WAVE-FRONT OBSERVATIONS AT FLASH

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Abstract

During the first year of user operation at the Free-Electron Laser in Hamburg (FLASH) wave-front measurements were recorded in the vacuum-ultraviolet region using a Hartmann sensor (by Imagine Optic). The Hartmann principle is based on a hole array, which divides the incoming beam into a large number of sub-rays monitored in intensity and position of individual spots. The identification of the local slope of the incident wave front makes the aberrations from a perfect spherical wave front visible. Ray tracing in upstream direction accesses the beam path especially the focal spot in size and position.

The intense and coherent vacuum-ultraviolet FEL beam leads to unique requirements for the wave-front sensor setup. We report an optimized setup to observe the metrology of flat and curved mirrors at FLASH beam lines. The use of wave-front measurements to provide reliable machine parameter is discussed.

The wave-front sensor proved to be a valuable tool to observe the FEL beam quality and the performance of optical elements, filters and diagnostic tools.

GENERAL

FEL beam characteristics

The here-introduced wave-front sensor is used as tool in the photon diagnostics at FLASH. A free electron laser beam shows specific characteristics which demand certain requirements for any diagnostic tool.

Based on the SASE principle all FEL features differ from shot to shot depending on the degree of saturation. At a high level of some µJ per pulse the FEL operates in an intensity regime of two orders of magnitude. The required adaptations in the wave-front sensor setup and the needed data statistics which can document the shot to shot changes are discussed in the following sections.

The wavelength regime of 13 nm to 60 nm is of no consequence for the achromatically wave-front sensor. The short pulse length of 10 – 50 fs and the variable rates of repetition will be a challenge if the wave-front sensor becomes an online diagnostic tool in the future.

Wave-front measurements

In the regime of visible light sensors based on the Hartmann respectively the Shack-Hartmann principle are of common use. Astigmatism, spherical aberration and coma are quantitatively determined. Aberrations of such kind are generally of lower amplitude in the extreme-ultra-violet or soft x-ray domain. For the first time Le Pape et al. used a wave-front sensor in the EUV regime. The experiment took place at a tabletop saturated soft-x-ray laser [1]. Here, the wave-front sensor shall be evaluated for

- FLASH beam line commissioning
- FEL characterisation
- Online diagnostics as part of user experiments

SETUP

Setup of the beam lines

Five beam lines are in operation mode for user experiments. At each an additional optical laser for pump-probe experiments is available. Figure 1 shows a scheme of the FLASH experimental hall. The beam lines discussed in the following are identified by the full-width-half-maximum (fwhm) beam size of their focal spot, considering the theoretical design parameters of the FEL. More than 10 switching or focusing mirrors are in use. Only one beam line can make use of the FEL beam at a time.

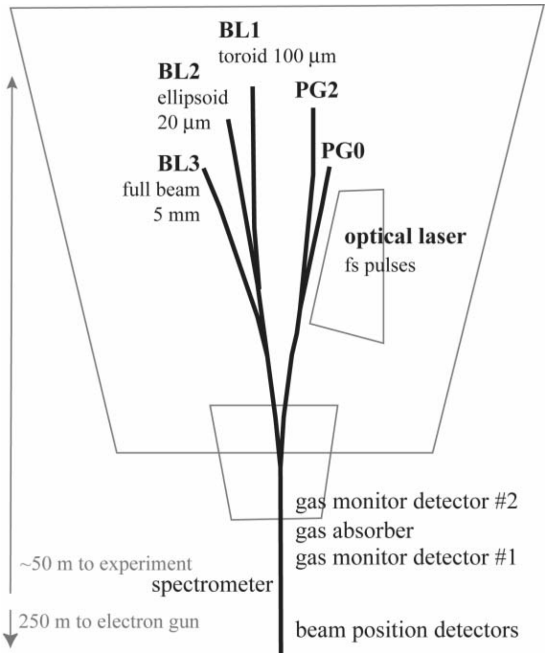

Figure 1: Scheme of the FLASH experimental hall and its beam lines. Some photon diagnostics tools are outlined along the FEL beam.

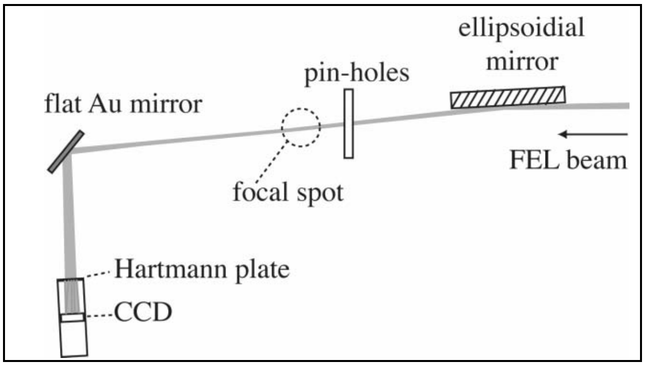

Figure 2: Setup for wave-front measurements at beam line BL2. The sensor is positioned 3.5 m behind the focal spot.

Up to now, the wave-front sensor was used at the beam lines BL1, 2, and 3. All are high intensity beam lines without a monochromator. Whereas at BL3 the unfocused FEL beam can be measured, BL1 and BL2 are designed to a focal spot size of approximately 100 µm and 20 µm, respectively. All switching and focusing mirrors working with an incident angle of 2 or 3 degree and have a carbon coating.

Setup of the wave-front sensor

A perfect spherical wave is compared with the actual beam to analyze its wave front. Therefore, both beams have to pass through a two dimensional array of holes (Hartmann plate) and are recorded under similar conditions on a CCD. Here, the Hartmann plate is made of nickel. It consists of 51 x 51 square holes each 110 µm in size and with a pitch of 387 µm. Therefore, the maximal field of view is 19.5 mm x 19.5 mm. The quadratic holes are tilted by 25° to prevent the long-range diffracted signal coming from one hole to interfere with the spot of the adjacent hole, generating an unpredictable error on data treatment. The sensor includes a direct CCD camera, PI-SX1300, with 1340 x 1300 pixels, each 20 µm in size. It is operated at –40° to minimize the noise level. In general, a zonal reconstruction is used to take as much pixels as possible into account [2]. To distinguish the contributions of higher order aberrations a modal reconstruction algorithm can be used, too. Imagine Optic provides the complete sensor.

Figure 2 is the sketch of a typical setup. The plotted example was build up at beam line BL2. The sensor is positioned in 3.5 m distance from the focal spot, more than the 2 m focal distance of the focusing ellipsoidal mirror. This allows for a full illumination of the sensor. A flat gold mirror placed in 45 degree absorbs 97% of the beam intensity at a wavelength of 32 nm. Currently, mirrors with gold, silver, and aluminium surfaces are used. The different mirrors are required to operate the sensor at different wavelengths and levels of intensity. Otherwise the camera pixels are generally saturated. Pinholes, generating a perfect spherical wave, can be moved in the beam to allow relative measurements. The sensor was calibrated using this setup in the direct beam without the additional mirror. Only than the FEL intensity was sufficient to illuminate the full field of view of the sensor. A pinhole 5 µm in diameter was used.

BEAM LINE COMMISSIONING

The spatial characterization of the wave front has important applications in discovering localized defects in beam line optics. The proposed intensities of FLASH forced the beam line design to work with grazing incidences of 2° to 4° for both switching and focusing mirrors. The FEL wavelength of 60 nm to 13.1 nm in the fundamental demands full vacuum and particle free equipment towards the experiment. The task is to prove the feasibility of the sensor for the use as commissioning tool at FLASH.

Documentation of the focal spot size

Beam line BL2 consists of two flat switching mirrors and one focusing ellipsoidal mirror. The design proposed a spot size of 20 µm at a focal distance of 2 m. Figure 3 shows the depth of focus reconstructed from wave-front measurements in October 05. Displayed are the full-width-half-maximum (fwhm) values of the beam size at distinguished positions relative to the calculated focal point. The focal spot is reconstructed to a fwhm-size of 31 µm x 31 µm, an error of ± 2 µm is given by the Gaussian fit of the reconstructed beam spot. A minor astigmatism can be seen in Figure 3 according the difference in horizontal and vertical minimal focal spot position. With further investigations this problem was imputed to a switching mirror and was eliminated by remounting the mirror.

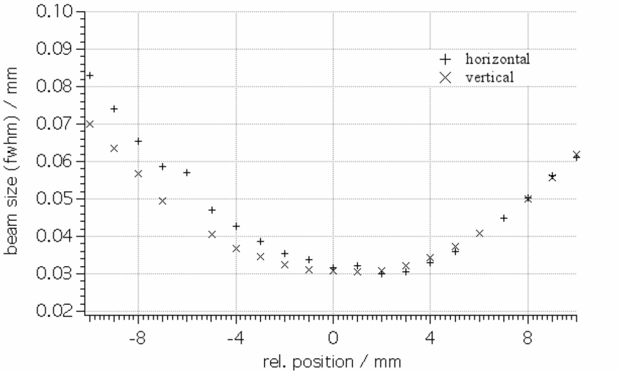

Figure 3: The depth of focus at beam line BL2 at a wavelength of 32 nm. Shown are fwhm values at distinguished distances from the measured focal position in vertical and horizontal direction. The minimal beam size is 31 µm x 31 µm (± 2 µm).

Nevertheless, the overall wave front here displayed in Figure 4 is of high quality. Displayed are absolute values of the difference to a perfect wave for each pixel. So the comparison of variable wavelengths of the FEL is possible. For wave-front analysis the generally used scaling in parts of lambda complicates the comparison and documentation of different measurements. The wave front can be characterized by the root-mean-square error rms=3nm and the peak-valley difference PV=19nm. The wave front used for the calibration of the sensor was measured with rms=0.64nm and PV=4nm. Additional the position of the focal spot is recorded to allow for the shot to shot characteristic of the FEL. In the here shown early phase of the FEL operation an unstable beam correspond to a standard deviation of 4.5 µm in spot size.

The design values for the beam line parameters are not achieved up to now. The wave-front measurements verify that the situation is not origin in a misalignment or in manufacturing errors of the optics. Further measurements at the unfocused beam line BL3 explain the discrepancy by the observation of a large source size, see section FEL Characterization.

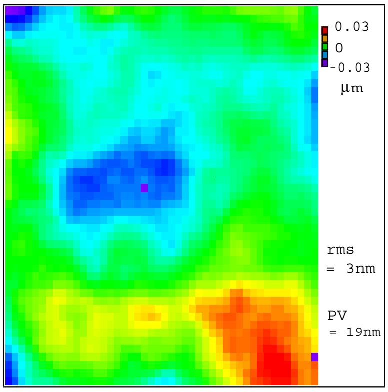

Figure 4: Full field of view (51 x 51 pixels) of a wave front. Displayed are the absolute discrepancies from a perfect wave front. The achieved result is close to the actual resolution limit of the used wave-front sensor.

Mirror alignment

A toroidal mirror with a focal length of 10 m is used at the beam line BL1. The critical alignment of the yaw angle is demonstrated in Figure 5. First the small field of view is obvious. Far from optimal for this kind of measurements it is due to the long focal distance of 10 m that we were forced to position the sensor only 2.55 m behind the focal spot, which leaves the here displayed beam size of ~3 mm. Image (a) shows a strong astigmatism. The overall ellipsoidal beam profile is narrow and tilted. The rms of 395 nm only documented the obvious misalignment. From image (a) to image (b) in Figure 5 the toroidal mirror was moved by 5 mrad in the direction of the yaw angle. A strong change in beam profile and shape took place. The beam profile is more of the true circle of the FEL itself but still tilted. The rms of the distortions is 70 nm, only. The centre of the beam stays at the same pixel position than before. From image (b) to image (c) the mirror was further moved by 5 mrad around the yaw angle. Closer to an optimal alignment the improvement is not as drastic as it had been before. The shape of the beam stays the same and only its diagonal becomes a perfect horizontal line. Therefore the centre of the beam moved by 5 pixels in x and in y direction. The wave front is of rms=50 nm. The detailed analysis of the best image (c) evaluated 73% of the distortions as astigmatism caused by a wrong position in the yaw angle direction, and 12% as coma, due to a minor misalignment in the roll angle orientation. Further alignments are planed in the future after improvements, concerning the field of view and some mirror mechanics, took place. The wave-front measurements proved the need of such upgrades at beam line BL1.

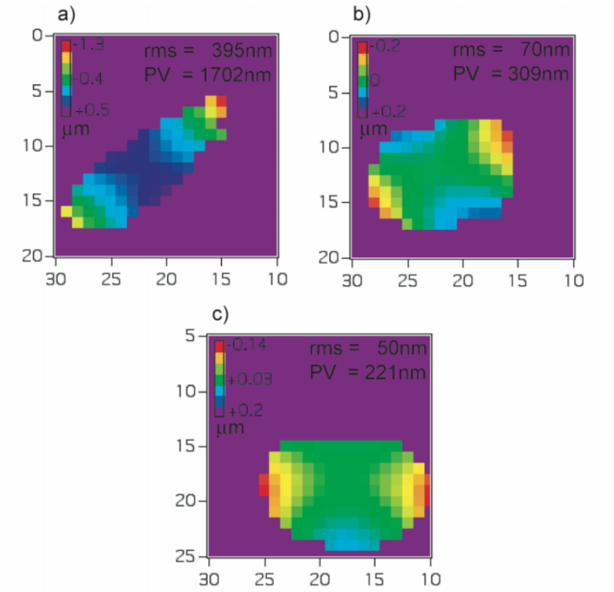

Figure 5: Wave front changes during the optimisation of the toroidal mirror in the direction of the yaw angle at beam line BL1. The scales are different for the images to identify the shape of each wave front. To document the position of the spot the illuminated pixels of the CCD are displayed, bottom and left. Between the images the mirror was tilted in the yaw direction by total 10 mrad.

Long-term documentation

In the last year the FLASH beam performance shown an incredible improvement. Especially the mean beam intensity increases by more than one order of magnitude. The long-term effects to the optical elements need to be observed. The highly sensitive wave-front measurements are excellent to show even slight damages to the carbon coating of the mirrors. No other diagnostic tool can provide us with such information during an operation mode of the FEL.

Filter performance

A FEL beam consists of higher harmonic parts. Less than 1% intensity of the fundamental can contribute in the third harmonic, the most intense higher harmonic. Nevertheless, orders up to the seventh harmonic were measured. The application of filters and filter systems is required to make detailed use of these lower wavelengths or to eliminate any ill effects for some experiments.

The standard used nitrogen gas absorber not influences the FEL wave front. This was checked during a FEL operation with a wavelength of 32 nm. The use of the absorber to a transmission of only 0.1% leaves the FEL wave front unchanged.

More critical is the use of solid filters, metal foils or crystalline membranes. A generally used thickness of such a filter is 200 nm. Up to now, no effect in this regime is recorded. To get a change in wave front an aluminium foil of > 2 µm had to be put in the beam. Even then, the wave front distortions are homogenous and of only 13 nm rms. Therefore, the effect to the optical geometry by creating a second source component is of more consequent for an experiment.

This result eased the wave front measurements itself in the future, as the still complicated reactions on changes in intensity can be countered with additional filters without questioning the achieved results.

FEL CHARACTERIZATION

FLASH is the first working FEL in the EUV and soft x-ray regime [3, 4]. Source size, shape, and position can vary on a shot to shot characteristic. The importance for most beam line optics has been pointed out in the section above. Here the characteristic of the FEL itself and any conclusions considering the machine operation is discussed. The task is to evaluate the resolution of the sensor for the requirements at FLASH.

A good wave front of 4 nm rms was recorded at the end of beam line BL3 with four flat mirrors along the regular beam path. Relative measurements to a beam origin in a 50 µm pinhole in front of these mirrors lead to a portion of 2 nm rms caused by the optics and of 2 nm rms origins in the incident FEL beam. In this regime the measurements are close to the limit of the sensor calibration. Further, the shot to shot variations of the FEL pulses were observed with the same magnitude. To allow an analysis of such a beam we are in need of a better calibration of the sensor.

Similar limits are recorded concerning the source size and distance. In general the realistic value of 82 m distance to the source is reproduced. Nevertheless, the current setup and software can produce errors of some meters for a focal spot in a distance of more than 80 m. This is unacceptable by at least one order of magnitude.

The beam size at the experimental station of BL3 in February 06 was 10 mm fwhm. In a situation of not fully reached the saturation level such a large beam size is not surprising. The standard deviation of the x- and y-position of the beam centre was 1.3 mm and 2.3 mm respectively, translated in an angle of ~24 µrad. These results match the theoretical parameters of a FEL just close to saturation [3].

A qualitative measurement of relevant machine parameter is not resolved with the current wave-front sensor setup. Improvements are foreseen: First an automatic alignment of some equipment parts is planed to minimize the sensor alignment time in respect to the limited beam time available. In this context the diffraction limit of the sensor design λ/120 at 13 nm [5] shall be reached at the FEL, too. Therefore a new and perfect calibration is required. Thinkable is the use of a different Hartmann plate or the development of a new sensor specialized for the different and progressed circumstances at a FEL facility like FLASH.

ONLINE IMPLEMENTATION

In contrast to other diagnostic tools the here-introduced sensor measured the wave front in a distance of some meters behind the focal spot. A use as online diagnostic is possible when the direct beam path is not blocked by the experiment itself, e.g. most experiments operating in the gas phase. Even if a target block the beam a verification of the FEL performance in between some measurements is useful.

Main problems are the intensity and geometric circumstances, which will be dictated by the experiment itself and not by the wave-front measurements anymore. As critical as these adaptations have been so far it is a challenge to provide a setup with even more flexibility.

CONCLUSION

The here reported measurements proved the feasibility of wave front observations under FEL conditions. The high sensitivity of the wave-front sensor is required for the high beam quality at FLASH. First order aberrations were recorded during first beam line commissioning. The ongoing improvement of the FLASH beam quality in stability, source size, and intensity as well as optimized optics alignment was documented during the last year. The non-invasive and remote sensor can be used as online tool to document the shot to shot characteristics of the FEL.

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