PHOTON DIAGNOSTICS REQUIREMENTS AND CHALLENGES AT THE EUROPEAN XFEL*

J. Grünert#, European XFEL, DESY, Hamburg, Germany

Abstract

The European XFEL (X-ray Free Electron Laser) [1] will provide radiation with properties that will challenge standard photon diagnostics tools. Especially its unique pulse train structure of up to 3000 pulses of 100 fs duration, each at only 200 ns spacing between neighboring pulses, requires novel approaches to the characterization of the x-ray beams. In addition, the intense peak power of 20 GW rules out many conventional techniques that were developed for 3rd generation synchrotron radiation (SR) sources. At the European XFEL, intensity and position monitors will use the interaction of the photons with dilute gases, while other online devices could also use parasitically available scattered light. Intrusive but removable detectors will be dedicated to commissioning and optimization before user runs. One of these devices is the K-monochromator which ensures that the magnetic gap and the phasing between modules are correctly adjusted during photon based undulator alignment. The paper presents an overview of the requirements for these baseline components of the European XFEL diagnostics system.

INTRODUCTION

The European XFEL will have five independent undulators and a beam distribution to 15 experimental stations. In the start-up version, 3 undulators and 6 experimental stations will be built initially. The scientific areas of these initial experiments will cover a wide range of applications, including coherent scattering, single particle imaging, plasma physics and time-resolved diffraction and spectroscopy.

The x-ray pulses created in the undulators have to be characterized by photon diagnostics in order to find and tune the SASE (Self-Amplified Stimulated Emission) process and to provide beam information to users.

A pulsed x-ray laser beam has several properties: the beam geometry is described by local transverse dimensions, center position, divergence, and longitudinal focus position. The photon energy is described by the pulse energy and its spread or bandwidth. The pulse intensity is the number of photons per pulse and is related to the total pulse energy via the photon wavelength. The pulse itself has a temporal shape and a maximum intensity. Timing information consists of the pulse arrival time and the pulse duration. Other properties are the degree of linear or circular polarization, the longitudinal and transverse coherence and finally the quality of the wavefront.

The photon diagnostics devices measuring these qualities have to account for various conditions:

- commissioning and operating requirements
- different beamlines
- different energies during ramp-up and operation
- different accuracies at different energies and ranges
- different measurement rates (shot-to-shot, pulse-train-resolved, integrated)

As an example, the accuracy of the beam position measurement will be different in shot-to-shot compared to integration mode.

In this paper, we give an initial overview of requirements which will be detailed later for the different beamlines and operating modes.

COMMISSIONING REQUIREMENTS

Intensity

The number of photons/s has to be measured from the low intensity spontaneous radiation up to FEL saturation, directly in front of and behind the attenuators to derive the attenuation factor, and close to experiments to determine beamline optics losses and the intensity delivered to the user target.

Non-destructive x-ray gas monitor detectors (XGMD) [2] will be used during FEL commissioning as well as during user operation for shot-to-shot intensity measurements. PIN diodes and calibrated PtSi photodiodes (saturation at 100-500 nJ, destruction threshold ~10 mJ/cm^2) are useful mainly for low intensities and spontaneous radiation.

Table 1: Requirements for intensity measurements

accuracy	1 %	for commissioning
	< 0.1%	for operation
	1% or better	after mirrors to measure reflectivity (0.2-80 keV)
range	10^6 to 10^{14} photons/s	

Photon beam position

- Both spontaneous and FEL radiation should be monitored shot-to-shot and online, in both x and y direction
- Two positions are required to determine photon beam pointing. The separation of the two monitors and their distance to the undulator should be as large as possible, but they should be placed upstream of a K-monochromator
- Precision (accuracy not required): ±10 µm for beam position variations within ±2 mm; δx=10 µm for a distance of 100 m between two monitors for 0.1 µrad angular resolution; 1/10 of beam size sigma

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# jan.gruenert@xfel.eu

- X-ray beam position monitors (XBPM) [3,4] will have a relative accuracy of 0.2 % of the beam diameter. Quadrant diodes and PIN diode arrays assist during commissioning.

Alternative position monitors

For commissioning purposes, two partially transparent solid-state BPMs with micrometer accuracy would also be suitable. They distort the wavefront of the beam but, in return, offer good pulse-resolved spatial resolution.

CVD (chemical vapor deposition) diamond photocurrent pixel detectors [5] have resolved beam displacements of 2 µm at signal decay times below 1 ns.

Coded-aperture imaging [6] aims at a resolution of a few micrometers at a sub-nanosecond response time. This allows for shot-to-shot profiles; however, these detectors are not transmissive.

Thinned-down (5-10 µm) transmissive silicon position sensitive detectors [7] have ~95 % transmission at 12.4 keV. At synchrotrons, a submicron position resolution up to 1 kHz (S/N=$6 \cdot 10^4$ at 10 Hz) has been demonstrated. The lower flux limit for these detectors is ~10^7 photons/s, but their behavior under intense FEL radiation needs to be studied.

Transverse beam profile, shape and position

Complementing the pure beam position data from the XBPMs, a 2D beam viewer employing a scintillator or fluorescence screen will provide a beam profile and assist in beam-based alignment of components. Suitable positions are before the K-monochromator and close to the user setups in the experimental hall.

- accuracy ± 5 µm (in 0.2 - 80 keV range) to align beamline optics using the x-ray beam
- accuracy ± 50 µm over ± 5 mm range to align other components during commissioning.

Total Energy in radiation pulse + photon beam image

The total pulse energy has to be measured for detection and tuning of the SASE process over the range from spontaneous to FEL radiation, see Table 2. An MCP (multi-channel plate) based photon detector [8] has a sufficiently large dynamic range, while a bolometer or thermopile [9] is only useful for small intensities.

Table 2: Requirements for intrusive measurements of the total pulse energy

Rel. accuracy	fraction of 1%
Spatial resolution of MCP image	10 to 30 µm
Wavelength range	0.1-10 nm
Pulse energy range	1 nJ - 10 mJ

The detector should be positioned before any spectrometer or monochromator. A combination of an MCP with a phosphor screen can provide a direct 2D image of the x-ray beam. The same is achieved by fluorescence in a YAG screen. Neither method will be able to resolve all pulses in a full pulse train, but serve as a single pulse mode tool for operators during commissioning and maintenance.

Photon-based undulator tuning / spectral content

To commission the undulators, the undulator gap and phasing have to be adjusted after optimizing the trajectory. Imaging the photon beam is also desirable.

One possible method is described in detail in [10]. The intensities in the first and fifth harmonic are simultaneously recorded under two angles by inserting a crystal into the x-ray beam. Although this device is mainly intended for commissioning with spontaneous radiation from single or pairs of undulator segments, it could be used with the attenuated FEL in single pulse mode. While an integrating mode is sufficient for undulator turing, using 1D direct-UV stripline detectors would allow for pulse-resolved energy scans.

Tunability is required since the undulator K is variable. This is even true for the “fixed energy” beamline SASE1, which can be set to longer wavelengths during ramp-up and commissioning. The spectral range should cover at least 10 to 15 harmonics.

Spectrum

Measuring the spectral distribution is required for several purposes, see Table 3.

Table 3: Spectral accuracy requirements

350 - 3000 eV	4 - 25 keV	purpose
0.01%	0.01%	energy calibration with electron beam
0.1%	0.01%	undulator checks, BL transmission, monochromator setup
0.001% within 0.1%	0.0001% within 0.01%	temporal structure

An intrusive K-monochromator for undulator tuning determines the spectral content in different harmonics. It will mainly be used during commissioning. Photoelectron spectroscopy (PES) could be used to measure online and shot-to-shot spectra [11]. Another proposed method [12] uses dispersive X-ray Raman Scattering (XRRS), where the ultimate goal would be a single-shot spectrum with 25 meV energy resolution.

OPERATING REQUIREMENTS

While some photon beam properties are less crucial for the start-up of the SASE process, they are of rather high priority to users during operation. Explicit requirements concern the polarization, the timing, and the wavefront.

Polarization

The degree of linear and circular polarization is measured in the experimental hall. User demand calls for a measurement accuracy of 1 %. Photoelectron spectroscopy is a promising technology for this task.

Timing information

Pump-probe experiments require synchronization at the sub-10 fs level. The accuracy of the beam arrival time should be <1 %, and the pulse duration needs to be measured.

Wavefront

Wavefront measurements will help to adjust transport and focusing optics. They will be used to determine FEL-induced changes in beamline optics and the FEL wavefront itself for use in experiments. The wavefront determination accuracy is required at a level of λ/15.

Current Hartmann wavefront sensors [13] were tested on EUV sources at low repetition rates, and the expectation is to use gated detection for multiple acquisitions within one pulse train.

2D IMAGING

Great efforts are made to develop large ultrafast pixelated 2D-detectors for direct x-ray imaging [14]. These sophisticated detectors will record several hundred images during one pulse train and will be available for user experiments rather than for basic x-ray photon beam diagnostics. Concerning diagnostics applications, however, 2D-detection of secondary, visible radiation, e.g. originating from phosphor or YAG screens is needed. It will not be possible to acquire full frame images at the intra-pulse-train repetition rate of 5 MHz with commercially available cameras; however, state-of-the-art fast 2D detectors already allow at least for the acquisition of more than one image during a pulse train:

- Interline transfer CCD cameras [15] produce two fast successive images in gated dual-image mode without an external shutter at exposure times as low as 100 ns. The charge transfer from imaging pixels into shielded storage pixels typically takes 1 ms and the readout about 7 ms.
- Intensified digital (12 bit) CCD cameras [16] record two discrete images with an interframing time of 500 ns at exposure time settings from 3 ns to 1000 s. Typical phosphor decay times to 10% of the initial intensity are 0.2 - 0.4 μs (down to 1 % in 2 μs).

SUMMARY

This paper gives an overview of the diagnostics tasks at the European XFEL and the consecutive requirements that set the frame for the development of devices and methods. The application of methods from 3rd generation synchrotrons is not straightforward, due to the large increase in peak power at a pulse repetition rate in the MHz range. In particular, novel online devices that use the ionization of gases need to be moved from the experimental stage to become reliable and accurate photon beam monitors.

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[16] As an example: 12 bit CCD camera dicam pro by the company pco.imaging as used in a spectrometer at FLASH