Compact spectrometer for on-line photon diagnostics at FLASH

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Abstract. We present the design and characterization of a compact and portable spectrometer that has been realized to analyze in real time the high-order harmonic contents of the free-electron-laser beam at FLASH in Hamburg. The spectrometer can be installed at the end of any of the broad-band FEL beamlines at FLASH, to monitor in the single-shot operation the emissions of the fundamental FEL and the high-order harmonic content. The design is compact in order to obtain a portable instrument within a total envelope of less than one meter. It is based on the use of two flat-field grazing-incidence gratings and a EUV-enhanced CCD detector to cover the spectral range 1.7-40 nm (720-30 eV). The absolute response of the spectrometer, i.e. grating and detector efficiency, has been measured in the whole spectral region of operation. This allows to make calibrated measurements of the photon flux. Furthermore, the use of a bidimensional detector allows to measure also the angular divergence of the FEL beam in the direction parallel to the entrance slit. We present some experimental data of the FEL emissions taken at the beamline BL1 at FLASH. The high-order harmonic emissions have been characterized in terms of photon flux, temporal fluctuations and angular divergence. Measurements of the harmonics up to the 5th order at 3.8 nm have been done with the fundamental tuned at 19 nm. Measurements of the harmonics up to the 3rd order at 2.3 nm have been done with the fundamental tuned at 6.8 nm.

1. Introduction

FLASH at DESY (Hamburg, Germany) has been the first user-dedicated FEL facility operating in the XUV. Since 2005 it is providing intense, ultra-short and coherent radiation in the 6-47 nm wavelength range [1]. The last upgrade [2] has increased the capabilities of this facility permitting to obtain photons at wavelengths shorter than 5 nm at the first FEL harmonic. Due to the high nonlinearities involved in the FEL amplification process, the beam features, as spectral purity and intensity, can change from shot to shot. The monitoring of these fluctuations is consequently a mandatory task for a correct data interpretation [3, 4].

It is here presented a compact spectrometer designed for the installation at the FLASH facility, and usable for the monitoring of the high-harmonics content of the FEL emission and of the shot-to-shot fluctuations of the beam spectral features. The novelty represented by this diagnostic tool relies in the acquisition of the FEL spectral content in the experimental chamber in single-shot operation. We emphasize that such a characterization is essential in order to optimize the SASE process, and consequently, the experimental conditions. Being compact, this tool can be easily placed behind a generic experimental set-up.
2. The instrument

The instrument is shown in Fig. 1. The source point of the spectrometer is the entrance slit, that is remotely controlled and can be opened in the 20-100 μm range. The grating is a spherical varied-line-spaced (SVLS) grazing-incidence grating, used to obtain a flat-field spectrometer, in which the spectral focal curve is almost parallel to the normal to the grating surface and almost flat [5-7]. The spectral range of operation spans from 2 to 40 nm. It is covered using two gratings (manufactured by Hitachi, Japan) mounted on a motorized rotation stage that is used to select one of them. The gratings have the same input arm and share an overlying spectral focal curve. The grating parameters are summarized in Tab. 1. The CCD detector is connected to the chamber by a 63mm-diameter bellow and is moved by a motorized linear stage along the straight line coincident with the focal curve [8].

![Diagram of the instrument](image)

Figure 1. a) Horizontal view of the instrument: \( p \) and \( q(\lambda) \) are respectively the input and the output arms. b) Picture of the instrument installed at the BW3 beamline at the DORIS Synchrotron (Hamburg, Germany) during the calibration phase.

| Table 1. Instrumental parameters. |
|-----------------------------------|
| G1200 | Spectral coverage 5-40 nm; central groove density 1200 gr/mm; radius 5650 mm; incidence angle 87 deg |
| G2400 | Spectral coverage 2-20 nm; central groove density 2400 gr/mm; radius 15920 mm; incidence angle 88.65 deg |
| Distance \( d \) | 235.3 mm |
| Entrance arm \( p \) | 237 mm |
| Accepted angle | G1200: 10 mrad (spectral) × 10 mrad  
G2400: 5 mrad (spectral) × 10 mrad |
| Detector | Format 1340 × 400; pixel size 20 μm; imaging area 26.8 mm × 8 mm; digitalization 16 bits; full well capacity 300,000 e\(^{-}\); readout noise 3.5 electrons @ 100 kHz |

The limited detector field-of-view prevents the simultaneous acquisition of the high-order harmonic content in the whole spectral range covered by the instrument, nevertheless the acquisition procedure is fast enough to acquire of the fundamental emission, then move the detector at the proper spectral position and acquire the high-order harmonics within less than one minute. The instrument has been fully characterized in order to determine the two normalized spectrometer responses, one for each of the gratings. Therefore, the amount of the high-order harmonics relative to the fundamental emission can be measured.

3. Commissioning results

During the commissioning phase, FLASH has been tuned at four different wavelengths: 6.8 nm, 13.02 nm, 19.3 nm, 25.6 nm. The spectrometer has been placed at the end of BL1, 3.5 m behind the focal...
spot as shown in Fig. 2. The distance between the focal spot and the entrance slit of the spectrometer is large enough to accommodate an experimental chamber at the FEL focal spot as long as the sample is transparent, i.e., when one is dealing with gas phase targets in the experimental chamber. The FEL spectrum can be acquired either in the single-shot operation or in integration mode, as the average of multiple shots. Some spectra obtained as an average over 600 shots with an integration time of 60 s are shown in Fig. 3. Panel a) shows the spectrum of the fundamental emission at 6.8 nm and its harmonics. Krypton at 0.006 mbar was used to attenuate the radiation at 6.8 nm, therefore both the fundamental and the harmonics were acquired simultaneously without saturating the detector. Panels b) and c) show the spectrum of the fundamental at 19.3 nm and its harmonics. No gas attenuator was used. The flux at the harmonics compared to the fundamental is shown in Fig. 4. The calculated harmonics content is based on the measured spectra. As an example, an image of the single-shot FEL spectrum as acquired on the CCD is shown in Fig. 5. The shot-to-shot spectral fluctuation at the fundamental of 19.2 nm are shown in Fig. 6. The measurement of the vertical extension on the CCD of the different spectral features gives the beam divergence, that has been measured 0.53 mrad at 19.3 nm and 0.35 mrad at 6.8 nm. The harmonics of the 19.3 nm have an almost constant divergence that is equal to the fundamental. The harmonics of the 6.8 nm, differently, have a divergence that is decreasing to 0.30 mrad for the 2\textsuperscript{nd} and 0.25 mrad for the 3\textsuperscript{rd}.

4. References

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Figure 2. Scheme of the optical arrangement used during the commissioning phase at FLASH. The spectrometer was positioned 3.5 m after the focus of BL1. The gas attenuator [8] was used to reduce the contribution of the fundamental radiation from the FEL.
Figure 3. FEL spectra: a) 6.8 nm fundamental and harmonics acquired using the gas attenuator filter; b, c) 19.3 nm fundamental without gas filtering; c) harmonics of the fundamental at 19.3 nm. \( m \) is the grating diffraction order, \( h \) the FEL harmonic order.

Figure 4. Relative intensity of the FEL harmonics at the end of BL1 at FLASH: a) fundamental at 6.8 nm; b) fundamental at 19.2 nm.

Figure 5. Single-shot FEL spectrum of the fundamental at 6.8 nm and its harmonics. The scale of the region in the center has been enhanced to show the faint 2\textsuperscript{nd} harmonic. \( m \) is the grating diffraction order, \( h \) the FEL harmonic order.

Figure 6. Shot-to-shot fluctuations of the FEL emission at 19.2 nm. The dashed line is the average of 30 shots [9].