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Vacuum Birefringence Measurements Using the Dark-Field Concept at the European XFEL

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Quantum field theory predicts that the vacuum exhibits a nonlinear response to strong electromagnetic fields, giving rise to phenomena such as vacuum birefringence. Despite its fundamental significance, this effect has remained experimentally inaccessible and has yet to be observed in the laboratory. Detecting it would provide a distinct signature of the optical activity of the quantum vacuum and enable a precision test of nonlinear quantum electrodynamics in an unexplored regime.

A central difficulty in such experiments is isolating the weak signal from the photon background of the probe beam. In the strong-field region created by a tightly focused IR pump pulse, the X-ray probe acquires a tiny vacuum-induced polarization rotation and an angular deflection. Conventional approaches rely on ultra-high-contrast polarimetry to suppress the background and reveal the signal.

We introduce here the dark-field concept, a promising alternative that creates a controlled shadow in the probe' s near field, enabling a clean angular separation between the vacuum-induced signal and the background. We report on recent experimental campaigns at the European XFEL's High Energy Density (HED) instrument, where this technique was implemented using the X-ray beam as the probe and the ReLaX IR laser as the pump. The dark-field configuration reduced the background by roughly 15 orders of magnitude. This design not only increases the sensitivity of the measurement, but also gives access to both the polarization-flipped and non-flipped components of the probe, enabling a direct determination of the fundamental QED parameters that can be confronted with theoretical predictions. We present an overview of the setup, the experimental results from the last campaings, the expected measurable signal for the upcoming campaign, and the current status of the advanced simulation framework that models both the vacuum birefringent signal and its background.

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