03pC01

ナノチューブ加速器によるプロトン加速
Proton Beams from Nanotube Accelerator

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1. Introduction

Ion acceleration driven by ultraintense ultrashort laser pulses has been intensively studied in the past decade because a number of future applications are expected. For practical use of the accelerated ions, it is crucial to produce high-quality beams that are monoenergetic and collimated. We here propose a novel ion acceleration scheme using carbon nanotubes (CNTs) [1], in which embedded fragments of low-*Z* materials are irradiated by an ultrashort intense laser to eject substantial numbers of electrons [2, 3]. Due to the resultant unique electrostatic field, the nanotube and embedded materials play the roles of the barrel and bullets of a gun, respectively, to produce highly collimated and quasimonoenergetic ion beams.

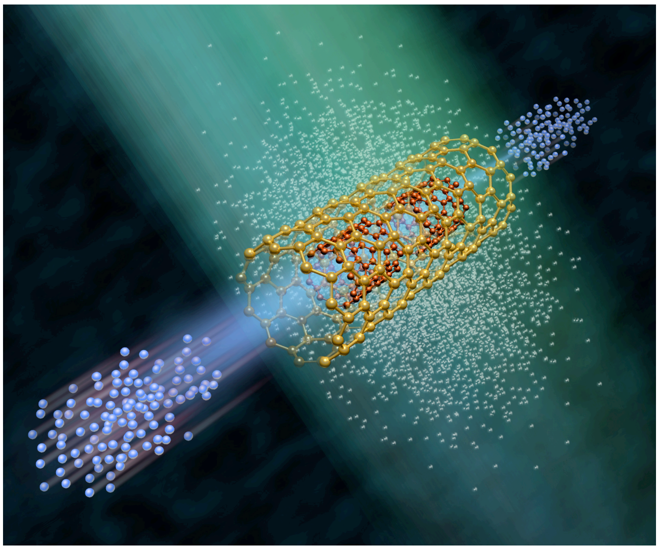

Fig.1 Schematic view of a nanotube accelerator. Upon laser irradiation, electrons inside the nanotubes are ejected within a few laser cycles. The remaining nanotubes composed of positive ions generate a characteristic electrostatic Coulomb field so that the inner ions are accelerated along the axis symmetrically toward both ends of the outer nanotube.

2. The nanotube accelerator

Figure 1 shows the schematic view of a nanotube accelerator. The double nested nanotubes are irradiated by an ultrashort intense laser pulse. The outer carbon nanotube is chemically adsorbed with heavy atoms such as gold, while the inner nanotube is made of light materials such as hydrogen and carbon to form the projectiles. Upon laser irradiation, electrons inside the nanotubes are ejected within a few laser cycles (comprising the small white particles around the nanotubes). The remaining nanotubes composed of positive ions generate a unique electrostatic Coulomb field so that the inner ions are accelerated along the axis symmetrically toward both ends of the outer nanotube. As a result, a pair of quasimonoenergetic collimated ion beams are obtained.

3. N-body simulation

We have performed *N*-body charged particle simulations, in which all of the particle-to-particle Coulomb forces are computed exactly. The relativistic version of the Newtonian equations of motion are used, similar to molecular dynamics simulations of microwave heating of salty water and ice. Moreover, our simulation includes the Lennard-Jones attractive potentials for pairs of like atoms, and repulsive potentials for other species as a core exclusion to avoid numerical divergences. Such *N*-body simulations are the most suitable numerical approach for treating parametric domains in which the plasma scale becomes significantly shorter than the Debye length.

Figure 2 shows snapshots of the nanotube accelerator dynamics at sequential times, obtained in the *N*-body simulations in a side view (upper row) and top view (lower row). The outer nanotube is of 30 nm in length and 15 nm in diameter, with gold atoms (yellow) chemically adsorbed onto the carbon atoms (green). Inside the nanotube, two cylindrical bullet nanotubes made of hydrogen (red) are embedded. Sinusoidal laser light is applied with intensity $I_L = 10^{18}$ W cm^{-2}. During the first laser cycle, ionized electrons (white) are ejected by the laser field. Simultaneously the saddle-shaped Coulomb field forms to squeeze and accelerate the projectile ions along the *z*-axis.

At t = 0, sinusoidal laser light is incident on the nanotube from a radial direction normal to the axis. The linearly polarized electric field is E_L=E_0 sin(2 π T)

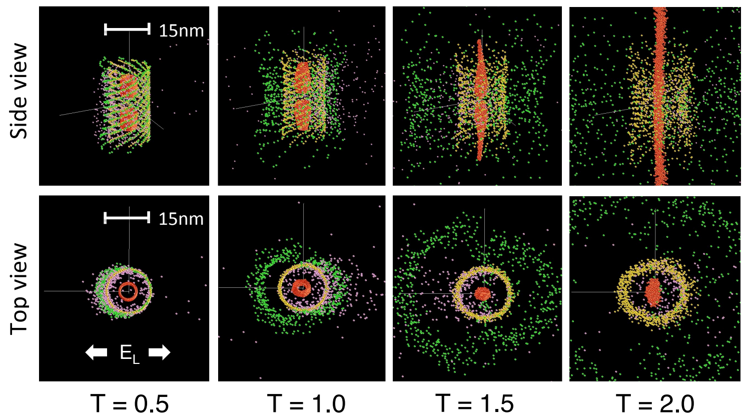

Fig.2 Temporal evolution of Nanotube Accelerator

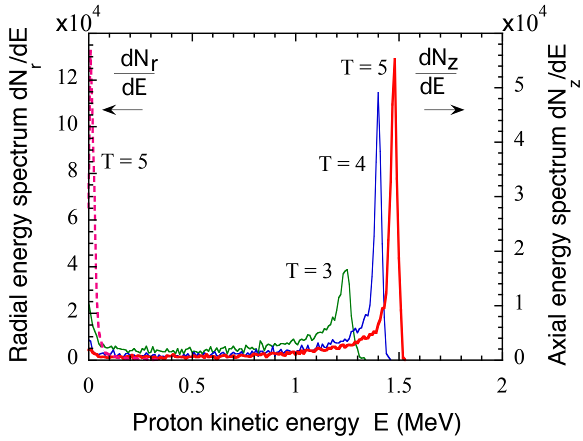

Fig.3 Temporal evolution of proton energy spectrum

for $T > 0$, where $T = t/t_0$ is the time normalized to the laser period $t_0 = 2.7$ fs for a titanium-sapphire laser at a wavelength of $l_L = 0.8\ \mu$m.

In Fig. 2, the field amplitude is $E_0 = 3 \times 10^{12}$ V m^{-1}, corresponding to a laser intensity of $I_L = 10^{18}$ W cm^{-2}. At such an intensity, the gold atoms are photoionized to a state of about $Z_{Au} = 20$, while the carbon and hydrogen atoms are fully ionized to $Z_C = 6$ and $Z_H = 1$, respectively. If the laser is irradiated from one side, the present scheme has an applicable upper limit ($I_L \sim 10^{20}$ W cm^{-2}) to keep high collimation performance, over which the ions are also accelerated by ponderamotive force along the same direction of the incident laser. The maximum ion energy is expected to increase with the system size and laser intensity according to the principles of a Coulomb explosion [4, 5].

4. Energy spectrum

Figure 3 shows temporal evolution of the proton energy spectrum in the axial (solid curves) and radial (dashed curve at $T = 5$) directions. Corresponding two-dimensional dynamics has been shown in Fig. 2. Quasimonoenergetic protons with an energy of $E_{max} =$ 1.5 MeV are produced at $T = 5$. If the hydrogen atoms are replaced by carbon atoms, the maximum ion energy increases to 10 MeV for the same target structure. The maximum energy can also be increased by enlarging the target size.

A good measure of the collimation is E_z/E_r, where E_z and E_r denote the average kinetic energies of the projectile ions in the axial and radial directions, respectively. In Fig. 3, $E_z \sim 1.4$ MeV and $E_r \sim 0.017$ MeV for the final stage of acceleration at $T = 5$, so that Ez/Er ~ 85, which indicates a strikingly high degree of collimation. Finally, the energy coupling efficiency h_c is an important index of the ion beam generation from an engineering point of view. It is defined as the ratio of the integrated kinetic energy of the projectile ions to the absorbed laser energy. In the present work, the values of h_c are of the order of 1% or less. By optimizing the design of the nanotube structure and laser parameters, h_c is expected to increase to several percent.

5. Summary

We have proposed an ion acceleration scheme using structured nanotubes, that operate under irradiance of ultrashort ultraintense laser pulses, to produce high-quality ion beams. Detailed three-dimensional particle simulation has demonstrated the generation of quasimonoenergetic highly-collimated 1.5-MeV proton beams. The present concept leads to a view of CNTs different from an existing one, that until now had only been considered to be solid-state devices. It has been demonstrated that spatial control in nanoscale fabrication is as crucial as temporal control in femto-scale laser operation. For further practical studies of the present scheme, it will be crucial that multiple nanotubes are uniformly produced in size and uniformly arranged in direction.

References

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