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GEANT4 FOR INVERSE COMPTON RADIATION SOURCE SIMULATIONS*

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Abstract

In this paper, creation and implementation of the Compton backscattering module into the Geant4 package are under consideration. Created module of Compton backscattering has been implemented as a discrete physical process and operates with a fixed light target (a virtual volume with the properties of a laser beam), with which a beam of charged particles interacts producing x-rays. Such a description allows user to flexibly change necessary parameters depending on the problem being solved, which opens up new possibilities for using Geant4 in the studied area.

INTRODUCTION

Compton backscattering or inverse Compton scattering (ICS) [1, 2] is a promising mechanism for engineering of a bright, compact and versatile X-ray source: with dimensions being significantly smaller, the brightness of this source is comparable with that of synchrotron radiation. Nowadays, active researches are underway on various aspects of this phenomenon [3, 4] aiming at increasing of radiation intensity and quality. In modern science, such kind of research is necessarily accompanied by the computer simulations. In this paper, we are discussing creation and implementation of the Compton backscattering module into the Geant4 package [5-7], which is the leading simulation toolkit in high-energy physics [8], accelerator physics [9], medical physics [10], and space studies [11]. This paper is organized as follow. First, we show brief theoretical description of the ICS process, and then some issues of ICS implementation into Geant4 are considered. We finish with Geant4 simulation results and conclusion.

BRIEF THEORETICAL DESCRIPTION

Let us adduce theoretical description of scattering process shown in Fig. 1. We consider here collision of electron and laser beams under arbitrary angle α . In this case ICS photon spectral-angular distribution reads

$$\frac{d^2N(\mathbf{n},\omega)}{d(\hbar\omega)d\theta}=\frac{\sin(\theta)d\phi}{137}\frac{\omega}{4\hbar\pi^2c^2}\times \left|\sum_{s=1}^{\omega/\omega_0}\frac{\sin\left((A-s\eta)NT/2\right)}{(A-s\eta)/2}\frac{J_s(B)}{(-1)^{-s}}\left\{\mathbf{H}-s\frac{\mathbf{K}}{B}\right\}\right|^2, \quad (1)$$

where

$$A=\omega-\frac{\omega}{c}\left[n_x\left(v_{0x}+\frac{a_0c}{\gamma}\right)+n_yv_{0y}+ n_z\left(v_{0z}+\frac{a_0v_{0x}}{\gamma(1-\beta_{0z})}\right)\right], \quad (2)$$

$$B=\frac{\omega}{c}\left[n_x\frac{a_0c}{\omega_0\gamma(1+\beta_{0z})}+n_z\left(\frac{a_0v_{0x}}{\omega_0\gamma(1-\beta_{0z}^2)}\right)\right], \quad (3)$$

$$T_{\text{int}}=NT=N\frac{2\pi}{\omega_0(1+\beta_{0z})}, \quad (4)$$

$$\mathbf{H}=(\mathbf{e}_xn_y-\mathbf{e}_yn_x)\left(v_{0z}+\frac{a_0v_{0x}}{\gamma(1-\beta_{0z})}\right)+ (\mathbf{e}_yn_z-\mathbf{e}_zn_y)\left(v_{0x}+\frac{a_0c}{\gamma}\right)+(\mathbf{e}_zn_x-\mathbf{e}_xn_z)v_{0y}, \quad (5)$$

$$\mathbf{K}=(\mathbf{e}_xn_y-\mathbf{e}_yn_x)\left(-\frac{a_0v_{0x}}{\gamma(1-\beta_{0z})}\right)+ (\mathbf{e}_yn_z-\mathbf{e}_zn_y)\left(-\frac{a_0c}{\gamma}\right), \quad (6)$$

$$\eta=\omega_0+\frac{k_{0z}z}{t}\simeq\omega_0(1+\beta_{0z}), \quad (7)$$

$$n_x=\sin\theta\cos\varphi,\ n_y=\sin\theta\sin\varphi,\ n_z=\cos\theta. \quad (8)$$

Here ω is the frequency of the scattered photon, ω_0 is the laser frequency, γ is the electron Lorentz factor (here we consider moderately relativistic electrons), c is the speed of light, $\beta_{0z}=v_{oz}/c$ is longitudinal component of the reduced speed of electron, with v_{0x},v_{0y},v_{0z} being electron velocity projections; $\mathbf{e}_x$, $\mathbf{e}_y$, $\mathbf{e}_z$ are unit axes, θ is the polar angle of observation, φ – is the azimuthal angle of observation, $\hbar$ is the Planck constant, N is the number of electron oscillations in the laser field, T – is the laser wave period, a_0 is the nonlinearity parameter of laser beam. In this paper we consider only linear scattering i.e. $a_0\to 0$.

The frequency of a scattered photon (in a head-on collision of laser and electron beams) is determined by the relation

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$$\omega \approx \frac{4\gamma^2\omega_0}{1+\gamma^2\theta^2}, \quad (9)$$

with the cutoff frequency of the radiation (in the case of scattering in the direction of the pulse of the primary electron)

$$\omega_{\max} = 4\gamma^2\omega_0. \quad (10)$$

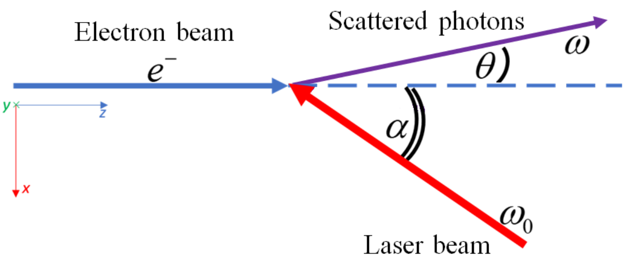

Figure 1: Layout of the ICS. Electron beam (blue) collides with laser beam (red) under angle α producing x-rays (magenta).

ICS IMPLEMENTATION INTO GEANT4

The current version of Geant4 (Geant 10.07.p02) includes several x-ray production processes such as X-ray transition radiation, synchrotron radiation, bremsstrahlung, particle induced x-ray emission. To add ICS physics into Geant4 we took as a basis x-ray transition radiation module (G4VXTRenergyLoss class) developed by Grichine and others [12-15]. Thus, created module of Compton backscattering has been implemented as a discrete physical process. Instead of real laser beam we introduce a so call fixed light target (a virtual volume with the properties of a laser beam), with which a beam of charged particles interacts (see Fig. 2). We start with the estimation of the total number of ICS photons using Poisson distribution with mean value obtained via numerical integration of Eq. (1) over energies and angles. In case when we have non zero number of photons, angular and energy physical tables from the base class G4BackCompton can be filled with corresponding values calculated from Eq. (1). ICS photons production is described by a family of classes shown in Fig. 3. The base class also contains PostStepDoIt function providing ICS photon generation when relativistic charged particle enters the G4LogicalVolume LightTarget. ICS photons are generated randomly along the particle trajectory with random energy and angle taken from corresponding physical tables. Number of photons generated on particle trajectory is defined by GetMeanFreePath function exploiting information about total number of photons and target length. Photon energies is subtracted from the kinetic energy of the incident particle.

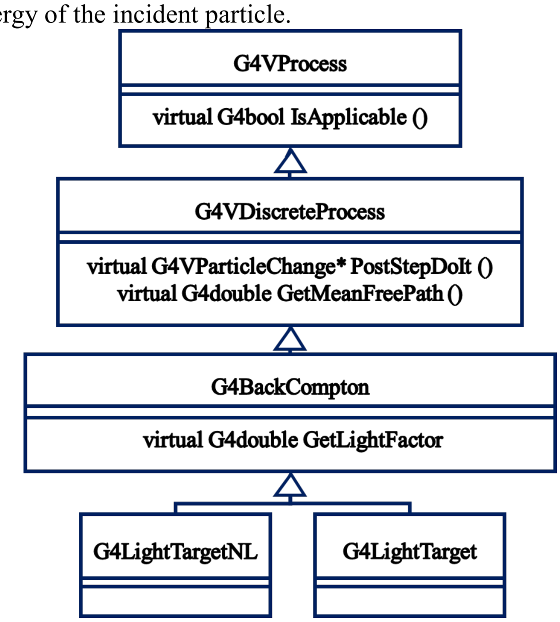

Figure 3: Inheritance diagram for GEANT4 classes describing ICS photon generation from the Light Target. The base class G4BackCompton inherits from G4VDiscreteProcess. G4LightTarget and G4LightTargetNL (not constructed yet) implement pure virtual function GetLightTarget for laser beam parameters transfer.

ICS SIMULATIONS IN GEANT4

In Fig. 4 one can see the results of a ICS simulation using the created module described above. These distributions were obtained for an observation angle θ of 3 mrad relative to the initial trajectory of the 20 MeV electron beam in a head-on collision with a laser beam with wavelengths of 532 and 1064 nm and a pulse time of 9 ns, $a_0 = 0.03$. The figure shows distinct peaks with energies precisely determined by the expression (9) and coincided with experimental data (see Figure 6a from [16]).

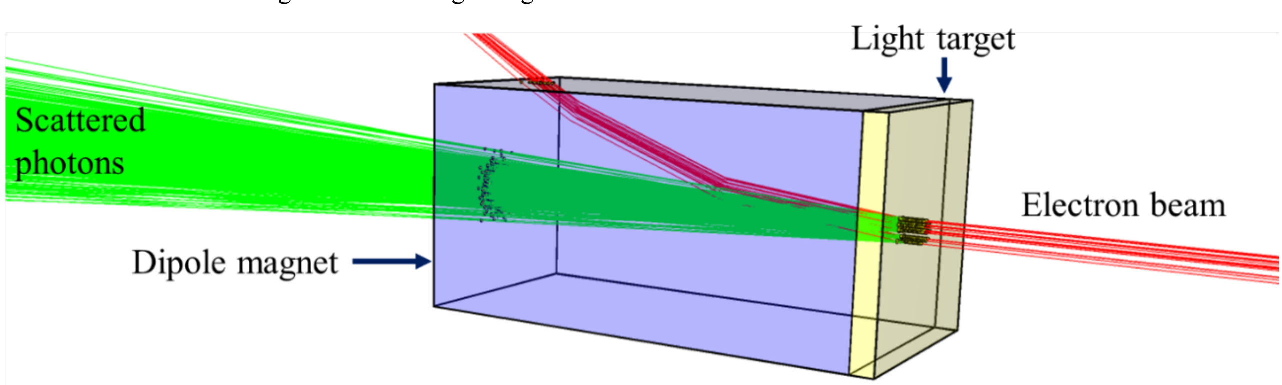

Figure 2: Visualisation of ICS process in Geant4. Electron beam interact with light target producing x-rays, and then it is being declined by dipole magnet.

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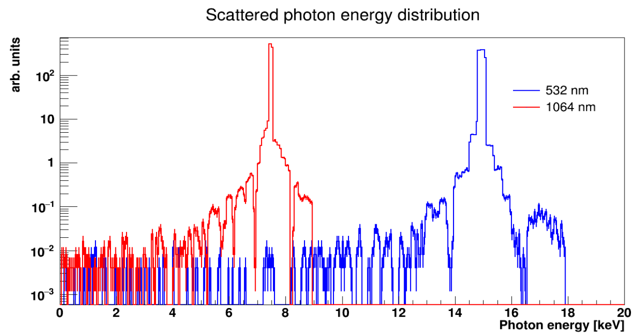

Figure 4: Geant4 simulation of ICS. Head-on collision of the 20 MeV electron beam with a laser beam with wavelengths of 532 (blue) and 1064 (red) nm, pulse time is 9 ns, $a_0 = 0.03$, observation angle θ is 3 mrad relative to the initial trajectory of electrons.

Figure 5 shows the case of electron beam laser collision under angle $\alpha = 7°$ with other conditions being the same like it was for Fig. 4. One can see that peak positions move to lower energies as well as intensities decrease. Such a result shows correct behaviour of ICS module. Indeed the energy and number of photons should decrease with increasing of α .

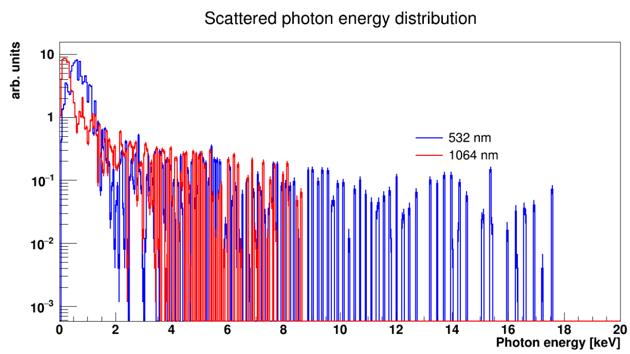

Figure 5: Geant4 simulation of ICS. Collision of the 20 MeV electron beam with a laser beam with wavelengths of 532 (blue) and 1064 (red) nm, pulse time is 9 ns, $a_0 = 0.03$, collision angle $\alpha = 7°$, observation angle θ is 3 mrad relative to the initial trajectory of electrons.

CONCLUSION

We constructed a basis for new discrete physical process in Geant4 using G4FastSimulation principles. It has been shown that the created physical module provides predictable results. Next step is to add a model for non-linear scattering regime, validate created code via comparison with pure theory and experimental data, and after that officially apply for merging with Geant4.

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