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Study of the underlying physics of CSBA (Converging Shock-based Blow-off Acceleration) and the extension to two-dimensional rod/string configuration

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In laser-plasma ion accelerations by a high-power laser irradiation to the matter, high-energy and quasi-monoenergetic protons are required especially for medical applications. Due to the recent advances in laser technology and ion acceleration techniques, e.g., the target normal sheath acceleration (TNSA) and the radiation pressure acceleration (RPA), the maximum proton energy is close to 100 MeV [1-3]. However, the generation of high-energy (~200 MeV) protons with a narrow energy spread and a high particle flux is still a critical issue. Recently, the collisionless shock acceleration (CSA) has been widely studied to obtain a highly directional ion beams with a narrow energy spread. However, the maximum energy is limited up to ~20 MeV at present.

Here, in order to widen the possibility for obtaining high quality protons which satisfy the strict conditions mentioned in the above, we propose a new approach [4] to produce highly-directional and quasi-monoenergetic protons reaching 300 MeV by utilizing the internal and external degrees of freedom of spherical hydrogen cluster. The interaction process of a PW class ($I \sim 10^{21\text{-}22}$ W/cm^2), ultrashort ($\tau \sim 40$ fs) laser pulse and a micron-size ($R \sim 1$-2 μm) hydrogen cluster is investigated by using the three-dimensional particle-based integrated code EPIC3D [5].

By the action of the laser pulse into the cluster, an electrostatic collisionless shock is launched at the laser-irradiated hemisphere of the cluster. The shock propagates into the cluster center with converging due to the spherical shape of the cluster. The intensity of the electric field associated with the shock becomes large due to the converging effect and upstream protons are reflected by the shock potential in the shock rest frame. The reflected protons are accelerated forward as a high energy proton bunch. When the pulse peak reaches the shock, the laser

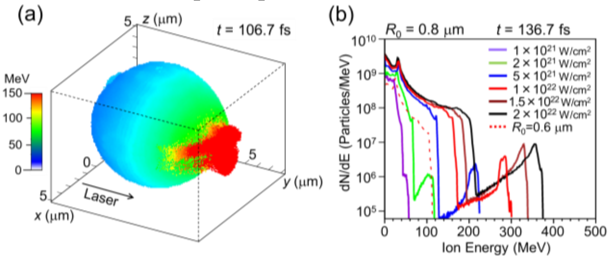

Fig. 1. (a) 3D image of the kinetic energy distribution of cluster ions at t = 106.7 fs. The quasi-monoenergetic proton bunch (red) is ejected from the cluster expansion front. (b) Proton energy spectra for various laser peak intensities at t = 136.7 fs. The spectrum for the radius of R_0 = 0.6 μm is also shown as red dotted line.

fields starts to penetrate into the shock, referred to as a relativistically-induced transparency (RIT), which results in the enhancement of the monochromaticity of the bunch. After the RIT, the bunch is further accelerated by the electric field of the shock remnant and ejected from the cluster expansion front like a *bullet* [see Fig. 1(a)]. The bunch is again further accelerated by the sheath field in the outside of the cluster with keeping a narrow energy spread and a low energy divergence. Finally, highly-directional (divergence angle ~5 degree) and quasi-monoenergetic ($\delta E/E \sim 10\%$) protons with energies reaching 300 MeV are obtained [see Fig. 1(b)].

We found that a series of acceleration mechanisms result from the synchronization of multiple processes in a self-consistent manner, which is referred to as CSBA (Converging Shock-induced Blow-off Acceleration) [5]. This mechanism works for finite ranges of parameters with threshold values concerning the laser peak intensity and the cluster radius. The proposed acceleration mechanism can be considered as a future candidate in laser-driven proton sources exceeding 200 MeV with the upcoming advanced multi-PW lasers.

In the presentation, we report the fundamental processes of CSBA in two-dimensional (2D) rod or string-like configuration. Moreover, based on the idea of CSBA scheme, we also propose a new approach for obtaining extremely high energy protons exceeding 500 MeV by the irradiation of an ultrashort ($\tau \sim 20$ fs) super-Gaussian laser pulse to the micron-size solid/liquid hydrogen by the two-dimensional PIC simulations. We find that the quality of the proton bunch, e.g., the maximum bunch energy, bunch length and current density, spatial divergence etc., is determined by the scale length of the laser pulse, not by the total pulse energy. These results indicate that further development of the laser technique concerning the pulse width, we can obtain sub-GeV level protons, which can apply to the academic and medical applications such as understanding the acceleration mechanism of high energy cosmic ray and cancer therapy, by using currently available laser intensity.

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