Operational Programme Competitiveness

Extreme Light Infrastructure – Nuclear Physics (ELI-NP) – Phase II
Project co-financed by the European Regional Development Fund

Ultra-intense laser and gamma beam systems at ELI-NP

Kazuo A. Tanaka and N. Victor Zamfir
for the ELI-NP researchers and collaborators

Prof T Tajima’s 70th Birthday Symposium
UC Irvine,
Jan. 26, 2018
Extreme Light Infrastructure: Nuclear Physics at Bucharest Romania

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Outline of My Talk

• Introduction
• Team Structure
• High Power Laser System
  Gamma Beam System
• Proposed Experiments
• Nuclear Photonics 2018
• Summary
Three laser labs are being constructed with 300 MEuro each. Those are planned in Romania, Czech, and Hungary. Each has its own characteristics.
We are located in Bucharest.
Introduction

Laser System with Highest Focused Intensity

The wavelength, pulse width, energy, and beam diameter are 820 nm, 25 fsec, 250 J, and 50 cm.
Focused laser intensity may reach $10^{23}$ W/cm$^2$.
The laser light will accelerate electrons up to the speed of light.

Gamma Beam System with Highest Photon Number

The Gamma Beam photon energy is 19.5 MeV with 2 psec pulse width.
The number of photons may reach $10^9$ photons/sec.
The gamma light will interact directly with nuclei for excitation and fission.
Laser system can be operated as stand alone or combined with Gamma beam system.

- Experiments under extreme conditions, so far not possible, can be conducted.

For example, we will perform
- Electron acceleration more than 10 GeV
- Nuclear fission and fusion
- Head-on collision of the laser and relativistic electron beam

Then these experiments will clarify
- History of the Universe
- Important Issues on nonlinear QED
- Isotope production for medical use

These achievements may lead to the Nobel prize and/or realistic outcomes for our society.
ELI–NP Building

Platform supported on dampers

Anti-vibration platform

±1 μm @ < 10 Hz
Team Structure

General Director of IFIN/HH & Project Director
Prof Dr Nicolai Victor Zamfir (US-Romania)

Scientific Director
Prof Dr Kazuo A Tanaka (US-Japan)

Technical Director
Dr Dan Gabriel Ghita (Rom)

RA1 Laser Group
Dr Daniel Ursescu (Germany Rom)

RA2 Gamma Beam Grp.
Dr Calin Ur (Italy Rom)

RA3 Laser plasma nuclear physics Grp.
Dr Dan Stutman (US Rom)

RA4 Gamma Beam nuclear Physics Grp.
Dr Dimiter Balabanski (Bulgaria)

RA5 Combined Laser and Gamma Beam Grp.
Dr Ovidiu Tesileanu (Italy Rom)

Currently 130 members (20 Senior Sci., 60 Junior Sci. Rest Eng.)

Will boost up to 250 members.
High intensity laser system has started from these two.

When they were at Laboratory for Laser Energetics, Univ. of Rochester in early 80’s.

Gerard Mourou
IZEST France

Dana Strickland
University of Waterloo in Ontario, Canada
Intensity could reach $10^{22}$-$10^{23}$ W/cm$^2$
Laser system sits in a 70 x 70 m² clean room.
Installation in progress.

Both Front ends and one amplifier for 100TW operational
All pump lasers in final position
All vacuum vessels in final position

8x 100J pump lasers

2x 10 PW compressors
# High Power Laser System

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<tr>
<th>Parameter</th>
<th>min</th>
<th>max</th>
<th>Unit</th>
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<td>Energy/pulse</td>
<td>150</td>
<td>225</td>
<td>J</td>
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<td>Central wavelength</td>
<td>814</td>
<td>825</td>
<td>nm</td>
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<td>Spectral bandwidth (FWHM)</td>
<td>55</td>
<td>65</td>
<td>nm</td>
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<td>Spectral bandwidth (at nearly zero level of intensity)</td>
<td>120</td>
<td>130</td>
<td>nm</td>
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<tr>
<td>Pulse duration (FWHM)</td>
<td>15</td>
<td>22.5</td>
<td>fs</td>
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<td>FWHM beam diameter/Full aperture beam diameter</td>
<td>450/550</td>
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<td>mm</td>
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<td>Repetition rate</td>
<td>1</td>
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<td>pulse /min</td>
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<td>Strehl ratio</td>
<td>0.8</td>
<td>0.95</td>
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<td>Pointing stability</td>
<td>2</td>
<td>5</td>
<td>μrad</td>
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<tr>
<td>Beam height to the floor</td>
<td>1500</td>
<td>1510</td>
<td>mm</td>
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10 PW Laser System Layout

- High performance parameters: 250 J in 25fs, 0.9 Strehl ratio, <10^{-13} contrast
- Outputs: 2x 10 PW/min
  2x 1 PW/1 Hz
  2 x 0.1 PW/10 Hz

Station E4
0.1 PW

Station E5
2x1 PW

Stations E1 and E6
2x10 PW

Station E7
Laser-gamma
1-10 PW

Front end
Laser arm 1
Laser arm 2

70 m
Thales at Elancourt France has reported the performance.

- **Simulation and Results**
  - Simulation result:
    - 16mJ
    - 77nm FWHM
  - Experimental result:
    - 11.6mJ (< 1.6% rms over 500 shots)
    - 67nm FWHM
We expect to have $10^{13}$ contrast ratio.

$E_{-40ps:-0.4ps} = 30$ mJ
Typically the peak intensity is set at $10^{15} - 10^{16}$ W/cm$^2$ on the plasma mirror.
New 10 PW LBTS design
Gamma Beam System

RF Photoinjector
Components of Gamma Beam System

1) **Warm electron RF Linac** (innovative techniques)
   - multi–bunch photogun (32 e− microbunches of 250 pC @100 Hz RF)
     - 2 x S–band (22 MV/m) and 12 x C–band (33 MV/m) acc. structures
     - low emittance 0.2 – 0.6 mm·mrad
     - two acceleration stages (300 MeV and 720 MeV)

2) **High average power, high quality J–class 100 Hz ps Collision Laser**
   - state–of–the–art cryo–cooled Yb:YAG (200 mJ, 2.3 eV, 3.5 ps)
   - two lasers (one for low–Eγ and both for high–Eγ)

3) **Laser circulation with µm and µrad and sub–ps alignment/synchronization**
   - complex opto/mechanical system
   - two interaction points: $E_\gamma < 3.5$ MeV & $E_\gamma < 19.5$ MeV

4) **Gamma beam collimation system**
   - complex array of dual slits
   - relative bandwidths $< 5 \times 10^{-3}$

5) **Gamma beam diagnostic system**
   - beam optimization and characterization: energy, intensity, profile
### GBS Specification

<table>
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<tr>
<th>Parameter [units]</th>
<th>Value</th>
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<tr>
<td>Photon energy [MeV]</td>
<td>0.2 – 19.5</td>
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<tr>
<td>Spectral density [ph/s/eV]</td>
<td>&gt; 0.5 x 10^4</td>
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<tr>
<td>Bandwidth</td>
<td>&lt; 0.5 %</td>
</tr>
<tr>
<td># photons / shot FWHM bdw.</td>
<td>1.0 – 4.0 x 10^5</td>
</tr>
<tr>
<td># photons/sec FWHM bdw.</td>
<td>2.0 – 8.0 x 10^8</td>
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<tr>
<td>Source rms size [µm]</td>
<td>10 – 30</td>
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<tr>
<td>Source rms divergence [µrad]</td>
<td>25 – 250</td>
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<tr>
<td>Peak brill. [N_ph/sec mm^2 mrad^2 0.1%]</td>
<td>10^{22} – 10^{24}</td>
</tr>
<tr>
<td>Radiation pulse length [ps]</td>
<td>0.7 – 1.5</td>
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<tr>
<td>Linear polarization</td>
<td>&gt; 95 %</td>
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<tr>
<td>Macro repetition rate [Hz]</td>
<td>100</td>
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<tr>
<td># of pulses per macropulse</td>
<td>&gt; 31</td>
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<tr>
<td>Pulse–to–pulse separation [ns]</td>
<td>16</td>
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![Diagram showing the number of photons/s after a collimator and pulse separation](image)
• We will focus on the characterization of each machines: 10PW laser and 19 MeV Gamma beam systems.

10 PW Laser System
• Laser intensity: $10^{22} \text{ W/cm}^2$
• Electron acceleration > GeV
• Proton acceleration > 200 MeV

Gamma Beam System
• Gamma photon energy calibration-Nuclear excitation 3.5 or 19.5 MeV
• Polarization > 95%
Day 1 Experiments with 10 PW

- Radiation Reaction: Classical to QED
- Photo Nuclear Reaction
- Ion Stopping & Excitation in Plasmas
- Fission Fusion Mechanism: r process $^{232}$Th
- Dark Matter Physics
- Vacuum Birefringence
- Photo-excitation of isomers

Etc.

Romanian Report in Physics 68 Supplement 2016
New Horizons

Fission-fusion
Dark matter
Radiation effect
Nuclear Resonance
Gamma Imaging
Material Science
Medical Isotopes

Astrophysics
Astrophysics
Biology
Nuclear Physics
Nuclear Security
Fusion Reactor Eng.
Cancer Therapy
Proton >200 MeV is possible.

Predicted proton energy for LP and CP I=10^{22} W/cm², 0.2 µm CH₂ target

(Psikal et al J Phys Conf 2016)
Tens of % gamma conversion efficiency in µm-thick plastic or dense gas targets

GeV dense ion bunch acceleration using same setup with thinner targets

Plasma mirror + baffle for protection against laser back-reflection, debris

We consider also membrane protection for the parabola
Path to Extreme pressures by irradiation of aligned nanowire arrays

Sun Core
240 Gbar

Nanowire array plasma
I = 1 x 10^{22} W cm^{-2}

NIF Implosion
150 Gbar

A Pukhov Heinrich Heine Univ., Germany
Nanoscale Ultradense Z-Pinch

Longitudinal current distribution

4/14/2017
pukhov@tp1.uni-duesseldorf.de

A Pukhov Heinrich Heine Univ., Germany
Astrophysical r process: waiting point N=126

- r process:
  - path for heavy nuclei far in 'terra incognita'
  - astrophysical site(s) still unknown:
    - waiting point N=126: bottleneck for nucleosynthesis of actinides
    - last region of r process ‘close’ to stability
Nonlinear QED may be confirmed.

Led by Dr. Keita Seto

ELI-NP Research Activity 5
Fundamental Phys.

Laser Light
Gamma Radiation
Pair Production

Electron
Vacuum perturbation

Led by Dr. Keita Seto
We may expect to see the drastic down shift in Electron spectrum.

G Sarri, Queens’ Univ. Belfast, UK.
**Commissioning laser experiment schedule**

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**Assumes 10 PW LBTS commissioning by Q3 2019**
**1 PW “Laser performance” experiment in Q4 2018**
**10 PW experiments paced by LBTS delivery and installation to ~Q1 2020**
Li problem: cosmological & theoretical

- BBN predicts the abundances of light elements \(^4\)He, \(^{3}\)He, and \(^{7}\)Li
- good agreement between calculated and observed abundances for all light nuclei except for \(^{7}\)Li
- factor of 3-4 discrepancy between the calculated and the observed abundance of \(^{7}\)Li.

- Li-7 made by the mirror alpha capture reactions \(^{3}\)He(\(\alpha,\gamma\))\(^{7}\)Be and \(^{3}\)H(\(\alpha,\gamma\))\(^{7}\)Li
- theoretical models could provide the capture cross section at lower energies where experiments are not possible
- good agreement with measurements of \(^{3}\)He(\(\alpha,\gamma\))\(^{7}\)Be
- no agreement with measurements of Brune et al for \(^{3}\)H(\(\alpha,\gamma\))\(^{7}\)Li

from Neff et al, PRL 106, 042502 (2011)
ELISSA — ELI Silicon Strip Array

- silicon array would make it possible to measure reactions on solid targets
- good energy resolution, almost 100% efficiency, small thresholds
- successfully designed and applied to nuclear astrophysics, e.g. ORRUBA
- array developed in collaboration with INFN-LNS, Catania

- 3 rings of 12 position sensitive X3 silicon-strip detectors (1000 μm) by Micron
- 2 end cap detectors from 4 QQQ3 segmented detectors by Micron (300 μm)
- 512 channels readout with standard DAQ or GET electronics
Experiments with high-brilliance gamma beams at ELI-NP


Photodisintegration ($\gamma$,n), ($\gamma$,p), ($\gamma$,α) – Rom. Rep. Phys. 68, S699 (2016)


Instrumentation for Physics

ELIADe array: 8 segmented HPGe Clover detectors with anti-Compton shields + 4 LaBr3 detectors

Gamma above neutron threshold (GANT)
Commissioning GBS experiment schedule

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<td>Components Delivered</td>
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<td>Components Delivered</td>
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Radioisotopes play a crucial role in nuclear medicine being used for the diagnosis and the treatment of ones of the most spread diseases: the cancer and the cardiovascular disease.

Medical radioisotopes have a limited lifetime, the production centers and the clinics should be placed relatively close one to each other.

The main medical radioisotopes are produced in nuclear reactors (ex. $^{99m}$Tc) the production could be affected by long maintenance periods, safety issues, etc. (see the Tc crisis from 2009).

An important part of medical radioisotopes are produced in cyclotrons (ex. $^{11}$C, $^{13}$N, $^{15}$O, $^{18}$F). Cyclotrons have big dimensions (and price) they could deserve a relatively small amount of hospitals concentrated in the big cities.

Alternative technologies are a necessity.
Could **High Power Lasers** play a role in this field?

Lasers provide a flexible way for reaching different characteristics of the accelerated particle beam (type of particle, energy spectrum, etc) based on different targets.

Laser-based particle beams have big density ➔ many activations/shot produced.

Acceleration field more intense than at accelerators and less shielding against radiation is needed ➔ potential for size reducing.

The actual challenges are related to the “quality” of the proton beam, the repetition rate and the size minimization.

Many synergies with cyclotron-related isotope production and with laser-related physics experiments.
The Production Next Door

In laser based systems the shielding against radiation is needed only after laser-target interaction, in a much smaller volume/space than in the case of cyclotrons. Possibility of producing short-live isotopes with small laser-based accelerators and deserving hospitals far away from the big cities.

Very short lived isotopes such as $^{15}$O ($T_{1/2} = 122 s$ !) from $^{15}$N(p,n)$^{15}$O are hardly accessible by conventional cyclotrons. They could be produced in the future with “table-top” lasers at dedicated production centers inside clinics.
Be part of this great adventure, join our team!
Acknowledgment

• A Pukhov  Heinrich Heine University
• A Zilges  University of Cologne
• M LaCognata  INFN-LNS, Catania
• All the co-authors from Technical Design Report and Romanian Report in Physics 2016
Summary

• ELI-NP is under active implementation. 10 PW laser beam will be available in June 2019. 3 MeV and 19.5 MeV gamma beams in June 2019.

• Fission-fusion, Non linear QED, Plasma Physics, Dark Matter Physics, and Applications to Bio and Medical fields are to be tested.

• This experimental platforms can offer excellent opportunities to young scientists to test their original ideas.

• Your proposal is welcome. You can talk to me first.
Thank You Very Much for Your Listening

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Document edited by
Horia Hulubei National Institute for Research and Development in Physics and Nuclear Engineering
Publication date of the document: August 2013

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