Contribution ID: **57** Type: **Poster (participant)**

Advancing LWFA Beams for FEL Operation Using Synergies between Experiment, Simulation and Automation

Tuesday, 15 April 2025 17:10 (1h 30m)

The first FEL light from LWFA beams has recently been demonstrated. However, achieving shorter wavelengths requires stable and optimized beams, which remains a challenge due to the nonlinear nature of cavity formation and injection, and because many critical parameters are not directly accessible in experiments, making it difficult to fully characterize the 6D phase space.

We present a simulation-driven approach to study the stability of LWFA sources using automated parameter scans in the self-truncated ionization-injection (STII) regime. Using PIConGPU, we generate stability maps for laser and gas parameters and compare them with recent LWFA FEL experimental data. These simulations reveal the conditions that maximize beam quality and clarify the regime where STII does not produce optimal beams. By analyzing the ionization-injection dynamics, we uncover a transition between different beam quality regimes and manifests itself in substructures of the bunches that could be studied experimentally with Coherent Transition Radiation (CTR).

In addition, we explore other synthetic diagnostics - such as few-cycle shadowgraphy and far-field radiation - to validate our findings. We also discuss the limitations of electron spectrometer optimization for FEL drivers, highlighting the need for an integrated approach combining simulation and experimental diagnostics.

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Session Classification: Poster Session

Track Classification: Theory and simulations