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Laser-driven ion acceleration from the interaction of ultrashort ultrahigh-contrast multi-petawatt laser and thin solid target

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Ion acceleration driven by an ultraintense laser has become a very active area of research in relativistic laser-plasma interaction due to several unique properties of laser-based ion sources, such as a small source size of micrometers, ultrashort pule duration of picoseconds, low emittance, and good laminarity [1, 2] etc. These peculiar properties have stimulated innovative applications of the sources to ultrafast radiography, studies on hadron therapy and nuclear physics, driver for warm dense matter, and an injector for conventional accelerators. Laser-driven ion acceleration can be described mostly by the basic mechanisms [3], namely target normal sheath acceleration (TNSA), radiation pressure acceleration (RPA), Coulomb explosion, shock wave acceleration, and magnetic vortex acceleration. Several composite mechanisms, such as directed Coulomb explosion, relativistic transparency, and break-out-afterburner have been also tested and proposed as the combination and the enhancement of the basic ones in simulations and experiments.

Ion acceleration mechanisms have been investigated to find out the most efficient scheme to accelerate ions in terms of maximum energy, spectral distribution of energy, particle number in a bunch of beam, and spatial beam property. Among them, the ion energy scaling with respect to laser intensity, i. e. the dependence of ion energy on laser intensity, is one of the most interesting issues. The energy scaling may provide a pathway on how to produce the highest ion energy achievable with a certain maximum power of multi-petawatt (PW) lasers being constructed worldwide. Because of the slow scaling of proton energy to laser intensity, i. e. $E_p \sim I^{1/2}$ in the TNSA scheme, where maximum energy is determined by thermal electron temperature, the highest proton energy obtained up to date was 85 MeV [4]. The RPA scheme, on the other hand, provides a fast and favorable scaling that varies from the square to the linear power of laser intensity, i. e. $E_p \sim I^{1\text{-}2}$. The light-sail radiation pressure acceleration (LS-RPA) [3] occurs at a relatively low laser intensity over ~10^{20} W/cm^2, now feasible with state-of-the-art lasers.

Since multi-PW Ti:sapphire lasers have been installed at our institute, we have directed our efforts at studying the ion energy scaling with respect to laser intensity, and accelerating proton and carbon ion with energies over 100 MeV/nucleon. The ion acceleration experiments have been performed by irradiating ultraintense laser pulses onto ultrathin foil targets, mainly based on LS-RPA and composite acceleration schemes. A double plasma mirror system provided ultrahigh-contrast laser pulses to ensure the use of ultrathin targets through cleaning the pedestals of amplified spontaneous emission and pre-pulses present prior to a main pulse. The ultrashort ultrahigh-contrast laser pulse was focused onto an ultrathin target using an off-axis parabolic mirror to achieve an ultraintense laser intensity over 10^{20} W/cm^2. The ultrathin target was fabricated using a conjugate polymer material, F8BT, with a thickness ranging from 10 nm to 100 nm. Spectral energy distribution and species of the accelerated ions were characterized in real-time operation using Thomson parabola spectrometers equipped with microchannel plate and charge-coupled device detectors.

The experimental parameters of the PW laser (intensity, polarization, focal spot size) and target (thickness) were adjusted so as to achieve a highest ion energy. The highest proton energy of 93 MeV has been achieved by employing an ultrahigh-contrast circularly polarized laser pulse with an intensity of 6.1×10^{20} W/cm^2 focused onto a 15-nm thick target [5]. The quadratic scaling of proton energy to laser intensity, the existence of an optimum target thickness, 15 nm, for the highest proton of 93 MeV, and the superior performance of circularly polarized laser over linearly polarized laser pulse confirm that the proton acceleration occurs mainly through the PRA process.

Recently, we have successfully upgraded one of the previous PW laser beamlines to a 20-fs, 4-PW laser [6]. A highest laser intensity of up to ~10^{23} W/cm^2 would be achievable using the 4 PW laser and an off-axis parabolic mirror with a smaller f-number. Having learned that the RPA played a main role in the highest energy proton generation from the previous experiments using 1 PW laser, we will study further the ion energy scaling in a much higher intensity regime and try so as to boost ion energy well beyond 100 MeV/nucleon.

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