Energetic electron and ion beam production from ultrashort intense laser-plasma interactions shows promise for application in radioisotope production for positron emission tomography [1, 2]. The experiments in this work employed an infrared subpicosecond laser, e.g., a Nd:glass laser ($\lambda = 248$ nm) or a Ti:sapphire laser ($\lambda = 800$ nm) for two main reasons. The first reason is technical: it is difficult to produce an ultraintense laser with other wavelengths. However, KrF laser systems ($\lambda = 248$ nm) could produce irradiance intensities of the order of $10^{18}$ W/cm$^2$ [3, 4]. The second reason is due to the $I\lambda^2$-scaling laws [5], where $I$ is the laser intensity and $\lambda$ is the laser wavelength. The $I\lambda^2$-scaling laws indicate an advantage in using long wavelength lasers to generate energetic particles. In our previous paper [6, 7], we stated that the interaction of intense laser pulses with solid-density plasmas is not governed solely by the $I\lambda^2$-scaling laws.

Typically, an ultrashort intense laser pulse has a prepulse or pedestal. Therefore, a controlled or uncontrolled underdense preplasma forms in front of a solid-density target before the main pulse arrives at the target surface. The scale length of the underdense preplasma strongly influences the energetic electrons produced by the laser-plasma interaction [8].

In this study, we investigate the interaction of an intense ultrashort laser pulse with finite scale-length dense plasmas at normal incidence, using one dimensional particle-in-cell (1D PIC) simulation code [9]. The effects of various laser wavelengths on laser absorption and energetic electron and ion production are characterized.

In the simulation, the parameters used for the laser pulse were as follows: a sine-squared envelope with a duration of 400 fs (i.e. the width at half maximum is 200 fs), irradiated intensity $I = 5 \times 10^{18}$ W/cm$^2$, and three different wavelengths $\lambda = 0.25, 0.5, \text{ and } 1 \mu$m. The schematic of the density profile used in the PIC code is shown in Fig. 1. A thin target is expressed by an ion density of $1 \times 10^{22}$ cm$^{-3}$, mass number $A = 100$, and effective charge $Z = 10$ with a thickness of 0.3 $\mu$m. Preformed plasma sets are positioned at the front of the laser incidence. The preformed plasma, where $A = 12$ and $Z = 6$, has temperature 1 keV and an exponentially decreasing density profile $n_0 \exp(-x/L)$, where $n_0 = 2 \times 10^{22}$ cm$^{-3}$ is the density at the interface between the thin target and preformed plasma, and $L$ is the scale length of the preformed plasma. The scale length is varied from $L = 1-2.5 \mu$m. Protons are positioned behind the rear surface to investigate ion acceleration because of a high-energy electron sheath formed at the rear surface [10]. The protons have a density and thickness of $1 \times 10^{22}$ cm$^{-3}$ and 0.1 $\mu$m, respectively.

At all laser wavelengths and scale lengths, the laser pulse interacts with the preformed plasmas at a critical density, this implies, the pulse does not interact with the solid target. The interaction point varies with the wavelength, and the critical density for $\lambda = 0.25 \mu$m is 16 times higher than that for $\lambda = 1 \mu$m.

![Fig. 1 Schematic of the density profile used in the particle-in-cell code.](image-url)
temperature of the high-energy electron is low. The energetic electrons created by the laser-plasma interaction using a 1D-PIC simulation code. Multi-dimensional effects, such as surface deformation [5], are important in experiments. These simulations assume the ideal and collisionless plasma. In addition, electron transport in a solid-density target is affected by resistivity, which depends on the material used in experiments. Relatively low-energy electrons may be more strongly influenced by ambient plasma.

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Table 1 Laser absorption fraction as a function of the scale length $L$ and laser wavelength $\lambda$.

<table>
<thead>
<tr>
<th>scale length ($\mu$m)</th>
<th>laser wavelength ($\mu$m)</th>
<th>0.25</th>
<th>0.5</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>7.33%</td>
<td>7.25%</td>
<td>11.5%</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>12.2%</td>
<td>9.79%</td>
<td>13.0%</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>15.4%</td>
<td>12.4%</td>
<td>13.0%</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>21.6%</td>
<td>15.7%</td>
<td>13.2%</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 gives the absorption fraction as a function of scale length and laser wavelength. For $\lambda = 1 \mu$m, the absorption fraction is approximately constant while the normalized scale length $L/\lambda$ increases from 1 to 2.5. For $\lambda = 0.25 \mu$m, the absorption fraction triples while $L/\lambda$ increases from 4 to 10. For $\lambda = 0.25 \mu$m and $L = 2.5 \mu$m, the absorption fraction is greater than 20%, even at normal incidence.

Electron-energy distributions after 215 fs, near the time of the laser-intensity peak, for $L = 2.5 \mu$m are shown in Fig. 2. The hot-electron temperatures are 320, 500, and 500 keV, for $\lambda = 0.25$, 0.5, and 1 $\mu$m, respectively. The temperature of the hot electrons is estimated using the equation $T_h \sim [(1 + L/\lambda^2)/(1.4 \times 10^{18})^{1/2} - 1] \times 511$ keV [5], where $I$ is the laser intensity in W/cm$^2$, and $\lambda_0$ is the wavelength in $\mu$m. For $\lambda = 1 \mu$m, the measured temperature agrees with this estimation. However, for $\lambda = 0.25$ and 0.5 $\mu$m, the measured temperatures are higher than the estimation. Parametric processes at plasma densities below the quarter-critical density are involved in the principal mechanism instead of the mechanism originated from the ponderomotive potential. The number density around 500 keV for $\lambda = 0.25$ and 0.5 $\mu$m is about thrice that for $\lambda = 1 \mu$m.

The energy distribution of the rear side proton after 415 fs, coinciding with the end of the laser pulse, for $L = 2.5 \mu$m are shown in Fig. 3. The maximum proton energies are 4.7, 4.5, and 3.4 MeV for $\lambda = 0.25$, 0.5, and 1 $\mu$m, respectively. These results show the influence of high energy electron temperature and density on ion acceleration because of the sheath at the rear surface. The temperature of the energetic electron for $\lambda = 0.25 \mu$m is no more than two thirds of that found at other wavelengths, while the density is about twice that for $\lambda = 0.5 \mu$m, and thrice that for $1 \mu$m. As a result, energetic ions are generated with energies comparable to the case for $\lambda = 0.5 \mu$m, although the temperature of the high-energy electron is low.

This paper characterizes the effect of the different laser wavelengths on the temperature and density of energetic electrons created by the laser-plasma interaction using a 1D-PIC simulation code. Multi-dimensional effects, such as surface deformation [5], are important in experiments. These simulations assume the ideal and collisionless plasma. In addition, electron transport in a solid-density target is affected by resistivity, which depends on the material used in experiments. Relatively low-energy electrons may be more strongly influenced by ambient plasma.

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