CHALLENGES FOR DETECTION OF HIGHLY INTENSE FEL RADIATION: PHOTON BEAM DIAGNOSTICS AT FLASH1 AND FLASH2

K. Tiedtke*, M. Braune, G. Brenner, S. Dziarzhytski, B. Faatz, J. Feldhaus, B. Keitel, H. Kühn, M. Kuhlmann, E. Plönjes, A. A. Sorokin, R. Treusch, DESY, Hamburg, Germany

Abstract

Photon beam diagnostics play an essential role for tuning free-electron lasers (FEL) and delivering the requested beam properties to the users. An overview of the FLASH1 and FLASH2 photon diagnostic devices will be presented with emphasis on the new pulse resolving intensity monitor covering an extended energy range.

INTRODUCTION

In spite of the evident progress in the development of FEL facilities, the characterization of important FEL photon beam parameters during FEL commissioning and user experiments is still a great challenge. In particular, pulse-resolved photon beam characterization is essential for most user experiments, but the unique properties of FEL radiation such as extremely high peak powers and short pulse lengths makes the shot-to-shot monitoring of important parameters very difficult. Therefore, sophisticated concepts have been developed and used at FLASH1 in order to measure radiation pulse intensity, beam position and spectral as well as temporal distribution - always coping with the highly demanding requirements of user experiments as well as machine operation. Here, an overview on the photon diagnostic devices operating at FLASH1 and planned for FLASH2 (see [1] and referendes therein) will be presented, with emphasis on pulse resolving intensity and energy detectors based on photoionization of rare gases.

LAYOUT OF THE PHOTON DIAGNOSTIC SECTION

On its way from the source to the user endstations the FEL radiation passes through a set of photon diagnostics and beam manipulation tools, such as a set of four gas-monitor detectors (GMD) for intensity and beam position determination, an attenuation system based on gas absorption, a set of filters and a fast shutter [2]. Downstream of the undulators a set of photon diagnostics is installed mainly for use by operators during setup of SASE. The FEL beam passes two diagnostic units equipped with apertures and Ce:YAG screens for visualization of the XUV radiation. Centering the FEL beam with respect to these apertures ensures an accurate propagation of the photon beam across all beamlines towards the experiments. For fast intensity measurements an MCP tool [3] and one of the GMD detector pairs (see below) are located in front of the beam distribution system, as well as a grating spectrometer and a detector system based on photo-electron and -ion spectroscopy (OPIS) for online determination of the spectrum in parallel to the user experiments.

At the same time, most user experiments need online information about important photon beam parameters, such as intensity, spectral distribution, and temporal structure. Furthermore, due to the stochastic nature of the SASE process and the resulting pulse-to-pulse fluctuations of the FLASH photon beam, photon diagnostics need to be capable of resolving each individual pulse within a pulse train. This requires diagnostic tools which operate in parallel to the experiments in a non-destructive way, i.e. not blocking the beam for the experiments behind.

Monitoring of the Spectral Distribution

Some user experiments require knowledge of the spectral distribution of the individual FEL pulses to interpret their data, but may not want to use the plane-grating-monochromator (PG) beamline at FLASH, because of temporal broadening of the pulse or a reduction of photon flux. Three options have been developed and are available to users for this purpose, an online photoionization spectrometer (OPIS) located in the photon diagnostic section, a mobile compact spectrometer which can be setup at the endstation or behind user experiments, and a variable-line-spacing (VLS) grating spectrometer integrated into the FLASH BL beamline branch. The latter will not be provided for FLASH2, since the short wavelength end of the FLASH2 range requires shallow incidence angles of 1° for the beam distribuion optics to avoid damage of the coatings and would finally require extreme long and hardly available gratings.

Online photoionization spectrometer The wavelength measurement with the online photoionization spectrometer is based on photoionization processes of gas phase targets like rare gases and small molecules e.g. N_2 and O_2 [4, 5, 6]. Therefore it is in principle not limited in the wavelength range. For wavelength determination the relevant quantities of the ionization process are the binding energies and photoionization cross sections which are well known from literature. Typical target gas pressures are in the range of 10^{-7} hPa which allows a photon transmission to the user experiment of essentially 100 %. The OPIS device (see Fig. 1) comprises a set of time-of-flight spectrometers for detection of photo-ions and photo-electrons, respectively. Measuring the detector signals by means of fast digitizers recording traces of full bunch trains it is possible to have a monitor for micro bunch resolved determination of the spectral distribution. The ion spectrometer is used to measure the intensities of different charge

* kai.tiedtke@desy.de

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states of the created photo-ions. Since the partial cross sections of the different charge states evolve differently with increasing photon energy, the ratios of the according intensities are a unique measure of the photon wavelength in a certain wavelength interval. Literature data of partial cross sections for the different charge states of various rare gas species cover basically the full wavelength range of FLASH1 and FLASH2. The major advantages of the ion spectrometer are the high signal intensity due to the extraction fields collecting all ions created by the radiation and its insensitivity against beam position changes. In the electron time-of-flight spectra the arrival times of the photoelectrons reflect directly their kinetic energy. The values of the electron binding energy of the orbitals, which the photo-electron were emitted from, are the only information needed for wavelength determination. Hence, with only a few well known constant quantities, the FEL wavelength can be derived over the full wavelength range which is the main advantage compared to the ion method described above. In addition, further spectral information like higher harmonics contribution or the number of FEL modes can be, in principle, deduced as well. On the other hand, the electron signal intensity is lower compared to the ion spectrometer due to limited apex angles and it is quite sensitive to external magnetic and electric fields.

High precision online VLS grating spectrometer A variable line spacing (VLS) grating spectrometer installed at the non-monochromatized BL-beamline branch allows to parasitically measure the spectral distribution of the FEL laser pulses. The optical design of the spectrometer has been carried out in a collaboration of DESY, *Scientific Answers and Solutions* (SAS) in Madison and the *Council for the Central Laboratory of the Research Councils* (CCLRC) in Daresbury [7]. Making use of two interchangeable plane VLS diffraction gratings the spectrometer covers basically the wavelength range from 6 to 60 nm (shorter wavelengths could be covered by using second order diffraction). The main vacuum vessel which houses the optics as well as the mechanics for the movement of the grating have been designed in a joint project of *Helmholtzzentrum Berlin* (HZB) and DESY. The instrument can either be operated in the 'spectrometer mode' by choosing one of the two gratings or if no information of the spectral distribution is requested or if the full beam intensity should be sent to the sample, a mirror can be moved in place of the gratings. In the spectrometer mode the major fraction ($\sim 85 - 99\%$ depending on wavelength and grating) of the radiation is reflected in zeroth order to the experimental station, while only a small fraction is dispersed in first order and used for the online measurement of the spectral distribution. In the current setup, the dispersed radiation is focused on a detector unit containing a Ce:YAG single crystal screen which is imaged by an intensified CCD camera with an effective pixel size of 12µm. The gated camera is able to record single shot spectra with a repetition rate of 10 Hz. Up to now, the instrument has reached a resolving power of 1000 at 25 nm FEL wavelength. In the near future, the gated CCD camera will be complimented by a fast line detector for spectral analysis of all pulses within a complete bunch train.

Compact spectrometer In collaboration with the *CNR-Institute of Photonics and Nanotechnologies in Padova* a compact and portable spectrometer has been built for real time monitoring of the high-order harmonic contents in the FEL radiation [8]. This spectrometer can be installed at the end of the beamlines at FLASH in order to determine the emissions of the fundamental FEL and the high-order harmonic content in single-shot operation mode. Its design is based on two flat-field grazing-incidence gratings combined with a EUV-enhanced CCD. The spectrometer covers the spectral range from 1.7 nm to 40 nm (720 eV-30 eV).

Monitoring of the Temporal Properties

A key measure of the performance of FELs are the temporal properties of the photon beam. The pulse *length* is required for the integral power at the experiment; the pulse *profile* determines the "quality" of the pulse in terms of length and heigth of the ideal pedestal shape; the pulse *jitter* is a random fluctuation in the arrival time of a pulse. By necessity this needs to be correlated to another timing event. Thus, for pump-probe experiments this is obviously a crucial parameter. Since the temporal properties of FEL radiation are going to change on a pulse by pulse basis by an amount that will cause difficulty to at least some experiments, there is a general need for the temporal online diagnostics. Such tools for the whole parameter range of FLASH are not a straightforward choice and therefore they are still under development. A choice of techniques like cross-correlation with an optical laser, intensity autocorrelation, reflectivity modulation of a semiconductor by an FEL pulse or the utilization of phase-correlated terahertz radition have been tested and at this time each has shown its pros and cons. For details see [9] and references therein.

Monitoring of the Intensity and Beam Position

A detailed knowledge of the pulse energy of each individual FEL pulse is essential for almost all user experiments. Depending on the operating conditions of the FEL, the average energy per bunch is typically in the range of 10 µJ to 500 µJ. Intensity monitors have to cover the full spectral range as well as the extended dynamic range from spontaneous undulator radiation to SASE in saturation. To accomplish these requirements a gas monitor detector (GMD) has been developed [10, 11] to perform non-invasive measurements of the intensity of each individual pulse within a pulse train. Four gas monitor detectors, which are also used to determine the beam position of FLASH1 for each pulse, are positioned in the FEL beam-lines. A set of two GMDs is located at the end of the accelerator tunnel and a second one at the beginning of the experimental hall. Between these two sets of GMDs is a 15m long gas filled attenuator, providing means to reduce the FEL intensity by many orders of magnitude without chang-

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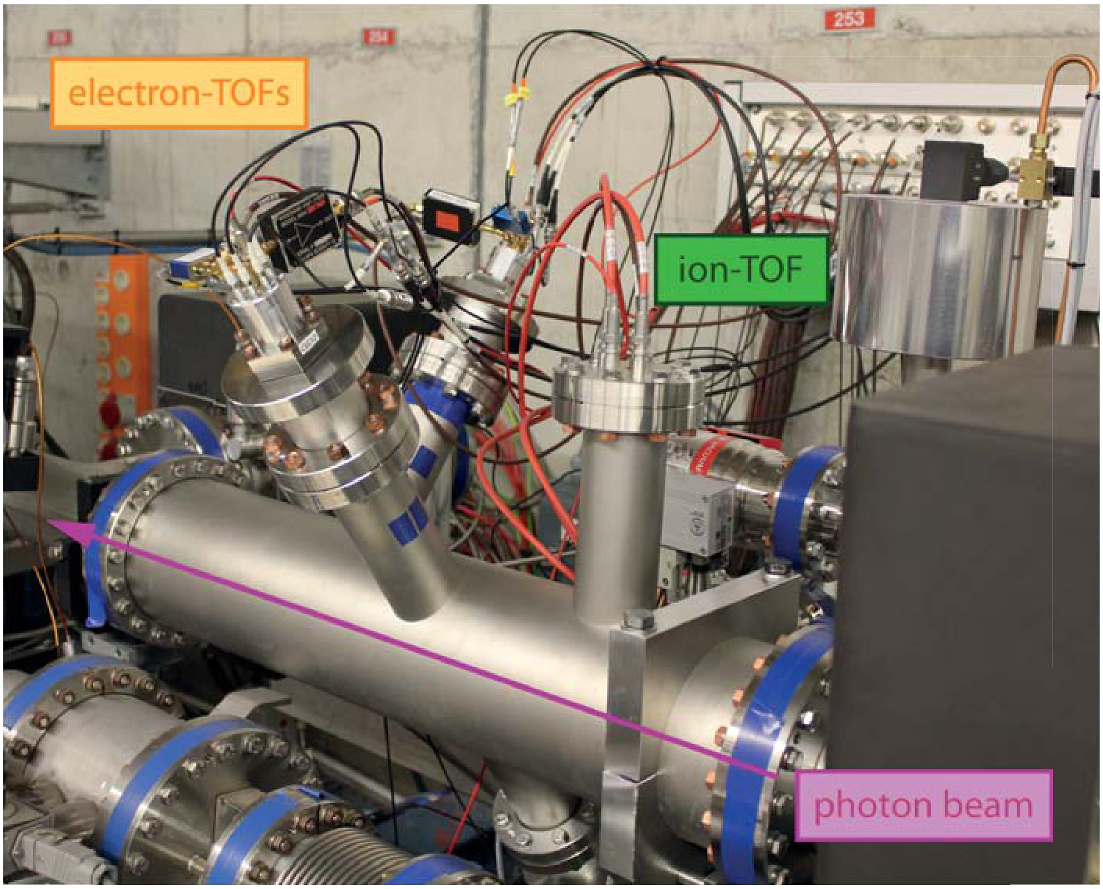

Figure 1: Online photoionization spectrometer located 30m behind the last undulator.

ing the accelerator parameters. When an FEL pulse passes through the ionization chamber of the GMD detector, the gas inside is ionized, and an electric field accelerates the ions upwards and the electrons downwards to be detected by Faraday cups. The absolute number of photons in each shot can be deduced with an accuracy of 10% from the resulting electron and ion currents. Furthermore, the FEL pulse passes between two split electrode plates, allowing the pulse-resolved determination of the horizontal and vertical position of the beam. The gas in the ionization chamber has a very low pressure of about 10^{-6} mbar, and it is nearly transparent to the FEL pulse that proceeds unaltered to the experimental stations.

For FLASH2 an upgraded version of the GMD with an extended energy as well as dynamic range will be used. In contrast to the FLASH1 GMD, the new detector combines the FLASH1 detection scheme with an open electron multiplier which is located behind a small slit in the ion Faraday cup. A small fraction of the created ions hits the multiplier with an amplification factor of up to 10^6 which makes the device sufficiently sensitive for the hard X-ray regime where the atomic photoionization cross sections are by orders of magnitude lower than in the VUV and soft X-ray spectral range. This so-called XGMD will also be used for the pulse energy and photon beam position monitoring at the European XFEL. First successful test of this device have been performed recently at the Japanese hard x-ray laser SACLA in the energy range from 4.4 keV to 14 keV [12].

SUMMARY

Sophisticated photon diagnostics concepts providing shot-to-shot information about important beam parameters, such as intensity, beam position, and spectral distribution, have been developed over the past 15 years at FLASH1. These tools are in routine operation and measure in parallel to the user experiments in a non-destructive way. Since these diagnostic tools demonstrated an overall good performance they will also be used in the photon diagnostics section at FLASH2. As the user demand for delivering beams with specific properties increase, machine capabilities and diagnostic tools need to be further developed to meet this demand. One of the goals will ultimately include the pulse-to-pulse analysis of the temporal distribution. Such tools for the whole parameter range of FLASH are not a straightforward choice and therefore they are still under development.

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