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# Guiding of X-rays from Inverse Compton Scattering as a means to enhance flux and brightness

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ABSTRACT

Guiding of the X-ray photons emitted in an Inverse Compton Scattering (ICS) device is possible using small diameter tubes. Whereas guiding of the electron and laser beams can directly increase the flux output of ICS interactions, manipulating the beams' propagation can be very challenging. Guiding the output X-rays can be straightforward and offers three enhancements of the usable flux: off-axis X-rays are collimated along the tube; out of bandwidth photons are not guided and therefore filtered out; and, the guiding can be extended far from the interaction region towards the intended application. A tube, acting as a waveguide for the X-rays, can increase the brightness relative to free space propagation by the square of the number of reflections. We present preliminary calculations of the guiding mechanism and explain why Liouville's theorem is not violated. Typical achievable parameters and application scenarios are also described including practically realizable waveguides and materials.



## 1. Introduction

Inverse Compton Scattering (ICS) sources provide a promising path to the generation of high-brightness X-ray fluxes from a compact device [1]. The brightness of a given ICS-based source is a function of the electron beam density, the laser fluence, and the overlap of the two. A simple expression for the output photon count can be obtained under the assumption that the laser Rayleigh length, $Z_R$, and electron beam minimum beta-function, $\beta^*$, are both shorter than either pulse length ($\sigma_z = c\sigma_t$):

$$N_\gamma = \left[\frac{N_L N_e}{4\pi\beta^*\varepsilon}\right]\sigma_{th}, \tag{1}$$

where $\varepsilon$ is the electron beam emittance, $\sigma_{th}$ the Thomson cross-section, $N_L$ and $N_\varepsilon$ are the laser and electron fluxes, respectively [2]. The above assumption minimizes the "hour-glass" effect on the luminosity. In Eq. 1 a smaller $\sigma_z$, and thus smaller $Z_R$ or $\beta^*$, seems to imply larger fluxes, but this is only at the cost of increase of the off-axis red shifts that degrade the desired monochromaticity. In all cases, it is clear that greater overlap between the beams would produce greater X-ray flux and in some cases higher brightness output.

Guiding can provide a means of increasing the desired interaction between the beams. We briefly consider the possible effects of guiding each of the three beams in an ICS interaction: the laser, the electron, and the X-ray beams. For this discussion, we consider a highly simplified model with uniform cross-section and monochromatic beams. For free space, the "uniform" laser propagation length is set by the Rayleigh range $L_R = 2Z_R = 2\pi w_0^2/\lambda_L$, and in general we take the propagation length equal to the pulse length: $L_R = L_L$. A numerical example is useful to examine all the forms of guiding: we take a 10 ps IR laser, $L_R = 3$ mm and $\lambda_L = 1\,\mu$m, with an electron beam of 30 MeV ($\gamma \approx 60$) and a normalized emittance $\varepsilon_n = 1\,\mu$m. Then, we see that $2w_0 \approx 40\,\mu$m. Because $\varepsilon = \varepsilon_n/\gamma = \lambda_L$, the laser beam diffraction limits the minimum spot size. Guiding the laser beam seems worth considering as a means of overcoming this limit.

## 2. Laser guiding

Guiding the laser [3–5] reduces the effects of diffraction and the Gouy phase shift. Assuming some form of waveguide (e.g. fiber) is used to guide the interaction laser (Fig. 1), we can estimate the flux enhancement. In practice, the fiber (waveguide) will be overmoded: the radius of the guide $R_g \gg \lambda_L$. On the other hand, a very small bore is required to obtain significant enhancement from guiding. For the example case of the last section, we can take $2R_g = 20\,\mu$m. The naive flux enhancement factor is simply given by $(2w_0/2R_g)^2$, which in our example is 4. The brightness may be enhanced further, beyond this modest amount, as the generated X-ray bandwidth is also narrowed (lower Gouy phase shift).

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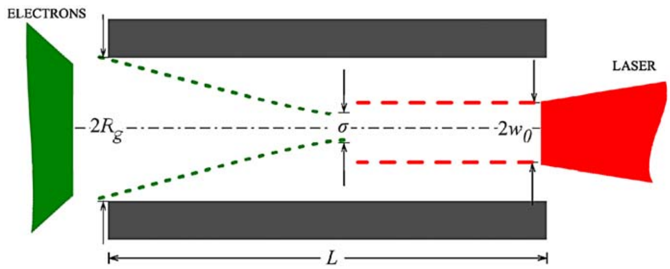


**Fig. 1.** Guiding of the laser, entering from the right, is shown schematically in an ICS interaction with an unguided electron beam, entering from the left. A guiding tube of length $L$ is shown.

We note that there are many additional practical considerations in order for laser guiding in ICS to be realizable, including: breakdown, vacuum, and electron beam transmission. For instance, the electron beam waist is nearly the size of the example guide

$$\sigma = \sqrt{\frac{\varepsilon_n \beta}{\gamma}} = \sqrt{\frac{\varepsilon_n L}{\gamma}} \approx 7\,\mu\text{m}. \tag{2}$$

## 3. Electron guiding

Given the challenges in laser guiding, and the modest results, it is natural to consider guiding the electron beam as well. Electron beam guiding can ameliorate the detrimental effects of emittance and space charge, and can aid in implementing laser guiding. In a general context, a number of approaches to guiding electrons have been considered [6–8].

Within the context of an ICS, at least one approach has been proposed for laser guiding: Yoder and Rosenzweig [9] examined self-guiding in a plasma column. They found that to achieve even modest (factors of 4–5) enhancement of the ICS flux, it was necessary to use long (3–6 mm) electron beams with high charge (10–100 nC). In such cases, guiding through blowout was found along with guiding of the laser over 5–10 Rayleigh ranges.

## 4. X-ray guiding

While laser and electron beam guiding are promising, they are both challenging and appear to only apply in certain regimes. X-ray guiding may be more widely beneficial. Guiding of X-rays has been studied since at least as early as 1965 [10]. Guiding of the output X-rays from an ICS source can enhance the brightness through angular and energy filtering. In addition, guiding provides a means of delivering the X-rays to an off-axis target (e.g. a patient undergoing medical imaging).

There are at least three ways to consider guiding X-rays: hollow glass-fibers (capillaries); metal tubes; and photonic bandgap (PBG) structures. For simplicity, we consider the tubes and capillaries. A Drude model can be applied in these cases. The index of refraction is then given by

$$n(\omega)^2 = 1 - \frac{\omega_p^2}{\omega^2}, \tag{3}$$

where

$$\omega_p^2 = \frac{e^2 n_e}{\varepsilon_0 m_e}, \tag{4}$$

is the plasma frequency, $e$ is the electron charge, $m_e$ is the electron mass, $\varepsilon_0$ is the permittivity of free space, and $n_e$ is the density of electrons with binding energy less than the photon energy. At high energies (i.e. hard X-rays), $n_e$ can be all the electrons in the material.

The transmission of an X-ray will depend strongly on its angle, and there is a critical angle for total internal reflection

$$\theta_c = \frac{\omega_p}{\omega} = 1. \tag{5}$$

We note that while the above analysis uses a simplistic model, in all cases one expects a transmission curve that falls off rapidly at some critical angle. Indeed, more sophisticated models and experimental measurements agree with this expectation (Fig. 2).

We now consider the effect of the transmission cut off with angle in an extended source such as the ICS. Under our assumptions, we can model the ICS as emitting uniformly over its interaction length, and then use an equivalent planar source of finite cross-section (Fig. 3).

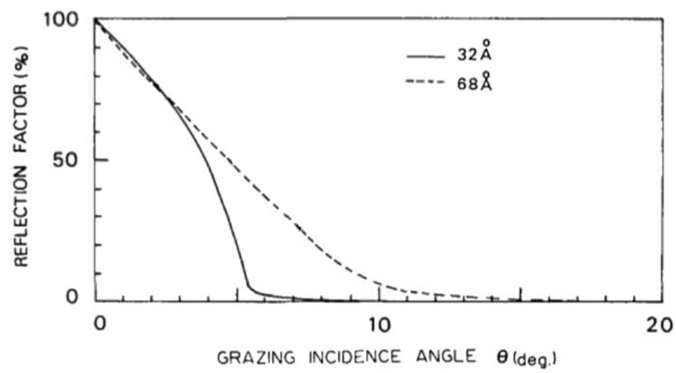


**Fig. 2.** A plot of the measurement of internal reflection of X-rays versus incidence angle in a tube, taken from Ref. [11].

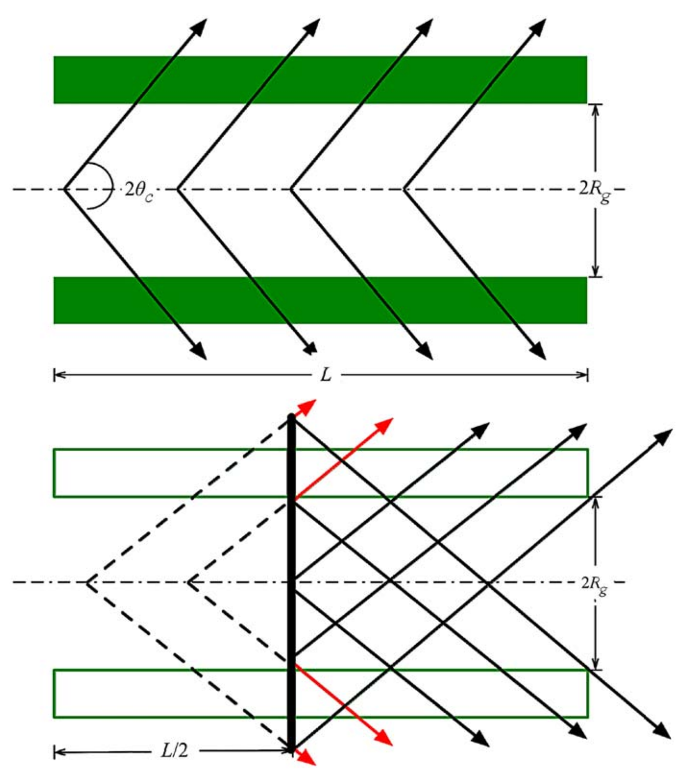


**Fig. 3.** (Top) An ICS source modeled as uniformly emitting over its length, and (bottom) the equivalent finite cross-section source, emitting from midway down the ICS interaction length.

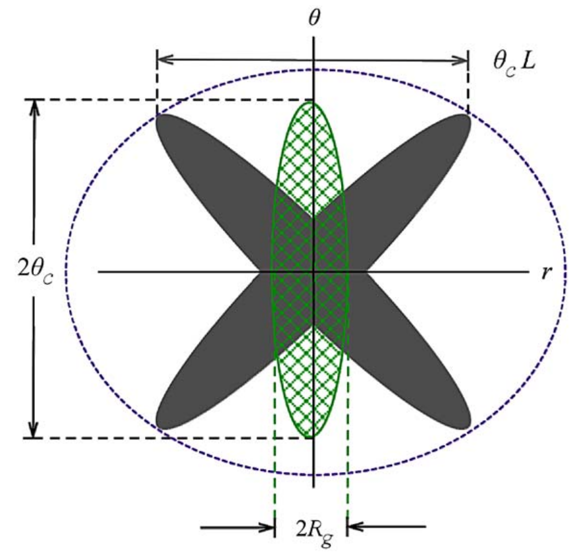


**Fig. 4.** The minimum phase space area of an unguided extended source is shown in the shaded diagonal ellipses, and the maximal phase space area of a guided source is shown in the cross-hatched upright ellipse.

With the above simplifications, it is easy to compare the phase space area of a guided and unguided source. In the unguided case, the equivalent phase space area is given by $2\theta_c{}^2L$, assuming that $\theta_c L \gg 2R_g$ (i.e. the natural source size is much larger than the guide). This area is best understood via the diagram of Fig. 4. As can be seen, the smallest circumscribing ellipse is larger than the area we specified.

The guided case has a phase space area of at most $2\theta_c 2R_g$ (again, Fig. 4). Thus, the phase space area reduction obtained from guiding the X-rays is at least

$$\frac{2\theta_c^2 L}{4\theta_c R_g} = \frac{\theta_c L}{2R_g}. \tag{6}$$

The above factor is nothing more than the inverse of the number of zig-zags in the tube — the number of reflections performed by an X-ray incident at the critical angle — as seen in Fig. 5.

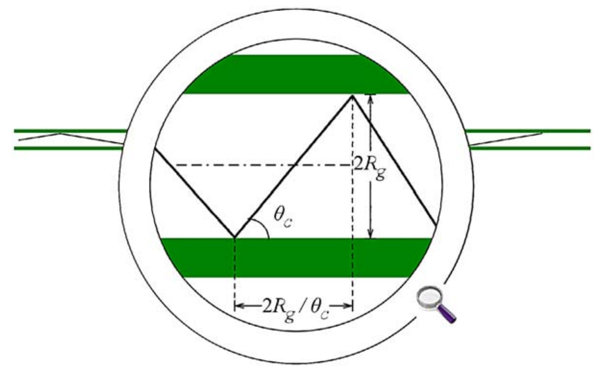


**Fig. 5.** A cartoon showing the path of an X-ray, incident at the critical angle, would take traversing a guiding tube.

We consider an example with a relatively short tube, $L = 3$ mm, a typical critical angle $\theta_0 = 1/40$ rad, and a small tube diameter, $2R_g = 13\,\mu$m. Then, the enhancement factor is $\approx 10$ in each plane. Hence, we expect a phase space area reduction in the order of 100. This considerable enhancement of the brightness comes with the attendant challenges already mentioned for both the laser and electron beam guiding: breakdown, propagation, etc.

Finally, it is important to recognize that Liouville's theorem is not violated by our brightness enhancement assertion as this is not a conservative system: the source is providing power throughout the interaction length.

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