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Time-delay-compensated grating monochromator for FEL beamlines

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ABSTRACT

We present the design of a time-delay-compensated monochromator explicitly designed for extreme-ultraviolet FEL sources, in particular the upcoming FLASH II at DESY (Hamburg). 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. Accounting for typical FLASH II divergences, the grazing angles on the different optics have been chosen so that the mirrors and gratings are respectively shorter than 500 mm and 300 mm. The proposed design: 1) minimizes the number of optical elements, since just one grating is added with respect to a standard VLS monochromator B-L; 2) guarantees high focusing properties in the whole spectral range of operation; 3) requires simple mechanical movements, since only rotations are needed to perform the spectral scan.

Keywords: Time-delay-compensated monochromator, diffraction, variable-line-spaced grating, free-electron laser

1. INTRODUCTION

The consolidation of the FEL sources, from experimental machines to reliable sources, has opened the door to the development of demanding beamlines. In particular, due to the intrinsic multi-harmonics generation process, one of the most demanded BL feature is the possibility to monochromatize the FEL beam even beyond the intrinsic FEL resolution. Inherited from the synchrotron experience, grating monochromators are used in FEL beamlines, both at FLASH [1, 2] and LCLS [3, 4]. They give both tunability in a broad spectral range and high spectral selectivity.

Unfortunately, especially for operation in the extreme-ultraviolet region of FLASH, the monochromator temporal response strongly affects the FEL pulse duration. As well known, from the expertise gained in the field of the ultrafast optics, the use of a single stage monochromator affects the temporal structure of the selected pulses by introducing a pulse-front tilt due to diffraction [5, 6]. The temporal broadening can be tolerated in many experiments, nevertheless the full exploitation of the particular temporal characteristics of a FEL source requires the use of a grating monochromator that compensates for the temporal stretch, that we define as Time-Delay-Compensated Monochromator (TDCM). The design consists in using two gratings in a time-delay compensated configuration, where the second grating compensates for the front-tilt and for the spectral spread introduced by the first one [7–13]. TDCMs have been realized and used in high-order laser harmonics beamlines. Pulses as short as 8 to 10 fs have been measured at the output of TDCMs in the 20-45 nm spectral region [14-17]. The layouts proposed and realized for the high-order laser harmonics beamlines cannot be directly used for FEL pulses, due to the different source parameters, particularly the source peak intensity, and the different requirements, particularly the definitely larger size of the optics.

Here we present the design of a TDCM explicitly tailored for extreme-ultraviolet FEL sources, in particular the upcoming FLASH II, the major extension of FLASH [18]. This substantial upgrade will lead to a new experimental hall and many new beamlines operated in parallel with FLASH. The monochromator design originates from the variable-line-spaced (VLS) grating monochromator that is already used at LCLS (see Ref. 3) by adding a second grating to compensate for the pulse-front tilt. 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 100 fs; d) minimum lateral displacement to let space to

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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 main characteristics of the proposed configuration are here resumed as: 1) it minimizes the number of optical elements, since just one grating is added with respect to a standard VLS monochromator beamline; 2) it gives very low displacement of the output beam with respect to the input; 3) it guarantees high focusing properties in the whole spectral range of operation; 4) it requires simple mechanical movements, since only rotations are needed to perform the spectral scan.

2. ULTRAFast MONOCHROMATIC BEAMLINE

2.1 Beamline design

To realize a TDCM, two gratings are used in a compensated configuration, i.e., the first grating is demanded to perform the spectral selection on the intermediate slit plane, and the second grating has to compensate for the pulse-front tilt given by the first grating, therefore guaranteeing the ultrafast response. The use of two gratings makes the optical design more complex than a standard monochromator. Aim of the design is to find a simple configuration that is capable to work in compensated design and minimizes the complexity of the optical system.

The concept here presented adopts four optical elements to realize a TDCM for FLASH2. The design originates from the variable-line-spaced (VLS) grating monochromator, that has been proposed by Hettrick [19] and adopted both for synchrotron radiation beamlines [20] and high-order laser harmonics [21, 22]. Recently, the VLS design has been adopted also for the monochromatic beamline at LCLS (see Refs. 3 and 4).

A concave mirror produces a converging beam and a VLS plane grating 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 photon energy 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 design is adapted to realize a TDCM by adding a second section with an identical VLS plane grating illuminated by the diverging light coming out from the slit and mounted in a compensated geometry. In principle, only three optical elements are required to realize a TDCM, namely the concave mirror and two VLS plane gratings, that are separated by an intermediate slit that carries out the beam monochromatization.

The design has been specialized to the requirements of FLASH II and to its expected performances:

- a) Due to the high angular and lateral stability of FLASH II, the monochromator works without an entrance slit, i.e., the FEL itself acts as the source point for the monochromator. In this way, also a pre-focusing mirror is avoided, therefore limiting the number of optical elements. Note that this is also the case of the monochromator at LCLS.
- b) Due to the required minimum lateral displacement of the whole beamline with respect to a straight propagation, an additional plane mirror has been inserted between the two gratings to fold the beamline.
- c) Due to high photon flux, horizontal and vertical foci have to be kept separated to reduce the radiation density on the slit blades. In particular, the first mirror, that is demanded to illuminate the grating in converging light, is a plane-elliptical one. Also the final focusing section is a Kirkpatrick-Baez section consisting of plane-elliptical mirrors.

The optical layout is presented in Fig. 1. The FEL beam is focused by the plane-elliptical mirror M1 toward the plane VLS grating G1. The latter is illuminated in converging light and diffracts the radiation toward the intermediate slit, where the beam is 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 symmetrically to G1 with respect to the slit, to realize the time-delay compensated configuration. The diverging radiation coming out from G2 is finally focused to the sample area by two plane-elliptical mirrors in KB configuration: M4 is focusing the beam in the dispersion plane, M3 in the perpendicular plane.

The use of cylindrical mirrors has been also considered, since they are definitely less expensive than plane-elliptical ones, but the simulations show that, given the actual source divergence, the aberrations introduced by the cylindrical optics compromise the good focusing properties of the beamline.

The whole TDCM beamline consists of four mirrors and two gratings. Only two optical elements, the grating and the plane folding mirror, have been added to obtain the ultrafast response. Note that the folding plane mirror is added to minimize the lateral displacement, since other FEL beamlines are located very close to the monochromatic beamline. In case a larger lateral displacement is tolerated, this additional optical element may be removed.

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. TDCM optical layout. In the side view (the spectral dispersion plane), the exit beam is parallel to the input one.

The incidence angle on the last focusing mirror has been chosen to have the output beam parallel to the input beam in the spectral dispersion plane, that is here assumed as the side view. The final displacement of the output beam with respect to the input is really kept restrained, since the output beam is parallel to the floor, therefore parallel to the entrance in the side view, and at a height that has been increased by about 20 cm. The lateral displacement with respect to the entrance direction in the top view is also about 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 final output mirror M4. Given the output direction of the other FLASH II beamlines, the angle on M4 may be selected to have the output of the TDCM beamline parallel to the other beamlines. Therefore, it will be easy to use the same experimental chambers in different beamlines, since all the output axes are expected to be parallel.

The proposed design has the additional advantage that, if the FEL is polarized in the horizontal plane, five of the six optics are illuminated in s-polarization, where the efficiency is higher especially at the long wavelengths.

The source parameters that have been adopted to simulate the beamline performance are listed in Tab. 1.

The optical parameters of the beamline are resumed in Tab. 2. Two sets of gratings are used to cover the 6 - 60 nm spectral region. Given the source divergence as reported in Tab. 1 and the size of the optical elements as reported in Tab. 2, 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. Parameters of the FLASH II source. The source divergence has been taken to be 75 μrad FWHM @ 40 nm and scaled as $\lambda^{3/4}$.

Source size	200 μm FWHM
Source divergence	18 μrad FWHM @ 6 nm
	27 μrad FWHM @ 10 nm
	45 μrad FWHM @ 20 nm
	75 μrad FWHM @ 40 nm
	102 μrad FWHM @ 60 nm

2.2 Optical performance

The optical performances have been simulated by a ray-tracing program that includes the capability of calculating the pulse-front tilt after the grating diffraction. The wavelength scanning is performed by the rotation of the two gratings around an axis passing through its center. G1 is operated in the internal spectrum, i.e., $\beta_{G1} < \alpha_{G1}$, to have the incident angle on G1 higher than 84° : $85.0^\circ < \alpha_{G1} < 87.3^\circ$. On the contrary, G2 is operated in the external spectrum to realize a compensated configuration, i.e., $\beta_{G2} > \alpha_{G2}$, which results in $80.7^\circ < \alpha_{G2} < 83.0^\circ$. 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, which carries out the monochromatization, the FEL beam intensity on G2 is much lower than at G1.

Table 2. Parameters of the TDCM beamline

<i>Distances</i>			<i>Gratings</i>		
			G1-A G2-A		
S – M1	m	60	Type		VLS Plane
M1 – G1	m	1	Spectral Region	nm	6 – 20
M1 – Slit (S')	m	2	Central groove density	mm ⁻¹	600
M2 – G2	m	1.5	Deviation Angle	deg.	168
G2 – M3	m	2.5	Ruled coated area	mm × mm	250 × 20
M3 – M4	m	0.5			
M4 – S''	m	1.5			
<i>Mirrors</i>			G1-B G2-B		
M1			Type		VLS Plane
Type		Plane / Elliptical	Spectral Region	nm	18 – 60
Entrance Arm	m	60	Central groove density	mm ⁻¹	200
Exit Arm	m	3	Deviation angle	deg	168
Incidence Angle	deg	87	Ruled coated area	mm × mm	300 × 40
Coated Area	mm × mm	500 × 40			
M2					
Type		Plane			
Incidence Angle	deg	88.5			
Coated Area	mm × mm	400 × 40			
M3					
Type		Plane / Elliptical			
Entrance Arm	m	67.5			
Exit Arm	mm	2000			
Incidence Angle	deg	87			
Coated Area	mm × mm	500 × 30			
M4					
Type		Plane / Elliptical			
Entrance Arm	mm	5000			
Exit Arm	mm	1500			
Incidence Angle	deg	85.5			
Coated Area	mm × mm	400 × 25			

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

Figure 2. FWHM resolution, $\lambda/\Delta\lambda$: a) 600 gr/mm grating; b) 200 gr/mm grating.

The FWHM pulse-front tilt is shown in Fig. 3 in the intermediate plane and in Fig. 4 at the output of the monochromator. The compensated configuration is really effective, being able to compensate for the front-tilt from the picosecond time scale down to few femtoseconds. The temporal resolution of the beamline is increased by almost three orders of magnitudes.

Finally, the FWHM spot size is shown in Fig. 5, being in the 10-15 μm range, and so compatible with the typical experimental requirements at a generic FEL target area.

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

Figure 4. FWHM pulse-front tilt at the output: a) 600 gr/mm grating; b) 200 gr/mm grating.

Figure 5. FWHM spot size in the focal plane: a) 600 gr/mm grating; b) 200 gr/mm grating.

2.3 Efficiency

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. As an example, the efficiency curve of the VLS plane grating (provided by Jobin-Yvon, France) that has been used to realize the spectrometer-monochromator described in Ref. 20 for the spectral region 5-30 nm is shown in Fig. 6. Taking the values shown in Fig. 6, the efficiency of the TDCM beamline is expected to be 5-15 times lower than the efficiency of a standard VLS grating beamline.

Figure 6. Efficiency curve of a plane VLS grating (provided by Jobin-Yvon) used to realize a spectrometer-monochromator for high-order laser harmonics. The central groove density is 600 gr/mm, the profile is laminar with groove height of 20 nm and duty cycle of 60%. The coating is gold.

3. CONCLUSIONS

We have presented the design of a TDCM explicitly tailored for extreme-ultraviolet FEL sources, in particular the upcoming FLASH II. The configuration here presented shows that a TDCM beamline may be realized in a relatively simple configuration, extending the VLS-plane-grating monochromator configuration to the use with ultrashort pulses in the extreme-ultraviolet region. Only six optical elements are required: four mirrors and two gratings. Despite the necessity of operate two gratings in the *compensated* configuration, the mechanical complexity is very low: 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 beamline.

The proposed configuration 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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