Modeling a Novel Laser-Driven Electron Acceleration Scheme: Particle-In-Cell Simulations at the Exascale


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Laser Wakefield Acceleration (LWFA) of e- is a promising technique but...

Intense femtosecond lasers focused on low-density gas jets can accelerate ultra-short electron bunches up to very high energies (from 100s of MeV to several GeV) over a few mm or a few cm. However, with conventional LWFA techniques, it is hard to accelerate more than a few 10s of picoCoulomb of charge at high energy and with high quality, severely hindering potential applications.

...accelerating high quality and high charge e-bunches is difficult

We propose a novel injector concept to accelerate more charge

In LWFA, injecting a high charge from a low-density gas jet is challenging. To address this issue, we have devised a novel injector consisting of a gas jet coupled to a flat solid target. By interacting with the high-density target, the laser should be able to extract a substantial amount of charge. The laser is subsequently reflected and propagates in the gas jet, as in conventional LWFA setups, generating a density perturbation that traps and accelerates the electrons up to high energies.

We validated this concept with numerical simulations & experiments

WarpX: a Particle-In-Cell code for the exascale era

WarpX is an open-source Particle-In-Cell code conceived to address the challenge of simulating kinetic plasmas at the exascale. WarpX supports mesh-refinement, advanced solvers, dynamic load balancing, highly scalable 1/D- routines, and several additional physics modules. WarpX is well-tested to simulate ultra-intense laser-plasma interaction scenarios, including LWFA, and is routinely used on the top supercomputers in the world. A scientific work describing the technical innovations implemented in WarpX was awarded the Gordon Bell Prize in 2021.

We validated Mesh refinement at scale in an EM Particle-In-Cell code

Mesh-refined, massively parallel simulations show that with a PW-class laser a substantial amount of charge can be extracted from the solid part of the target, much more than what would be accelerated with just the gas jet. The extracted charge is then accelerated by LWFA in the gas. Electron injection is highly localized, leading to peaked electron spectra with an energy spread below 10% and an energy above 100 MeV. The simulation was carried out on 4096 nodes on the Summit supercomputer, using two MR levels: a first level with 5840 x 1920 x 5840 grid nodes and a second level with 7680 x 2151 x 5120 grid nodes.

We validated our concept with a proof-of-principle experiment

In 2022 we validated our concept with proof-of-principle experiments carried out at the 10 TW-class LOA laser facility (France). We observed a 2.5x increase of the conversion efficiency of laser energy into electron energy with respect to the best result obtained at that facility with more conventional LWFA setups.

Mesh refinement in electromagnetic Particle-In-Cell codes

Mesh refinement is among the most advanced features of the WarpX code, which is indeed the only electromagnetic Particle-In-Cell code providing this capability. The implementation of mesh refinement requires the use of absorbing layers to deal with the spurious reflection of electromagnetic waves at the boundary. WarpX allows defining a rectangular region where a mesh refinement is activated. The resolution is then increased near the absorbing layers while other regions remain at the coarsest level. We validated Mesh refinement at scale in an EM Particle-In-Cell code using two MR levels: a first level with 5840 x 1920 x 5840 grid nodes and a second level with 7680 x 2151 x 5120 grid nodes.

References