Spatial characterization of the focus produced by an EUV Schwarzschild objective

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Abstract. Schwarzschild objectives are used in the EUV spectral range because of their large aperture, high mechanical stability and excellent achromaticity. The large aperture results in a small, theoretically diffraction limited focus diameter with ideal values of below 200 nm with the current configuration. We employed a zone plate with matched numerical aperture (0.19) to image the focus onto an X-ray CCD camera. Emission from high harmonic generation and a liquid-jet laser-plasma were used as light sources. Images at magnifications of about 150-fold were acquired and focus diameters of 300 nm (FWHM) were observed.

1. Introduction
To examine non-linear interaction of electromagnetic radiation with matter at short wavelengths, focused beams from free-electron lasers (FELs) can reach the required peak irradiance levels where effects like multiphoton ionization takes place [1]. Methods to analyze spot-sizes of higher-harmonic generation (HHG) sources with a spatial resolution of 1 - 2 µm via knife-edge and fluorescence screen have been presented before [2, 3]. To characterize the ability of the objective to focus EUV radiation using the specified wavelength of 13.5 nm, raytracings and focusing experiments were conducted. After using a He-Ne laser to establish an alignment strategy, experiments using the emission from high harmonic generation were conducted due to the similar beam geometry compared to a free electron laser. In order to examine the focus profile with a high spatial resolution, an imaging method using a zoneplate as second optic was chosen. By imaging the focus of the Schwarzschild objective with a zoneplate optic on a CCD, one can avoid using, potentially more complex, indirect methods like scanning suitable

Figure 1. Dimensions and raytracing of a parallel beam through the objective.
resolution targets. The practical use of spatial characterization of EUV laser-plasma sources with zoneplates has been shown before [4]. In the case of a strongly demagnified source using the Schwarzschild objective, the requirements on the spatial resolution of the setup increase.

2. Objective properties and setup

The experimental setup is shown in Figure 2. It consists of the objective mounted on a motorized stage. The zoneplate is mounted on an encoded two-axis piezo scanner to achieve the necessary precision for the lateral positioning. Both optics can be moved in the z-direction to focus the imaged spot on the CCD camera. The same experimental setup was used at a liquid jet laser-plasma source at the Institute for X-Optics in Remagen, Germany [5].

![Figure 2. Experimental setup and geometry used to image the focal spot](image1)

![Figure 3. Principal setup to image an X-ray focus on a CCD with a zoneplate](image2)

The different components of the setup were mounted in multi-purpose vacuum chambers with piezo driven three-axis positioners. Due to the weight of the Schwarzschild objective, a separate mount allowing six degrees of freedom was developed and manufactured. The focused beam results in a spot and its magnified image is recorded with an X-ray CCD camera. This arrangement is shown in Figure 3. The Schwarzschild objective has an effective focal length of 27 mm, which results in a distance of 42 mm between the last surface of the objective and the focal plane. The focal length of the zoneplate at the wavelength of 13.5 nm is 400 µm. As shown in Figure 2 the short distances involved allow for a very compact setup.

3. Experimental Results

Using the results from the raytraces shown in Figure 1, an alignment strategy using a He-Ne laser was developed. By aligning the concentric images from the different reflection orders, the mirrors of the objective could be correctly positioned relative to each other. After that, only minimal adjustments with the motorized mirror holders were necessary during the actual in-vacuum experiment. The procedure to focus the imaged spot on the X-ray CCD camera is shown in

![Figure 4. Montage of images taken during the process of finding the optimal position of the zoneplate to the objective in order to focus the image on the CCD](image3)
Figure 4. By changing the distance of the zoneplate relative to the spot and camera, the hollow cone of the beam close to the focal spot could be observed. Due to the high numerical aperture of the optics (NA = 0.19), even small lateral movements of the zoneplate could remove the image from the detector field of view. As a result only a small magnification of 150 was chosen, which led to an effective pixel size of 86 nm. Images were taken at a high harmonic generation and a laser induced laser-plasma source. Due to the optimized layout of the objective for the use at FLASH, small focus sizes could only be achieved with the high harmonic generation source with its similar, parallel beam geometry. One resulting image of the focused beam is shown in Figure 5.

4. Discussion
In experiments at laboratory soft X-ray sources, minimal imaged spot diameters of 300 nm were observed. The imaged spot is surrounded by a plateau of about 4 μm diameter as can be seen in Figure 5. If this is an effect of an distorted incoming wavefront or due to the imaging system is not clear. Due to the scheduled experiments at FLASH (DESY), procedures were evaluated and tested to prealign the objective relative to the vacuum chamber with a pilot laser. This should minimize the amount of beamtime needed to align the system. As a next step, additional to the direct imaging of the spot size with a zoneplate, an ion microscope will be combined with the current setup. The charge states of Xe ions in the focus of the objective are related to the intensity in this area and can be resolved spatially with the ion microscope setup [6]. Both results combined will help to calculate the actual number of photons in the focus area contributing to experiments using the Schwarzschild objective.

References
[1] R Guichard, M Richter, JM Rost, U Saalmann, AA Sorokin, and K Tiedtke. Multiple ionization of neon by soft x-rays at ultrahigh intensity. arXiv preprint arXiv:1302.0021, 2013.
[2] L Le Déroff, P Salieres, and B Carré. Beam-quality measurement of a focused high-order harmonic beam. Optics letters, 23(19):1544–1546, 1998.
[3] H Mashiko, A Suda, and K Midorikawa. Focusing multiple high-order harmonics in the extreme-ultraviolet and soft-x-ray regions by a platinum-coated ellipsoidal mirror. Applied optics, 45(3):573–577, 2006.
[4] U Vogt, M Lindblom, P Charalambous, B Kaulich, and T Wilhein. Condenser for Koehler-like illumination in transmission x-ray microscopes at undulator sources. Optics letters, 31(10):1465–1467, 2006.
[5] L Henning. Charakterisierung der Spotgröße eines Schwarzschild Objektivs im EUV Bereich. diploma thesis, HS Koblenz, 2013.
[6] Marek Wieland, Thomas Gebert, Dimitrios Rompotis, Ulrike Fröhling, Johannes Ewald, Thomas Nisius, Thomas Wilhein, Elke Plönjes, and Markus Drescher. Following non-linear x-ray physics in the time-domain proposal f-20110346/progress report 2012.