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Coherent Correlation Imaging for resolving fluctuating states of matter

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Fluctuations and stochastic processes are ubiquitous in nanometer-scale systems, especially in the presence of disorder. Real-space access to fluctuating states is impeded by a fundamental dilemma between spatial and temporal resolution. Averaging over an extended period of time (or repetitions) is key for the majority of high-resolution imaging experiments, especially in weak contrast systems. If, by lack of better knowledge, averaging is indiscriminate, it leads to a loss of temporal resolution and to motion-blurred images.

We present coherent correlation imaging (CCI) [1] –a high-resolution, full-field imaging technique that realizes multi-shot, time-resolved imaging of stochastic processes. The key idea of CCI is the classification of Fourier-space coherent scattering images based on the speckle fingerprints of the real-space state –even at a low photon count where imaging is not possible. Contrast and spatial resolution emerge by averaging selectively over same-state frames. Temporal resolution down to the acquisition time of single frames arises independently from an exceptionally low misclassification rate, which we achieve by combining correlation-based similarity metric with powerful classification algorithm.

We apply CCI to study previously inaccessible magnetic fluctuations in a highly degenerate magnetic stripe domain state with nanometer-scale resolution. Our material is a Co-based chiral ferromagnetic multilayer with magnetic pinning low enough to exhibit stochastically recurring dynamics that resemble thermally-induced Barkhausen jumps near room temperature. CCI reconstructs high-resolution real-space images of all domain states by holographically aided phase retrieval [2, 3] and, unlike previous approaches, also tracks the time when these states occur. The spatiotemporal imaging reveals an intrinsic transition network between the states and unprecedented details of the magnetic pinning landscape allowing us to explain the dynamics on a microscopic level.

CCI massively expands the potential of emerging high-coherence X-ray sources and paves the way for addressing large fundamental questions such as the contribution of pinning and topology in phase transitions and the role of spin and charge order fluctuations in high-temperature superconductivity.

[1] C. Klose et. al., Coherent correlation imaging for resolving fluctuating states of matter. *Nature* 614, 256-261 (2023)

[2] S. Zayko et al., Ultrafast high-harmonic nanoscopy of magnetization dynamics. *Nat. Commun.* 12, 6337 (2021).

[3] R. Battistelli, et. al., Coherent x-ray magnetic imaging with 5 nm resolution, *Optica*, DOI 10.1364/OP-TICA.505999

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