2D Imaging Spectrometer for EUV and Soft X-ray[a)]

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An off-plane spectrometer with near grazing incidence geometry capable of both spatial and spectral imaging, and having efficient response is presented. The spectrometer design is intended for extreme and vacuum ultraviolet wavelengths, 8 to 125nm. Capable of resolving power in excess of 500, the spectrometer equipped with two dimensional CCD detector can be used for spectral analysis and multiple view chord techniques. We describe the grazing incidence off-plane optical system, related efficiency, and image formation at two dimensional detectors. Our goal is to acquaint investigators with a unique spectrometer (spectrograph) that may be useful for plasma diagnostics.

I. INTRODUCTION

Acquisition and study of optical spectra is a key diagnostic method for magnetic and inertial fusion, and generally, plasma-physics research. Optical spectroscopy allows non-invasive diagnosis and provides information on impurities, ionized species, plasma temperature, formation and confinement. Techniques monitoring Stokes shifts, line broadening or splitting are used. In order to map the formation and confinement of large plasmas, visible spectroscopy systems may use multiple view chords coupled by fiber optics to a spectrometer. In this manner hundreds of sight lines can be monitored with one spectrometer[1]. For example, Figure 1. depicts an image collected by CCD (DU-888, Andor Technology) showing low pressure Mercury lamp emission at 546.07nm collected simultaneously by one hundred separate input fibers mounted to the entrance port of a one meter imaging Czerny-Turner spectrometer (Model 2061, McPherson.)

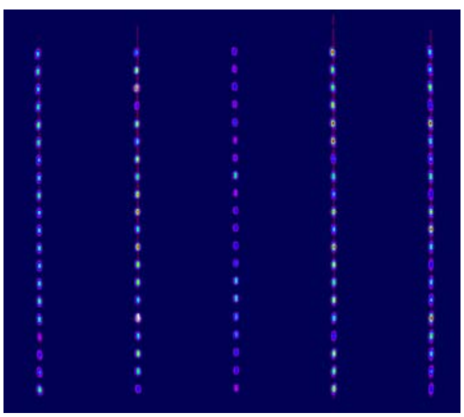

Figure 1. CCD image (raw data) from one hundred input signals dispersed and imaged by one meter focal length spectrometer. Each illuminated point represents a single input fiber and Mercury emission at 546.07nm.

At shorter wavelengths, use of fiber optics is not possible. Conventional fibers do not transmit light shorter than approximately 185 nanometers. The region of shorter wavelengths - variously referred to as vacuum ultraviolet (VUV), extreme ultraviolet (EUV), and soft x-ray (SXR) – can be monitored by single reflection grating instruments. Some of these instruments are low resolution survey spectrometers[2]; others provide exceptional spectral resolution with limited spectral coverage[3]. To emulate the imaging capability of visible multiple view chord spectrometers, some VUV experiments add apertures to normal-incidence spectrometer designs.[4] Combined with low efficiency broadband reflectors, these may also limit the wavelength range of this approach. Others use multiple instruments (nine[5]) organized at different sight lines as means to collect multiple spectra simultaneously.

The subject off-plane spectrometer follows visible Czerny-Turner spectrometer designs in that it uses a plane diffraction grating in combination with separate collimating and focusing optics. Near grazing angles used to achieve good reflective efficiency at short wavelengths and grating rulings rotated 90 degrees and parallel to instrument axis remove many other similarities. This x-ray Czerny-Turner (XCT) design features better throughput efficiency than on-plane designs, it works well in the 10 to 150eV region, houses multiple gratings, and point-to-point imaging provides capability of simultaneous spectral and spatial imaging in the EUV similar to that of multiple fiber instruments in the visible wavelength region.

II. TECHNICAL DESCRIPTION

The off-plane XCT spectrometer is stigmatic and uses conventional planar diffraction gratings in an efficient off-plane optical mount. Reflective efficiency at the 85 degree angle-of-incidence selected for this design allows work in the range from ~8nm to 125nm (10eV to 150eV). Simple grating rotation scans wavelengths when the instrument operates as a monochromator. It operates as an imaging spectrograph when grating angle is fixed and suitable two dimensional (2D) detectors are employed (e.g. film, CCD or CMOS.) Figure 2. shows the optical layout consisting of toroidal collimating and focusing mirrors in combination with a plane ruled replica diffraction grating. To help describe utility in imaging applications, the entrance image is shown as a point source, and the exit plane is a 2D detector.

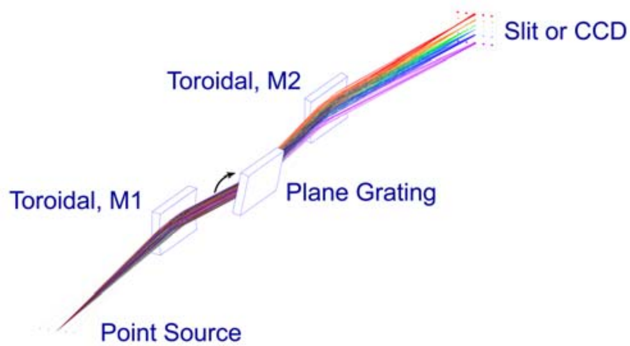

Figure 2. Elements of the off-plane XCT spectrometer include entrance point source, optics, and a 2D detector at the exit. In order to measure multiple view chords, the entrance point-source must be replaced with a linear array of pinholes.

Optical aberrations are significant at the large angle of incidence used in the off-plane XCT and toroidal mirrors are adapted to compensate and provide point-to-point focus. The spectrometer has a triple grating mount inside the vacuum vessel that allows gratings with different optimal blaze wavelengths or groove densities to be used. Gratings can be selected according to application requirements for spectral resolution and wavelength range. The performance parameters provided by three possible gratings are shown in Table I. The spectral resolution values given in the table are based on diffraction limited image size. The histogram data in Figure 5. also illustrates the line formation for the 1200g/mm grating case.

Grating (g/mm)	1200	600	333
Facet Angle (degrees)	5.17	5.17	5.7
Blaze Wavelength (nm)	13	26	52
Wavelength Range (nm)	0 – 70	0 – 140	0 - 260
Dispersion (nm/mm)	1.05	2.1	3.75
Spectral Resolution (nm)	0.01	0.02	0.06

Table I. Off-plane XCT spectrometer performance with three different diffraction gratings.

A. Efficiency

Near grazing incidence angles improve mirror reflective efficiency and set overall wavelength range accessible by the instrument. Reflective efficiency of a gold coating layer at 85 degree angle-of-incidence in the EUV is shown in Figure 3. Poletto[6] et al built off-plane instruments with geometries quite similar to the XCT and measured diffraction grating efficiency significantly higher than comparable on-plane designs. In this respect, their experimental results support the data obtained from modeling software (PCGrate, I.I.G., Inc.) shown in Figure 4.

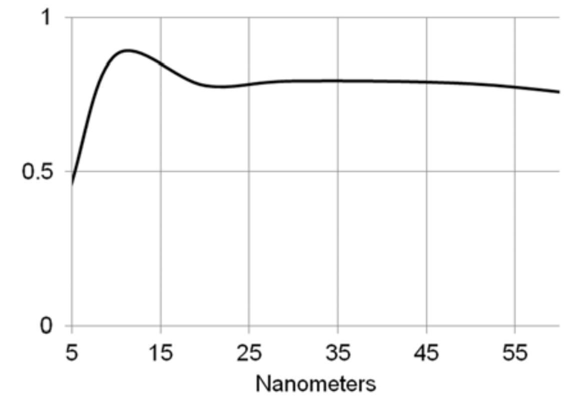

Figure 3. Model data for the reflectivity of Gold at 85 degree angle of incidence as used in the off-plane XCT system

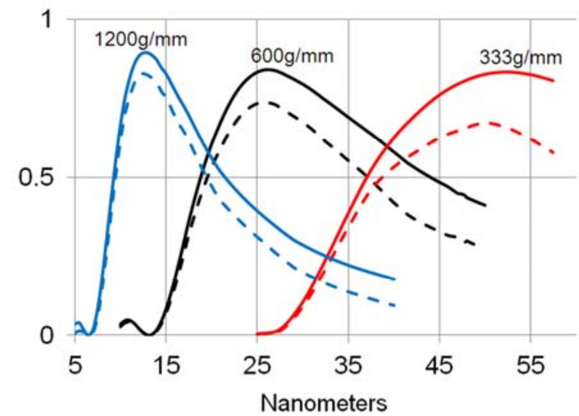

Figure 4. Model data of absolute grating efficiency vs. wavelength showing TM and TE (broken lines) response. (courtesy of Richardson Grating Lab)

Plane gratings used in the off–plane XCT are available with many blaze angles from commercial suppliers. The wavelength of best efficiency is $2 \sin\alpha \sin\beta \, d$ for instrument angle of incidence (α) and diffraction grating saw-tooth blaze angle (β).

B. Spectral Resolution and Imaging

The large aperture ratio and grazing incidence angles require consideration of the smallest possible spot size possible with such an instrument. Setting entrance aperture to the minimum diffraction limited image size is one way to estimate achievable spectral resolution. For purposes of estimation the diffraction limit for incoherent light is given by $1.22\ F\#\ \lambda$ where $F/\#$ or aperture-ratio given by f/D. f is instrument focal length and D is the diameter of the instruments limiting aperture or optical surface. For the off plane XCT this is 0.009 millimeters at 40eV. Longer focal length and higher density gratings directly influence attained resolving power. Initial ray trace models (Beam Four, Stellar Software) indicate resolving power $\lambda/\Delta\lambda$ at 40eV is >500 with 800mm focal length optics, 1200g/mm diffraction grating, 0.01mm source. Graphical depiction of the resolving power is shown in Figure 5. where the central ray (30nm) flanked by closely adjacent wavelengths (29.95 and 30.05nm) are plotted as they would appear at the focal plane.

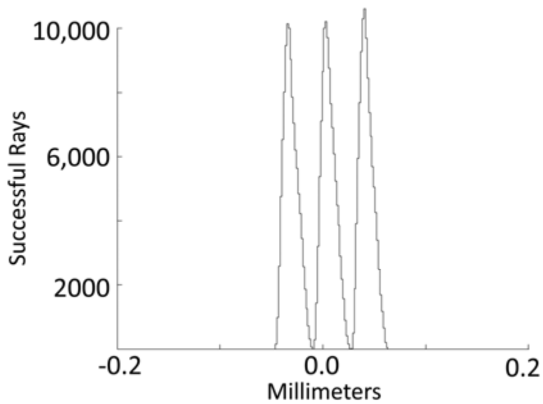

Figure 5. Ray trace histogram for wavelength axis, modeling three closely spaced wavelengths, 40±0.07eV (30±0.05nm)

When the exit focal plane is equipped with a two dimensional (2D) detectors like CCD or CMOS, the off-plane spectrometer works as an imaging spectrograph. Model data indicates it is possible to survey a very broad EUV wavelength range and maintain spatially distinct spectra. The ray trace spot diagram shown in Figure 6. displays wavelengths from 10 to 140nm dispersed across approximately 12 millimeters. To create the image six unique pinholes are distributed in the spatial direction at the entrance to emulate unique view chords of a plasma event.

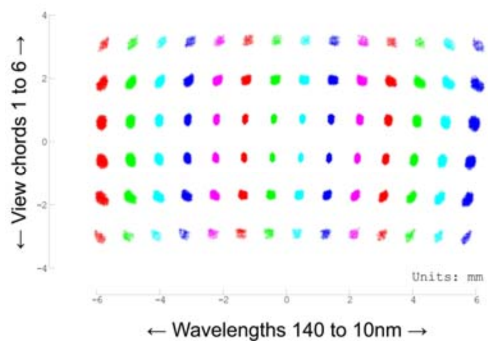

Figure 6. Ray trace spot diagram showing six unique spatial channels reaching two dimensional detector surface. Each spatial channel provides coverage from 10 to 140 nanometers

C. Wavelength Selection

The off-plane XCT spectrometer wavelength selection conforms to the grating equation $sin^{-1}[(n\lambda)/(2dsin\alpha)]$ where n is diffracted order, d is grating constant, and α is grazing angle of incidence. In the McPherson off-plane XCT design a sine-arm and precision screw mechanism rotate the grating. Wavelength selection is linear, e.g. one revolution of the drive motor advances wavelength by a fixed increment. This allows use with conventional motors and also means to mechanically interpret wavelength position. Commercial micro step motors, as those with 36,000 steps per revolution, over-sample attainable optical resolution. Total range of grating rotation up to approximately 30 degrees allows calibration at air with conventional laboratory calibration sources like low pressure Mercury pen lamps for data points at zero order, 184.9, and 253.6 nanometers with 333g/mm or coarser gratings. The proven sine wavelength drive method for wavelength selection, in combination with means to calibrate response off-line, and at atmosphere, make this instrument generally user friendly and easy to characterize.

III.CONCLUSION

Spectral analysis is a useful diagnostic for any plasma. The off-plane XCT spectrometer features several unique attributes that may be exploited in EUV and VUV spectral diagnostic applications. The instrument attributes include fixed slit positions making it suitable for use with large immovable sources and detectors, excellent reflective and off-plane grating efficiency, it can access a wide wavelength range, and point-to-point imaging offers capability to perform spatial and spectral imaging. In combination with a suitable detector, the off-plane XCT spectrometer is a valuable tool and may find use in plasma physics and in particular fusion diagnostics.

IV. ACKNOWLEDGEMENTS

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