An Inverse Compton Scattering Radiation Source via Self-Guiding in a Plasma

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Abstract. In an inverse-Compton scattering source, in which a relativistic electron beam collides with a high-power laser pulse, the x-ray flux produced is proportional to the brightness of the two beams and the size of their overlap region in three-dimensional space. In vacuum, this overlap is limited by the diffraction of the two beams, but the diffraction limit can be overcome by confining both beams in a plasma guiding channel. A dense, bunched electron beam injected into an underdense plasma will self-guide via ``blowout," in which the beam head creates a focusing ion channel through which the body of the beam is guided; this same channel can also guides a counterpropagating laser beam. Constraints include the need for long laser wavelength (1 to 10 μm) and high beam densities. We present a possible configuration for a gamma-ray source using 180° Compton scattering in a uniform plasma, including 2D simulation results. Estimated photon yields are up to a factor of 5 larger than in vacuum scattering, with production of nearly 10^{10} photons per nanocoulomb of electron beam charge.

Keywords: Compton scattering, radiation source, plasma channel.
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INTRODUCTION

High-brightness sources of short-wavelength radiation (from the ultraviolet to x-rays and gamma rays) have become indispensable tools for the chemical and biological sciences. Conventional light sources have limitations in spectral purity and energy, and there is demonstrated need for laser-based x-ray sources which can be extended well into the keV region, are well-collimated and peaked at a single energy, are bright enough for single-shot measurements, and have arbitrarily high temporal resolution. Ongoing experimental approaches to this goal include x-ray free-electron lasers in development at SLAC (LCLS) and DESY (TESLA), emission from laser-excited solids or plasmas, and also several types of electron-laser scattering experiments, collectively known as Thomson or Compton scattering, in which high-energy photons are produced by the scattering of long-wavelength laser light from a relativistic electron beam. The scattered radiation will naturally be collimated in a cone of angle $1/\gamma$ around the electron beam direction. While large FELs are projected to produce record-breaking numbers of x-ray photons, they are ultimately limited in photon energy to a few tens of keV due to lower limits on achievable undulator wavelengths. Scattering-based systems have the considerable advantage of compactness, and can in principle be scaled into the γ-ray regime, where high-brightness sources do not currently exist. Current or recent experimental efforts include those at Lawrence Livermore National Laboratory [1,2], Sumitomo Heavy Industries [3], the University of Michigan [4], and Brookhaven National Laboratory [5]. In general, the goals of such experiments are to achieve greater and greater photon flux per pulse and/or peak spectral brightness.

The scheme proposed here represents one possible approach to increasing the brightness of scattered x-ray pulses. To obtain the highest yield at the highest energy from a given e-beam and laser, one must use head-on scattering (180° incident angle) and match the sizes of the laser and electron beams to the largest possible degree. However, in practice the photon density achievable is constrained by the focal parameters of both e-beam and laser, and the flux is diffraction-limited. We propose to avoid the diffraction limit by confining both electron and laser beams within a self-created plasma channel, which can act as a guide to preserve high beam densities over many times the diffraction length. This approach increases yield while avoiding the difficulties of creating and timing a pre-formed channel.

Photon Production and Geometry

The total photon number N_x produced per collision is given to order-of-magnitude approximation by

$$N_x = \sigma_T \frac{N_b N_\gamma}{A} \frac{L}{Z_R} \tag{1}$$

where σ_T is the Thomson scattering cross-section (0.665 barn), N_b, N_γ are the e-beam and photon populations, A is the cross-sectional overlap area of the two beams, the Rayleigh range $Z_R = \pi w_0^2/\lambda$, and L is the effective interaction length of the two beams. For most practical experiments, $L = 2Z_R$, the confocal parameter. The decrease in A as the laser focus is sharpened is then cancelled by a proportional decrease in L (i.e. the product of waist size w_0 and diffraction angle is invariant). To further increase photon density, one must use higher laser power; however, as the value of a_0 approaches unity, transverse effects become important, leading to relativistic wiggle velocities in the electron beam and multiple harmonics in the scattered radiation spectrum, which may not be desired.

The electron beam focus is limited in a similar way by diffraction effects related to the beam's intrinsic emittance ($\varepsilon \approx \sigma_r \sigma_{r'}$ for a round beam), which is an invariant; increasing brightness on axis comes at the expense of faster divergence. Axial compression of the electron bunches, to fit within $2Z_R$, also has the effect of increasing space charge and leading to poorer beam quality.

Channel guiding, in effect, increases the interaction *volume* in order to avoid high-field and space-charge effects.

LASER AND ELECTRON BEAM GUIDING

Laser Guiding in a Plasma Channel

It has long been known that a laser can be guided over long distances by a density depression, or channel, in an otherwise uniform plasma [6]. Plasma guiding over many Rayleigh ranges has been demonstrated experimentally using both pre-formed and laser-formed plasma channels [7,8]. Laser pulses can in fact self-guide in a uniform plasma if the head of the laser pulse is intense enough to remove plasma electrons from the axis; the main body of the beam is guided by the channel created, though the head will erode. It has been shown, however [9,10], that self-guiding requires the laser pulse length L to be at least several times λ_p; with $L < \lambda_p$, diffraction occurs nearly as quickly as in vacuum. Also, to remove electrons from the channel, the laser power must be at least a certain critical value [11,12], which is given in units of gigawatts by $P_{crit} = 17.4\ (\lambda_p/\lambda)^2$. For reasonable laser power, this expression leads to very high values of n_0, and in turn to extremely dense electron beams.

Use of a pre-formed channel reduces the stringent requirement on laser power [6]. A weak pulse will be guided by a plasma density depression Δn if

$$\Delta n = \frac{1}{\pi r_e w_0^2} \ . \tag{2}$$

Here, Δn is the difference in plasma density between the edge of the channel (at $r = w_0$) and the value on axis, and r_e is the classical electron radius, 2.82×10^{-13} cm. The optimal channel profile is parabolic. For a hard-edge profile with no electrons on axis, we may denote a critical ambient density for guiding by $n_{crit} = \Delta n = n_0$, which may not be given exactly by Eq. (2) Note that while Eq. (2) is nominally wavelength-independent, the achievable waist size depends naturally on the wavelength, with more ambitious guiding required for long-wavelength radiation. The problem then becomes the creation of a suitable guiding channel using an electron beam.

Electron Beam Self-Guiding

Intense, relativistic electron beams (having density greater than the ambient plasma density) will drive a nonlinear plasma response in which electrons are ejected entirely from the channel of the driving beam (the ‘blowout’ regime). The resulting electron-rarefied region has electrostatic focusing fields which are linear in radius [13]; the focal strength depends linearly on the plasma density. When a long ($\sigma_z >> \lambda_p$) electron beam is injected into a plasma, the beam head will drive the plasma excitation and will expand radially, but the body of the beam will be focused by the channel created. If the beam's depth of focus (or beta function) at injection is correctly matched to the plasma ‘lens’ ($\beta_{eq} = \sigma_r^2/\varepsilon = K^{-1/2}$), the body of the beam can propagate over long distances with little change in radius [14]. Recent experimental demonstrations of such self-guiding in the relativistic regime have been performed at Argonne National Laboratory [15] and SLAC [16].

A similar situation has been considered by Shvets and Fisch [17], who proposed a laser acceleration scheme in which a relativistic electron beam self-guides in a plasma; the tail of the beam is then accelerated by a co-propagating laser pulse which is guided in that case by the plasma channel.

γ-RAY PHOTON SOURCE: DESIGN AND SIMULATION

While a scattering-based photon source is scalable to any x-ray energy, it is of particular interest to design a high-intensity, well-collimated source of γ-ray photons, for which no conventional sources exist. Such photons could then be used for e.g. positron production in a collider [18]. Here, we investigate a source of 61 MeV photons, using an 800-nm laser scattering at 180° from a 1.6 GeV electron beam.

The shape and depth of the channel created by the electron beam will necessarily determine the extent to which the laser is guided. The laser should be timed to arrive at the downstream end of the newly-formed plasma channel as the head of the electron beam emerges from it. The electron bunch should also be much longer than the laser pulse (here, $\sigma_{z,b} \sim 100\sigma_{z,\gamma}$). The ideal electron beam radius is related to the energy and plasma density by

$$\sigma_r = \left(\gamma\varepsilon^2 / 2\pi r_e n_0\right)^{1/4} \tag{3}$$

However, the value of n_0 appropriate for the electron beam may be less than n_{crit} for a given laser wavelength. To investigate the importance of this limit for a hard-edged channel, we have simulated the guiding of a laser pulse in such a channel using the particle-in-cell code OOPIC [19]. Results are shown in Fig. 1, where the spot size and

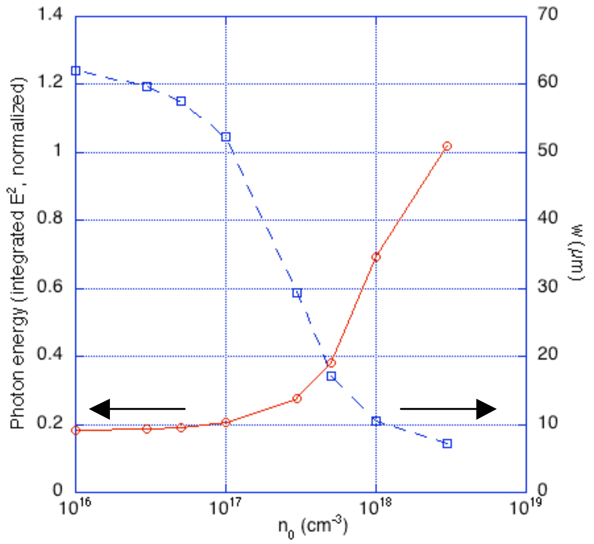

FIGURE 1. Outcome of propagating a laser pulse in a pre-formed, hard-edged plasma channel over 7.6 Z_R, as a function of plasma density. Solid curve shows laser spot size w, dashed curve represents the total photon energy within the channel (proportional to the integral of E^2), normalized to the value at the laser focus. Laser λ = 800 nm, waist size w_0 = 8 µm, channel width = 11 µm. Critical density for this case is 2×10^{18} cm^{-3}.

energy within the channel, after propagation over $7.6Z_R$, are plotted for a range of plasma densities. We see that the photon number within the channel is quite sensitive to density, and that little advantage is gained by channeling if n_0 is much less than about 0.5 n_{crit}, which for a 1-μm laser will typically be in the range of 10^{18} cm^{-3}. Such a value leads to very dense electron beams ($\sigma_r \leq 1$ μm for kinetic energy of 1.6 GeV). We conclude that a more plausible strategy is to decrease the electron beam density from its ideal value; though the beam will then be overfocused by the plasma, adverse effects can be ameliorated if the beam exits the plasma before the pinch point (typical plasma length should be roughly equal to σ_z).

Results of PIC simulation of channel creation by a 1.6 GeV electron beam in a denser-than-optimal plasma are shown in Fig. 2. There is a noticeable taper in channel radius, as plasma electrons near the beam tail have interacted longer with the beam's fields. Optimization of channel shape and more detailed study of its effects on the laser and x-ray beams is ongoing.

Full PIC simulation of the photon yield from this source is challenging, particularly because of the variety of length scales involved when the laser is guided over many Rayleigh ranges. As a preliminary study, we have estimated the total and peak x-ray photon flux using the convolution integral

$$\frac{dN_x}{dt} = \sigma_T \int n_b(x,y,z-ct)\, n_\gamma(x,y,z+ct)\, d^3x \tag{4}$$

where n_b and n_γ are the density of electrons and photons, respectively, and the integral is calculated numerically. An analytic approximation to the photon density for a guided Gaussian laser beam was obtained from empirical fits to PIC simulation data. The electron beam was assumed to be Gaussian and of the same width as the channel, and with $\beta_{\mathrm{eq}} >> Z_R$ we neglect electron beam diffraction and overfocusing effects. While such an approach cannot be used to investigate the x-ray beam characteristics (e.g. opening angle), it is a reasonable approximation for the total photon yield.

Results are shown in Fig. 3, where the peak and total photon yields are calculated per nanocoulomb of beam charge, assuming a short-pulse (150 fs) terawatt laser with

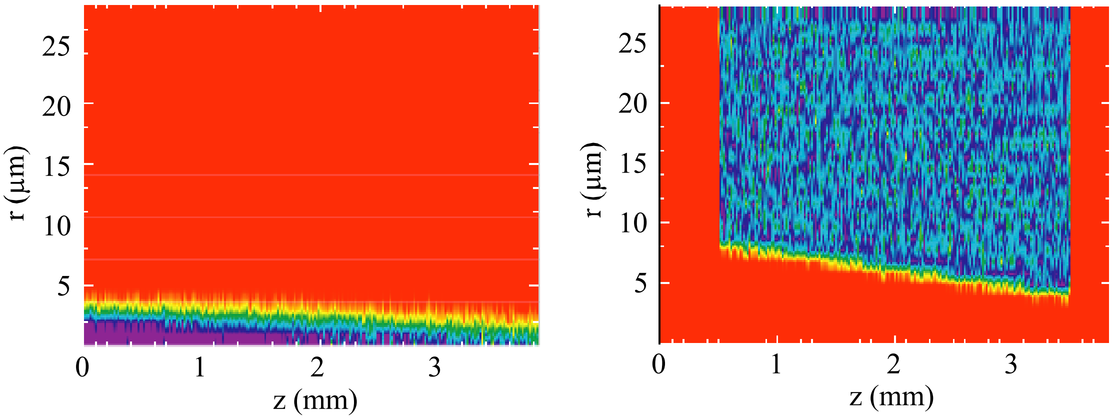

FIGURE 2. False-color maps (from PIC simulation) of electron-beam density (left) and plasma electron density (right), showing the channel created as a 1.6 GeV, 5 nC electron beam enters a finite plasma with $n_0 = 10^{18}$ cm^{-3}. The beam is Gaussian, with $\sigma_r = 2$ μm and $\sigma_z = 3$ mm; $n_b/n_0 \sim 10$.

λ = 800 nm. While the peak yield barely changes, as expected, the total yield increases by a factor of 4 in this example. Larger gains in yield are possible, though it is unlikely that a full order of magnitude increase over the unguided case can be obtained.

Beam and laser parameters for this gamma-ray source are listed in Table 1.

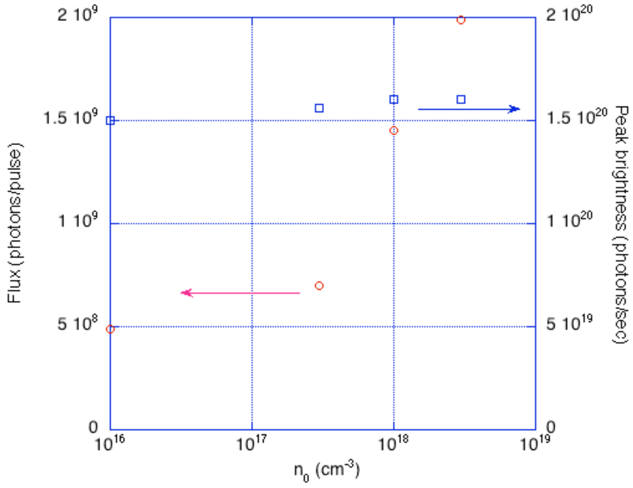

FIGURE 3. Gamma-ray photon flux per pulse (circles) and peak flux per second (squares), per nanocoulomb of electron beam charge, calculated semi-analytically as a function of plasma density. Laser and channel parameters are as in Table 1.

TABLE 1. Parameters for Scattering-Based γ Photon Source.

Parameter	Value
E-beam energy	1.6 GeV
E-beam spot size (σ_r)	2.3 µm
E-beam normalized emittance (ε_n)	20 π mm mrad
E-beam length	3 mm
E-beam charge	100 nC
Laser wavelength (l)	800 nm
Laser energy/pulse	1.5 J
Confocal parameter ($2Z_R$)	81 µm
Plasma density	2×10^{18} cm^{-3}
Plasma thickness	3 mm
Blowout factor n_p/n_b	8.6
Guiding lengths	16
Scattered photon energy	61 MeV
Total photon yield	~8×10^{11}

SUMMARY

Laser guiding in a beam-created plasma channel has the potential to enable a high-brightness, long-pulse x- or gamma-ray photon source via inverse Compton scattering. The scheme is conceptually simple and easy to time, relying only on simultaneous electron and laser beams. By avoiding laser diffraction, photon production can be increased well beyond the level obtained from 180° Compton scattering in vacuum, and can in principle reach or exceed one photon per electron. Furthermore, the increase in yield provided by this method enables high photon flux to be produced using a short-wavelength (e.g. 800 nm) laser rather than the typical 10.6 μm; this in turn leads to low laser field ($a_0 \leq 0.1$). Operating at lower field strength avoids nonlinear interaction and the concomitant generation of higher radiation harmonics.

Preliminary investigation indicates that photon yields from guided Compton scattering may be on the order of 4 to 5 times larger than those in the unguided case. A gamma-ray source at 60 MeV could be obtained using electron beams typical of collider facilities (E = 1.6 GeV, q = 10–100 nC), resulting in photon flux on the order of at least 10^{11} photons/pulse. This yield is comparable to that of other proposed scattering schemes involving pre-formed channels or multiple lasers, while being potentially simpler to operate.

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