Contribution ID: **21** Type: **not specified**

Energy Bunching from Sub-Cycle Ionization Injection in Laser Wakefield Acceleration

Monday 6 October 2025 12:15 (30 minutes)

Electron energy spectra featuring multiple quasi-monoenergetic peaks with uniform, narrow spacing are observed when a few-cycle (~9 fs), multi-terawatt laser pulse is used to drive laser wakefield acceleration in a helium–nitrogen gas mixture. This comb-like energy structure results from periodic ionization injection triggered by successive half-cycles of the laser electric field. Crucially, the evolving carrier-envelope phase (CEP) during laser propagation through the plasma enables this sub-cycle injection process. Our experimental findings provide the first direct observation of CEP-driven energy bunching in a plasma accelerator, establishing a scheme where electron injection and beam shaping can be precisely synchronized to the laser's optical waveform. This work opens a new pathway toward attosecond-scale control in laser-plasma acceleration.

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Session Classification: Session 1: High-Brightness X-rays for Biology/Chemistry