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# Beam parameters of FLASH beamline BL1 from Hartmann wavefront measurements

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ABSTRACT

We report on online measurements of beam parameters in the soft X-ray and extreme ultraviolet (EUV) spectral range at the free-electron laser FLASH. A compact, self-supporting Hartmann sensor operating in the wavelength range from 6 to 30 nm was used to determine the wavefront quality of individual free-electron laser (FEL) pulses. Beam characterization and alignment of beamline BL1 was performed with $\lambda_{13.5\,\mathrm{nm}}/90$ accuracy for wavefront rms ($w_{rms}$). A spot size of 159 μm (second moment) and other beam parameters are computed using a spherical reference wavefront generated by a 5 μm pinhole. Beam parameters are also computed relative to a reference wavefront created by a laser-driven plasma source of low coherence, proving the feasibility of such a calibration and reaching $\lambda_{13.5\,\mathrm{nm}}/7.5\ w_{rms}$ accuracy. The sensor was used for alignment of the toroidal focusing mirror of beamline BL1, resulting in a reduction of $w_{rms}$ by 25%, and to investigate wavefront distortions induced by thin solid filters.

## 1. Introduction

Hartmann–Shack and Hartmann sensors are routinely used for real-time wavefront detection and laser beam characterization in the near infrared, visible and ultraviolet spectral region. Both the wavefront (directional distribution) and the beam profile (intensity distribution) of a radiation field can be recorded for a single pulse, enabling evaluation of paraxial beam parameters such as beam diameter $d$, divergence $\theta$, beam propagation factor $M^2$, Rayleigh length $z_R$, waist position $z_0$ and waist diameter $d_0$ for coherent radiation [1]. Solving the Fresnel–Kirchhoff integral allows also numerical propagation of the beam and thereby prediction of intensity distribution in any plane [2].

The Free-electron LAser in Hamburg (FLASH), operating in the extreme ultraviolet (EUV) spectral region, is based on the self-amplified spontaneous emission (SASE) process, which builds up laser emission from spontaneous undulator radiation. The photon beam characteristics relevant for user experiments can differ from pulse to pulse, leading to a strong requirement for single-pulse photon diagnostics and on-line characterization of the beam propagation parameters [3,4]. Recently, we reported on a compact EUV Hartmann wavefront sensor that was jointly developed by Laser-Laboratorium Göttingen (LLG) and DESY for photon diagnostics, beamline alignment and monitoring of FEL radiation at FLASH [5]. The validity of beam parameters, computed in the framework of second moments, was confirmed using data from beamline BL2. In this paper, we present results from measurements at beamline BL1, including determination of beam parameters relevant for many user experiments as well as alignment of the toroidal focusing mirror. One of the major challenges using the Hartmann technique is to create a known reference wavefront. Two approaches are taken here: using a laboratory-scale laser-driven plasma source and spatial filtering at FLASH.

Great effort is currently undertaken to design optical elements that preserve coherence and wavefront properties of FEL pulses. The gas attenuator, developed at FLASH [3], and thin solid filters are standard techniques for intensity attenuation at FELs. Both techniques were investigated at FLASH, and it was reported that in general the gas attenuator induces less wavefront aberrations [4]. Solid filters provide other features such as very high attenuation levels and spectral characteristics that may outweigh this disadvantage in certain applications. In this context the Hartmann sensor has proven to be a useful tool for pulse resolved beamline monitoring.

## 2. Hartmann sensor and reference wavefront generation

The setup for the Hartmann sensor is based on the ideas Hartmann [6] presented in 1900. The essential parts are the Hartmann plate, a pinhole array consisting of a 7 μm thick tantalum foil with laser drilled holes (pitch 320 μm, diameter 65 μm), which divides the incoming beam into an array of smaller beams, and a 12bit camera with a

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charge-coupled device (CCD) chip at the distance $l = 97$ mm behind the plate, which monitors the position and intensity of the beams from each subaperture. The CCD chip ($1279 \times 1023$, 6.45 μm pixel size) is coated with $Gd_2O_2S$:Tb (grain size 1–2 μm, central emission wavelength 545 nm) for EUV-to-VIS conversion. The Hartmann sensor is described in greater detail in Ref. [5].

The displacement of a spot centroid $\Delta x$ divided by $l$ yields the local wavefront gradient inside one subaperture relative to a known reference wavefront. The wavefront is reconstructed from local gradients in a modal approach according to Refs. [7–9], using 37 Zernike polynomials in the ordering referred to in Ref. [10]. Summation over pixel data inside the individual subapertures samples the intensity distribution or beam profile $I(x,y)$. The Hartmann data, consisting of sampled intensity and wavefront gradients, allows for computation of the first and second order moments of spatial $(x,y)$ and angular $(u,v)$ coordinates over the intensity distribution [1].

For paraxial coherent beams this information is sufficient to compute the following beam parameters: beam width $d$, divergence $\theta$, beam propagation factor $M^2$, waist diameter $d_0$, Rayleigh length $z_R$ and waist position $z_0$ as shown in Refs. [1,11]. Influences from partial coherence are neglected in this evaluation. For our purposes, this is justified by the high degree of spatial coherence reported for the FLASH beam [12]. The computation of second moment beam parameters from the Hartmann data for EUV FEL radiation and general agreement with caustic scan techniques was reported in Ref. [5]. Once intensity and phase of a beam are known from the Hartmann measurement, the Fresnel–Kirchhoff propagation yields intensity distribution at different positions $z$ [2].

The wavefront quality is given in terms of wavefront peak-to-valley $w_{pv}$ and wavefront root-mean-square $w_{rms}$ values. Tilt and the best-fitting sphere are subtracted prior to computation of these values. The selection of area of interest (AOI) for wavefront and beam profile evaluation is based on clipping of noise at a level of 1% of the full dynamic range of the camera. The largest circle inscribed into this AOI defines the evaluation radius $a$.

Two techniques, spatial filtering at FLASH and a lab-scale EUV plasma source were used to create near-spherical reference wavefronts. For the latter, a Nd:YAG laser (1064 nm, 1 Hz, 800 mJ, 7 ns) is focused down to about 60 μm into a Krypton (Kr) gas jet (backing pressure 15 bar) centered in a vacuum chamber, producing a 250 μm × 150 μm plasma (FWHM) (Fig. 1a). For blocking of out-of-band radiation from the plasma a 200 nm titanium filter is used, resulting in broadband radiation (Kr XXV–Kr XXXVI) in the spectral range $\lambda = 2.5$–6.5 nm as seen from the measured spectrum in Fig. 1b. The EUV spectrometer (1–7 nm) used for the spectral investigation of the plasma source consists of a 100 μm entrance slit, an aberration corrected flat-field grating (2400 lines/mm) and a back-side illuminated CCD camera. The plasma was monitored with a pinhole camera, consisting of a CCD chip with an EUV-to-VIS quantum converter and a pinhole (diameter 50 μm) coated with a titanium foil (thickness 200 nm). A more detailed description of the EUV source is given in Ref. [13].

The Hartmann sensor described above was placed at a distance of 1213 mm from the plasma. The reference spot patterns shown in Fig. 2a were recorded, averaging over 100 frames, each containing 50 pulses. The directional characteristic of the plasma source, emitting into $4\pi$ steradian, results in a homogeneous intensity profile.

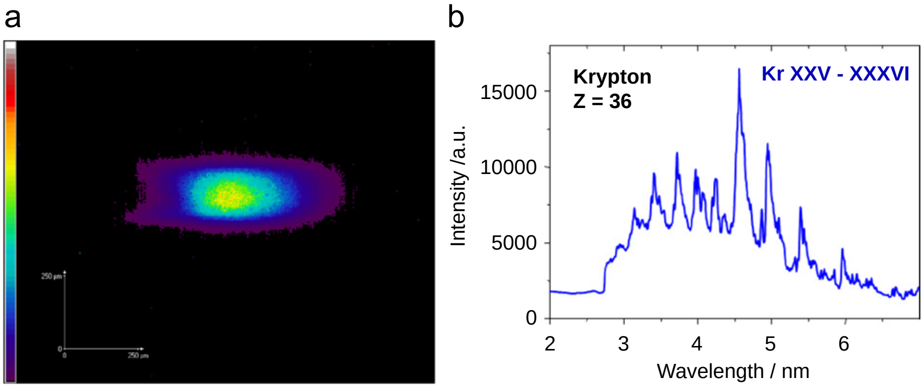

**Fig. 1.** Laboratory-scale EUV source: a Nd:YAG laser is focused into a Kr gas jet in a vacuum chamber, creating a plasma emitting in the EUV spectral range. A pinhole camera image is shown in (a). The radiation of the plasma is filtered by a 200 nm titanium foil, producing the spectrum shown in (b).

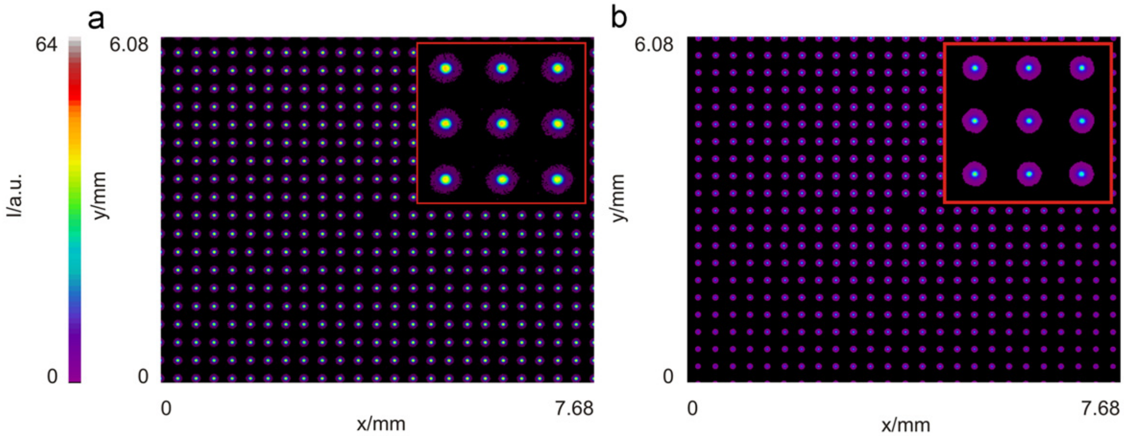

**Fig. 2.** Reference spot patterns taken at the EUV laser-driven plasma source (a) and at FLASH with a 5 μm pinhole at $\lambda = 13.5$ nm (b); the center pinhole on the Hartmann plate is omitted for alignment purposes.