Cluster-Gas Targets as Efficient Media for Laser-Driven Ion Acceleration

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The laser-driven ion acceleration via the interaction of short, intense laser pulses with matter, known as laser-plasma acceleration, is featured by its high accelerating electric fields and short pulse length compared to conventional rf-accelerators. The recent advancements of novel laser-driven ion acceleration techniques now allow and even exceed the maximum energy of ions up to several tens of MeV. The state of material is a key ingredient here, which determines the characteristics of the interaction, and has to be chosen properly according to the purpose. For example, substantial enhancement of the accelerated ion energies has been demonstrated by utilizing a unique property of a cluster-gas target [1], where submicron-size CO_2 clusters with an average diameter of 220 nm [2] are embedded in background He gas produced by using a three-staged conical nozzle designed based on the Boldarev's model [3]. Numerical simulations indicate that acceleration enhanced by the generation of a quasistatic magnetic field [4,5] was the dominant mechanism, and that the role of the clusters was apparently that of enhancing the self-channeling and focusing of the laser pulse, leading to an increase of the intensity in the plasma, rather than contributing to ion acceleration via cluster explosions. However, the recent experimental result conducted with a high contrast laser indicates that other mechanisms could work [6].

In order to further investigate the underlying physical mechanism of high power laser interaction with cluster medium, we have performed simulations using EPIC3D (Extended Particle based Integrated Code) [7], which includes key atomic processes and relaxation processes self-consistently in fully relativistic three dimensional configuration, and systematically investigated the interaction processes of medium of carbon clusters embedded in helium gas. We found that the synergetic interplay of different mechanisms such as

1) acceleration of ions due to Coulomb explosion of individual carbon clusters,
2) compression and acceleration of background helium gas due to the Coulomb explosion of clusters,
3) magnetic vortex generation and associated pinching near the rare surface,
4) sheath acceleration at the interface between the medium and vacuum,

could play an important role in realizing the particle acceleration observed in the experiments. We also found that a self-organization process resulting from the complex interaction between clusters and background gas regulates the dynamics. More interestingly, in laser intensities of a relativistic ion regime, a new mechanism of ion acceleration can be incorporated with the Coulomb explosion.

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