Stable single channel formation in long scale plasma for fast ignition

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Abstract. We observe a single plasma channel in long scale plasma created on the plane target. Smaller electron divergence and enhancement on moderate energy electrons are obtained than those from plane target. The experimental results also show that slight laser energy is used for the channel formation and the conversion efficiency to electrons is comparable to the plane target. These results imply efficient heating at “Super-Penetration” fast ignition.

1. Introduction
Since the Fast Ignition (FI) scheme is proposed in 1994 [1], interactions of ultra-intense laser beam with plasmas have been intensively investigated and the fruitful results significantly contribute for expansion of scientific understanding and technological applications such as high energy density science. In FI scheme, the required dense fuel is formed via conventional laser driven implosion, but the ignition temperature is achieved via quick heating by a separate ultra-intense laser beam, resulting in significantly reduction of total laser energy required for the ignition. However, the intense laser should propagate into mm scale plasma where the many laser instabilities such as SRS or filamentation can be driven before reaching the critical density. The cone-in-shell geometry, which can reduce such instabilities, was successfully demonstrated about 100 times of heating of the core compared with no intense beam injection [2]. However, this geometry breaks the implosion symmetry and therefore makes difficult to achieve high-gain target designs.

An alternative approach is to inject ultra-intense laser pulses directly into the coronal plasma, so called “Super-Penetration” fast ignition [3]. When the laser power exceeds the critical power of relativistic self-focusing, the laser beam can propagate in the overdense plasma due to relativistic induced transparency and laser hole boring. In our previous works, a long plasma channel was observed penetrating into overdense plasma when the intense laser pulse irradiated onto a long scale plasma with 80µm overdense region [4]. In this experiment, the transmitted laser energy is also detected and we found that the transmittance depends on the focus position of the intense laser beam in the long scale plasma [5].
From the viewpoint of FI, it is important to measure the fast electrons under these conditions. In order to observe energy distribution of the accelerated electrons, and to estimate the conversion efficiency from laser energy to fast electrons, we measured energy distribution of fast electrons generated by an intense laser interacting with a long scale plasma.

2. Experimental setup

The experiment is performed at GEKKO MII 60TW system in Osaka University. This system has three separate beams: one is the short pulse beam operated in 1µm wavelength. The output energy is 30J with 500fs pulse duration. The laser is focused onto a thin plastic target via F3.3 off-axis parabolic mirror to be around 20~30µm diameter focal spot, resulting in up to $10^{19}$ W/cm$^2$ of peak intensity. The long pulse beam ($\omega/30J/0.5ns$) is irradiated onto the target from 25° away of the short pulse beam to create the pre-created long scale plasma. The low energy probe beam ($2\omega/5ps$) is injected parallel to the target surface to observe the plasma density gradient via optical interferometer. We put several diagnostics such as electron spectrometer (ESM) on the laser axis and the side to observe the electron energy distributions, X-ray Pin-hole camera (XPHC) for X-ray image on the interaction point, and K$\alpha$ photon counting detector to estimate the number of electrons inside the target.

Figure 1 shows the electron density scale of plasma created by the long pulse beam focused with 200µm dia. ($\sim 10^{19}$ W/cm$^3$). A 1D-radiation MHD calculation, represented by solid line, well reproduces the density scale from the experiment by the dashed one [6]. According to the calculation, the scale length to $n_c$ is about 30µm and there is a long under dense plasma from $10^{19}$ to $10^{20}$ cm$^{-3}$ about 400µm length. In this experiment, the focusing position of intense laser pulse is changed from 100 to 500µm from the initial target surface in order to find an optimal laser penetration.

3. Channel formation inside plasma

When the laser is focused around 200~500µm from the initial target surface, we observed a long plasma channel inside the underdense region. Figure 2 shows an interferometer image taken at -200µm focusing conditions ($\sim 1x10^{19}$ cm$^{-3}$ density plasma). In the image, short pulse laser came from left boundary and created a straight plasma channel indicated by black dashed lines where the fringe lines are rapidly bended. Observed channel position is from 100 to 400µm where the plasma density is relatively constant (0.5-1.0x10$^{20}$ cm$^{-3}$). Although similar channel images are observed for other focusing conditions such as -500µm, for 200µm focusing condition a strongest 2 self-emission is detected exactly corresponding to the critical surface position (light blue spot on the axis in the figure). In addition, we observed a strong X-ray emission only for this condition whereas no signal is measured for other focusing positions. From these results, we assume that most of laser energy is propagated around critical surface at the 200µm focusing condition.
Analyzing the fringe shifts, the electron densities of channel wall and center are about 2 and 1/10 of background density (immediately before short pulse injection), respectively. Channel expansion speed is estimated from the probe beam timing and the length of channel, resulting in $90\mu m/80ps = 1.1 \times 10^8 cm/s$. This ion sound speed is comparable to the previous channel formation experiments, ex. $5 \times 10^8 cm/s$ [7]. In order to estimate the energy to create the channel, we adapt the similarity solution assuming blast wave expansion in cylindrical symmetry. The rate of expansion can be given by [8,9]

$$R(t) = \left(\frac{E}{\rho_0}\right)^{1/4} t$$  

(1)

Here $R(t)$ is the channel expansion length in given $t$, $E$ the deposited energy per channel length, $\rho_0$ the plasma density and $t$ the time of observation. Substituting $R=90\mu m$, $\rho_0=8.27 \times 10^{-4} g/cm^3$, and $L=300\mu m$, we obtain the energy to create plasma channel is 1.6J. In this experiment, the laser energy in the focal spot is about 12J, so that the energy for channel creation is only 13% of laser energy.

4. Conversion efficiency

Electron energy distribution is measured with two different methods: one is the magnet spectrometer (ESM) for escaping electrons from the target and other is K photon counting from added Cu layer at the target rear. Figure 3 represents typical ESM electron spectra from -200μm (green) and -500μm (red) focusing conditions with the plane target (blue) result. Comparing the electron spectra from plane target and plasma cases, two significant difference can be clearly appeared: (a) electron spectrum from the side for plane target has a higher temperature than the preplasma cases whereas the almost same for on-axis spectra, and (b) moderate energy (up to 10MeV) electrons at on-axis for 200μm focus condition are almost 20 times enhanced compared with the plane target. These results, the reduction of beam divergence angle and enhancement of moderate energy electrons, have already presented in the previous papers [3], which implies relativistic self-focusing of intense laser beam in long scale plasma resulting in laser penetration into higher density plasma.

It is known that ESM electrons detected with some distance in vacuum suffer a strong sheath potential created at the target rear side [10], so that the detected spectra might be modified in particular for lower energy electrons. For this reason, we also measure Cu-K emission intensity generated through scattering of electrons passing through the Cu layer. We also added a Ti layer between plastic and Cu (10μm) to reduce the electron energy reaching to Cu layer. By changing the Ti thickness, we can estimate electron energy distribution according to the energy reduction at the Ti layer. The stopping power and ranges in various Ti thickness are calculated with Electron Gamma Shower (EGS) code. Table 1 shows the K photon intensities changing the Ti layer thickness. Clearly the photon counts decrease with increasing of Ti thickness.

Figure 4 shows the electron energy distributions from K data, converting from X-ray intensity to the electron number according to K fluence cross section, as shown by solid dots, and also several ESM spectra (dashed lines). In the result, the electron energy distribution seems two temperature Maxwellian (K $T_e$: 165keV and ESM $T_e$:5MeV). Assuming the electron spectrum inside the target is the two temperature Maxwellian, the total energy of electrons is 3.1J (Emission angle is assumed to be 30° for ESM data [3]). In the result, conversion efficiency from laser energy to fast electrons is 26%. Surprisingly this efficiency is comparable to the efficiency for plane target [11,12].

![Figure 3. Electron energy spectra for laser axis (left) and side (right). Black, Dark gray, and Light gray dots represent the spectra from 200, 500μm focusing position and plane target.](image)
5. Summary

In the summary, a stable single channel is created in a long scale plasma when the laser is focused around 200–500µm from the initial target surface. From the analysis of optical interferometer, the channel formation uses 13% of laser energy. Under this condition, electron emission angle becomes smaller and moderate energy electrons up to 10MeV are enhanced compared with those from plane target. ESM spectra and K\textsuperscript{α} photon counting indicates that the conversion efficiency from laser to electrons is about 26% where is comparable to the plane target. These results imply that most of laser energy can be transported around critical surface without significant consumption by optimizing focusing position to the density scale gradient, and can be expected effective heating to the core.

It is interesting to note that Atzeni and co-workers show required electron energy for ignition to NIF size plasma, \( E_\text{ig} = 22kJ \times (1 - \exp(-1.45\text{MeV}/E)) \), where \( E \) is the temperature of accelerated electrons [13]. In our case, it is required 252kJ short pulse from the conversion efficiency with the electron spectra in Fig. 4. On the other hand, Hatchett et al. indicate 60% conversion efficiency in the plane target when the laser intensity increases to 10\textsuperscript{20}W/cm\textsuperscript{2}, resulting that only 109kJ laser energy is needed. If we can obtain such high conversion efficiency under long scale plasma for high intensity laser beam, “Super-Penetration” will be feasible and attractive way to real ignition.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Ti thickness (µm) & 0 & 50 & 100 & 300 \\
\hline
K counts \( \times 10^{11} \) & 2.91 & 0.97 & 0.60 & 0.25 \\
\hline
\end{tabular}
\caption{K\textsuperscript{α} photon intensities changing the Ti layer thickness.}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4}
\caption{Electron energy distribution from K\textsuperscript{α} emission (dotted circles) and 3 ESM spectra (taken in different shots with same laser and plasma conditions).}
\end{figure}

References

[1] M. Tabak et al., Phys. Plasmas 1 (1994) 1626.
[2] R. Kodama et al., Nature 418 (2002) 933.
[3] A.L. Lei et al., Phys. Plasmas 16 (2009) 056307.
[4] A.L. Lei et al., Phys. Rev. E 76 (2007) 066403.
[5] T. Matsuoka et al., Plasma Phys. Control. Fusion 50 (2008) 105011.
[6] K. Adumi et al., Phys. Plasmas 11 (2004) 3721.
[7] J. Fuchs et al., Phys. Rev. Lett. 80 (1998) 1658.
[8] A.J. Mackinnon, et al., Phys. Plasmas 6 (1999) 2185.
[9] Ya.B. Zel’dovich, et al., “Physics of shock waves and high temperature hydorodynamic phenomena” (Academic New York, 1966).
[10] T. Yabuuchi, et al., Phys. Plasmas 14 (2007) 040706.
[11] M. Nakatsutsumi, et al., New J. Physics 10 (2008) 043046.
[12] R. Kodama, et al., Phys. Plasmas 8 (2001) 2268.
[13] S. Atzeni et al., Phys. Plasmas 15 (2008) 056311.
[14] S. Hatchett et al., Phy. Plasmas 7 (2000) 2076; K. Yasuike et al., Rev. Sci. Instrum. 72 (2001) 1236.