Towards stable multi-GeV laser-wakefield operation on PW lasers

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Laser-driven particle accelerators have made tremendous progress over the last two decades, with ion acceleration breaking the 100 MeV barrier, and electron energies approaching 10 GeV. Despite refined ways to control the injection and acceleration process, the relatively large particle energy spread and poor shot-to-shot reproducibility are still the major challenges for their suitability as a future replacement of conventional RF accelerator technology. Indeed, poor reproducibility is also a key inhibitor of progress towards narrower bandwidth, as it makes the required fine-tuning of beam parameters impossible. The instability of laser-driven accelerators originates in fluctuations of the laser, target and injection parameters. Especially the former are exacerbated by the trend towards larger laser systems with long beam paths in air, large beam sizes and higher wavefront aberrations of large optics. After the upgrade of the ATLAS-laser at LMU from 300 TW to 2 PW peak power, the same system turned from an accelerator driver with world-leading reproducibility into one with average performance in that respect at best.

Over the course of 4 years, through many detail improvements, we recently were able to recover the previous stability in experiments, as we will show in the case of GeV and multi-GeV electron acceleration. We will discuss the influence of air turbulence, spatio-temporal coupling and fast thermal drift in the laser on the acceleration process and present measures taken to keep those influences under control. A new injection method largely eliminates shot-to-shot jitter in the injection position and affords new levels of control over the injected charge, thus allowing to fine-tune the electron bandwidth. In that way, we are now able to reliably produce 2.5-GeV electron beams from gas cells and >1GeV monoenergetic beams in gas jet targets.

Finally, recent highlights from hybrid PWFA-LWFA acceleration and multi-objective machine-learning-based optimization of electron beams will be presented.