CO₂ Laser Interaction with Dense Plasma *

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There are different approaches to realize the laboratory of controlled thermonuclear fusion. Recently, according to the theoretical paper, it is very important to have rapid fusion reaction by means of compression using the lasers. The most interesting investigation is the interaction between intense electromagnetic waves and plasma. Because it determines how to deposit the laser energy effectively. It is well known that the mechanism of collisional absorption due to the ineffective inverse bremsstrahlung produces the reflection. However, the strong coupling collectively between incident wave and electronic plasma wave or ion acoustic wave causes the excitation of instability, therefore, another effect of absorption or expansion happens predominantly except the mechanism of collision. This effect appears in the region of plasma that the electron density n_e is nearly equal to the critical density n_c where the frequency of incident wave ω_e is equal to plasma frequency ω_p .

We study interaction of CO₂ laser light with plasma as following conditions. At the threshold in which the parametric instability appears, if one can consider the plasma to be almost homogeneous, it can be assumed that the density gradient is small and plasma is quasi-stationary. The interest for CO₂ laser is to obtain the threshold of the instability at about the critical density plasma comparing the threshold of instability in Nd glass laser. The performance of CO₂ laser is to provide particularly interesting system for the experiment of compression. We present the experimental results of absorption and reflection by different experiments.

Experimental Apparatus

a) Interaction between laser and plasma (fig.1)

A target plasma is obtained by confining in a spatially uniform magnetic field. It has been created by focusing the output of a 250 MW ruby laser onto a polyethylene foil. The magnitude of the magnetic field is 65 KG.

We obtained the plasma density of about $9 \times 10^{18} \text{ cm}^{-3}$. The size of plasma where n_e is maximum is cylindrical of 2 mm in diameter and about 1.5 cm long. On account of diffusion of particles along the magnetic line of force, the lifetime of plasma is from 50 to 100 ns. Fig.2 shows the radial electron density distribution in the plasma at two different instants. The electron temperature T_e was determined from the intensity ratio of two carbon lines, CII and CIV (fig.3). The value of T_e , obtained by assuming local thermodynamic equilibrium, is $9 \pm 1 \text{ eV}$. This value is in agreement with the one obtained by considering the equilibrium between plasma kinetic and magnetic pressure. A Lumonics CO₂ laser, a peak power of 40 MW, focused by a 70 mm NaCl lens, and its maximum power density was $(2-4) \times 10^{10} \text{ W/cm}^2$ at the focal point.

At the second experiment, the CO₂ laser of Lumonics type which has a peak power of 1 GW in a pulse with an 40 ns was used. The intensity at a focal point was about 10^{12} W/cm^2 . The spatial

diagnostics(fig.1) was obtained by time-resolved Mach-Zehnder interferometry with the high speed camera of 5ns exposure time. The spectroscopic measurement of visible and near ultraviolet region was done for the reflected, scattered and transmitted light. The detector was a photon drag.

b) Interaction between laser and target(fig.4)

The polyethylene plane target was irradiated by 1 GW laser with a spherical mirror of focal length of 300 mm and the laser power intensity at the focal point was $8 \times 10^{11} - 1.5 \times 10^{12} \text{ W/cm}^2$ with the beam divergence of 0.5 mrad. The focusing mirror has an orifice of 15 mm diameter at the center of it and it is possible to observe the plasma directly along the laser axis same as the detection of ion and reflection. The reflection of at 10μ and 5μ was measured by means of photon drag detector and HgTe-CdTe photo voltaic detector. One measurement was from the orifice of focal mirror(R1) and the other was from the definite solid angle of focal mirror(R2). As the laser flux had the structure of ring, it should be noted that the incident and reflected light could not be observed to the direction of R1. We observed the ion of plasma with charge collectors and measured the enegy by time of flight. Finally, the x-ray emission from plasma was up to 1Kev observed by plastic scintillator through the aluminum window of 18,30, and 100 μ thickness.

The laser trasmission light through the plasma was shown as a function of incident intensity. The variation of absorption coefficient of plasma was shown in fig.5. The solid line of fig.5 was the absorption coefficient which was calculated by the inverse bremsstrahlung. The heating time of particles is the transit time of CO_2 laser at the focal point and is the order of $4 \times 10^{-9} \text{ sec}$. The additional ionization by heating and the expansion is neglected. According to the theoretical model, heated gy the laser intensity oy 10^{10} W/cm^2 , the electron temperature of plasma is about 100 ev. The refraction was one factor of errors in the measurement of transmission. When the laser flux transverse the plasma, it's trajectory in the vaccum is deflected and the laser flux is missed from the solid angle of the system of detection. It's solid angle is 40° . We have computed the deviation of flux taking into account the plasma density gradient(fig.6) and we showed the deviation as a function of distance P of the flux. We measured the temperature of plasma by means of spectroscopy. The determination of T_e before the heating was done by the ensemble mean of plasma obtained with the poor spatial resolution. In the case of heating, the irradiated zone was so small compared with the plasma that the observed effect about the variation of radiation intensity was very small. It is possible to study the spectral emission of the center of plasma at the focal point of laser flux by the improvement of spatial resolution. The Stark broadening of the carbon line due to high electron density is very important and its line can be distinguished from the continuous spectral of plasma. When the plasma traverses the focal point, the electron temperature is elevated rapidly. Consequently, the equilibrium is affected and the ionization differs. In the ideal case, we computed the elevation of T_e from 10 to 100 ev during 4ns of plasma ionization. The ionization is very small(fig.8), if we assume the radiative-collision equilibrium and the local thermal equilibrium(ETL).

If the transition stage exists, it is possible to interpret the measurement of temperature at the time of heating based on the intensity of carbon line.

b) Interaction between laser and target

We studied the following values when the focal position to the target was varied: the reflection of R1 and R2 directions, the emission of second harmonic (5.3 μ), the intensity of x-ray and the maximum velocity of ions. The merit of the long focus was to have a range in focus about 2 mm. The relative position was regulated at the accuracy of about 0.1 mm. In fig.9 and 10 the horizontal axis shows the relative position between the target and the focusing point. Therefore, the position is assured by the zone of hatching. The reflections of 10.6 μ of R1 and R2 directions and the variation of emission of 5.3 μ of R1 direction are shown in fig.9. Each measured value is relative one and calibrated by the maximum value of reflection coefficient. The 10.6 μ (fig.9) of R2 direction is 3-4% of the total incident light. The value in R1 direction is 7-8% in regard to the identical solid angle which is determined by the mirror. The maximum intensity of second harmonic emission of R1 direction is about 10^{-5} of the reflection intensity of 10.6 μ of the same direction and about 10^{-6} of the incident intensity. We have measured the velocity of plasma front as a function of position of focus by moving the target. The measured maximum velocity was $(1.5-2) \times 10^8$ cm/sec. This optimum was obtained in a relative large domain and extended to the zone of the second harmonic generation. The emission of x-ray (fig.10) has been observed at the same time in the same domain of the second harmonic. By Elton (7), the electron temperature was from 1.2 to 1.6 Kev. However, it should be noted the temperature obtained by very thin absorber not always corresponded to the plasma temperature. But another people (8) pointed out clearly that it showed the partial superthermal of the emission. This emission, however, was sufficiently intense and could be observed easily. Consequently, the emission mentioned above superposed the emission X_b existed in the narrow region where the second harmonic generation was maximum. Moreover, the reproducibility of shot to shot was very bad and the intensity was about twenty times of the emission X_a .

It is impossible to interpret all of the results. However, in the experiment of laser interaction with plasma, it is apparent that the absorption agrees with the inverse bremsstrahlung at the lower intensity of 10^{10} W/cm². At above this value, (fig.5), the mechanism is anomalous. We have calculated the threshold of parametric instability of heating (fig.11) and our observation was good agreement with the mechanism of anomalous absorption.

The experiment of the direct interaction with the target seems to present the confirmation of this result: the reflection of 10.6 μ (fig.9) presents the maximum in the direction of R1 and R2. The variation of the focusing position is an effect associating with the variation of flux on the target. The absorption is very strong at the intensity of about 10^{11} W/cm². The effect of refraction (9) can be computed about the decrease of the reflection of plasma by the computation at 0° and intervenes certainly to explain the reflection in the direction R1. Moreover, the emission of radiation X_a which gives the superthermal equivalent temperature of 1.2 to 1.6 Kev can't be attributed to the mechanism of heating by the absorption of inverse bremsstrahlung (8).

The experiment of interaction with target has shown the presence of second harmonic. However, the intensity is small as compared with the incident one (it is the order of 10^{-6} in the direction of R1 because of the equivalent solid angle of the aperture of the focusing mirror).

The origin of second harmonic is certainly due to the non-linear effect which occurs when the electromagnetic wave propagates in the density gradient. It is not always the attribution to the mechanism of intensity. In our experiment, we have not observed another type of harmonic but it might be due to the experimental difficulty of detection.

The superthermal emission X_p , we have confirmed has been already obtained by different people (8). The very intense emission X_p and poor reproducibility were not understood clearly and they might be due to the excitation of instability. These experiments are to pursue the correlation with this emission and the reflection of 10.6 μ and the harmonic generation.

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ray of emission from the plasma

Fig. 3 The emission of target plasma before heating.

Fig. 1 Experimental set up for laser interaction with plasma.

Fig. 2 Radial density profile of target plasma before heating.

Fig. 4 Experimental set up for laser interaction with target.

Fig. 8 Comparison of ionization between the transit and equilibrium region.

Fig. 7 Comparison of the spectral emission with and without heating. The jet corresponds with the dense phase of plasma.

Fig. 5 Attenuation of laser flux by plasma as a function of radiation intensity.

Fig. 6 Derivation of laser flux when it traverse the target plasma.

Fig. 9 Reflection of 10.6 μ m and emission of 5.3 μ m as a function of position of focus when the target is moved

Fig. 10 X ray emission and reflection R₁ of 10.6 μ m as a function of focusing position when the target is moved.

Fig. 11 The intensity of threshold of instability of heating as a function of plasma frequency.