Feasibility studies of all-optical and compact $\gamma-$ray blaster by patawatt-class laser pulse and its application

J. F. Ong, A. C. Berceanu, K. Seto, S. Aogaki, L. Neagu, S. Ataman, Y. Nakamiya, O. Tesileanu

Extreme Light Infrastructure - Nuclear Physics (ELI-NP)/Horia Hulubei National Institute of Physics and Nuclear Engineering, 30 Reactorului Street, 077125 Magurele, Romania

With the experiment capability of ELI-NP, the $\gamma-$ray can be produced in two ways: Inverse Compton scattering (ICS) and Bremsstrahlung. For ICS, the laser pulse scatters off a relativistic electron bunch from the linear accelerator (LINAC). This produces a $\gamma-$ray beam with spectral density at the order of 10^4 photons/s with the energy up to 19.5 MeV [1]. The Bremsstrahlung can also give a similar order of $\gamma-$ray spectral density. In fact, both processes originate from the electron acceleration in a strong background field. The difference of Bremsstrahlung is that the strong background field derives from the Coulomb field of the high-Z materials.

Instead of LINAC, the electron bunch can be obtained from the plasma-based accelerator via Laser Wakefield Acceleration (LWFA) [2]. This uses the wake created by short, intense laser pulses propagating through underdense plasmas to accelerate electrons to high energies. The main advantage of plasma over conventional accelerators is that the maximum electric field gradients it can withstand—3 orders of magnitude higher than the breakdown fields of an RF cavity—allowing cm-scale acceleration distances and multi-GeV electrons [3]. Plasma-based accelerator has become an important tool in constructing a compact $\gamma-$ray factory.

The electron bunch from LWFA can replace LINAC as the $\gamma-$ray sources in a compact configuration. The electron bunch at the exits of the underdense plasmas is sent to a high-Z target for bremsstrahlung. On the other hand, a plasma mirror can be placed right inside the plasmas such that the laser pulse is bounced to scatter with the electron behind it. This method is known as the all-optical Compton backscattering which was proposed by Ta Phuoc, *et al* [4, 5]. This scheme, in turn, has been demostrated experimentally to be capable in producing 10^4 fold brighter x-rays than conventional accelerator. In fact, both methods can be combined by placing a high-Z or thick target inside the plasmas to generate double $\gamma-$ray beams at MeV-level.

In this paper, we report the numerical study of the feasibility in producing a $\gamma-$ray blaster by using 1 PW laser. This study combined the all-optical Compton backscattering—in a regime where radiation reaction is not negligible—and bremsstrahlung to generate double $\gamma-$ray beams by just a single laser pulse. The $\gamma-$photon at the Giant Dipole Resonance energies (15-30 MeV) is ideal for photonuclear transmutation or isomer production for medical applications [6, 7],

Table 1: Parameters for PIC simulation

Plasma density, n_e [cm^{-3}]	$0.0035n_{cr}$
Plasma density ramp, L_{ramp} [μm]	100
Laser intensity, I_0 [W/cm^2]	1×10^{21}
Laser wavelength, λ_L [μm]	0.8
Laser pulse duration, τ_{FWHM} [fs]	33
Laser waist radius, w_0 [μm]	10

which is one of the experiment designed in E7 area at ELI-NP.

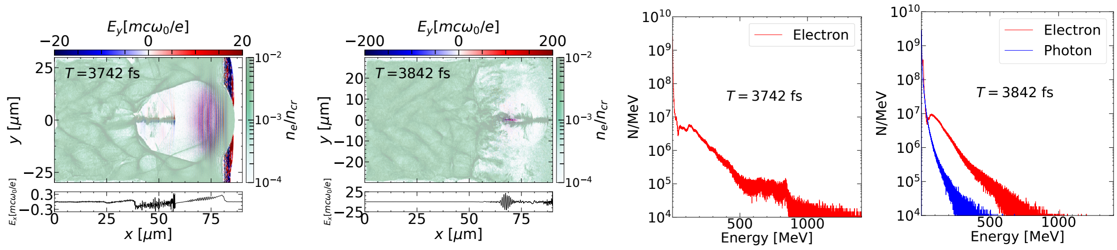
Results

We present the 3D PIC simulation results for the parameters lasted in Table 1. The simulation box has the size of $x\times y\times z = 90\,\mu\text{m} \times 60\,\mu\text{m} \times 60\,\mu\text{m}$ with $2048\times256\times256$ cells. The helium and aluminium particle species are both 8 macroparticles per cell. The helium plasma has a length of $L = 1$ mm. A parabolic aluminium mirror with a focusing length of 15 μm is used as a reflecting foil.

Figure 1 (a) and (b) show the LWFA slices in the bubble regime before and after reflection from the parabolic foil. A very strong effect of beam-loading is observed at T=3742 fs as shown in the E_x lineout plot between $x = 37.5-56.2$ μm. The laser intensity after the reflection from the parabolic foil is $I_{max} = 100I_0$. The length of the electron bunch is comparable to the radius of the bubble due to continuous charge injection. Apparently, the electron bunch starts interacting with the laser before it reaches the focal point. At the focal point, the laser intensity is $\sim 8\times10^{22}\,\text{W/cm}^2$ with a waist smaller than 1 μm. The energetic electrons in the bunch ($\gamma > a_0$) can interact with the strong laser field at $a_0 = 200$, with gamma-ray emission.

The corresponding energy spectra are shown in Fig. 1 (c) & (d). The electron energy spectrum in Fig. 1 (c) shows a maximum energy of 1.4 GeV with a total charge of 5.6 nC, which is slightly above the value estimated by using the scaling law in Ref. [8] (3 nC). When the reflected laser pulse undergoes a head-on collision with the electron bunch, its maximum energy reduces to 1 GeV, with a charge of 5.2 nC as shown in Fig. 1 (d) while the photons have a maximum energy of 600 MeV. The peak brilliance of NCBS is measured to be 6.7×10^{20} photons/s/mm^2/mrad^2/0.1%BW at 15 MeV.

Subsequently, the electron bunch passes through a 5 cm thick aluminium foil. The comparison between bremsstrahlung and NCBS is shown in Fig. 2 for the electron bunch with an energy above 1 MeV. The peak brilliance is measured to be 2.1×10^{16} photons/s/mm^2/mrad^2/0.1%BW



(a) (b) (c) (d)

Figure 1: 3D PIC simulation results. The 2D slice of electron density in the $x-y$ plane (white to green color table) and laser pulse (blue to red) at $z=0$ (a) before, and (b) after reflection from the parabolic foil. The line plots represent the electric field E_x along the center of the simulation domain. (c-d) The electron and photon energy spectra with the total electron bunch charge of 5.6 nC and 5.2 nC, respectively, and 7×10^9 photons.

at 15 MeV. Both the bremsstrahlung and NCBS energy spectra share similar characteristics, as can be seen from Fig. 2, except for the endpoint energy, which is much higher in the NCBS case. Since the electrons travel at almost the speed of light, the two spectra cannot be distinguished at energies below 500 MeV. This method makes a γ-ray blaster an important tool for various photonuclear interactions.

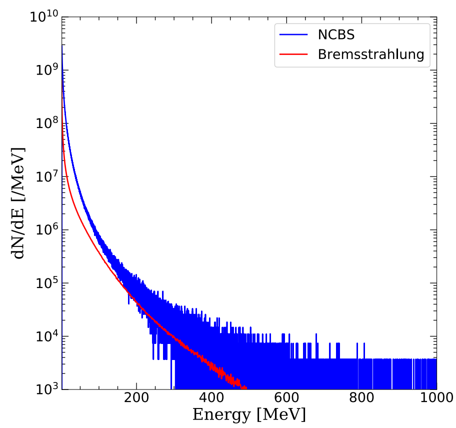


Figure 2: *The photon number spectrum for NCBS and bremsstrahlung.*

References

[1] "ELI-NP homepage," http://www.eli-np.ro.

[2] T. Tajima and J. M. Dawson, "Laser electron accelerator," *Phys. Rev. Lett.*, vol. 43, no. 4, pp. 267–270, Jul. 1979.

[3] W. P. Leemans, A. J. Gonsalves, H.-S. Mao, K. Nakamura, C. Benedetti, C. B. Schroeder, C. Tóth, J. Daniels, D. E. Mittelberger, S. S. Bulanov, J.-L. Vay, C. G. R. Geddes, and E. Esarey, "Multi-gev electron beams from

capillary-discharge-guided subpetawatt laser pulses in the self-trapping regime," *Phys. Rev. Lett.*, vol. 113, p. 245002, Dec 2014. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevLett.113.245002

[4] K. Ta Phuoc, S. Corde, C. Thaury, V. Malka, A. Tafzi, J. P. Goddet, R. C. Shah, S. Sebban, and A. Rousse, "All-optical compton gamma-ray source," *Nature Photonics*, vol. 6, p. 308, 2012.

[5] S. Corde, K. Ta Phuoc, G. Lambert, R. Fitour, V. Malka, A. Rousse, A. Beck, and E. Lefebvre, "Femtosecond x rays from laser-plasma accelerators," *Rev. Mod. Phys.*, vol. 85, pp. 1–48, Jan 2013. [Online]. Available: https://link.aps.org/doi/10.1103/RevModPhys.85.1

[6] H. Ejiri, T. Shima, S. Miyamoto, K. Horikawa, Y. Kitagawa, Y. Asano, S. Daté, and Y. Ohashi, "Resonant photonuclear reactions for isotope transmutation," *J. Phys. Soc. Jpn.*, vol. 80, p. 094202, 2011.

[7] H. Ejiri and T. Shima, "Resonant photonuclear isotope detection using medium-energy photon beam," *Phys. Rev. ST Accel. Beams*, vol. 15, p. 024701, 2012.

[8] W. Lu, M. Tzoufras, C. Joshi, F. S. Tsung, W. B. Mori, J. Vieira, R. A. Fonseca, and L. O. Silva, "Generating multi-GeV electron bunches using single stage laser wakefield acceleration in a 3D nonlinear regime," *Phys. Rev. ST Accel. Beams*, vol. 10, no. 6, p. 061301, Jun. 2007.