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In recent years, several new sources of soft x-ray (10–100 Å) and extreme ultraviolet (100–1000-Å) radiation have been developed. These include laser-produced plasmas[1] and storage ring insertion devices such as wigglers and undulators.[2] Efficient utilization of these new sources requires correspondingly novel optical systems. In the case of plasmas, collecting a maximum solid angle of the isotropically emitted radiation is desired, coupled with modest spectral resolution ($\Delta\lambda/\lambda < 10^{-2}$) to discriminate among the available spectral lines arising from atomic transitions. Whereas full exploitation of the high brightness, directionally emitting sources for experiments in holography, diffractive microscopy, and spectroscopy requires high spectral resolution. In all cases, it would be of advantage to focus without astigmatism in the image, a condition we shall call stigmatism (sometimes called anastigmatism or quasi-stigmatism).

Conventional normal incidence monochromators are capable of stigmatic imaging combined with either high spectral resolution or large geometrical aperture. However, the reflection efficiency of gratings at normal incidence is generally quite low (<1%) for soft x-ray and extreme UV radiation. Conventional grazing incidence systems overcome this problem but introduce severe image aberrations. For example, a spherical grating at grazing incidence has little focusing power in the sagittal direction (along its grooves) and thus forms highly astigmatic spectral lines, of whose lengths only a fraction is used in most measurements. The low luminosity (photons/s/cm^2) of these images at the focal plane also inhibits demanding experiments such as photoelectron or fluorescence spectroscopy.

A currently popular solution to this problem uses a toroidal grating.[3] In this approach, the low inherent sagittal focusing power of a grazing incidence optic is compensated by using a grating blank with an equatorial (minor) radius of curvature ρ along the length of the grooves that is smaller than the (major) radius R in the plane of incidence (meridional direction). If r is the object distance, r' the image distance, α the angle of incidence, and β the angle of diffraction, stigmatism requires that

For example, given the Rowland circle focusing condition ($r = R\cos\alpha$, $r' = R\cos\beta$), the ratio of minor to major radius is $\rho/R = \cos\alpha\cos\beta$, which becomes exceedingly small at grazing incidence. By this means, astigmatism can be removed in the spectral image using a single optical element. Due largely to this simplicity, it has become the widely accepted method by which to construct stigmatic monochromators or spectrometers at grazing incidence [e.g., the toroidal grating monochromator (TGM)].[4–6]

However, aspherical surfaces such as toroidal grating blanks are difficult to fabricate to high accuracy and can result in significant wavefront errors. More fundamentally, the removal of astigmatism by use of a toroid is at the expense of an increase in the higher-order aberration of sagittal coma (alternatively referred to as astigmatic coma or second-type coma). Because this wavefront error grows as the square of the groove length and linearly with the ruled width, the ray aberrations are responsible both for asymmetrical broadening of the spectral image from a point source and for curvature of an entrance slit. Consider the practical case of a bicycle-tire toroid, i.e., one having constant radii of curvature. After removing astigmatism, according to Eq. (1), the results of Haber[3] can be used to show that image broadening of a point source due to sagittal coma degrades the spectral resolution (for extreme rays) according to

$$\frac{\Delta\lambda}{\lambda} = \left|\frac{r^2 a_y^2/8}{\sin\beta - \sin\alpha}\left[\frac{\sin\alpha}{r}\left(\frac{1}{r} - \frac{\cos\alpha}{\rho}\right) - \frac{\sin\beta}{r'}\left(\frac{1}{r'} - \frac{\cos\beta}{\rho}\right)\right]\right|, \tag{2}$$

where a_y is the sagittal acceptance (in radians). In Fig. 1 we have plotted this aberration vs incidence angle on the Rowland circle. For definitiveness, we assumed the use of an

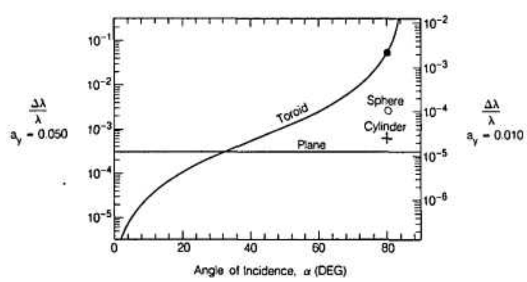

Fig. 1. Sagittal coma for various stigmatic grating solutions as a function of the angle of incidence α. For convenience, it is assumed that the angle of diffraction is 4° larger. The plane, cylindrical, and spherical gratings are fed by a premirror operated at unit magnification with aperture a_y in the sagittal direction of the grating. The toroidal, cylindrical, and spherical gratings are assumed to focus meridional rays on the Rowland circle. Results of ray trace simulations are plotted as ●, ○, and +. The full width at half-maximum resolution is better than the extreme ray aberrations plotted here.

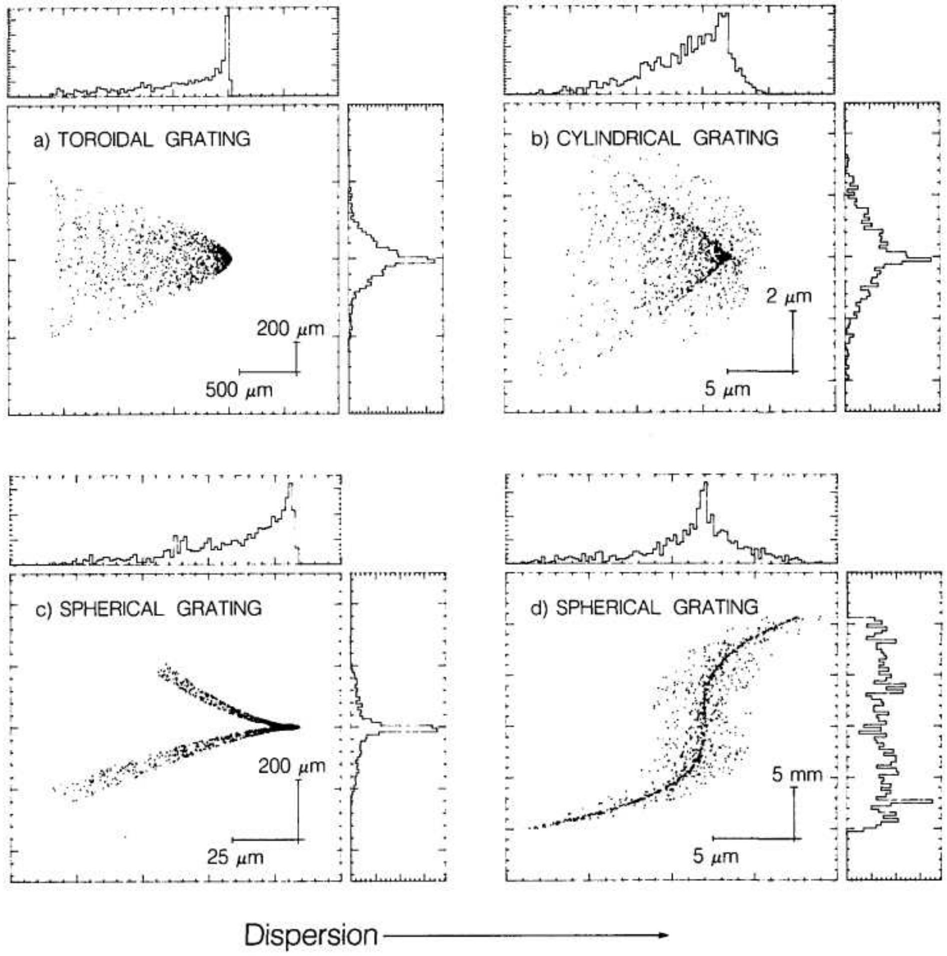

Fig. 2. Ray trace simulations comparing the imaging of a toroidal grating to that of a monochromator using either cylindrical or spherical gratings (Fig. 3) preceded by a concave mirror. All results shown here assume a 2400-groove/mm grating with a collection aperture of 0.050 rad (sagittal) by 0.010 rad (meridional) and an angle of incidence of 80°. The spectral image at a wavelength of 40.5 Å is shown at the exit slit plane. In panel (d), the mirror is adjusted in radius to focus at a detector plane situated 100 cm behind the exit slit.

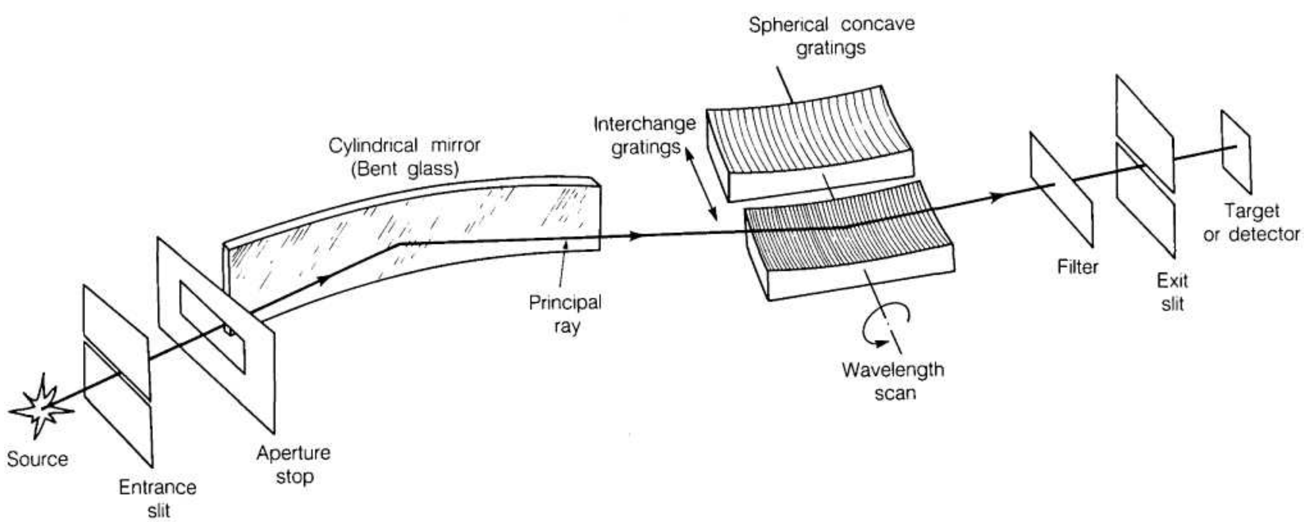

Fig. 3. Schematic diagram of the optical configuration for a high-throughput monochromator (HTM). The cylindrical mirror images a light source (or the entrance slit length) onto a target (or exit plane) in the direction perpendicular to the grating dispersion. A spherical grating is rotated about its pole to select a wavelength using fixed slits. The cylindrical mirror may be replaced by a spherical mirror for small collecting apertures, and be placed anywhere along the optical path. High resolution versions of this design may employ slits which translate slightly along the principal ray and cylindrical gratings.

outside spectral order with the angle of diffraction 4° larger than the angle of incidence. Near normal incidence ($\alpha \sim 0°$), sagittal coma is insignificant for most applications as concluded by Haber.[3] However, for $\alpha > 30°$, when the ratio of minor to major radius becomes significant, we see an enormous rise in this aberration. For example, if $\alpha = 80°$ (grazing angle = 10°) and $a_y = 0.050$, the spectral resolution is $\Delta\lambda/\lambda \sim 1/20$. This prediction is confirmed by the ray tracing result shown in Fig. 2(a). In this simulation, we consider a 2400-g/mm toroidal grating (R = 300 cm, ρ = 5.445 cm), which accepts a rectangular aperture of 0.050 sagittally by 0.010 in the plane of incidence. The spectral image at a wavelength of 40.5 Å is shown on an image plane oriented perpendicular to the principal ray, clearly displaying the characteristic shape resulting from sagittal coma. Given the plate scale of 1.39 Å/mm, the image width envelope of 1650 μm converts to a spectral resolution $\Delta\lambda/\lambda = 5.5 \times 10^{-2}$. This situation improves by only a factor of ~3 if the incidence and diffraction directions are interchanged.

To partially overcome this limitation, advocates of the toroidal grating have proposed introducing a second apsherical element, a premirror, to compensate somewhat for the aberrations of the toroidal grating.[7–9] Even with this addition, the quadratic increase of sagittal coma with aperture has limited the use of such designs to slow input beams, typically $a_y <$ few $\times 10^{-3}$ and to spectral resolutions of $\Delta\lambda/\lambda \sim 10^{-3}$. The solid angle acceptance ÷ image size, therefore, remains low for toroidal grating instruments. This conclusion holds as well for more exotic aspherical grating surfaces, such as ellipsoids or football-type toroids[10] (where radii of curvature are not constant across the aperture) provided one considers the results over a finite bandpass rather than at some correction wavelength along the axis of symmetry.

Our approach is motivated by some earlier work on varied-space plane gratings[11,12] in which the task of removing astigmatism was transferred from the grating to a separate mirror. The stigmatic condition (1) is thereby enforced using infinite ρ and a virtual point source with $r = -r'$. If the grating is fed by a collecting mirror which focuses an object to this virtual source at unit magnification, Eq. (2) reduces to the result previously reported:

$$\Delta\lambda/\lambda = a_y^2/8, \tag{3}$$

which is independent of the incidence angle. For example, a sagittal collecting aperture of 0.050 permits a spectral resolution of 1/3,200 as plotted in Fig. 1. Given an aperture of 0.010, more than adequate for collection of most directionally emitting sources, the plane grating converging-beam geometry permits a spectral resolution of 1/80,000. These values represent an improvement over the single-element TGM by more than 2 orders of magnitude.

We have adapted some aspects of this geometry to construct a high throughput monochromator (HTM). In particular, Eqs. (1) and (2) are independent of the grating curvature R in the plane of incidence. Thus one intuitively expects similar results from a conventionally ruled cylindrical grating curved only in the plane of incidence. A single premirror could then be oriented orthogonally to the grating and provide the required virtual line focus for sagittal rays incident to the grating. This is analogous to the imaging mirror system of Kirkpatrick and Baez.[13] It decouples imaging in the two directions, permitting a high collection aperture along the grating grooves while avoiding the deleterious effects of sagittal coma present in toroidal gratings. Ideally, the premirror would be elliptical, and the grating would focus along the Rowland circle. A ray tracing of this system, with physical parameters otherwise identical to the previous TGM case, is shown in Fig. 2(b). Compared to the TGM, a factor of 90 reduction in image width, and a factor of 120 reduction in image height, is obtained. These results are only a factor of 2 worse than expected for a varied-space plane grating as given by Eq. (3).

Further simplifications are possible at moderate resolutions. Given the insensitivity of Eq. (1) to large values of ρ, we expect that a spherical grating ($\rho = R$) can approximate the results of the ideal cylinder. Furthermore, we can replace the elliptical premirror by a circular cylinder which should have excellent focusing properties at unit magnification. The large collection aperture a_y desired requires a long premirror and is conveniently provided by a bent strip of glass.[14] (For applications requiring a smaller collection aperture, a simple concave spherical mirror could be used.) Figure 2(c) demonstrates that such a simplified system maintains a large improvement over the toroid. The factor of 20 reduction in image width yields a spectral resolution of $\Delta\lambda/\lambda = 2.8 \times 10^{-3}$ and, combined with a factor of ~3 reduction in image height, delivers an image significantly brighter than does the TGM, even after accounting for the <100% reflectance of the premirror.

Such a design is illustrated in Fig. 3. The use of a spherical grating is of great practical significance, allowing easy and accurate fabrication of the substrate. While a seemingly obvious solution, this simple configuration and its advantages over the TGM have previously been overlooked. Other designs of related interest have used toroidal premirrors[15] or have suggested the use of a cylindrical grating with the cross section defined by a polynomial.[16] As the main intent of those works was to reduce astigmatism, the potential for avoiding sagittal coma in this manner appears not to have been fully appreciated.

With design parameters optimized for moderate spectral resolution and maximum acceptance in solid angle, we constructed a prototype HTM for use with a laser-produced plasma. This light source is sufficiently small (~200 μm) to act as an entrance slit, resulting in a net collection efficiency (including the efficiency of the optics) of 10^{-4} steradians and a spectral resolution of $\Delta\lambda/\lambda = 3–10 \times 10^{-3}$ over the 40–250 eV band. The monochromator employs two tripartite 3-m ruled spherical gratings, with either one selectable by an external feedthrough, providing coverage from 30 to 300 eV (40–400 Å). Final wavelength selection is accomplished by a simple grating rotation about its pole (central groove) using a sine-bar drive and an included angle of 164° between fixed entrance and exit slits. This results in two wavelengths for which the dominant term in spectral defocusing is eliminated[4] (45 and 105 Å for the 2400-groove/mm grating; 135 and 315 Å for the 800-groove/mm grating). This scanning motion also fixes the direction for the principal ray and maintains the astigmatism correction at all wavelengths. A practical feature of the present instrument is the ability to replace quickly the inexpensive strip glass mirror when contaminated by plasma debris.

In Fig. 4 we show a preliminary spectrum obtained using the 800-groove/mm grating when fed by a Penning discharge lamp[17] and entrance slit and where the detector was a Galileo Channeltron having a MgF_2 coating. Rather than imaging stigmatically onto the exit slit, we maximized the count rates by adjusting the mirror radius to focus at a magnification of ~5 onto a detector (which was situated ~100 cm from the exit slit). As shown in Fig. 2(d), this further decreases the level of sagittal coma due to the fivefold decrease in a_y incident to the grating. Using 150-μm entrance and exit slits and collecting apertures of 0.030 (sagittal) and 0.015 (meridional) the aver-

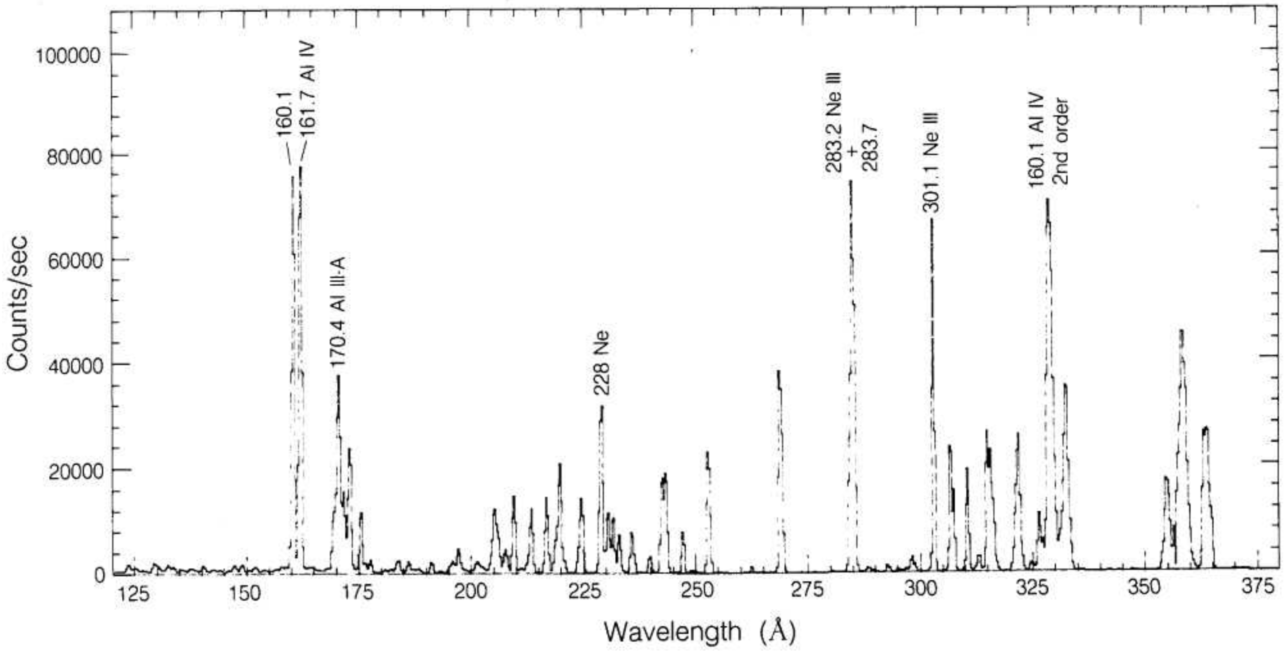

Fig. 4. Spectrum obtained with a prototype high throughput monochromator using an 800-groove/mm spherical grating and 150-μm slits. The light source was a Penning discharge using aluminum cathodes and neon gas at an operating current of 0.3 A. At a current of 0.75 A, an Al IV line at 129.7 Å is also detected with ~30,000 counts/s.

age spectral resolution is $\Delta\lambda/\lambda = 4 \times 10^{-3}$ and the line intensities exceed published values[17] obtained using commercial monochromators by a factor of 50–100. The monochromatized beam exiting the HTM was designed to enter a reflectometer for efficiency measurements of soft x-ray and extreme UV optics.

Alternatively, one may trade throughput for higher spectral resolution. For example, as shown in Fig. 1, a sagittal aperture of 0.010 radians permits $\Delta\lambda/\lambda = 10^{-4}$. Given a slight adjustment of either the exit or entrance slit along the principal ray as a function of λ, defocusing due to the simple rotational grating scan is largely eliminated[8,9] and a meridional aperture of ~0.003 radians is acceptable. The high quality to which a spherical (grating) surface can be routinely formed permits the practical realization of such high resolution. Of particular interest is the use of this design with the low divergence radiation from soft x-ray undulators.[2]

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