Monte Carlo simulation of a collimation system for low-energy beamline (1-5 MeV) of ELI-NP Gamma Beam System

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*EuroGammas*
The Extreme Light Infrastructure – ELI Project

ELI is a European Project, involving nearly 40 research and academic institutions from 13 EU Members Countries, forming a pan-European Laser facility, that aims to host frontier high-power lasers, as well as various radiation beam-lines (electrons, protons, x-rays and gamma rays) for different applications.

- **ELI-Nuclear Physics** (Bucharest, Romania): dedicated to the development of laser beams and the generation of high-intensity gamma beams for frontier research in nuclear physics.

- **ELI-Beamlines (med-biomed)** (Prague, Czech Republic)

- **ELI-Attosecond** (Szeged, Hungary)
EuroGammas for ELI-NP gamma beam system

One of the goals of ELI-NP infrastructure is the production of gamma beam (ELI-NP-GBS) using inverse Compton scattering of laser light from an accelerated electron beam for nuclear physics experiments.

- The gamma beam produced is expected to have:
  - Energy tunable in the interval between 1 MeV and 20 MeV,
  - Energy bandwidth $\Delta E/E < 0.5\%$,
  - About $10^8$ photons per second within FWHM

- EuroGammaS Association is composed by INFN, as leader, the Università degli Studi di Roma "La Sapienza", CNRS, ACP S.A.S., Alsyom S.A.S., Comeb Srl, ScandiNova Systems AB.

- EuroGammaS will provide the design, manufacturing, delivery, installation, testing, commissioning and maintenance of the Gamma Beam System (GBS), for the benefit of the ELI-NP project, managed by the Horia Hulubei National Institute for Physics and Nuclear Engineering Bucharest - Magurele, ROMANIA.
## ELI-NP gamma beam system parameter list

### Table 63: Gamma-ray beam for selected collision examples (from Start-to-end simulations)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy (MeV)</strong></td>
<td>2.00</td>
<td>3.45</td>
<td>9.87</td>
<td>19.5</td>
</tr>
<tr>
<td><strong>Spectral Density (ph/ps/eV)</strong></td>
<td>39,760</td>
<td>21,840</td>
<td>16,860</td>
<td>8,400</td>
</tr>
<tr>
<td><strong>Bandwidth (%)</strong></td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td># photons per shot within FWHM</td>
<td>1.210^5</td>
<td>1.110^5</td>
<td>2.610^5</td>
<td>2.510^5</td>
</tr>
<tr>
<td># photons/sec within FWHM</td>
<td>4.010^9</td>
<td>3.710^8</td>
<td>8.310^6</td>
<td>8.110^6</td>
</tr>
<tr>
<td>Source rms size (µm)</td>
<td>12</td>
<td>11</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Source rms divergence (µrad)</td>
<td>140</td>
<td>100</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Peak Brilliency (N0ν/sec/mm²/mrad² 0.1%)</td>
<td>9.110^11</td>
<td>1.910^22</td>
<td>1.810^23</td>
<td>3.310^23</td>
</tr>
<tr>
<td>Average Brilliency (N0ν/sec/mm²/mrad² 0.1%)</td>
<td>2.910^13</td>
<td>6.210^12</td>
<td>5.910^14</td>
<td>1.110^15</td>
</tr>
<tr>
<td>Rad. pulse length (rms, psec)</td>
<td>0.92</td>
<td>0.91</td>
<td>0.95</td>
<td>0.9</td>
</tr>
<tr>
<td>Linear Polarization (%)</td>
<td>&gt; 99.8</td>
<td>&gt; 99.8</td>
<td>&gt; 99.8</td>
<td>&gt; 99.8</td>
</tr>
<tr>
<td>Macro rep. rate (Hz)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td># of pulses per macropulse</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Pulse-to-pulse separation (nsec)</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Contrast ratio</td>
<td>1 / 2 / 3rd harmonic</td>
<td>1.510^5</td>
<td>8.510^4</td>
<td>7.010^4</td>
</tr>
<tr>
<td>Luminosity @ (1.0, 5) psec delay</td>
<td>(54.99, %)</td>
<td>(92.98, %)</td>
<td>(91.98, %)</td>
<td>(85.96, %)</td>
</tr>
<tr>
<td>Lumin. @ (5, 2) µm misalignment</td>
<td>(98.99, %)</td>
<td>(96.99, %)</td>
<td>(90.97, %)</td>
<td>(87.95, %)</td>
</tr>
</tbody>
</table>

### Gamma beam specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy</td>
<td>0.2-19.5 MeV</td>
</tr>
<tr>
<td>Spectral Density</td>
<td>0.8-4 10^4 ph/sec/eV</td>
</tr>
<tr>
<td>Bandwidth (rms)</td>
<td>≤ 0.5%</td>
</tr>
<tr>
<td># photons per shot within FWHM</td>
<td>≤ 2.6 10^6</td>
</tr>
<tr>
<td># photons/sec within FWHM</td>
<td>≤ 8.3 10^5</td>
</tr>
<tr>
<td>Source rms size</td>
<td>10 - 30 µm</td>
</tr>
<tr>
<td>Source rms divergence (µrad)</td>
<td>25 - 200 µrad</td>
</tr>
<tr>
<td>Peak Brilliance (N0ν/sec/mm²/mrad² 0.1%)</td>
<td>10^20 - 10^23</td>
</tr>
<tr>
<td>Radiation pulse length (rms, psec)</td>
<td>0.7 - 1.5</td>
</tr>
<tr>
<td>Linear Polarization (%)</td>
<td>&gt; 99 %</td>
</tr>
<tr>
<td>Macro rep. rate (Hz)</td>
<td>100</td>
</tr>
<tr>
<td># of pulses per macropulse</td>
<td>≤ 32</td>
</tr>
<tr>
<td>Pulse-to-pulse separation (nsec)</td>
<td>16 nsec</td>
</tr>
</tbody>
</table>

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**Technical Design Report**

EuroGammaS proposal for the ELI-NP Gamma beam System

With 73 tables and 230 figures

Inverse Compton radiation is not intrinsically monochromatic, the energy is related to the emission angle. The required energy band-width can be obtained only by developing specific methods of collimation of gamma beam.

\[ \Delta \theta \approx \frac{1}{\gamma} ; \quad \Delta \nu_\gamma \approx 50\% \]

\[ \approx \frac{n}{x} ; \quad \approx \left( \frac{2}{n} \right) \]

no red shift considered

Courtesy C. Barty - LLNL
To obtain the desired energy bandwidth < 0.5 % at 20 MeV a collimation at 40 μrad semi-divergence is needed, demanding a very challenging design. These divergence corresponds to collimation apertures that varies from few mm to less than 0.7 mm, depending on the distance IP-CS and on the selected beam energy.

Main requirements of the collimation system:

- Low transmission of gamma photons (high density and high atomic number)
- Continuously adjustable aperture (to adjust the energy band-width in the entire energy range)
- Avoid contamination of the primary beam with production of secondary radiation
Low energy collimation system in a vacuum chamber
All movement are synchronized and servocontrolled
Fine adjustment in X, Y, θ and Φ
Low energy collimation system composed by two elements of six slits
COLLIMATION ELEMENT

- Fixing frame and block guide
- Stepping motor
- Treaded rod
- W block (4 x 2 x 2 cm³)
MC simulation for LE (~5 MeV)

2 mm (200 pixels × 10 µm)

Simulated radiography of the collimator assembly (log scale)

3D plot
MC simulation for HE (~19.5 MeV)

Simulated radiography of the collimator assembly (log scale)

3D plot
Alignment accuracy for the collimation system structure at HE (~19.5 MeV)

5 µrad

50 µrad

100 µrad

200 µrad

(angles with respect to the center of the structure)
MC simulations of collimation system

- In order to define the specifications and to design the collimation system for the low-energy beamline (1-5 MeV), a detailed MC simulation activity has been carried out using **MCNPX and Geant4**.

- The simulation consists in transporting a realistic gamma beam produced in the IP through the vacuum pipes and chambers, the collimation system and the concrete shielding.

- The gamma beam used as input was obtained performing a simulation of the interaction transported electron beam with the laser pulse using CAIN (Petrillo, Drebot, Curatolo)

- Performed simulations of beam with energies of **2.5 and 5.0 MeV**
MC simulations geometry

Accelerator Bay Wall

Gamma beam

Concrete shield

Scoring Screen

Collimation system
5 MeV collimation results (MCNPX)

![Graph showing photons distribution before and after collimation]

CAIN output

After collimation
5 MeV collimation results (MCNPX and Geant4)

- Collimation aperture corresponding to 80 µrad semiaperture
- $\Delta E/E$ obtained = 0.44%
- Results from MCNPX and Geant4 completely compatible
2.5 MeV collimation results (MCNPX and Geant4)

- Collimation aperture corresponding to 200 µrad semiaperture
- ∆E/E obtained = 0.3%
- Results from MCNPX and Geant4 completely compatible
Collimation system misalignment simulation

- To evaluate effects of misalignment, simulation has been performed rotating the whole slits stack on its center, with respect to the beam axis direction.
Collimation system scattering shielding

- To avoid scattered radiation and secondary particles to reach the experimental area and the gamma beam characterization system, a concrete block (2x2x1 \(m^3\)) will be placed after the collimation system.
Collimation system shielding results

- Scoring screen (10 m x 10 m) at the exit from the concrete block
- On the left surface plots, photons/pulse over an area of 20x20 cm²
- Below, the energy distribution of the background radiation over the entire 10 m x 10 m scoring screen.
Conclusions

• The results of the simulations carried out show that the collimation system allows to obtain monochromatic beams with an energy distribution compatible to the parameters required ($\Delta E/E < 0.5\%$).

• The study of the effect of misalignment has been fundamental to define the specifications of tolerances and stability, required to finalize the mechanical engineering and realisation of the system.

• The simulation of a realistic collimated beam it is been necessary to evaluate the expected performances of the detectors composing the characterisation system downstream the beam line and to finalise the design.

• Also, the results of the background radiation produced were used to evaluate the effect of the background signal on these detectors to optimise the performances in a realistic operating situation.
Thank you very much for your attention
Inverse Compton radiation is not intrinsically monochromatic, the energy is related to the emission angle.

The required energy band-width can be obtained only by developing specific methods of collimation of gamma beam.