Single shot coherence properties of SACLA in the hard X-ray regime

With the advent of X-ray free electron lasers such as SACLA, chemical and physical properties of matter can be studied that were not accessible before. Many of these applications rely on the coherence properties of the X-ray beam, e.g., imaging of biological macromolecules by coherent diffractive imaging, the study of ultrafast magnetization processes and temporal and spatial correlation spectroscopy. Detailed knowledge of the coherence properties of the X-ray pulses is in particular crucial for experiments on ultrafast dynamics using split-and-delay devices [1]. Due to the stochastic nature of the SASE process, the coherence properties are expected to differ from optical lasers and show shot-to-shot fluctuations. Nevertheless, it is expected that SASE beams show superior transverse coherence. For soft X-rays the degree of coherence is usually studied by double-slit experiments. In the hard X-ray regime this information can be obtained by analyzing diffraction patterns from disordered samples, allowing the determination of coherence properties on a shot-to-shot basis. In our study we measured the coherence properties of SACLA for single shots at a photon energy of 8 keV [2].

The experiment was performed at beamline **BL3** of SACLA in small-angle X-ray scattering geometry. We measured diffraction patterns from amorphous colloidal samples with μm sized X-ray pulses using the MAXIC sample chamber [3]. A sketch from the setup is shown in Fig. 1, including a typical diffraction pattern recorded with the MPCCD detector. These patterns show a grainy structure in coherent scattering experiments, called speckle pattern. The degree of coherence of the X-ray beam is reflected in the contrast of these speckle patterns [4], given by the normalized standard deviation of the intensity. In this way, we extracted the contrast for a series of 2000 single shots, see Fig. 2(a). The contrast varies between about 0.5 and 1, with an average value of 0.70. We did not observe any significant q-dependence of the contrast (Fig. 2 (b)) within the studied q-window.

The experimentally obtained speckle contrast β_{exp} is defined by the transverse and longitudinal coherence of the X-ray beam and $\beta_{exp} = \beta_t \beta_l\ (q)$, with the transverse coherence β_t and a q-dependent correction β_l that depends on the scattering geometry and energy bandwidth. For the experiment at BL3 we found $\beta_l = 0.89$ and thus a transverse coherence of $\beta_t = 0.79 \pm 0.09$ which corresponds to a transversely almost fully coherent beam.

At very low count rates, that are typically present at large q-values and expected for experiments using split-and-delay devices studying sample dynamics down to femtoseconds [1], the presented method for contrast determination breaks down due to statistical limitations. In this case the contrast can be extracted from histograms of the scattered intensity [3]. Experimental intensity histograms are however not discrete because of detector read out noise and charge sharing of neighboring detector pixels.

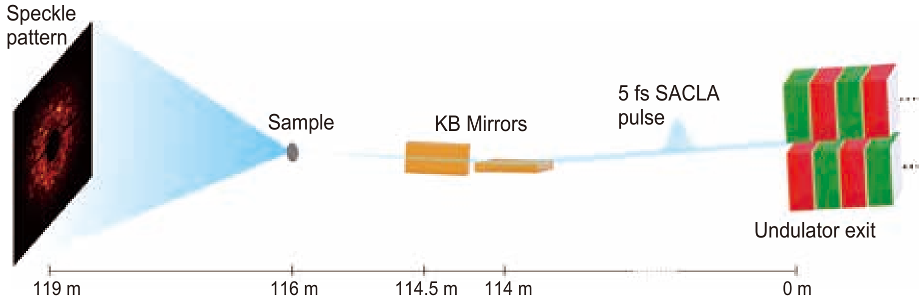

Fig. 1. Schematic set-up of the experiment performed at EH3 of BL3.

Therefore, such data is discretized or a so-called droplet algorithm is used [5], resulting in systematic artifacts or time-consuming analysis procedures, respectively. To overcome these limitations, we developed a simulation model taking detector read-out noise and charge sharing of pixels into account. The intensity histogram of 600 single shots at large q-values is shown in Fig. 3 together with the resulting histogram from simulation. The values obtained within the model resemble the expectations of the detector properties. Most importantly, we obtained the same degree of coherence with both methods.

In conclusion, we determined the degree of coherence at SACLA for hard X-rays on a single shot basis. The transverse coherence was found to be close to 100%, superposed by variations originating from the random SASE fluctuations. Deviations from full transverse coherence depend on set-up and machine parameters such as saturation lengths, bunch compression schemes and photon wavelength, indicating good agreement of our results with the expectations from FEL theory. Our findings will pave the way for subsequent experiments making use of the coherence properties of SACLA, e.g. studies of ultrafast dynamics via split-and-delay methods.

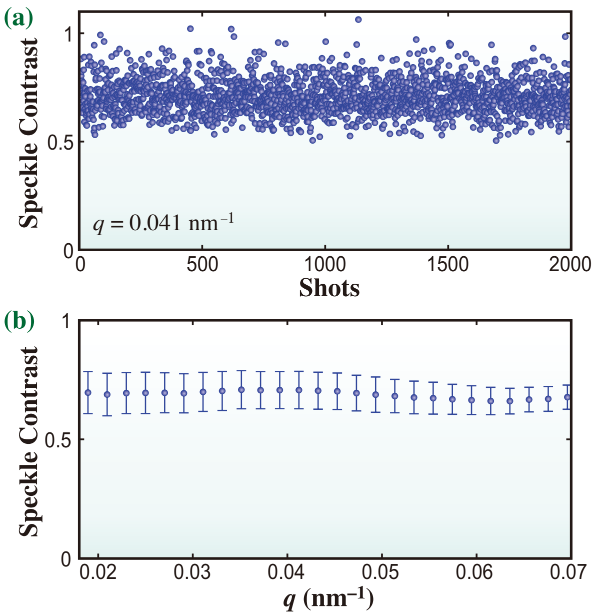

Fig. 2. **(a)** Single shot speckle contrast from 2000 shots calculated at q=0.041 nm^{-1}. **(b)** Contrast as function of q averaged over 2000 shots. The error bars reflect the degree of shot-to-shot fluctuations.

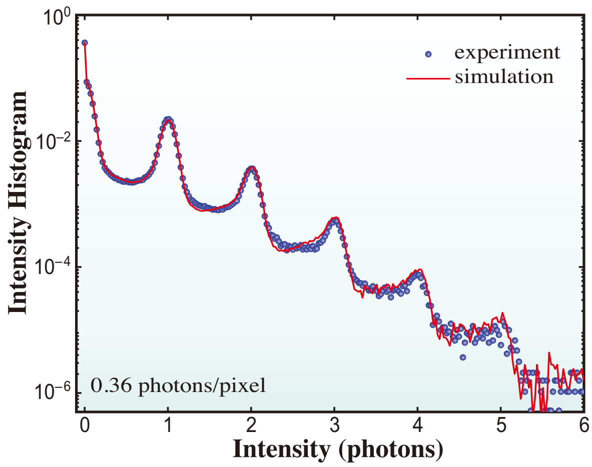

Fig. 3. Intensity histogram at q=0.07 nm^{-1} averaged over 600 shots together with simulation results. The intensity is converted to photon number by correcting for the analog-digital-unit of the MPCCD detector.

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