Photon Diagnostics for the study of Electron Beam Properties of a VUV SASE-FEL

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Abstract

A single-pass free-electron laser operating in the self-amplified spontaneous-emission (SASE) mode at around 100 nm is currently under test at the TESLA Test Facility at DESY. After first observation of SASE in February 2000, the photon beam has been characterized by different techniques. We present the methods of VUV photon diagnostics that were used to measure the spectral and angular distribution of the photon beam and the effect of the electron beam parameters on these properties. The angular and spectral distribution of the FEL radiation are particularly sensitive to the electron orbit in the undulator, and we indicate ways of on-line photon beam diagnostics to enhance the electron beam quality and the FEL gain.

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1. Introduction

The TESLA collaboration is currently developing a Free-Electron Laser (FEL) at the TESLA Test Facility (TTF) at DESY. The FEL is based on the principle of self-amplified spontaneous emission (SASE) and operates in the Vacuum Ultraviolet (VUV) energy region [1]. In the SASE process, coherent radiation is emitted by a high-current, low-emittance electron beam during a single pass through a high-precision undulator. The spontaneous radiation emitted in the first part of the undulator overlaps and interacts with the electron bunch and amplifies the power and coherence of the radiation. Since the early theoretical work on the SASE process [2–5], considerable theoretical and experimental efforts have been made to study the physics of SASE. Experimental evidence of SASE in the infrared region 5–16 μm has been reported recently by several groups [6–8] with FEL gains up to 10^5 [9]. Efforts in reducing the wavelength to the visible began with Babzien *et al.* [10] who observed SASE at 633 nm, and FEL operation in the SASE mode at 530 nm was demonstrated by Milton *et al.* [11]. A decisive milestone on the way to Å

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wavelengths has been achieved in February 2000 when the first FEL output in SASE mode at around 100 nm was observed at the TTF [12]. In none of the experiments saturation has been reached, and the requirements for SASE at still shorter wavelengths are increasingly demanding in terms of electron beam quality and steering through the undulator. In this paper, we report on the VUV photon diagnostics used at the TTF FEL for the determination of the spectral and angular distribution of the photon beam at around 100 nm and indicate ways of studying the electron beam properties in order to enhance the beam quality.

2. VUV photon diagnostics

For the complete characterization of the FEL photon beam properties, an experimental station for photon diagnostics, including a grating monochromator and various detectors, provides all the instrumentation necessary to measure the photon pulse intensity and its angular, spectral and temporal distribution. New detection concepts have been employed in order to measure all SASE specific properties on a single pulse basis. The detectors and the principle layout of the photon diagnostics unit have been described in detail in Ref. [13].

FEL photon diagnostics is particularly challenging in the VUV region. Due to the high absorbance of radiation below 200 nm by any material, neither window materials to outcouple the radiation nor attenuating filters are available. Thus, in order to cover the full dynamic range of intensity from spontaneous undulator emission to SASE in saturation (about 5 orders of magnitude), different types of detectors, suitable for operation under ultra-high-vacuum (UHV) conditions, are employed. Since the photon diagnostics cannot be separated from the undulator and the accelerator vacuum, all components were assembled under cleanroom conditions. This avoids dust particles which could migrate to the accelerator cavities. In addition, all devices are fully remote controlled because radiation background in the accelerator tunnel prevents access during operation.

3. Spectral distribution

For the determination of the spectral distribution, the photon beam is deflected by a plane mirror onto the entrance slit of a commercial 1m normal-incidence monochromator. The width of the entrance slit can be varied by a precise piezo actuator from 1 to 195 μm. For the initial FEL commissioning phase, the monochromator has been equipped with a 1200 lines/mm spherical grating. Spectra of the dispersed FEL radiation are recorded by a thinned, back-illuminated UV-sensitive CCD [14] that has been placed in the focal plane of the spherical grating, attached directly to the monochromator vacuum.

The upper part of Fig. 1 presents an image of the dispersed FEL radiation with an acquisition time of 30 s. The FEL was operated in single-bunch mode with 1 Hz repetition rate. Despite a 20 cm lead shielding of the camera, the background radiation in the accelerator tunnel caused a noticeable pixel damage and, therefore, a background image had to be subtracted and a median filter was applied. The horizontal (x-) axis of the image corresponds to the dispersive direction and the vertical (y-) axis is parallel to the entrance slit. The full CCD image covers a wavelength range of 20 nm in the dispersive direction. The intensity distribution in y-direction reflects the vertical beam profile and is mainly defined by a 5-mm-diameter aperture in front of the monochromator.

The spectral distribution, integrated in the vertical direction, is depicted in the lower part of Fig. 1. The wavelength scale has been calibrated with the use of a hollow-cathode lamp [15] and a Hg-lamp. The spectral distribution of the FEL radiation is centered at 92.1 nm with a full-width at half-maximum (FWHM) of 0.74 nm.

When an electron beam passes through a planar undulator, it emits electro-magnetic radiation at the wavelength

$$\lambda_{ph} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right), \tag{1}$$

where $\gamma = E_e/mc^2$ is the relativistic factor of the electrons and $K = eB_u\lambda_u/2\pi m_e c$ the undulator parameter with the peak magnetic field B_u and the undulator period λ_u. The FEL at the TTF (phase I) consists of three fixed-gap undulator modules with a length of 4.5 m each; the wavelength λ_{ph} of the FEL radiation can be varied by changing the electron beam energy E_e. Since K and λ_u are precisely known (see Table 1), the electron beam energy can be determined from the measured wavelength. The determination of the absolute wavelength can be achieved with an accuracy of 0.5 %; this results in an accuracy of 0.25 % for the electron energy. For instance, the spectrum of Fig. 1 centered at 92.1(5) nm corresponds to an electron beam energy of 254(1) MeV. This value is in good agreement with an energy of 250(5) MeV determined from the deflection of the electron beam by a bending magnet. Meanwhile SASE has been observed between 80 and 181 nm at the TTF-FEL. The corresponding parameters are summarized in Table 1.

A series of three single-pulse spectra, centered at around 110 nm, is shown in Fig. 2(a). Each spectrum represents the spectral distribution of the FEL radiation emitted by a single bunch. The spectra were taken subsequently in intervals of several seconds with a slit width of 195 μm which results in an instrumental bandwidth of 0.17 nm. The variation of the centre position of the spectra reflects the energy variation of the electron beam. Here, the shift of 0.2 nm (0.2%) corresponds to an energy jitter of the electron beam of 0.1% [see Eq. (1)]. Fig. 2(b) depicts a spectrum which was accumulated during an interval of 30 s, i.e., this spectrum represents the spectral distribution averaged over 30 subsequent electron bunches. As a consequence of the energy jitter, the width of the spectrum of 1.1 nm (FWHM) is larger than the 0.8 nm (FWHM) for each of the single-bunch spectra [Fig. 2(a)]. The shoulder at the long wavelength side is possibly caused by a fraction of electrons within the bunch with slightly smaller energy.

The minimal interval between two single-pulse spectra is limited by the readout time (8 s) of the CCD camera. To overcome this restriction, the back-illuminated CCD camera has been replaced by an intensified CCD camera [16] with a readout time of 125 ms. It utilizes a fast fluorescent screen in the focal plane of the monochromator which is imaged through a Suprasil viewport. The ICCD camera is equipped with a micro-channel-plate (MCP) as an intensifier which operates as a fast shutter with exposure times down to 5 ns. This enables one to select single pulses from a sequence of pulses and to study, e.g., the variation of electron beam parameters within a bunchtrain. Furthermore, with photon beam intensities expected for the FEL close to saturation, the fine structure in the spectral distribution[17], which stems from the startup from shot noise in the SASE process, can be studied. A 3600 lines/mm grating in conjunction with an 10 μm entrance slit results in a resolving power of $E/\Delta E = 2\times10^4$ at $\lambda = 120$ nm, which is sufficient to fully resolve the fine structure. The parameters of the back-illuminated and the intensified CCD camera are compared in Table 2.

4. Angular distribution

The vertical photon beam profile, recorded at a distance of about 12 m behind the undulator, is shown in the upper part of Fig. 3. A 10 x 10 mm^2 PtSi-photodiode [20] with a 1-mm-diameter spherical aperture in front was moved in steps of 1 mm through the photon beam [3], and for each step the signal of

[3] For further details on the diode and beam profile recording see Ref. [21]

5 subsequent pulses was accumulated; the FEL was operated in single-bunch mode with 1 Hz repetition rate. The solid line represents a fit of a Gaussian profile with a width of 7.7(7) mm (FWHM) and a centre at a vertical position of 3.6(3) mm. The zero position of the detector coordinate system has been aligned to the centre axis of the undulator with an accuracy of ± 0.5mm with the use of a theodolite. Similar vertical displacements of the photon beam have been observed on the CCD image of the normal-incidence spectrometer, depending on the steering of the electron beam into the undulator. Obviously the direction of the electron beam in the gain region can be varied by a few 10^{-4} radian without much change in gain such that the light is emitted into different directions. This has been corroborated by using steerers (corrector coils) along the last undulator module to deflect the electron beam only in this area. Starting from the situation of a vertically displaced beam with all steerers turned off (Fig. 3, top), it was possible to deflect the electron beam down using five steerers such that the centre of the FEL radiation moved to the nominal zero position (Fig. 3, bottom). Again, in this case the light intensity did not change significantly. These results suggest that the on-line observation of the photon beam position might be very useful as a monitor when the electron beam orbit is adjusted, e.g. using beam based alignment techniques.

As in the case of the spectral distribution, the photon beam profile shown in Fig. 3 is most probably broadened by a spatial and angular jitter of the electron beam in the undulator. Hence, single-pulse measurements are required to avoid such a superposition. In a first approach, the fluorescent light of different crystals, such as Ce:YAG and $PbWO_4$, has been imaged with a conventional CCD camera. Using crystals with fast decay channels in conjunction with a gated ICCD camera it will be possible to observe the intensity distribution of single FEL pulses.

5. Summary

The methods used for the determination of the spectral and angular distribution of the VUV radiation generated by the SASE-FEL at the TESLA Test Facility at DESY and a selection of characteristic results have been presented. The angular and spectral distribution of the FEL radiation are particularly sensitive to the electron beam energy and orbit in the undulator. These techniques can therefore be used as on-line diagnostics of electron beam parameters and are promising tools to enhance the electron beam quality and, thus, the FEL gain.

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Table 1
Measured parameters of the SASE-FEL at the TESLA Test Facility (phase I) at DESY (August 2000).

Parameter	
Photon beam	
Wavelength λ_{ph}	181 nm – 80 nm
Energy	7 eV – 15 eV
Angular divergence at 91 nm	0.7(3) mrad (FWHM)
FEL gain [a]	1–9 10^3
Undulator	
Length	13.5 m
Gap	12 mm
Period λ_u	27.3 mm
Peak Magnetic Field B_u	0.497 T
Electron beam	
Energy	181 MeV – 272 MeV
No. of Bunches per Bunchtrain	1 – 10
Bunch Separation	1 μs
Repetition Rate	1 Hz

[a] see Ref. [12]

Table 2
Parameters of the back-illuminated and the intensified CCD cameras.

	Photometrics ATC 300L	LaVision Nano Star 25
Principle	back-illuminated thinned CCD	Fluorescence screen, Optics 1:2.17, MCP
No. of pixels	1024 x 1024	1280 x 1024
Pixel size	24 μm	6.7 μm
A/D converter	16 Bit @ 0.2 MHz	12 Bit @ 12.5 MHz
Shutter	mechanical	MCP
Readout time	8 s	125 ms
Min. exposure time	1 ms	5 ns
Resolution	24 μm	$\approx 12\mu$m

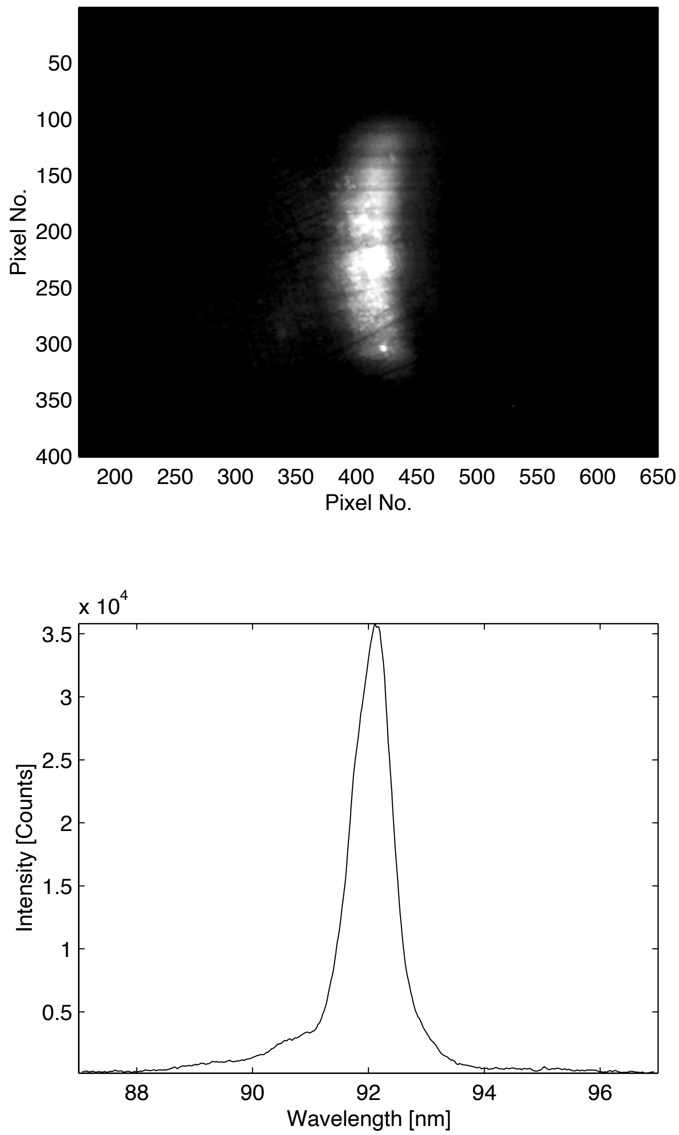

Fig. 1. Upper part: CCD image of the dispersed FEL radiation in SASE mode taken in the focal plane of a 1 m normal-incidence monochromator. Lower Part: Spectral distribution obtained by integration of the image above in vertical direction.

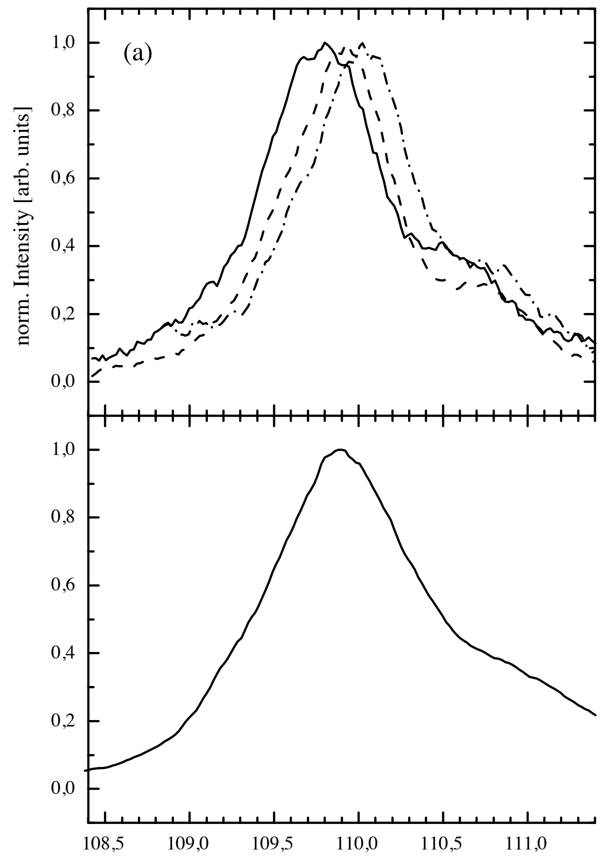

Fig. 2. (a) Series of single-pulse spectra; (b) spectrum of 30 pulses.

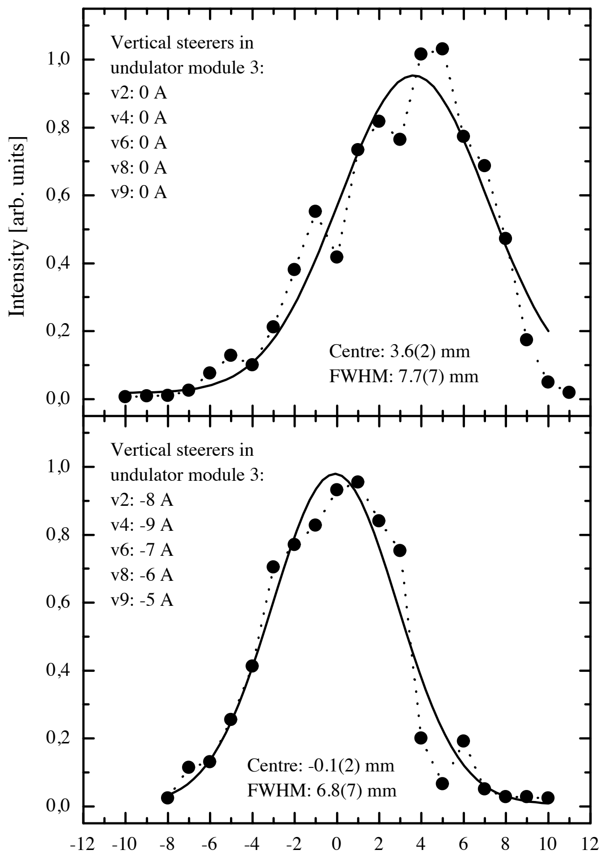

Fig. 3. Vertical beam profile of FEL radiation in SASE mode at 91 nm; (a) without and (b) with the effect of vertical electron beam steerers v2–v9 in the last undulator module.