ELI-NP Experimental Capabilities Update

Dan Stutman for the ELI-NP Team

US-ELI JOINT WORKSHOP September 2019
ELI-NP: two extreme light sources in one facility

- High power laser system: 2 x 10 PW maximum power  (March 2019)
- High intensity gamma beam system: high brilliance & variable energy up to 20  MeV (2022)
- 8 experimental areas: laser + laser, gamma, laser +gamma
- Workshops, laboratories, offices, guest house, cafeteria
- International research center with many surrounding physics institutes
High Power Laser System
2x10 PW (1 pulse/min)
2x1 PW (1 Hz)
2x0.1 PW (10 Hz)

Labs + shops + user rooms

10 PW E1 “Nuclear Physics”
10 PW E6 “QED”

10 PW E7 “Laser-gamma”

E8 “Gamma nuclear-reactions”

Gamma Beam System

GBS control/laser rooms

E2 “Gamma NRF”
E3 “Gamma positron source”
E4 0.1 PW “Applications”
1 PW E5 “Material sciences”
10 PW E7 “Laser-gamma”

f=30 m

80 m
Heavily shielded, vibration free experimental building specially designed for laser-based nuclear physics experiments

- Shielding for high energy nuclear radiation
- 120,000 ton, ±1 µm @ 10 Hz stable “optical table” made of 1.5 m thick concrete
Long term scientific directions

- *Exotic Nuclear Physics and astrophysics*
- *Nuclear Physics experiments to characterize laser – target interaction*
- *Photonuclear reactions*
- *QED and fundamental physics*
- *Applied research*

*Start of operations: laser experiments gradually 2019-2020, gamma experiments 2023*
High Power Laser System (HPLS)
High Power Laser System designed and built by Thales, France

HPLS
- Oscillator + OPCPA + XPW
  - 10mJ@10Hz / <20fs

100TW compressor
- 100TW amplifier
  - Ti:Sapphire
  - 2.5J@10Hz / <25fs

100TW amplifier
- Ti:Sapphire
  - 25J@1Hz / <25fs

1PW compressor
- 1PW amplifier
  - Ti:Sapphire
  - 25J@1Hz / <25fs

10PW amplifier
- Ti:Sapphire
  - 220J@1shot/min

LBTS
- E4: 2x0.1PW, 10Hz experiments
- E5: 2x1PW, 1Hz experiments
- E6: 2x10PW, 1shot/min QED experiments
- E7: Combined laser-gammas experiments

GBS

E1: 2x10PW, 1shot/min Nuclear Physics experiments
Key laser components successfully manufactured

ATLAS 100 J pump laser

OPCPA Front End

Meter size compressor gratings

Ti:Sa crystals

200 mm
December 2018 – The two arms integrated
March 2019 – 10PW laser beam demonstration

Near field beam profile recorded at output of the last amplifier running at 327J

Pump energy limited at 80% of the total capacity on last amplifier
March 2019 – 10 PW laser beam demonstration

- Good temporal contrast: $10^{-13}$ on hundred ps scale, $10^{-12}$ on ps scale
- Few microradian pointing stability
Energy and duration of 10 PW output measured at full beam size

- HPLS amplifier A1
- HPLS amplifier A2
- HPLS amplifier A3
- Calibrated energy meter

8x SAGA  →  HPLS amplifier A1  →  Front - End

6x GAIA  →  HPLS amplifier A2

8x ATLAS 100  →  HPLS amplifier A3

Diagnostic bench

Pulse duration $\tau = 22.3$ fs

Compressor efficiency $\eta = 0.742$

Energy before compressor $E = 327$ J

$P = \eta E / \tau = 10.8$ PW
April 2019 – Stable amplification demonstrated also in second 10 PW beam

Near field beam profile recorded during long term test over 90 minutes:

- Average energy 300J
- RMS stability < 2%

- High Power Laser System commissioning nearing completion
- Soon ready for experiments
Laser Beam Transport System (LBTS)
LBTS designed by ELI-NP and built by Thales and ALSYOM, France

- 2x10 PW beams + 1 PW/1Hz auxiliary beam to any of three experimental areas
- f=30 m F/50 mirror for electron LWFA at 10 PW
- 1 PW deformable mirror, provision (turning box) for 10 PW deformable mirror
LBTS construction nearing completion, soon commissioning

Utilities & vacuum in the basement

2 m

f = 30 m
Meter-size 10 PW beam transport mirrors finalizing construction

- Acquisition of 10 PW focusing mirrors ongoing (tender on-line now)

February 2019
Laser experimental areas
Laser driven experiments

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

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

- **Strong-field QED**
  - 10 PW laser + solid target
  - 10 PW laser + GeV LWFA electrons
  - PW $\gamma$-source "QED plasma"
  - Radiation reaction Breit-Wheeler pairs
  - QED vacuum

"Commissioning"

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
  - Neutron-rich nuclei

Goals of commissioning experiments:
- physics based validation of laser experiments system at full power
- start developing particle beams for nuclear physics and QED experiments
Construction of 10 PW E1 and E6 interaction chambers nearing completion

- Two identical Al chambers of 5 x 4 meters
- Floor supported Al optical tables for vibration insulation
- Wide range of 2x10 PW optical setups possible
Installation of 2x0.1 PW E4 experimental area to be completed Nov 2019

Designed for experiments with multiple laser beams in ultrahigh vacuum (e.g. axion search) and for applications (e.g. X-ray phase contrast imaging)
Installation of 2x1 PW E5 experimental area to begin Dec 2019

- Designed for material science and biomedical experiments with simultaneous mixed radiation fields
- 2x1 PW/1Hz synchronized beams to any of the vacuum chambers
E5 optical layout designed for simultaneous electron and ion beams
ISAB approved commissioning experiments - physics based validation of entire experimental system at full power

- **10 PW E1 - solid target experiments:**
  - Demonstrate extreme focal intensity through laser-$\gamma$ conversion ("$\gamma$-flash")
  - Demonstrate 200 MeV proton acceleration (neutron generation add-on)
  - Dense ion beams for nuclear physics

  All experiments use a single setup with only target thickness changed

- **10 PW E6 - gas target experiments:**
  - 10 PW laser wakefield acceleration of GeV electron beams

- **1 PW E5 - solid + gas target experiments:**
  - Benchmark TNSA proton acceleration
  - Benchmark LWFA electron acceleration

- Experiments to be performed by ELI-NP researchers and international expert users
E1 10 PW solid target commissioning setup

**Target**
0.1-10 µm CH foils or liquid crystal film

**Instrumentation**
Laser/target alignment system
Plasma mirror
CsI energy-resolved calorimeter array
Forward-gamma spectrometer
Optical Probe
Thomson Parabola
Passive: RCF, CR39/IP, Activation

**Detection**
All-optical (scintillators + FO)
*Muon detector to confirm GeV gammas*

*Instrumentation will also be available to users for “Day-1” experiments*
E6 10 PW gas target commissioning setup

Instrumentation
- 5 GeV in-vacuum electron spectrometer
- Laser beam diagnostics
- Probe beam plasma diagnostic
- NIR to UV spectroscopy
- Optical beam dump
- Variable length (1-5 cm) gas cell target
US scientists already have key roles in the ELI-NP commissioning experiments

A Arefiev, F Beg (UCSD) – Laser-gamma conversion
D Gordon (NRL) – 10 PW LWFA theory
K Krushelnick (U Michigan) – 10 PW LWFA experiment
D Schumacher (OSU) – Liquid crystal plasma mirror & target
S Regan (LLE) – Plasma diagnostics

*Wake and Beam Phase Space after 5 cm LWFA at 10 PW*
D Gordon, NRL, State Department Science Fellows Program
Gamma Beam System (GBS)
Nuclear Physics with Gamma Beam System

ELI-NP Gamma Beam System:
- Inverse Compton scattering
- < 20 MeV energy
- ≤ 0.5% bandwidth
- ~10^4 $\gamma$/s/eV,
- ≥ 95% linearly polarized

Status: under contracting

Nuclear Physics:
- Nuclear Resonance Fluorescence (NRF)
- Giant/Pigmy Dipole Resonances (GANT)
- Photodisintegration ($\gamma,n$), ($\gamma,p$), ($\gamma,\alpha$)
- Photofission ($\gamma,ff$)

Applications:
- Nuclear forensics
- Material science with positron beams,
  industrial and medical application
Gamma experimental areas
Detectors and EDAQ ready
Mechanical structure ready

Ready for experiments – December 2019

Self-absorption measurements ($\Gamma_0/\Gamma_1$)
Low-energy dipole response (e.g. Actinides)
Dipole response and parity measurements for weakly-bound nuclei
Investigation of the Pigmy Dipole Resonance
Rotational $2^+$ states of the scissor mode
Constraints on the $0\nu\beta\beta$-decay matrix elements of the scissors mode decay channel: $^{150}$Sm

Gamma: 8 segmented Ge Clover det.
4 LaBr$_3$(Ce) det.
$(\gamma,n)$ cross sections measurements – ELIGANT-TN

**Neutron:** \(28^3\text{He detectors}\)

**Systematics of the photonuclear C.S. measurements**

- Most of the photoneutron cross section measurements were performed in period 1962 – 1986 using quasi-monochromatic annihilation – QMA photons using positron in flight annihilation at two major facilities:
  - Saclay (France)
  - Lawrence Livermore National Laboratory (USA)
- Large discrepancies in $(\gamma,\text{n})$ c.s. measured at the two facilities:
  - $(\gamma, 1\text{n})$ c.s. are generally noticeably larger at Saclay than at Livermore
  - $(\gamma, 2\text{n})$ c.s. are generally larger at Livermore than at Saclay.

No systematic way to resolve the discrepancies: New and reliable measurements are required!
Detectors and EDAQ ready
Mechanical structure ready
Ready for experiments – December 2019

ELIGANT-GN

Gamma : 30 LaBr₃ and CeBr₃
Neutron: 20 ⁷Li glasses
30 Liquid Scint.

Day ONE:
- studies of GDR and PDR decay (⁹⁰Zr, ²⁰⁸Pb)
- combine with information from (γ,n) experiments
- combine with information from (γ,γ') experiments (e.g. Polarization)
- γ-decay to gs and excited states as a function of excitation energy

Giant Dipole Resonance measurements – ELIGANT-GN
Supporting laboratories
ELI-NP Targets Laboratory capabilities

**Deposition techniques**
- UHV RF/DC sputtering
- UHV e-beam evaporation

**Structuring techniques**
- Optical/ electron beam lithography
- Reactive ion etching/ Ar ion milling

**Characterization**
- Scanning Electron Microscope / EDS, EBSD detectors
- X-ray Diffractometer
- Optical Profilometer
- Atomic force microscope
Production of nano/μ-structured targets and of free-standing targets has begun.

- **Free-standing C film (15 nm)** on Cu grid for high-power laser ion acceleration.
- **Plastic microspheres on Si substrate** for enhanced laser absorption, on the front side of the target.
- **Au and Cr (right) nano-dots** fabricated by electron beam lithography (EBL).
- **Si diffraction gratings** (500 nm height) for front side laser absorption amplification.
- **Metallic gratings** (Au, Cr, 600 nm height) for front side laser absorption amplification.
- **Elemental composition and mapping** with Energy Dispersive Spectroscopy (EDS).
- **Phase composition** in Scanning Electron Microscopy.
Additional laboratories and workshops ready to assist user experiments

- Optics Laboratory
- Diagnostics Instrumentation Laboratory
- Dosimetry Laboratory
- Detectors Laboratory
- Radiobiology Laboratory
- X-Gamma Optics Laboratory
- Mechanical workshop
- Vacuum workshop
- Electronics workshop
Timeline and milestones

High power lasers

- **HPLS contract signed**: 6/11/2013
- **LBTS contract signed**: 12/21/2017
- **HPLS starting of commissioning**: 2/25/2019
- **HPLS 10 PW demonstration**: 3/13/2019
- **HPLS testing completed**: 2019
- **LBTS installation ready**: 11/25/2019

2020

- **100 TW interaction chambers**
- **1 PW interaction chambers**
- **10 PW interaction chambers**
- **ELIGAN-TN ready**
- **ELIGANT-GN ready**

2021

- **1 PW final optics commissioning experiments**
- **10 PW final optics commissioning experiments**

2018 - 2023

- **All gamma beam experimental setups ready**
- **Gamma beams commissioning experiments**
10 PetaWatts, World Premiere at ELI-NP Măgurele High Power Laser

1st ELI-NP User Workshop
October 7th-11th, 2019
Măgurele-Bucharest, Romania

Useful information

Dates:
October 7-11th / Magurele (Bucharest), Romania

Format of the workshop:
The workshop will consist of two main sections. The first one (Mon-Wed) is dedicated to experiments based on the high-power lasers. The second one (Wed-Fri) is dedicated to experiments based on the high intensity gamma photon beams.

Each of the sections will comprise presentations of the status of implementation and the capabilities of the equipment in the facility, aims of the commissioning experiments, and contributed talks by external researchers presenting new ideas for future experiments at ELI-NP.

Round-table discussions and a visit to the experimental areas of the facility will allow for a better understanding of the experimental capabilities and a fruitful exchange of ideas between the

Organizing Committee
Kazuo A. Tanaka, Scientific Director
Calin A. Ur, Technical Director
Dimitor L. Babanski
Dan Stutman
Ioan Dancus
Marian Toma
Ovidiu Tesleteanu
Catalina Oprea, Workshop secretary
Alexandra Carlig, PR
Laurentiu Serban, IT

Important Dates

October 7 – 11, 2019
First User Workshop for Commissioning and Day-1 experiments @ELI-NP
Summary

• The implementation of ELI-NP is progressing well

• First laser experiments to begin Dec 2019

• US scientists already have key roles in ELI-NP commissioning experiments

• Strong US presence at 1st ELI-NP User Workshop

• US researchers can make breakthrough science at ELI-NP
How to Measure Extreme Light?

Ultra intense $\gamma$ source

Solid target conversion efficiency

Gamma spectra

P McKenna et al, ELI-NP TDR2

J. Fuchs @ ELI-NP

- Goal: demonstrate extreme focal intensity of 10 PW lasers
- Tens of % laser-$\gamma$ conversion efficiency in low-Z target (PW gamma source)
- Scale conversion efficiency with nominal intensity
How to Measure Extreme Light?

Measurement methods/detectors from nuclear spectroscopy

- Few micron thick plastic target
- Intensity scaling of laser-γ output by scanning target through focus
- Energy and angle resolved gamma detectors
- Plasma mirror for debris and laser back-reflection protection
Studies under Extreme Conditions

**Strong-field QED**

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

**Radiation Reaction**

- QED theory verified to high precision in weak fields but never in strong fields
- BW process (light + light -> matter) yet to be experimentally proved

G. Breit and J.A. Wheeler, Phys. Rev. 46 (1934) 1087
Laser Driven Neutron Sources

Path to Extreme pressures by irradiation of aligned arrays of nanowires
→ Ultrahigh-energy density physics

A.Pukhov, Heinrich Heine Univ.

Deuterated nanowires arrays  D-D fusion
intense high energy neutron bursts

\[ I = 10^{19} \text{ W/cm}^2, \ 60 \text{ fs}, \text{ ultrahigh contrast} \ > 10^{11} \]
\[ E_n = 2.45 \text{ MeV} \]
→ n-flux = 2.2 × 10^6 n/J/shot

In the wires: 10 Gbar  – pressure
2 GJ/cm³ – thermal energy density