HIGH-QUALITY PROTON BEAM OBTAINED BY COMBINATION OF PHASE ROTATION AND THE IRRADIATION OF THE INTENSE SHORT-PULSE LASER *

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Abstract

Ion production from laser-induced plasma has been paid attention because of its very high acceleration gradient more than thousands times higher than that of conventional RF accelerator. Its energy spectrum, however, has 100 % energy spread up to now, which limited its application. We have succeeded in real-time measurement of proton signal with use of time-of-flight (TOF) measurement detected by a plastic scintillation counter for the first time, which was specially shielded from the heavy background induced by the intense pulse laser. A phase rotation scheme, which rotates the ions in the longitudinal phase space by an RF electric field synchronous to the pulse laser, was applied to proton beam up to 0.9 MeV emitted from Ti foil with 3 μm thickness irradiated by laser-pulse. Multi-peaks with $\sim$ 6 % width (FWHM) were created and intensity multiplication up to factor 5 was attained around 0.6 MeV region.

INTRODUCTION

A particle acceleration scheme using a laser-plasma interaction first proposed by Tajima and Dawson [1] has indicated a possibility to exceed largely a limitation of conventional accelerators. Proof-of-principle experiments of electron acceleration by the laser-plasma interaction have been performed at many laboratories . Studies on acceleration of ions by an irradiation of intense laser on solid target have also been reported . Such laser-driven particle beams exhibit unprecedented characteristics, which are short pulse lengths, high currents and low transverse emittance, but their energy spectra are Maxwell-Boltzmann distribution, which limited their real application. However, a quasi-monoenergetic electron beam has been observed in several experiments of a laser-plasma interaction [2] and a controllable way of the electron energy and their energy spectrum has been reported [3], recently. On the other hand, a quasi-monoenergetic ion beam has also been observed in experiments of intense laser irradiation on foil target [4, 5]. Now the laser-driven ion is one of the candidates to realize a downsizing of the apparatus for a hadron-therapy synchrotron to be replaced for the injector linac [6].

In the scheme for the production of the quasi-monoenergetic ion beam above mentioned, high-energy lasers operated by a single shot [4], or technical treatments on targets [5] in case of using low-energy lasers with high repetition rate, are required. Here, we report on a scheme of a generation of the quasi-monoenergetic proton beam with multi-peaks by combination between laser produced protons and an RF electric fields synchronous to the pulse laser. This scheme is based on a conventional technique called phase rotation. We also report on a real-time optimization of proton generation by the irradiation of intense short-pulse laser on a thin foil [8], which played an essential role for investigation of the phase rotation scheme.

REAL-TIME MEASUREMENT

For the purpose of energetic ion production by the irradiation of an intense laser on a foil target, the optimization of the various conditions, such as the laser parameters, material, position and thickness of the target and so on, has an important role. A solid-state track detector, for example CR-39 has mainly been utilized so far for the data analysis of ions produced by an intense laser. Because CR-39 has sensitivity only for heavy particles (ions, atoms, and so on), it is suitable for ion detection under heavy backgrounds as laser-light itself, laser-generated hard X-rays, self-emission light and electrons. The detection with the CR-39, however, needs rather longer time. Therefore, it had been difficult to optimize many parameters in detail in a rather limited available time of the laser.

To optimize the experimental parameters in the limited time, we measured the TOF of laser produced protons utilizing the signal from the scintillation counter [8]. The scintillation counter was attached to a photomultiplier tube through a light guide made of acrylic plastic, as shown in Fig. 1. A signal from the photomultiplier tube, operated with a current mode, was directly guided to a high-speed

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oscilloscope whose sampling ratio is 20 G/s. The scintillator is thin enough not to have sensitivity for X-rays but thicker than the stopping range of proton under 4 MeV. Evaporated aluminum layer with a thickness of $\sim$2 μm is coated on the front surface of the plastic scintillator in order to shut out any scattered light from the laser or plasma. Even though the sensitivity might be reduced for lower energy protons whose range is near the coated Al thickness, the Al filter played an essential role to discriminate signals due to protons from backgrounds. Between the detector and the target, two pair of dipole magnets are installed to prevent lower energy electrons from entering the detector. The field strength and the length of the dipole magnets are 0.03 T and 50 mm, respectively. The directions of the two dipole magnetic fields are opposite each other. The shift due to the pair of the magnetic fields is 2mm even for the proton having minimum energy for transmitting Al coated layer. Therefore, the effect on the energy measurements of these magnets is negligible.

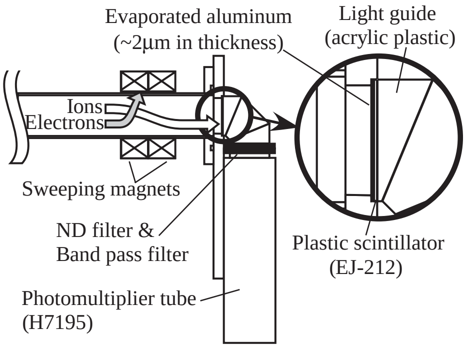

Figure 1: Schematic view of the plastic scintillation counter.

PHASE ROTATION SCHEME

The ion bunch with the energy spread, which is produced by an interaction between intense short pulse laser and foil target, is lengthened during its flight. At some distance from the production target, faster ions come earlier than slower ones. Applying decelerating RF electric field, which is synchronized to the laser, for the earlier arrived ions and accelerating one for the later arrived ions, we can compress the energy spread [7]. By application of this phase rotation scheme, the ion beams in the energy range of ± 5 % is expected to be compressed into the range within ± 1 % of our goal (see Fig 2).

For application of RF electric field, we use an RF-cavity: a quarter wave resonator with double-gaps, which was designed for the ions with center energy of 2MeV/u (see Table 1 for details). For synchronization with the laser pulse, RF frequency is made to be the same as the frequency of laser master oscillator (80.6 MHz). Because of the very short pulse width of this laser, we estimate that the initial time spread of ions is less than the order of 1ps. After passage of some distance, the time spread of whole ions becomes broad, although the time spread of ions with the same energy does not change. Comparing with a period of the RF applied for the phase rotation, this time spread is small enough and the ions with the same energy are applied the same electric field.

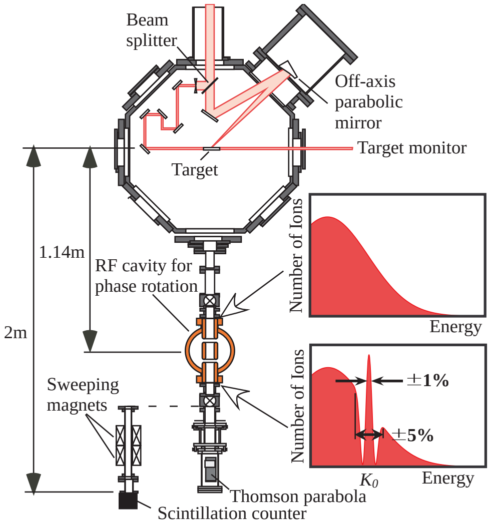

Figure 2: Schematic view of the experimental setup and the phase rotation scheme. Thomson parabola should be replaced by the scintillation counter in the TOF measurements.

Table 1: Cavity specification

Frequency	80.6 MHz
Gap voltage	100kV/gap (@30 kW)
Repetition	10 Hz
Pulse width	1 msec
Q value	2000
Structure	λ/4 resonator with 2 gaps
Drift tube length	100 mm
Gap length	20 mm
Aperture	ϕ 50 mm

EXPERIMENTAL SETUP

We used a Ti: Sapphire laser system, called JLITE-X, at Kansai Photon Science Institute, Japan Atomic Energy Agency, with a maximum energy of 350 mJ and a minimum pulse duration of 35 fs with 10 TW peak power. The central wavelength of the laser is 800 nm and the maximum repetition rate is 10 Hz. This system is based on a chirped-pulse-amplification technique. Figure 2 shows a schematic view of the experimental setup. A laser pulse, operated with 1 Hz, was focused with an off-axis parabolic mirror (OAP) with a focal length of 646 mm and an off-axis angle of 15 °. The laser pulse was incident on the target surface with an angle of 45 °. A thin foil tape target of Ti with a thickness of 3 or 5 μm and a width of 5 mm was utilized.

It can be rolled up for continuous irradiation with a rate of ∼5 mm/sec. The focal spot size was typically 11 × 15 μm (FWHM, horizontal × vertical) containing 23.5 % of the laser energy, giving a peak laser power density of up to 9×10^{17} W/cm^2. The protons produced by this intense laser were mainly emitted in the direction normal to the target with the spread of 10 ° (FWHM). Such protons are detected by a Thomson parabola ion analyzer (TP) or the scintillation counter (Fig. 2). Parallel magnetic and electric fields (0.16 T, 2×10^5 V/m) were applied in the TP which has a pinhole with a diameter of 0.3 mm to collimate the protons.

EXPERIMENTAL RESULTS

At first, we measured the TOF signal to optimize the experimental parameters. Figure 3(a) shows a typical TOF signal in the case of the Ti target of 3 μm in thickness with the optimized parameters. The pulse duration and the pulse energy were 250 fs and 240 mJ on the target, respectively, giving an intensity of 1.7×10^{17} W/cm^2. Taking sensitivity of the plastic scintillator into account, it is found that TOF measurement gives consistent results over 0.6 MeV with the measurement by the TP as shown in Fig 3(b).

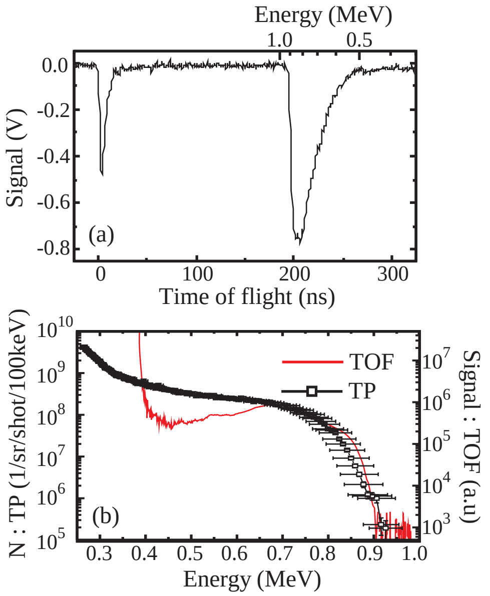

Figure 3: Typical TOF signal obtained by the photomultiplier (a) and energy spectra of protons (b) obtained by the photomultiplier and the TP in the case of the Ti target of 3 μm in thickness with an optimized parameter.

After the optimization of various parameters by the TOF measurements, the proton energy spectrum, of which the maximum energy was over 0.9 MeV in Fig. 3(b), was obtained by the TP integrated over 120 laser shots. On the same experimental parameter, the RF-voltage was applied and rotated the proton beam. As a result, the quasi-monoenergetic proton beams were obtained as shown in Fig. 4(a), and the position of the energy peaks were known to be determined by an initial phase of the RF (Fig. 4(b)). The peak width around 0.6 MeV region was obtained ∼ 6 % (FWHM), which is the narrowest energy peak up to now.

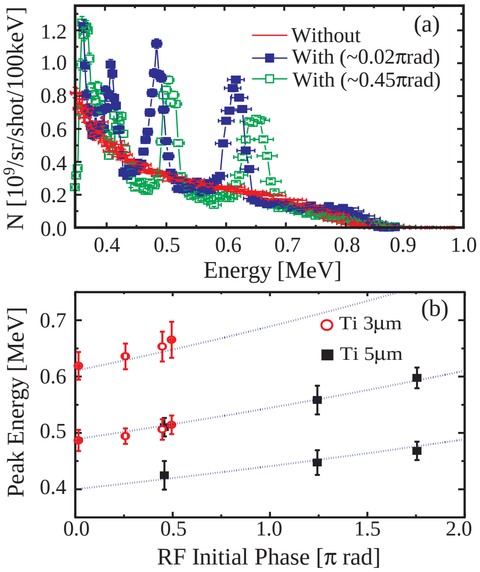

Figure 4: Energy spectra of protons with and without the phase rotation scheme in the case of the Ti target (3 μm) (a) and peak energy dependence on RF initial phase (b).

SUMMARY

We could generate quasi-monoenergetic proton beam from a thin foil target of Ti with a thickness of 3 μm and 5 μm by employing an intense short-pulse laser using the phase rotation scheme. The energy peaks of the protons could be chosen by adjusting the phase of the RF electric field relation to the pulse laser. The real-time measurement by the TOF plays a significant role to optimize the proton energy spectrum quickly. As a result, the conditions of the laser and the target parameter could be determined efficiently in real-time.

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