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Ion generation in a low-density plastic foam by interaction with intense femtosecond laser pulses

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Energetic proton generation in low-density plastic (C_5H_{10}) foam by intense femtosecond laser pulse irradiation has been studied experimentally and numerically. Plastic foam was successfully produced by a sol-gel method, achieving an average density of 10 mg/cm^3. The foam target was irradiated by 100 fs pulses of a laser intensity 1×10^{18} W/cm^2. A plateau structure extending up to 200 keV was observed in the energy distribution of protons generated from the foam target, with the plateau shape well explained by Coulomb explosion of lamella in the foam. The laser-foam interaction and ion generation were studied qualitatively by two-dimensional particle-in-cell simulations, which indicated that energetic protons are mainly generated by the Coulomb explosion. From the results, the efficiency of energetic ion generation in a low-density foam target by Coulomb explosion is expected to be higher than in a gas-cluster target.

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Recent progress in intense femtosecond lasers has revealed a new regime of laser-matter interactions known as nonlinear relativistic plasma physics. Energetic ions generated by this interaction are thought to be of interest to applications such as ion beam sources [1–3] or for inducing nuclear reactions in gases [4]. Ion emission processes can be divided into two categories. The first is ion acceleration through electrostatic forces, in which electrons are ejected from the plasma in the direction of a laser by $e\mathbf{v}\times\mathbf{B}$ force of the intense laser, generating a strong electrostatic field between the ejected electrons and ions in the plasma [1–3]. The second is the Coulomb explosion, in which cluster molecules in a gaseous target are instantaneously ionized by the intense ultrashort-pulse laser field (optical field ionization), inducing Coulombic forces that tear the molecule apart [4–7].

Ions generated by the Coulomb explosion are characterized by isotropic emission, while laser-accelerated ions exhibit beamlike emission. The ion energy distributions resulting from the two mechanisms are also quite different. Ions accelerated by the electron-induced electrostatic field generally exhibit a Boltzmann distributions of energies, $dN/dE \propto \exp(-E/kT_{\mathrm{h}})$, where T_{h} is hot electron temperature and k is the Boltzmann constant. Generally, a combination of Boltzmann distributions with different electron temperatures is needed. The energy distribution is then quite broad, with a maximum energy $E_{\max}$ of about $10kT_{\mathrm{h}}$. Ions generated by Coulomb explosion, however, exhibit an energy distribution of $dN/dE \propto E^{1/2}$ having a finite maximum $E_{\max}$ [5,6]. As an indicator of the efficiency of high-energy ion production, $\alpha(E)$ is defined as the fraction of emitted ions with energies between $(1-\xi)E$ and E. At $E=E_{\max}$ with $\xi=0.1$, $\alpha=7.8\times10^{-5}$ for ions accelerated by ejected electrons, whereas for the Coulomb explosion $\alpha=1.5\times10^{-1}$. The Coulomb explosion thus produces a much greater fraction of high-energy ions. However, due to the low density of the gases used, interaction rates are quite low, and so the overall efficiency of high-energy ion generation is much less than in the ejected electron method which takes place in over-dense plasmas. Although the Coulomb explosion is generally only induced in low-density gases by intense femtosecond lasers, it may be possible to induce the effect more efficiently in foam-structured material in which local density is high enough to support the Coulomb explosion, but average density is low enough to allow laser propagation. From the viewpoint of applications, Coulomb explosion profits nuclear reactions, such as D-D neutron generation and positron emitter production. Both the ion generation and the subsequent nuclear reactions between accelerated ions occur in the gas (or foam), therefore the laser beam can be guided directly into the reaction target. In the case of the beam emission from a laser-irradiated foil, the foil ion generator is separated from the nuclear reaction target, and some metal foil windows are necessary to extract the ion beam for the subsequent reaction.

In this paper measurement of the energy distribution of protons emitted from low-density plastic foam by intense laser interactions is presented. The observed energy distribution is discussed with reference to the cluster Coulomb-explosion model and two-dimensional (2D) particle-in-cell (PIC) simulations.

An ultralow-density plastic poly (4-methyl-1-pentene) foam target was prepared using the sol-gel-aerosol method reported previously [8], producing a foam with an average density of 10 mg/cm^3 and a lamella structure with a 20 nm period. The hydrocarbon plastic used to make the foam exhibits fine structure with the ultralow density, as shown in the electron micrograph of Fig. 1. The average density of 10 mg/cm^3 is 70% of the plasma cutoff density for 800 nm light. Thickness of the foam block target was ~100 μm with the product of density and thickness giving an area density equal to 2.5 μm thick Mylar ($H_8C_{10}O_4$) film, as was used in a previous ion generation experiment [3].

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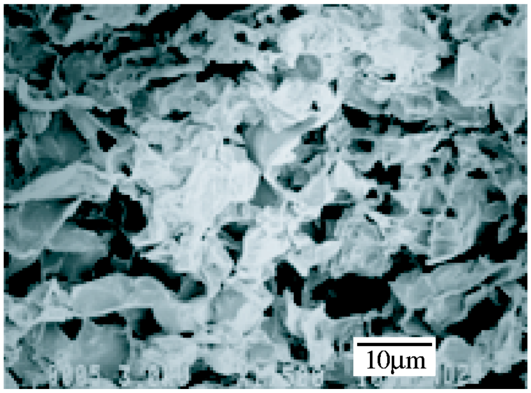

FIG. 1. Electron micrograph of a C_5H_{10} foam target. Average lamella thickness in the foam is ≈20 nm, and density is 10 mg/cm^3.

The experimental setup is shown in Fig. 2. Energy spectra of the protons emitted from the irradiated foam were measured using CR-39 nuclear track detectors fitted with metal filters. The CR-39 is sensitive to energetic protons in the range of 100 keV–10 MeV, but does not detect either energetic electrons or x rays. Spectra in the ranges 100–180 keV and 180–560 keV were obtained without and with a 0.8 μm thickness aluminum filter, respectively. In each energy range, the energy was more precisely resolved by microscopic examination of radiation track size. The size resolution is 2 μm and it corresponds to the energy resolution 7–8 keV. By microscopic examination of radiation track size, protons were easily discriminated from background noise. Heavier fast ions, such as nitrogen, oxygen, and carbon, were selectively filtered using aluminum filters a few micrometer thick. Seven detectors were set around the target, allowing the spatial distribution of proton emissions to be measured.

Experiments were conducted using the T^6 laser at the Institute of Laser Engineering [9], which is a Ti:sapphire chirped-pulse amplifier laser, delivering 150 mJ, 130 fs pulses at a wavelength of 0.8 μm and repetition rate of 10 Hz. Laser pulses were focused onto a 10 μm diameter spot (full width at half maximum of intensity) via a $F/3$ ($f = 16.5$ cm) off-axis parabolic mirror, giving a peak intensity of 1×10^{18} W/cm^2 across the spot. The laser was incident normally onto the surface of the foam target.

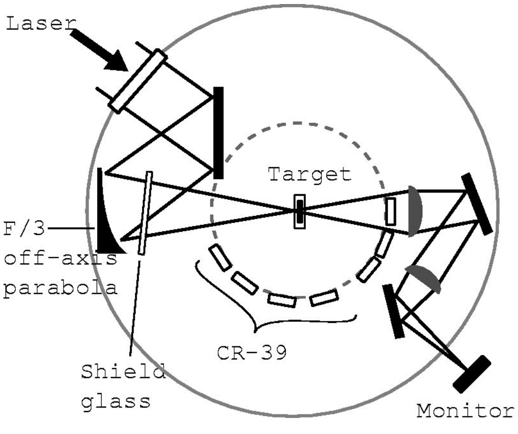

FIG. 2. Experimental setup.

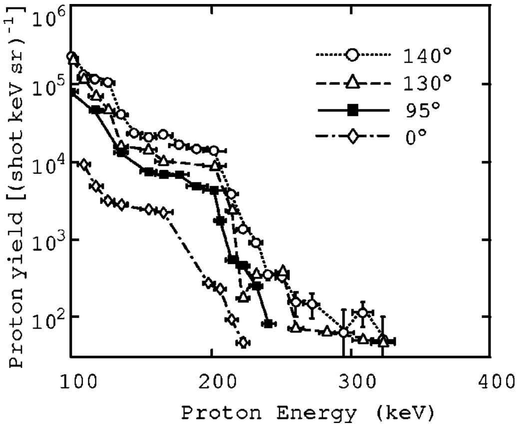

FIG. 3. Energy distributions of protons emitted from the foam at different directions for a laser intensity of 1×10^{18} W/cm^2.

Figure 3 shows the measured energy distribution of protons emitted from the laser-irradiated foam target. A remarkable plateau that ends at about 200 keV is evident. This kind of structure has not been seen in thin plastic film targets before. Although the foam structure is quite complex, for the purpose of analyzing the results, the foam is assumed to be composed of clusters. Then from the simple spherically uniform cluster model of Coulomb explosion given in Ref. [5], laser intensity I (10^{18} W/cm^2) required to expel all electrons from a cluster and resulting maximum ion energy $E_{\max}$ (MeV) are

$$a = 0.85\lambda I^{1/2} = 34 Z^{1/2} n^{1/2} R, \tag{1}$$

$$E_{\max} = 300 Z^2 n R^2, \tag{2}$$

where a is dimensionless amplitude of laser electric field, Z is the charge state of atoms composing a cluster, n is cluster density in 5×10^{22} cm^{-3}, R is cluster radius in micrometer and λ is laser wavelength in micrometer. In the present experiment, I is 1×10^{18} W/cm^2 and so $E_{\max}$ is 200 keV and R is 20 nm. Thus, $E_{\max}$ agrees fairly well with the edge of the energy plateau and R corresponds to the average thickness of the lamella structures in the foam. This suggests that Coulomb explosion of elements in the foam contributes to the plateau structure. However, the plateau energy distribution cannot fully be explained by this simple spherical cluster model. For a spherical explosion, the theoretical energy distribution is proportional to $E^{1/2}$. However, the foam elements are lamellar not spherical. For a one-dimensional explosion, the theoretical distribution is proportional to $E^{-1/2}$. The distribution in Fig. 3 can be qualitatively interpreted using this kind of nonspherical explosion [10].

Dynamics of the ions in the foam was studied using 2D PIC simulations with the code REMP [11]. The simulation area was 100 μm wide and 120 μm long, with a mesh size of 0.008 μm, giving mesh numbers of $N_x = 15\,000$ and $N_y = 12\,800$, where laser propagation is taken to be along the x axis. The foam structure was modeled as a 2D composite of randomly distributed bars. Assuming a number density of bars n_{bar} of $n_{\text{bar}}/n_{\text{cr}} = 140$, where n_{cr} is plasma critical density 1×10^{21} cm^{-3} for the 0.8 μm light, the number of bars is

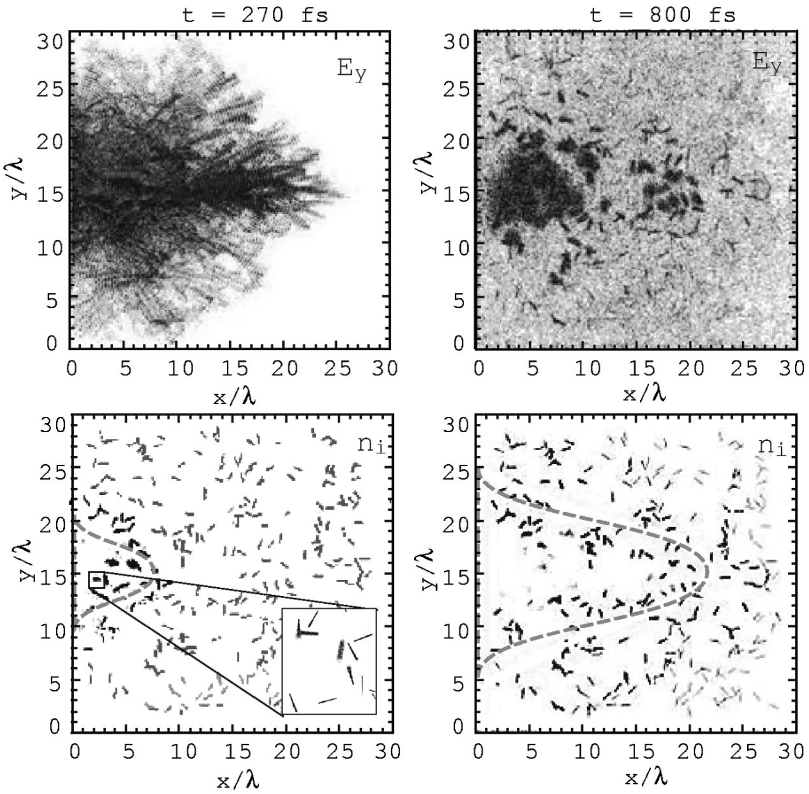

FIG. 4. 2D PIC simulation results showing spatial distributions of (a) electric field and (b) ion density at 270 fs and 780 fs after laser pulse arrived on the surface.

5 882, each of size $0.02\times 3\ \mu\mathrm{m}^2$. Each bar is composed of electrons, protons, and carbon ions in the ratio of 8:2:1. The laser pulse is linearly polarized, has a duration of 130 fs and the peak intensity $1\times 10^{18}\ \mathrm{W/cm}^2$. Laser spot size on the foam surface is assumed to be 8 μm. Simulations were done on the supercomputer NEC SX-5 in Cybermedia Center of Osaka University. Figure 4 shows ion density and electric field distributions at 270 fs and 780 fs after the laser pulse arrives on the surface. The laser light is scattered throughout the foam, widely in the area of about $30\ \mu\mathrm{m}\times 30\ \mu\mathrm{m}$. In the electric magnetic field, electrons are dynamically quivering, and the quivering radius can be significantly larger than the bar thickness. By the edge effect, the electric field is intensified at the bar edge and electrons are efficiently expelled as seen the Fig. 4. The significant part of electrons is swept from each bar in the area where the laser light is scattered. The remaining core is positively charged and can be no longer neutralized by hot electrons distributed in the wide area. The core ions are exploded and accelerated by Coulomb force repulsion (Coulomb explosion). Protons on the most outer layer acquire largest kinetic energy. Here, we cannot compare the experimental result with the present simulation on the energy distribution, because the simulation is limited in two dimension and the Coulomb-exploded ion energy distributions in two and three dimensions are quite different from each other. The present simulation, however, allows us to conclude that the lamellas (bars in the simulation) in the foam can be instantaneously ionized by the optical field, and they explode due to repulsive Coulomb forces. Figure 3 shows that proton emissions are largely uniform across the backward scattering directions, but are less uniform in the forward direction due to proton energy losses in the forward propagation through the foam. This is examined qualitatively by the simulation.

In previous experiments, a Mylar thin film was found to produce a broad Boltzmann energy distribution with $\alpha = 5.6\times 10^{-3}$ at $E = T_{\mathrm{h}}$, while for a cluster gas $\alpha = 6\times 10^{-2}$ at $E = E_{\max}$ [3,10]. Table I shows a comparison of ion yields of the Mylar film, foam, and cluster-gas targets with energy distributions drawn schematically. The number of ions having energies between E and $E+\Delta E$ are shown for $\Delta E/E = 0.1$. As expected, higher yields are achieved from the foam target than from the cluster-gas target. It should be emphasized that the foam target emits 40 times more ions ($E = E_{\mathrm{term}}$) than even the Mylar film ($E = T_{\mathrm{h}}$), where E_{term} represents the upper energy edge of the plateau. Thus the foam target is the most efficient ion emitter.

In conclusion, an intense femtosecond laser-foam interaction experiment was conducted. In the energy distribution of

TABLE I. Comparison of proton yields between Mylar film, foam, and cluster targets.

	Thin film	Foam	Cluster
Reference	[2]	This work	[14]
Target	$C_{10}H_8O_4$	C_5H_{10}	H-cluster
Average target electron density (cm^{-3})	$<1\times 10^{23}$	8×10^{20}	10^{18}–10^{20}
Laser intensity ($\mathrm{W/cm}^2$)	1.2×10^{18}	1×10^{18}	6×10^{16}
Laser energy (mJ)	300	150	150
Yield of protons	1.9×10^5	8.7×10^6	1.6×10^6
Proton energy (keV)	180–200	180–200	3.8–4.2

protons generated in the foam, a plateau structure with an edge was observed. The structure was interpreted by Coulomb explosion of lamellas forming the foam, and the Coulomb explosion dynamics was confirmed by the 2D PIC simulation. The foam target was demonstrated to be more efficient for emitting ions over a narrow-energy band than Mylar thin film or cluster-gas targets.

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