Evaluation of laser-driven ion energies for fusion fast-ignition research

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We investigate laser-driven ion acceleration using kJ-class picosecond (ps) laser pulses as a fundamental study for ion-assisted fusion fast ignition, using a newly developed Thomson-parabola ion spectrometer (TPIS). The TPIS has a space- and weight-saving design, considering its use in an laser-irradiation chamber in which 12 beams of fuel implosion laser are incident, and, at the same time, demonstrates sufficient performance with its detectable range and resolution of the ion energy required for fast-ignition research. As a fundamental study on laser–ion acceleration using a ps pulse laser, we show proton acceleration up to 40 MeV at 1 × 10¹⁹ W cm⁻². The energy conversion efficiency from the incident laser into protons higher than 6 MeV is 4.6%, which encourages the realization of fusion fast ignition by laser-driven ions.

Subject Index J20, J25, J27

1. Introduction

The acceleration of energetic (> 1 MeV) ions driven by relativistic-intensity (> 10¹⁸ W cm⁻²) laser pulses [1,2] is attracting much interest from the point of view of realizing a novel source of intense ions for ion-driven fast ignition [3–5]. Fusion fast ignition assisted by laser-driven ion beams requires 10 kJ energy deposition onto fuel cores with ~ 500 g/cm³ densities, when a kinetic energy of 10–30 MeV/u is required for the ions.

The investigation into laser ion acceleration was triggered by studies on the target normal sheath acceleration (TNSA) mechanism [6–9], where relatively thick (~ μm) solid foils are used as the targets and the ions on the target rear surface (opposite the laser-irradiated side) are accelerated by the charge separation field reaching ~ 1 MV/μm. Currently, there is a great deal of interest in other mechanisms of ion acceleration, including radiation pressure acceleration (RPA) [10–12], magnetic vortex acceleration (MVA) [13–17], and so on. Most of the experimental investigations above were performed using laser pulses with durations ranging from 10 to 500 femtoseconds (fs).

From the viewpoint of fast ignition, higher laser energy is desirable because the energy conversion efficiency from laser into ions linearly depends on the laser energy [18]. However, because of the damage limit of optical systems, it is not easy to achieve kJ-class laser energy in fs pulse duration. One promising way to achieve kJ-class laser energy is to use picosecond (ps) laser pulses. However, there have been only a few studies [18,19] on the ion acceleration by kJ-class ps lasers.
In this study, we investigate laser-driven ion acceleration using kJ-class ps laser pulses delivered from LFEX [20], known as one of the world’s most powerful laser facilities. In order to evaluate the energy distribution of laser-accelerated ions, we have developed a Thomson-parabola ion spectrometer (TPIS) [21,22], which was designed to analyze the kinetic energy of protons up to 80 MeV with sufficient resolution. We performed energy calibration of the TPIS on-site using LFEX laser shots. As a result, protons accelerated up to 40 MeV were successfully analyzed. We also evaluate the energy conversion efficiency from the laser into protons higher than 6 MeV, reaching 4.6% (46 J of a 1 kJ laser), followed by discussion on the mechanism of proton acceleration in the ps region as a comparison with the TNSA scheme.

2. Development of the Thomson parabola

2.1. Experimental setup

The laser-driven ion acceleration experiment was performed using the LFEX laser at Osaka University. The setup is shown in Fig. 1. LFEX delivers laser pulses with a duration of 1.5 ps (FWHM), a central wavelength of 1.05 μm and an energy of 800–1000 J. The pulse is focused by an F/10 off-axis parabolic mirror (OAP) onto the target placed in the center of the spherical vacuum chamber. The laser intensity reaches $1 \times 10^{19}$ W cm$^{-2}$. As shown in Fig. 1(b), the laser pulse is normally incident on a 5 μm thick aluminum foil, and the ions accelerated from the rear side of the target are observed by the new Thomson-parabola ion spectrometer (TPIS) located in the normal direction of the target rear surface. In a future experiment on fast ignition (Fig. 1(c)), the laser-accelerated ions will be injected into the fusion fuel imploded by the beams of a Gekko-XII laser system, whereas the LFEX
laser is focused on the target foil located inside a cone-shaped structure shielding the implosion plasma.

Figure 2(a) shows a schematic picture of the TPIS. The TPIS consists of static electric and magnetic fields that are oriented parallel to each other. The ions, accelerated in the z-axis direction, as shown in the figure, are collimated by a pinhole made on a 20 mm thick tungsten plate and pass through the electric and magnetic fields. The ion trajectory is bent in the x and y directions according to its charge-to-mass ratio \( Q/A \) (\( Q \) and \( A \) are the charge number and the mass number of the ions, respectively) and measured on a detection device as a parabolic curve (Fig. 2(b)), where the ion energy is determined by the displacement along the x axis. The static magnetic field is applied by a pair of neodymium permanent magnets with a length of \( L_1 = 200 \) mm. The areal average of the magnetic field is around 0.8 T. The electric field (15 kV/cm at maximum) is supplied by parallel plate electrodes placed between the two magnets. The distance between the magnets and detection device is set to be \( L_2 = 125 \) mm. As a detection device, we use an imaging plate (IP), BAS-TR 2025 from Fuji Photo Film Co. Ltd according to Ref. [23].

By using the permanent magnets, our TPIS is free of the complicated high-current-circuit and cooling-water-loop systems seen in electromagnets. In order to realize further space-, weight-, and cost-saving designs, we downsized the permanent magnets in the x direction by shifting the entrance position of the ions by 20 mm from the center line of the magnets, as shown in Fig. 2(a). We successfully performed energy calibration of ions passing through the magnetic field asymmetrically in the x direction; see the next subsection for details.

2.2. Energy analysis and calibration

Ion trajectory in the TPIS is governed by the following equation of motion under a static electric field \( \mathbf{E} = (0, E, 0) \) and a magnetic field \( \mathbf{B} = (0, B, 0) \):

\[
\frac{d\mathbf{p}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}),
\]

where \( q \) is the charge number, and \( \mathbf{v} \) is the velocity of ions. \( \mathbf{p} = \gamma m \mathbf{v} \) is the momentum of an ion with a static mass \( m \). \( \gamma = 1/\sqrt{1 - (\mathbf{v}/c)^2} \) is the Lorentz factor and \( c \) is the speed of light in vacuum. In the nonrelativistic case, when the kinetic energy of the ions is sufficiently smaller than \( mc^2 \), the lateral displacements in the x and y directions are given by

\[
x = \frac{qB}{2mv_z}L_1(L_1 + 2L_2)
\]

\[
y = \frac{qE}{2mv_z^2}L_1(L_1 + 2L_2)
\]
Fig. 3. (a) A schematic picture of copper filters over the IP detector and (b) raw data obtained in the experiment. A proton with energy higher than 11.5 MeV can reach the IP for a 300 \( \mu \)m thick copper filter.

in the detection device. \( v_z \) is the initial velocity of ions in the \( z \) direction. Then, we obtain the following relation between \( x \) and \( y \):

\[
y = \frac{2mE}{qB^2L_1(L_1 + 2L_2)x^2}
\]  

(4)

and the initial kinetic energy of ions

\[
\epsilon = \frac{1}{2m} \left\{ \frac{qBL_1(L_1 + 2L_2)}{2x} \right\}^2.
\]

(5)

One can see in Eq. (5) that the strength of the magnetic field is of crucial importance for determining the ion energy. However, spatial distribution of the magnetic field is not uniform on the \( x-z \) plane. The field strength has a peak around the magnet’s center and spreads beyond the magnet’s edge. Hence, it is necessary to calibrate the relationship between the lateral displacement on the detector and the energy of the ion passing through the actual magnetic field spread. We performed the calibration by determining the energy of protons stopped by a thin metal filter covering the IP detector. In Fig. 3(a), we used copper filters with two different thicknesses, 300 and 400 \( \mu \)m. Then, the proton signal shows a noncontinuous parabolic curve, as shown in Fig. 3(b). Here, the proton energy is higher when the \( x \) position is smaller. In the region covered by the 300 \( \mu \)m thick copper (\( x = 80–90 \) mm), protons with energy lower than 11.5 MeV never reach the IP, which is confirmed by a particle simulation with SRIM code [24]. Note that the incident angle of ions onto the filter is taken into account on the SRIM calculation. Therefore, we can identify the left end position of the signal, \( D_B = 83.8 \pm 0.3 \) mm in this case, corresponding to the actual lateral displacement for the 11.5 MeV protons. The values of \( D_B \) are determined for several ion energies of protons and carbons, as shown in Table 1.

As a next step, we newly define the effective strength of the magnetic field \( B_{\text{eff}} \), assuming a uniform value over the magnet region with the length \( L_1 \), but completely zero outside the magnets. \( D_B \) has a
Table 1. The result of stopping power obtained from the SRIM calculation, the displacement in the x direction and the effective strength of the magnetic field obtained from the experiment on different filters and ion species.

| Filter         | Ion     | $D_B$ [mm] | $\epsilon_{\text{min}}$ [MeV/u] | $B_{\text{eff}}$ [T] |
|----------------|---------|------------|----------------------------------|----------------------|
| Al (100 $\mu$m) | C$^5^+$ | 46.5 ± 0.3 | 6.28 ± 0.19                      | 0.885 ± 0.018        |
| Al (100 $\mu$m) | C$^6^+$ | 55.9 ± 0.3 | 6.30 ± 0.19                      | 0.882 ± 0.018        |
| Al (100 $\mu$m)+RCF | H$^+$ | 105 ± 0.7 | 6.40 ± 0.19                      | 0.790 ± 0.010        |
| Cu (300 $\mu$m) | H$^+$   | 83.8 ± 0.3 | 11.5 ± 0.35                     | 0.882 ± 0.018        |
| Cu (400 $\mu$m) | H$^+$   | 76.8 ± 0.3 | 13.4 ± 0.40                     | 0.867 ± 0.017        |

Fig. 4. The effective strength of the magnetic field $B_{\text{eff}}$ for the actual lateral displacement in the x direction.

different value for each ion energy and species according to

$$B_{\text{eff}} = \frac{2D_B \sqrt{2m\epsilon_{\text{min}}}}{qL_1(L_1 + 2L_2)}, \quad (6)$$

where $\epsilon_{\text{min}}$ is the minimum kinetic energy with which the ion can be detected by the IP, which is calculated with the SRIM simulation. The relation between $D_B$ and $B_{\text{eff}}$ is summarized in Table 1 and Fig. 4. Here, the error bar on $D_B$ represents the spread of ions on IP after passing through a pinhole of 0.5 or 1 mm in diameter. The error of $\epsilon_{\text{min}}$ corresponds to the deviation originating from the Energy Struggling of ions passing through the filter. The errors on $D_B$ and $\epsilon_{\text{min}}$ are both taken into account for the evaluation of the $B_{\text{eff}}$ errors.

In Fig. 4, we derive a universal curve of $B_{\text{eff}}$ as a function of the lateral displacement along the x axis $D_B$ in the form of

$$B_{\text{eff}} = a_0 + a_1 D_B + a_2 D_B^2, \quad (7)$$

where the coefficients are determined to be $a_0 = 7.35 \times 10^{-1}$, $a_1 = 4.93 \times 10^{-3}$, and $a_2 = -3.97 \times 10^{-5}$ by fitting the data points. Here, one can see that ions laterally displaced with $D_B \simeq 60$ mm feel the highest effective field strength. This is a result of the ions passing through the vicinity of the magnets’ center, which generates the highest magnetic field.

By using Eqs. (6) and (7), we accurately convert the lateral displacement $x$ into the kinetic energy of ions. The results are summarized in Fig. 5, where the displacement along the x direction is shown...
for proton (p) and carbon ions $C^{Q+} (Q = 1–6)$ as a function of the kinetic energy of the ion in units of MeV/u. As seen in Table 1, the minimum value of $D_B$ is observed to be 46.5 mm for the $C^{5+}$ ion. Turning to Fig. 5, the displacement $x = 46.5$ mm corresponds to the proton energy around 35–40 MeV. This fact ensures that our TPIS is well calibrated for proton energies up to 40 MeV.

The novelty of our TPIS is that by the benefit of the sub-tesla-class magnetic field of permanent magnets, our TPIS can analyze high-energy protons up to 80 MeV with a relatively compact system. In Ref. [22], the length between the pinhole and the detector was 24 cm and the highest measurable energy was 10 MeV for protons. On the other hand, the length in our case is comparable to that of Ref. [22] (35 cm), although its analyzable proton energy is much higher (80 MeV).

2.3. Evaluation of energy resolution

The energy resolution of TPIS is governed by several parameters including the strength of the magnetic field, the length of the ion flight path, and the diameter of the pinhole. In general, stronger magnetic field or longer ion flight path lead to higher energy resolution. On the other hand, larger pinhole diameter, which leads to larger beam size on the detector, degrades the energy resolution. Here, we determine the energy resolution as a function of the pinhole diameter. The energy resolution $\delta E_{\text{kin}}/E_{\text{kin}}$ can be written as in the following equation:

$$
\frac{\Delta E_{\text{kin}}}{E_{\text{kin}}} = \frac{2S_{\text{ion}}}{D_B[1 - (\frac{S_{\text{ion}}}{2D_B})^2]^2} \approx \frac{2S_{\text{ion}}}{D_B},
$$

where $S_{\text{ion}}$ is the diameter of a virtual, monoenergetic ion beam being collimated by the pinhole. On the detector, $S_{\text{ion}}$ is given as a diameter of the pinhole image of the ion source according to

$$
S_{\text{ion}} = S_{\text{laser}} + (1 + b/a)(\phi - S_{\text{laser}}),
$$

where $a$ is the distance from the target to the pinhole, $b$ is the distance between the target and the pinhole, $\phi$ is the pinhole diameter, and $S_{\text{laser}}$ is the focal diameter of the laser, which roughly corresponds to the size of the ion source. Figure 6 shows the energy resolution $\Delta E_{\text{kin}}/E_{\text{kin}}$ for protons $(Q/A = 1)$ and $C^{6+}$ ions $(Q/A = 1/2)$ with pinhole diameters of 0.5 or 1 mm. One can see that $\Delta E_{\text{kin}}/E_{\text{kin}} = 1.4\%$ is obtained for 30 MeV protons with the 0.5 mm pinhole.
Fig. 6. Comparison of energy resolution for protons ($Q/A = 1$) and $C^6+$ ions ($Q/A = 1/2$) with a pinhole diameter of 0.5 or 1 mm.

Fig. 7. The calculated parabolic curves of protons and carbon ions with a pinhole diameter of 0.5 mm at the IP. Only ions that avoid colliding with the electrodes and reach the IP are shown. The inset shows the actual IP signal of protons around 40 MeV, which corresponds to the maximum energy cutoff seen in Fig. 9.

Figure 7 shows the parabolic curves of ions arriving at the detection surface calculated for the 0.5 mm pinhole. Here, the width of the parabolic curves corresponds to $S_{ion}$ seen in Eq. (9). As seen in the inset, the width of the parabolic curve obtained in the experiment is around 400 μm, which is close to the calculated width $S_{ion} = 370$ μm. It is found that the line of $C^6+$ ions (blue) encounters the $C^5+$ line (green) around $x = 47$ mm, when the energies of $C^6+$ and $C^5+$ are 8.8 and 5.8 MeV/u, respectively. This fact indicates that $C^6+$ and $C^5+$ ions can be distinguished when their energies are lower than 8.8 and 5.8 MeV/u, respectively. In the same way, the proton line (red) overlaps those of carbon ions when its energy reaches 80 MeV, indicating that protons up to 80 MeV can be analyzed independently of the signals for heavier ions.

2.4. Calibration of imaging plate on the signal intensity

In order to acquire the absolute number of ions detected on the IP, we have performed the calibration according to the following procedure. The IPs were scanned using a commercial IP reader (Typhoon FLA 7000, GE Healthcare, Japan) with 16 bit resolution, which was converted from the quantum level (QL) to photo-stimulated luminescence (PSL) using the formula given by

$$PSL = \left( \frac{Z}{100} \right)^2 \times \left( \frac{4000}{S} \right) \times 10^{L(QL/2^{16}-1/2)},$$

(10)
Fig. 8. The relation between incident ($W_{\text{pre-filter}}$) and transmitted energy ($W_{\text{IP}}$) for protons (black), carbon (blue), and oxygen ions (red) as obtained by SRIM.

where $Z = 25$ (in units of $\mu m$) is the pixel size, $S$ is the sensitivity of the scanner, and $L = 5$ is the number of digits.

The PSL signals fade away along time after exposure due to the spontaneous decay of excited electrons in the IPs. This fading effect, found on the BAS-TR-type IPs, has been examined by several groups [25–28], showing that the PSL is reduced to 80% 20 min after the irradiation time. We determine the PSL value 20 min after the irradiation (PSL$_{20}$) according to $\text{PSL}_0 = \text{PSL}_{20}/0.8$.

The number of protons ($N$) bombarding the IP correlates with the PSL 0 through the following calibration function [25]:

$$\frac{\text{PSL}_0}{N} = 0.333\ 57 W_{\text{IP}}^{-0.913\ 77} \quad \text{for} \quad W_{\text{IP}} > 5 \text{ MeV}. \quad (11)$$

Here, $W_{\text{IP}}$ is the kinetic energy of protons arriving at the IP after passing through the filter covering the IP surface. In our experiments, IPs are covered with an aluminum filter with a thickness of 100 $\mu m$ in order to decrease the signals of background radiation, including Bremsstrahlung X-rays generated from the laser–target interaction chamber. The relationship between $W_{\text{IP}}$ and the proton energy before entering the aluminum filter ($W_{\text{pre-filter}}$) is evaluated with the Monte Carlo code SRIM [24], when the incident angle of the protons onto the filter is taken into account. As seen in Fig. 8, a 10 MeV proton, for instance, is decelerated to 8 MeV when it arrives at the IP surface.

As the final step, we obtain the number of protons as a function of their kinetic energy in the form of $dN/dE_{\text{kin}}d\Omega$, where $E_{\text{kin}}$ is the energy of protons (corresponding to $W_{\text{pre-filter}}$) and $d\Omega$ corresponds to the opening aperture of the pinhole, $1.851 \times 10^{-4}$ millisteradian (msr).

3. Proton energy spectrum

A typical energy distribution of protons analyzed by the TPIS is shown in Fig. 9. The proton spectrum was obtained with a laser pulse of 930 J, 1.5 ps (FWHM) focused on a 5 $\mu m$ thick aluminum foil target. The laser intensity reaches $1.1 \times 10^{19}$ W cm$^{-2}$ at the peak. One can clearly see that the protons have a continuous energy distribution spreading up to the cutoff at 40 MeV. It is worth noting that the cutoff energy (40 MeV) significantly exceeds the framework of a conventional TNSA model [29] predicting about 30 MeV proton acceleration under the laser parameters used in this experiment. The enhancement of the maximum proton energy can attributed to the effect of temporal evolution of the electron temperature [30] caused by the nonlinear interaction between the laser and plasma.
Fig. 9. A typical spectrum of laser-accelerated protons obtained in the experiment with the LFEX laser pulse focused on a 5 μm thick aluminum foil target.

In the spectrum, one can see a signal drop on the proton number around 8 MeV. We have to emphasize that the signal drop is attributed to physical phenomena, not to any problem or error on our TPIS system, because we found no signal decrease around 8 MeV in our previous work [30] using the same TPIS as the present paper. One candidate for the physical mechanism underlying the peak structure around 10 MeV in our spectrum is shock acceleration from the front side of the target [31]. According to this scheme, protons can be accelerated by the shock of the $\sim 10^{19} \text{ W cm}^{-2}$ laser up to 5 MeV. These shock-accelerated protons may again be accelerated by the electric field on the target rear surface and reach 10 MeV. To demonstrate the scenario above, however, requires more precise discussion involving particle-in-cell simulation performed on a ps timescale, which is beyond the scope of this paper.

4. Discussion

From the viewpoint of fast ignition by laser-driven ions, it is of crucial importance to determine the conversion efficiency from the laser energy into the ion’s kinetic energies. For this purpose, we measured the angular distribution of the protons with radiochromic film (RCF) stack detectors. The RCF stack detectors were placed in the normal direction of the target rear surface. Therefore, the TPIS result shows the proton energy distribution at the center point of the proton areal distribution. Note the RCF measurement was performed in a different laser shot from the TPIS measurement. The protons were recorded in an almost isotopic shape along the target normal axis. The cone angles (FWHM) of the proton divergence were obtained for each RCF by averaging the values in the vertical and horizontal directions. One can find the result in Ref. [30]. The cone angle can be expressed as a function of the proton energy $E$ as

$$\Omega(E) = 1.174 - 1.171 (E/E_{\text{max}}) \ [\text{sr}],$$

where $E_{\text{max}}$ is the maximum proton energy measured. This result is consistent with a universal curve in the literature [32]. Here, we obtain the energy conversion efficiency $CE$ from the laser into protons via

$$CE = \frac{1}{E_l} \int_{E_{\text{min}}}^{E_{\text{max}}} \Omega(E) \frac{dN}{dE} dE,$$
where \(dN/dE\) is the proton number distribution observed by TPIS and \(E_L\) is the laser energy in units of MeV. We set the lower limit of the integration region on the proton energy to be \(E_{\text{min}} = 6\ \text{MeV}\). As a result, we obtain \(CE = 4.6\%\) from the proton spectrum of Fig. 9. It is noteworthy that identical values of CE have been reported for the laser intensity around \(10^{20}\ \text{W cm}^{-2}\) [18]. On the other hand, in our study, a conversion efficiency close to 5\% is obtained at \(10^{19}\ \text{W cm}^{-2}\) intensity. The mechanism underlying the high efficiency is explained by the long pulse duration exceeding 1 ps [33].

In our scheme, a 1 kJ, \(10^{19}\ \text{W cm}^{-2}\) laser generated protons of \(\sim 50\ \text{J}\). Assuming that the laser–proton energy conversion efficiency is maintained around 5–10\% with higher laser energy, then 5–10 kJ protons can be generated by a 100 kJ, \(10^{21}\ \text{W cm}^{-2}\) laser pulse. This scenario indicates that fusion fast ignition assisted by protons, under the condition discussed in the introduction, can be realized by a laser facility on the border of what can be reached by current technology.

5. Summary

We have developed TPIS for the investigation of fusion fast ignition assisted by laser-driven MeV ions. The TPIS was calibrated on-site using the world’s highest-power laser facility, LFEX, and demonstrated the performance on its detectable energy range (up to 80 MeV for protons) required for fusion fast-ignition research (up to 30 MeV). In the experiment, which was performed as a fundamental study on laser–ion acceleration using a ps pulse laser, we have succeeded in accelerating protons up to 40 MeV at \(1 \times 10^{19}\ \text{W cm}^{-2}\). This result exceeds the conventional scaling law based on the TNSA model [29]. The energy conversion efficiency from the laser into kinetic energies or protons higher than 6 MeV was measured to be 4.6\%. These results can be a milestone toward the realization of fusion fast ignition by laser-driven ions.

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