



Experimental verification of soft X-ray imaging and RIXS mapping with a reflection zone plate

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Abstract: We demonstrate two-dimensional (2-D) imaging and resonant inelastic X-ray scattering (RIXS) spectroscopy in the $h\nu^2$ “mapping” scheme using a reflection zone plate (RZP) at soft X-rays. Experiments at the PETRA III storage ring (DESY) around the N K_α line (392.4 eV) verify that an RZP can be used in the paraxial regime combined with the 1-D line scanning mode for time-efficient full-field imaging of an extended object with an angular size of 2.5 mrad at low aberrations, even for off-design energies, at a spatial resolution of (14–24) μm . A similar setup collects the RIXS spectra of acetonitrile within (388.6–401.8) eV for a variable incident photon energy between 399 eV and 400 eV, at a potential resolution of (0.3 ± 0.1) eV. RZPs with their precise manufacturability, efficiency, and strong dispersion can serve as advantageous diffractive optical elements in soft X-ray microscopy or “photon-in vs. photon-out” spectroscopy.

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1. Introduction

Spectroscopy and imaging are cornerstone techniques for interrogating matter across complementary dimensions. Spectroscopy provides direct access to the electronic structure, revealing energy levels, chemical bonding, charge transfer, and excited state dynamics, while imaging resolves the spatial arrangement of atoms and nanostructures, capturing morphology, heterogeneity, and structural evolution. Together, they form an indispensable toolkit in modern research, enabling correlations between structure and function that are essential for understanding and controlling complex materials, chemical reactions, and biological systems. Resonant inelastic X-ray scattering (RIXS) has evolved into an indispensable spectroscopic tool to elucidate the electronic structure of matter [1]. RIXS provides a uniquely detailed and symmetry-sensitive view of low-energy excitations, including charge transfer [2–5], crystal field (dd) [5], orbital [6], magnetic [7,8], and lattice-coupled dynamics [3,6,9].

As the name implies, the technique is sensitive to the excitation energy $E_{in} = h\nu_{in}$, such that its variation allows recording a series of independent emission spectra at $E_{out} = h\nu_{out}$ [10]. For that RIXS “mapping” of E_{out} vs. E_{in} on a 2-D detector – therefore also known as “ $h\nu^2$ ” [11], several

instrumental arrangements with diffractive optical elements and mirrors have been developed and applied, taking advantage of the non-dispersive direction of the grating for simultaneous, fast data acquisition [11–13]. However, these specialized instrumental setups require significant financial investment and incorporate multiple optical elements, making alignment and optimization time-consuming.

Imaging is an essential complement to spectroscopy because it provides direct, real-space information on matter, including morphology, heterogeneity, and interfaces – features that often control functionality but are hidden in ensemble-averaged signals. Consequently, X-ray imaging and microscopy have enabled significant advances in energy materials, catalysts, and complex soft matter by revealing where key structures form and how they evolve under in situ / operando conditions [14–18]. Combining spectroscopy with imaging would merge both modalities into a single experiment, enabling concurrent measurement of electronic-structure and real-space information. The first experimental demonstration of this concept utilized transmission zone plates (TZPs) [19,20]. Off-axis segments of TZPs provide this additional degree of freedom to apply a range of input energies E_{in} along their transverse dimension, while the signal E_{out} is observed along the grating vector [19–21]: the authors studied a dilute sample [22,23] in a liquid jet at a dedicated beamline station [24,25]. Alternatively, one-dimensional (1-D) imaging spectroscopy at a certain energy E_{in} can be performed [20,26], both techniques can be combined [27], and even 2-D “time-to-space mapping” [28] in pump-probe studies has been demonstrated with TZPs.

Around 10 years ago, RZPs were established as efficient tools for “photon-hungry” RIXS spectroscopy at fixed energy E_{in} [29] and, in a different context, also for narrow-field imaging [30], though they violate the Abbe sine condition. Recently, we simulated spectromicroscopy with an RZP in the “1-D line scanning mode” [31]. The moving sample is imaged as a sequence of narrow stripes in the paraxial regime, and computational stitching reconstructs the full object at low aberrations. This paper presents results of experiments in which the RZP is used in this way for wide-field imaging at distinct energies, as well as to record a $h\nu^2$ [11] map of RIXS spectra from a liquid jet sample [20]. Section 2 details the RZP and the setup, followed by measurement and simulation results for imaging in Section 3 and $h\nu^2$ mapping in Section 4. We conclude with a discussion and an outlook in Section 5.

2. Reflection zone plate

We used a super-polished, planar Si substrate of $(100 \times 30 \times 10) \text{ mm}^3$ with a maximal slope error of $\pm 0.2 \text{ arcsec}$ (rms) in tangential and $\pm 0.6 \text{ arcsec}$ (rms) in sagittal direction. The micro roughness is specified by the manufacturer (Helmholtz-Zentrum Berlin) to be no more than $\pm 0.3 \text{ nm}$ (rms), using white light interferometry. An RZP is defined as the projection of a TZP on the inclined substrate, and the pattern of elliptical Fresnel zones at a 2-D line density distribution enables simultaneous focusing and dispersion of X-rays, emitted by a point-like source [29–31]. An off-axis segment of the RZP with an aperture of $\approx 40 \times 8 \text{ mm}^2$ (length $L \times$ width W) separates the specular reflection in 0th order from the (+1)st diffraction order of the photon energy E_0 , for which the device is designed. In Table 1 and Fig. 1, R'_i with $i \in \{1, 2\}$ denotes the distance from the RZP to the source and detector, respectively, and the corresponding incidence and exit angles are labeled by (α_0, β_0) . Shifted by a certain amount X_0 from the optical origin [31], the RZP segment works as a curved variable line space grating with a nonlinear, on-axis groove density $d_l(x) = d_l(X_0) + \partial_x d_l(X_0) \cdot (x - X_0) + \frac{1}{2} \partial_x^2 d_l(X_0) \cdot (x - X_0)^2 + \dots$. In this series expansion, $\partial_x d_l(X_0)$ specifies the gradient along x at the central position X_0 , which – together with higher derivatives $\partial_x^2 d_l(X_0)$ etc. – determines the focusing properties. From the detector’s point of view, the meridional spatial frequency $d_l(X_0)$ in Table 1 corresponds to a mean projected grating period of 63 nm, which is comparable to the pattern size of the TZP used in a previous experiment [20] and is beneficial for the strong angular dispersion of our reflective device.

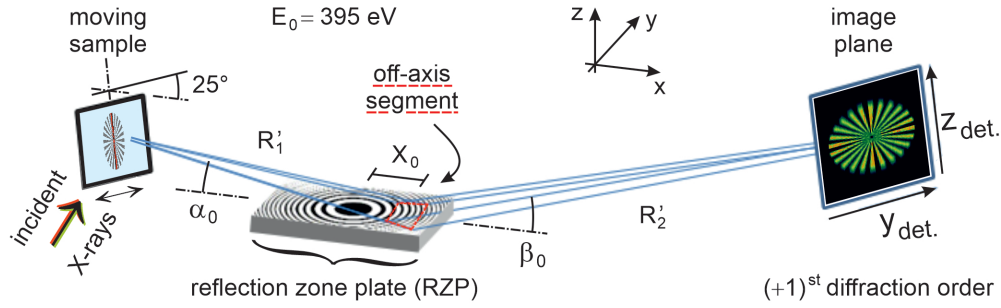


Fig. 1. Schematic of the imaging setup with the off-axis RZP, optimized for the design energy E_0 . The nearly monochromatic line source (red stripe) on the sample is focused incoherently on the CCD camera, and the sample is moved stepwise along the horizontal double arrow. R'_1 and R'_2 are entrance and exit arm lengths, respectively, corresponding to the grazing angles α_0 and β_0 . The sketch is not to scale. Note that the setup with the coordinates as displayed is rotated by 90° in the actual laboratory system at DESY. Adapted with permission from [20,31].

Table 1. RZP design energy E_0 , arm lengths R'_1 and R'_2 , grazing angles (α_0, β_0) , off-axis distance X_0 , and the central line density $d_l(X_0)$ with its derivative $\partial_x d_l(X_0)$. All symbols follow the nomenclature used in Fig. 1 and describe the zone plate uniquely.

E_0	R'_1	R'_2	α_0	β_0	X_0	$d_l(X_0)$	$\partial_x d_l(X_0)$
395 eV	200 mm	1000 mm	2.00°	6.35°	129.02 mm	1761 mm^{-1}	5.837 mm^{-2}

The structure was written by electron beam lithography. Its laminar profile, made with an etch depth of 9 nm and a land-to-groove ratio of 35 : 65, is coated with Ni (30 nm) and a native NiO layer of 2 nm. The diffraction efficiency $P_{+1}(E_0)$ is evaluated using the rigorous coupled wave approach (RCWA) to $(12.9 \pm 1.1)\%$ across the beam footprint in the central grating region, as specified below. For the $h\nu^2$ experiment (Sect. 4), the RZP will operate between 388.6 eV and 401.8 eV. Within that range, the efficiency is nearly fixed at $(12.9 \pm 0.1)\%$. Hence, we take $P_{+1}(\vec{r}, E)$ as uniform and constant.

The image generated by such single-bounce reflective optics, violating the sine condition [31], typically suffers from severe aberrations for extended objects: a source point, laterally displaced by 0.2 mm, could be spread and distorted to a blur of $\lesssim 0.5$ mm in diameter. However, the beam cross-section on the RZP can be controlled by an adjustable 2-D slit. We select an acceptance $\Delta\vartheta_{H,V} \approx 4 \times 4 \text{ mrad}^2$, or an active area of $\approx 23 \times 0.8 \text{ mm}^2$ ($L \times W$), at which the system operates in the paraxial regime (Fig. 1). Together with the line scanning technique [31], this choice allows wide-angle imaging even at off-design energies (Sect. 3) and off-axis spectroscopy (Sect. 4).

3. Monochromatic imaging

The first experiment explored the ability of an RZP to image an extended object: For the solid test sample, 250 nm of Si_3N_4 was deposited on a Si wafer, followed by a 20 nm Au layer. The etched Au structures comprise Siemens stars with a diameter of $500 \mu\text{m}$, and the lettering “RIXS” at a height of $250 \mu\text{m}$.

The soft X-ray beamline P04 [24] within PETRA III, DESY (Hamburg) provides a source brilliance of $10^{20} \text{ ph/s/mm}^2/\text{mrad}^2/0.1\% \text{ bw}/100 \text{ mA}$. Low wavefront errors, though not essential for incoherent scattering as investigated in our experiment, are ensured by the small slope error ($\pm 0.1 \text{ arcsec}$) of the optical elements. We utilized the ChemRIXS end station [25]. In the vacuum chamber, the X-ray beam is oriented perpendicular to the optical line [sample – grating – detector]. Hence, as sketched in Fig. 1, the sample surface is inclined by 25° to

the x -axis in a convenient arrangement for precise and efficient illumination. Obviously, this mounting also “compresses” the apparent width (y) to 42 % of its physical size while the source depth is enlarged in proportion. However, the axial (x) source elongation is negligible for an entrance arm of 200 mm (Table 1) with its depth of field (DoF) around ~ 1 mm [31]: By adjusting the exit slit of the beamline, we create a line focus of $\approx (10 \times 1000) \mu\text{m}^2$ ($H \times V$) with an approximately rectangular intensity profile in the $x - z$ plane at the position of the Siemens star, nearly monochromatic at a bandwidth of $\pm 10^{-2}$ eV around the selected energy E_{in} [24]. For these settings, a flux of $\gtrsim 10^{11}$ photons/s is available [24].

The object information is recorded sequentially in the “1-D line scanning mode” [31] at a constant photon energy: The sample is moved perpendicular to the long side of the focus (double arrow in Fig. 1) in the inclined plane (blue square in Fig. 1), while RZP (Sect. 2) and camera (ANDOR iKon-M 934, 1024×1024 pixels at $13 \mu\text{m}$) are fixed. In this way, the surface of the 2-D object can be scanned in 99 steps, each with an exposure time of ~ 10 s and with an increment of $14.6 \mu\text{m}$. The slightly larger step size compared to the beamline focus width of $\approx 11 \mu\text{m}$ on the inclined object (“undersampling” for time-saving data acquisition) can be accepted, given that the expected spatial resolution is limited by aberrations:

To estimate the imaging properties and the achievable spatial resolution in the object plane, we simulate the point spread function (PSF) along the beamline focus on the sample ($y = 0$ in Fig. 1) at 392 eV. Figure 2 displays the correspondence between the sample and the detector plane. Our Monte-Carlo approach approximates the experimental conditions. The horizontal ($\Delta\tilde{y}_s$) and vertical ($\Delta\tilde{z}_s$) resolution (FWHM) in the inclined ($\zeta = 25^\circ$) object plane is determined by the geometrical PSF ($\Delta y_g, \Delta z_g$) and the diffraction limit $\Delta y_d = 1 \mu\text{m} = \Delta z_d$ for the paraxial beam with the solid angle $\Delta\vartheta_{H,V}$ (Sect. 2). Using the magnification $M_y = 5.00$ and $M_z = 1.58$,

$$\Delta\tilde{y}_s = [M_y \sin(\zeta)]^{-1} \sqrt{\Delta y_g^2 + \Delta y_d^2} \quad \text{and} \quad \Delta\tilde{z}_s = [M_z]^{-1} \sqrt{\Delta z_g^2 + \Delta z_d^2}. \quad (1)$$

The results indicate an object resolution which is mainly determined by the photon energy and the vertical position of the source emission $|z| \leq 0.25$ mm: The Siemens star can be resolved to $18 \times 8 \mu\text{m}^2$ ($H \times V$) near its center, whereas the vertical resolution (V) degrades from a few to several $10 \mu\text{m}$ in the outer, i.e., upper and lower regions of the test pattern. The finite width of the beamline focus ($10 \mu\text{m}$) has only a minor effect on performance: as seen from the RZP, the source emission from the inclined sample is confined to $\approx 4.7 \mu\text{m}$ in the y -direction (FWHM), slightly increasing the effective sample resolution in the transverse direction (H) by $\approx 3 \mu\text{m}$.

For image reconstruction, a custom MATLAB™ routine extracted a narrow stripe of 9×621 pixels ($H \times V$), which contains the relevant information, from each of the 99 sequentially recorded CCD frames (1024×1024). Apparent intensity discontinuities after their computational stitching without overlap are finally smoothed to some degree by averaging the 9 pixel entries from each row within one stripe. Nevertheless, residual striping artifacts in the reconstructed images, still visible after stitching as spiky or blurred edges of some spokes, can be ascribed to that “binning.”

The described procedure records an image of circular objects (e.g., the stars) 27 times faster than in a conventional 2-D scan with a spot of $\approx (11 \times 11) \mu\text{m}^2$ at the same sampling frequency [31]. As expected from the anisotropic magnification of 5.00 (H) $\times$ 1.58 (V), the inclined (25°) Siemens stars and “RIXS” characters will be displayed at an aspect ratio $M_z/M_y \sin(\zeta) = 75\%$.

First, the set of objects is excited at $E_{in} \approx 400$ eV and the relatively intense signal is observed at $E_{out} = 392$ eV, near the resonant inelastic N K_α emission (392.4 eV) from the etched region, i.e. blank Si_3N_4 , with a contrast of $\approx 80\%$ between the brightest and darkest regions of the image, as depicted in Fig. 3(a). Compared to an image taken at the design energy $E_0 = 395$ eV, Siemens stars and “RIXS” lettering are shifted upward from the center by 29 pixels on the CCD. The beamline monochromator is then switched to $E_{in} = 392$ eV, while the RZP spectrometer still records at $E_{out} = 392$ eV. Clear Siemens stars and the “RIXS” lettering are partially imaged by

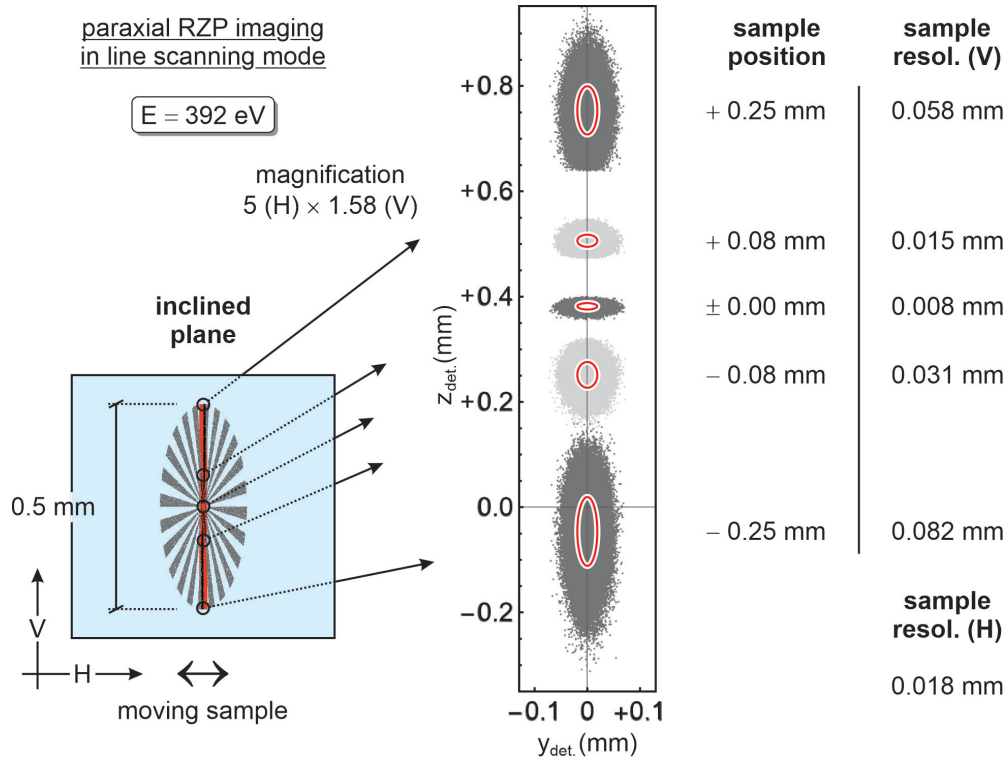


Fig. 2. On-axis PSF for the “paraxial RZP imaging in the line scanning mode” at 392 eV. The point source is placed at various positions ($y = 0, -0.25 \text{ mm} \leq z \leq +0.25 \text{ mm}$), i.e., within the vertical line focus of the beamline (red stripe on the Siemens star). Chromatic ($E \neq E_0$) and off-axis (source at $z \neq 0$) geometrical aberrations blur the focal spots (light / dark gray). Red ellipses on the footprints (RAY-UI) mark the FWHM. The object resolution, which is constant in horizontal (H) direction but dependent on the vertical (V) position within the Siemens star, includes diffraction at the RZP aperture.

elastic scattering from Au in Fig. 3(b), albeit with a reduced quantum yield. Consequently, the general contrast of $\approx 40 \%$ is reversed compared to Fig. 3(a).

From both excitations, the spatial resolution in the object plane is estimated via the visibility $V(r)$ of the spokes along an elliptical path around the center of each star, with the long semi-major axis $r \leq 0.25 \text{ mm}$. A reliable definition, suitable for a consistent and fast evaluation of the variable and irregular signal, normalizes the standard deviation σ by the angular (360°) mean $\langle I \rangle$ of the intensity, such that $V = \sigma / \langle I \rangle$. For the two examples in the elastic case (Fig. 3(b)), the fit

$$V(r) = V_0 \sqrt{1 + \xi_\infty \cdot r^2} \quad \text{with} \quad V_0 = (4.6 \pm 0.3) \% \quad \text{and} \quad \xi_\infty = (5.7 \pm 1.7) \times 10^3 \text{ mm}^{-2} \quad (2)$$

reveals a mean resolution of $(16 \pm 3) \mu\text{m}$, corresponding to a minimum visibility $V \geq 20 \%$. In the inelastic case (Fig. 3(a)), we omit the blurry star with 16 spokes. For the version with 8 spokes, the 20 % criterion, applied to the same fit model, indicates a resolution of $24 \mu\text{m}$. These results are qualitatively in agreement with expectations from the simulated PSF in Fig. 2.

In comparison, simulations are performed, adapting the recently developed code [31] to a flat substrate and the off-design photon energy: For a spatial resolution of $25 \mu\text{m}$ on the camera due to “split events,” object patterns on a length scale of $\approx 14 \mu\text{m}$ could be distinguished at 392 eV in theory, while $\approx 11 \mu\text{m}$ are still visible on the $V = 20 \%$ level at 395 eV. At this design energy,

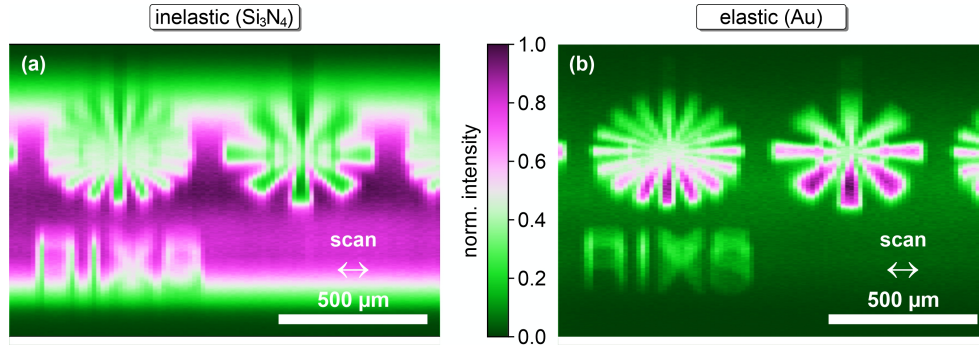


Fig. 3. Reconstructed images of geometric figures for the inelastic signal from Si_3N_4 (a) and elastic scattering from Au (b), both recorded at $E_{\text{out}} = 392$ eV and at a pixel size of $13 \mu\text{m}$. Two Siemens star samples and the “RIXS” lettering are recognizable. See [Visualization 1](#) for the analysis of the visibility and [Visualization 2](#) for two simulations.

fine structures down to $\approx 7 \mu\text{m}$ might even be resolved if the (low noise) CCD image can be further de-convolved from the electronic blur back to the physical pixel size of $13 \mu\text{m}$ [31].

4. RIXS mapping

The setup described in Section 3 was modified by replacing the solid sample with a liquid jet of $\approx 20 \mu\text{m}$ in diameter, oriented along the y direction in Fig. 4 and at 90° to the optical axis. Acetonitrile ($\text{H}_3\text{C} - \text{C} \equiv \text{N}$) was dissolved 1 : 1 in ethanol [22,23,25]. Laminar flow at 1 ml/min is possible on a length of a few mm [25], along which the liquid jet is probed: the line focus of $\approx (1000 \times 10) \mu\text{m}^2$ ($H \times V$) carried a spectrum of linearly dispersed photon energies E_{in} in the range $(398.2 - 400.6)$ eV, provided by the beamline grating [24]. Figure 4 illustrates this mapping scheme, where both dispersive (z) and non-dispersive (y) directions of the RZP are used to record spectra of E_{out} . Within the liquid jet, the “rainbow” is described as a linear relation $E_{\text{in}}(y) = [2.4 \text{ mm}^{-1} \cdot y + 399.4] \text{ eV}$.

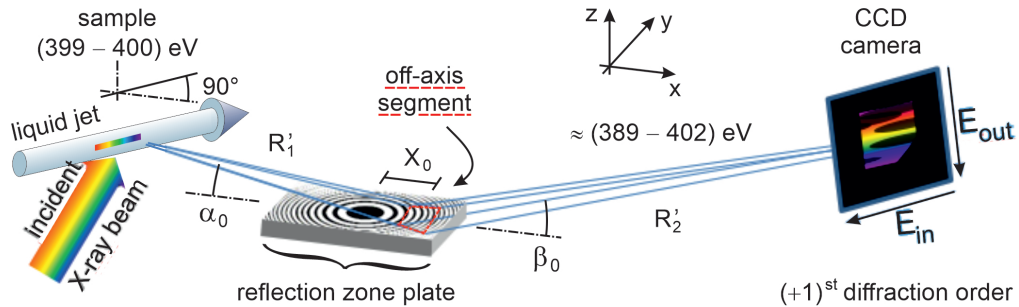


Fig. 4. 2-D RIXS spectroscopy using a “rainbow” of incident energies E_{in} along the line focus on a transverse (y) liquid jet of $20 \mu\text{m}$ in diameter, containing the dilute sample. Emitted X-rays are diffracted at their energy E_{out} between about 389 eV and 402 eV in the dispersive (z) direction of the RZP. Like in Section 3, the liquid jet runs from top to bottom in the “real world,” and the whole spectrometer rotates. Adapted with permission from [20,31].

Along $-0.17 \text{ mm} \leq y \leq +0.25 \text{ mm}$, we simulate (RAY-UI) a sequence of 11 equidistant point-like sources of $(42 \times 10) \mu\text{m}^2$ ($H \times V$), each emitting a test spectrum of three photon energies $(395.2 \pm 6.6) \text{ eV}$. Due to the lens-like imaging properties of the RZP, the focal spots appear in

the detector plane on the opposite side of the $x - z$ plane. On the optical axis ($E_{in} = 399.4$ eV) and near the central energy $E_{out} = 395.2$ eV $\approx E_0$, the spectrum is of the highest quality. Off-axis aberrations for $E_{in} \neq 399.4$ eV at $y \neq 0$ and for E_{out} far from the design energy $E_0 = 395$ eV distort the focal points to some extent, as visualized in Fig. 5. Assuming an effective pixel size of $25 \mu\text{m}$ again, the mean resolution ΔE_{out} within the recorded energy range (388.6 – 401.8) eV varies between 0.24 eV around 399.4 eV, i.e. near the axis, and (0.37 – 0.50) eV at the edges of the interval $399 \text{ eV} \leq E_{in} \leq 400$ eV. On the E_{out} scale as shown in Fig. 6, the two spectral regions covering the inelastic peaks around 392.5 eV and the vibrational / elastic group around 399.1 eV are resolved to $0.20 \text{ eV} \lesssim \Delta E_{out} \lesssim 0.39 \text{ eV}$, depending on the excitation E_{in} . These values are comparable to those reported in a similar study of acetonitrile [23], where “the overall energy resolution of the RIXS measurements was better than 0.4 eV.”

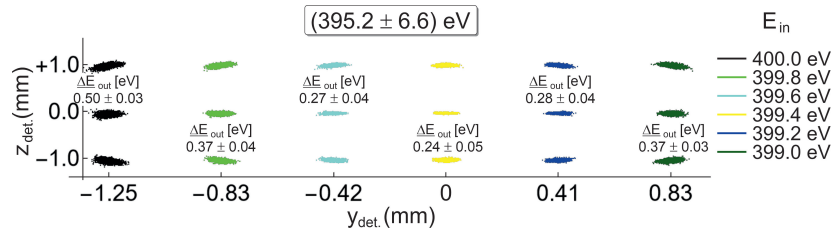


Fig. 5. Simulated spectra of three energies $E_{out} = (395.2 \pm 6.6) \text{ eV}$ for selected excitation energies $E_{in}(y)$ at transverse source displacements y (see text). The resolution ΔE_{out} [eV] for each E_{in} is estimated with its standard deviation ($\pm$) around the mean in $388.6 \text{ eV} \leq E_{out} \leq 401.8 \text{ eV}$. At $E_{in}(0) = 399.4$ eV, we get $\Delta E = (0.24 \pm 0.05) \text{ eV}$. See Visualization 3 for a statistical evaluation of the resolution at variable E_{in} and E_{out} .

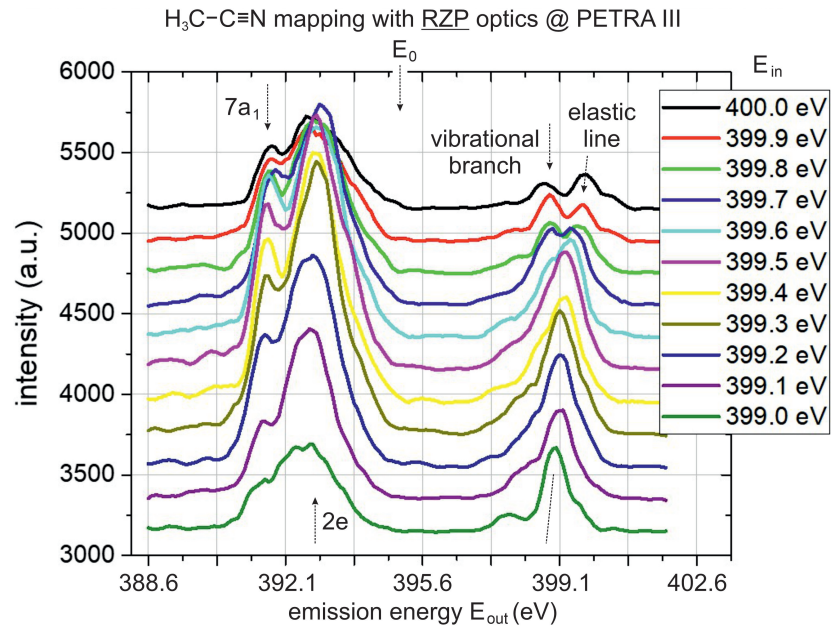


Fig. 6. X-ray emission of acetonitrile ($\text{H}_3\text{C} - \text{C} \equiv \text{N}$) around the $\text{N K}\alpha$ line at different excitation energies E_{in} , measured in the RIXS mapping mode. The spectra are subsequently shifted on the intensity scale by 200 units for convenient presentation.

In contrast to a recent study [20], where an off-axis TZP segment was applied, we record the full RIXS map (photon-in vs. photon-out) covering both the inelastic transitions and the elastic line in a single measurement, without modification of the setup. Figure 6 shows the emission of acetonitrile at the N K-edge in the range (388.6 – 401.8) eV, at a total exposure time of 220 s (11 images at 20 s each), varying E_{in} in steps of 0.1 eV. In the abscissa (E_{out}), one pixel (13 μm) corresponds to 8.79×10^{-2} eV, which coincides approximately with the angular dispersion $\partial_E \beta_{RZP}(E) = -0.00725^\circ/\text{eV}$ [31] of the RZP if the surface normal on the camera is tilted by 35° off the x -axis (Fig. 4). At $E_{in} = 399.4$ eV, the energy loss of the ($7a_1 \rightarrow 1s$) and ($2e \rightarrow 1s$) electron transitions [20,22] in nitrogen (N) is estimated to -7.79 eV and -6.58 eV, respectively. These inelastic scattering peaks are found in reasonable agreement with the literature values of 391.4 eV and 392.6 eV reported for an excitation energy of 400 eV [25]. The vibrational branch [20] at $E_{out} \approx 398.84$ eV becomes increasingly separated with E_{in} from the elastic line.

This fact may be used to estimate an upper limit on the experimental energy resolution. We select the spectrum for $E_{in} = 399.9$ eV (red plot in Fig. 6), which allows us to distinguish the vibrational branch from the elastic line around $E_{out} = 399.7$ eV. A multi-Gaussian fit of the intensity (a.u.) in this energy range reveals an FWHM of 0.58 eV for the elastic peak, which is the combined resolution of our spectrometer and the beamline. Assuming $\Delta E \sim 0.4$ eV for the latter, the RZP would provide an intrinsic resolution of 0.42 eV, in agreement with the simulated value of ≈ 0.42 eV for this region of the RIXS map as discussed previously in Section 4. In any case, our results are well competitive with the TZP study [20], reporting 0.8 eV.

5. Conclusion

With our proof-of-principle experiments at the “ChemRIXS” station [25] attached to the beamline P04 [24] at PETRA III storage ring (DESY), we have shown for the first time that even diffractive single-bounce optics like RZPs on a flat substrate can be used for wide-field imaging and spectral mapping if off-axis aberrations are minimized in the paraxial regime, supported by line scanning of the object.

First, an angular divergence of the incident beam confined to $\Delta\theta_{H,V} \approx 4 \times 4 \text{ mrad}^2$ expands the accessible bandwidth to (2 – 3) % around the design energy of 395 eV. A spatial resolution of about $(19 \pm 5) \mu\text{m}$ and a spectral selectivity of (0.24 – 0.50) eV are achieved within that range. Second, strip-like illumination with a 10 μm wide monochromatic focus from the beamline and stepwise recording of the moving sample enables microscopy across an angular size of at least 2.5 mrad [31]. For such an object, this 1-D mode leads to an overall measurement time of $\approx 3.4 \times 10^2$ s, almost 30 times shorter than that required for pointwise 2-D scanning. Using a “rainbow” line of excitation energies between 399 eV and 400 eV on the sample, 1-D RIXS mapping is accomplished along the transverse, non-dispersive direction of the RZP, whose spatial dispersion of 11.4 pix/eV [31] and the grating efficiency of $P_{+1} \approx 13$ % allow medium energy resolution ($E/\Delta E \lesssim 10^3$) time-saving spectroscopy, within an exposure of 3.7 min.

The operating energy range of an RZP is not limited by a membrane such as TZPs, which must typically be manufactured on a Si_3N_4 or SiC layer [20]. However, their stability is usually maintained only for small apertures, and consequently, the transmission efficiency of TZPs is reduced compared to that of RZPs: The photon throughput of our reflective device, relative to isotropic source emission, is given as $P_{+1} \cdot \Delta\theta_{H,V}/2\pi \approx 3.1 \times 10^{-7}$. Moreover, using a TZP, the setup must be modified to measure the inelastic and elastic peak at a good energy resolution [20]. In contrast, with the RZP, both signals can be recorded in the same geometry. Unlike competitive instruments composed of multiple components, including Wolter mirrors providing “the spatial imaging capability [...] in the spectroscopic studies” [32], our setup comes with an efficient, easy-to-align, all-in-one optical element for reflection, focused imaging, and dispersion.

Our versatile, efficient and highly dispersive RZP could be applied in the future to conventional or coherent imaging and spectral (RIXS) or elemental mapping. High harmonic generation

sources with $\sim$ mrad divergence [33] would be well matched to the paraxial regime as utilized in this project. Furthermore, RZPs might also work well with free-electron lasers, due to their ability to withstand the heat load in, e.g., nonlinear spectroscopy, where the beam is fed into the instrument directly after passing the sample [34]. Laser-driven plasma [35] and electron-excited fluorescence sources could also benefit from a relatively large solid angle of acceptance, in the present case up to 2.8×10^{-4} sr for the full RZP aperture of $40 \times 8 \text{ mm}^2$ (Sect. 2).

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