ELI-NP: Nuclear Science and applications with the next generation of High Power Laser and Gamma beams: Project Status and Roadmap

The world’s first international laser Research Infrastructure
Pan–European distributed research infrastructure based initially on 3 facilities in CZ, HU and RO

ELI–Beamlines, Prague, CZ
High–Energy Beam Facility
development and application of ultra–short pulses of high–energy particles and radiation

ELI–ALPS, Szeged, HU
Attosecond Laser Science Facility
new regimes of time resolution

ELI–NP, Magurele, RO
Nuclear Physics Facility with ultra–intense laser and brilliant gamma beams (up to 20 MeV) novel photonuclear studies
Extreme Light Infrastructure
A world laser roadmap

Gerard Mourou 1985: Chirped Pulse Amplification (CPA)

Electric field in the laser focus is function of laser intensity:

\[ E(V/cm) = 27.4 \times \sqrt{l(W/cm^2)} \]

\[ l = 10^{23} \text{ W/cm}^2 \]

\[ E = 8.7 \times 10^{12} \text{ V/cm} = 8.7 \times 10^6 \text{ MV/cm} \]

\[ I(\text{Schwinger}) = 2.3 \times 10^{29} \text{ W/cm}^2 \]

\[ E_s = 1.3 \times 10^{16} \text{ V/cm} \]
P = 10^{11} \text{ PW}

I > 10^{22} \text{ W/cm}^2!

500 \text{ J}
50 \text{ fs} = 50 \times 10^{-15} \text{ s}

\text{P = 10 PW}

\text{I = 10}^{22} \text{ W/cm}^2

10 \text{ micron}

Take the sun...

\text{S.Gales-ECOS-Town meeting -Orsay -Oct-27-29-2014}
ELI Nuclear Physics in Romania

Structural Funds approved in Sept. 2012
Start construction   June 2013

Projected completion date: spring 2018-
Fully operation facility +1-2 years

Building under construction
( Completed June 2015)
staff hiring in progress (~60→>240)

Major equipment:
two 10PW lasers under construction
Gamma Beam System under construction

293 Meuro 83% EC , 17% Romania

Budget break-down 2012 – 2017:

<table>
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<tr>
<th>Category</th>
<th>Amount</th>
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<tr>
<td>Building</td>
<td>66 M€</td>
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<td>Stafff</td>
<td>34 M€</td>
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<tr>
<td>Scientific equipment</td>
<td>169 M€</td>
</tr>
<tr>
<td>Others</td>
<td>24 M€</td>
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<td><strong>Total</strong></td>
<td><strong>293 M€</strong></td>
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ELI-NP
Observation of matter with new powerful probes
Two machines of extreme performances
Large discovery potential

Two 10 PW lasers, $10^{23}$ w/cm$^2$
Extreme E-M fields

Laser + e- Acc

Femto scale

BCS Brilli ant Gamma Beams
0.2-19 MeV, $10^{11}$ γ/s, 0.3% BW
Bucharest-Magurele Physics Campus
National Physics Institutes

“Horia Hulubei” National Institute for Physics and Nuclear Engineering

NUCLEAR

Lasers Plasma Optoelectronics Material Physics Theoretical Physics Particle Physics

ELI-NP

BUCHAREST ring rail/road
ELI-NP Milestones – Facility Construction

Buildings – one contractor, 33000 m² total

- Experimental area building
- Canteen
- Guest house
- Office building

Ready by June 2015
ELI–NP Nuclear Physics Research

• Nuclear Structure
  Nuclear Photonics (NRF)
  Photo–disintegration, Photo–fission & Exotic Nuclei
  Nuclear Astrophysics

  Complementary to other ESFRI Large Scale Physics Facilities (FAIR, SPIRAL2)

Laser–Target interaction characteristics : NP diagnostics
Laser Ion driven nuclear physics : fission–fusion
Laser – Extreme E-M Fields–Acceleration – Beyond QED

• Applications based on high intensity laser and very brilliant $\gamma$ beams complementary to the other ELI pillars

• ELI–NP in Romania selected by the most important science committees in Europe – ESFRI and NuPECC, in the ‘Nuclear Physics Long Range Plan in Europe’ as a major facility

S.Gales-ECOS-Town meeting -Orsay -Oct-27-29-2014
ELI–NP Scientific Coordination

Research Activities

HPLS
1. Laser delivery and beam lines
2. Fission–fusion experiments
3. Strong field QED
4. Laser + Gamma interaction
5. Applications

GBS

Experiments with HPLS

Experiments with GBS

1. Gamma Beam Delivery & Diagnostics
2. NRF Experiments
3. Photo–fission experiments
4. \((\gamma,n)\) experiments
5. \((\gamma,p)\) experiments
6. Positron source for material science
7. Applications

Engineering office Interface
(building, safety, RP, Vacuum, C&C, labs, workshops)

20 MoU With major Laser and NP labs and Institutions

S. Gales-ECOS-Town meeting - Orsay - Oct-27-29-2014
The workshop "Towards Technical Design Reports (TDR) of experiments with intense laser beams at ELI-NP" was held in Bucharest-Magurele, on June 27th - 28th, adjacent to a workshop "Towards Technical Design Reports (TDR) of experiments with brilliant gamma-ray beams at ELI-NP" held at the same location on June 25th - 26th, 2013.

**Next ELI–NP International Workshop**

- “ELI–NP Science Program and Instruments”

**Technical Design Reports-February 18 – 20, 2015**

*External reviews March-May 2015*

*International Scientific Advisory Board (20 members)*

2nd Trimester of 2015

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ANR proposals FR-RO dedicated to ELI-NP (18/11/2014)
ELI–NP Experiment Building

8 Expt Halls 7000 m²

- HP Lasers
- E1 10PW
- E5 1PW @ 1 Hz
- E4 0.1PW @ 10 Hz
- E3 Positron source

E8, Gamma Nuclear reactions 3-19 MeV

E7, QED High field gamma + electrons

E2, NRF 0.2-3.5 MeV

S. Gales - ECOS - Town meeting - Orsay - Oct 27-29, 2014
ELI–NP HPLS

Provided by THALES Optronique – France

Based on OPCPA

2 HPLS up to 10 PW – 6 outputs

2 x 0.1 PW 10Hz
2 x 1 PW 1Hz
2 x 10 PW 0.1Hz

July 12th, 2013
Electrons are expelled from the target due to the chock wave induced by the powerful laser. Heavy ions are accelerated in the field created by the electrons.
Electrons and ions accelerated at solid state densities $10^{24} \text{e cm}^{-3}$ never reached before (Classical beam densities $10^8 \text{e cm}^{-3}$) on very short distance ($\mu\text{m-mm}$)

$E \sim I_{\text{laser}}$

Energy reached equal to a 400m up-to-date accelerator (up to GeV reduction of scale of $10^9$)
1. **Circular polarized Laser beam** incident on production target produces a beam of $^{232}$Th, $^{12}$C and $^2$D ions through the Radiation Pressure Acceleration.

2. **Fission reactions:** a) $^{232}$Th interacts with $^{12}$C (or $^1$H) in the 1$^{\text{st}}$ layer and b) $^{12}$C and $^2$D nuclei interacts with $^{232}$Th in the 2$^{\text{nd}}$ layer of reaction target. One light and another heavy fragments are produced:

   
   $^{232}$Th + ($^{12}$C, $^1$H) $\rightarrow$ $X_L + X_H$
   $^{12}$C (or $^2$D) + $^{232}$Th $\rightarrow$ $Y_L + Y_D$

3. **Fusion:** Two light fission fragments ($X_L$, $Y_L$) fuse in the reaction target. Neutron rich nuclei (close to N=126) are produced.

**Study of heavy ions acceleration mechanism at laser intensities > 10$^{23}$ W/cm$^2$**

- Deceleration of very dense electron and ion beams
- Understanding influence of screening effect on stellar reaction rates using laser plasma
- Nuclear techniques for characterization of laser–induced radiations

**fission–fusion reactions.**

n–rich nuclei around N = 126  Z=66,70 waiting point
The Gamma Beam System (GBS)

Laser Compton Back-scattering (LCB)
- the most efficient frequency amplifier

‘Photon accelerator’

Low cross section (~$10^{-25}$ cm$^2$) need of high photon flux and electron densities

Maximum upshift
- head–on collision ($\theta_L=0$) & backscattering ($\theta_\gamma=0$)

$$E_\gamma \sim 4\gamma_e^2 E_L$$

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- Laser-Photo cathode
- Yag Laser
- \( E_e \sim 300 \text{ MeV} \)
- \( E_e \sim 720 \text{ MeV} \)
- \( E_{\gamma} < 3.5 \text{ MeV} \)
- \( E_{\gamma} < 20 \text{ MeV} \)
- \( E_L \sim 2.4 \text{ eV (green)} \)
The GBS of ELI–NP

Provider – EuroGammaS Association

Academic Institutions
Sapienza University (Italy), INFN (Italy), CNRS (France), IN2P3 (France)

Industrial Partners
ACP (Amplitue Group, France), Alsjom (Aicen Group, France), Comeb (Italy), ScandiNova Systems (Sweden)

and several Sub-Contractors:
Alba (Spain), Cosylab (Slovenia), Danfysik (Denmark), IT (Slovenia), M+W Group (Italy), Menlo Systems (Germany), RI (Germany)

The Challenges:

• design the most advanced Compton Gamma Beam Source based on state–of–the–art components

• combining electron accelerator physics with a photon–electron collider

ELI–NP Gamma Beam Source: Bright, Monochromatic ($\approx 0.5\%$), High Spectral Flux ($\approx 10^4$ ph/s·eV), Tunable (0.2–19.5 MeV), Polarized ($\approx 99\%$)

## GBS – Beam Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low–energy stage: ( E_\gamma &lt; 3.5 \text{ MeV} ) March 2017</th>
<th>High–energy stage: ( E_\gamma &lt; 19.5 \text{ MeV} ) September 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>0.2 – 19.5</td>
<td>10^20 – 10^23</td>
</tr>
<tr>
<td>Spectral Density (ph/s·eV)</td>
<td>0.8 – 4·10^4</td>
<td></td>
</tr>
<tr>
<td>Bandwidth rms (%)</td>
<td>( \leq 0.5 )</td>
<td></td>
</tr>
<tr>
<td># photons per shot within FWHM bdw.</td>
<td>( \leq 2.6 \cdot 10^5 )</td>
<td>( \leq 8.3 \cdot 10^8 )</td>
</tr>
<tr>
<td>Source rms size (( \mu \text{m} ))</td>
<td>10 – 30</td>
<td></td>
</tr>
<tr>
<td>Source rms divergence (( \mu \text{rad} ))</td>
<td>25 – 200</td>
<td></td>
</tr>
<tr>
<td>Peak brilliance (( N_{\text{ph}}/\text{sec} \cdot \text{mm}^2 \cdot \text{mrad}^2 \cdot 0.1% ))</td>
<td>( 10^{20} – 10^{23} )</td>
<td></td>
</tr>
<tr>
<td>Radiation pulse length rms (ps)</td>
<td>0.7 – 1.5</td>
<td></td>
</tr>
<tr>
<td>Linear polarization (%)</td>
<td>&gt; 99</td>
<td></td>
</tr>
<tr>
<td>Macro rep. rate (Hz)</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td># pulses per macropulse</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Pulse–to–pulse separation (nsec)</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

**Low energy IP**
- \( E_{\text{beam}} = 300 \text{MeV} \)
- \( E_{\gamma} = 3.5 \text{MeV} \)

**High energy IP**
- \( E_{\text{beam}} = 720 \text{MeV} \)
- \( E_{\gamma} = 19.5 \text{MeV} \)
**NRF Physics cases @ ELI-NP**

**Physics above the neutron threshold**

**Nuclear Astrophysics**

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**Nuclear structure**
- Modes of excitation below the GDR, Scissor modes, Parity Violation, M1
- Decay of PDR, GDR,
- Impact on nucleosynthesis
- Gamow window for photo–induced reactions in explosive stellar events

**Understanding exotic nuclei**
- E1 strength will be shifted to lower energies in neutron rich system

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**Diagram:**
- E1 strength distribution
- NRF
- ELI–NP NRF Working group
- ELI-NP above Threshold WG
- ELI-NP Charged Particles WG

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Production of neutron rich fission fragments by photo-fission at ELI-NP

$\Phi = 1.4 \cdot 10^{11} \gamma/s$

Low Energy Gamma Beam fully efficient at 15 MeV for producing in thin U targets, short live and refractory elements using gas cell catcher with high efficiency due low ionizing power of pure $\gamma$ beams. Limited investments, minimize radioactivity, a real niche!! $10^9$

Coll IPN Orsay, Leuven, GSI, Giessen, JYVL

$\Phi \cdot s \cdot N = \Phi \cdot 6.4 \cdot 10^{-3} \text{ f/s}$
Astrophysics – related studies

- Production of heavy elements in the Universe
  – a central question for Astrophysics

- Neutron Capture Cross Section of s-Process Branch - Nuclei with Inverse Reactions ($\gamma$, $n$)

Measurements of ($\gamma$, $p$) and ($\gamma$, $\alpha$) Reaction Cross Sections for p–Process-Nucleosynthesis:

Key reaction: $\gamma + ^{16}\text{O} \rightarrow ^{12}\text{C} + \alpha$

Determination of the reaction rates by an absolute cross section measurement is possible using mono-energetic photon beams produced at ELI-N

Tremendous advance to measure these rates directly - very high intense $\gamma$ beam needed
Potential Nuclear Photonics Applications

- **HEU Grand Challenge**: detection of shielded material
- **Nuclear Fuel Assay**: 100 parts per million per isotope
- **Waste Imaging & Assay**: non-invasive content certification
- **Industrial NDE**
  - Precision Imaging: micron-scale & isotope specific
  - Medical Imaging: low density & isotope specific
  - Dense Plasma Science: isotope mass, position & velocity
Perspectives

- a new research facility, open to the European and International community is being under construction at Bucharest with state of art instruments 2X10 PW HPLS and 0.2-19 MV brilliant ,monochromatic GBS

- Research opportunities
  - nuclear astrophysics
  - Nuclear physics
    - Nuclear photonics
  - HP laser driven nuclear physics
  - strong field QED
  - Large Spectrum of Applications

- we are open for collaboration

- young researchers are invited to join the fun!

S.Gales-ECOS-Town meeting -Orsay -Oct-27-29-2014
### ELI-NP Core Team

**Board of Directors**


**Research Activities** Assistant G.I. Apetrei

#### Gamma Beam
- C.A. Ur (GBS)
- D. Balabanski
- O. Tesileanu
- D. Filipescu
- A. Oprisa
- N. Ivanov
- V. Leca
- K. Sato
- P. Constantin
- G. Sullivan
- V. Iancu

#### High Power Lasers
- D. Urcescu (Expts)
- R. Dabu
- F. Negoita
- E. Turcu
- I. Dancus
- S. Balascuta
- L. Neagu
- T. Asavei
- G. G. Acbas
- M. Bobeica
- I. Morjan (HPLS)

#### Engineering
- M. Toma
- C. Petcu
- M. Risca
- M. Cernaianu
- B. De Boisdeffre
- B. Tatulea
- M. Tataru
- M. Conde
- D. Popa
- V. Buznea
- C. Paun
- I. Garagaianu

#### Radioprotection, EMP
- M. Gugiu, I. Mitu
- S. Bercea, H. Stancu
- D. Aranghel, E. Iliescu

+ IFIN-HH
+ International TDR’s working groups

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Extreme Light Infrastructure – Nuclear Physics

www.eli-np.ro

Thank you for your patience
**ELI–NP Project Timeline**

- **WB & Feasibility Study**
- **Cost estimate 293M€**
- **Preparation of the Application**
- **E.C. Eval. & Funding Approval**
- **Civil engineering construction**
- **Procurement Gamma Beam**
- **Procurement Laser System**
- **Experiments Instruments**
- **Gamma Beam – installation**
- **Laser System – installation**

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- **TDR’s**
- **Cons**

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2010 2011 2012 2013 2014 2015-2018

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2010 - 2018

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MoU’s signed with the following entities (May 2014)

<table>
<thead>
<tr>
<th>Institute</th>
<th>Country</th>
<th>IFIN-HH/ELI-NP Website</th>
<th>Responsible</th>
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<tr>
<td>Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland</td>
<td>Poland</td>
<td>[website]</td>
<td>Dr. Daniel Ursescu</td>
</tr>
<tr>
<td>Institute of Laser Physics, Siberian Branch Russian Academy of Sciences</td>
<td>Russia</td>
<td>[website]</td>
<td>Dr. Razvan Dabu</td>
</tr>
<tr>
<td>Institute of Nuclear Research of the Hungarian Academy of Sciences</td>
<td>Hungary</td>
<td>[website]</td>
<td>Dr. Dimitar Balabanski</td>
</tr>
<tr>
<td>Konan University, Kobe, Japan</td>
<td>Japan</td>
<td>[website]</td>
<td>Dr. Dan Mihai Filipescu</td>
</tr>
<tr>
<td>University of Connecticut, USA</td>
<td>USA</td>
<td>[website]</td>
<td>Dr. Ovidiu Tesileanu</td>
</tr>
<tr>
<td>Institute of Nuclear Physics, University of Cologne, Germany</td>
<td>Germany</td>
<td>[website]</td>
<td>Dr. Calin A. Ur</td>
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<td>Italy</td>
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<td>Dr. Nicolae Zamfir</td>
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<tr>
<td>Triangle Universities Nuclear Laboratory, Durham, NC, USA</td>
<td>USA</td>
<td>[website]</td>
<td>Dr. Sydney Gales</td>
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<td>Friedrich Schiller University, Jena, Germany</td>
<td>Germany</td>
<td>[website]</td>
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<td>&quot;II. Physikalisches Institut&quot; of Justus-Liebig University, Gießen, Germany</td>
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</tr>
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<td>The University of Strathclyde, Glasgow, UK</td>
<td>UK</td>
<td>[website]</td>
<td>Dr. Edmond Turcu</td>
</tr>
<tr>
<td>GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany</td>
<td>Germany</td>
<td>[website]</td>
<td>Dr. Sydney Gales</td>
</tr>
</tbody>
</table>
Table 1: A sample of the laser installations associated with the IZEST partnership.
Laser acceleration
Exciting Perspectives

Enormous reduction in scale
Applications of NRF To Nuclear Materials

Photon energy (MeV)

2.176 MeV for U-238

\[ \Delta E/E < 1\% \]

NRF signal U-238 2.176 MeV

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Attracting the best competencies:

- public announcements
- international recruitment
- head–hunting for management positions
- junior researchers specializing in a unique and top-level field of research
- PhD students will benefit of a very high specialization with enormous possibilities
HPLS - Applications
Materials in Extreme Environments for Energy, Accelerators and Space

materials for fusion reactors

- testing of new materials for **accelerator** components
  - high power targets: for RIB production, spallation targets
  - new materials are needed for accelerators
  - collimator jaws for the upgrade of the LHC
- testing materials for space science (electronics components, hypervelocity impacts)
  - the radiation environment used for ground testing should ideally mimic the natural environment probed by the satellite
- biological science research (effects on bio-molecules, cells)
- testing radiation hardness and developments of detectors
- irradiated optical components testing
GBS – Photonuclear Reactions

Absorption

\[ \gamma \rightarrow gs \quad A_X \]

Separation threshold

\[ \gamma' \]

\[ \beta \]

\[ \sim 8 \text{ MeV} \]

\[ A_Y \]

Nuclear Resonance Fluorescence (NRF)

Photoactivation

Photodisintegration (activation)

Photo–fission

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Location of the IGISOL gas catcher
Laser driven Fusion-Fission
Experimental layout

- characterization of reaction products
  - decay spectroscopy
- precision mass measurements:
  e.g. Penning trap

Penning trap
mass measurements
($\Delta m/m = 10^{-8}$)

gas stopping cell
cooler/buncher
(gas-filled) separator

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NRF – Applications

Non-destructive computerized tomography of objects

CT setup @ AIST, Tsukuba, Japan
- 10 MeV LCB gamma–ray beam
- off–line reconstruction of the object image with the filtered–back–projection method
- less prone to artifacts due to radiation hardening
- need of high intensity to reduce scanning time

electrode of the TH571A tetrode tube

H. Toyokawa, NIM 545, 469 (2005)
Strong field QED physics...

Require electrons with a large Lorentz factor ($\gamma$) interacting with strong electromagnetic fields. Ultra-intense lasers should be able to provide both the Lorentz factor and the fields.

ELI-NP Delivering 20fs pulse at $> 10^{23}$ W/cm$^2$ will enable this exciting new regime to be investigated.

(1) Interaction of GeV electron beam (Wakefield) with TW-PW laser

(2) >10PW laser pulse interactions with dense plasma

Reaction rates are high due to high electron density

$10\text{PW} = 10^{23} \text{Wcm}^{-2} \rightarrow \gamma = 300 \rightarrow \eta \approx 0.2$

Radioisotopes for medical use

• New approaches and methods for producing radioisotopes urgently needed

• Mo-99 and other medical isotopes used globally for diagnostic medical imaging and radiotherapy

• $^{195m}$Pt: In chemotherapy of tumors it can be used to exclude ”non responding” patients from unnecessary chemotherapy and optimizing the dose of all chemotherapy
ALTO, ARIEL, etc.

ELI-NP

γ–beam spectrum at the IP (without collimator)

\( \sim 10^{11} \gamma/s \)
Laser Recirculation at IP
POWER : $10 \text{ PW} = 10^{16} \text{ W}$

1 Million Billions light bulbs!

DURATION : $50 \text{ fs} = 50 \times 10^{-15} \text{ s}$

1 Thousandth Billionth blink eyes!