Spatiotemporal beam-plasma instabilities in the ultrarelativistic regime

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The propagation of particle beams through plasma can give rise to instabilities, relevant for a large number of astrophysical and laboratory systems, for example for their role in the energy transfers and dissipation of kinetic energy into heat or radiation. For ultrarelativistic beams, the oblique two-stream instability (OTSI) generally prevails the early beam-plasma interaction. For conditions relevant to the E305 experiment, which is devoted to study such beam-plasma instabilities with the FACET-II facility at SLAC, we have shown that the instability is spatiotemporal due to the finite length of the beam, with the front and rear of the beam experiencing different plasma conditions and the instability growing in time and from front to rear.

Here, we show that this spatiotemporal character is not only prominent during the linear growth, as demonstrated with our recently developed OTSI theory [San Miguel Claveria *et al.*, PRR 4, 023085 (2022)], but also during the nonlinear evolution and saturation of the instability. The spatiotemporal saturation is understood from the time history of plasma electrons, the shorter growth at the front resulting in a much smaller saturation level than at the rear of the beam. Next, we will discuss how this spatiotemporal instability can be probed experimentally, through the combination of two innovative methods, namely ultrafast dark-field shadowgraphy for the time evolution and single-shot energy-resolved transverse-momentum-spread measurements for the front-to-rear spatial evolution. The latter method relies on the use of ultrahigh-quality chirped beams with a correlation between the particle energy and its longitudinal position, allowing to access the front-to-rear spatial coordinate $\xi = ct - z$ from energy-resolved measurements in a single shot. Our modeling and synthetic measurements demonstrate their very high potential to benchmark OTSI theory and codes against experimental data. Finally, while the instability generally starts from noise, we have also shown that it can be seeded and controlled using the beam interaction with a nano-structured solid target, that induces a transverse modulation of the beam whose scale is imposed by the nano structure. Our work thus opens the way to a powerful experimental platform for the study of ultrarelativistic beam-plasma instabilities.

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