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Off-axis reflection zone plate for quantitative soft x-ray source characterization

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A compact system for high-resolution spectroscopy and quantitative photon flux and brilliance measurements of pulsed soft x-ray sources is described. The calibrated system combines a novel elliptical off-axis reflection zone plate with charge-coupled device detection for simultaneous spectral and spatial measurements. Experiments on a water-window droplet-target laser-plasma source demonstrate $\lambda/\Delta\lambda \approx 1000$ spectral resolution and absolute flux and brilliance measurements.

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nally, a 10 nm Ni layer is evaporated onto the Ge, giving a higher reflectivity for the wavelength region $\lambda = 1.5$–5 nm.

For quantitative measurements, the optical components and the detector have to be calibrated. The diffraction efficiency of the ORZ was measured at the x-ray microscopy beamline at the Berlin electron storage ring (BESSY). The solid line in Fig. 2 shows the $-1$ order diffraction efficiency of the ORZ as a function of wavelength. The maximum efficiency is $0.06$ at $\lambda = 2.2$ nm. The low efficiency at short wavelengths is due to the Ni $L_{\text{III}}$ absorption edge at $\lambda = 1.45$ nm. Consequently, ORZs designed for $\lambda < 1.6$ nm should be coated with a different material. The decreasing efficiency for $\lambda > 2.2$ nm is probably due to destructive phase effects, but not fully understood yet. The calibration of the thinned, back illuminated CCD (Photometrics AT200L with Tektronix TK1024AB) was performed at the PTB (Physikalisch Technische Bundesanstalt) radiometry beamline at BESSY. The dashed line in Fig. 2 shows the fairly uniform quantum efficiency of the CCD, which was measured down to $\lambda = 1.55$ nm and extrapolated to $\lambda = 1.1$ nm (dotted).

The spectrograph consists of two vacuum chambers, containing the ORZ and the CCD, which are connected with vacuum tubes and adapted to the source chamber. In front of the ORZ a 200 nm freestanding Al foil is placed to remove scattered visible light from the plasma and a shutter to control the exposure time. To record a larger spectral range than that of a single CCD image, the ORZ is rotated so that the total deflection angle is kept constant.

The performance of the spectrograph was tested on the liquid-droplet-target laser-plasma source. In this regenerative and practically debris-free source, x-ray emission is generated by focusing $\sim 70$ mJ, $\sim 100$ ps, 10 Hz frequency-doubled Nd:YAG laser (Continuum PY61C) pulses onto single $\sim 15$ $\mu$m droplets. For the test measurements concentrated ammonium hydroxide was used as target liquid, resulting in strong N VII and N VI emission at $\lambda = 2.478$ and 2.879 nm. A 3 mJ ultraviolet prepulse was employed for enhanced x-ray emission. The source size was determined to be $\sim 30$ $\mu$m full width half maximum (FWHM), which was confirmed by a separate pinhole camera measurement. Figure 3 shows the measured pulse brilliance in the 1.5–3.0 nm wavelength range. The exposure time varies for the different spectral regions from 1 to 10 s. The calibrated spectrum is dominated by line emission from highly ionized oxygen and nitrogen. For $\lambda < 2$ nm, the oxygen lines are superimposed on a significant continuous background. In contrast, the $1s^2-1s2p$ N VI line at $\lambda = 2.879$ nm is isolated except for the small satellites at $\lambda = 2.95$ nm, with a background intensity of less then 0.4% of the peak intensity within 0.1 nm spectral distance from the line. The low background may be measured due to the high dynamic range of the CCD. When employing the source for x-ray microscopy using zone plates it is important to minimize the background in order to reduce image noise.

Integrating the pulse brilliance over linewidth and source size results in the total photon flux per line. For the $\lambda = 2.879$ nm N VI line this number is $3.2 \times 10^{11}$ photons/(sr×pulse). The accuracy of this value is estimated to be better than 50%, where the major source of uncertainty is in the calibration of the spectrograph. The reported photon flux is approximately a factor of 3 below previous measurements with filters and x-ray diodes. In addition to the 50% uncertainties, the difference may be explained by the influence on the diode measurements by the significant and previously unknown continuum background below $\lambda = 2$ nm.

In the above experiments, the spectral resolution is prob-
ably limited by the source size due to the absence of an entrance slit. The spectral resolution of the spectrograph was therefore investigated by applying only the 3 mJ prepulse to the droplets, resulting in a source diameter of less than 10 μm. Figure 4 shows a fraction of the spectrum with the N VII 1s - 2p (λ = 2.478 nm) and N VI 1s^2 - 1s3p (λ = 2.490 nm) lines. Due to different plasma parameters resulting from the use of only the UV prepulse, the peak intensity of the two lines is now equal. Under these conditions, the linewidth of the N VII 1s - 2p line was determined to be 0.0024 nm, corresponding to λ/Δλ ≈ 1030. Up to now it is not possible to decide whether this value is limited by the actual linewidth or the performance of the spectrograph.

To estimate the influence of deviations from the design geometry, e.g., finite source size, alignment errors, or defocusing, a ray tracing program has been developed. It shows, e.g., that for the current ORZ a source diameter of ~40 μm restricts the resolving power to λ/Δλ ≈ 500. Thus, for large sources an entrance slit will be added to the optical arrangement. The ray tracing also demonstrates that in order to avoid coma the source needs to be positioned onto the optical axis within ~0.05°. This is accomplished in the present arrangement by rotating the ORZ with a stepper motor.

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