Traveling-Wave Electron Acceleration: Breaking the dephasing and depletion limits of laser-wakefield acceleration

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We show how to simultaneously solve several longstanding limitations of laser-wakefield acceleration that have thus far prevented laser-plasma electron accelerators (LWFA) to extend into the energy realm beyond 10 GeV. Most prominently, our novel Traveling-Wave Electron Acceleration (TWEAC) approach [1] eliminates both the dephasing and depletion constraints, which fundamentally limit the maximum energy gain of a single LWFA stage. This is complemented with a focusing geometry, which does not require any guiding structures, such as plasma-capillaries, and does not rely on laser self-guiding in plasma. This opens up acceleration regimes that were previously inaccessible.

The wakefield driver is a region of overlap of two obliquely incident, ultrashort laser pulses with tilted pulse-fronts in the line foci of two cylindrical mirrors, aligned to coincide with the trajectory of subsequently accelerated electrons. First, such a laser geometry drives a wakefield moving at the vacuum speed of light instead of the sub-luminal group-velocity $v_g<c$, thus preventing electrons from outrunning the plasma wave (dephasing limit). Secondly, this leads to a stable and experimentally controllable plasma cavity by having at every instant a new, unspoilt section of the laser pulse, which has not yet undergone self-phase modulation, transversely entering the plasma and, after only a short propagation distance, form the acceleration cavity in plasma regions previously unperturbed by lasers. That latter mechanism eliminates the pump depletion limit of LWFA.

TWEAC presents a prospect of vastly reducing or even completely disposing the problem of staging between several LWFAs to achieve higher energies and hence averts the loss of electron beam quality, such as charge decrease due to inter-stage beam transport or laser-stage-coupling inefficiencies. Given enough laser pulse energy and in contrast to LWFA and PWFA, TWEAC can arbitrarily be extended in length to higher electron energies without changing the underlying acceleration mechanism.

We show that TWEAC leads to quasi-static acceleration conditions, which do not suffer from laser self-phase modulation, parasitic self-injection or other plasma instabilities. Similarly, the TWEAC geometry greatly facilitates reducing beam transport distances between the laser-plasma accelerator and subsequent insertion devices, such as undulators, plasma lenses or colliding laser pulses, to below millimeters. This is especially critical for reducing emittance growth during beam transport.

We introduce the new acceleration scheme, show results from 3D particle-in-cell simulations using PIConGPU, discuss energy scalability for both laser and electrons and elaborate on experimental realization requirements.

References

[1] Debus *et al.*, “Breaking the dephasing and depletion limits of laser-wakefield acceleration”, *paper submitted*.