A characterization system for the monitoring of ELI-NP gamma beam

University of Florence and INFN

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Outline

0 Characterization System for ELI-NP $\gamma$ beam

1 Compton Spectrometer

2 Nuclear Resonant Scattering System

3 Gamma Profile Imager

4 Gamma Calorimeter
Characterization System for ELI-NP $\gamma$ beam

1. Compton Spectrometer

2. Nuclear Resonant Scattering System

3. Gamma Profile Imager

4. Gamma Calorimeter
ELI: Extreme Light Infrastructure

**ELI-ALPS**
*Hungary*
Investigation of ultrafast dynamics at attosecond and nm spatiotemporal scales

**ELI-NP**
*Romania*
Ultra-intense laser and gamma ray pulses enabling photonuclear studies

**ELI-Beamlines**
*Czech*
Applications of high brightness sources of energetic particles and x-rays
**ELI-NP**: Extreme Light Infrastructure - Nuclear Physics

ELI-NP will study a wide range of research topics in fundamental physics, nuclear physics and astrophysics, and also applied research.

1. **High Power Laser System**: (HPLS)
   - 2x10 PW Laser System
   - Focused laser intensity can reach $10^{23}$ W/cm$^2$

2. **High Intensity Gamma Beam System**: (GBS)
   - *Production method*: laser photons Compton inverse scattered on high energy electrons
   - Two energy lines
The source of ELI-NP $\gamma$ beam

Inverse Compton radiation is not intrinsically monochromatic

$$E_\gamma \sim E_L \cdot \frac{4\gamma_e^2}{1 + a_0^2/2 + \gamma_e^2\theta^2} \cdot (1 - \Delta)$$

- $a_0$, laser parameter
- $\Delta \sim (4\gamma_e E_L)/mc^2$

Collimation system

- Stack of 14 slits with aperture independently adjustable (0-25 mm)
- Each slit composed of two $40 \times 40 \times 20$ mm Tungsten blocks.

Gamma beam energy distribution vs collimator aperture
## The requirements of ELI-NP γ beam

<table>
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<tr>
<th>Requirement</th>
<th>Specification</th>
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<td>Bandwidth</td>
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<td>Average diameter of beam spot</td>
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<tr>
<td>Peak brilliance [N_{ph}/s·mm^2·mrad^2·0.1%]</td>
<td>10^{22} – 10^{24}</td>
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<td>Linear polarization</td>
<td>&gt; 90 %</td>
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**Gamma Beam Characterization System:**

Give a measurement of the gamma beam characteristics.
The requirements of ELI-NP $\gamma$ beam

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**Gamma Beam Characterization System:**

Give a measurement of the gamma beam characteristics.

![Diagram showing pulse and bandwidth](image-url)
Two Characterization System:

- low-energy line ($E_\gamma < 3.5$ MeV)
- high-energy line ($E_\gamma < 19.5$ MeV)

This talk is about the low energy line characterization system.
A specific system equipped with **four detectors** has been developed to *measure* and *monitor* the beam parameters during the commissioning and the operational phase.
Next Section

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4 Gamma Calorimeter
Compton Spectrometer (CSPEC)

CSPEC is used for online energy spectrum monitor, using a non-destructive method.
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CSPEC is used for online energy spectrum monitor, using a non-destructive method.

**Working Principle**

The basic idea is to measure the energy ($T_e$) and the scattering angle ($\phi$) of electrons recoiling at small angles from Compton interaction of the beam on a micrometric target (1-100\(\mu\)m).

\[
E_{\text{beam}} = \frac{m_e \cdot T_e \cos(\phi)}{\sqrt{T_e \cdot (T_e + 2m_e)} - T_e}
\]

- $T_e$: measured with HPGe detector
- $\phi$: determined by a double sided strip detector
- The scattered gamma is acquired for trigger purpose
Energy reconstruction: Expected performance

### Peak energy

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Detector resolution on measurement of peak energy and bandwidth ≤ 0.5%, then better than the beam bandwidth.
Energy reconstruction: Expected performance

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Detector resolution on measurement of peak energy and bandwidth $\leq 0.5\%$, then **better than the beam bandwidth**.
The HPGe detector, chosen for its excellent energy resolution, will measure the energy of the scattered electron.

Detector design:
- The HPGe crystal is built in a planar custom configuration by CANBERRA:
  - 80 mm, diameter
  - 20 mm, thickness
  - electrically cooled
- To minimize the energy loss:
  - 100 µm, cryostat Be-window thickness
  - ≤ 1 µm, electrical contacts
HPGe detector tests

Energy resolution

Energy resolution at 1332 keV:

\[ R_E = \frac{\text{FWHM}}{E} = 0.157 \pm 0.002 \% \]

Electron source test

Verified the accuracy of Monte Carlo simulation using electrons of definite energy emitted by \(^{207}\text{Bi}\) source.

The measured peak positions are in agreement with the simulated ones with a precision better than 1 keV.
The angle of the Compton scattered electron is determined by double-sided silicon strip detector.

Detector design:
- Silicon strip detector produced by Hamamatsu
  - $5.33 \times 7 \text{ cm}^2$
  - 300 $\mu\text{m}$ thickness
- 1024 strips for each view implanted along orthogonal directions
- readout by VA1 chip, with 128 charge sensitive amplifiers
- Impact point resolution:
  - 3 $\mu\text{m}$ on the junction side ($x$-view)
  - 11 $\mu\text{m}$ on the ohmic side ($y$-view)
Si-strip preliminary test with cosmic rays

Cluster characteristic:

- Cluster inclusion cuts
  - seed: $S/N > 10$
  - neighbours: $S/N > 3$

- Cluster Multiplicity - y view
  - $\mu = 2.90 \pm 0.03$

Cluster Signal/Noise:

\[
\left(\frac{S}{N}\right)_{\text{cluster}} = \sum_{i=1}^{m} \frac{S_i}{\sigma_i}
\]

- Y-view: larger noise, due to a greater capacitance
CSPEC: the BaF$_2$ detectors

The scattered photon is detected, in coincidence with the electron, by BaF$_2$ crystals to provide a trigger for the CSPEC data acquisition. This coincidence is very effective in suppressing the background.

Detector design:

- Small calorimeter made of a matrix of 4×4 BaF$_2$ crystals (1.2×1.2×5 cm$^3$)
- Read out by a multianode PMT manufactured by HAMAMATSU (H12700 model)
- BaF$_2$ has two scintillation components:
  - fast: $\tau = 0.6 - 0.8$ ns
  - slow: $\tau = 630$ ns
The BaF$_2$ detectors tests

- Signal shape identification

![Graph showing the signal shape identification with energy levels and acceptance regions.]

- Typical detector signal

![Graph showing the typical detector signal with ADC channels and time scales.]

The intrinsic radioactivity of BaF$_2$, originated from natural $^{226}$Ra impurities, can be used to self-calibrate the detector.
The BaF$_2$ detectors tests

- Signal shape identification

- Typical detector signal

The intrinsic radioactivity of BaF$_2$, originated from natural $^{226}$Ra impurities, can be used to self-calibrate the detector.
Characterization System for ELI-NP $\gamma$ beam

Compton Spectrometer

Nuclear Resonant Scattering System

Gamma Profile Imager

Gamma Calorimeter
NRSS has to provide an absolute energy calibration for GCAL and CSPEC.
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**Working Principle**
Detect the resonant $\gamma$ decays of properly chosen nuclear levels when the beam energy spectrum overlaps the selected level.

**Detector design**

**Target nuclear levels**

<table>
<thead>
<tr>
<th>$^A$X</th>
<th>$E_r$(MeV)</th>
<th>$\Delta E_r$(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6$Li</td>
<td>3.56288</td>
<td>$1.0 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$^{11}$B</td>
<td>2.124693</td>
<td>$2.7 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>4.43891</td>
<td>$3.1 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$^{27}$Al</td>
<td>2.21201</td>
<td>$10 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$^{27}$Al</td>
<td>2.98200</td>
<td>$5 \cdot 10^{-5}$</td>
</tr>
</tbody>
</table>
The NRSS $\gamma$ detector is made of a screened array of four $\text{BaF}_2$ crystals ($5 \times 5 \times 8 \text{ cm}^3$) surroundings a LYSO crystal ($3 \times 3 \times 6 \text{ cm}^3$).

Two operation modes

- **Fast Counting mode**: Use the $\text{BaF}_2$ fast response to provide a prompt information on the established resonant condition.

- **Energy mode**: Use LYSO crystal to perform a energy spectrum measurement. In this configuration the $\text{BaF}_2$ act as Compton shield.
Background rejection

- Photons with energy comparable with the signal → come out of time.

- NRSS at $\theta = 135^\circ$ to move away from signal energy region.

**Main problem:** pile-up of low-energy photons back-scattered from the target.

![Graph showing photon energy distribution with different categories: Compton-scattered, beam line scattered, and outside beam line.](image)
Background rejection

- Photons with energy comparable with the signal → come out of time.

- NRSS at $\theta = 135^\circ$ to move away from signal energy region. **Main problem:** pile-up of low-energy photons back-scattered from the target.

A peculiar technique based on dual readout of *Cherenkov* and *scintillation light* has been developed. The basic idea is to use only the signal which have both the light components.

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![Graph showing photon counts and energy distribution](image-url)

**In time background for a 3 MeV beam on a 0.25mm thick Al target**

Compton-scattered $\gamma$ energy at 135°

- From the target
- Scattered by the beam line
- From outside the beam line

**$S/N = 0.4$**

**$S/N = 990$**
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Gamma Profile Imager (GPI)

GPI has to provide an image of the beam spatial distribution to display the location and the uniformity of the beam.

- **Scintillator target** material placed at 45° with respect to the beam axis and hosted in a target holder which support interchangeable materials.

- The scintillator light is focused onto a **CCD camera** with a mirror and a lens system.
**GPI: the Scintillator target**

1. **The target material:**
   - good conversion efficiency (high density and thickness)
   - high-Z
   - good light yield

![Graph showing light emission vs scintillator thickness]

**LYSO scintillator crystal**
GPI: the Scintillator target

1. **The target material:**
   - good conversion efficiency (high density and thickness)
   - high-Z
   - good light yield

2. **The target thickness:**
   cannot be increased without losing resolution.

- Thickness: 300 µm
- Thickness: 700 µm

Selected thickness: 100-500 µm
GPI prototype testing and expected performances

An **analytical model** has been developed to work out an expression for the signal expected on the CCD as a function of the system configuration.

The **parameters** in the model were tuned with a set of **experimental tests** on a GPI prototype, using the radiation produced by an x-ray tube.

**Expected signal with the ELI-NP gamma beam**

<table>
<thead>
<tr>
<th>Beam energy [MeV]</th>
<th>Signal (gray level/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>305</td>
</tr>
<tr>
<td>3</td>
<td>2165</td>
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</table>

Far above the expected readout and thermal **noise of ~ 45** gray level.
Characterization System for ELI-NP $\gamma$ beam

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Gamma Calorimeter (GCAL)

The calorimeter has to provide a fast destructive measurement of the beam average energy and intensity.
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- **Problem**: the photon energy can not be derived simply from the total energy released.
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- **Problem:** the photon energy can not be derived simply from the total energy released.

- **Solution:** The beam energy can be estimated from the energy dependence of the $\gamma$ absorption cross-section for low-Z materials.

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![Graphs of absorption cross-section for Hydrogen (Z=1) and Lead (Z=82).](image)
Gamma Calorimeter

**Working principle**

In a light calorimeter the average energy of the beam can be measured by fitting the measured longitudinal profile against parametrized distributions. Once the photon energy has been known, the intensity is obtained from the total energy released.

**Expected Performances:**

Simulated energy release for $10^5\gamma$

![Graph showing energy release vs. layer number for different energy levels (1 MeV, 3 MeV, 5 MeV, 10 MeV, 20 MeV).]

Expected resolution on $N_\gamma$ and on $E_\gamma$ for $10^5\gamma$

![Graph showing resolution vs. energy for different energy levels (1 MeV, 3 MeV, 5 MeV, 10 MeV, 20 MeV).]
GCAL: Detector design

The sampling calorimeter is made by 22 identical layers of Polyethylene (PE) absorber interleaved with active Si-strip detectors.

- **PE absorber:**
  - 3 cm thickness
  - $8.8 \times 8.8 \text{ cm}^2$

- **Si-strip:**
  - test structure of the CMS tracker detectors, developed by Hamamatsu
**GCAL: One layer design**

- **Si-Strip technology:**
  - **Fast response**
  - **Radiation hardness:** can sustain up to 100 kGy irradiation
  - **Linearity**

- **Silicon detector:**
  - $10.32 \times 80.0$ mm$^2$ active area
  - $320 \mu$m thickness

- Si-strip sensors bonded together.

- Custom electronics.
GCAL: Time response test

**Very fast response** of detector and custom readout electronics optimized and tested with *infrared laser*

7 Si-strip sensors response to single laser pulse

Detector response to a train of 32 pulses separated by 16 ns, which reproduces the temporal structure of the ELI-NP gamma beam.

These tests prove the capability of our system to cope with the demanding time structure of the ELI-NP beam.
GCAL: Energy response

Test to verify silicon and electronics linearity has been performed at DEFEL facility at INFN-LABEC in Florence. A pulsed and intensity controlled 3 MeV proton beam was used.

Spectra are fitted with Poisson distribution convoluted with a sum of Gaussian.
Summary

• The beam characterisation and monitoring of the ELI-NP γ beam parameters is a challenging task.
• An overview of the four detectors composing the characterisation system has been presented:
  1. **Compton Scattering Spectrometer**: Energy distribution
  2. **Nuclear Resonant Scattering System**: Absolute energy calibration
  3. **Gamma Profile Imager**: Spatial distribution
  4. **Gamma Calorimeter**: Average energy and intensity
• All the sub-system have been designed and optimized from realistic simulations.
• Tests of each subsystem performed at INFN of Ferrara, Firenze and Catania have been reported.
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Next steps

Assembly the whole system for final tests in Ferrara.
Installation at ELI-NP Magurele, Bucharest.
1 Compton Spectrometer
INFN- Firenze

2 Nuclear Resonant Scattering System
INFN- Catania

3 Imager
INFN- Ferrara

4 Gamma Calorimeter
INFN- Firenze
Why characterization of the $\gamma$ beam is it important?

- A characterisation system providing the diagnostic of the $\gamma$ beam is essential for the **commissioning and development** of the source.

- A precise energy calibration of the gamma beam and a continuous monitoring of its parameters (peak energy, energy and space profile, intensity...) during **operation** are also necessary.

- Given the unprecedented characteristics of the beam, these tasks are themselves an experimental challenge.
Nuclear Physics with ELI-NP $\gamma$ beam

- **Nuclear Resonance Fluorescence (NRF) studies**

  - Connection of intrinsic level properties (width, spin, parity) to observables (cross section, angular distribution)

  - By using electromagnetic probes to study nuclear structure the interaction is well-known and one can determine in a model independent way the observables.

  - The high brilliance of the gamma beam will provide an increase in sensitivity leading to a reduction of the material required for the target.
Nuclear Physics with ELI-NP $\gamma$ beam

- **Studies of photo-fission**
  - The ELI-NP $\gamma$ beam provide a new-perspective for photofission research, as high-resolution studies become possible.
  - In particular the investigations of the fission potential-barrier landscape in the actinide nuclei.
  - Rare photofission events, such high-asymmetric fission or ternary fission will be investigated.

- **Production of exotic nuclear beams in photofission**
  - Studies of neutron-rich nuclei, lying away from the valley of $\beta$ stability, are the main topic of recent nuclear structure research.
  - Beams of such nuclei are produced with the isotope- separation on-line (ISOL) technique, or with the in-flight separation technique.
  - Photofission provides another possibility to create exotic nuclei in the laboratory.
Astrophysics studies

- Measuring capture reactions (astrophysical) by means of the inverse photodisintegration reactions (with the ELI-NP gamma beam), has the advantage of having different systematic uncertainties.
- Nuclear astrophysics needs highly accurate measurements of small cross sections for nuclear reactions of the H and He burning processes in order to enhance the reliability of stellar evolution models and simulations.
- Key reaction: $\gamma + ^{16}\text{O} \rightarrow ^{12}\text{C} + \alpha$

The ratio between the abundances of carbon and oxygen (C/O) at the end of this stellar evolution stage has been identified remains today, as one of the main open questions in nuclear astrophysics.
Nuclear Physics with ELI-NP $\gamma$ beam

- **Nuclear collective excitation modes**
  The brilliant ELI-NP $\gamma$-ray beam will open up new horizons for the investigation of the nuclear photo-response at and above the particle separation threshold.
Inter-calibration procedure

1. **Timing setting**
   - NRSS in FC mode + high-Z target

2. **Establish the resonant condition**
   - NRSS in FC mode + NRS target

3. **NRS redundant measurements**
   - NRSS in ES mode

4. **Cross Calibrations**
   - CSPEC + NRSS
   - CSPEC + NRSS + GCAL

5. **Change nuclear level and perform other measurements**

6. **Fit 2 or more resonances**

7. **Calibration check using a different resonance**

- Establish the correct delay between the beam trigger and signal at detectors.
- Scan the electron beam increasing and decreasing energy to find the resonance condition.
- Signal region + AC shield = energy meas
  Compton region = absolute intensity
- Absolute calibration of the CSPEC
  To reach good resolution in absolute intensity measurements.
- Get the correlation law between electron beam and gamma beam energies.
Barium Fluoride

- The fast scintillation light is emitted in the UV in bands centered at 220 and 195nm. The decay time of the fast component varies between 600 and 800ps.
- The BaF$_2$ also emits a relatively slow scintillation component in a band centered at 310nm. The decay time of this component has an average value of 630ns.
- The ratio between the intensity of the fast and the slow scintillation components of BaF$_2$ depends on the ionizing power of the absorbed particle. That allows gamma discrimination and particle identification by pulse shape analysis.