Measurement of gigawatt radiation pulses from a VUV/EUV free-electron laser

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In order to measure the photon flux of highly intense and extremely pulsed VUV and EUV radiation in absolute terms we have developed a gas-monitor detector which is based on the atomic photoionization of a rare gas at low particle density. The device is indestructible and almost transparent. By first pulse resolved measurements of VUV free-electron laser radiation at the TESLA test facility in Hamburg, a peak power of more than 100 MW was detected. Moreover, the extended dynamic range of the detector allowed its accurate calibration using spectrally dispersed synchrotron radiation at much lower photon intensities.

Recent developments in nanotechnology and fundamental research on non-linear processes in matter rely on radiation sources of extremely high intensities at wavelengths much shorter than in the optical regime, i.e. in the spectral regions of the vacuum ultraviolet (VUV) and the extreme ultraviolet (EUV, i.e. VUV at a wavelength around 13.5 nm). Moreover, the radiation of highly intense VUV sources, such as commercial F_2 lasers[1] EUV-lithography sources[2], or free-electron lasers (FEL)[3-5], is strongly bunched by short radiation pulses. Hence, the peak radiant power within a radiation pulse is much higher than the average power which may saturate, degrade or even destroy the solid state detectors commonly used for VUV radiation measurements.[6,7]

The VUV-FEL at the TESLA Test Facility (TTF) at DESY in Hamburg[4] is expected to deliver an average radiant power of at least 20 W distributed among 10 pulse trains per second of 7200 pulses with a pulse separation of 111 ns. A pulse duration as short as 0.1 ps leads to a peak power in the range of 1 GW. A peak irradiance in the VUV at a level of 10^{16} W cm^{-2}, as expected for a focused FEL beam at the TTF, is sufficient to considerably extend the experiments of strong-field physics to the investigation of non-linear dynamics and multi-photon excitation of matter from the optical region to shorter wavelengths, i.e. to the spectral range of photoionization thresholds, which promises better understanding of many new and fundamental phenomena.[8,9] The proof-of-principle and test experiments of the VUV-FEL and almost all scheduled studies of strong-field physics phenomena using VUV-FEL radiation require thorough determination of the photon intensity.

In this context we have developed a gas-monitor detector (Fig. 1), for measuring the photon flux of the highly intense and strongly pulsed VUV radiation of the TTF-FEL in absolute terms.[10] The detector is based on the atomic photoionization of a rare gas at low particle density in the range of 10^{11} cm^{-3} which is about five orders lower than for classical ionization chambers.[11] Hence, the detector is not only indestructible but also almost transparent which allows the device to be used as a permanently operating photon-beam intensity monitor. Electrons and ions created upon photoionization are extracted and accelerated in opposite directions by a homogeneous electric field. In contrast to a former approach[12], they are detected by simple Faraday cups only, in order to avoid saturation of any amplifying particle detector due to the great number of secondary particles in the range of 10^6 to 10^9 created during one single FEL pulse.

The signal electronics provides single-pulse read-out for both, the electron signal and the ion signal which can be measured at the same time. Into the ion path, a drift section is integrated which allows the measurement of the ion's time-of-flight (TOF) and thus the distinction with respect to the ion charge ($q \sim TOF^{-1/2}$). Moreover, ions may be

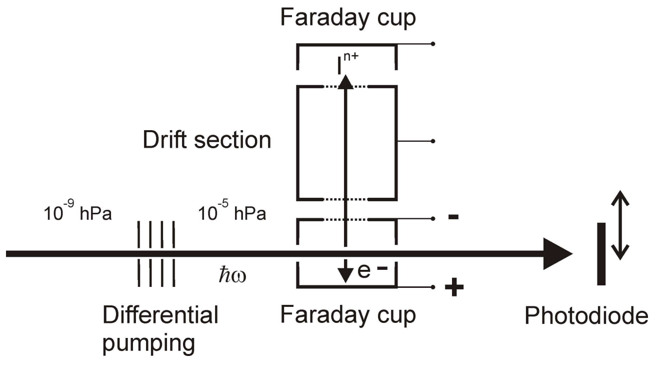

FIG. 1. Schematic diagram of the gas-monitor detector.

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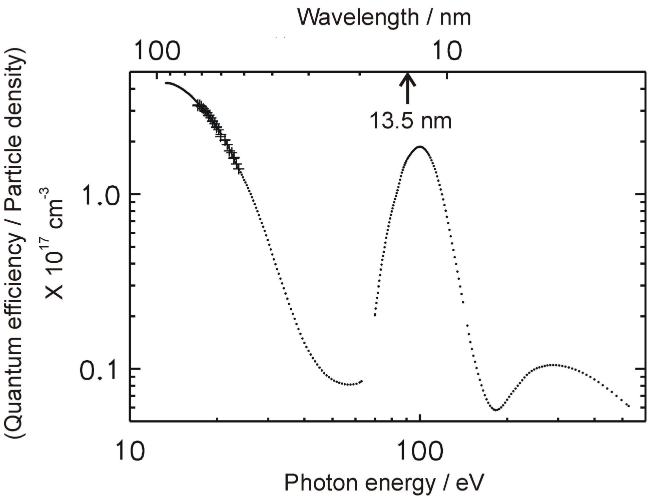

FIG. 2. Quantum efficiency of the photoion-current signal of the gas-monitor detector operated with xenon, normalized to particle density. The dots, using xenon cross section data[15], stand for an extrapolation of the calibration values (crosses) which were measured in the Radiometry Laboratory of PTB at BESSY.

alternatively detected by a slow averaging ion-current signal with a time constant of a few seconds which is not affected by any time structure of the radiation. The extended dynamic range of this ion-current signal guarantees, on the one hand, high linearity even at saturation of a non-focused FEL beam, i.e. at a peak irradiance of about 10^{10} W cm^{-2}, and allows, on the other hand, its calibration using spectrally dispersed synchrotron radiation at low photon intensities, i.e. at a peak irradiance of less than 10^{-2} W cm^{-2}.

The detector was tested and calibrated with dispersed synchrotron radiation in the Radiometry Laboratory of the Physikalisch-Technische Bundesanstalt (PTB) at the electron storage ring BESSY in Berlin using a calibrated semiconductor photodiode as the secondary standard. PTB is Germany's national metrology institute and offers radiometric calibrations with relative uncertainties below 1 % in the spectral range from the ultraviolet to X-rays which are based on two different primary standards, i.e. electron-storage rings as primary radiation-source standards of calculable synchrotron radiation and cryogenic electrical substitution radiometers as primary detector standards.[13,14]

Fig. 2 shows the measured quantum efficiency *Q.E.*, i.e. the number of detected ions per incident photon $N_{\mathrm{ion}}/N_{\mathrm{photon}}$ for the slow photoion-current signal of the gas-monitor detector, operated with xenon as the target gas, in the wavelength region from 75 nm to 50 nm. The data are normalized to atomic particle density which was obtained according to $n_{\mathrm{atom}} = p/kT$ by determination of the gas pressure p in the range of 10^{-5} hPa, using a calibrated spinning rotor vacuum gauge, and the temperature T, using a calibrated Pt100 resistance thermometer. From basic definitions, in the case of an almost collimated photon beam which has a constant beam cross section A and is not attenuated significantly by an optically thin gas medium, the normalized quantum efficiency is proportional to the total photoionization cross section σ according to:

$$\frac{Q.E.(\lambda)}{n_{\mathrm{atom}}} = \frac{N_{\mathrm{ion}}/N_{\mathrm{photon}}}{N_{\mathrm{atom}}/(A\,z)} = \sigma(\lambda) \times z \times \eta \qquad (1)$$

where z denotes the length along the photon beam accepted by the ion detector and η the ion-detection efficiency. Hence, the dependence on the wavelength λ of the normalized quantum efficiency is dominated by that of the total photoionization cross section. Recently measured total photoionization cross section data[15] have therefore been used to extrapolate the calibration values for the gas-monitor detector from 93 nm down to 2.4 nm, which is shown by the dots in Fig. 2. The overall relative standard uncertainty for the calibration curve in Fig. 2 amounts to 4 %. The measured calibration data were reproduced after one year within 1 %. It should be noted that the so-called $4d \mapsto \varepsilon f$ giant dipole resonance of xenon[16] leads to a strong local maximum of the quantum efficiency very close to 13.5 nm, the wavelength of EUV lithography, which proves the gas-monitor detector as a versatile tool also for pulse resolved monitoring and absolute detection of highly intense 13-nm radiation as emitted from EUV-lithography sources.

The upper part of Fig. 3 shows a pulse resolved measurement of FEL radiation emitted by the TTF at a wavelength of 87 nm. Single-pulse readout was realized by the detection of photoelectrons emitted from xenon as the target gas. The 10 pulses of the measured pulse train have photon numbers in the range from 1 to 6 x 10^{12}, as shown in the bottom part of Fig. 3. These values correspond to a peak power of up to 140 MW for a pulse duration of 0.1 ps.[4] The absolute photon numbers per pulse were obtained by (a)

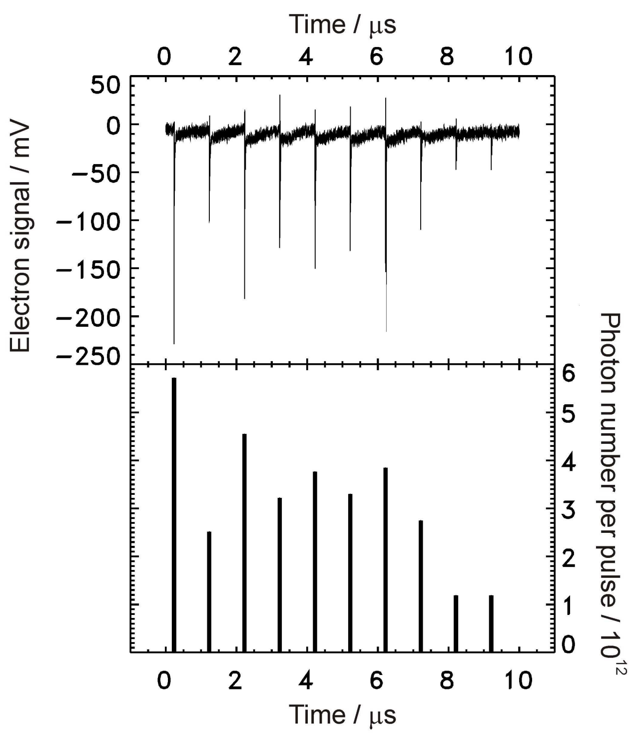

FIG. 3. Photoelectron signal of an FEL pulse train of 10 pulses (top) and evaluated photon numbers per pulse (bottom), measured at a photon energy of 14.3 eV (87 nm wavelength) at TTF with the developed gas-monitor detector using xenon as the target gas.

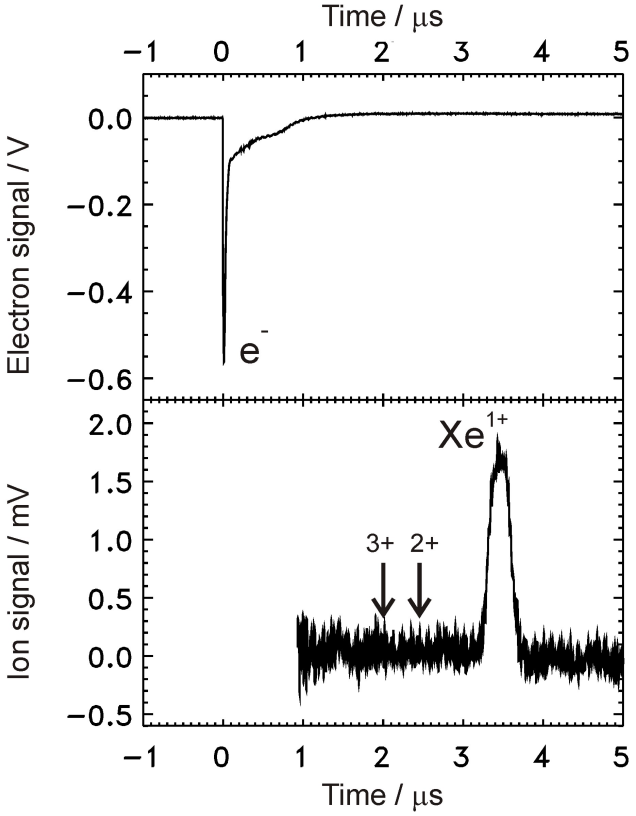

FIG. 4. Photoelectron signal (top) and photoion-pulse signal (bottom) from the gas-monitor detector of a single FEL pulse, measured with xenon (Xe) at a photon energy of 12.8 eV (97 nm wavelength). The time difference between the two signals is mainly defined by the time-of-flight of the Xe^{1+} photoions. The time-of-flight for 2+ and 3+ ions are also indicated.

simultaneously measuring the pulse resolving photoelectron signal and the calibrated slow photoion-current signal and (b) comparing for both the mean intensities of 500 photon pulses distributed over 50 pulse trains with a repetition rate of 1 Hz. Due to this averaging procedure, the relative uncertainties of about 15 % for the measured photon numbers are dominated by the inherent statistical fluctuations of the FEL-pulse intensities[4] which are also apparent in Fig. 3.

The upper part of Fig. 4 shows the photoelectron signal of a single FEL pulse at a photon energy of 12.8 eV (97 nm wavelength), i.e. slightly above the photoionization threshold of xenon at 12.1 eV. In the bottom part of Fig. 4, the pulse resolved photoion signal of the same pulse is depicted. The time delay between the two signals of about 3.5 µs is mainly defined by the time-of-flight of the Xe^{1+} photoions from the interaction zone to the ion detector. The absence of any signal from higher-charged ions at shorter time-of-flight indicates that our photon intensity measurements were not affected by higher-order effects, such as higher harmonics contribution to the FEL radiation or atomic multi-photon excitation in the gas. However, limits of the gas-monitor detector might be defined by the linear regime of atomic photoionization and are expected to be observed in an extremely focused FEL beam.

In conclusion, we developed a gas-monitor detector based on the atomic photoionization of a rare gas at low particle density. It was tested and calibrated in the Radiometry Laboratory of the Physikalisch-Technische Bundesanstalt at the electron-storage ring BESSY in Berlin. First measurements of absolute photon numbers and peak power of VUV-FEL radiation at the TESLA Test Facility in Hamburg have proven the gas-monitor detector to be a versatile tool for the monitoring and absolute detection of highly intense and strongly pulsed VUV and EUV radiation sources.

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