Low Time-dispersion Bragg Optics for use with Ultrafast Hard X-ray Sources

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X-ray sources with sub-picosecond pulse lengths are now becoming available, and there is a need for optical components which can manipulate these beams without significantly degrading their temporal or coherence properties. This highlight describes a dispersion compensation technique, based on the properties of dynamical diffraction by highly perfect crystals, which allows such devices to be fabricated.

Diffraction by highly perfect crystals must be analyzed using the dynamical theory of x-ray diffraction, which takes full account of the multiple scattering processes that dominate, and give rise to a range of interesting properties. In the past these effects have been much studied in terms of angular and spatial diffraction profiles[1]. Recent work by Wark and collaborators[2] has pointed out that the temporal response of Bragg reflections may be calculated by taking the Fourier transform of the complex frequency response as calculated using the standard time-independent dynamical theory. In this theory, the important parameter is a dimensionless quantity that expresses the deviation of the incident beam from the exact Bragg condition. Usually the deviation is considered as resulting from the change in incidence angle of a monochromatic plane wave. Wark's point was that this deviation also results from wavelength changes in the incident beam at constant angle. This situation is close to that found in free-electron laser or high brightness synchrotron radiation sources. In the first case, a Fourier transform of the angular amplitude profile forms the spatial amplitude profile (see ref. 8). In the second, the transform of the wavelength (or frequency) profile produces the time dependence. Unlike mirror reflections in optics, Bragg reflection can take place in two basic geometries: the Bragg geometry, in which the incident and reflected beams occur at the same surface, and the Laue or transmission mode in which the beam traverses the crystal thickness and emerges from the opposite surface. Most of the studies of the temporal behaviour of dynamical diffraction have concentrated on the Bragg case. This letter draws attention to the fact that, although single Laue reflections produce serious pulse stretching, the use of consecutive reflections by two or more crystal plates can produce an almost pure single delay. This effect is quite counter-intuitive, and has until now gone unnoticed. One would expect a second diffraction to cause greater time smearing, and for the Bragg case this is indeed true[3]. The Laue case allows the second diffraction to provide almost complete compensation of the dispersion introduced by the first crystal. Using this idea, we show how to make an isochronous two-crystal monochromator and a three-crystal interferometer with similar properties. Both of these devices should find application with the new generation of ultra-fast x-ray sources such as x-ray free-electron lasers or linac-driven synchrotron radiation sources.

Figure 1 shows the symmetric Laue geometry. The active crystal planes are perpendicular to the crystal surface, and the incident beam makes an angle θ with those planes. Near the Bragg angle, the crystal becomes birefringent, i.e. the dispersion surface has two branches[4]. As the Bragg condition is traversed, either by small changes in angle or in wavelength, the energy flow within the crystal sweeps from the incident direction to the reflected direction or *vice versa*, depending on which branch of the dispersion surface is considered. On leaving the crystal, each ray decomposes into a wave in the forward direction and another

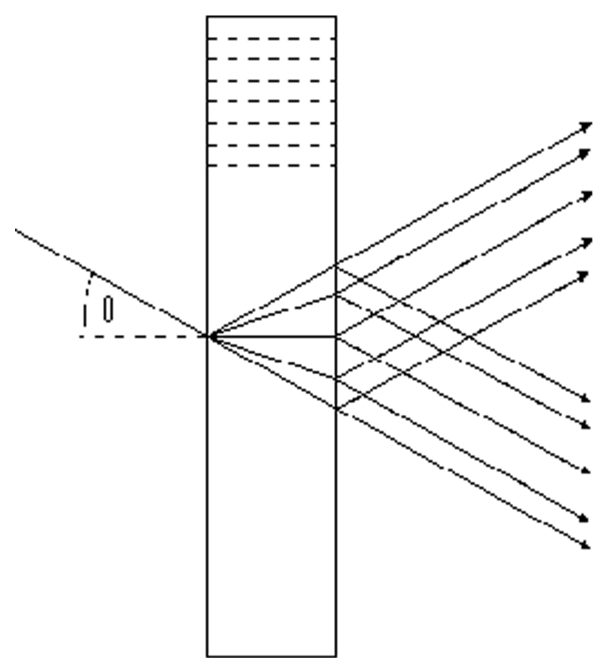

***Figure 1.** The Laue case diffraction geometry, illustrating the formation of the Borrmann fan filled by the wavefields during dynamical diffraction.*

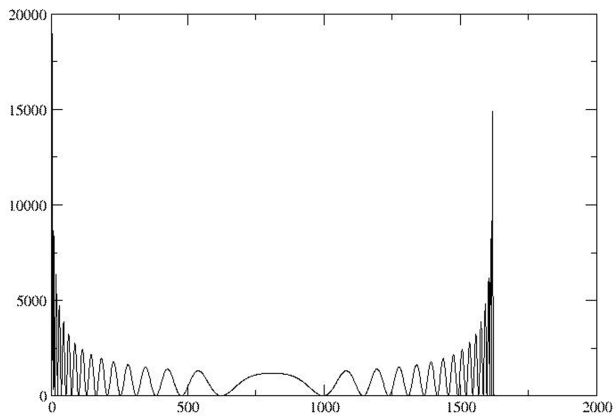

Figure 2. *The intensity of the reflected outgoing beam from a single Laue case diffraction. The horizontal axis can be interpreted as either position perpendicular to the beam direction or time relative to the incident pulse. The full width of the curve is 220fs or 0.35mm for the conditions described in the text.*

in the diffraction direction. If we now consider an incident beam which 'overfills' the range of Bragg reflection, then it is clear from the diagram that the outgoing beams are spatially spread out by this process. The transit time of rays traveling along the possible different routes varies significantly if we observe in a plane perpendicular to the diffracted beam direction. This time difference will depend on the Bragg angle and the crystal thickness. Figure 2 shows the intensity distribution along the beam cross-section. As a consequence of the hyperbolic shape of the dispersion surface, the rays are concentrated about forward -diffracted and diffracted directions, with relatively low amplitudes in the central part of the pattern. Since this spatial amplitude distribution over a fraction of a millimeter maps onto a temporal dispersion of hundreds of femtoseconds, this is a serious problem. If we now allow this time-dispersed amplitude distribution to be diffracted in the opposite sense by an identical crystal, the energy flow directions of each component is reversed, resulting in a pseudo-focus at the exit of the crystal. Figure 3 shows the situation, and figure 4 shows the calculated spatial (and therefore, temporal) profile at this point.

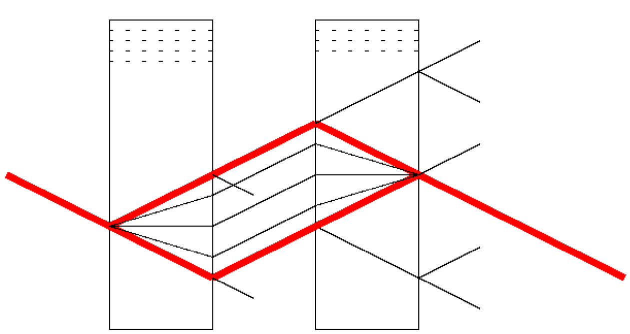

Figure 3. *The double Laue diffraction device. The rays indicated in red indicate the spatial and temporal focusing action of this arrangement.*

This spatial pseudo-focus was first predicted by Indenbom and coworkers in 1974[5]. The effect was almost forgotten since that time, and those authors were not concerned with the temporal dimension. Figure 5 shows experimental spatial profiles of the singly-diffracted beam from one of the crystal plates, and doubly-diffracted beam from both in the monolithic device shown in figure 5a. The incident beam was shaped by a 25µm high x 3mm wide slit. The diffraction plane was vertical. The incident radiation from beamline X27A had a continuous spectrum and the crystal was set to diffract 17keV x-rays. For the single reflection the image is 0.35mm high, and shows fringes both along and transverse to the slit length. The transverse fringes are those described by figure 2 (smeared by the slit height),

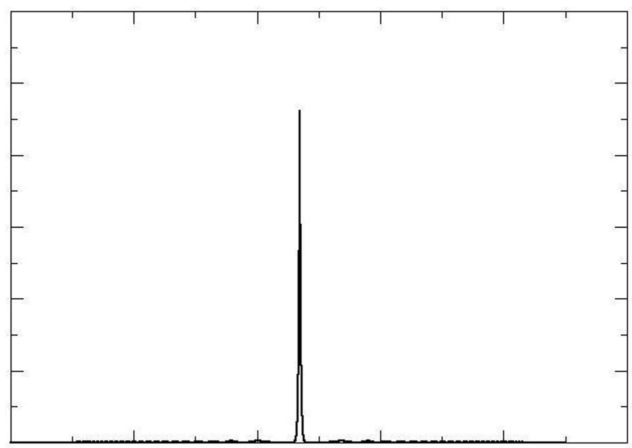

Figure 4. *The calculated spatial (or temporal) profile produced by the device in figure 3. The full width of the central peak is 1µm or 3fs.*

while the longitudinal ones arise from the fact that the crystal plates are slightly wedge-shaped. For the double reflection the image size is essentially the incident beam size. Multiple images of the slit are seen due to the fact that the incident spectrum was polychromatic. The calculated 'diffraction limit' of this central peak is given by Indenbom as $\Delta_0 \tan\theta/2\pi$, where Δ_0 is the pendellosung length (35µm in this case). For the conditions mentioned above this is around 1 µm or 3fs. This is significantly shorter than any currently existing or proposed ultrafast x-ray source. The fact that our experiment used a 25µm slit height does not affect the isochronous nature of the device. Each entrance point on the crystal is imaged to a conjugate exit point, with the minimal time or space smearing described above.

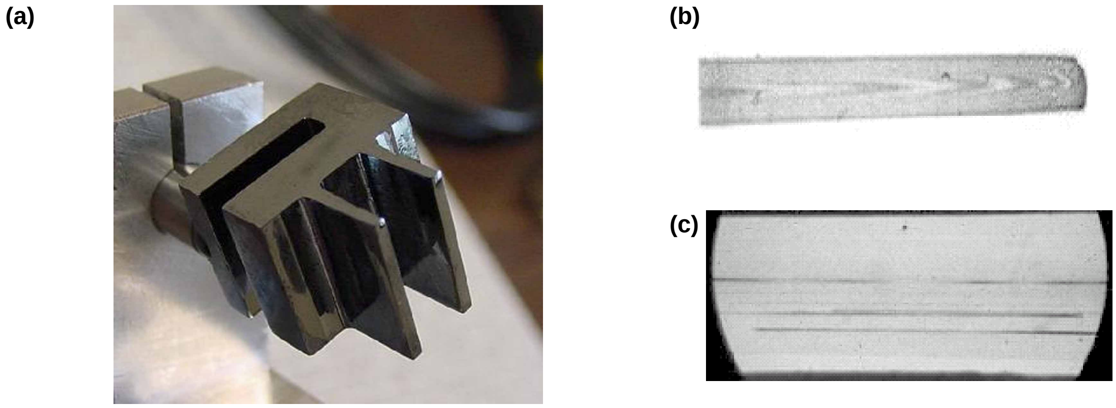

Figure 5. *(a) the test device, a 1cm³ device cut to allow the (2 2 0) reflection. (b) the diffracted beam image after a single Laue-case reflection. The height of the image is due to the spatial spreading discussed in the text. The hook-shaped fringes result from the fact that the plate is slightly wedge-shaped. (c) the image of the doubly-reflected beam. Multiple images of the 25um x 3mm slit are seen, resulting from the fact that the incident beam had a continuous energy distribution so multiple Bragg reflections were excited. For the single reflection, these other beams separate in angle and so are not seen. After two reflections they are rendered parallel and so cannot easily be separated.*

Free-electron laser x-ray sources have interesting coherence properties which merit exploration. For such purposes one needs an interferometer. The most successful hard x-ray interferometers to date are based on Laue case diffraction to provide beam splitters, steering elements and recombiners[6]. For steady state measurements the temporal dispersion described above is unimportant; it is the time-averaged behaviour which is of interest. For fast pulses, we must consider how to mitigate these effects in a useful interferometer design. The standard design of such devices is not suitable for this purpose. The ideas developed above can be extended to the case of three consecutive Laue reflections, and the resulting design is shown in figure 6. The second reflecting plate is made twice as thick as the first and third. This places the initial double-reflection focus in the middle of the second wafer, and this focus is used as the virtual source for a second double reflection. The resultant calculated spatial (and temporal) profile is shown in figure 7a. Figure 7b shows an image of the beam from such a device, illuminated with the same slit as before. This interferometer design was first mentioned by Bonse and Graeff [7] in 1977, but again, the time domain was not considered, and the author is unaware of any prior x-ray measurements made on such a device.

In summary, this highlight shows how the unique properties of dynamical Laue-case diffraction can be used to build isochronous optical devices suitable for use in ultra-fast x-ray sources currently in existence or under development, and a two-crystal monochromator and a three-crystal interferometer have been demonstrated. It is also interesting to consider how these pseudo-focusing devices might enhance the spatial

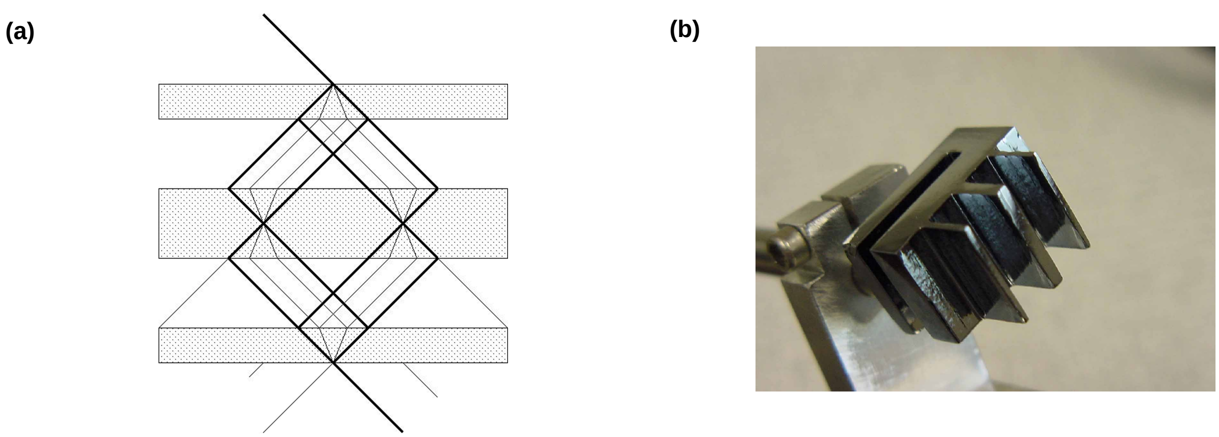

Figure 6. *The isochronous interferometer design. (a) The ray diagram illustrating the focusing mechanism. (b) The test device (roughly 1cm³).*

resolution in imaging applications of the x-ray interferometer. The dynamical spreading has until now been the limiting factor in such applications. Such a compensated device could lead to truly high-resolution phase contrast x-ray microscopy.

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(a) (b)

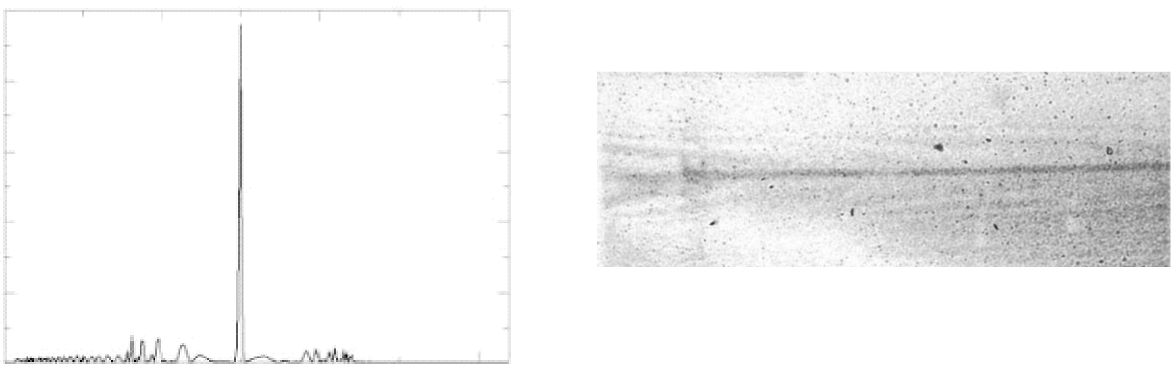

Figure 7. *(a) The calculated profile from the device of figure 6. (b) The experimental image from the test device in figure 6. The strong central line is seen, together with weak fringes on either side. The fringes die away faster on one side than the other, as the calculation indicates.*