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Propagation of ultra-intense laser pulses in near-critical plasmas: depletion mechanisms

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Although the weakly nonlinear regime of LWFA is known to be the optimal for reaching the highest possible energy of electrons for a laser pulse of given energy, the capabilities of upcoming grand laser systems will provide the possibility of running highly nonlinear regimes of laser pulse propagation in underdense or near-critical plasmas. These regimes could open new routes towards various applications, including the reaching of unprecedentedly high electron currents and the creation of unique gamma and X-ray sources. Here we show that such regimes can be implemented with external guiding for a relatively long distance of propagation. This provides a way for the stable transformation of laser energy into several channels, including the kinetic energy of a large number of electrons and their incoherent emission. We use an extended PIC model that takes into account all the relevant physics and reveal the relative contribution of various channels of energy depletion for the laser pulse. In particular, our study shows that up to intensities of the order of (at least) $10^{26} W/cm^2$ a stable structure, similar to the one known for LWFA, is formed and propagates through the plasma for a long distance. This is despite the fact that the high intensity of the laser pulse triggers a number of new mechanisms of energy depletion, which we investigate in our study. Firstly, the electrons, being pushed by the leading edge of the laser pulse, not only take away the kinetic energy gained due to the light pressure, but also transfer a relatively large portion of energy into incoherent emissions. Secondly, some of these electrons are found to be captured by the effect of radiation reaction trapping in the front part of the laser pulse. Apart from this, the electromagnetic energy of the laser pulse is redistributed within the bubble in a sophisticated way that includes irregular detachment and the deviation to the sides of new small bubble-like structures (non-linear solitons) formed at the front edge. This process, however, does setup but for different intensities. We perform a systematic analysis by accounting separately for the channels by not break the main structure quickly. To reveal the relative contribution of the various channels of energy depletion we perform simulations for a particular realistic which energy can leave the system, and switching on and off different basic physical phenomena (radiation reaction and ion motion), as well as using different models for their description (a stochastic QED-based routine and a classical radiation reaction force).

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