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A new acceleration scheme to obtain high-purity sub-GeV protons by utilizing an explosion dynamics of laser-irradiated solid/liquid hydrogen medium

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Generation of high-energy protons utilizing the irradiation of high-intensity lasers in the range of $10^{18\text{-}22}$ W/cm^2 on various kinds of targets has attracted wider attention and extensively studied for use in many applications. A typical application is to realize compact accelerators available for cancer therapy, whose spatiotemporal scales of acceleration are micro- to millimeter (μm~mm) and femto- to nano-second (fs~ns), respectively. Recently, high-energy protons from several tens to over 100 MeV have been obtained from hydrogen compounds attached to the rear surface of a solid target accelerated by the sheath electric field. In this scheme, protons suffer from a gradual acceleration in a time-varying field that lasts longer time scale than the laser pulse, and only a small number of protons selected from the bulk target material are accelerated. Therefore, obtaining high-energy protons over 200 MeV with sufficient flux while keeping the high purity of the beam is an open issue.

Here, we propose a new approach [1] for obtaining extremely high-energy protons exceeding 0.4 GeV with high purity by the irradiation of an ultrashort (τ ~20 fs) laser pulse to the solid/liquid hydrogen medium by the two-dimensional PIC simulations. When the laser pulse hits the medium, a large amplitude shock-like structure with the electric field exhibiting even parity is induced due to the strong ponderomotive force. By the successive compression, the density of the structure shows exponential growth and reaches 20 times the initial solid density to a width narrower than the local Debye length. Then, transient bifurcation from shock-like to localized soliton-like structure takes place, and an "explosion" of the soliton-like structure is triggered by an induced bipolar field exhibiting an odd parity with a 100 TV/m range. The explosion splits the soliton-like structure into two shocks propagating in opposite directions, i.e. one is the front shock boosted forward as the reaction of the other, i.e. the latter shock, ejected backward. Simultaneously, the front shock boosts the bulk component of the upstream medium forward, which leads to the high-energy bulk component accelerated to nearly 70% of the light speed.

This mechanism is found to be a rigid and robust process ascribed to a new function of relativistic plasma dominated by the frozen-in condition [2]. That is, the frozen-in parameter defined as ρ_e/γ_e becomes an almost constant value, where ρ_e and γ_e represent the electron charge density and the relativistic factor of electrons, respectively. Namely, as the laser intensity increases, both ρ_e and γ_e increase simultaneously, so that the increment of the numerator and denominator in ρ_e/γ_e cancel each other. This makes it possible to create a new extreme state in which highly compressed dense plasma and intense laser fields coexist stably [3].

We also found that the quality of high-energy bulk component, e.g., the maximum bulk energy, particle flux and spatial divergence, etc., is determined by the scale length of the laser pulse, not by the total pulse energy. For the longer laser pulse (τ = 40 and 60 fs), the explosion does not take place and protons are accelerated by the former mechanism [4] and the maximum proton energy for τ = 40 and 60 fs is smaller than that for τ = 20 fs. For the shorter laser pulse (τ = 10 fs), the compression of the shock-like structure by the laser ponderomotive force finishes within a few laser cycles. Consequently, the shock-like structure collapses before the explosion. These results indicate that the rising time of the laser pulse width is a key parameter of the present mechanism.

More sophisticated technology to produce micro-size rods could further increase the efficiency to the sub-relativistic regime. The proposed mechanism is found to uniquely happen in the solid hydrogen medium with a charge-to-mass ratio of unity among all substances in nature. To explore the target with materials heavier than solid hydrogen is key to expanding the range of applications. The further development of the laser technique concerning the pulse shape, we can obtain sub-GeV level protons, which can apply to academic and medical applications such as understanding the acceleration mechanism of high energy cosmic rays and cancer therapy, by using currently available laser technology.

References

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