Guiding of X-rays from Inverse Compton Scattering as a Means to Enhance Flux and Brightness

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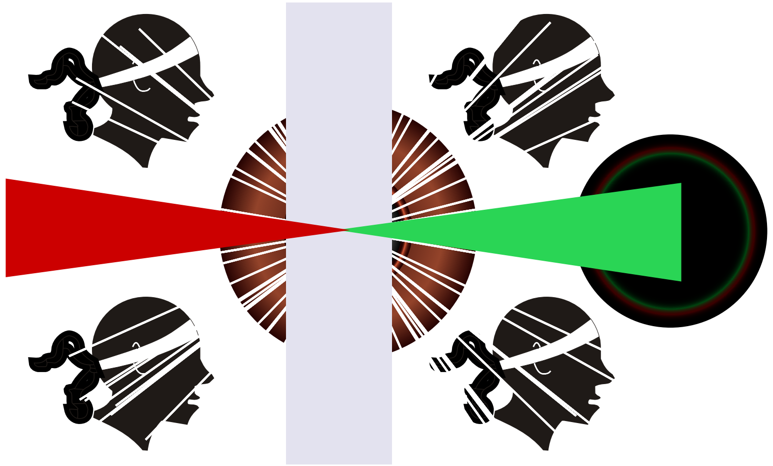
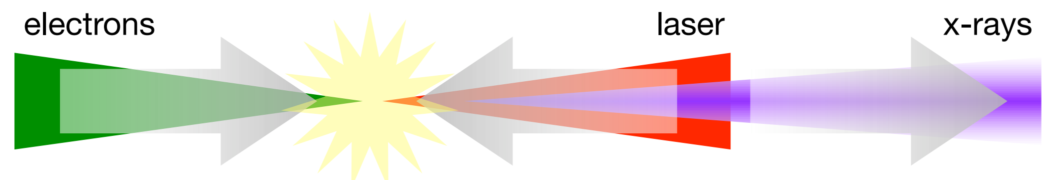


Abstract

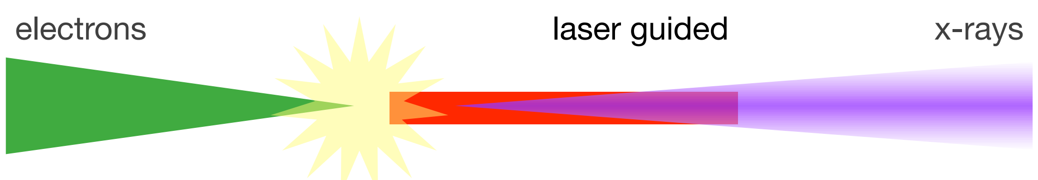
Guiding of the x-ray photons emitted in an ICS device is possible using small diameter tubes. Whereas guiding of the electron and laser beams can directly increase the flux output of ICS interactions, manipulating the beams' propagation can be very challenging. Guiding the output x-rays can be straightforward 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.

There are three beams to guide in the ICS interaction

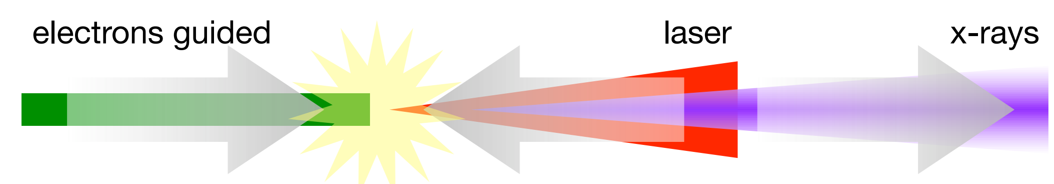
ICS interaction



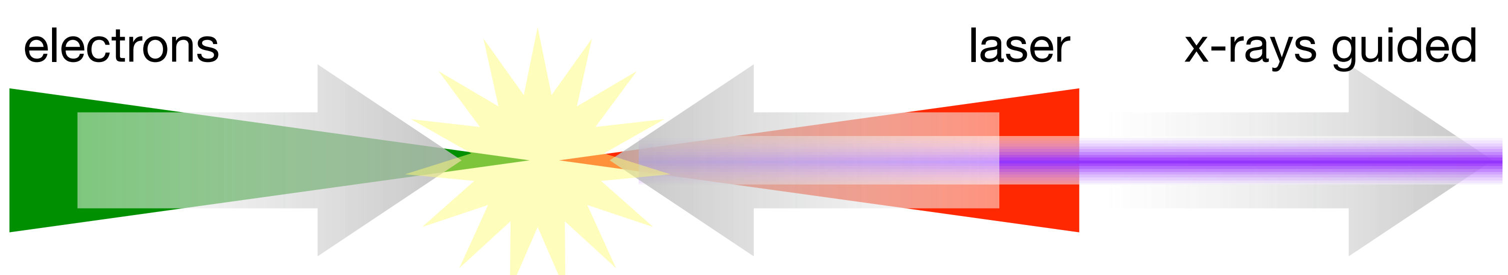
1 laser guiding



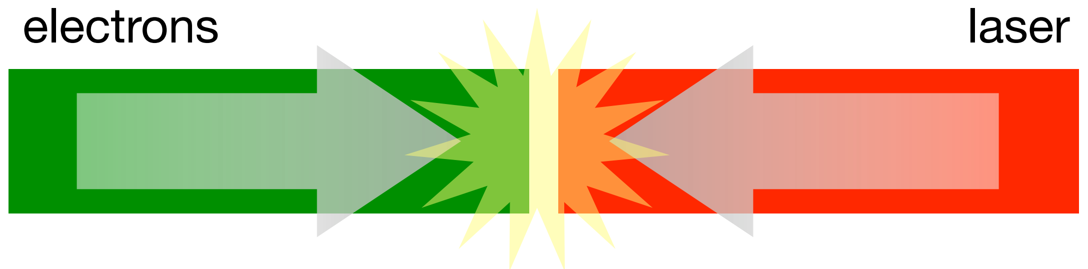
2 electron guiding



3 x-ray guiding



We consider a simplified model with uniform cross sections and monochromatic / monoenergetic beams



For free space, the "uniform" laser propogation length is set by the Rayleigh range

$$L_R = 2Z_R = 2\frac{\pi w_0^2}{\lambda}$$

In general, we take

$$L_R = L_L$$

Our baseline parameters:

$$\tau_L = 10\text{ ps} \Rightarrow \mathrm{L}_L = 3\text{ mm}$$

$$\lambda = 1\,\mu\text{m}$$

$$\varepsilon_n = 1\,\mu\text{m}$$

$$\mathrm{E}_b = 30\text{ MeV}$$

For our example case:

$$2w_0 \approx 40\,\mu\text{m}$$

So, the laser beam limits the spot size here:

$$\varepsilon = \varepsilon_n / \gamma \ll \lambda$$

Guiding of the laser reduces the effects of diffraction and the Gouy phase shift

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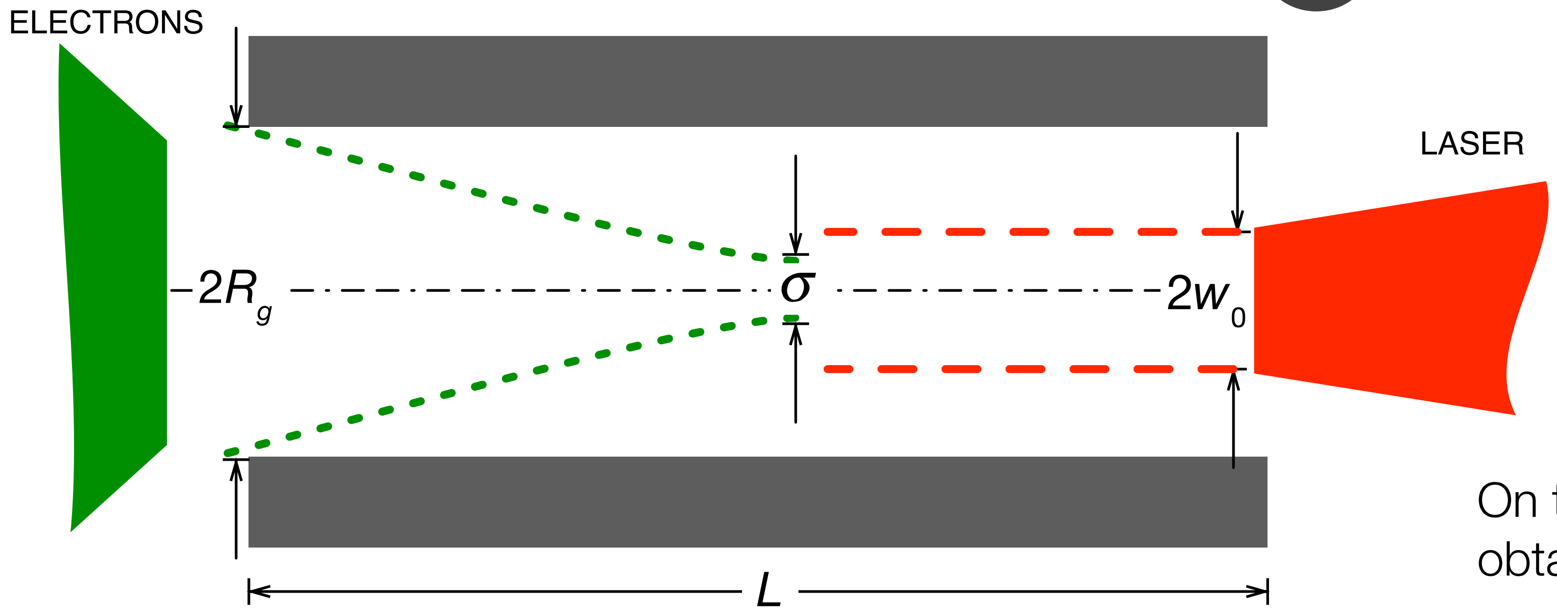


In practice, the fiber (waveguide) will be overmoded

$$R_g \gg \lambda \approx 1 \mu m$$

On the other hand, a very small bore is required to obtain significant enhancement from guiding. We take

$$2R_g = 20\ \mu m$$

Propagating the electron beam through the tube is necessary:

$$\sigma = \sqrt{\frac{\varepsilon_n \beta}{\gamma}} = \sqrt{\frac{\varepsilon_n L}{\gamma}} \approx 7\ \mu m$$

The naive flux enhancement factor is simply

$$\left(\frac{2w_0}{2R_g}\right)^2 = 4$$

Electron beam transmission will be very challenging at low energies. There are many additional considerations such as vacuum, breakdown, plasma formation, etc.

The brightness is enhanced further as the bandwidth may be reduced.

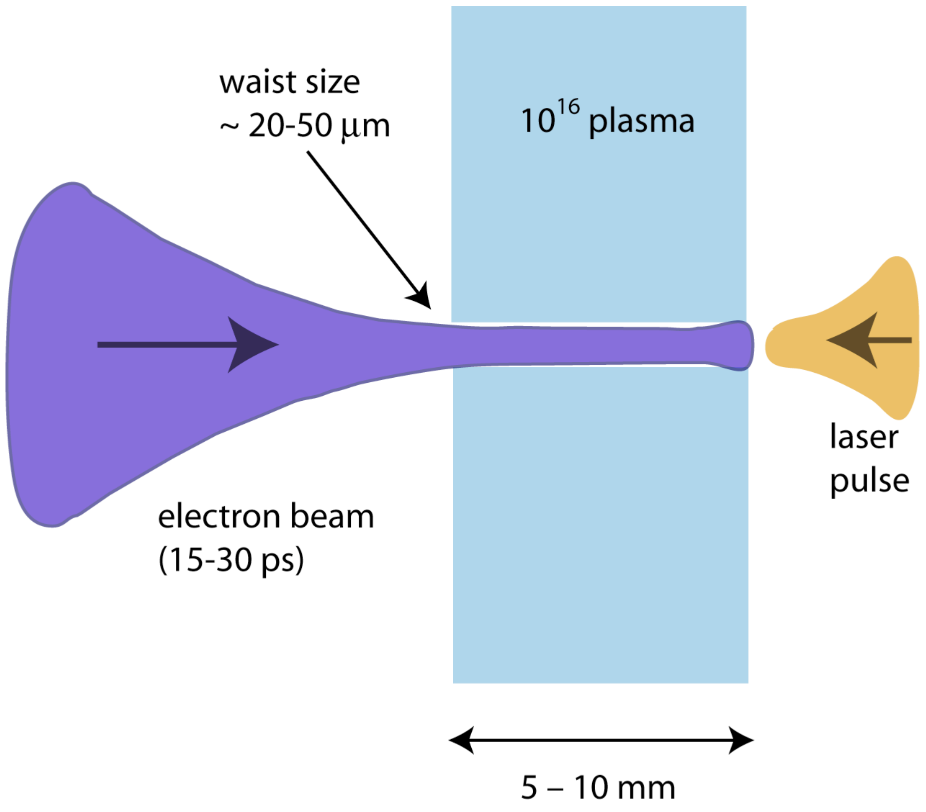
Electron beam guiding can ameliorate the effects of emittance and space charge

❷

R. B. Yoder & J. B. Rosenzweig, *An Inverse Compton Scattering Radiation Source via Self-Guiding in a Plasma*, Proc. AAC 2006.

Parameter	X-ray source	γ-ray source
E-beam energy	37 MeV	1.6 GeV
E-beam spot (σ_r)	7.3 μm	2.3 μm
Normalized emittance (ε_n)	5 mm mrad	20 mm mrad
Beam length (σ_z)	3 mm	6 mm
Beam charge	100 nC	100 nC
Laser wavelength (λ_0)	800 nm	800 nm
Laser energy/pulse	0.5 J	1.5 J
Confocal parameter ($2Z_R$)	833 μm	81 μm
Plasma density n_0	1 x 10^{16} cm^{-3}	1 x 10^{18} cm^{-3}
Blowout factor n_b/n_0	25	8.6
Laser guiding lengths	3.6	37
Scattered photon energy	33 keV	61 MeV
Photon number	~6 x 10^{10}	~8 x 10^{11}

Enhancement of x4-5 is calculated over unguided case



Need: long electron beam (3–4 mm) with high charge (~10-100 nC)
Get: self guiding via blowout
Bonus: laser guiding over 5–10 Z_R

Note: The laser pulse arrives when beam head exits plasma

X-ray guiding can enhance the brightness of the source through angular and energy filtering

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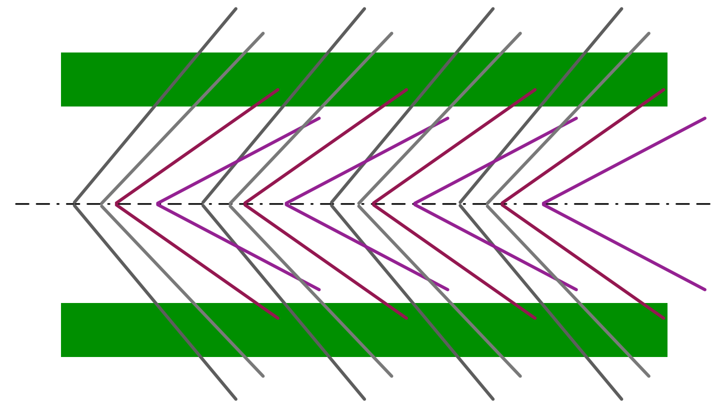
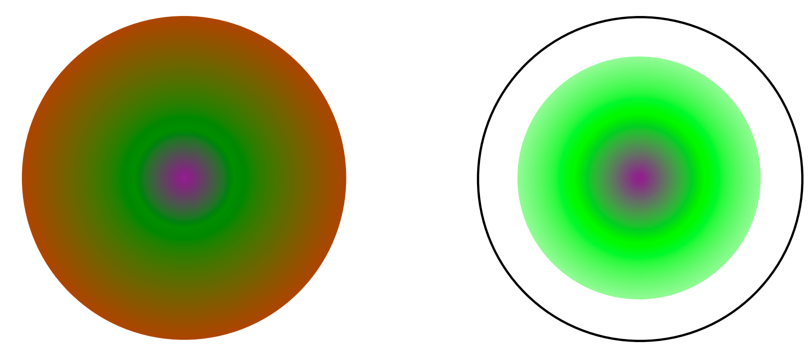
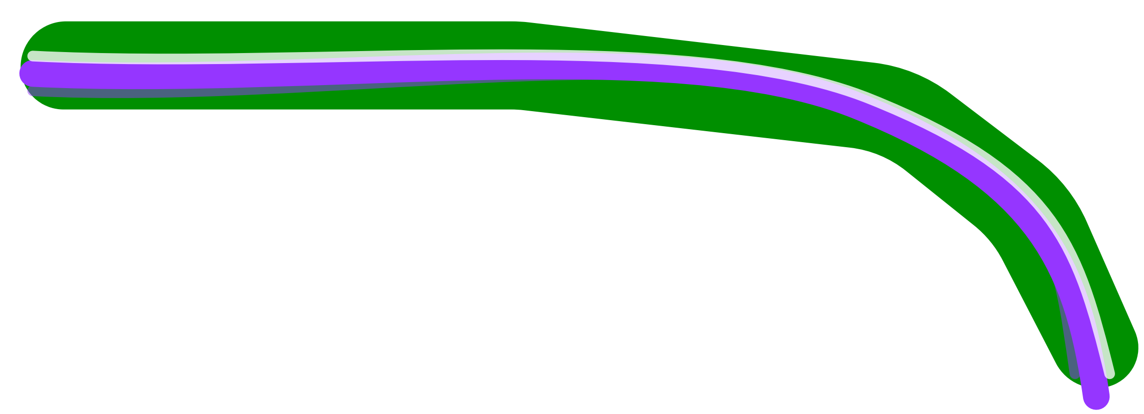
Angular selection



Photon energy filtering

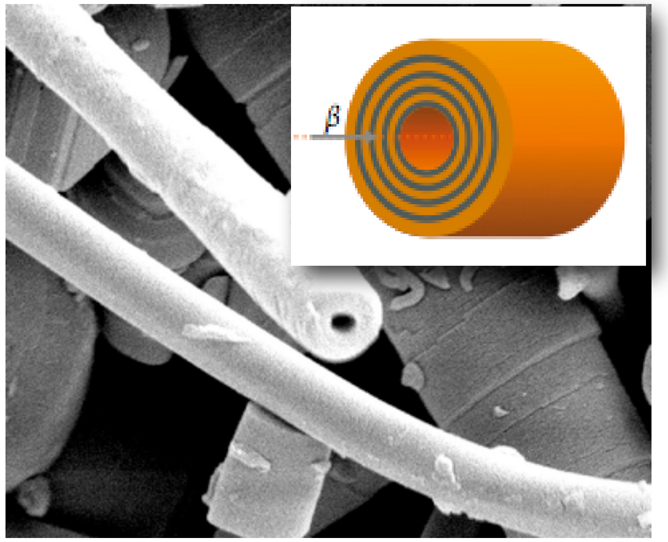


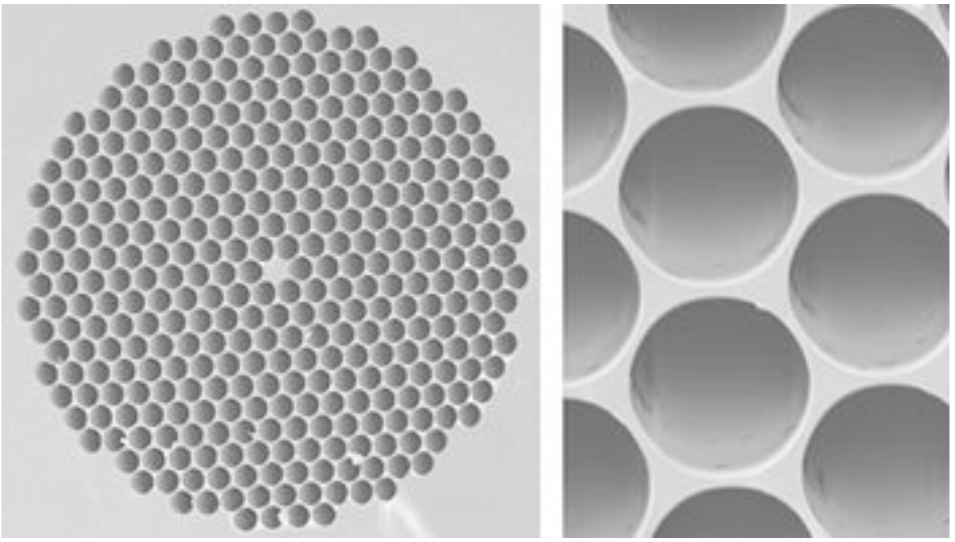
X-ray delivery



There are at least three ways to consider guiding the X-rays

Hollow glass fibers (capillary)
Photonic BandGap (PBG) fibers
Metal tubes





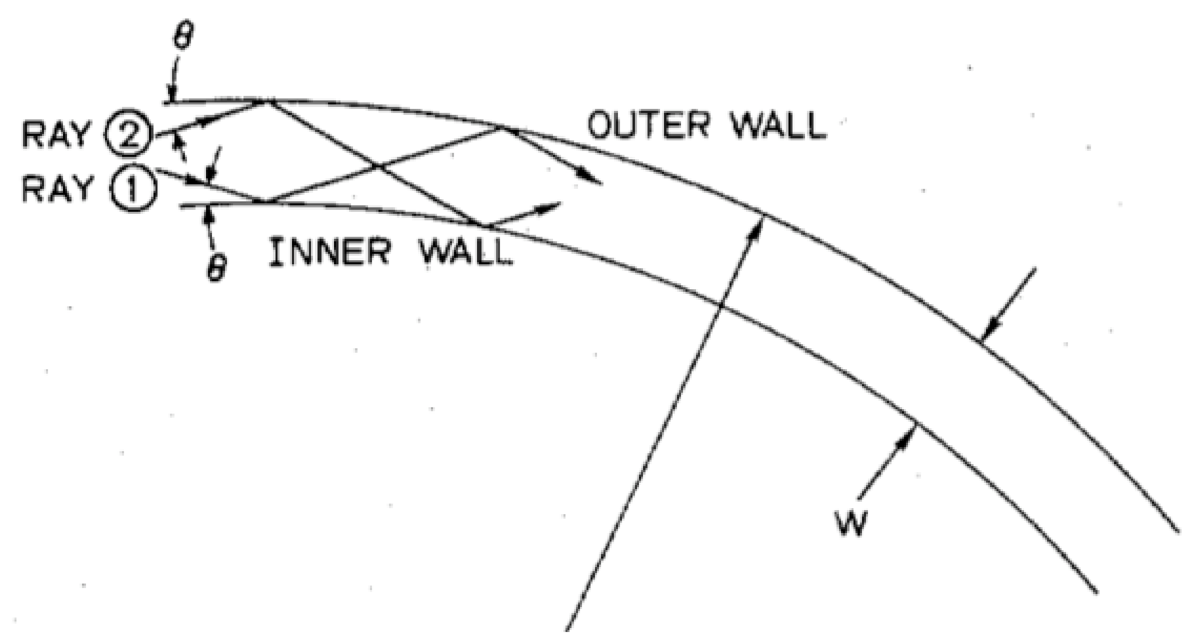
The Drude model can be applied to understand guiding of the x-rays in a tube

The transmission of an x-ray in a tube depends strongly on its angle

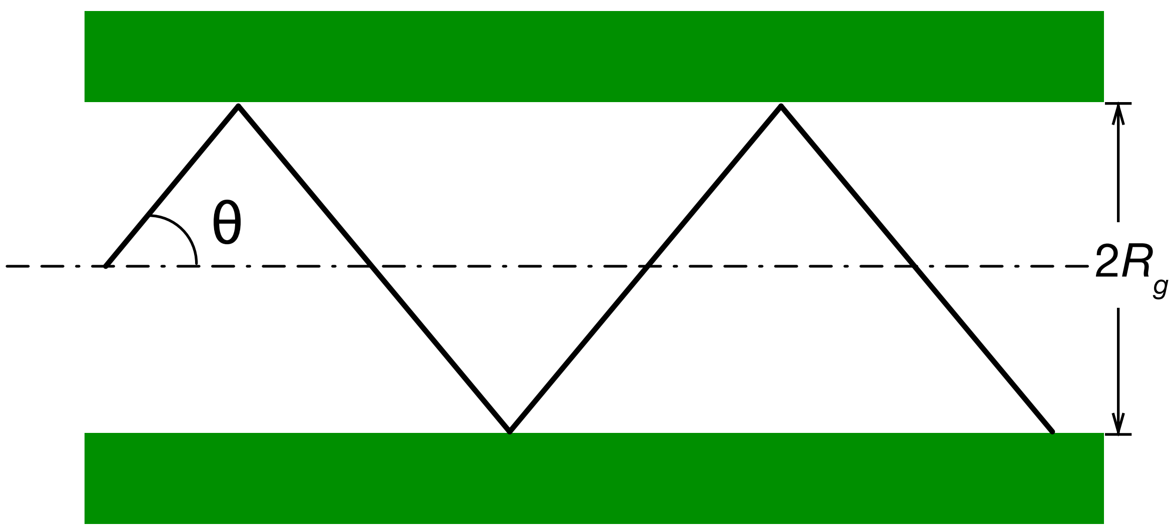
$$n(\omega)^2 = 1 - \frac{\omega_p^2}{\omega^2} \qquad \omega_p^2 = \frac{e^2 n_e}{\varepsilon_0 m_e}$$

here, n_e is the density of unbound (free) electrons. At high energies (hard x-rays), this can be all the electrons in the material.

Guiding of x-rays has been studied since at least 1965. For instance: R. H. Pantell and P. S. Chung, IEEE J. Quantum Electronics, QE-14 **9** (1978)



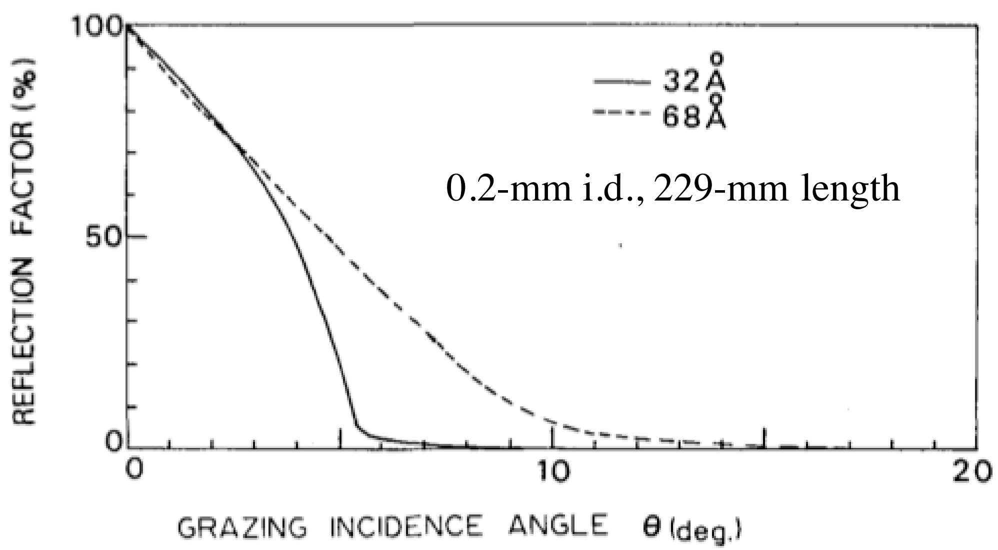
There is a critical angle for total internal reflection and this leads to interesting effects in an extended source



Drude:

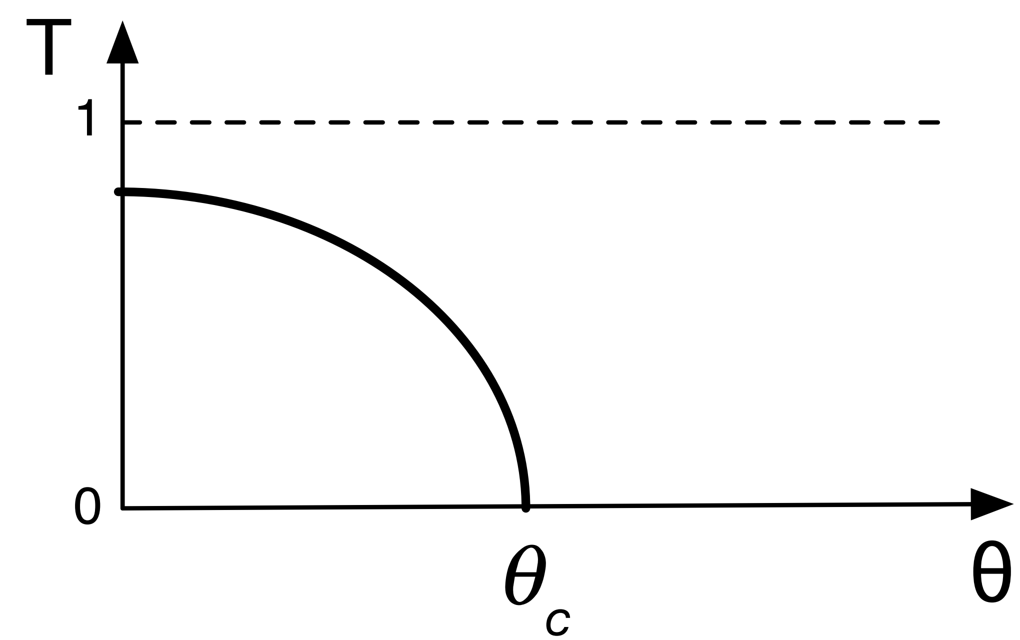
$$\theta_c = \frac{\omega_p}{\omega} \ll 1$$

Measurement agrees:

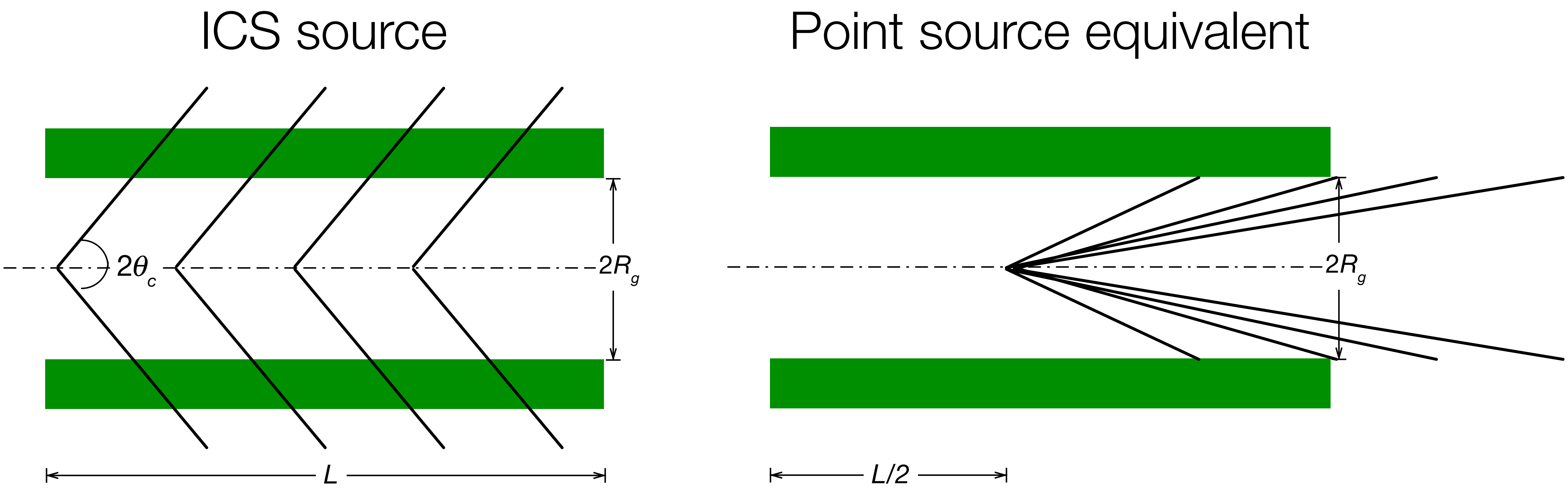


M. Wantanabe, et al., APPLIED OPTICS / Vol. 24, No. 23 / **1** December 1985

Regardless of the model, we expect:

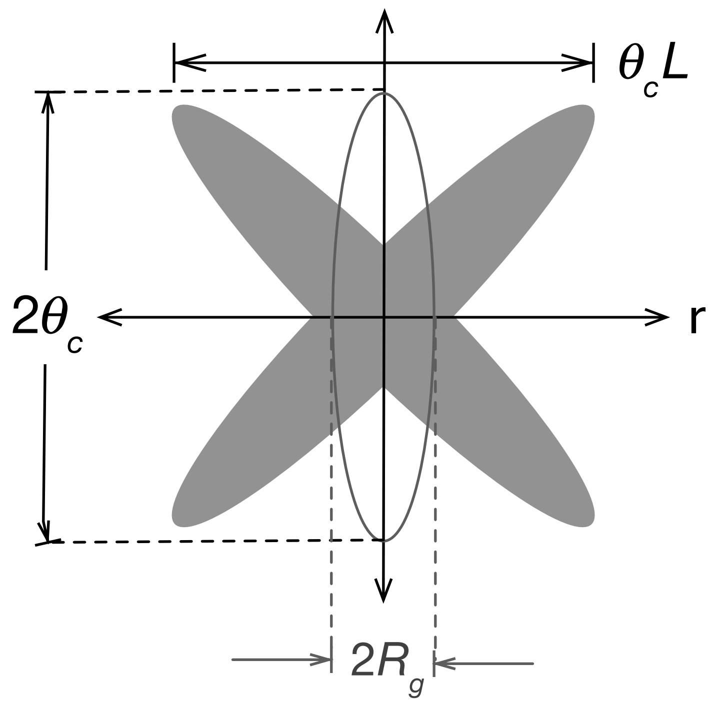


The ICS is an extended radiation source which we model as emitting uniformly over its interaction length



Guiding the x-rays reduces the phase space area of the source by the number of zig-zags

Unguided



Equivalent phase space area:

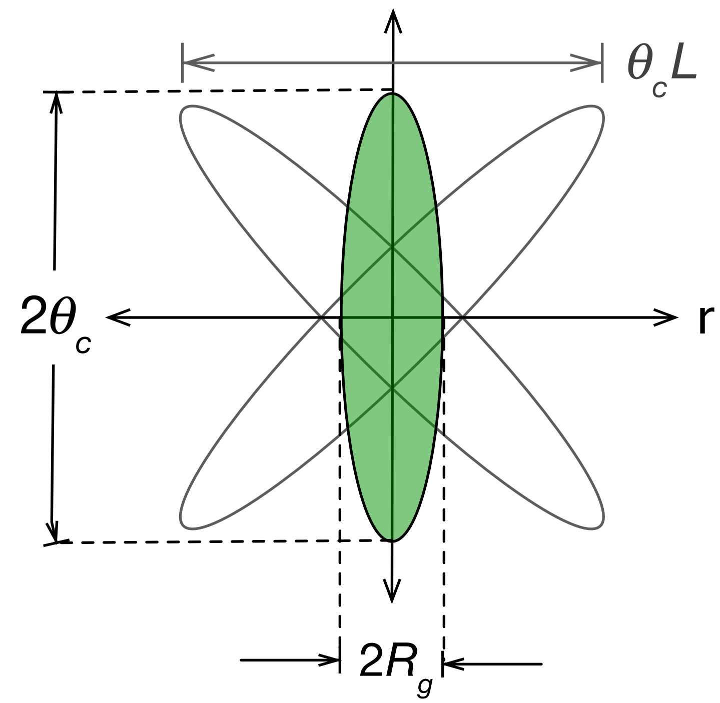
$$2\theta_c^2 L$$

assuming

$$\theta_c L \gg 2R_g$$

(smallest ellipse is at least x2 bigger)

Guided



For the guided source, the phase space is at most

$$2\theta_c 2R_g$$

The phase space reduction factor is

$$\frac{2\theta_c^2 L}{4\theta_c R_g} = \frac{\theta_c L}{2R_g} = \frac{1}{N_{zz}}$$

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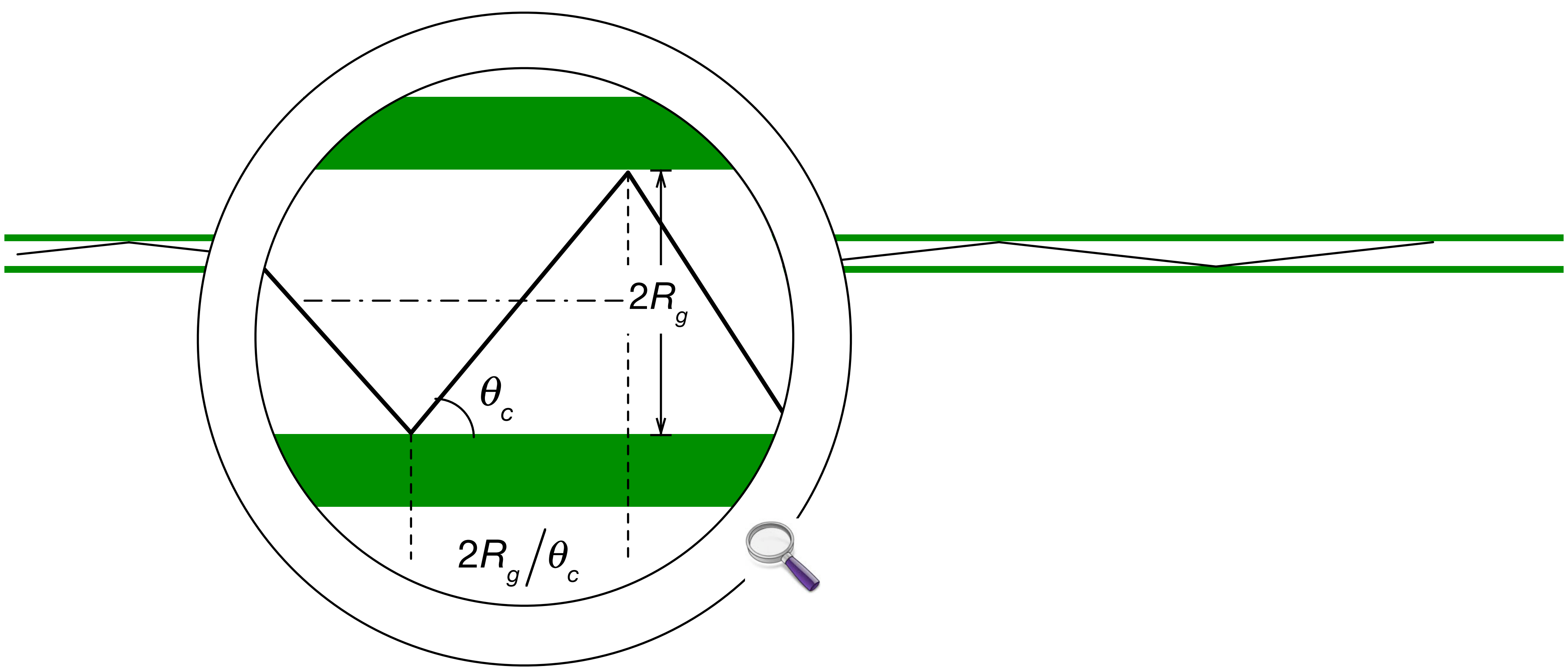
Example:

$$L = 3 \text{ mm}$$

$$\theta_c = 1/40 \text{ rad}$$

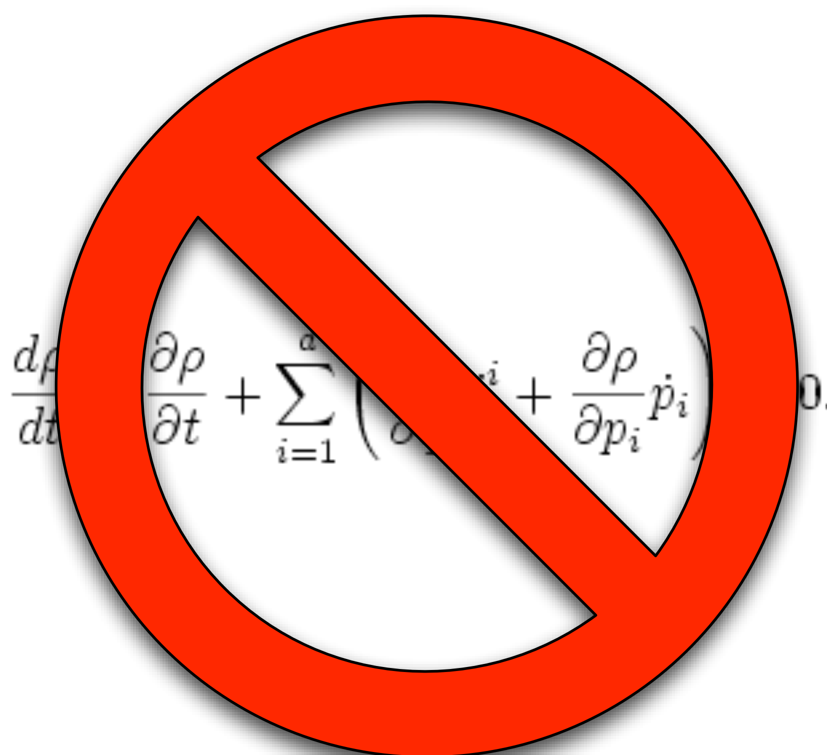
$$2R_g = 13\ \mu\text{m}$$

the enhancement factor is ≈10 in each plane.
100 in transverse phase space area!



Liouville's Theorem is not violated as this is not a conservative system

The source is providing power throughout the interaction length



Guiding needs to be revisited, in all its flavors

Many challenges remain...

Destruction or breakdown of any material is likely

Beam propagation is challenging

More work is needed to model guiding

More work is needed to find the right operating regime end of slides