Kinetic modelling of autoresonant beat-wave excitation of plasma waves

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If two co-propagating lasers are detuned from each other by the electron plasma frequency, their beating can resonantly excite a large-amplitude, high-phase-velocity plasma wave. For fixed beat frequency, the peak longitudinal electric field is constrained by detuning effects, the Rosenbluth-Liu (RL) limit [1]. By including a negative frequency chirp in the laser with the higher frequency, an autoresonant phase-locking of the plasma wave to the beat-wave frequency of the driving lasers can be achieved [2]. This scheme can drive plasma waves beyond traditional detuning limits and has several advantages, e.g. insensitive to uncertainties and variations in plasma and laser parameters. Previous investigations of the autoresonant wakefield excitation were performed with fluid models [2], and did not include the kinetic response of the background plasma and the self-consistent propagation of the lasers, which could impact phase-locking during the strongly nonlinear regime.

Here we use particle-in-cell simulations performed with SMILEI [3] to reveal significant fluid nonlinearities of the laser self-consistent evolution occur under high plasma density, invalidating the fluid model of quasi-static approximation. However, when considering low underdense plasma, a remarkable agreement emerges between the fluid model and kinetic simulation results. In this regime, the frequency chirp offers effective control over wave amplitude and self-injection of particles. Optimal laser and plasma parameters are identified (laser intensity of $\sim 10^{17}\mathrm{W/cm^2}$, the bandwidth in the laser beam of $\sim 0.5\%$, and the plasma density of $\sim 10^{18}$ cm^{-3}) for amplifying the wakefield to the point of wave-breaking, enabling acceleration of particles via a high-gradient electric field, and ∼30 pC charge of the high-energy (∼ 250 MeV) electrons is expected to be obtained over ∼ 3.5 mm acceleration length. This versatile and efficient acceleration scheme holds promise for a wide range of applications, from tens to hundreds of MeV energies, making it worthy of investigation as a potentially attractive option for various industrial and medical applications.

References

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