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Gamma Beam System at ELI–NP

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Abstract. The Gamma Beam System of ELI–NP will produce brilliant, quasi–monochromatic gamma–ray beams via Inverse Compton Scattering of short laser pulses on relativistic electron beam pulses. The scattered radiation is Doppler upshifted by more than 1,000,000 times and is forward focused in a narrow, polarized, tunable, laser–like beam. The gamma–ray beam at ELI–NP will be characterized by large spectral density of about 10^4 photons/s/eV, narrow bandwidth (< 0.5%) and tunable energy from 200 keV up to about 20 MeV. The Gamma Beam System is a state–of–the–art equipment employing techniques and technologies at the limits of the present–day's knowledge.

INTRODUCTION

The Extreme Light Infrastructure – Nuclear Physics (ELI–NP), under construction in Magurele, near Bucharest, is one of the three pillars of the Pan–European research facility ELI [1]. The scientific program of the research center ELI–NP [2] covers a broad range of topics based on the use of laser driven radiation beams, such as laser–matter interaction, nuclear science and material science. The research center will host two major facilities: a high power laser system consisting of two 10 PW lasers and a high brilliance gamma beam system.

The Gamma Beam System at ELI–NP is based on the concept of inverse Compton scattering of intense light from short–pulse lasers on a high brightness relativistic electron beam provided by a linear accelerator. This method allows production of highly mono–chromatic gamma rays with energies tunable up to almost 20 MeV, rms bandwidths better than 0.5% and spectral density larger than 10,000 photons/s/eV. The properties of the gamma–ray beams provided by the system are order of magnitudes superior as concerns bandwidth and spectral density as compared to the presently running systems based on inverse Compton scattering with electrons in storage rings [3,4]. The system is being built by an European association of academic and research institutions and industrial partners called EuroGammaS [5].

The narrow bandwidth of the gamma–ray beams allows for the selective population of individual excited states in nuclei opening new possibilities for nuclear photonics and astrophysics studies and for a wide range of applications.

In the present paper an overview of the ELI–NP Gamma Beam System is given.

THE GAMMA BEAM SYSTEM

Inverse Compton Scattering

The first mentioning of the inverse Compton scattering as a source of high–energy polarized gamma–ray photons dates back in 1963 [6,7]. LADON [8] was the first facility to produce a mono–chromatic polarized gamma beam following the collision of a laser with the electrons from the ADONE storage ring [9] in Frascati.

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The process of inverse Compton scattering of photons on relativistic electrons is schematically shown in Fig.1. The name of 'inverse Compton scattering' (ICS) is due to the fact that in this process the photons are gaining energy rather than the electrons. The energy of the photons after the collision can be approximated as follows:

$$E_\gamma = 2\gamma_e^2 \frac{1 + cos\theta_L}{1 + \left(\gamma_e\theta_\gamma\right)^2 + a_0^2 + \frac{4\gamma_e E_L}{m_0 c^2}} E_L$$

where: $\gamma_e = 1/\sqrt{1-\beta^2}$ is the relativistic factor; θ_L and θ_γ are the incoming angle of the laser photon and the outgoing angle of the gamma–ray photons with respect to the electron direction; $a_0 = \frac{eE_0}{m_0 c\omega_0}$ is the normalized vector potential with E_0 the laser electric field and ω_0 the laser frequency; m_0 is the electron rest mass; E_L is the energy of the laser photons; $\frac{4\gamma_e E_L}{m_0 c^2}$ is the electron recoil parameter. For given laser energy E_L and electron energy E_e, the formula shows that the maximum energy is achieved in the case of a head–on collision for backscattered photons collinearly with the electron beam direction. Since a_0 and the recoil parameter are much smaller than 1, the energy of the scattered photons can be approximated, in this case, as $E_\gamma \approx 4\gamma_e^2 E_L$. For relativistic electrons this means a gain in the energy of the photons of more than one million times. It can be concluded that ICS is one of the most efficient photon energy amplifier processes.

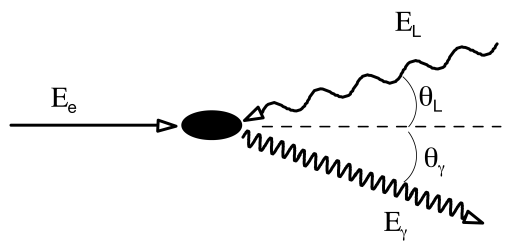

FIGURE 1. Illustration of the inverse Compton scattering; laser photons with energy E_L are incident on a relativistic electron beam with energy E_e at an angle θ_L and gamma rays with energy E_γ are scattered at an angle θ_γ.

Due to the relativistic boost the resulting gamma–rays are strongly forward focused in a laser–like incoherent beam. The energy of the scattered photons is distributed between the minimum energy (~ E_L) and the maximum energy (~ $4\gamma_e^2 E_L$) strongly correlated with the scattering angle. The strong energy–angle correlation allows to improve the bandwidth of the gamma beam by collimating the beam while the forward focusing ensures high spectral densities in small bandwidths. Typical spectra for the energy and angular distributions following ICS are shown in Fig.2. These spectra were produced with the simulation code CAIN [10] and correspond to the scattering of a 0.2 J laser light of 515 nm on an electron beam of 371 MeV energy at an incident angle θ_L of about 7^o [11] resulting in gamma rays up to almost 5 MeV energy emitted at $\theta_\gamma \approx 0^o$. For small incidence angle θ_L the minimum in the energy distribution of the photons corresponds to a scattering angle θ_γ of about $1/\gamma_e$ and the corresponding energy value is of ~ $2\gamma_e^2 E_L$. In the case considered in Fig.2 the Lorentz factor for the electron beam is about 725 meaning that half the energy distribution of the scattered gamma–ray photons are confined in less than 1.4 mrad.

The ICS cross sections are small, of the order of 10^{-25} cm^2. To produce high brilliance gamma beams with this method one needs to achieve high densities of electrons and laser photons at the interaction point and to maximize the repetition rate. The main ingredients needed to realize these conditions are the following:

- High brightness, small emittance and low energy spread electron beams
- Very brilliant and high repetition lasers
- A small collision volume at the interaction point ensuring the spatial and temporal overlap of the electron beam and the laser.

Another important feature of ICS is the preservation of the laser polarization in the scattered photons. If the interaction laser photons are 100% polarized, linear or circular, realistic simulations [11] show that the degree of polarization of the scattered gamma–ray photons will be maintained in the scattered radiation to more than 99%. This feature is of high relevance for the photo–nuclear reactions proposed to be used at ELI–NP.

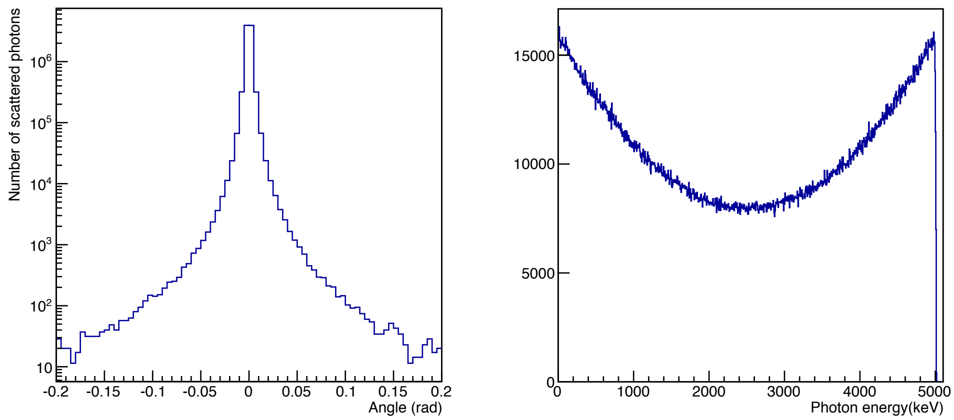

FIGURE 2. Angle and energy distributions of the gamma beams produced through ICS. The spectra were simulated with the CAIN [10] code for an electron beam with 371 MeV energy and laser photons of 515 nm and 0.2 J energy. The collision angle between the laser photons and the electrons was of about 7^{o}.

The ELI–NP Gamma Beam System

The main design criteria for the ELI–NP Gamma Beam System were: the energy of the gamma–ray beam, the photon spectral density, the peak brilliance and the bandwidth. The photon spectral density is measured in photons/s/eV. The brilliance (or spectral brightness) of a light source is defined as the number of photons emitted by the source in unit time, in a unit solid angle, per unit surface of the source, and in a unit bandwidth of frequencies around the given one. Usually the brilliance is expressed in units of photons/s/mm^{2}/mrad^{2}/0.1%BW. The brilliance characterize not only the photon flux (photons per second in a given bandwidth) but also on the high phase space density of the photons, i.e. on being radiated out of a small area and with low angular dispersion. The gamma–ray beam bandwidth is the width of the range (or band) of frequencies in which the beam energy spectrum is concentrated.

The Gamma Beam System for ELI–NP will provide a very intense and brilliant gamma beam with tunable energy in the range 0.2 – 19.5 MeV based on the incoherent inverse Compton scattering of a high repetition pulsed laser light off a high intensity, low emittance, relativistic electron beam with energies up to 720 MeV. The experiments proposed to be performed with the gamma beam at ELI–NP [2] have imposed the following key parameters of the gamma beam: bandwidth (BW) better than 0.5% with spectral densities of 10,000 photons/s/eV, photons energy up to 19.5 MeV to access the region of all GDR, peak brilliance higher than 10^{21} photons/mm^{2}/mrad^{2}/s/(0.1%BW), highly polarized state (better than 95%).

The building and installation of the ELI–NP Gamma Beam System will be performed by an European Consortium of academic and research institutions and commercial companies with expertise in the field of electron accelerators and laser technology [5]. The name of the Consortium is EuroGammaS.

The main components of the Gamma Beam System are: the electron accelerator, the interaction lasers, the laser recirculators and the collimation systems.

The solution proposed by EuroGammaS is challenging from the point of view of building a state–of–the–art electron accelerator to deliver a low–emittance beam with small energy spread combined with a photon–electron collider with tight time and space conditions and high mechanical accuracy laser recirculators.

The Electron Accelerator

The electron accelerator is a high brightness normal conducting linac consisting of two S–band and twelve C–band RF structures. The main advantage of using a linac accelerator is the excellent emittance of the provided electron beams. The accelerator will be operated at a radiofrequency repetition rate of 100 Hz. For every RF pulse 32 electron microbunches, separated at 16 ns, will be accelerated. Every microbunch will have an electrical charge of 250 pC. In this way the effective repetition rate of the electron beam will become 3.2 kHz and the average current of the beam is increased. To achieve this mode of operation a new photo–injector will be designed to operate in multi–bunch mode. A schematic illustration of the electron beam structure is shown in Fig.3.

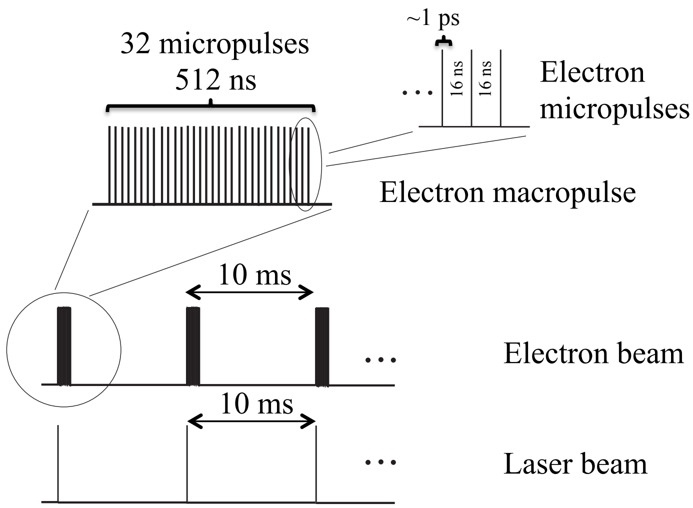

FIGURE 3. The electron beam will have a macrostructure repetition rate of 100 Hz. Each macropulse will be filled with 32 electron microbunches of 250 pC separated by 16 ns. The length of every microbunch will be of about 1 ps while their diameter at the interaction point will be of 15–30 μm.

The characteristics of the electron beam are fundamental for the production of the gamma beam through ICS. It is required to achieve a normalized emittance in both directions better than 0.6 mm·mrad and and energy spread below 0.1%. The pointing stability of the beam is also important and it should be below 1 μm. The main characteristics of the electron beam are summarized in Table 1.

TABLE 1. The parameters of the electron beam for the ELI –NP Gamma Beam System [5].

Electron beam parameter	Value
Energy [MeV]	180 – 750
Microbunch charge [pC]	25 – 400
Microbunch length [μm]	100 – 400
$\varepsilon_{n\ x,y}$ [mm·mrad]	0.2 – 0.6
Microbunch energy spread [%]	0.04 – 0.1
Focal spot size [μm]	15 – 30
# microbunches in the train	32
Microbunch separation [ns]	16
Energy variation along the train [%]	0.1
Energy jitter shot–to–shot [%]	0.1
Time arrival jitter [ps]	< 0.5
Pointing jitter [μm]	1

The accelerator is designed in two stages: the first stage will produce electrons with energies up to 300 MeV while in the second stage the electrons will be further accelerated up to 720 MeV. Figure 4 shows a schematic layout of the accelerator. The first stage of the accelerator is located in Accelerator Bay 1 and contains the photo–injector six accelerating structures (two S–band and four C–band). The Photo–cathode laser is based on a cryo–cooled Ti:Sa amplifier and it is operated at 100 Hz. For every pulse 32 replicas are generated. The laser produces UV light (266 nm) with an energy larger than 3 mJ for the 32 pulses. The second stage is divided between Accelerator Bay 1 and Accelerator Bay2 and it is composed of 8 C–band RF structures.

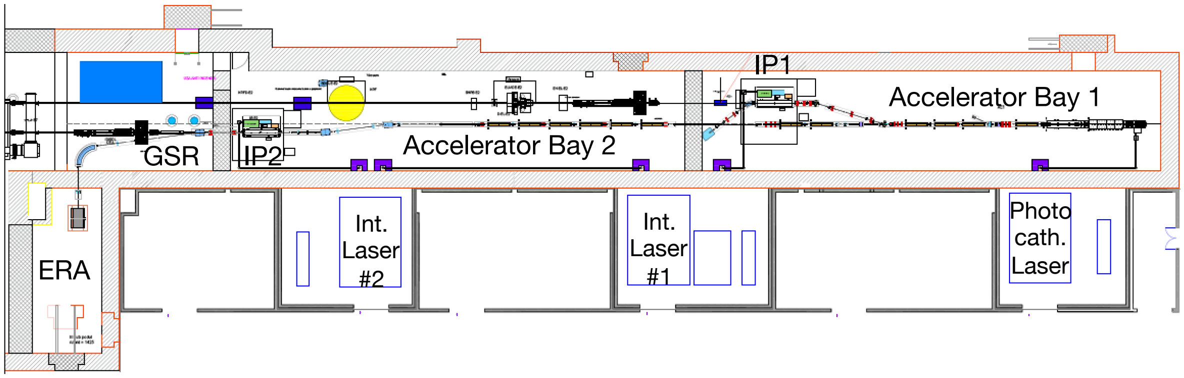

FIGURE 4. Schematic layout of the ELI–NP Gamma Beam System. The accelerator is design in two stages, one of low energy up to 300 MeV located in Accelerator Bay 1 and a second one provideing electrons up to 720 MeV is located in Accelerator Bay 2. The beam dump for the high–energy electrons is located in the ERA room.

There are two beam dumps located in Accelerator Bay 1 for the low–energy electron beam; one is design for electrons up to 140 MeV and a second one is design for electrons up to 300 MeV. The high–energy dump has to stop electrons up to 720 MeV and it is located in the ERA room.

The electrons are fed to the interaction points (IP) through dog–legs to avoid transmission of background radiation to the interaction points.

The Interaction Lasers

There will be two J–Class, diode pumped, Yb:YAG interactions lasers: one for the low–energy gamma–ray beams production and another one to be used in combination with the first one for the production of the high–energy gamma–ray beams. The two lasers The accelerator is designed in two stages: the first stage will produce electrons with energies up to 300 MeV while in the second stage the electrons will be further accelerated up to 720 MeV.are similar. They will operate at 100 Hz repetition rate (see Fig.3) and they will deliver green light (515 nm) with energy of 0.2 J. The two lasers are cryo–cooled to improve the gain and thermal properties of the laser gain medium. Table 2 summarizes the main characteristics of the interaction lasers.

TABLE 2. The parameters of the Yb:YAG interaction lasers.

Parameters	Low–energy Int. Laser	High–energy Int. Laser
Pulse energy [J]	0.2	2 x 0.2
Wavelength [eV, nm]	2.3, 515	2.3, 515
FWHM pulse length [ps]	3.5	3.5
Repetition rate [Hz]	100	100
M^2	≤ 1.2	≤ 1.2
Focal spot size [μm]	> 28	> 28
Bandwidth rms [%]	0.1	0.1
Pointing stability [μrad]	1	1
Synchronization to ext. clock [ps]	< 1	< 1
Pulse energy stability [%]	1	1

The interaction lasers are located in the technical rooms labeled Int. Laser #1 and Int. Laser #2 in Fig. 4. The laser light is transported to the interaction points through laser beam transport lines located in the two accelerator bays. The electron accelerator, the lasers and the laser recirculators are placed on the same anti–vibration platform that ensures vibration levels of less than 1 μm below 10 Hz.

The Laser Recirculators

The laser recirculators are needed to match the electron beam time structure with the repetition rate of the lasers. The laser repetition is 100 Hz and in order to ensure the interaction with the 32 microbunches it is needed to circulate the laser light between mirrors with minimal deterioration of the laser beam. It was chosen an optical recirculator with multi–pass geometry [5] and a fixed focus point. To produce a quasi-monochromatic gamma beam the system has to ensure that the collision between the laser light and the electron microbunches occurs always at the same incident angle. Moreover the polarization of the gamma beam has to be preserved. The recirculator consists of two confocal parabolic mirrors that focus the laser beam at the interaction point and recirculate it parallel to the electron beam axis. To maintain the same crossing angle between the laser beam and the electrons, one has to consider the possibility to switch between interaction planes. This is done with a system of pairs of mirrors. Figure 5 shows a schematic design of the recirculator with the two parabolic mirrors at the extremities of the device and the system of pairs of mirrors in between the parabolic mirrors. The pairs of mirrors are also used for the fine matching of the RF frequency with the round–trip circulation of the laser inside the recirculator. The two parabolic mirrors have holes in the center to allow for the passage of the electron beam. More details on the principles of operation of the laser recirculators are given in ref. [12].

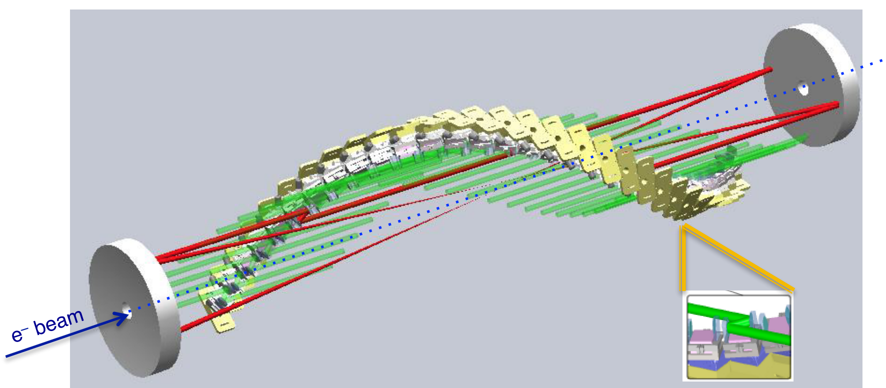

FIGURE 5. The recirculator geometry for the interaction points of the Gamma Beam System at ELI–NP [5]. At the extremities of the recirculator are placed two confocal parabolic mirrors. The collision angle at the interaction point is maintained with a system of pairs of mirrors as shown in the inset.

The Collimation System

The gamma beam produced by ICS will have an energy spectrum in the range from E_L up to the maximum energy. To achieve the target bandwidth of the beam one has to take advantage of the strong angle–energy correlation of the scattered photons and to place a collimator in the scattered photon beam to select the energy and the desired bandwidth by adjusting the aperture. In designing the collimation system one has to consider the following requests:

- The material of the collimator should stop the gamma–ray photons outside the aperture.
- The aperture has to be continuously adjustable to permit the selection of the optimum bandwidth for all energies.
- Minimize the production of secondary radiation.

The adopted solution [5] consists of modular collimators built up of tungsten dual slit elements as shown in Fig.6. The slits will be placed rotated one respect to the other such to create a pin–hole at the end of the structure. The opening of the slits can be continuously modified from 20 mm to less than 1 mm. There are two configurations considered for the collimators setup:

- For the low–energy stage (energies up to 3.5 MeV): 12 tungsten dual slits with a relative rotation of 30^o each. The slits aperture is of 0.96 mm.
- For the high – energy stage (energies up to 19.5 MeV): 14 tungsten dual slits with a relative rotation of 25.7^o each. The slits aperture is of o.48 mm.

The collimators are placed at about 10 m from the interaction points. To avoid secondary scattered radiation off the collimator to reach the detectors a concrete wall will be placed after the collimator.

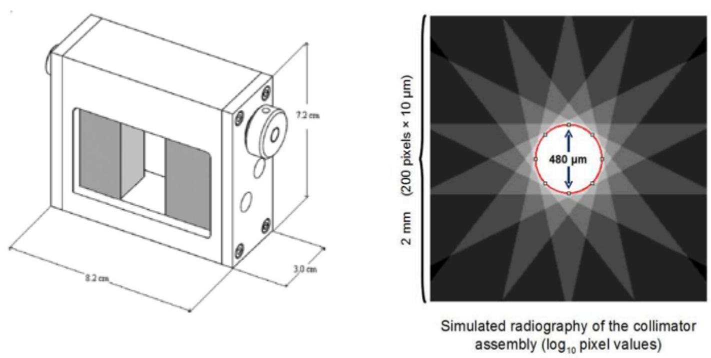

FIGURE 6. The collimators for the gamma beam at ELI–NP will consist of dual slit tungsten elements placed in stacks with relative rotation one to the other. On the left–hand side one dual slit element is shown. On the righ–hand side it is shown the pin–hole collimation produced by 14 dual slit placed with relative rotation of 25.7^o each and slit aperture of 0.48 mm. The image was produced with GEANT4 simulations [5].

The Gamma Beam at ELI–NP

The gamma beam produced by the system proposed by EuroGammaS will have the characteristics listed in Table 3. The main characteristics are: photon energy tunable from 200 keV up to 19.5 MeV, rms bandwidth smaller than 0.5%, spectral density larger than 10^4 photons/s/eV and linear polarization larger than 99%.

The time structure of the gamma beam will be the same as the one for the electrons. There will be a macro repetition rate of 100 Hz and each macropulse will contain 32 micropulses with duration of about 1 ps and pulse–to–pulse separation of 16 ns.

The gamma beam at ELI–NP will be used for basic research and application studies. The characteristics of the beam, such as bandwidth and spectral density, are by orders of magnitude better than the beams available at the present–day facilities and offer new opportunities for the nuclear research.

Some of the basic research topics to be investigated with the gamma beams at ELI–NP are as follows:

- Study of the electromagnetic dipole response of nuclei through Nuclear Resonance Fluorescence (NRF). The NRF technique allows the determination of several physical quantities in a model independent way. The studies will concentrate on rare nuclei such as the p–nuclei and actinides. The main problems to be investigated are scissor modes in nuclei, structure of the Pygmy Dipole Resonances below and above the particle threshold, determination of level widths and decay branching ratios.
- Investigation of astrophysics hot topics such as heavy elements synthesis in the Universe. The measurement of neutron capture cross sections for s–process branching nuclei is possible in inverse reactions induced by gamma rays. The measurement of (γ,p) and (γ,α) reaction cross sections will allow for the investigation of

p–processes nucleo–synthesis, clustering phenomena in light nuclei and photo–disintegration cross sections measurements relevant for the CNO cycle.

- Photo–fission phenomena will be studied. The experimental setups will be dedicated to: the study of photo–fission barriers, cross sections and rare fission modes; separation, manipulation and experiments with fission fragments.

TABLE 3. The parameters of the gamma beam at ELI –NP Gamma Beam System.

Gamma beam parameter	Value
Energy [MeV]	0.2 – 19.5
Spectral density [ph/s/eV]	$0.8 – 4{\cdot}10^4$
Bandwidth rms [%]	≤ 0.5
#Photons/shot within FWHM bdw.	$\leq 2.6{\cdot}10^5$
#Photons/s within FWHM bdw.	$\leq 8.3{\cdot}10^8$
Source rms size [μm]	10 – 30
Source rms divergence [μrad]	25 – 200
Peak brilliance [N_{ph}/s·mm^2·mrad^2·0.1%bdw]	$10^{20} – 10^{23}$
Pulse length rms [ps]	0.7 – 1.5
Linear polarization [%]	> 99
Macro repetition rate [Hz]	100
Number of pulses/macropulse	32
Pulse–to–pulse separation [ps]	16

Application research will make use of the ultra–bright, energy–tunable, quasi–monochromatic gamma beams for non–destructive testing applications, nuclear waste management, industrial radioscopy and tomography with high–energy gamma rays, studies of radioisotopes production for medical applications, positron production:

- An intense source of moderated positrons will be provided via the (γ,e^+e^-) reaction. Moderated positrons are useful for material science as probes for defect spectroscopy. One can investigate the type and concentration of defects in metals, semiconductors and isolators to depths up to several 100 nm.
- The gamma beam can be used for non–destructive detection and characterization of objects. Non–destructive elemental analysis based on Nuclear Resonance Fluorescence is possible. This is a key feature in nuclear industrial applications such as nuclear waste management, nuclear material accounting and safeguard. The high energy of the gamma rays open the possibility to investigate large size and complex products in aeronautics and automotive industries.
- Investigation of new production schemes of medical radioisotopes, such as ^{195m}Pt used in determining the efficiency chemotherapy, are among the proposed studies at ELI–NP.

CONCLUSIONS

A new facility for delivering gamma beams with characteristics beyond the state–of–the–art is under construction at ELI–NP in Magurele, Romania. Production of the gamma beam is made by a complex facility were advanced electron acceleration techniques are combined with sophisticated photon–electron colliding schemes. The very narrow bandwidth of the gamma beam will be achieved through the use of a complex collimation system.

The intense, high brilliance and quasi–monochromatic gamma beams will be used for advanced nuclear physics studies covering topics from both basic research and applications. The experimental setups to be installed at ELI–NP will be the results of a broad international collaboration and are currently under definition.

ACKNOWLEDGMENTS

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REFERENCES

1. ELI – Extreme Light Infrastructure Science and Technology with Ultra–Intense Lasers Whitebook, edited by G. A. Mourou *et al.* (THOSS Media GmbH, 2011).
2. ELI–NP White Book, http://www.eli-np.ro/documents/ELI-NP-WhiteBook.pdf .
3. V. N. Litvinenko *et al.*, *Nucl. Instr. Meth.* **A375**, 580 (1996).
4. S. Amano *et al.*, *Nucl. Instr. Meth.* **A602**, 337 (2009).
5. O. Adriani *et al.*, *Technical Design Report; EuroGammaS proposal for the ELI–NP Gamma beam System*, arXiv:1407.3669v1 [physics.acc-ph].
6. R.H. Milburn, *Phys. Rev. Lett.* **10**, 75 (1963).
7. F. R. Arutyunian and V. A. Tumanian, *Phys. Lett.* **4**, 176 (1963).
8. I. Federici *et al.*, *Nuovo Cim.*, **59B**, 247 (1980).
9. F. Amman *et al.*, *Lett. Nuovo Cim.* **1**, (1969) 729.
10. P. Chen *et al.*, *Nucl. Instr. Meth.* **A355**, 107 (1995).
11. L. Serafini and I. Drobet (private communication).
12. K. Dupraz *et al.*, *Phys. Rev. S.T. Accel. Beams,* **17**, 033501 (2014).