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Mössbauer-Fresnel zone plate as nuclear monochromator

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ABSTRACT

Zone plates currently used in x-ray optics derive their focusing power from (a spatial variation of) the electronic refractive index—that is, from the collective effect of electronic x-ray-scattering amplitudes. Nuclei also scatter x rays, and resonant nuclear-scattering amplitudes, particularly those associated with Mössbauer fluorescence, can dominate the refractive index for x rays whose energies are very near the nuclear-resonance energy. A zone plate whose Fresnel zones are filled alternately with ^{57}Fe and ^{56}Fe (^{57}Fe has a nuclear resonance of natural width $\Gamma = 4.8$ nano-eV at 14.413 keV; ^{56}Fe has no such resonance) has a resonant focusing efficiency; it focuses only those x rays whose energies are within several Γ of resonance. When followed by an absorbing screen with a small pin-hole, such a zone plate can function as a synchrotron-radiation monochromator with an energy resolution of a few parts in 10^{12} . The energy-dependent focusing efficiency and the resulting time-dependent response of a resonant zone plate are discussed.

I. INTRODUCTION

There are several methods currently in use or under development for monochromatizing synchrotron radiation to the neV level. All involve x-ray scattering through a narrow nuclear resonance, such as the 14.413 keV resonance in ^{57}Fe (of natural width $\Gamma = 4.8$ neV) that has seen wide application in Mössbauer spectroscopy. With some injustice, all can be introduced to a general audience as demonstrations of a sharply resonant nuclear contribution to the x-ray refractive index, applied to otherwise classical optics. Usually, however, there is a twist—some attempt to solve what is currently a dominant problem in the field: the roughly nine-order-of-magnitude difference between the nuclear-resonance width and the energy bandpass of a high-heat-load monochromator.

Thus, we have resonant-crystal monochromators^{1,2,3} that Bragg scatter resonant x rays but not nonresonant x rays, resonant mirrors^{4,5} with antireflection coatings that

discriminate against electronic scattering, and, most recently, resonant multilayers⁶, in which layers of ^{56}Fe alternate with layers of ^{57}Fe to produce a reflecting structure that only resonant photons can see. The resonant zone plate that we have proposed⁷ is similar, in this respect, to a resonant multilayer.

The zone-plate monochromator is illustrated schematically in Fig. 1. Odd-numbered Fresnel zones are filled with ^{56}Fe , and even-numbered zones are filled with the same thickness of ^{57}Fe (or vice-versa). Regarding electronic x-ray scattering, ^{56}Fe and ^{57}Fe are essentially identical. Therefore, only resonant photons will see a zone plate, while nonresonant photons will see a featureless metal disc. A screen with a pinhole at the zone-plate focal spot can block a large fraction of unfocused, nonresonant photons while transmitting all focused, resonant photons.

The effectiveness of such an arrangement as a monochromator depends on the focusing efficiency of the zone plate, the energy bandwidth over which the plate focuses, and the relative cross-sectional areas of the incident beam and the focal spot. Accordingly, we will examine the focal properties of a resonant zone plate, and estimate the focal-spot size, which depends not only on the zone plate but also on the spatial coherence of the incident x-ray beam.

II. ZONE-PLATE FOCAL PROPERTIES

The focusing efficiency of the first-order focus of a zone plate (assuming a rectangular zone profile) is given by⁸ $|C|^2$, where

$$C = \frac{1}{\pi i} [e^{kd(i\delta_1 - \beta_1)} - e^{kd(i\delta_2 - \beta_2)}]. \quad (1)$$

Here, $k = 2\pi/\lambda$, d is the zone-plate thickness, δ_i and β_i are given by $n_i = 1 - \delta_i - i\beta_i$, n_1 and n_2 being the refractive indices for odd-numbered and even-numbered Fresnel zones, respectively. δ_1 and β_1 describe ^{56}Fe , while δ_2 and β_2 describe ^{57}Fe .

The refractive index of ^{56}Fe at 14.413 keV is attributable completely to nonresonant electronic scattering; δ_1 and β_1 are given by⁴

$$\delta_1 = \frac{2\pi}{k^2} \rho f' = 7.4 \times 10^{-6} \quad (2)$$

and

$$\beta_1 = \frac{2\pi}{k^2} \rho f'' = 3.4 \times 10^{-7}, \quad (3)$$

where ρ is the number of Fe atoms per unit volume, and f' and f'' are, respectively, the real and imaginary parts of the electronic-scattering amplitude per atom.

The refractive index of ^{57}Fe near 14.413 keV includes the effects of both electronic and resonant nuclear scattering. Assuming negligible Zeeman splitting of nuclear magnetic substates, δ_2 and β_2 are given by⁴

$$\delta_2 = \delta_1 + \frac{3\pi}{k^3} \rho \frac{\Gamma_\gamma}{\Gamma} \frac{x}{x^2 + 1} \quad (4)$$

and

$$\beta_2 = \beta_1 + \frac{3\pi}{k^3} \rho \frac{\Gamma_\gamma}{\Gamma} \frac{1}{x^2 + 1}, \quad (5)$$

where $x = (E - E_{res})/(2\Gamma)$, and where E is the x-ray energy, E_{res} is the resonance energy, Γ is the resonance energy width, and Γ_γ is the partial width for decay by photon emission.

The focusing efficiency for the first-order focus of a Mössbauer-Fresnel zone plate, calculated using equation 1, is displayed in Fig. 2. Near the resonance energy, the efficiency is dominated by the imaginary part of the nuclear refractive index; it saturates, for thicknesses greater than about .2 μm , at the maximal efficiency ($1/\pi^2$) of an amplitude zone plate⁹. Away from resonance, the real part of the refractive index dominates, and the efficiency depends periodically on zone-plate thickness as is expected for a phase zone plate. For the rectangular zone profile considered here, the maximal efficiency of a phase zone plate is $4/\pi^2$.

The size of the focal spot depends both on the zone-plate geometry and on the spatial coherence of the incident x-ray beam. The zone-plate geometry can be specified by the quantity r_m , the outer radius of the m^{th} Fresnel zone, which, in the limit $f \gg m\lambda$, is given by⁹ $r_m = \sqrt{mf\lambda}$. The spatial coherence of the incident beam can be specified, in effect, by the size of the beam source and the distance from source to zone plate.

For incident radiation emanating from a point source, the diameter d_f of the focal spot is roughly the same as the radial width of the outermost (M^{th}) zone, Δr_M . But with an extended source, the focal spot can be no smaller than the (demagnified) image of that source. Assuming image size is the determining quantity and considering the zone plate as a thin lens⁹, the focal-spot diameter is given by $d_f = d_s(L_f/L_s)$, where d_s is the source diameter, and where L_f and L_s are, respectively, the lens-to-focus and the lens-to-source distances.

III. DISCUSSION

Fig. 2 represents the focusing efficiency of a zone plate for *monochromatic* radiation. Under illumination by broad-band, short-pulse-length synchrotron radiation, the zone-plate monochromator acts as a bandpass filter, and the time dependence of the transmitted radiation is well approximated by the impulse response of that filter, i.e., by the Fourier transform of the energy-dependent focusing efficiency. Fig. 3 shows the focusing efficiencies (Zeeman splitting of nuclear magnetic substates is now

included) and the corresponding temporal responses of 1.0- and 0.2- μm -thick zone plates. The broader linewidths of the thicker zone plate result in more rapid decay of the coherent, focused fluorescence.

The performance of the Mössbauer-Fresnel zone plate as a monochromator can be estimated from the energy broadening and focusing efficiency displayed in Fig. 2. The nonresonant-background suppression (the signal-to-background ratio of the monochromatized beam divided by the signal-to-background ratio of the incident beam) is given approximately by $S = \Gamma_{eff} \bar{\eta} A_z / A_f$, where Γ_{eff} is the energy width (in units of the natural resonance width) over which focusing occurs, $\bar{\eta}$ is the average focusing efficiency over Γ_{eff} , A_z is the area of the zone plate, and A_f is the area of the focal spot. Using the zone-plate equation and focal-spot considerations given earlier, S can be expressed as

$$S = \Gamma_{eff} \bar{\eta} \left(\frac{\lambda L_s}{\Delta r_M d_s} \right)^2, \quad (6)$$

where we stipulate $L_s \gg L_f$ to justify the approximation $L_f \simeq f$.

Taking Γ_{eff} as 10, $\bar{\eta}$ as .15, L_s as 60 m, d_s as 100 μm , and Δr_M as .2 μm , and given $\lambda = .86 \text{ \AA}$, background suppression by a factor of 10^5 is expected. For concreteness, a zone-plate geometry consistent with the above suppression has a focal length of 2 m, a zone-plate diameter of .86 mm, and a focal-spot diameter of roughly 3 μm .

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FIG. 1. Schematic depiction of the zone-plate/pinhole-screen monochromator.

FIG. 2. Focusing efficiency of the first-order focus of a $^{56}\text{Fe}/^{57}\text{Fe}$ nuclear-resonant zone plate, for various plate thicknesses. Zeeman splitting of nuclear magnetic substates has been suppressed for clarity.

FIG. 3. Focusing efficiency and temporal response of a 1 μm -thick (solid line), and a 0.2 μm -thick (dotted line) nuclear-resonant zone plate.

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