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2013 J. Phys.: Conf. Ser. 425 072004

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## Development status of the X-ray beam diagnostics devices for the commissioning and user operation of the European XFEL

Jan Grünert, Jens Buck, Wolfgang Freund, Cigdem Ozkan, Serguei Molodtsov  
European X-ray Free Electron Laser Facility GmbH,  
Albert-Einstein-Ring 19, 22761 Hamburg, Germany  
E-mail: jan.gruenert@xfel.eu

### ABSTRACT

X-ray Free-Electron-Lasers (XFEL) as the Linac Coherent Light Source (LCLS) in the USA, SACLA in Japan, and the European XFEL under construction in Germany are 4<sup>th</sup> generation light sources which allow research of at the same time extremely small structures (Ångström resolution) and extremely fast phenomena (femtosecond resolution). Unlike the pulses from a conventional optical laser, the radiation in these sources is created by the Self-Amplified Spontaneous Emission (SASE) process when electron bunches pass through very long segmented undulators. The shot noise at the origin of this process leads to significant pulse-to-pulse variations of pulse intensity, spectrum, wavefront, temporal properties etc. so that for user experiments an online monitoring of these properties is mandatory. Also, the adjustment of the long segmented undulators requires dedicated diagnostics such as an undulator commissioning spectrometer and spontaneous radiation analysis.

The extremely high brilliance and resulting single-shot damage issue are difficult to handle for any XFEL diagnostics. Apart from the large energy range of operation of the facility from 280 eV to 25 keV in FEL fundamental, the particular challenge for the European XFEL diagnostics is the high intra bunch train photon pulse repetition rate of 4.5 MHz, potentially causing additional damage by high heat loads and making shot-to-shot diagnostics very demanding. This contribution reports on the facility concepts, recent progress in instrumentation development, and the optimization of diagnostics performance with respect to resolution/accuracy, shot-to-shot capabilities and energy range.

**Keywords:** X-ray FEL, photon diagnostics, X-ray beam diagnostics, commissioning, user operation

### 1. INTRODUCTION

The requirements for X-ray diagnostics of the European XFEL were initially assessed in [1]. The full systematics of these diagnostics were recently laid out in a framework document [2] which is accompanied by Conceptual Design Documents on the individual devices [3–5]. The present paper can only give a brief overview to these devices, and it highlights recent developments, mainly for the commissioning devices. To understand the “complete picture”, we refer the reader to the framework document [2].

### 2. COMMISSIONING DEVICES

All commissioning diagnostics devices are invasive devices, and some of them are mainly dedicated to ensure the initial lasing. Common to all invasive devices is that they must be retracted from the beam before the full FEL pulse train is transported to the experimental hall.

#### 2.1 Undulator commissioning with the K-monochromator

A precise adjustment of the K-parameters of all individual undulator segments is required in order to allow for lasing of the European XFEL. The differences of K between the segments must be minimized, e.g. below  $1.5 \cdot 10^{-4}$  at 12 keV. Firstly, this will be guaranteed by precise magnetic measurements prior to installation of the undulators in the tunnel. Secondly, photon beam based measurements will verify the correct K settings using directly the spontaneous radiation X-ray beam. This undulator commissioning device [5] is called K-monochromator, as it follows the successful design pioneered at LCLS. It contains two channel-cut Si(111) crystals on two rotation stages: Huber 410D vacuum compatible goniometers with rotation repeatability better than 1  $\mu$ rad. The second stage allows for higher energy resolution, four-bounce inline geometry without beam offset, and by detuning the second crystal, higher harmonics can be suppressed. Current status: the UHV chamber was constructed and outfitted with the first stage, so one channel-cut crystal on one goniometer, and a preliminary detection unit was built containing a photodiode for measurements of integral flux, and an imaging part consisting of a YAG scintillator, a high numerical aperture optical lens and a high-sensitivity sCMOS camera (see section 2.3). This setup was recently thoroughly tested during two synchrotron beamtimes at the

DORIS BW1 and PETRA3 P01 beamlines. Details on and results of these measurements are presented on poster TH-G-P-43 in these proceedings.

## 2.2 Undulator commissioning simulations

A possible method for undulator parameter mismatch ( $\Delta K$ ) minimization using the K-monochromator is double segment tuning with a kick to the electrons – 20  $\mu\text{rad}$  in fig. 1 – between successive segments as proposed by Tanaka [7].

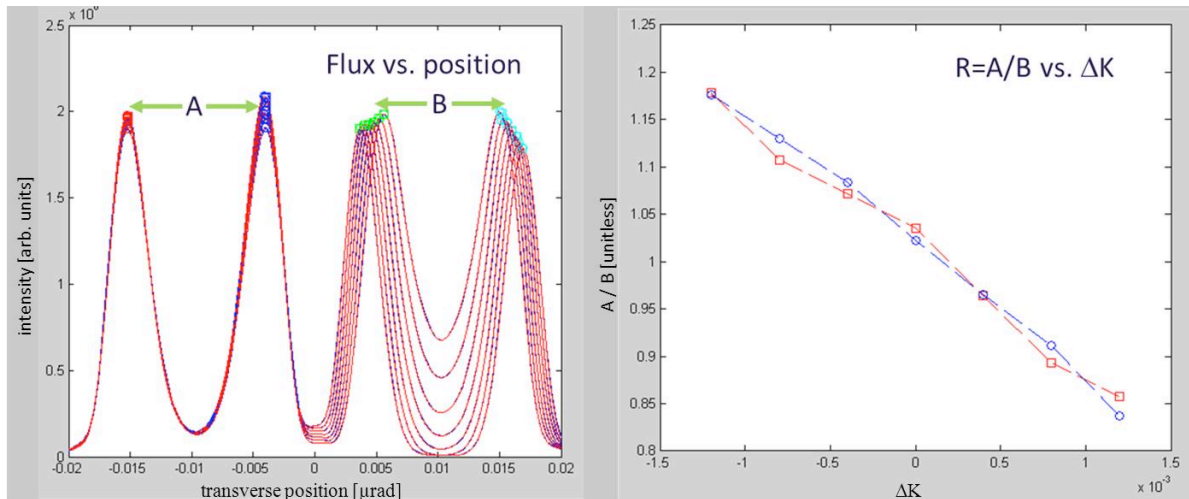


Figure 1. Left: Simulated spontaneous radiation transverse profile (intensity [arb. units] vs. transverse position [ $\mu\text{rad}$ ]) in double-segment tuning with kicked electrons; when detuned below undulator resonance, the well-known donut structure is seen here as two peaks at a distance A. The next undulator segment creates another double peak shifted due to the kicked electrons, and the peak separation B is changed by tuning the gap of only this segment, while the first segment is kept at fixed gap. Right: Optimum tuning – minimized  $\Delta K$  – occurs when the ratio of the peak separations is unity (two sets of simulations are shown).

Calculation of the required pixel size for spatial resolution of the resulting spontaneous radiation (see fig. 2):

- the minimum size is determined by the detector noise (min. number of photons)
- the maximum size is set by the constraint that the peak distance must be spatially resolved

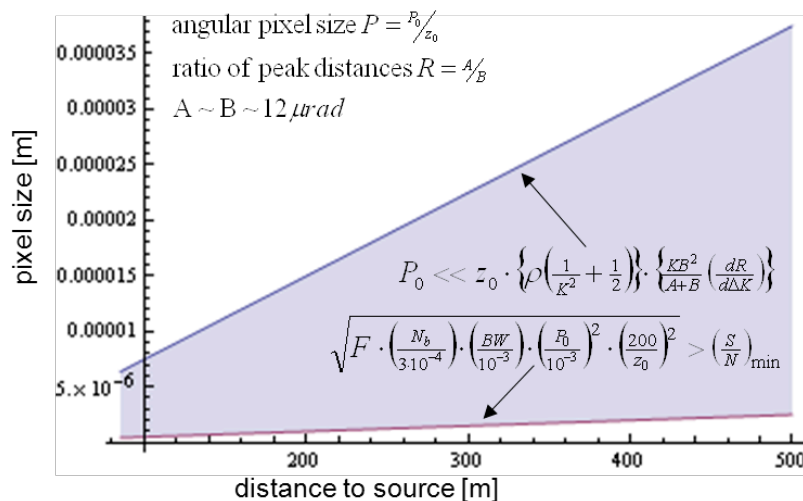
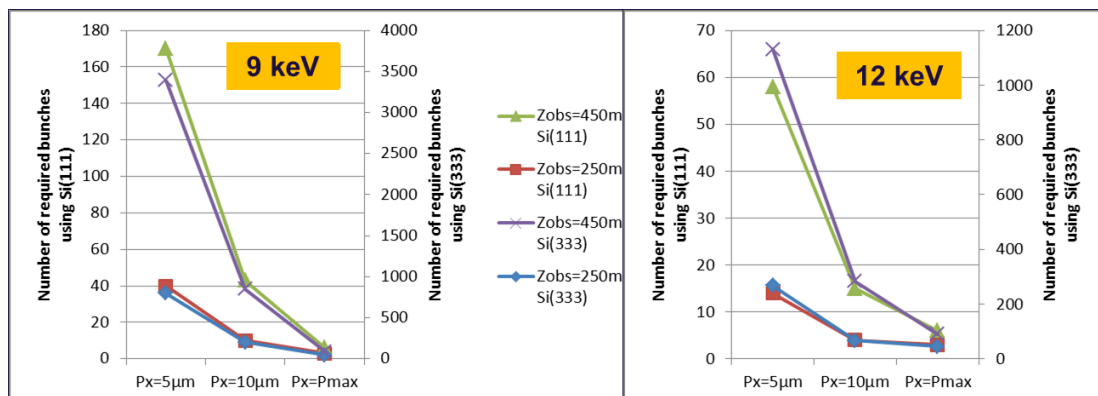


Figure 2. Required pixel size to resolve spatially the spontaneous radiation profile, depending on the distance between observed undulator segment and K-monochromator; allowed region is shaded grey and shows the boundary condition formulas.

The tuning time is determined by the required number of bunches to reach  $(S/N)_{\min}=10$ ; the signal-to-noise is given here by the detected photon flux into one pixel compared to the Poissonian shot noise; the values for  $E_e=14$  GeV (10 GeV);  $E_{\text{obs}}=12325$  eV (8975 eV),  $Q=1$  nC,  $r_0=4 \cdot 10^{-4}$  are summarized in table 1 and fig. 3.

Photon Energy	250 m	450 m
12325 eV	12 $\mu\text{m}$	22 $\mu\text{m}$
8975 eV	21 $\mu\text{m}$	38 $\mu\text{m}$

Table 1. Maximum pixel size for two photon energies and the two extreme distances between segment and imager.

Figure 3. Tuning time for tuning at 9 and 12 keV for three pixel sizes  $P_x$  where  $P_{\text{max}}$  are the values in table 1.

### 2.3 Imaging stations

The imaging stations at the European XFEL will serve various purposes: any imager will be retractable and allow for visualization of the photon beam when inserted. In combination with the K-monochromator, one imager will allow to assess K-values of undulator segments by detuning the monochromator several percent below the undulator resonance and determining the diameter of the transversely observable intensity ring structure. Furthermore, two imaging stations in succession will deliver beam pointing information, where the first imager is semi-transparent by using a thin scintillator and a coated membrane as optical mirror under  $45^\circ$ . Numerous imagers will be placed along the beamlines near X-ray optical elements such as the mirrors and monochromators for their adjustment. A conceptual design sketch is shown in fig. 4.

Commercial sCMOS chip cameras satisfy the following requirements: frame rate  $> 10\text{fps}$ , dynamic range  $> 65\text{ dB}$ , low noise, external trigger, hardware and software compatibility with the European XFEL DAQ & Control system. The lens design requires an extended depth-of-field and short working distance, two different field-of-views for SR and FEL, and a high numerical aperture for SR. A linear manipulator moves a scintillator holder in and out of the beam, and stops at different targets: there is a calibration scintillator with a laser engraved central cross, a YAG:Ce, a pc-CVD diamond, and another scintillator for redundancy. The transmissive mirrors allow for  $>50\%$  transmission at energies above 5 keV.

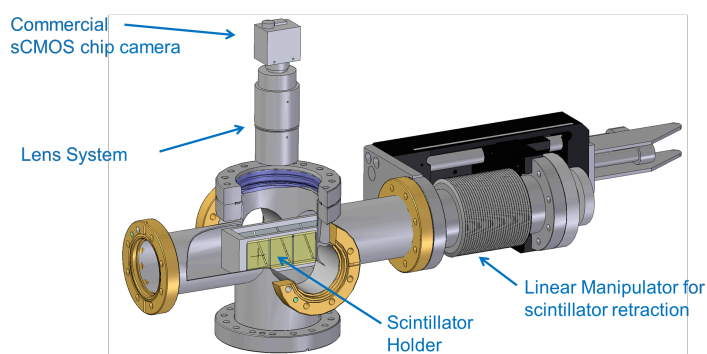


Figure 4: Conceptual 3D sketch of the imaging stations [4]; the four main parts labeled in the graph are explained in the text.

### 2.4 MCP based detector

The MCP based detector is an intrusive monitor for pulse intensity, and it provides a direct 2D beam image. Two directly illuminated MCPs ( $\text{Ø}14\text{mm}$ ) are instrumental for the initial SASE search and later SASE optimization. The transverse intensity profile is obtained by a combination of another MCP stack ( $\text{Ø}14\text{mm}$ ), a phosphor screen and a CCD camera.

A large intensity range (1nJ – 10mJ required [2]) is obtained by using not only the beamline attenuators (diamond, graphite) but also the offset mirrors [6] as attenuators. Very large horizontal translation ranges [-7 cm, +9 cm] are necessary due to the horizontal offset mirror shift during energy changes, so there are several operation modes:

- no offset mirror = direct beam, analyze full undulator
- one / two mirrors = attenuate + cut-off *Bremsstrahlung* > 25 keV
  - one mirror / 0.05 nm /  $\theta_1=3.6$  mrad  $\rightarrow x=+9$  cm
  - two mirrors / 0.4 nm /  $\theta_1=3.6$  mrad /  $\theta_2=31.5$  mrad  $\rightarrow x=-6.75$  cm

The first prototype has arrived at Hamburg in July 2012 and will be tested with hard X-rays at a DORISIII beamline in September 2012.

### 2.5 Wavefront sensing

Wavefront sensing can determine defects of beamline optics, help optimizing adaptive optics, and provide information on the lasing source position in the undulator. Results of wavefront measurements at the Linac Coherent Light Source (LCLS) were published in [8]: Using a grating interferometer, the source-point position was determined laterally with an accuracy of few  $\mu\text{m}$  thanks to the extremely high angular sensitivity. Longitudinally, the absolute accuracy was on the order of 4 m and the relative accuracy was 1 m.

## 3. ONLINE DEVICES

During user operation in principle only gas-based online devices will remain in operation since they are indestructible, deliver pulse-to-pulse information, but do not change the exceptional beam properties such as the transverse coherence. X-ray gas monitor detectors (XGMD) deliver absolute pulse intensity and X-ray beam position monitors (XBPM) deliver position information. The 1<sup>st</sup> XGMD chamber contains metal plate electrodes and a small-aperture electron multiplier; a *huge aperture open multiplier* (HAMP) is placed in the 2<sup>nd</sup> XGMD chamber; the XBPM is based on split electrodes (and similar to the 1<sup>st</sup> XGMD chamber). In November 2011, the XGMD was for the first time and successfully tested [9] at a hard X-ray FEL at SACLA, Japan.

Spectral shot-to-shot information is obtained with a photoelectron spectrometer (PES) which is also based on photoionization of rare gases. Details on the progress concerning the PES are shown on poster WE-H-P-01 in these proceedings.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge G. Geloni for the undulator commissioning simulations; K. Tiedtke and his group at HASYLAB for the XGMD status; J. Viehhaus and his group at PETRAIII for the PES collaboration; E. Syresin and collaborators from JINR/Russia for the work on the MCP based detector; and C. David and his group at PSI/Switzerland for the collaboration on grating interferometer based wavefront sensing.

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