Creating an X-Ray Standing Wave with Bragg Optics[†]

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This paper will describe the design of an optical system to create an x-ray standing wave over a region ~1 μm^2. Although the examples given are for hard x-rays, the concepts are applicable to optical designs involving multilayer optics for soft x-rays.

The strength of a standing wave potential is proportional to the square of the electric field strength of the photon field, E^2. The photon flux Φ times $h\omega$ also is proportional to E^2. The photon flux Φ from a 12 mW laser in the visible is ~2×10^{16} photons/sec, while the photon flux at the Cu $K_{\alpha 1}$ emission line (0.15405974 nm) from an 18 kW rotating anode x-ray source with a Cu target is 5.5×10^{14} photons/sec/steradian. Thus, assuming an appropriately-designed, curved crystal monochromator could intercept and collimate x-rays from a solid angle of only ~0.01 steradian, the increase in ω at the x-ray wavelength would compensate for the lower photon flux from the x-ray source, resulting in a standing wave potential of equivalent or higher strength as from a laser in the visible.

It is common to classify coherence into two categories, temporal (sometimes called longitudinal) and spatial (also called transverse), which are addressed in turn below. In the case of an x-ray tube, the temporal coherence length $\xi_{\_}$ is given by the speed of light c (3×10^8 m/s) times the time τ over which random phase changes in the emission occur. The latter can be estimated from the frequency spread of the radiation. The natural width of the Cu $K_{\alpha 1}$ line (λ 0.1541 nm) as emitted from the source, without having been further refined by a monochromator crystal, is $\Delta\lambda$ 5×10^{-5} nm (2.61 eV). Calculating the coherence time τ from the inverse of the frequency spread of the emission gives:

$$\tau \sim (\Delta\nu)^{-1} \sim \lambda^2/c\Delta\lambda \; \_ \; (0.1541\ \mathrm{nm})^2/(3\times10^8\ \mathrm{m/s})(5\times10^{-5}\ \mathrm{nm}) \quad 1.6\times10^{-15}\ \mathrm{s}$$

Multiplying this coherence time by the velocity of light *c* gives ~0.5 μm for the temporal coherence length $\xi_{\_}$. High resolution monochromators could reduce this linewidth, and thus increase the coherence length, by a factor of as much as ~10^3. However, such increases would come at the cost of x-ray flux.

As for the spatial coherence length ξ , in the case of a disk-shaped source of diameter *D* located a distance *R* from the image plane, interference fringes of visibility 0.88 or better will be obtained over a diameter of size ξ at least

$$\xi = 0.32R\lambda/D$$

where λ is the wavelength of the light (0.154 nm), *R* is the distance between the source and image plane, and *D* is the size of the x-ray source at the exit of the focussing optics. Thus, to obtain spatial coherence over a size ξ of ~1 μm at a distance of ≈1 meter would require demagnifying a 0.5 mm × 10 mm focal spot on the x-ray tube to about 50 microns. The standard takeoff angle of an x-ray tube of approximately 6° already reduces these dimensions to 0.5 mm × 1 mm, which would then need to be demagnified by another factor of ~20. How this will be achievable in the design of an overall x-ray optical system will be discussed.

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