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Spectral focusing characteristics of a grazing-incidence flat-field grating spectrometer*

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The spectral focusing characteristics of a grazing-incidence flat-field spectrometer with a spherical variable-line-spacing grating in the 5–40nm spectral range are presented. The spectrometer can be used for any object at a distance in the 50mm–infinity range from the grating apex with a diffracted spectrum sharply focused on an almost flat focal plane at a constant distance from the grating apex.

Keywords: spectrometer, grating
PACC: 0765E, 4280F

1. Introduction

Soft x-ray spectroscopy is one of the important techniques for determining temperature and density conditions, atomic and ionic species and abundance in high temperature plasmas, such as fusion-related discharge plasmas, plasmas in sun or some other planets, laser plasmas, etc. It is also an essential diagnostic tool for measuring the gain coefficients of soft x-ray lasers and the orders and the efficiency of the high harmonic generation by the interaction of high intensity laser pulse with gas or solid. For a grating spectrometer working in the soft x-ray region, a grazing-incidence mount is adopted to increase the reflectance from the grating surface.[1] In a conventional grazing-incidence spectrometer with a spherical uniform-line-spacing grating (ULSG), the grating and the slit are located tangentially to the Rowland cylinder and the diffracted spectrum from the grating is also focused on the same cylinder. In order to obtain a clear and sharp spectrum over a large wavelength range, detectors must be also mounted in coincidence with the cylinder surface. That is no problem for the flexible detectors such as film or thin plates, but it is another story for the vigorously developing photoelectric detectors with a sort of flat sensitive surface, such as photodiode array, microchannel plate, charge-coupled device, and the photocathode of an x-ray streak camera. At the beginning of the 1980s, a new kind of grating—variable-line-spacing grating (VLSG)—was developed,[2] followed by the so-called 'flat-field' grating spectrometer (FFGS) using the new grating as a dispersion element.[3–6] In the grazing-incidence FFGS, the diffracted spectrum is focused sharply onto a plane, instead of a cylinder. Therefore, the problem with the coupling between the faced photoelectric detectors and the focal plane of the spectrometer was solved straightforwardly. However, in such a standard FFGS, there is a severe limit to the distance of the source from the grating apex, i.e. the object distance is fixed at 237mm. This imposes a significant restriction on the applications of the grazing-incidence FFGS.

In this paper, we present the calculated results in connection with the focusing characteristics of the grazing-incidence FFGS for any object distance. The calculated results show that for any given object distance in the 50mm–infinity range, there always exists an appropriate incident angle. At this angle, the

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diffracted spectrum in a wavelength range from 5 to 40nm is sharply focused on the flat focal plane which is almost normal to the incoming rays and located at 235mm from the grating apex.

2. Standard flat-field grating spectrometer

The standard grazing-incidence FFGS is widely used in many laboratories for laser plasma x-ray spectroscopy, soft x-ray lasers and high harmonic generation. This kind of spectrometer has an object distance of 237mm and a spectral focal plane at 235 mm from the grating apex. Such a spectrometer is mostly equipped with a Hitachi 1200 lines/mm mechanically ruled aberration-corrected concave grating, and has an incidence at 87° in standard design. In comparison with an ordinary ULSG spectrometer, this spectrometer has a higher efficiency and spectral resolution, and possesses a flat focal plane desirable for the coupling with the photoelectric detectors having a faced sensitive surface.

However, in the standard flat-field spectrometer, the source or slit must be placed at a distance of 237mm from the grating apex. The requirement for the object distance restricts the usage of the FFGS and makes experiments difficult to do in some cases. In the limited space of less than 237mm from the source to the grating, it is very difficult to locate any other optics, such as a pre-optics system for collecting more light to increase the efficiency of the spectrometer or for obtaining one-dimensional spatially resolved spectrum, and an x-ray reflecting filter composed of a pair of reflecting mirrors for repressing high order spectra to get an undisturbed spectrum. In addition, the drivers for laser fusion, x-ray lasers and high harmonic generation–the high power laser facilities have all the laser target chambers of their own. It is difficult for the standard flat-field spectrometer with a fixed object distance of 237mm to be fitted into a different laser target chamber. So the spectrometer is accommodated inside the laser target chamber in some laboratories or located outside the laser target chamber in other laboratories. And different laser target chambers should have to be equipped with their own dedicated spectrometers. The flexibility and adaptability of the grazing-incidence FFGS are thus restricted. Neely *et al*[7] have paid attention to this problem, and designed and constructed a flat-field grating spectrometer with an object distance different from 237mm to meet the requirement in their experiments, but their design was only for an object distance of 620mm.

3. Spectral focusing curve calculations and results

We study the spectral focusing characteristics of the grazing-incidence FFGS with a widely used Hitachi 1200 lines/mm mechanically ruled aberration-corrected spherical grating. The grating has a radius of 5649mm and a blaze angle of 3.2°, and is replicated on a gold-coated surface of 50mm×30mm. It was designed originally for a flat-field spectrometer covering the 5–20nm wavelength range at an incident angle of 87°. The grating has a groove number density of 1200 lines/mm at its apex with the line-spacing varying from 0.690μm to 0.985μm across the 50mm grating length.

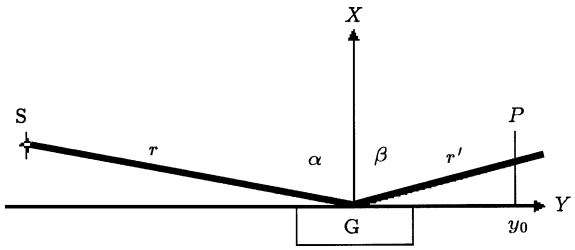


Fig.1. Schematic diagram of the flat-field spectrometer.

Figure 1 is the schematic diagram of the spectrometer with VLSG as a dispersion element. In the figure, S is the source or slit, G is the VLSG, α and β are the incidence and the diffraction angles, respectively, and P is the flat focal plane. As usual, a rectangular coordinate system is adopted with its origin on the grating apex, the X-axis along the normal to the grating surface at its apex and the Y-axis perpendicular to the ruled lines of the VLSG. In Fig.1, r is the object distance and r' is the spectral image distance, i.e. the distance from spectral focus to the grating apex.

From the grating equation and the horizontal focusing condition,[2] we have, respectively,

$$m\lambda = \sigma_0(\sin\alpha + \sin\beta), \tag{1}$$

$$\cos^2\alpha/r - \cos\alpha/R + \cos^2\beta/r' - \cos\beta/R = 40m\lambda/(\sigma_0 R). \tag{2}$$

Equations (1) and (2) describe the relation among wavelength λ, incidence angle α, diffraction angle β, object distance r, spectral order m, spectral image distance r', the nominal line-spacing σ_0 and grating

radius R. In comparison with the ordinary ULSG spectrometer, the grating equation Eq.(1) is the same, but the horizontal focal condition Eq.(2) is different: the term on the right-hand side of Eq.(2) is zero for the ordinary ULSG spectrometer, but $40m\lambda/\sigma_0 R$ for the flat-field VLSG spectrometer. It is the term of $40m\lambda/\sigma_0 R$ on the right-hand side of Eq.(2) that leads the flat-field grating to focus horizontally the spectrum on a flat plane. For a given wavelength λ, incidence angle α and object distance r, the spectral image distance r', both $y' = r' \sin\beta$ and $x' = r' \cos\beta$ can be calculated from Eqs.(1) and (2).

For the standard flat-field grating spectrometer with α=87° and r=237mm, it is found that $y' \approx y'_0$=235mm, near a constant over a wavelength range from 5 to 40nm, and $x' \approx$235cotβ. As a result, the spectral focal plane is a flat plane perpendicular to the Y-axis, i.e. nearly perpendicular to the incoming rays. This is the unique feature of the flat-field VLSG spectrometer due to the term of $40m\lambda/\sigma_0 R$ on the right-hand side of Eq.(2), which is different from the ordinary ULSG spectrometer.

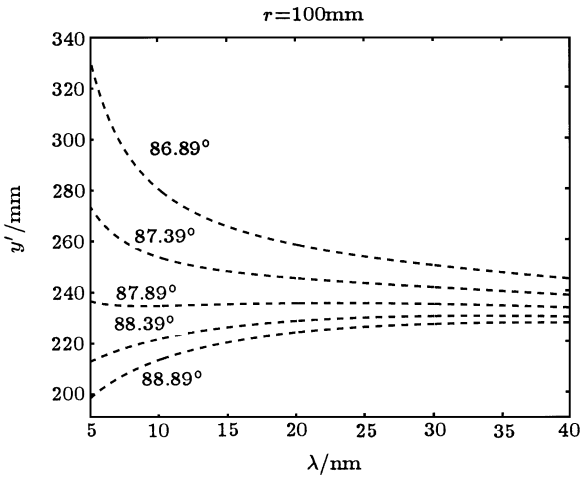


Fig.2. Calculated spectral focusing curves for r=100mm.

With Eqs.(1) and (2), we have calculated the spectral focusing curves for an object distance r from 50mm to infinity with the incidence angle as a parameter. Figure 2 is the calculated spectral focusing curves for r=100mm and for several incidence angles. As can be seen, for any object distance r larger than 50mm, we can always find an optimal incident angle at which the spectrometer focuses the spectrum in a wavelength range from 5 to 40mm on a flat focal plane at y'_0=235mm from the grating apex. The calculated results show that except for the wavelengths near 5nm and 40nm, the differences between the y' and y'_0 are all less than 0.5% of y'_0, i.e. the values of $y' - y'_0$ are all less than 1mm.

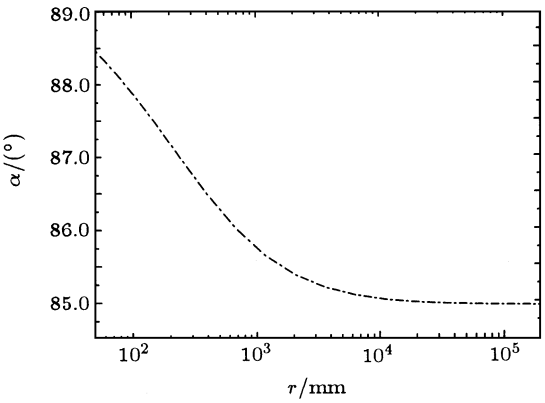


Fig.3. Optimal incident angle α versus object distance r.

Figure 3 shows the optimal incident angle α as a function of the object distance when the optimal focusing at y'=235mm in a wavelength range from 5 to 40nm is obtained. The optimal incident angle decreases with the object distance and thus the optimal grazing angle increases with the object distance. For an object distance r in a range from 50mm to infinity, the corresponding optimal incident angle ranges from 88.5° to 84.9° and thus the optimal grazing angle ranges from 1.5° to 5.1°.

4. Conclusion and discussion

From the calculated results, we can draw the following conclusions. For the source at a distance in the 50mm–infinity range from the grating apex, one can always find an optimal incident angle, at which the Hitachi mechanically ruled aberration-corrected spherical 1200 lines/mm grating can focus the spectrum in the 5–40nm wavelength range onto a flat focal plane nearly normal to the incoming rays at a distance 235mm from the grating apex. The optimal grazing-incidence angle increases with the object distance and ranges from about 1.5° to 5.1° for the object at a distance in the 50mm– infinity range. For the object distances required by the different experimental arrangements equipped with different target chambers, one can determine the optimal incident angle to obtain a clear and sharp spectrum on the flat focal plane. Therefore, the restriction of the object distance in a standard flat-field spectrometer can be removed by choosing an optimal incident angle. This improves the flexibility and adaptability of the flat-field grating spectrometer in the experiments with different target chambers. For example, the spectrometer can work

with a parallel light beam coming from a distant star or from a synchrotron radiation source.

Under the grazing-incidence condition, the reflectivity at the surfaces for a given wavelength decreases with the grazing-incidence angle. Our calculation shows that the corresponding grazing-incidence angle for the source at infinity is about 5.1°. The minimum wavelength reflected from a gold surface at a critical angle θ is $\lambda = 15.4 \sin\theta$=1.3nm.[1] Therefore, for the range of the grazing angle from 1.5° to 5.1° calculated in this paper, the gold-coated grating surface has a high reflectivity for the wavelengths ranging from 5 to 40mm. The grazing-incidence FFGS with a large object distance still has high efficiency.

It is required that the incident angle on the grating should be adjusted accurately for a given object distance. Therefore, the grating should be mounted onto a precise goniometer with an adjustment precision of 0.1° at least. In experiment, the incident angle will be adjusted until the sharp spectral lines are obtained on the flat focal plane in a whole wavelength range from 5 to 40nm. For a given object distance r and an incident angle α, the spectral image distance r' of the zero order can be calculated from Eq.(2) or from the imaging formula of a mirror in the meridian plane

$$1/r + 1/r' = 2/(R\cos\alpha). \tag{3}$$

For a given r, the corresponding r' and α values are determined. One can use these relations to carry out the angle measurement, which is more difficult and less precise. Alternatively, one can use them in the length measurement, which is easier and more precise. From Eq.(3), we have

$$\Delta r'/r' = \tan\alpha \times \Delta\alpha. \tag{4}$$

For an incident angle of 87°, Eq.(4) shows that a change of 0.03° in α ($\Delta\alpha/\alpha \approx 3.5\times10^{-4}$) will cause a change of about 3mm in r' ($\Delta r'/r' \approx 10^2$). Since a small change in the incident angle will cause a remarkable change in r', the zero order of r' can be used as a sensitive monitor to examine the position and imaging quality of the zero order image, leading to the precise adjustment of the incident angle of the grazing-incidence flat-field grating spectrometers.

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