gas and admixture of ≈ 2 GeV**
- **Electron diagnostics**: spectrometer (up to 3 GeV) – 30 cm long dipole magnet with 3 cm gap and ~1 T B-field, and a Lanex screen

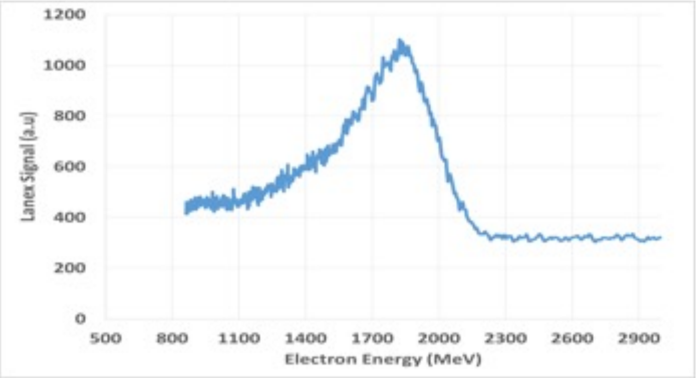
Experimental setup



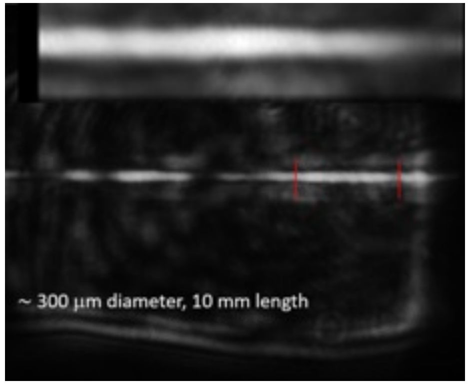
zero point

Electron deviation on lanex

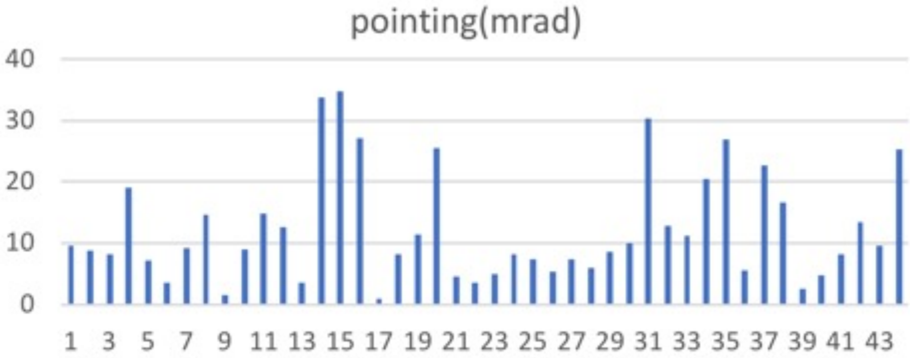




Electron Beam Energy Spectra for pure He



Shadowgraphy and WFS (plasma channel)

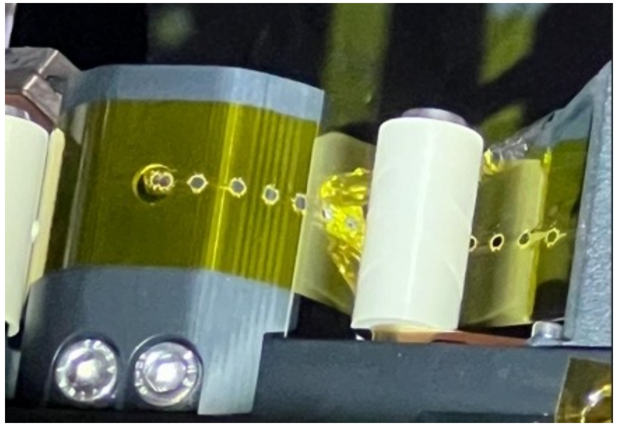


Electron Beam Pointing in a typical day from gas admixture

1 PW Commissioning @1 Hz repetition rate using a tape target (E5)

TNSA experiment at high repetition rate

Tape target system developed by STFC within the IMPULSE project tested at ELI-NP in collaboration with ELI Beamlines and STFC



Sequence of shots on the Kapton ribbon obtained shooting with 2 J laser energy and best laser pulse compression

Ribbon moving at 11 mm/s

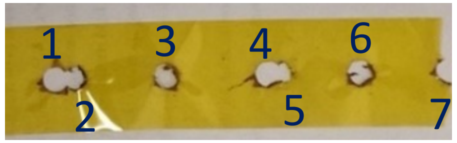
Courtesy of D. Doria

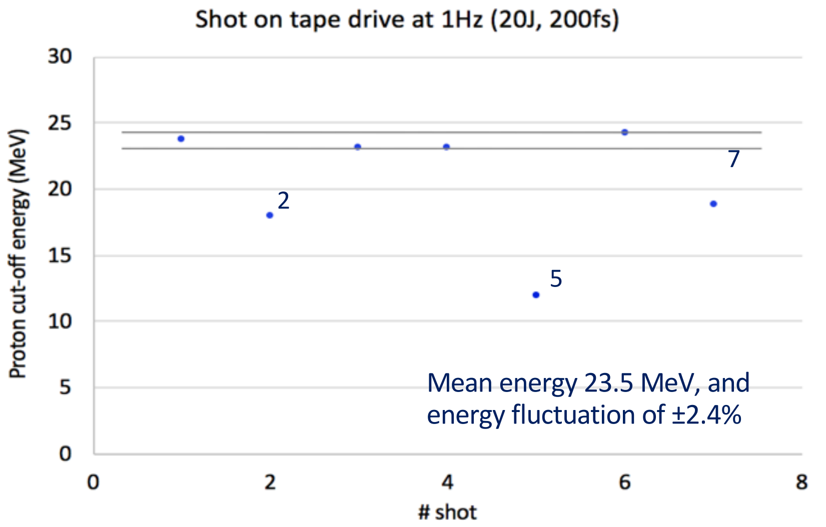
High laser energy shots

RAW image from Thomson parabola spectrometer

7 Proton traces on Image Plate

Damage on the Kapton after the shots



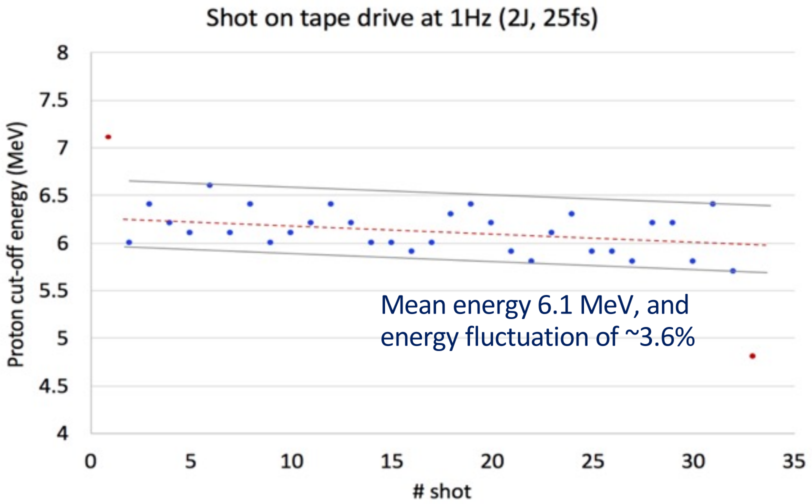


Maximum proton energy of 7 consecutive shots close obtained with the laser energy of 20J (close to maximum) and stretched laser pulse (~200fs) on a Kapton ribbon 13 µm thick.

Low laser energy shots

RAW image from Thomson parabola spectrometer

33 Proton traces on Image Plate



Maximum proton energy of 33 consecutive shots at low energy (~2J) and best compression (~25fs) on a Kapton ribbon 13 µm thick.

Center for High Power Optics

IFIN-HH

eli nuclear physics

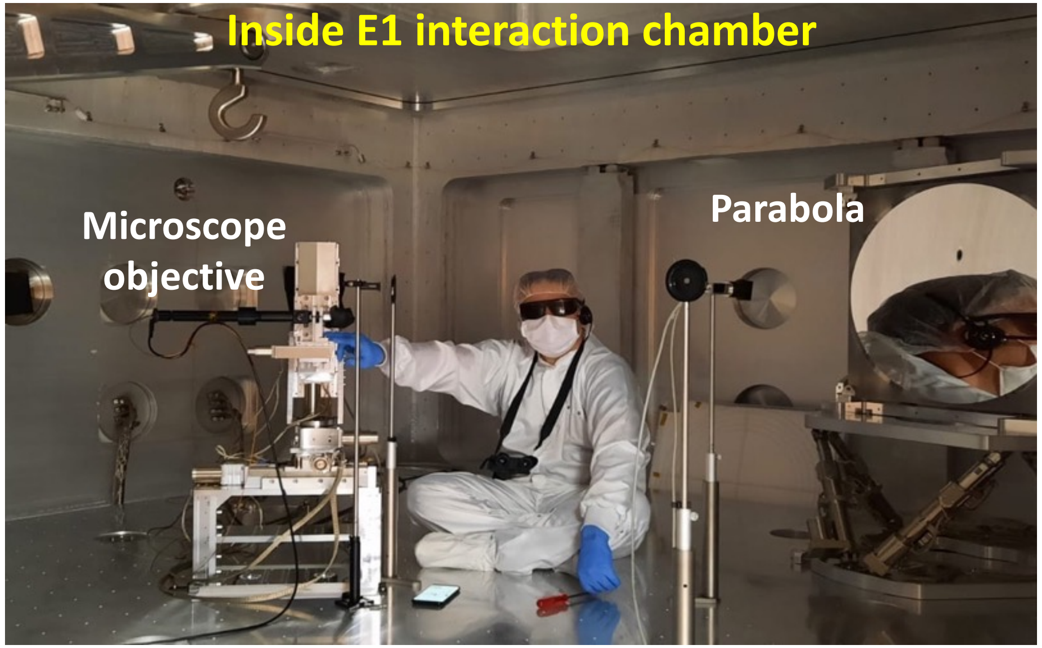
CNI Compania Națională de Investiții

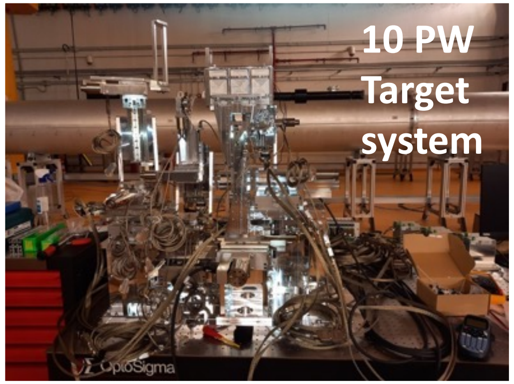
GUVERNUL ROMÂNIEI

MINISTERUL DEZVOLTĂRII, LUCRĂRILOR PUBLICE ȘI ADMINISTRAȚIEI

- A Centre for High Power Laser Optics adjacent and synergistic to the Extreme Light Infrastructure - Nuclear Physics (ELI-NP)
- Equipped with the technologies to carry out manufacture and/or repair of the high-power optical components used at the ELI-NP research infrastructure (**polishing system for large optical components, spectral technology for metrology, thin layer coating deposition system**)
- A green energy efficient building at the very highest standards, equipped with the latest technologies (air to water heat pump units, solar power system)
- **Collaboration with Osaka University and Okamoto Optics**

Commissioning of 10 PW experiments in E1 and E6



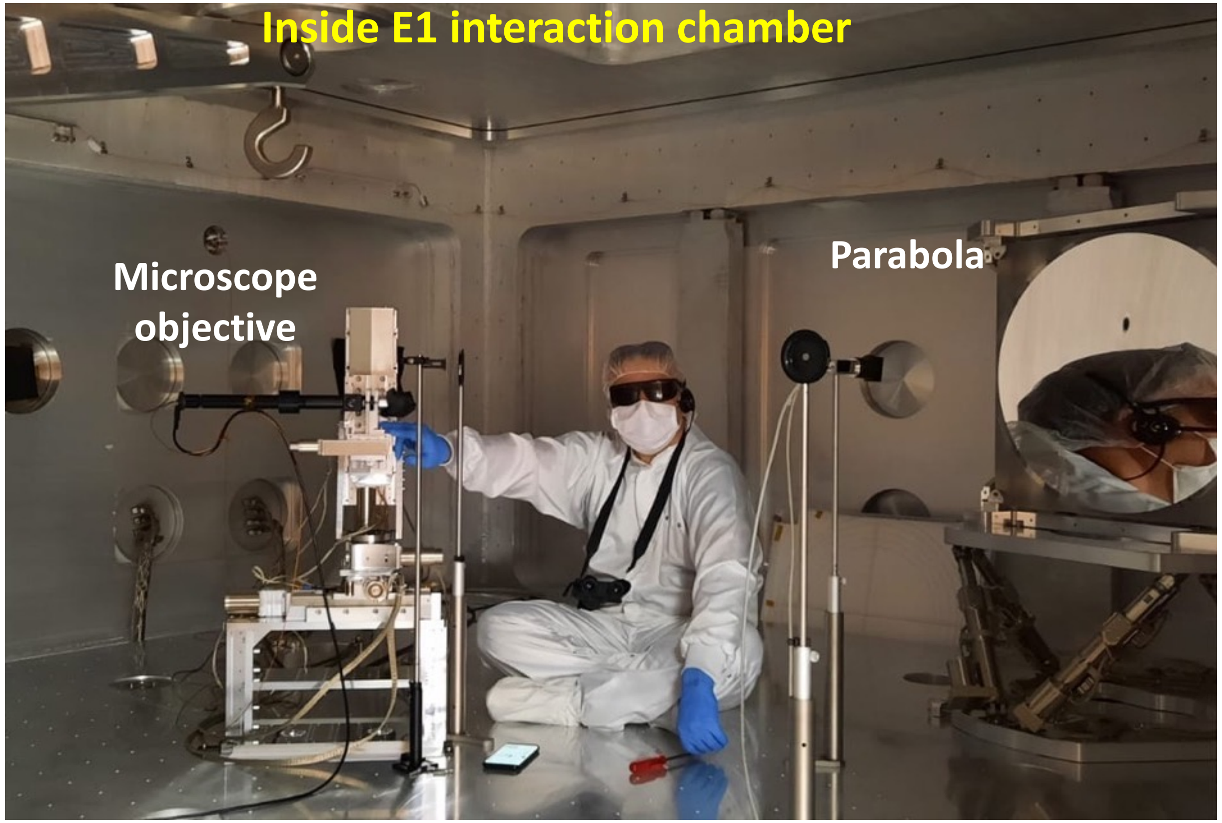


Large Optics 10 PW

- 1.5 m short focal off-axis parabolas
- 30 m focal spherical mirror

First tests show focal spot below 3 μm $\Longrightarrow \lesssim 10^{23}$ W/cm^2

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



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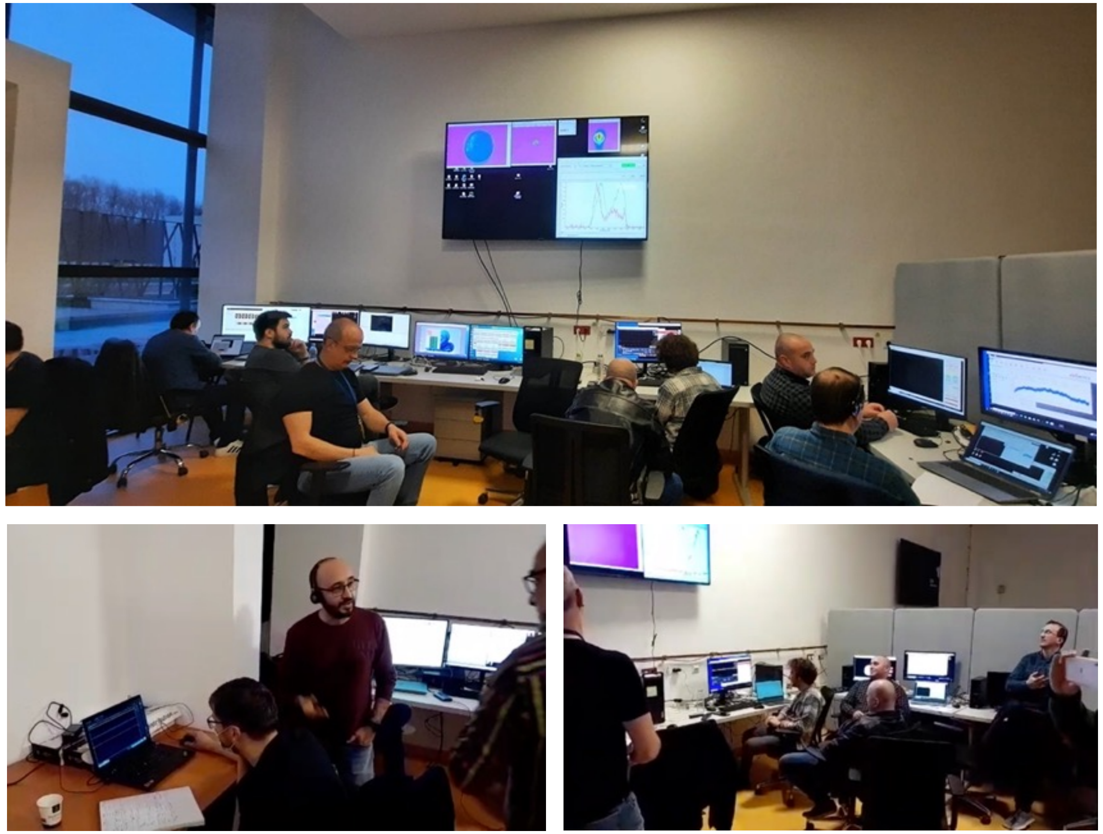


Images from the Control room for the experiments with 10 PW

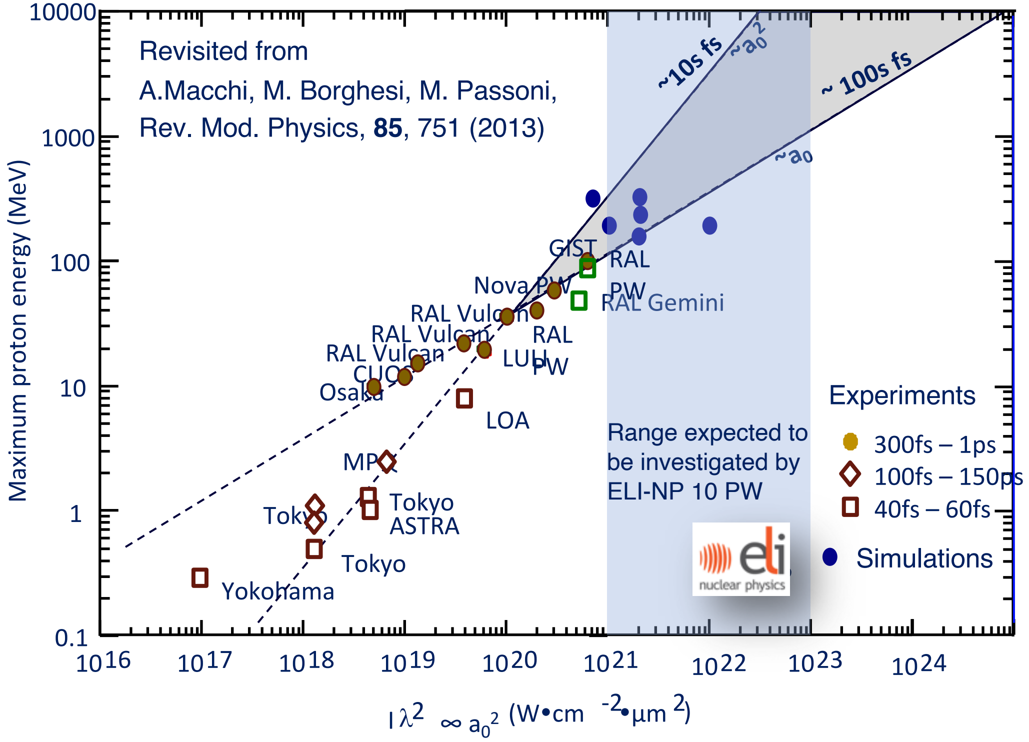
On **April 13, 2023** the most powerful laser system in the world, at ELI–NP, has **focused for the first time in the world 10 PW laser pulses on solid targets** marking an important milestone in laser plasma physics.

This is a **key milestone in science and technology** enabling opportunities in many research directions both in fundamental physics and in societal applications.

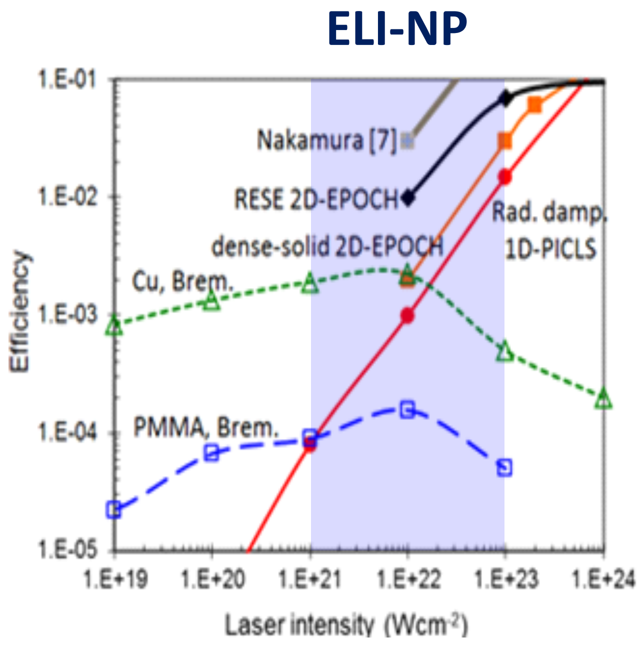
First Experiments at 10 PW – 2023

TNSA regime : accelerating protons above 200 MeV (E1)

TNSA scaling law and state-of–the-art



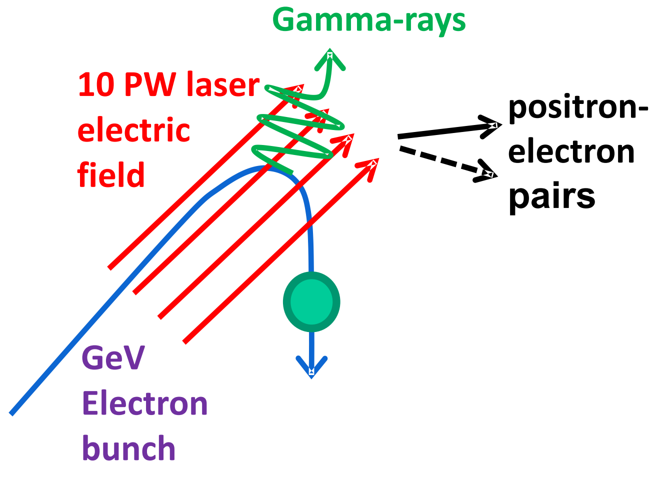
Ultra–intense gamma–ray source (E1)



P McKenna et al, ELI-NP TDR2

Tens of % laser-γ conversion efficiency in low-Z target ($\Longrightarrow$ PW gamma source)

Strong–field QED (E6)



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

- Synchrotron radiation or Nonlinear Compton:

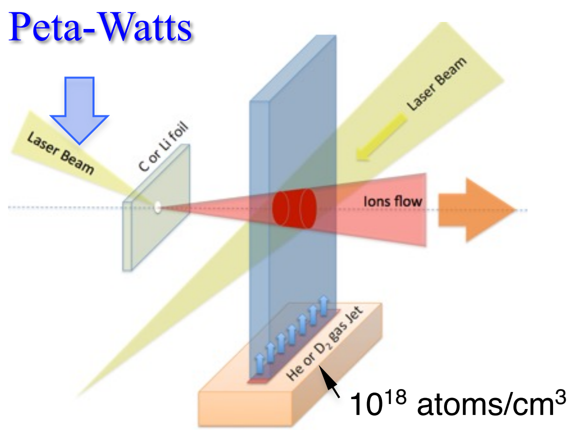
$$e^- + n\gamma_L \rightarrow e^- + \gamma_R$$

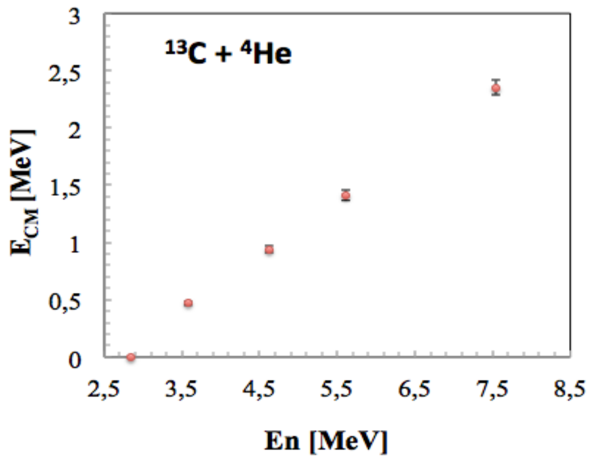
- Breit-Wheeler pair production:

$$\gamma_R + n\gamma_L \rightarrow e^- + e^+$$

Laser–Driven Nuclear Physics

Study of electron screening factor in nuclear reactions of astrophysical interest

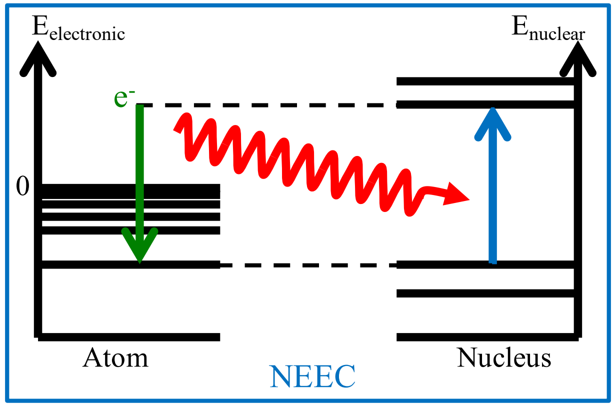




Nuclear reactions in hot plasma created by laser beams simulating stellar environments in the laboratory

S. Tudisco et al., INFN

Nuclear de-excitations in plasma



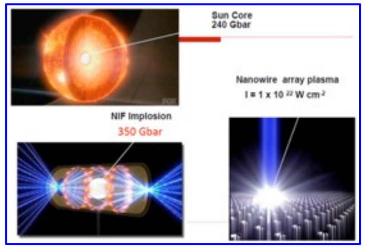
NEEC = Nuclear Excitation by Electron Capture

- ^{93m}Mo (E=2.4 MeV $t_{1/2}$=6.5 h) important case, NEEC claimed by Chiara *et al.*, Nature **554**, 216 (2018) release *via* 4.85 keV intermediate state.
  - Tandem accelerator ANL - NO real plasma conditions

Program at ELI-NP:

- Creating ^{93m}Mo *via* laser-induced proton reaction and exposing to REAL keV plasma with 1 & 10 PW system

Laser–driven bright neutron sources



Development of high-intensity short-pulsed laser-driven neutron source (LDNS)

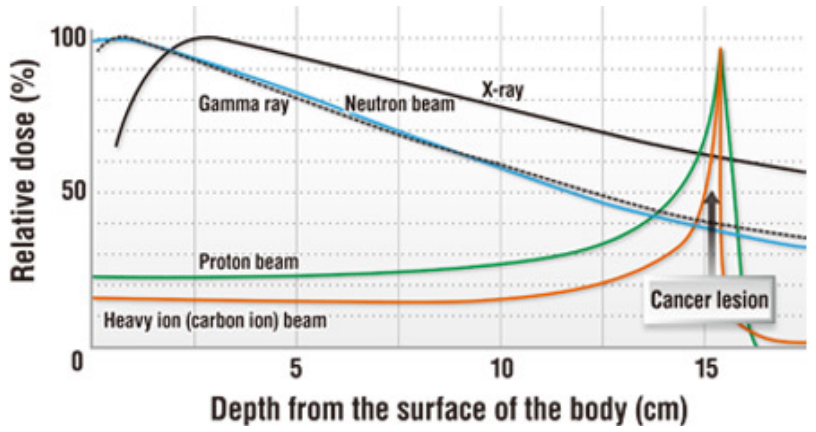
- Photonuclear (γ,n) reaction at high-rep. rate
- Laser-induced implosion causing shock-compression on deuterated nanowires and 10's of Gbar pressure: 10^{19} W/cm^2, 60 fs, ultrahigh contrast >10^{11}, E_n = 2.45 MeV ⟶ n-flux = 2.2 x 10^6 n/J/shot, A. Curtis *et al.*, Nat. Comm. **9** 1077 (2018)
- Spallation or (p,n) reactions with laser-driven high-energy protons

Program at ELI-NP:

- Radiography by a bright source of laser-driven thermal neutrons and X-rays, Yogo *et al.* 2021 Appl. Phys. Express **14** 106001 (2021)
- *N*- and maybe *2N* capture studies (long-term) of waiting-point nuclei in stellar evolution, Hill & Wu, PRC Phys. Rev. C **103**, 014602 (2021)

Medical Applications of High–Power Lasers

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)
- Proposed medical focus on long term: **start from skin-level cancer, progressing to HNC and breast cancer** (#1 cause of cancer mortality for women)

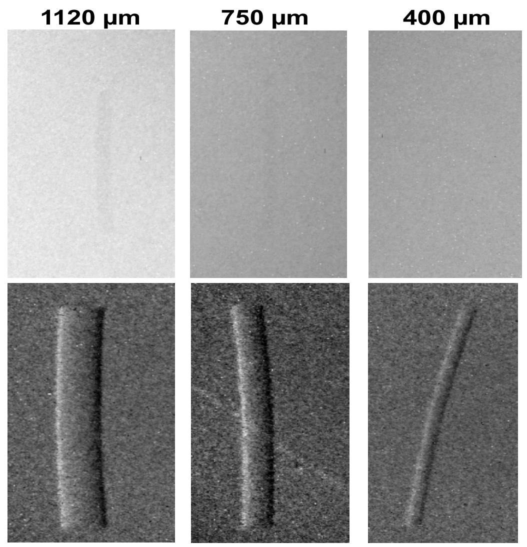
Interferometric phase contrast X–ray imaging

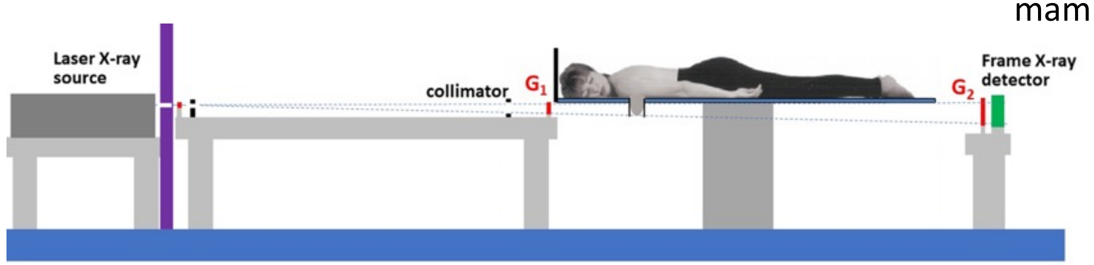
- **Conventional**, absorption-contrast **X-ray imaging has poor visibility of soft tissue tumors**
- **Phase-contrast X-ray imaging investigated as alternative**
- Method requires intense, directional, short–pulse and spatially coherent X–ray source: **100 TW class lasers can do this**
- Proposed medical focus: **breast cancer and later lung cancer**

Fibrils simulating early breast cancer in mammographic accreditation phantom

Conventional mammography

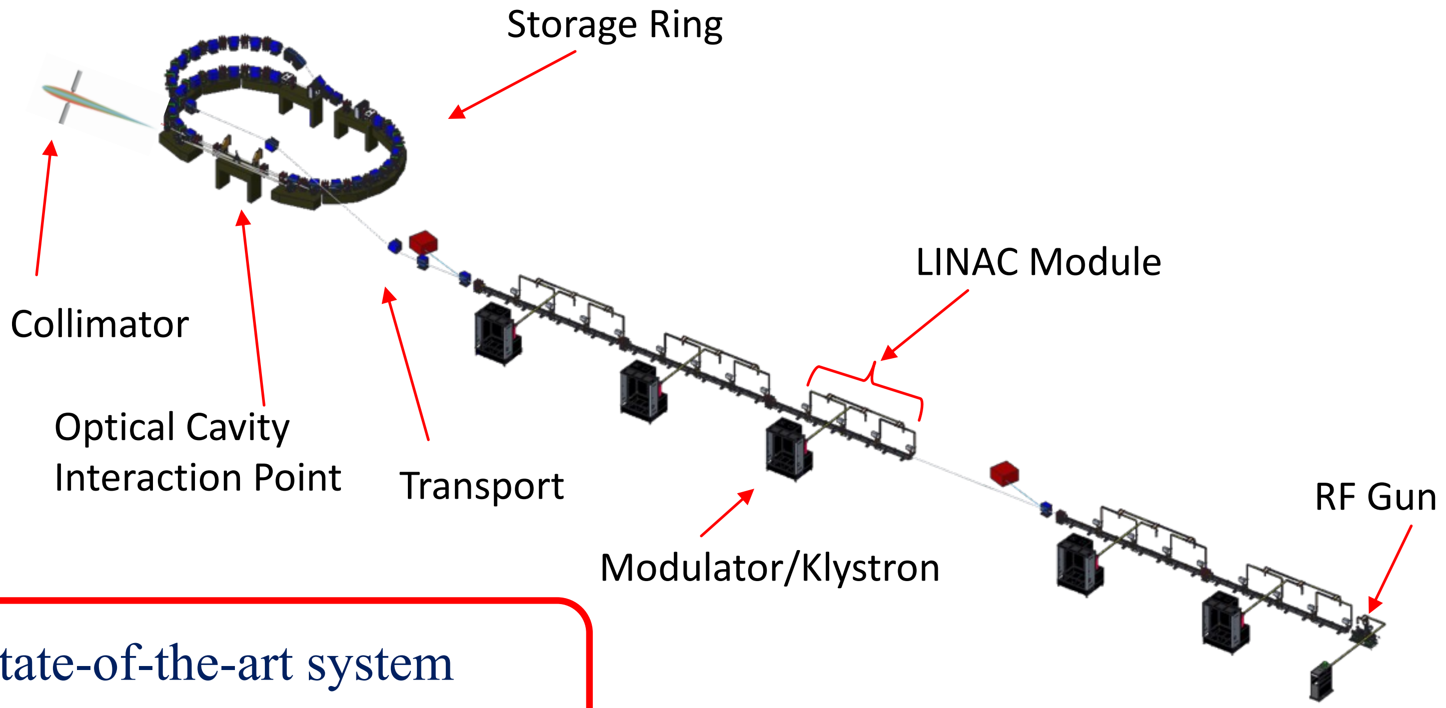
Interferometric mammography

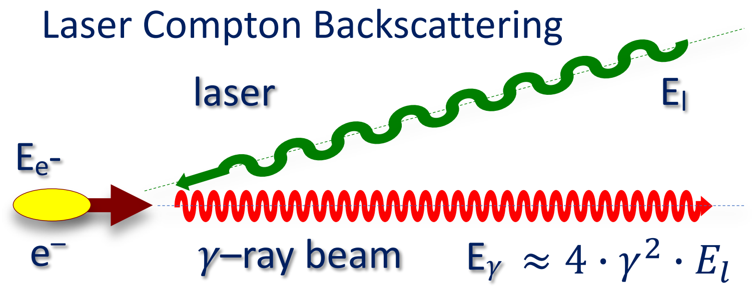




N.Safca *et al*, Phys Med Bio 2022

ELI–NP Gamma Beam System





$$N_\gamma = L\sigma_T \qquad \sigma_T = 0.67 \cdot 10^{-24}\ \text{cm}^2$$

$$L = \frac{N_L N_{e-}}{4\pi\sigma_x^2} f \qquad f \sim 70\ \text{MHz}$$

$$L \sim 10^{35}\ \text{cm}^{-2}\ \text{s}^{-1}$$

State-of-the-art system

Energy up to:

19.5 MeV

Quasi-monochromatic

< 0.5 % relative bandwidth

High spectral density

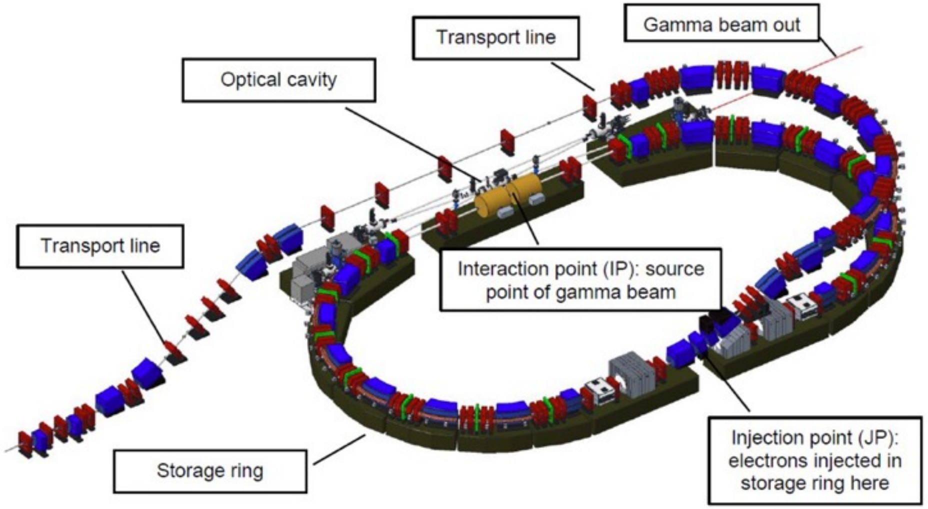
> 5000 photons/eV/s

High-degree of linear polarization

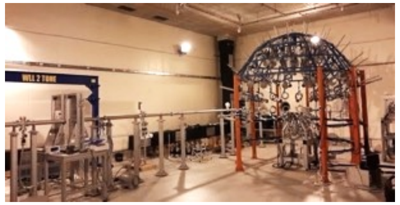
> 95 %

Implementation completion taken over by ELI-NP

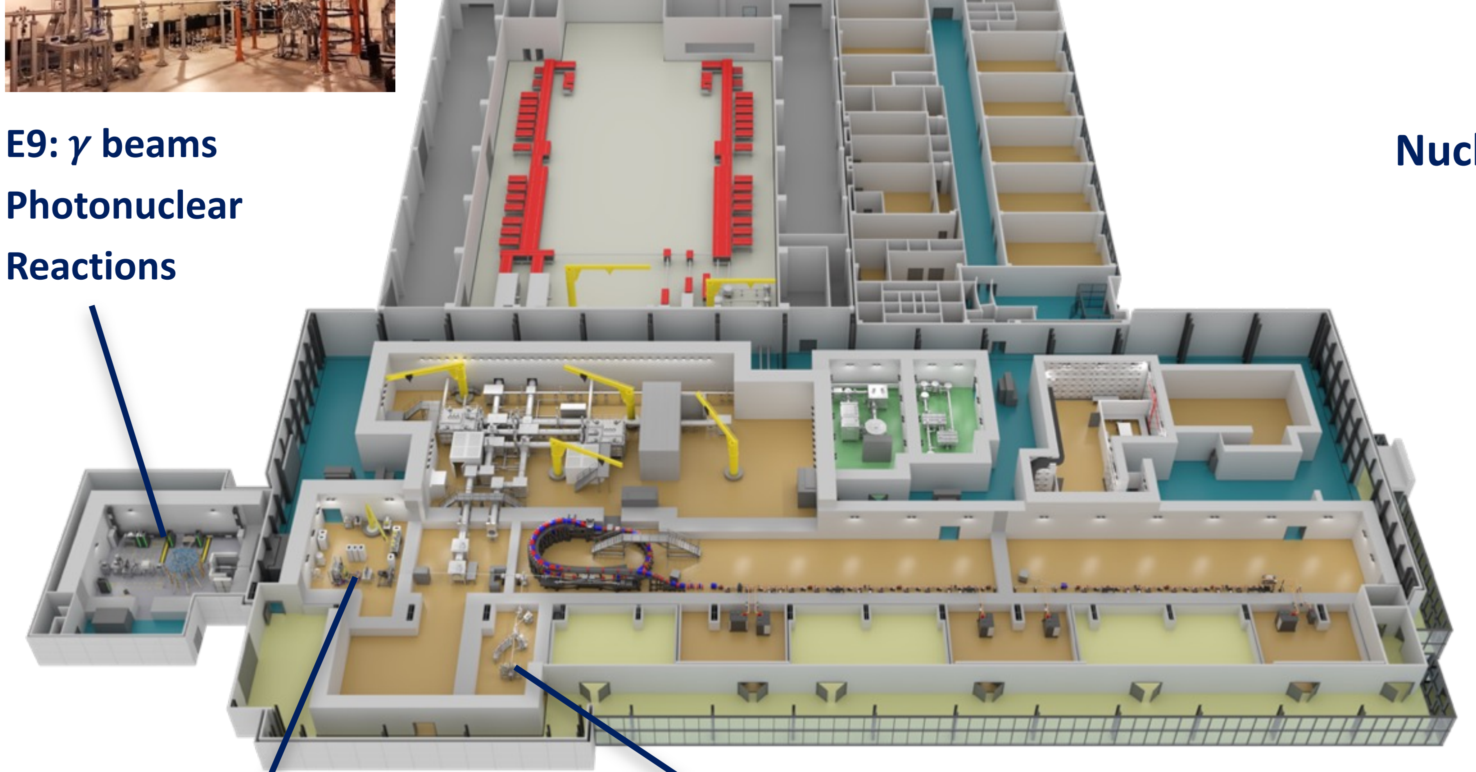
$\Longrightarrow$ **delayed to 2026**



Gamma-Driven Experiments Areas

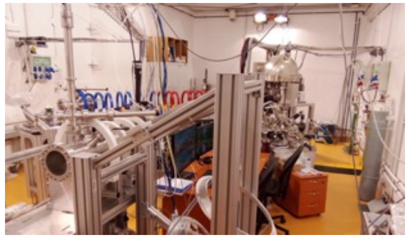


E9: γ beams
Photonuclear
Reactions

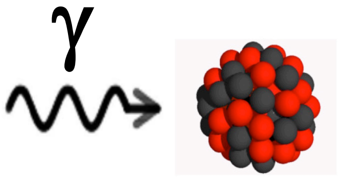


E8: γ beams
Photonuclear
Reactions

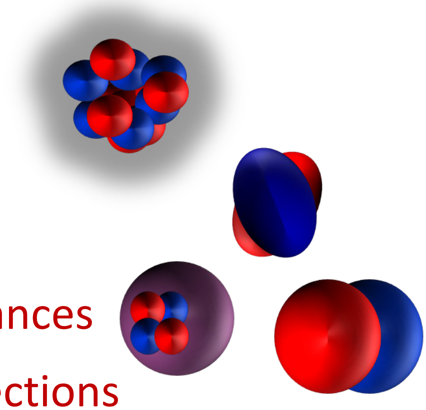
ERA: positrons
Material Studies



Physics Case: photonuclear reactions



Nuclear physics

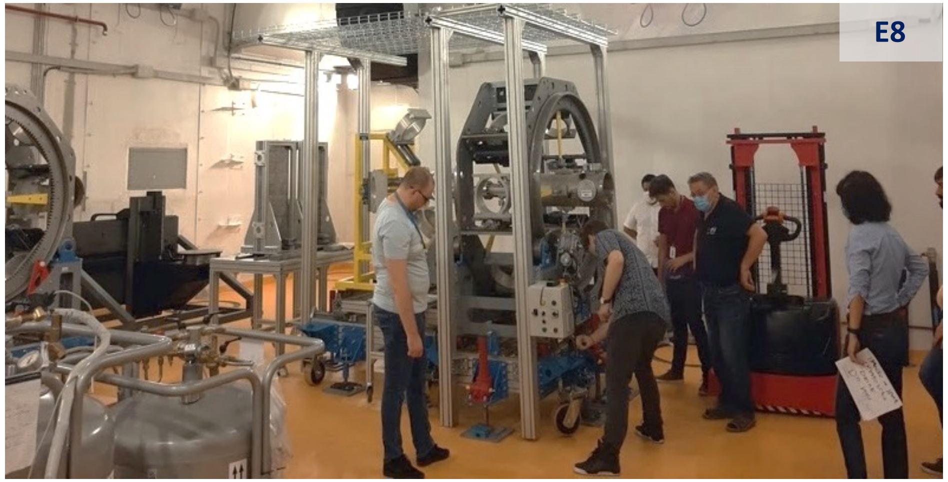


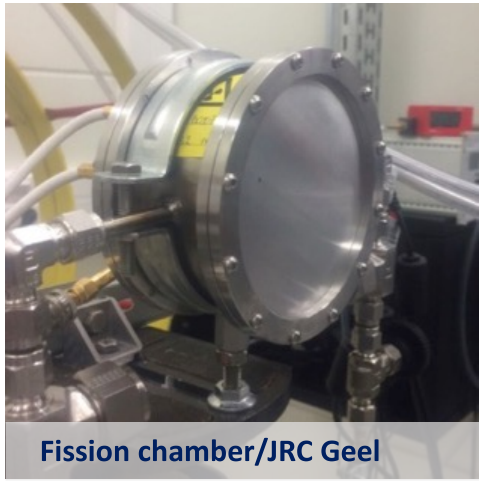
- Nuclear structure
- e.m. dipole response of nuclei
- Pygmy and Giant Dipole Resonances
- Photonuclear reactions cross sections
- Nuclear astrophysics
- Photofission and exotic nuclei

Applications

- Industrial imaging
- Radioisotopes generation
- Material studies with positrons

ELI–NP Gamma Beam Experimental Setups





E8 experimental area

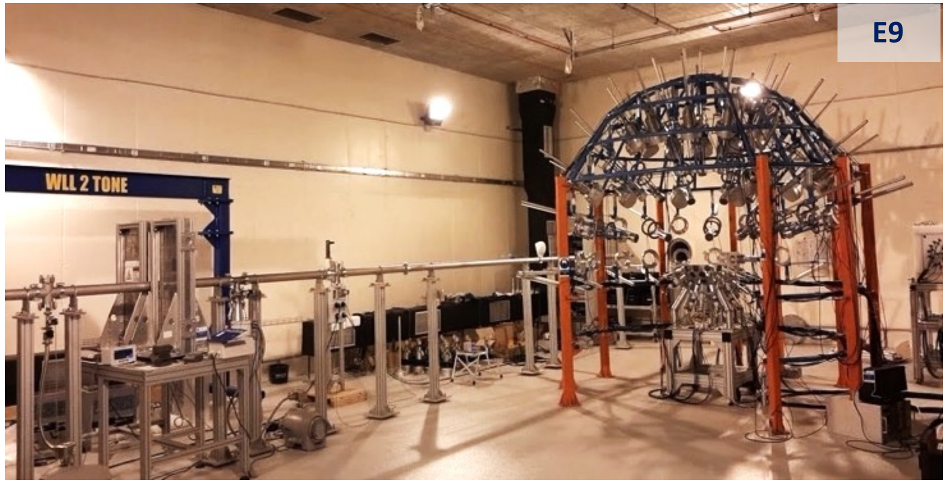
ELIADE

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

Gamma-Ray Imaging

ELISSA

- DSSSD



E9 experimental area

ELIGANT-GN

- 34 $LaBr_3$ & $CeBr_3$
- 25 ^{7}Li glass
- 36 liquid scintillators

Gamma beam diagnostics

- energy, flux, polarization

ELI–NP as User Facility

1st Common Call for Users with ELI ERIC

Period: October 2022 – March 2023

ELI-NP **17 proposals**: 6 @ 100 TW & 11 @ 1 PW
(Romania, UK, Japan, France, Spain, Canada, Italy, Russia, Israel, India, Germany, Poland)

PAC Meeting: 3 – 4 October 2022

- Grade A: 1 @ 100 TW, 2 @ 1 PW
- Grade A-: 2 @ 100 TW, 4 @ 1 PW
- Grade B: 3 @ 100 TW, 5 @ 1 PW

Successfully performed 2 exp. @ 100 TW and 2 exp. @ 1 PW

2nd Common Call for Users with ELI ERIC

Period: July 2023 – December 2023

ELI-NP **18 proposals**: 2 @ 100 TW & 16 @ 1 PW
(Romania, UK, Japan, USA, China, Israel, India, Germany, Poland)

PAC Meeting: 11 – 12 May 2023

- Grade A: 5 @ 1 PW
- Grade A-: 1 @ 100 TW, 6 @ 1 PW
- Grade B: 1 @ 100 TW, 4 @ 1 PW
- Grade C: 1 @ 1 PW

Scientific evaluation of experiment proposals
ELI-NP Program Advisory Committee (PAC)

Peter Thirolf (Chair)	Technische Universität München
Leonida Gizzi	INO-CNR Pisa
Karl Krushelnick	CUOS - University of Michigan
Paul McKenna	University of Strathclyde, Glasgow
Akifumi Yogo	ILE, Osaka University
Stuart Mangles	Imperial College of London
Antonino di Piazza	Max-Planck Institut für Kernphysik

User Office @ ELI-NP

Access based on the Terms & Conditions of Access with ELI ERIC
https://up.eli-laser.eu/downloads/Science-Call-TCA.pdf

Long Term Storage of Data

Access to ELI-NP Guesthouse and Canteen

Summary

- **ELI–NP Laser system fully operational on all outputs at nominal parameters**
- **Experimental areas E4 (100 TW) and E5 (1 PW) installed and commissioned**
  - First results – demonstrate good performance of the system
  - Available for users
- **Experimental areas E1, E6 (10 PW) are under commissioning in 2023**
- **VEGA System implementation is delayed to 2026**
- **Experimental setups for gamma beam experiments installed and commissioned**
- **User experiments with high power lasers**
  - First user experiments – started in November 2022
- **A large number of possible applications emerges from the use of laser-driven secondary sources and monochromatic gamma beams**
- **In June 2023 Romania was accepted as Founding Observer of ELI ERIC**

ELI-NP Team

260 employees

- 41 foreign researchers and engineers
- More than 100 youg researchers below 35
- 58 Students PhD, master and bachelor

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

Thank you !

www.eli-np.ro