# CALCULATION OF FORWARD AND BACKWARD PLASMA BOUNDARY PRODUCED BY EXCIMER LASER IN HIGH-PRESSURE ARGON GAS

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**Abstract**

A dense plasma produced by a focused XeCl excimer laser in high-pressure argon gas up to 150 atm developed not only backward but also forward. A model for the forward development mechanism called a forward breakdown wave has been proposed. This model could predict the forward development behavior considerably well in the first stage. However, in the latter stage the calculated forward development velocity was faster than the experimental one. Then, the forward development model was modified to explain the experimental result in the latter stage. The absorption of the laser energy by the backward plasma was considered in this model. It could predict the forward development behavior considerably well in the all stage of the development.

## 1. Introduction

When a XeCl excimer laser light was focused in a high-pressure argon gas up to 150 atm, a dense plasma developed not only backward but also forward [1]. The backward plasma was developing during the laser irradiation. While the development velocity of forward plasma increased with increasing time and the forward plasma stopped suddenly developing even during the laser irradiation. The backward plasma length was calculated on basis of a breakdown wave [2] and a radiation supported shock wave [3], and agreed with the experimental one. A model for the forward development mechanism, called a forward breakdown wave has been proposed [4]. The observed plasma radius at the front was much smaller than the theoretical light cone. Therefore, this model included the self-focusing effect of laser light by plasma. This model was able to predict the experimental behavior of forward development considerably well, in the first stage of the development. However, in the latter stage the calculated forward development velocity was faster than the experimental one. Moreover, this model could not explain such a phenomenon that the forward plasma stopped suddenly developing even during the laser irradiation.

Then, we modify the model taking into account the laser absorption by the plasma. The boundary of the forward plasma calculated by the modified is reported in this paper.

## 2. Self-focusing effect

The experimental set up is the same shown in the previous article [4]. The XeCl excimer laser with a maximum power of 17MW, a wavelength of 308nm is focused in high-pressure argon gas. Since the laser light is a rectangle of 11×24 mm, the focused laser light at the focal spot makes an ellipse of 120×80μm. The pressure ranges from 1 to 150 atm.

Typical streak trace of the plasma boundary is shown in Fig. 1. The laser light is irradiated from the right, and the time is scanned from top to bottom. The forward plasma development velocity increases with increasing time, and after that the forward plasma stops suddenly developing even during the laser irradiation.

The streak image of the plasma radial direction is taken. The theoretical plasma radius is calculated assuming the energy distribution of laser pulse to be Gaussian distribution. The observed plasma radius and the theoretical light cone channel are shown in Fig. 2. The backward plasma radius is nearly equal to the theoretical value of the light cone, but the forward plasma radius is much smaller than the light cone [1]. Then, the self-focusing effect of the laser light by plasma is taken into account in this model. Various studies about the self-focusing effect have been done [5]. This self-focusing effect is observed every pressure.

As the laser light is a rectangle of 11×24 mm, the focal length of perpendicular may differ from that of horizontal. To eliminate this influence, when the slit having the hole of 11 mm in diameter is put in the laser path, the plasma development is observed. The difference of the plasma development could not be observed. It is found that the transverse shape of the laser light could not affect the forward plasma development.

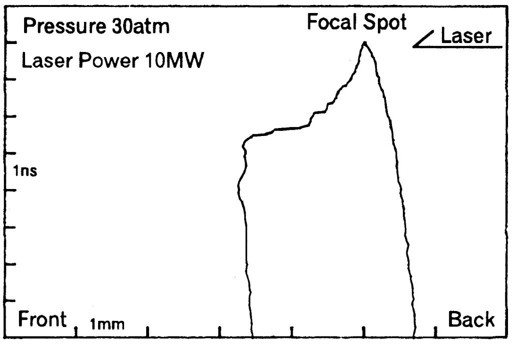


**Fig. 1.** Typical streak image of the plasma boundary.

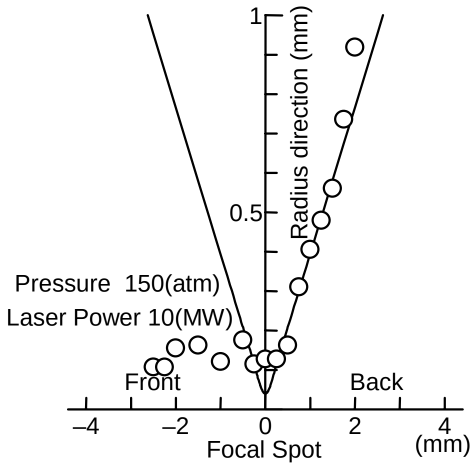


**Fig. 2**. Calculated light channel and observed radius of plasma.

## 3. Forward development mechanism

The development velocity of the forward plasma increases with increasing time, after that the forward plasma stops suddenly developing while the laser is irradiating. The forward development of plasma has not been enough explained yet. Then, the forward plasma is calculated using the forward breakdown wave and the radiation supported shock wave. The development mechanism of the forward plasma can be considered as a kind of the breakdown wave proposed by Raizer [2]. Since this model is taken into account the self-focusing effect of laser light by the plasma, the calculated forward plasma could predict considerably well in the first stage. However, in the latter stage the calculated development velocity is faster than the experimental one and the calculated forward plasma continues to develop while the laser is irradiating.

Then, we modify the model to explain the experimental result in the latter stage. This model is newly taken into account the absorption by the plasma. The modified forward plasma development mechanism is as follows. Before the breakdown, the laser light has a cone shaped light channel. After the breakdown, the backward plasma develops by the backward breakdown wave and the radiation supported shock wave into the cone shaped light channel, and simultaneously the plasma develops forward quickly by the forward breakdown wave and the radiation supported shock wave. The forward and the backward plasma should be calculated simultaneously in the modified model. However, it is difficult to calculate simultaneously the forward and backward plasma developments. Then, the backward plasma is calculated beforehand, and after that the forward plasma is calculated using the backward plasma length at the time. This model is not taken into account the decay process since the plasma develops forward quickly.

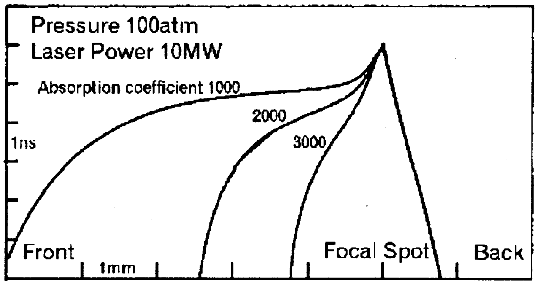

**Fig. 3**. Calculated forward plasma by forward breakdown wave and constant absorption coefficient.

## 4. Calculation Results

Using this modified model, the behavior of the forward plasma development is calculated assuming a constant absorption coefficient. The plasma boundary calculated with a constant absorption coefficient is shown in Fig. 3. This model is explained the phenomenon that the forward plasma development velocity is decreasing with increasing time in the latter stage. But the calculated plasma could not agree with the observed plasma in the latter stage.

Next, the forward plasma is calculated using the time variation of the calculated absorption coefficient. Since the absorption coefficient depends on the electron density, the electron density is calculated from the rate equation with only the cascade ionization and the recombination. The multi photon ionization and the diffusion are not dominant in the high-pressure gas. After the gas is broken down, the electron density is increasing quickly. The time variation of electron density is similar to the waveform of laser pulse.

The forward plasma development is calculated using the absorption coefficient at the focal spot. The behavior of forward plasma boundary calculated using the time variation of absorption coefficient is shown in Fig. 4. The forward plasma stops developing faster than the experimental result.

The electron density and the temperature differ from the position. The distribution of electron density and temperature is measured using a laser interferometer and a spectroscopic measurement. The electron density is $10^{27}$ $m^{-3}$ at the focal spot when the pressure is 150 atm. The electron density is highest at the focal spot and the electron density of the forward plasma

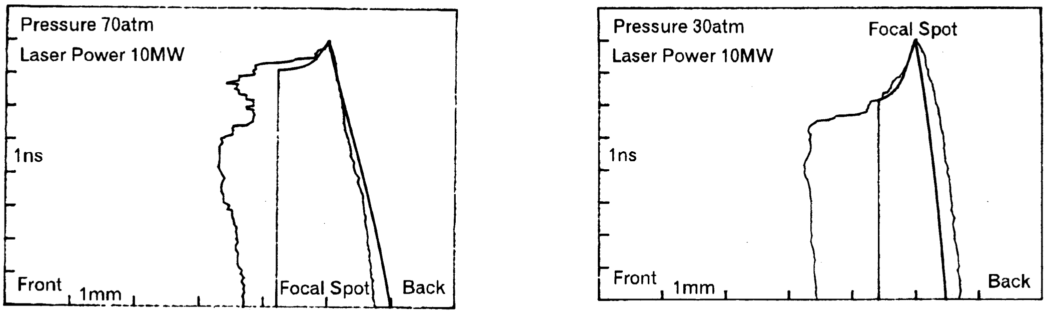

**Fig. 4**. Calculated forward plasma by forward breakdown wave and time variation of absorption coefficient and observed plasma.

is higher than that of the backward one. The electron temperature is highest at the focal spot and the forward electron temperature is lower than the backward one. The electron temperature is $10^5$ K at the focal spot [6].

The time variation of the averaged absorption coefficient is calculated using that of the averaged of electron density. The forward plasma calculated using the time variation of the averaged absorption coefficient is shown in Fig. 5. The experimental result is nearly equal to the calculated one not only in the first stage but also in the latter stage. But these models are not included the plasma decay process. So the forward plasma length is constant with increasing time after the forward plasma stops developing. If the absorption coefficient depending on the position is taken into account, it is expected that the forward plasma would better agree with the experimental one.

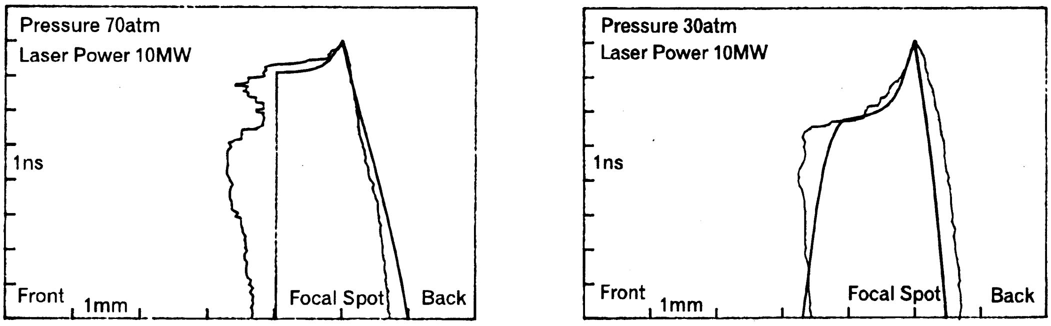


**Fig. 5** Calculated plasma by averaged absorption coefficient and observed plasma.

## 5. Conclusion

When the high-pressure argon gas is irradiated by ultraviolet laser light, a dense plasma is produced at the focal spot. The radius of forward plasma becomes to be smaller apart from the focal spot. The previous model could not explain the forward development behavior in the latter stage, since it is not taken into account the laser absorption by the plasma. Then, the forward plasma development is calculated taken into account the laser absorption by the plasma.

The forward plasma development calculated by a constant absorption coefficient or the time variation of the absorption coefficient at the focal spot could not agree with the observed plasma development. Then, the forward plasma is calculated using the time variation of the averaged absorption coefficient. This modified model could predict the forward plasma development behavior considerably well not only in the first stage but also in the latter stage. It is found that the modified model could better explain the forward plasma development than the previous model did.

## References


[1] J. Yamada, N. Tsuda, Y. Uchida, H. Huruhashi and T. Sahashi: Trans. IEE Jpn. A**114** (1994) 303.
[2] Yu.P. Raizer: Sov. Phys. JETP. **21** (1965) 1009.
[3] S.A. Ramsden and P. Savic: Nature **203** (1964) 1217.
[4] N. Tsuda and J. Yamada: J. Appl. Phys. **81** (1997) 582.
[5] A.B. Borisov, X. Shi, V.B. Karpov, V.V. Korobkin, J.C. Solem, O.B. Shiryaev, A. McPherson, K. Boyer and C.K. Rhodes: J. Opt. Soc. Am. B**11** (1994) 1941.
[6] N. Tsuda, Y. Uchida and J. Yamada: Jpn. J. Appl. Phys. **36** (1997) 4690.