DOUBLE-GRATING MONOCHROMATOR FOR ULTRAFAST FREE-ELECTRON-LASER BEAMLINES

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Abstract

We present the design of an ultrafast monochromator explicitly designed for extreme-ultraviolet FEL sources, in particular the upcoming FLASH II at DESY. The design originates from the variable-line-spaced (VLS) grating monochromator by adding a second grating to compensate for the pulse-front tilt given by the first grating after the diffraction. The covered spectral range is 6-60 nm, the spectral resolution is in the range 1000–2000, while the residual temporal broadening is lower than 15 fs. The proposed design minimizes the number of optical elements, since just one grating is added with respect to a standard VLS monochromator and requires simple mechanical movements, since only rotations are needed to perform the spectral scan.

INTRODUCTION

One of the most demanded features for free-electron-laser beamlines is the possibility to monochromatize the FEL beam even beyond the intrinsic FEL resolution. Grating monochromators are used both at FLASH [1, 2] and LCLS [3, 4]. Unfortunately, especially for operation in the extreme-ultraviolet region of FLASH, the monochromator temporal response strongly affects the pulse duration, because of the pulse-front tilt introduced by the grating after the diffraction [5]. The full exploitation of the ultrashort temporal characteristics of a FEL source requires the use of a grating monochromator that compensates for the pulse-front tilt, that we define Compensated Monochromator (CM). The design consists in using two gratings in compensated configuration, i.e., the second grating compensates for the pulse-front tilt introduced by the first one [6–10]. CMs have been realized and used in high-order laser harmonics ultrafast beamlines, giving at the output pulses as short as 8 to 10 fs in the 20-45 nm region [11-14]. A CM for FEL has to be designed taking into account the peculiar parameters of the source, particularly the peak intensity, and the different requirements, particularly the definitely larger size of the optics.

Here we present the design of a CM explicitly tailored for extreme-ultraviolet FEL sources, in particular the upcoming FLASH II. The driving parameters for the design are: a) spectral range 6–60 nm; b) spectral resolution in the 1000–2000 range; c) time response shorter than 50 fs; d) minimum lateral displacement to let space to adjacent beamlines; e) minimum vertical displacement to reduce the change of the beam height; f) mirror length shorter than 500 mm; g) grating length shorter than 300 mm.

The monochromator design originates from the variable-line-spaced (VLS) grating monochromator that is already used at LCLS (see Ref. 2) by adding a second grating to compensate for the pulse-front tilt.

BEAMLINE DESIGN

The design originates from the variable-line-spaced (VLS) grating monochromator, that has been adopted for synchrotron radiation beamlines [15], high-order laser harmonics [16] and FELs (see Ref.s 3 and 4). The light coming from the source is focused by a concave mirror, that produces a converging beam. This is intercepted by a VLS plane grating, that diffracts the radiation onto the exit slit. The variable groove spacing of the grating provides the additional free parameters to keep the focal distance almost constant as a function of the wavelength and to compensate for high-order aberrations. The VLS monochromator is also rather simple mechanically in that only two optical elements are required and the photon energy is scanned by a single rotation of the grating around an axis passing through its center.

The CM is realized by adding a second section with an identical VLS plane grating illuminated by the diverging monochromatic light coming out from the slit and mounted in a compensated geometry with respect to the first grating, i.e., internal and external diffraction orders are splitted between the two gratings.

The design has been specialized to the requirements of FLASH II:

a) The monochromator works without an entrance slit, being the FEL itself the source point (as the case of the monochromator at LCLS).
b) An additional plane mirror is inserted between the two gratings to fold the beam and give very low displacement of the output beam with respect to the input.
c) Horizontal and vertical foci are kept separated to reduce the radiation density on the slit blades, due to high peak intensity. In particular, the first mirror, that is demanded to illuminate the grating in converging light, is a plane-elliptical one, therefore the focus on the intermediate slit is astigmatic, i.e., the beam is focused only in the spectral direction.

The optical layout is shown in Fig. 1. The FEL beam is focused by the plane-elliptical mirror M1 toward the plane VLS grating G1. The latter diffracts the radiation toward the intermediate slit, where the beam is

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monochromatized. The plane mirror M2 is used to fold the beam, therefore reducing the lateral displacement of the beamline. The grating G2 has the same groove-space-variation parameters as G1 and is mounted to realize the compensated configuration. The diverging radiation coming out from G2 is finally focused to the sample area by two plane-elliptical mirrors in Kirkpatrick-Baez configuration.

The whole beamline consists of four mirrors and two gratings. With respect to a standard VLS monochromator beamline, only two optical elements, the grating and the plane folding mirror, have been added to obtain the ultrafast response.

With respect to the monochromator beamline at FLASH, which has five mirrors and one grating (see Ref. 1), the total number of optical elements is the same. With respect to the monochromator beamline at LCLS, which has three mirrors and one grating (see Ref. 3), one additional grating and the plane folding mirror have been added.

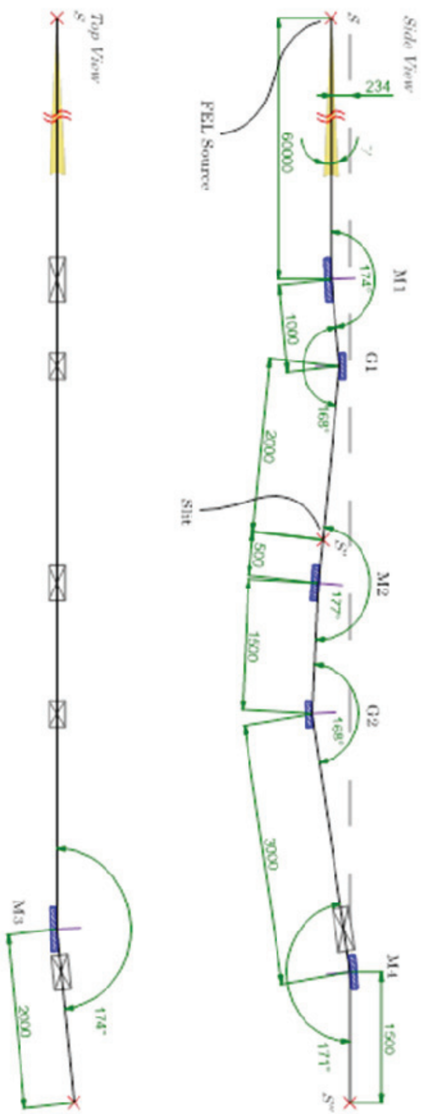

Figure 1: Beamline layout. Distances are in millimetres.

The spectral dispersion plane is assumed to be the side view, i.e., the radiation is dispersed in the vertical plane. The incidence angle on the last focusing mirror has been chosen to have the output beam parallel to the input beam in the vertical plane. The displacement of the output beam with respect to the input is kept very low in the vertical plane: the output is parallel to the input and just ≈20 cm higher. The lateral displacement with respect to the entrance direction is also ≈20 cm.

The direction of the output beam with respect to the horizontal axis may be exchanged just choosing a different incident angle on the mirror M4. Therefore, the angle on M4 may be selected to have the output of the CM beamline parallel to the other beamlines. This will give the additional advantage to have all the beamline output axes parallel, therefore it will be easy to use the same experimental chambers in different beamlines.

The beamline parameters are resumed in Tab. 1. Two sets of gratings are used to cover the 6 - 60 nm spectral region. The FLASH II source has been assumed to have size of 200 µm FWHM and divergence of 75 urad FWHM at 40 nm, that scales as $\lambda^{3/4}$. Given the limited size of the optical elements, a partial cut of the beam occurs at wavelengths longer than 40 nm. The vignetting is 4% at 40 nm, 6% at 50 nm, 20% at 60 nm.

Table 1: Beamline Parameters

M1	Plane-elliptical
Entrance arm	60 m
Exit arm	3 m
Incidence Angle	87°
Size	500 mm × 40 mm
M2	Plane
Incidence Angle	88.5°
Size	400 mm × 40 mm
M3	Plane-Elliptical
Entrance Arm	67.5 m
Exit Arm	2 m
Incidence Angle	87°
Size	500 mm × 30 mm
M4	Plane-elliptical
Entrance Arm	5 m
Exit Arm	1.5 m
Incidence Angle	85.5°
Size	400 mm × 25 mm
G1A-G2A	VLS plane grating
Spectral region	6-20 nm
Central groove density	600 gr/mm
Deviation angle	168°
Size	250 mm × 20 mm
G1B-G2B	VLS plane grating
Spectral region	20-60 nm
Central groove density	200 gr/mm
Deviation angle	168°
Size	300 mm × 40 mm

The optical performances have been simulated by a ray-tracing program that is able to calculate the pulse-front tilt after the grating diffraction. G1 is operated in the internal spectrum, i.e., $\beta_{G1} < \alpha_{G1}$, to have the incident angle on G1 higher than 84°: $85.0° < \alpha_{G1} < 87.3°$. On the contrary, G2

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is operated in the external spectrum to realize a compensated configuration, i.e., $\beta_{G2} > \alpha_{G2}$, which results in $80.7° < \alpha_{G2} < 83.0°$. The use of G1 at incident angles higher than 85° makes it safer to operate the grating under the intense FEL beam. G2 is illuminated at incident angles lower than 83°, but being it located after the intermediate slit, the FEL beam intensity is much lower than at G1.

The resolution is shown in Fig. 2 for a 50-um-wide slit. It has been calculated as $\lambda/\Delta\lambda_{FWHM}$, where λ is the wavelength and $\Delta\lambda_{FWHM}$ the full-width-at-half-maximum bandwidth that is transmitted through the intermediate slit. The resolution is higher than 1000 in the whole spectral range of operation, according to the requirements.

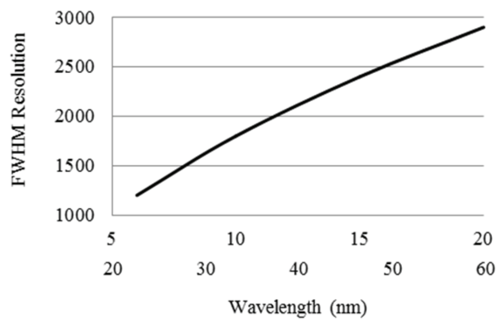

Figure 2: Resolution, $\lambda/\Delta\lambda$, 50–µm slit.

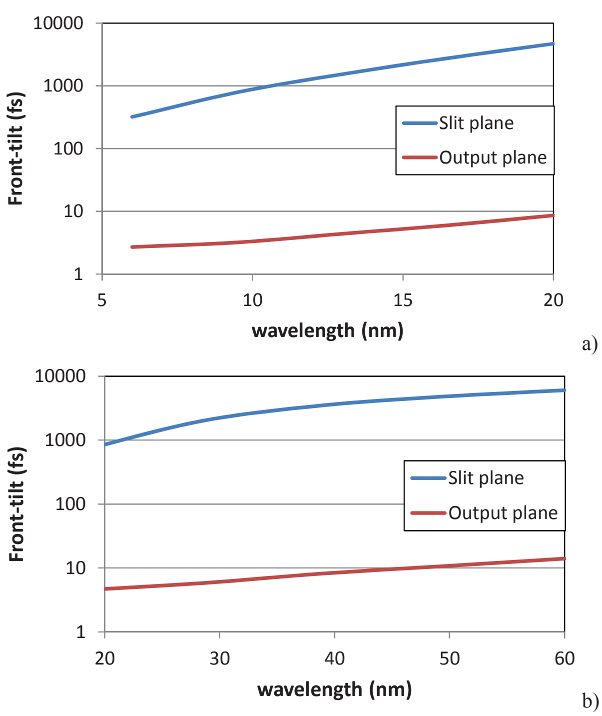

Figure 3: Pulse-front tilt at the intermediate plane and at the output: a) 600 gr/mm grating; b) 200 gr/mm grating.

As already outlined, there is no stigmatic focus within the optical path of the monochromator, with the exception of the end focus. In particular, the spot is astigmatic on the intermediate slit, to reduce the radiation density on the slit blades. The spot is focused only in the direction perpendicular to the slit by M1 and G1. In the direction parallel to the slit, there is no focusing power, therefore the size of the spot depends from the source divergence. It is 6 mm FWHM at 40 nm and scales as $\lambda^{3/4}$, therefore 8 mm at 60 nm, 3.6 mm at 20 nm and 2.1 mm at 10 nm.

The FWHM pulse-front tilt in the intermediate plane and at the output is shown in Fig. 3. The double-grating configuration is really effective in compensating the pulse-front tilt, being able to reduce it from the picosecond time scale down to few femtoseconds. Therefore, the temporal resolution of the beamline is increased by two to three orders of magnitudes.

Finally, the FWHM spot size is shown in Fig. 4. It ranges in the 10-15 um interval.

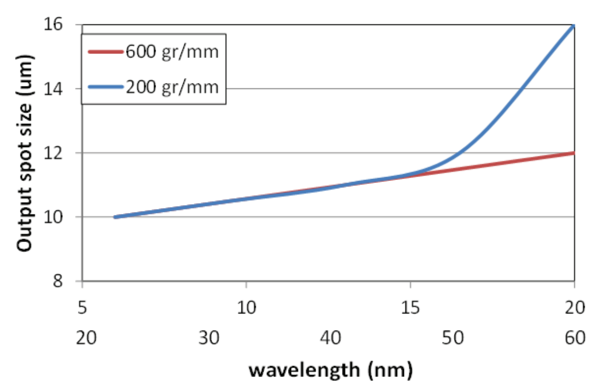

Figure 4: FWHM spot size in the focal plane.

The total efficiency of the beamline is mainly determined by the efficiency of the gratings, since there are two of them. The efficiency curve are strongly dependent on the available grating profiles. At present, VLS gratings for the extreme-ultraviolet are realized with laminar profile. The efficiency curve of the VLS plane grating (Jobin-Yvon, France) that has been used to realize the spectrometer-monochromator described in Ref. [17] is ranging in the 6-16% interval in the 5-20 nm spectral region. Taking these as typical values, the efficiency of the CM beamline is expected to be 5-15 times lower than the efficiency of a standard VLS grating beamline.

CONCLUSION

We have presented the design of an ultrafast monochromator explicitly tailored for extreme-ultraviolet FEL sources, in particular the upcoming FLASH II at DESY (Hamburg). The configuration here presented shows that a CM beamline may be realized in a relatively simple configuration, extending the VLS-plane-grating monochromator configuration to the use with ultrashort pulses. Only six optical elements are required: four mirrors and two gratings. The mechanical complexity is rather reduced, since only two rotations are required to perform the spectral scan. Furthermore, the temporal resolution of the beamline is increased by almost three orders of magnitudes with respect to a single-grating monochromator. Indeed, the proposed configuration

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minimizes the number of optical elements, since just one grating is added with respect to a standard VLS monochromator beamline, gives very low displacement of the output beam with respect to the input, and guarantees high focusing properties in the whole spectral range of operation.

It is worth to note that, although being tailored to the FLASH II requirements, the proposed concept can be extended to any extreme-ultraviolet FEL.

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