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Electrostatic capacitance-type acceleration of ions with an intense few-cycle laser pulse

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Laser-driven ion acceleration is expected to be a new generation of advanced accelerators for the production of compact high-energy ion sources with unique properties, such as extreme laminarity and large flux. Prospective applications include proton radiography, tumor therapy, and nuclear physics. However, most applications require generation of ion beams with high energy (>100 MeV) and small energy spreads (<10%), which has not yet been achieved and, in fact, is extremely challenging for the existing acceleration mechanisms.

To date, two main mechanisms have been identified and widely investigated in both theory and experiments: target normal sheath acceleration (TNSA) and radiation pressure acceleration (RPA). In TNSA, ions are accelerated by the electrostatic sheath field arising from the thermal expansion of hot electrons, which is characterized with a broad energy spectrum. In RPA, circularly polarized (CP) laser pulses are used to irradiate nanometer-scale targets. Ions and electrons constituting a quasineutral plasma slab undergo synchronous acceleration directly by the laser radiation pressure. Nevertheless, such synchronous acceleration is very susceptible to the interface instabilities. In practical experiments, the acceleration generally breaks prematurely, where the achievable ion energy is rather limited and the beam quality is heavily destroyed.

Here, we use large scale, three-dimensional particle-in-cell simulations to demonstrate that a high-quality energetic ion beam can be stably generated by irradiation of a multi-species nanofoil target with an intense few-cycle laser pulse. In this scheme named "electrostatic capacitance-type acceleration" (ECA), the light ions of the nanofoil are accelerated by a uniform capacitor-like electrostatic field induced by the laser-blown-out electrons that act like the cathode of a capacitor, while the heavy ions left behind serve as the anode. This scheme overcomes the inherent obstacles existing in the other acceleration mechanisms, such as uncontrollability of target normal sheath acceleration and instability of radiation pressure acceleration. Theoretical studies and three-dimensional particle-in-cell simulations show that this acceleration scheme is much more stable and efficient than the previous ones, by which 100 MeV monoenergetic proton beams (energy spread <10%) can be obtained with a laser energy less than 10 J, and the GeV ones with about 100 J.

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