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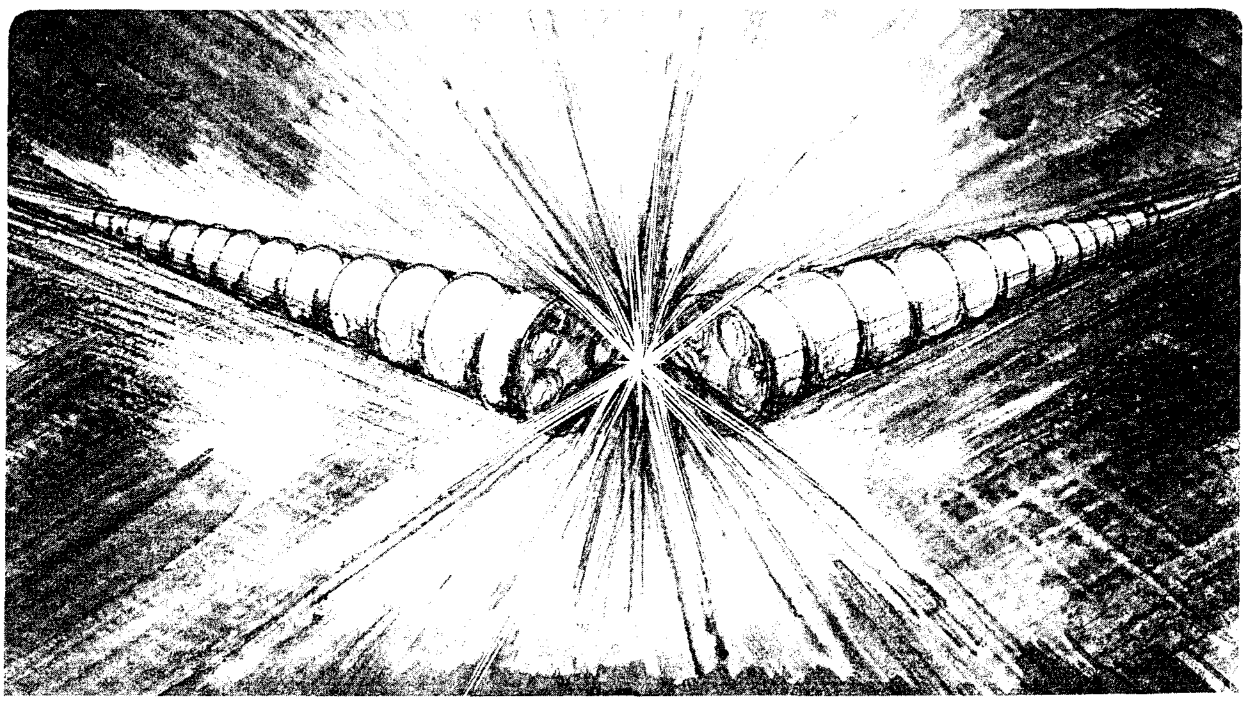

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Generation of Femtosecond X-Rays by 90° Compton Scattering*

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Abstract

We propose Compton scattering of a short pulse visible laser beam by a low energy (but relativistic) electron beam at a right angle for generation of femtosecond x-rays. Simple analysis to determine the qualitative and quantitative characteristics of the x-ray pulse is presented.

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Short radiation pulses are important probes for studying dynamic processes in physics, chemistry and biology. The limiting time scale in many body systems is of the order of h/kT, which is about 100 fs at ambient temperature. Thus, there is tremendous potential for radiation sources shorter than 100 femtoseconds. Recently, there has been remarkable progress in visible laser technology to generate femtosecond pulses [1]. In this Letter, we propose and analyze a method to generate ultrashort radiation pulses in the x-ray wavelength range. The method is based on Compton scattering of a femtosecond laser beam by a low energy electron beam at a right angle. Femtosecond x-rays are generated because the interaction takes place during the short interval in which the femtosecond laser pulse crosses a tightly focussed electron beam in the transverse direction. The method takes full advantage of the recent developments of ultrashort visible laser technology and bright electron beam sources.

Compton backscattering, in which a photon reverses its direction on colliding head-on with an electron, has been proposed as a way to generate x-rays with optical lasers and low energy electron beams either through the spontaneous emission or the free electron laser mechanism [2]. The 90° Compton scattering discussed in this Letter is related to Compton backscattering in that they both produce short wavelength radiation in the direction of the electron beam, with wavelengths shortened by a factor of order $1/\gamma^2$, where γ is the electron energy in units of its rest mass. However, they are quite distinct in the short pulse capability. In Compton backscattering, the pulse length of the generated x-ray beam is given roughly by the average of electron and the laser pulse lengths. Since it is difficult at present time to generate an intense electron bunch that is much shorter than a few picoseconds, this process does not appear to be useful for generation of femtosecond x-rays. However, we observe that a low emittance electron beam can be focussed tightly to a transverse dimension much smaller than the electron pulse length. Therefore, the possibility arises that much shorter pulses of x-rays can be generated by arranging the laser beam to meet the electron beam at a right angle rather than head-on. This is the basic idea behind the 90^o degree Compton scattering discussed in this Letter. The scheme is illustrated schematically in Fig. 1.

A simple way to analyze the Compton scattering in a general configuration is to notice the similarity between the role of a laser beam and a static magnetic undulator in inducing a sinusoidal motion of the electrons. Consider the general case where a laser beam propagates toward an electron beam at an angle ϕ. We assume that the electric field associated with the laser beam is in the direction perpendicular to the scattering plane with a peak amplitude E_0. In terms of the laser intensity dP/dA (power per unit area), we have

$$E_0 = \sqrt{2Z_0\frac{dP}{dA}} \quad , \tag{1}$$

where Z_0=377 Ohms is the free space impedance. The laser beam is equivalent to a static magnetic undulator with the peak magnetic field $B_0 = E_0(1+\beta\cos\phi)/c$ and period length $\lambda_u=\lambda_L/(\cos\phi+1/\beta)$. Here, c is the speed of light, β=v/c, and v is the speed of the electron, and λ_L is the wavelength of the laser radiation. In the following, we assume that the electrons are relativistic, i.e., $\gamma= 1/\sqrt{1-\beta^2} >> 1$, $\beta\approx1$. For the right angle case, $\cos\phi=0$, we have therefore

$$B_0 = \frac{E_0}{c} \quad , \tag{2}$$

$$\lambda_u = \lambda_L \quad . \tag{3}$$

For an undulator, it is convenient to introduce the deflection parameter K as follows:

$$K = eB_0\lambda_u/2\pi mc \tag{4}$$

The radiation characteristics from an undulator are well known [3], [4]. In the forward direction (the direction of the electron beam), the spectrum has a peak at a wavelength

$$\lambda_1 = \lambda_u(1+K^2/2)/2\gamma^2 \tag{5}$$

For laser parameters considered in this paper, the deflection parameter K turns out to be much less than unity. In that case, the number of photons generated by a single electron per unit wavelength is

$$\frac{dn_1}{d\lambda} = \pi\alpha K^2 N \frac{1}{\lambda} F\left(\frac{\lambda_1}{\lambda}\right) \quad . \tag{6}$$

Here, $\alpha \approx 1/137$ is the fine structure constant, N is the number of the undulator periods experienced by the electron, and $F(\chi)$ is a function that vanishes for $\chi > 1$. For $\chi \leq 1$,

$$\begin{aligned} F(\chi) &= \chi\left(\chi^2 + \tfrac{1}{2}(1-\chi)^2\right) && ;\ \sigma\text{-polarization} \\ &= \tfrac{1}{2}\chi(1-\chi)^2 && ;\ \pi\text{-polarization.} \end{aligned} \tag{7}$$

For N>>1, the spectrum and the angular distribution are correlated: the wavelength $\lambda \geq \lambda_1$ is emitted at an angle

$$\theta = \frac{1}{\gamma}\sqrt{\frac{\lambda-\lambda_1}{\lambda_1}} \quad . \tag{8}$$

The number of σ-polarized (polarization parallel to electron trajectory) photons emitted into a given bandwidth $\Delta\lambda/\lambda = (\lambda-\lambda_1)/\lambda_1 << 1$ is

$$\Delta n_1 = \pi\alpha K^2 N(\Delta\lambda/\lambda) \quad . \tag{9}$$

For an explicit calculation of the temporal characteristics of the emitted radiation pulse, we assume that the electron and the laser beams are propagating along the z- and y-directions, respectively. The intensity profile of the laser beam is taken to be Gaussian, given at time t by

$$I(x,y,z,t) = I_0 \exp - \frac{1}{2}\left[\frac{(y-ct)^2}{\sigma_L{}^2} + \frac{x^2+z^2}{\sigma_w{}^2}\right] \tag{10}$$

where σ_L and σ_w are the rms length and the width of the laser beam, respectively, and I_0 is the peak laser intensity proportional to $E_0{}^2$. (We note in passing that the rms width σ_w is one half of the waist in the laser terminology.) In Eq. (10), we have neglected the y-dependence of σ_w, assuming that the Rayleigh range is much longer than the laser pulse length σ_L. Similarly, we assume that the electron beam envelope function ("beta" function) is much greater than the electron beam pulse length. Electron trajectories can then be assumed to be parallel to the z-axis. The trajectory of a particular electron is

$$x = x_i,\ y = y_i \text{ and } z = ct\text{-}z_i \tag{11}$$

Inserting this into Eq. (10), we find the intensity felt by that electron as a function of time is given by

$$I_i(t) = I_0 \exp - \frac{1}{2}\left(\frac{(t-t_i)^2-t_i^2}{\sigma_\tau{}^2} + \frac{y_i^2}{\sigma_L{}^2} + \frac{x_i^2+z_i^2}{\sigma_w{}^2}\right) \tag{12}$$

where

$$\frac{1}{\sigma_\tau^2} = c^2\left(\frac{1}{\sigma_L^2} + \frac{1}{\sigma_w^2}\right) \ , \tag{13}$$

$$t_i = c\sigma_\tau^2\left(\frac{y_i}{\sigma_L^2} + \frac{z_i}{\sigma_w^2}\right) \ . \tag{14}$$

The function $I_i(t)$ is of a Gaussian shape with the maximum at $t = t_i$ and with an rms width σ_τ. The strength of the magnetic field of the equivalent undulator felt by the electron is also Gaussian in t with an rms width $\sqrt{2}\ \sigma_\tau$. The effective number of periods is then given by

$$N_{eff} = 2\sqrt{\pi}c\sigma_\tau/\lambda_L \ . \tag{15}$$

The undulator radiation pulse from ith electron is generated at $t = t_i$ and $z = \bar{z}_i = ct_i\text{-}z_i$, and moves parallel to and very closely behind the electron. Its length, $\lambda_1 N_{eff}$, is very short, and may be neglected compared to other dimensions of the problem. The pulse passes through the $z = 0$ plane at $t = z_i/c$. The number of photons generated by the ith electron that passes through $z = 0$ per unit time can therefore be written as follows:

$$\frac{d\Delta n_i}{dt} = \pi\alpha K^2 N_{eff} \frac{\Delta\lambda}{\lambda} \delta(t\text{-}z_i/c) \exp -\frac{1}{2}\left(-\frac{t_i^2}{\sigma_\tau^2} + \frac{y_i^2}{\sigma_L^2} + \frac{x_i^2+z_i^2}{\sigma_w^2}\right) \ . \tag{16}$$

We assume that the electron distribution is Gaussian. Thus, the number of electrons in the volume element $dx_i dy_i dz_i$ is

$$f(x_i,y_i,z_i)dx_i dy_i dz_i = \frac{n_e}{(2\pi)^{3/2}\sigma_x^2\sigma_z} \exp -\frac{1}{2}\left(\frac{x_i^2+y_i^2}{\sigma_x^2} + \frac{z_i^2}{\sigma_z^2}\right) dx_i dy_i dz_i \ , \tag{17}$$

where n_e is the total number of electrons. The total number of photons is obtained by multiplying Eq. (16) and (17), and integrating over x_i, y_i, and z_i.

After some calculation, we obtain

$$\frac{d\Delta n}{dt} = \pi\alpha K^2 N_{eff}\left(\frac{\Delta\lambda}{\lambda}\right)\left(\frac{I}{e}\right)\frac{\sigma_w\sqrt{\sigma_w{}^2+\sigma_L{}^2}}{\sqrt{\left(\sigma_x{}^2+\sigma_w{}^2\right)\left(\sigma_x{}^2+\sigma_w{}^2+\sigma_L{}^2\right)}}\exp-\left(t^2/2\,\sigma_T^2\right), \tag{18}$$

where I is the peak electron current, e is electron charge, and

$$\sigma_T = \frac{\sigma_z\sqrt{\sigma_x{}^2+\sigma_w{}^2+\sigma_L{}^2}}{c\sqrt{\sigma_z{}^2+\sigma_x{}^2+\sigma_w{}^2+\sigma_L{}^2}} \quad . \tag{19}$$

is the rms pulse length of the x-rays. By integrating Eq. (18), the total number of generated photons is

$$\Delta n = \pi\alpha K^2 N_{eff}\, n_e\left(\frac{\Delta\lambda}{\lambda}\right)\frac{\sigma_w\sqrt{\sigma_w{}^2+\sigma_L{}^2}}{\sqrt{\left(\sigma_x{}^2+\sigma_w{}^2\right)\left(\sigma_z{}^2+\sigma_x{}^2+\sigma_w{}^2+\sigma_L{}^2\right)}} \tag{20}$$

Inserting the expression for K from Eqs. (4), (2), and (1), and N_{eff} from Eq. (15) we find a convenient formula for Δn as follows:

$$\Delta n = 113 n_e\, J\, \lambda_L\, \frac{\Delta\lambda}{\lambda}\, \frac{1}{\sqrt{\left(\sigma_x^2+\sigma_w^2\right)\left(\sigma_z^2+\sigma_x^2+\sigma_w^2+\sigma_L^2\right)}} \quad , \tag{21}$$

where J is the energy in the laser pulse in Joules, and λ_L and beam dimension σ's are measured in microns.

As an example, we consider the electron and the laser beams characterized by Tables 1 and 2.

Table 1. Electron Beam

Energy	32 MeV ($\gamma = 63$)
RMS pulse length (σ_z)	3 ps
Charge/pulse	1.6 nC
Normalized rms emittance	5 mm-mrad
Focussed transverse rms width (σ_x)	50 μm

Table 2. Laser Beam

Wavelength (λ_L)	8000 Å
Energy/pulse	0.2 J
RMS pulse length (σ_L/c)	170 fs
Focussed transverse rms width (σ_w)	50 μm
Power density (dP/dA)	3×10^{19} W/m^2

The electron beam parameters listed in Table 1 are consistent with those obtained by the photocathode gun technology originally developed at LANL [5] and now being pursued at several other institutions. The electron beam focussing assumed in Table 1 is tight but achievable. The laser parameters listed in Table 2 are consistent with the recent development in "T^3" class lasers [6]. The parameters of the equivalent undulator are, $\lambda_u = 0.8$ μm, $B_0 = 500$ T, $K = 3.7\times10^{-2}$ and $N_{eff} = 156$. The wavelength of the x-rays generated is peaked at $\lambda_1 = 1$ Å, the rms pulse length calculated from Eq. (19) is $\sigma_T = 300$ fs. The number of the x-ray photons within a 10% bandwidth is, from Eq. (20), $\Delta n \approx 2.7 \times 10^5$. The half-angle of the pinhole required to collect 10% bandwidth is 5.0 mrad. The result is summarized in Table 3.

Table 3. Generated X-Ray Beam

Wavelength (λ_1)	1 Å
RMS pulse length (σ_T)	300 fs
Number of photons ($\Delta\lambda/\lambda = 0.1$)	2.7×10^5
Collection angle (2θ)	2 x 5 mrad

The above example is worked out to demonstrate what can be readily achieved with currently available accelerator and laser parameters. The performance could be significantly improved in several aspects: With tighter electron beam focussing and shorter laser pulses, generation of x-ray pulses shorter than 50 fs should be feasible. With a laser operating in a cavity configuration and a CW electron beam potentially achievable via the rapidly evolving technology of superconducting radio-frequency (RF) cavities and photocathodes, the collision frequency up to 100 MHz should be feasible, raising the average flux of ultrashort x-ray pulses to 10^{14} photons/sec.

Several schemes have been proposed recently for sub-picosecond x-ray generation. Some examples are that based on bunch rotation in a storage ring using RF cavities [7], chirping the electron beam energy [8], the FEL bunching mechanism [9], a laser-produced plasma [10], etc. The femtosecond x-ray source discussed in this Letter is based on a very simple physical process producing reasonably 'directed' x-rays and is also compact because it does not require high energy electron beams. The potential for eventual reliable use in scientific investigations seems promising.

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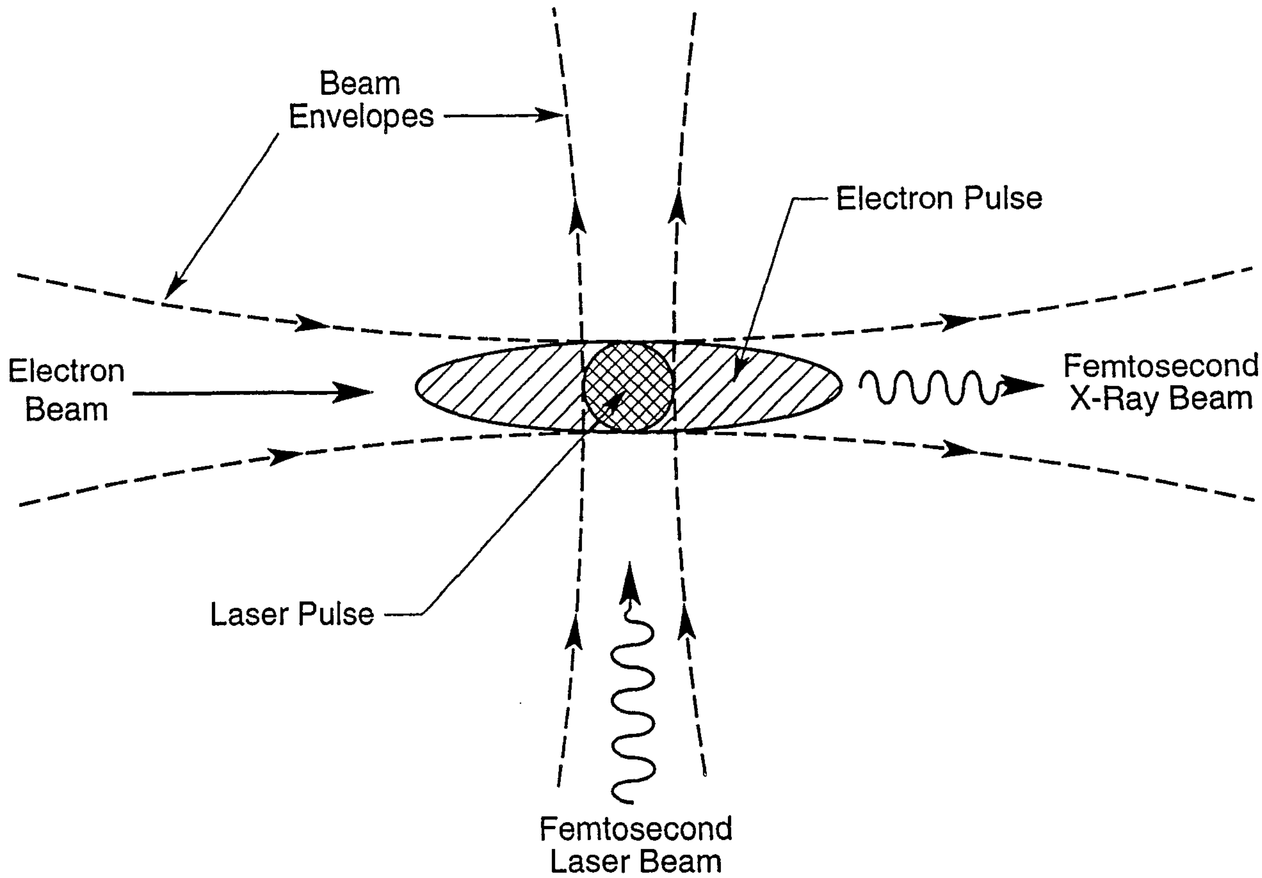

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Fig. 1 A schematic illustration of 90° Compton scattering.