Neutral Beam Generation by Laser Irradiation of Thin Foils

Y. Wada*, T. Kubota* and A. Ogata*

*Graduate School of Advanced Sciences of Matter, Hiroshima University
1-3-1 Kagamiyama, Higashi-Hiroshima 739-8530, Japan

Abstract. We irradiated thin (< 10 μm) plastic and metal foils by a 1 TW, 50 fs, Ti³ laser. The foil surface was located at π/4 to the laser injection. Particle beams were obtained at both sides of the foil with respect to the laser injection. The beam at the rear side, flowing to the direction perpendicular to the foil surface, was insensitive to the magnetic field. Measurements using the track detector CR39 tell that it has small divergence (~ 200 mrad) and suggest that their particles could have high energies (up to 1 MeV). We therefore conclude that these particles make a neutral beam. To the contrary, ions were obtained at the same side of the foil with respect to the laser injection. They also have energies up to ~ 1 MeV, but larger angular distribution.

INTRODUCTION

High energy (> 100 keV) ion generations using high-energy (~ kJ) and long-pulse (~ ns) lasers with plasmas were reported in 1970s ~ 1980s [1]. Recent experiments have used high-power (> 10 TW) and short-pulse (< 1 ps) lasers with solid targets to generate ions with much higher energies (> 1 MeV) [2, 3, 4]. Many simulation studies have been made on this phenomenon [5, 6, 7]. These experiments and simulations indicate that lasers with intensities over 10¹⁷ W cm⁻² can generate MeV ions. High-energy electrons play an important role in the high-energy ion generation. Two mechanisms proposed for the high energy electron generation are “vacuum heating” [8] and “J x B ponderomotive acceleration” [9]. In the vacuum heating, p-polarized laser pulses push and pull electrons with quiver velocity across the boundary between vacuum and solid. In the J x B ponderomotive acceleration, ponderomotive force of the laser pushes electrons toward the laser direction. In both cases, pulled or pushed electrons form a cloud of electrons between the plasma and vacuum interface. Ions pulled by this cloud are accelerated to several MeV.

In this paper, we report similar experiments to irradiate thin (< 10 μm) plastic and metal foils by a laser with smaller power (1 TW) and shorter pulse width (50 fs). Our motivation had been to develop an ion source of an ion accelerator using a Ti³ laser. Though ions were obtained at the same side of the foil, neutral particles were obtained at the rear surface of the foil with respect to the laser injection. As far as we know, this is the first observation of the neutral particles by the interaction of a high power laser with a thin foil target.

In the next two sections, we describe the experimental apparatus and the experimental results. The following section discusses the results. The final section gives conclusions.
FIGURE 1. Experimental setup. CR39 plates are located at forward, backward and on-axis directions.

FIGURE 1 shows the experimental setup. The experiment was performed with 1 TW (50 mJ, 50 fs) Ti:Sapphire laser, 800 nm in wavelength and 10 Hz in pulse frequency. A main pulse is accompanied with a pre-pulse, whose power is ~ 1/2000 of the main. An f=300 mm lens located outside of a vacuum chamber focused the laser to a target in the chamber. Diameter and depth of the chamber are 400 mm and 200 mm, respectively. The surface of the target foil was located at π/4 to the laser injection. The laser intensity on the target was ~ 4 × 10^{16} Wcm^{-2}. Three types of materials were tried as the target foils; Mylar (C_{10}H_{8}O_4)n, polypropylene (C_{3}H_{6})_n and aluminum (Al). Their thickness was mostly less than 10 μm. Once penetrated by a laser pulse, a target foil was bored, so the foil frame was moved after each laser shot so that the laser pulse always irradiates a virgin surface. Typical vacuum in the chamber was ~ 10^{-3} Pa.

A CR39 was used to detect generated particles. It is a track detector sensitive only to ion (and neutron generated by recoil protons or carbons) [10]. An energetic ion cuts chemical bonds of the CR39. Chemical etching enlarges and exposes these radiation damages so that we can observe the resultant pits by using a microscope. Typical etching used 7N NaOH solutions at 70°C for 5 hours, but other combinations of etching conditions were also tried. About 5 ~ 20 μm of the CR39 surface was scraped away in this operation. The size of each pit enables us to estimate the energy of the particle, if the particles are identified and the size of a pit is calibrated to the beam energy beforehand. We had done so by using proton beams (0.5 ~ 2.4 MeV) of a Van de Graff accelerator in Hiroshima University.

A magnetic energy analyzer combined with a CR39 plate was used to measure energies of the charged particles. The analyzer consists of a pair of dipole magnets behind a 200 μm slit. The computer code MAFIA\(^1\) was used to estimate the tracks of the charged particles under the magnetic field. This setup was designed to detect down to 50 keV protons, 150 keV C^{6+} ions and 300 keV Al^{13+} ions. FIGURE 2 shows experimental setup for the energy analysis and the estimation of particle deflection. We also measured

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\(^1\) See http://www.cst.de
FIGURE 2. (a): Experimental setup of energy analysis. (b): Estimation of particle deflection by MAFIA.

spectrum of the scattered laser light.

**EXPERIMENTAL RESULTS**

**CR39 Measurement of Particle Distributions**

In order to measure particle distributions, we placed the CR39 plates in both forward and backward directions across the target, and also in the direction on the laser axis, as shown in FIGURE 1. In the forward and backward directions the CR39 plates accept particles generated in the normal direction against the target. In the on-axis direction, the CR39 plates accept particles on the laser axis. Each CR39 plate is located with distance of 40 mm away from the interaction point. FIGURE 3 shows a photograph taken at the moment of the laser irradiation, from the direction parallel to the laser axis and perpendicular to the foil surface, Al in 3 μm-thick in this case. It shows a fine but bright trace to the forward direction, besides the backward laser reflection.

The target irradiation left many particle tracks on the CR39 detectors in the forward and the backward directions, while few tracks in the on-axis direction. In the forward direction, the tracks were concentrated within angular divergence of ~ 200 mrad. On the other hand, tracks in the backward direction had a larger angular distribution (> π/2).

FIGURE 4 shows the number densities of etched pits in the forward(a) and the backward(b) directions. In the forward direction, the number of pits increases as the foil thickness decreases in each material. Aluminum targets got more pits than plastics. The total number of the pits was ~ 1 × 10^5 at the most in the plastic targets and ~ 6 × 10^5 in Al targets. In the backward direction, the number of pits had weak but opposite dependence on the foil thickness; i.e., the thicker targets give the more particles. The total number of the pits was ~ 1 × 10^6 at the most in the plastic targets, greater than the case of the forward direction, and ~ 6 × 10^5 in Al targets.
FIGURE 3. A photograph at the laser irradiation taken from the direction parallel to the laser axis and perpendicular to the 3 \( \mu \)m thick Al target foil surface.

FIGURE 4. The relation between the number density of etched pits and target thickness. (a): The forward direction. (b): The backward direction. Thickness of each target is 0.8 \( \mu \)m, 1.5 \( \mu \)m, 3 \( \mu \)m, 6 \( \mu \)m, 10 \( \mu \)m in Al, 1.6 \( \mu \)m, 3.4 \( \mu \)m, 5.8 \( \mu \)m, 8.7 \( \mu \)m, 12.3 \( \mu \)m in Mylar and 4 \( \mu \)m in polypropylene.

**Particle Energy Measured by a Magnetic Energy Analyzer**

FIGURE 5 shows the distribution of etched pits in the forward direction in the setup of FIGURE 2, caused by 10 laser shots irradiation onto an Al foil in 3 \( \mu \)m-thick. Distributions of the etched pits with and without the magnetic field coincided within statistical errors. Similar results were obtained in plastic targets. Because these particles are insensitive to the magnetic field, we have to conclude that they are neutral. On the other hands, particles in the backward direction were deflected to a certain degree by the magnetic field. FIGURE 6 shows their energy spectrum caused by the irradiation of 4 \( \mu \)m-thick polypropylene, under assumption that all the particles were protons. Maximum proton energy then became \( \sim 1 \) MeV.
FIGURE 5. Deflections of etched pits caused by the magnetic energy analyzer. White circles represent the distribution without magnetic field. Filled diamonds represent the distribution with magnetic field. Target was Al in 3 μm-thick. Note: X-axis shows not deflections (FIGURE 2) but positions on the CR39 plate.

FIGURE 6. The energy spectrum estimated from the magnetic deflection in backward direction. Target was polypropylene in 4 μm-thick. The reduced curve is \( \sim \exp[-E[\text{MeV}]/0.13] \).

DISCUSSIONS

Particles in Backward Direction

The particles in the backward direction were deflected by the magnetic field. Their energies range from \( \sim 50 \text{ keV} \) up to 1 MeV. These results are consistent with the hitherto experiments [1, 3] using lasers of \( \sim 10^{16} - 10^{17} \text{ Wcm}^{-2} \), except that the maximum energy of 1 MeV is somewhat high. This may be because the assumption is wrong that all the particles were protons. Generated particles can include carbon ions (in plastic targets) or aluminum ions (in Al targets). Carbon ions or Al ions with mass larger than proton are caused smaller deflection than protons with the same energy/nucleon. We are going to introduce a Thomson parabola to identify the charges of the particles.
Particles in Forward Direction

The particles in the forward direction are neutrals. We should discuss here the mechanism of their generation, but we have to refrain from it, because we do not have enough data. Only clues we have are traces left on CR39 plates.

The effect of the neutral atoms onto the CR39 detectors has not been reported so far. However, studies of CR39 response to D-T neutrons report that neutrons with energies between 0.1 and 1 MeV knock out hydrogen atoms consisting CR39 and these hydrogen atoms leave tracks an it[11]. The conversion efficiency from neutrons to hydrogen atom is very low, $\sim 10^{-4}$ pits/n.

We cannot tell the components of the neutrals at present. They can be hydrogens, carbons, oxygens, and/or metals. We can neither tell whether the neutrals form clusters or not. The sizes of pits etched on the CR39 plates are various. Some are smaller than, some are same with, and some are larger than those created by accelerator protons with energy in the $0.1 \sim 1$ MeV range. These pits distribute homogeneously. Covering a CR39 by an up-to $3 \mu$m-thick Al foil, we found that particles penetrated it leaving fairly large ($\sim 5 \mu$m in diameter) holes. If the sizes of these holes were comparable to the particle size, the particles could be clusters, although we can attribute these sizes to some heat process after the penetration.

It is a standard technique to derive particle energies from pit sizes left on the CR39, if we know what the particles are. What if we apply this technique assuming that protons have made the pits? Comparing their sizes with those caused by high-energy accelerator protons, we depicted energy spectra of particles in the forward direction as shown in FIGURE 7 (a). Their energies would range up to 1 MeV and their temperatures would range between 200 and 500 keV.

We have made another experiment to study the ability of penetration of particles, putting Al filters with in front of CR39 plates. The filter thickness was 0.8 $\mu$m, 1.5 $\mu$m, 3 $\mu$m or 6 $\mu$m. Dependence of the number of pits on the filter thickness is shown in FIGURE 7 (b). Some particles penetrated 6 $\mu$m thick Al. If the particles were protons, they would have kinetic energies over 600 keV and if Al$^{13+}$ ions they were over 18 MeV. The SRIM code$^2$ was used in these calculations of penetration.

The particles in the forward direction could be neutrons. However, we do not have any conditions favorable for production of neutrons [12]. Assuming that the neutral particles were atoms or molecules, we tried to strip electrons from them using carbon foils, 30 to 100 nm in thick, locating them in front of the magnetic analyzer. Such stripping foils have been used for the purpose of charge exchange in ionaccelerators[13]. The results were unsuccessful. We only observed that the particles were scattered without regard to the magnetic field. Improvement of the vacuum ($\sim 5 \times 10^{-5}$ Pa) at the target brought little change.

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$^2$ The program code can be downloaded from http://www.srim.org/
FIGURE 7. (a): Energy spectra of particles in the forward direction under the assumption that all the particles were protons. The targets were Mylars with various thicknesses. Error bars are given only for the case of 12.3 \( \mu \text{m} \) thickness, but other data points also have similar errors. (b): Dependence of the number of pits on the filter(Al) thickness. The target was 3.4 \( \mu \text{m} \)-thick Mylar or 3 \( \mu \text{m} \)-thick aluminum.

Further Experiments

Some experiments are under way and some are planned with the purpose of identifying the particles and clarifying their mechanism of generation. In order to identify the charged state of the particles in the backward direction, a Thomson parabola has been introduced.

Energies of the particles in the forward direction can be measured by the time-of-flight method. We have constructed a larger vacuum chamber to carry out in with a better resolution. The most probable origin of the neutrals is the recombination of ions and electrons. An optical spectrometer has been introduced study of the recombination radiation, or radiation from excited ions after the recombination.

Dependence of the neutral particle generation on the laser intensity has been also studied. In order to increase the laser intensity, a new off-axis parabola mirror will be introduced in a new vacuum chamber. The gratings of a compressor of the CPA will be changed to a dielectric type in a future.

FIGURE 8. Measurement of spectrum of the scattered laser light. (a): Experimental setup. (b): Typical spectrum of the laser light. The target was either a polypropylene foil in 4 \( \mu \text{m} \)-thick aluminum foil in 3 \( \mu \text{m} \)-thick.

We have measured spectrum of the scattered laser light using the optical spectrometer.
FIGURE 8 shows typical spectrum of the scattered light (b) together with the experimental setup (a). Some blue shifts were observed when the laser irradiated targets. We have some comments on the blue shift of the scattered laser light. We cannot tell if this blue shift is due to the same mechanism observed in past experiments [14, 15] due to interaction between an underdense plasma and a laser light.

CONCLUSIONS

We have detected neutral beams in the interaction between high intensity (< $10^{17}$ W cm$^{-2}$) laser and thin foil. The neutral beams were detected at the rear side of the foil with respect to the laser injection. They were concentrated in an angle of ~ 200 mrad, and possibly had fairly high energies. Ions were detected at the same side of the foil with respect to the laser injection. They have larger angular distribution and energies up to ~ 1 MeV if they were protons. We have to refrain from telling what are the components of the neutrals and what is the mechanism to generate them at present.

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REFERENCES