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Laser-plasma interaction in the strong-field QED regime

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Femtosecond lasers based on the chirped pulse amplification (CPA) technique could reach light intensity up to 10^{22}–10^{23} W/cm^2. The 10 PW-class laser facilities, such as ELI, Apollo, Vulcan, and SULF, aim at boosting the focused intensity by another tenfold. Ambitious plans of 100 PW-class have been proposed worldwide, where the peak intensities of 10^{25} W/cm^2 are anticipated. Laser–plasma interaction at such intensities enters a new regime where photon emission and radiation reaction become significant and strong-field quantum electrodynamics (SF-QED) is necessary to account for the quantum effects. Electrons radiate gamma photons in a stochastic and discrete quantum manner such that phenomena prohibited in the classical regime could happen. It is further predicted that copious electron–positron pairs can be generated. Meanwhile, the generated electron–positron pairs further lose their energies by radiating gamma photons. In this case, laser energy can be efficiently transferred to a large number of pair plasma.

We investigate the interaction process at such extreme intensities and found that radiation of electrons in the laser field fundamentally changes the particle dynamics. When electrons collide with an ultraintense laser pulse, the quantum stochasticity leads to QED transmission that cannot happen when described via classical dynamics. In laser-driven plasmas, gamma-photons are emitted at a very high efficiency and become the main energy absorption channel at intensities beyond 10^{23} W/cm^2. Electrons experience strong radiation reaction force such that they are trapped inside the laser pulse instead of being scattered off. This anomalous trapping mechanism leads to a dense plasma bunch confined within the most intense region of the laser beam, as seen in Fig. 1. Further the laser-driven plasma field enhances gamma-photon emission and therefore induces strong radiation-reaction effects in the near-critical density regime.

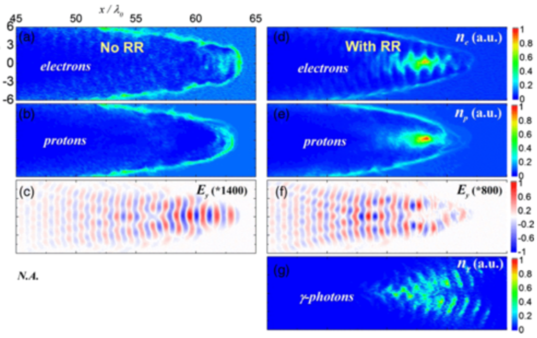

Figure 1. Trapping of electrons when taking into account the radiation reaction force in laser-plasma interaction.

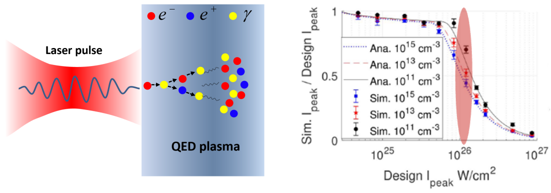

Figure 2. The onset of QED cascade, where electron-positron pair plasma is created and limit the light intensity attainable in non-ideal vacuum.

At even high intensities, the onset of QED cascade induces pair plasma and depletes the laser energy significantly, as seen in Fig. 2. The depletion is a dynamic process where the laser intensity gradually decreases during the development of a QED cascade, which changes the rate of photon emission and pair production. The latter would again deplete the laser energy. A self-consistent dynamic description of the process is therefore required. To this end, we developed a set of dynamic equations that take into account the above-mentioned effects self-consistently. We carried out particle-in-cell (PIC) simulations by including the QED models responsible for the two major reaction channels. Both the simulation and our theoretical model show that the attainable peak intensity depend on the vacuity. At electron density about 10^9 cm^{-3}, notable energy drain emerges from 10^{25} W/cm^2 and the upper limit of the laser intensity is modified ~10^{26} W/cm^2.

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Note: Abstract should be in 1 page.