Spatially Resolved Multiphoton XUV Ionization

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We used a novel technique to perform spatially resolved photoionization-yield measurements of gas phase ions created in the focus of XUV-pulses produced at the FLASH facility. The advantage of this technique termed 'ion microscopy' is that it overcomes the limitations encountered in standard experiments where the ion yield is usually integrated over the focal volume and recorded as a function of the peak intensity \( I_0 \) in the focus. The ion yield \( Y_{\text{tot}}(I_0) \) measured in such an experiment is thus a convolution of the intensity dependent yield \( Y(I) \), where \( I \) is the local peak intensity of the pulse, with the focal intensity distribution \( K(I, I_0) \):

\[
Y_{\text{tot}}(I_0) = \int_0^{I_0} Y(I) K(I, I_0) dI.
\]  

(1)

Due to the inherent noise in experimental data, the convolution (1) can mask important features of the yield curve \( Y(I) \), even if the focal intensity distribution is known exactly. One example is the expected decrease of \( Y(I) \) beyond the saturation intensity that occurs when the population of the measured charge state is depleted via ionization to a higher charge state. Furthermore the focal geometry (and thus the focal intensity distribution) is usually not precisely known, which makes the interpretation of measured data even more difficult. This hinders a comprehensive analysis of multiphoton or intense field photoionization data, as for instance those challenging results that have recently been obtained at FLASH [1, 2].

Our new technique tackles this problem from two sides, as it allows for intensity resolved ion yield measurements and at the same time provides a precise method for non invasive, in situ focus diagnostics. The ability to characterize the quality of the focussing is a crucial step if a high peak intensity is to be achieved, especially at short wavelength where the multi-layer mirror technology is close to its limits.

The ion microscope maps the distribution of ions created in the laser focus and contained in the object plane onto a position sensitive detector located in the image plane. The magnification is of the order of 100 and the resolution is approximately 2 \( \mu \)m. Gating the detector with a 7 ns time window enables us to mass select individual charge states. Assuming the ion distribution to be symmetric under rotation about the beam propagation axis, the full 3D distribution can be recovered after Abel-inverting the data.

Here we report on the application of the ion microscopy technique to the characterization of an XUV focus obtained using a spherical multi-layer mirror of 50 cm focal length. We used FLASH pulses of 13 nm wavelength in the single-bunch mode to generate Xenon ions with charge states up to \( \text{Xe}^{7+} \). Images of the spatial ion distributions of the charge states \( \text{Xe}^{2+} \) to \( \text{Xe}^{7+} \) were recorded at various positions \( z \) along the beam propagation axis by translating the focussing mirror along that direction. Measured distributions of \( \text{Xe}^{2+} \) to \( \text{Xe}^{7+} \) that where recorded at the beam waist are shown in Fig. 1 (a). We used the spatial distribution of \( \text{Xe}^{4+} \) ions, where saturation and depletion effects were found to be negligible, to characterize the focal geometry. The distribution was found to have a nearly gaussian shape. Since \( \text{Xe}^{4+} \) ions are produced in a two-photon process, the square root of the \( \text{Xe}^{4+} \) distribution is directly proportional to the intensity distribution. In Fig. 1 (b) the width \( w(z) \) (FWHM) of the measured \( \text{Xe}^{4+} \) distributions is plotted as a function of the position \( z \).
A beam diameter of 15 µm (FWHM intensity) and a Rayleigh length \( z_R \) of 1.8 mm are calculated from this curve. Note that the measured beam diameter is 10 times larger than expected for perfect focussing, which might result from an imperfect surface quality of the focussing mirror. This result also explains why charge states higher than Xe\(^{7+}\) where not observed in the present experiment.

In conclusion we have used a novel technique to perform precise, non-invasive in-situ diagnostics of focussed XUV-radiation at FLASH [3]. Combined with a high-quality focussing mirror, our method potentially allows for high precision experiments that could help elucidating the open questions recently raised in the study of Richter et al. [4] on the generation mechanisms of highly charged states in atoms. Higher intensities in the focus would also permit pump-probe measurements on the generation of Xe\(^{8+}\), where two photons are needed to overcome the ionization potential of Xe\(^{7+}\). These type of experiments would allow for a complete spatiotemporal characterization of the FEL pulses.

References