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Refractive and diffractive neutron optics with reduced chromatic aberration

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ABSTRACT

Thermal neutron beams are an indispensable tool in physics research. The spatial and the temporal resolution attainable in experiments are dependent on the flux and collimation of the neutron beam which remain relatively poor, even for modern neutron sources. These difficulties may be mitigated by the use of optics for focusing and imaging. Refractive and diffractive optical elements, e.g. compound refractive lenses and Fresnel zone plates, are attractive due to their low cost, and simple alignment. These optical elements, however, suffer from chromatic aberration, which limit their effectiveness to highly monochromatic beams. This paper presents two novel concepts for focusing and imaging non-monochromatic thermal neutron beams with well-known optical elements: (1) a fast mechanical transfocator based on a compound refractive lens, which actively varies the number of individual lenses in the beam path to focus and image a time-of-flight beam, and (2) a passive optical element consisting of a compound refractive lens, and a Fresnel zone plate, which may focus and image both continuous and pulsed neutron beams.

1. Introduction

Thermal neutron beams suffer from relatively low flux, and high divergence. A variety of optical devices have historically been employed for guiding, and focusing in order to overcome these difficulties. These devices have mainly relied on either small-angle reflection, e.g. Wolther mirrors [1,2], "lobster eye" lenses [3], Kumakhov lenses [4], curved supermirror lenses [5], Kirkpatrick-Baez optics [6,7], or on diffraction from e.g. bent Laue crystals [8].

Focusing of neutrons by compound refractive lenses (CRLs) [9] and diffractive lenses e.g. Fresnel zone plates (FZPs) [10] has been demonstrated, but has not found widespread use, most likely due to the high degree of chromatic aberration (i.e. the optical properties are dependent on the neutron wavelength) of these devices, which limit their effectiveness when used with a beam consisting of a broad spectrum of wavelengths.

In this paper, two strategies for design of optical devices for focusing and imaging neutrons with reduced chromatic aberration are presented: a fast mechanical transfocator constructed from refractive lenses, and a hybrid lens consisting of a combination of a FZP and a CRL. The latter concept is investigated analytically by ray transfer matrix analysis, and we present analytic expressions for the requirements for achromatic operation, and the resulting lens characteristics which take the finite thickness of the CRL into account. The results from ray transfer matrix analysis are further substantiated by simulations using a Fourier optics formalism. The analysis does not include the effect of gravity, as this is expected to be small for thermal neutrons.

To discuss the feasibility and merit of our two optics solutions, we will consider these in the context of the planned long pulse facility, the European Spallation Source, ESS.

The basics of CRLs, FZPs, an introduction to the formalisms employed in this work, and justification for their use may be found in the appendix.

2. Fast mechanical transfocator for use with time-of-flight neutrons

Transfocators are variable focal length CRLs, which are increasingly employed with synchrotron X-rays [11]. The focal length of the transfocator is varied by physically increasing or decreasing the number of lenses in the beam path. The main idea presented in this section is using the transfocator concept for focusing and imaging TOF beams, which is done by varying the number of lenses in the

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beam path in the duration of individual neutron pulses. We will substantiate the concept with a simple numeric example for the ESS. Finally, we will briefly discuss strategies for engineering such a device.

The maximal spread in wavelength for TOF measurements is given by $\Delta\lambda_{max} = h/(m_n L\nu)$, where h is the Planck constant, m_n is the neutron mass, L is the source-detector distance, and ν is the pulse frequency. The projected frequency at ESS is $\nu = 16\frac{2}{3}$ Hz, which at a long beam line with say $L = 200$ m implies $\Delta\lambda_{max} = 1.2$ Å. We choose a central wavelength of $\lambda_0 = 6$ Å, so we get a maximal bandwidth for TOF of $\Delta\lambda/\lambda = 20\%$. In this section, we assume for simplicity that the focal length of the CRL is well-approximated by the thin lens expression Eq. (A.2), as using expressions respecting the thickness of the CRL does not change the present analysis qualitatively.

The relative variation in focal length of a CRL is substantial for this wavelength spread: $\Delta f/f_0 \approx 41\%$. To compensate for this, it is beneficial to use lenses of relatively low optical power, so the optical power of the transfocator may be adjusted in small steps. We consider a transfocator of $N_{max} = 40$ identical beryllium lenses, each of radius of curvature $R = 1$ cm. The focal length for $N = N_{max}$ at the shortest wavelength (i.e. the fastest neutrons in a pulse) cf. Eq. (A.2) is $f_0 = 2.29$ m, which is chosen as the focal length to maintain by dynamic compensation.

The required number of lenses in the beam, and the resulting variation in focal length is shown in Fig. 1. The number of lenses in the beam path is varied from $N = 40$ for the fastest neutrons, to $N = 27$ for the slowest neutrons. The maximal relative deviation in this setup is then found to be $|\Delta f/f_0| < 2\%$.

In this example, we have assumed that the lens movements occur instantaneously. In engineering a transfocator for TOF neutrons, the main obstacle will be to ensure that lens movements are fast. As the variation of wavelength of the TOF neutrons in the device is on a timescale set by the macro-pulse length, which for the ESS is projected to be $t_{mp} = 2.86$ ms, this sets the required timescale for lens movements.

A possible solution to the engineering challenge of fast, reproducible lens movements may be provided by commercial technology, such as amplified piezoelectric actuators, see e.g. [12]. Depending on the size of the lenses, these actuators may require secondary mechanical amplification.

Some insight into the merit of the fast mechanical transfocator may be gained by examining the numerical aperture (NA) and obtainable image resolution σ. The fast mechanical transfocator will have a NA equal to that of a CRL, which may be estimated for a given setup with the methods of e.g. [13]. Currently, NA values for

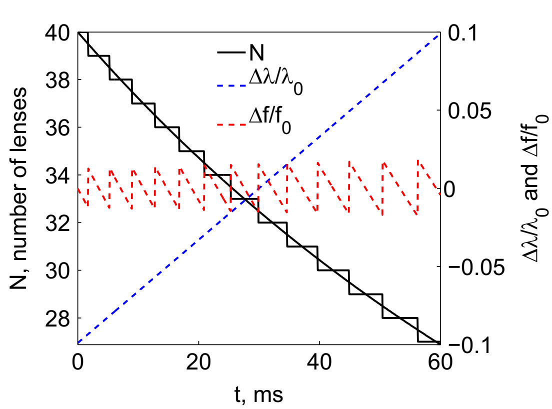

Fig. 1. Correction of chromatic aberration by a fast mechanical transfocator. The relative wavelength in the device $\Delta\lambda/\lambda_0$, number of lenses in the beam path N, and the relative focal length $\Delta f/f_0$ is shown as a function of time during an individual pulse at a 200 m long beamline at the ESS. In this example we use $\lambda_0 = 6$ Å, and $f_0 = 2.29$ m.

neutron CRLs are typically bounded by $\mathrm{NA} < 10^{-2}$ [14], and so may be comparable to mirror focusing devices, where the NA is determined by the critical angle of the mirror material, and is thus typically measured in milliradians.

The resolution of the fast mechanical transfocator is also related to that obtainable with a CRL, however, the non-instantaneous lens movements and the discontinuous variation in focal length will degrade the optical quality. If we neglect the effect of refraction by an individual lens during its movement (i.e. when the lens is neither fully in nor fully out of the beam path), we may estimate the degradation of resolution as being caused by defocus. For a good quality lens system, it is likely that this effect will dominate. The diameter of the circle of confusion in object space thus provides a rough approximation of the resolution, (i.e. the minimal distance points in object space must be separated to be distinguishable) so $\sigma \approx D_{eff}\Delta f/f_0$, where D_{eff} is the effective aperture diameter, which is usually smaller-but-comparable to the physical aperture diameter [13]. For a lens aperture of 1 cm, and $\Delta f/f_0 = 2\%$, we thus get a resolution of $\sigma \approx 200$ μm, which may be reduced by decreasing the effective aperture. It must be noted, however, that the NA and resolution shown here are rough estimates.

This approach to correction of chromatic aberration is relatively straightforward, but robustness may be an issue, and the remaining chromatic aberration is not ideal. Therefore, we consider an alternative static solution in the following.

3. A hybrid diffractive/refractive lens

Inspired by work with X-rays [15], we note that CRLs and FZPs both suffer from chromatic aberrations individually, but that two such devices may be combined to reduce the chromatic aberration around a central wavelength. Analysis based on the ray transfer formalism outlined in the appendix shows that a combination of a focusing FZP followed by a defocusing CRL (i.e. $f_{FZP} > 0 > f_{CRL}$) may be combined in two distinct ways to reduce the chromatic aberration for both focusing and imaging: placing a FZP and a CRL in contact allows for elimination of chromatic aberration to first order in $\Delta\lambda/\lambda_0$, while introducing a correctly chosen separation between the FZP and the CRL allows for elimination of chromatic aberration to second order in $\Delta\lambda/\lambda_0$. To distinguish the two cases, we shall use the superscripts *con* to denote when the FZP and the CRL are in contact, and *sep* when they are separated. It is found that the focusing FZP may be placed either upstream or downstream from the defocusing CRL, but the preferred placement is upstream, as this increases the effective numerical aperture slightly.

The key to achromatic operation is the different functional dependence on wavelength of the optical power exhibited by the FZP and the CRL, which may then be tuned to cancel over a wavelength range. As a simple illustration, consider two thin lenses of focal lengths $f_1 > 0$ and $f_2 < 0$ in contact. The resulting combination has a focal length f given by $1/f = 1/f_1 + 1/f_2$. Achromatic operation requires that this be invariant over some wavelength range, and so differentiation with respect to wavelength around some λ_0 gives the requirement $(df_1/d\lambda)/f_1^2 = -(df_2/d\lambda)/f_2^2$. If the functional dependence on λ of f_1 and f_2 is identical, the only solution is $f_1 = -f_2$, resulting in a device with no net optical power. For lenses with different dependencies on λ, it is seen that the resulting optical power may be non-zero. When allowing a separation between the FZP and the CRL, the distance gives a degree of freedom that allows for higher-order correction.

Unlike in Section 2, we do not here assume that the CRL performs like a thin lens, to allow us to make quantitative predictions. In the present analysis, we consider a CRL that is well-described by an expansion to first order in CRL thickness Nt (N: number of individual