A CONCEPT DESIGN OF A COMPTON SCATTERING LIGHT SOURCE BASED ON THE HLS ELECTRON STORAGE RING*

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Abstract

Hefei Light Source (HLS) is a 2nd generation light source lasering high flux ultraviolet and soft x-ray with 200 MeV to 800 MeV electron beam. To explorer other applications of the electron storage ring of HLS, a concept design of Hefei Compton Scattering Light Source (HCSLS) is proposed. In this paper, Compton Scattring Simulation Code(CSSC), a parallel code based on the analytical method to simulate the Compton scattering between the laser beam and the electron beam, is presented. Using the CSSC, it is computed that HCSLS will produce photons with a total flux of 10^9 s^{-1} to 10^{11} s^{-1}, and energy of 0.07 MeV to 1.15 MeV at the maximum spectral flux density with the 200 MeV to 800 MeV electron beam scattering with a kilo-watts CO_2 laser. With a much shorter wave laser beam from an Nd:YVO4 laser, the scattered photons energy at the maximum spectral flux density is improved by a factor of 10, while its flux is reduce by a factor of 10,000 due to the lower peak laser power.

INTRODUCTION

In 1920, the Compton scattering effect was discovered. In 1960s, a concept of hard x-ray/γ-ray light source was proposed by Milburn and others [1], which is based on the Compton scattering effect between a conventional laser beam and a high energy electron beam provided by a particle accelerator. This type of light source can provide highly polarized hard x-ray/γ-ray with very low background and tuneable energy in high resolution. They are widely used in medical science and nuclear physics [2]. Since 1978, many such light sources have been or being constructed around the world with the photon energy from few MeV to hundreds of MeV, such as LADON, LEGS, HIGS, BL-1, BL05SS, and SLEGS. In this paper, we will first introduce the theory of Compton scattering, and then the principle of CSSC, and finally the proposed HCSLS facility.

THEORY OF COMPTON SCATTERING

Energy of Scattered Photon

According to the conservation of total energy and momentum, the scattered photon energy is deduced as,

$$E_g = \frac{(1-\beta\cos\theta_i)E_p}{1-\beta\cos\theta_f + (1-\cos\theta_p)E_p/E_e} \quad (1)$$

is the relativistic speed of the incident electron (c and v are, respectively, the speed of light in vacuum and the speed of electron in the lab frame,);θ_i and θ_f are angle of the incident electron and scattered photon, and θ_p is the angle between the incident photon and electron. For the head on collision, the maximum scattered photon energy is obtained at $\theta_f = 0$, and it is approximately proportional to $4\gamma^2$, where $\gamma=E_e/m_0c^2$ is the Lorentz factor of the incident electron and m_0 is its rest energy.

Differential Cross Section

In the frame of Quantum Electrodynamics, the differential angular cross section of the Compton scattering in the electron rest frame is described by Klein Nishina formula [4] as,

$$\frac{d\sigma_c}{d\Omega} = \frac{R_e^2}{2}\frac{1}{(1+x)^2}(1+\cos^2\theta_{ef} + \frac{x^2}{1+x}) \quad (2)$$

$$x = \frac{h\nu'}{m_0c^2}(1-\cos\theta_{ef}) \approx \frac{h\nu'}{2m_0c^2}\theta_{ef}^2 \quad (3)$$

where R_e, is the classic radius of electron, θ_{ef} is the scattered electron polar angle in its rest frame, and is able to deduced from θ_f in the lab frame with Lorentz transformation. $h\nu' = \gamma(1+\beta)h\nu$, where $h\nu'$, $h\nu$ and h are, respectively, the incident photon energy in the electron rest and the lab frame, and Planck constant. In the lab frame, the differential angular cross section and the differential energy cross section can be deduced from their corresponding quantities in the electron rest frame by Lorentz transformation, which has been discussed in [3].

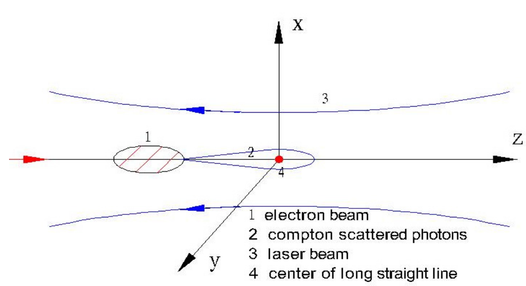

Figure 1: The coordinate system in the Compton scattering area, where the propagation directions of electro beam and laser beam are anti-parallel. And the waist centre of the laser beam is overlapped with the centre of long straight section of the storage ring. The origin is at the centre of long straight section(Fig. 4), z-axis is along the direction of electron beam motivation.

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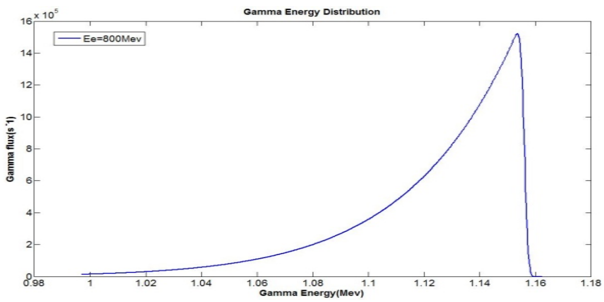

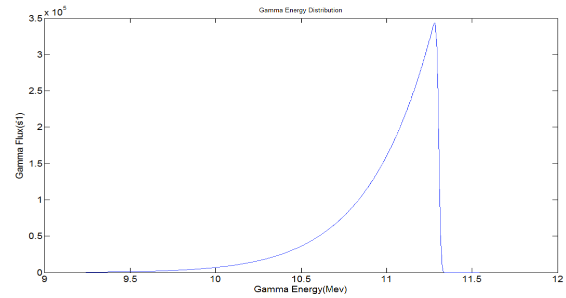

Figure 2: Energy spectrum of Compton scattered photons computed by CSSC; the left fig. for a 1 W CO2 laser and the right fig. for an 1 watt Nd:YVO4 laser; energy of electrom beam is 800 MeV, and other parameters of electron beam, laser beam are shown in Table 1, Table 2, and Fig. 3.

CSSC

CSSC, a code based an analytical method, is developed to simulate Compton scattering between the laser beam and the electron beam.

In the coordinate system defined in Fig. 1, the density distribution of electron beam and continuous laser beam can be expressed as

$$F_e(x,y,z,x',y',E_e,t)$$
$$= N_e\frac{1}{(2\pi)^2\varepsilon_x\varepsilon_y\sigma_p\sigma_z}\exp\left(-\frac{\gamma_x x^2+2\alpha_x xx'+\beta_x x'^2}{2\varepsilon_x}-\frac{(E_e-E_{e0})^2}{2\sigma_p^2}\right)$$
$$\times\exp\left(-\frac{\gamma_y y^2+2\alpha_y yy'+\beta_y y'2}{2\varepsilon_y}-\frac{(z-ct+A/2)^2}{2\sigma_z^2}\right) \quad (4)$$

$$F_p(x,y,z,\mathbf{k})=\frac{\mathrm{I}_0}{c}\frac{w_0^2}{w_z^2}\exp\left(-\frac{2(x^2+y^2)}{w_z^2}-\frac{(\mathbf{k}-\mathbf{k_0})^2}{2\sigma_p^2}\right) \quad (5)$$

$$\mathrm{w}_z=w_0\sqrt{1+\frac{z^2}{z_r^2}},\ z_r=\frac{\pi w_0^2}{\lambda},\mathrm{I}_0=\frac{P\lambda}{Chw_0\sqrt{\pi}}$$

Where N_e is the number of the electron beam; x' and y' are the angular divergences of the electron in the x and y directions, respectively; E_e is the mean energy of the electron beam; $\alpha_{x,y},\beta_{x,y}$ and $\gamma_{x,y}$ are the electron Twiss function; σ_p,ε_z and $\varepsilon_{x,y}$ are the electron beam momentum spread, RMS bunch length, and emittance; A, c and t is the length of long straight section, speed of light and time, respectively. t = 0 when the centre of electron beam at $(0,0,-A/2)$ i.e., the centre of electron beam entering the long straight section. $\mathbf{k}, \mathrm{w}_0, \mathrm{w}_z$, and z_r are the laser wave vector, the size of the laser beam waist, laser spot at z, and the Rayleigh radius, respectively; I_0 is the flux density at centre of beam waist, and P is the power of laser and λ is the wave length.

The energy distribution of Compton scattered photons can be calculated by:

$$\frac{\mathrm{d}N_{(Eg)}}{\mathrm{d}E_g}=\int c(1-\beta\cos\theta_i)F_eF_P\frac{\mathrm{d}\sigma}{\mathrm{d}E_g}\mathrm{dVd}^3k\mathrm{d}x'\mathrm{d}y'\mathrm{d}E_e\mathrm{d}t \quad (6)$$

where all the variables have been defined in Eq. (1), (4) or (5)

With the HCSLS parameters in Table 1 and 2, the energy stability of E_g caused by θ_i and θ_p is in order of 10^{-6} and 10^{-4}, respectively, much smaller than the typical value of x, x', y' at 10^{-2} to10^{-3}. Thus, the laser beam wave vector along the x-axis and y-axis is neglected, and the head-on collision ($\theta_i=\pi$) of electrons and the photons is assumed, for all the following calculation. In a storage ring, the vertical emittance of an electron beam is about 100 times smaller than that in the horizontal direction. The electron beam vertical distribution can be approximately described by a δ-function. Therefore, the scattered photon beam energy spectrum can simplified as,

$$\frac{\mathrm{d}N_{(E_g)}}{\mathrm{dE}_g}=\int c(1+\beta)F_e^{'}F_P^{'}\frac{\mathrm{d}\sigma}{\mathrm{d}E_g}\mathrm{dVd}k_z\mathrm{d}E_e\mathrm{d}x'\mathrm{d}y'\mathrm{d}t \quad (7)$$

$$F_e^{'}=\int F_e\mathrm{d}y, F_P^{'}=\int F_P\mathrm{d}k_x\mathrm{d}k_x,$$

where F_e and F_p are the density distribution of the electron beam and the laser beam, respectively, defined in Eq(4) and Eq(5).

Two constraints are applied to solve Eq. (6). First the Compton scattered photon energy E_g and the scattered polar angle θ_f are related as Eq. (1). Second, the geometric constraint assures that the Compton scattered photons can get through the collimator. It can be expressed as:

$$\frac{-X1/2-x}{L+A-ct}-\theta_f\cos\phi_f\le x'\le\frac{X1/2-x}{L+A-ct}-\theta_f\cos\phi_f \quad (8)$$
$$\frac{-Y1/2-y}{L+A-ct}-\theta_f\sin\phi_f\le y'\le\frac{Y1/2-y}{L+A-ct}-\theta_f\sin\phi_f \quad (9)$$

where the size of collimator is $X1\times Y1$; ϕ_f is azimuth angle of the scattered photon; all other variables has been defined in Eq. (1), (4) and (5).

With above described analytical method, a parallel code, CSSC is developed to solve Eq. (7) to study the energy spectrum and flux of the Compton scattered photons of HCSLS.

HCSLS FACILITY

HLS and its Storage Ring.

The Hefei Light Source, which was commissioned in 1989, is a second generation synchrotron radiation light source providing high flux ultraviolet and soft X-ray with the characteristic wave length 24 Å. Its operation parameters and the Twiss parameters are showed in Table 1 and Fig. 3.

Table 1: Parameters of HLS Electron Storage Ring

Parameters	Values	Units
Electron Energy	200 to 800	MeV
Energy Spread	0.1~0.5	%
Energy Acceptance	0.528	%
Maximal Beam current	300	mA
Horizontal emittance	166	nmrad
Long straight section	3.3622	m

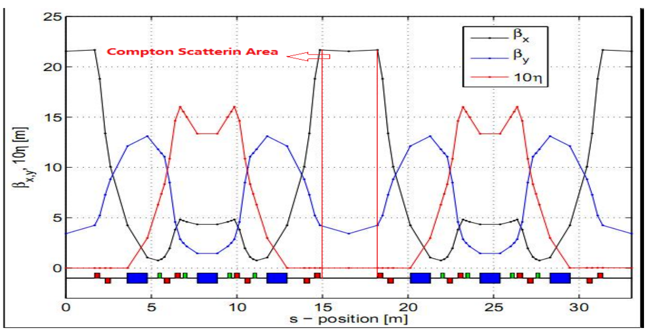

Figure 3: Twiss parameters of HLS.

Table 2: Parameters of Laser

Laser	Wave lenghth	Average. power	Rayleigh radius
CO_2	10.6 μm	1 W	5 mm
Nd:YVO4	1.06 μm	1 W	1 mm

HCSLS Facility

The scheme of the HCSLS facility is shown in Fig. 4. The laser system consists of a CO_2 laser, an Nd:YVO4 laser and a low power visible laser for setting optical system. Their parameters are shown in Table 2. The laser beam is focused and injected into long straight section of the HLS electron storage ring by the optical system. To obtain high energy resolution, the resultant Compton scattered photons are collimated by a 5 mm× 5 mm lead collimator placed 50 meters from downstream end of long straight section.

The energy spectrum and the total flux are obtained using the code, HCLSC with parameters of the electron beam, the laser beam and electron storage ring shown Table 1, Table 2, respectively. From the energy spectrum in Fig. 2, we can see that using a 1 watt CO_2 laser beam and an 800 MeV electron beam, the total flux of Compton scattered photons reaches $7.2\cdot10^8$ s^{-1} and FWHM of the energy is 2.5%. And it is verified that the flux increases linearly with the increase of the laser power, i.e., a 1 kilo-watts CO_2 commercial laser can produce a flux of $7.2\cdot10^{11}$ s^{-1}. When an Nd:YVO4 laser used with the same incident electron energy, the Compton scattered photons energy corresponding to the maximum spectral flux density reaches 11.3 MeV. And the total flux is $6.13\cdot10^7$ s^{-1} with FWHM 2.5%.

When the electron beam energy is varied from 200 MeV to 800 MeV, the energy corresponding to the maximum spectral flux density of the Compton scatter photons driven by a kilo-watts CO_2 laser is tuneable from 0.07 MeV to 1.15 MeV, and the total flux is from 10^9 to 10^{11} s^{-1}, while using a 1watt Nd:YVO4 laser, the energy will be tuneable from 0.7 MeV to 11.3 MeV, and the total flux from 10^5 s^{-1} to 10^7 s^{-1}.

The maximum energy change of electrons caused by Compton scattering with CO_2 laser beam is in the energy acceptance. When Nd:YVO4 laser used, the maximum loss rate of electrons caused by Compton scattering is smaller than 10^8 s^{-1}, which is much smaller than the original loss rate of storage ring. Then the Compton scattering influence over the electron beam can be neglected.

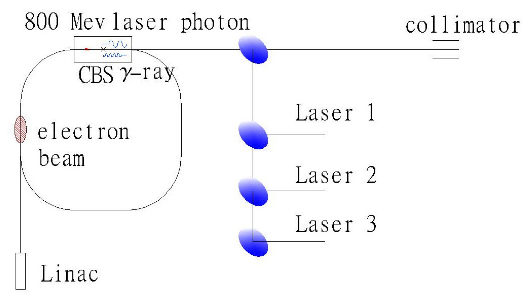

Figure 4: The scheme of the HCSLS facility.

CONCLUSION

The HCSLS driven by a kilo-watts CO2 laser can produce Compton scattering photons with a total flux 10^9 to 10^{11} s^{-1} and the energy corresponding to the maximum spectral flux density tuneable from 0.07 MeV to 1.15 MeV. When an Nd:YVO4 laser used, the total flux reaches 10^5 to 10^7 s^{-1}, and the energy is tuneable from 0.7 MeV to 11.3 MeV. The further explore shows that the influence of the Compton scattering over the electron beam life and beam dynamics of the storage ring can be neglected. It is possible for the upgraded HLS to operate in the SR/CS mode, in which synchrotron radiation mode and Compton scattering mode are operated simultaneously, where the two modes do not seem to affect each other, promising the radiation from UV to gamma-ray in one light source.

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