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Design and realization of a XUV plane-grating monochromator at variable included angle

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Abstract. A plane-grating monochromator for the extreme-ultraviolet region that uses a plane grating operated at variable included angle and illuminated in converging light has been realized. The configuration consists of three optical elements: the focusing mirror, the plane grating and the plane mirror. In the proposed design, the spectral focusing is kept on the exit slit plane by changing the grating included angle through the use of an additional plane mirror after the grating. The coma aberration given by the grating is compensated by an opposite coma introduced by the focusing mirror, that is used in a very asymmetrical configuration. The feasibility of the configuration has been demonstrated on a monochromator for the 10-80 eV region, with sub-10-meV output bandwidth. The correction of defocusing and coma at the proper included angle has been clearly demonstrated. The monochromator efficiency has been measured to be in the 0.08-0.18 range.

INTRODUCTION

Extreme-ultraviolet (XUV) sources based on high harmonic generation (HHG) have gained more and more interest over the last years [1]. HH sources are compact and provide coherent ultrashort intense pulses on a table-top scale. HHs are usually generated by mJ-scale laser pulses operated typically at relatively low repetition rates, in the few-to-several kHz range. High repetition rates are critical for experiments related to coincidence and time-of-flight spectroscopy and can also boost photoemission-based experiments on solid samples where electron space-charge effects require spreading the photon flux over many pulses [2, 3]. The extension of the repetition rate of such sources towards 50 kHz and beyond, would make them really advantageous for this kind of investigations [4-6].

HHs inherent bandwidth is often too wide for a large class of experiments, since multiple orders of harmonics are generated coaxially. Therefore a suitable broad-band monochromator with moderate-to-high resolution is required for the selection of a single harmonic over a broad spectral region. Grating monochromators using a single grating with tunability in a broad band, modest spectral resolution (100-200 meV) and high temporal resolution (few tens of femtoseconds) have been realized for HH beamlines [7, 8]. Also double-grating configurations with ultrafast response below ten femtoseconds are in operations [9, 10]. Unfortunately, the cited configurations lack of high energy resolution, as may be required for high-repetition HH beamlines for electron spectroscopy on solid-state samples. Many of the existing monochromators for HHs work without an entrance slit because of the limited size of the HH source [11]. On the other hand, high-resolution monochromators are usually operated with entrance and exit slits in order to obtain an energy calibration almost independent from the alignment of the source.

Aim of the paper is to present the design of a high-resolution XUV monochromator conceived mainly for application to table-top XUV sources using cost-effective optical elements: plane gratings, plane mirrors, spherical or cylindrical mirrors.

Plane grating monochromators require additional mirrors to focus the beam on the slit plane as the wavelength is scanned through grating rotation. The classical Czerny–Turner design, using a plane grating illuminated in collimated light, requires two concave mirrors (ideally, parabolic) for collimation and refocusing [12]. The well-

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known SX-700 design uses a plane grating plus a fixed concave (ideally, elliptical) mirror and a rotating plane mirror [13]. This design can be operated with [14, 15] or without [16, 17] a collimating beam and is at present adopted in several synchrotron beamlines [18, 19].

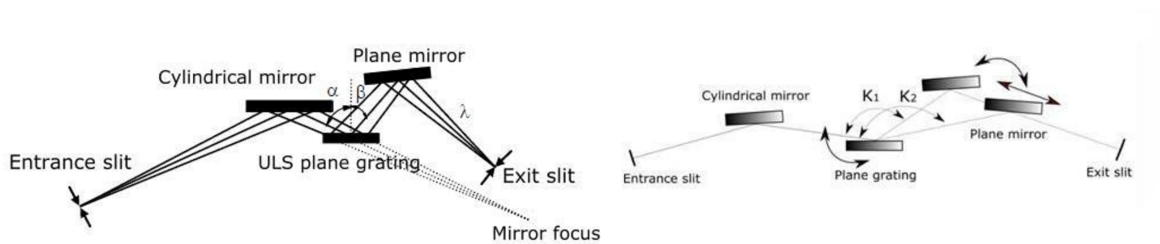
The number of optical elements can be reduced if concave gratings or variable-line-spaced (VLS) gratings are used. Monochromators with a single optical element can be realized by spherical or toroidal gratings [20, 21]. Two-elements monochromators can be realized by using a VLS gratings illuminated by the light focused by a concave mirror [22, 23]. These configurations, although well proven for synchrotron and free-electron-laser sources, require to use expensive components.

The present design originates from the proven SX-700 configuration. A plane grating is illuminated by a converging beam focused by a cylindrical mirror. The spectral focusing is maintained on the slit plane by changing the grating included angle using an additional plane mirror, giving a three-elements configuration. Once the spectral focusing has been obtained, the main higher-order aberration to be corrected is the coma. In the present design, the magnification of the focusing mirror is chosen to have a coma that compensates the coma given by the grating, giving an almost aberration-free focal image. The configuration uses simple optical components (the cylindrical mirror, the plane grating and the plane mirror), that are available on the market with high optical quality and low prices. Furthermore, differently from the two-elements configurations operated at constant included angle, the loss of efficiency due to the introduction of the additional plane mirror is almost recovered since the grating is operated at variable included angle and is maintained close to the blaze condition of maximum efficiency during the full wavelength scan.

The configuration here presented has been applied for the realization of a high-resolution monochromator for the 10-80 eV region with sub-10 meV bandwidth. The performances and the efficiency issues of the instrument are discussed in details.

MONOCHROMATOR DESIGN

The light from the entrance slit is focused by a cylindrical mirror, then diffracted by a plane grating and finally deviated by a plane mirror toward an exit slit. The included angle on the grating is changed by acting on the translation and rotation of the plane mirror. The optical layout is shown in Fig. 1. The spectral focus is maintained on the slit plane by varying the grating included angle through a translation and rotation of the plane mirror.



(a) (b)

FIGURE 1. Layout of the instrument. (a) Optical design of the instrument; (b) Operation at different included angles.

The complete analytical equations to design the configuration have been presented in Ref. 24 and are here briefly resumed. The equation to correct for spectral defocusing is

$$p_G = q_G \frac{cos^2\alpha}{cos^2\beta} \tag{1}$$

where α and β are respectively the grating incidence and diffraction angles at the wavelength λ.

From the previous equation, the condition to have the spectral focus with fixed arms, i.e. fixed entrance and exit slits is $(cos\alpha/cos\beta) = const.$ This condition must be fulfilled for each wavelength within the spectral interval of operation and, taking into account the grating equation, it can be expressed as

$$\frac{cos\left\{\frac{K}{2}+arcsin\left[\frac{m\lambda\sigma}{2cos\,(K/2)}\right]\right\}}{cos\left\{\frac{K}{2}-arcsin\left[\frac{m\lambda\sigma}{2cos\,(K/2)}\right]\right\}} = const. \tag{2}$$

where $K = \alpha + \beta$ is the included angle, σ is the groove density and m is the diffraction order.

Once the groove density has been chosen, the required included angle K is calculated for each wavelength λ to keep constant the ratio expressed by Eq. (2). The included angle is changed by translating the plane mirror along an axis parallel to the output direction and rotating it around an axis passing through its center.

Once the spectral defocusing has been corrected, the main higher-order aberration to be canceled is the tangential coma. The geometrical parameters of the focusing mirror, i.e. the arms and the incident angle, are chosen to have the coma given by the grating compensated by the coma that is specifically introduced by the mirror. The condition for coma compensation at the wavelength λ_c is

$$p_M = \left(q_G \frac{cos^2\alpha_{\lambda_c}}{cos^2\beta_{\lambda_c}} + D\right)\left[1 + A_{\lambda_c}\left(q_G \frac{cos^2\alpha_{\lambda_c}}{cos^2\beta_{\lambda_c}} + D\right)^{-1}\right]^{-\frac{1}{2}} \quad (3)$$

where p_M is the entrance arm of the mirror, i.e., the distance between the entrance slit and the mirror center, q_G is the exit arm of the grating, i.e., the distance between the grating center and the exit slit, D is the mirror-to-grating distance, and α_{λ_c} and β_{λ_c} are respectively the incidence and diffraction angles at the wavelength λ_c. The coefficient A_{λ_c} is given by

$$A_{\lambda_c} = 2q_G \frac{1}{tan\alpha_M} \frac{cos^3\alpha_{\lambda_c}}{cos^4\beta_{\lambda_c}}\left(sin\beta_{\lambda_c} - sin\alpha_{\lambda_c} \frac{cos^2\beta_{\lambda_c}}{cos^2\alpha_{\lambda_c}}\right) \quad (4)$$

where α_M is the incidence angle on the mirror.

Since the tangential focus of the mirror is the virtual source for the grating, the arms q_M and p_G are related by the expression:

$$q_M = p_G + D = q_G \frac{cos^2\alpha}{cos^2\beta} + D \quad (5)$$

The coma is corrected at the specific wavelength λ_c, while at different wavelength some residual coma appears.

The output spectral bandwidth depends on the size of the slits. The ideal condition is to have the exit slit open to fit exactly the size of the entrance slit as projected to the output. In this case, the bandwidth is minimized with no loss of flux. The entrance slit S_{IN} as projected to the output S_{OUT} at the wavelength λ is

$$S_{OUT} = S_{IN}\left(\frac{q_M}{p_M}\right)\left(\frac{q_G}{p_G}\right)\left(\frac{cos\alpha}{cos\beta}\right) = S_{IN}\left(1 + \frac{A_{\lambda_c}}{q_M}\right)^{\frac{1}{2}}\left(\frac{cos\beta}{cos\alpha}\right) \quad (6)$$

where the three factors giving the projection of the entrance slit are respectively the mirror magnification (q_M/p_M), the grating magnification (q_G/p_G) and the grating anamorphic factor $(cos\alpha/cos\beta)$.

The resulting output bandwidth at full-width-at-half-maximum (FWHM) is

$$\Delta\lambda_{FWHM} = \frac{cos\beta}{m\sigma q_G} S_{OUT} \quad (7)$$

The parameters to be initially defined are the wavelength λ_c, the groove density σ, the included angle at the wavelength λ_c, the grating output arm q_G, the mirror-to-grating distance D and the angle on the mirror α_M. Then, the entrance arm is calculated from Eq. (3) and the required included angles are calculated from Eq. (2). Hence, the resulting bandwidth is calculated following Eq. (7). The wavelength λ_c is typically selected at the center of the interval to be scanned.

In the following, the characterization of a plane grating monochromator adopting the present configuration is discussed.

CHARACTERIZATION OF THE INSTRUMENT

A monochromator with sub-10-meV output bandwidth in the 10-80 eV interval has been realized and characterized. The instrument design has been performed using the analytical equations shown in the previous paragraph. The design parameters are reported in Table 1. Two gratings with 600 gr/mm and 1200 gr/mm are used to cover the whole spectral range. The total length of the instrument is about 3 m.

TABLE 1. Parameters of the monochromator.

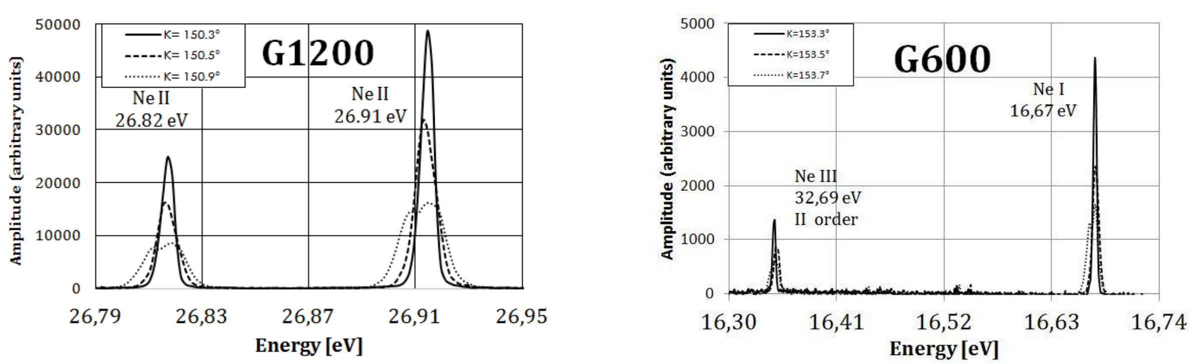
Input Slit	60 μm x 5 mm
Mirror M1	Cylindrical
Entrance arm (slit-to-mirror distance)	673 mm
Incidence angle	87 deg
Tangential focus	465 mm
Gratings G1/G2	Plane
Mirror-to-grating distance	115 mm
Groove density	1200 gr/mm (G1) 600 gr/mm (G2)
Energy range	25-80 eV (G1) 12-30 eV (G2)
Included angle	148-158 deg.
Grating-to-slit distance	2070 mm
Mirror M2	Plane
Incidence angle	77-84 deg
Output slit	100 μm x 5 mm

The optical performances of the instrument have been tested with a hollow-cathode source, in order to evaluate the residual aberrations and the resolving power of the monochromator. A 60 μm-wide input slit has been used. The output slit, as calculated from Eq. (6), is 100 μm.

Some of the spectral scans on the exit slit are shown in Fig. 2(a) and 2(b), respectively centered on two lines at ≈27 eV and ≈16,5eV. The grating included angle is tuned following Eq. (2) to keep the spectral focus of the monochromatic images. The correction of defocusing and coma at the proper included angle is clearly demonstrated.

The FWHM bandwidth on the exit slit has been measured to be 8.3 meV at 26.9 eV and 5.8 meV at 16,5 eV, in almost perfect agreement with the calculated resolving power reported in Fig. 3.

The instrument has been tested at several energies in the spectral interval of operation, confirming that the configuration is able to give excellent focusing properties if the included angle is selected following Eq. (2).



(a) (b)

FIGURE 2. Spectral images on the exit slit plane. (a) 1200 gr/mm grating, spectral lines of Ne II centred at 26.9 eV; (b) 600 gr/mm grating, spectral lines of Ne I and Ne III centred at 16,5 eV.

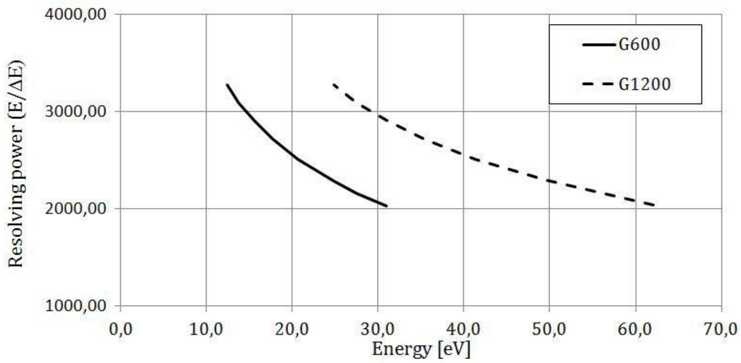


FIGURE 3. Calculated resolving power of the monochromator; 60 μm input slit, 100 μm output slit.

Efficiency

The efficiencies of the optical elements of the configuration (i.e., focusing mirror, plane grating and plane mirror) have been measured at the Circular Polarization Beamline @ Elettra, Trieste [25]. The total efficiency of the instrument for s-polarized light is shown in Fig. 4, being in the 0.08-0.18 range. Being the grating used at variable included angle, the loss of efficiency due to the introduction of the additional plane mirror is not critical because it is maintained close to the blaze condition of maximum efficiency during the full wavelength scan.

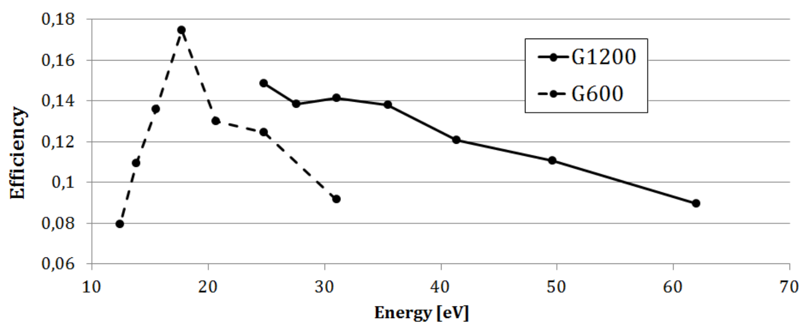


FIGURE 4. Efficiency of the monochromator measured for s-polarized light. Operation at the included angles for which the spectral defocusing is corrected.

Temporal response

The configuration aims to provide high spectral resolution with a single grating. The configuration is not compensated for the pulse-front tilt due to diffraction, that is the main factor limiting the temporal response of a monochromator with a single grating when used with HHs [26]. The calculated FWHM pulse-front tilt of the monochromator with a 3 mrad source divergence is shown in Fig. 5. The temporal response is limited in the sub-picosecond time scale, that is a typical value for XUV monochromators with a single grating stage used for high resolution, as most of the synchrotron beamlines.

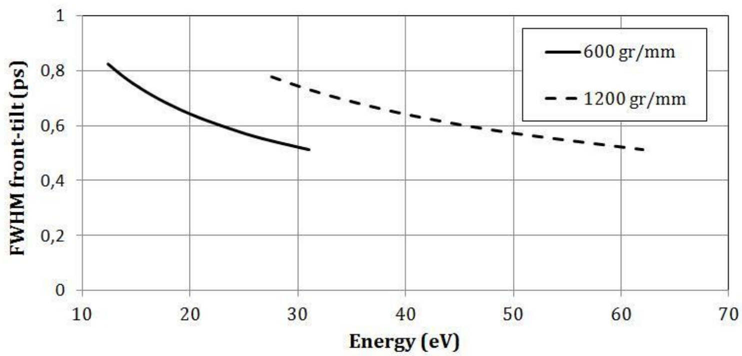


FIGURE 5. Calculated FWHM pulse-front tilt introduced by the instrument, 3 mrad source divergence.

CONCLUSIONS

A grating monochromator using a plane grating illuminated in converging light has been realized. The optical performances and the capabilities of the instrument have been demonstrated to be in agreement with the analytical design. The present configuration, although having three optical elements, uses only simple optical components, i.e., the cylindrical mirror, the plane grating and the plane mirror, that are available on the market with very good optical quality and low prices. Furthermore, with respect to the existing two-elements configurations working at constant included angle, the loss of efficiency due to the introduction of the additional plane mirror is partially recovered since the grating is operated at variable included angle and is maintained close to the blaze condition of maximum efficiency during the energy scan. The configuration could be useful for the realization of cost-effective monochromators with high energy resolution, as can be required for experiments on solid targets in HH beamlines at high repetition rates that could be complementary with large-scale facilities.

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