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Coherent 3D microstructure of laser-wakefield-accelerated electron bunches

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Recent breakthroughs in laser wakefield accelerator (LWFA) technology have allowed them to drive free-electron lasers (FELs) [1]. This is made more impressive by the relative lack of phase-space control in plasma accelerators when compared to conventional linear accelerators. However, the complicated phase spaces and microstructures in LWFA beams could be harnessed to accelerate the self-amplified spontaneous emission (SASE) process. Pre-bunched beams have been shown to achieve gain with shorter saturation length than conventional beams [2]. Because of the nature of the LWFA process, electron beams from LWFAs emerge from the plasma with preformed microstructures. The parameters of the accelerator dictate the shape, size, and coherence of these features. There is interest in creating and harnessing such substructures for the next generation of X-ray FEL [3]. However, to use these structures they must be measured and characterized. Coherent optical transition radiation (COTR) can diagnose such microfeatures in electron beams. We present experimental results across three different LWFA injection regimes demonstrating regime dependent levels of visible COTR. In each regime, we examined near field COTR images at eight different wavelengths from a foil directly after the end of the accelerator. Depending on the injection regime, we observe different levels of bunch substructure. How this structure evolves across optical wavelengths is also regime dependent. Wavelength-dependent variations in the size and radial distribution of the TR images can be correlated with features in the bunch longitudinal profile. Observed multispectral COTR images corroborate injection-regime-dependent beam substructures predicted by three-dimensional particle in cell (PIC) simulations. Moreover, with the aid of physically reasonable assumptions about the bunch profile, we present reconstructions of the three-dimensional electron bunch density distribution.

[1] Wang, et al. Free-electron lasing at 27 nanometres based on a laser wakefield accelerator. *Nature* 595, 516–520 (2021).

[2] A. H. Lumpkin et al., Evidence for Microbunching “Sidebands” in a Saturated Free-Electron Laser Using Coherent Optical Transition Radiation, *Phys. Rev. Lett.* 88, 234801 (2002).

[3] Xu, Xinlu, et al. “Generation of ultrahigh-brightness pre-bunched beams from a plasma cathode for X-ray free-electron lasers.” *Nature communications* 13.1 (2022): 1-8.

Acknowledgments

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