Study on the Two-Dimensional Density Distribution for Gas Plasmas Driven by Laser Pulse

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Abstract We perform an experimental study of two-dimensional (2D) electron density profiles of the laser-induced plasma plumes in air by ordinarily laboratorial interferometry. The electron density distributions measured show a feature of hollow core. To illustrate the feature, we present a theoretical investigation by using dynamics analysis. In the simulation, the propagation of laser pulse with the evolution of electron density is utilized to evaluate ionization of air target for the plasma-formation stage. In the plasma-expansion stage, a simple adiabatic fluid dynamics is used to calculate the evolution of plasma outward expansion. The simulations show good agreement with experimental results, and demonstrate an effective way of determining 2D density profiles of the laser-induced plasma plume in gas.

Keywords: laser breakdown, gas plasmas, 2D density distribution, optical interferometry, photoionization, avalanche ionization, laser propagation, fluid dynamics

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(Some figures may appear in colour only in the online journal)

1 Introduction

The laser-induced plasma has recently drawn a great deal of attention due to many important applications, such as stimulated Raman backscattering (SRBS) [1-4], plasma waveguide [5-7], high harmonic generation [8,9], plasma accelerator [10,11], etc. In most cases, the desired plasma needs to satisfy particular density conditions, e.g., a density distribution with gentle gradient to avert the detuning effect caused by mismatching of frequency in SRBS. Studying the detailed spatio-temporal density distribution of plasma—a spark breakdown by an intense laser beam irradiating the gas target—is quite inevitable.

For the experiment, the 2D spatial density distribution of plasma in gas can be extracted via the Mach-Zehnder interferometer and Abel transformation technique [1,2]. On the theoretical side, the models of fluid dynamics are often used to simulate the radial density profile of plasma, which included the codes of HYDRA [12], SPARC [13] and multispecies hydrodynamic [14]. However, these numerical simulations did not provide a 2D plasma density profile for exposing clearly the space-distribution character of a desired density.

In the present work, we present an efficient simulation for the 2D electron density distribution of plasma. The 2D transverse electron density profiles of plasma are obtained in an experiment of laser breakdown in gas. Then a simulation is conducted to reproduce the measurements. Generally, the major physical processes of laser pulse breakdown in gas contain two stages, i.e., plasma formation and plasma expansion. For nanosecond (ns) laser pulse, it may be assumed that the expansion stage arises after the laser pulse is terminated. Thus the two stages can be separately considered [14]. Since plasma formation is the result of interaction between laser field and gas medium, it can be fully described by the propagation of laser pulse in the medium combined with the evolution of electron density. The ionization rate of the optical field can be predicted effectively with the multiphoton regime or tunnel regime. Since the convective regime dominates the early expansion stage of $t < 200$ ns, the plasma plume expansion into an air environment is described by an adiabatic regime which can be fully predicted by the Euler model. Compared to the adiabatic regime of expansion into
a vacuum environment, the distinction is that a state of static background air is considered in the initial conditions of this adiabatic regime. It is convinced by the good agreements of 2D density profiles between our simulated and experimental results at a given time delay that our model can be used to extract the density profiles along transverse direction \( r \) at different times. Not only do the simulated results show the evolutionary process of outward expansion visually, but also predict extremely high electron density profiles at the early stage. Since it is difficult to measure these extremely high densities because of the high refraction of the probe, the simulations can be used for extending electron density profiles beyond the resolution of experimental measurements.

2 Experimental setup

Fig. 1 illustrates the experimental arrangement. In the experiment, we exploit a Nd laser system (1053 nm, 3 ns, 1 J). The beam is separated into two parts: one for the generation and the other for the detection of plasma. To achieve sufficiently high intensity for efficient initial free electrons generation, the main laser beam of diameter \( \sim 1.2 \) cm is tightly focused with a short focus lens L1 (the foci \( f_1=5 \) cm).

![Fig.1 The experimental setup for plasma generation and interferometry](image)

A small part of energy serves as probing laser. Because the laser with short wavelength is easier to propagate through an overdense region, we have detuned the Nd laser to a wavelength of 527 nm via a LBO crystal. A small part also obtained from the probing laser acts as a reference beam. The probing beam passes through the plasma channel, getting a phase shift induced by plasma, and is combined with the reference beam to form a two-dimensional pattern of linear interference fringes. If the plasma channel with a length of several millimeters, and width of hundreds of micrometer (\( \mu m \)) is clearly imaged on the charge-coupled-device (CCD) camera, this demands an optical imaging system to zoom into the interference fringes. Before the probing beam and reference beam arrive at the CCD, they are enlarged by a lens group composed of L2, L3 (the foci \( f_2=f_3=40 \) cm) and L4 (the foci \( f_4=200 \) cm). The image size of CCD camera is 2048\( \times \)2048 pixels, and the corresponding spatial resolution of the interferometry is \( \sim 7.4 \) \( \mu m \)/pixel. Due to the compression effect of the LBO crystal, the duration of the probing laser is less than 2 ns. In the density measurements, the time resolution of \( \sim 2 \) ns is determined by the duration of the probing laser.

The plasma density profile and the phase shift can then be extracted from the interferogram through an Abel transformation technique. As some researches indicated, the uncertainty of measurement was mainly dependent on three causes: the noise in the interferogram, the extraction of fringes, and the calculation of Abel transformation. When the measured density range was \( 5\times10^{18} \sim 5\times10^{19} \) cm\(^{-3} \), there was about 5% to 10% uncertainty. For the higher or lower values out of this range, the uncertainty could reach 20% [15]. The numerical noise introduced from Abel inversion can cause larger uncertainty in comparison with other causes [16]. In order to weaken the numerical error, a smooth function is introduced in the calculation and lessens the total error to 15% [17]. On balance, the uncertainty of this experimental setup is at a level of 10% to 15%.

3 Theoretical model

When the intense laser pulse interacts with gases, the neutral gases are ionized as electrons and ions. The process can be described theoretically by three parts, i.e. the initial photoionization, the electron-molecule collision ionization, and the electron-molecule recombination. Understandably, the evolution equation of the electron density \( n_e \) may be expressed as [18]

\[
\frac{\partial n_e}{\partial t} = W n_a + \frac{n_e \sigma}{U} I - a n_e, \tag{1}
\]

where \( t \) refers to the evolution time. The first term on the right hand side accounts for photoionization. The \( n_a \) is neutral molecule density, and \( W \) is ionization rate. When the laser pulse intensity \( I \sim |E|^2 \sim 10^{13} \) W/cm\(^2 \) (where \( E \) is laser electric field), the ionization rate can be described by the multiphoton regime: \( W \sim \sigma_n I^\kappa \). Here the integer \( \kappa = U/\hbar \omega + 1 \) is the minimum number of absorbed photons (where \( \omega \) is frequency of photons). For the conditions of ionization energy \( U=11 \) eV in air [18] and the pulse wavelength \( \lambda=1053 \) nm, the cross section for multiphoton ionization [19] \( \sigma_\kappa = 5.21\times10^{-13} \) cm\(^2\) with \( \kappa = 10 \). The avalanche ionization expressed by the second term depends on density and free electron temperature. The increases of electron density and temperature arise from the initial photoionization process and the electron heated by laser pulse with a long duration, respectively. In the process of heating, the energy absorbed per electron is described by formula [20] \( \partial E_n / \partial t = \sigma \), where the inverse bremsstrahlung cross section \( \sigma = e^2 \tau / m_e (1+\omega^2 \tau^2) \), the \( e, m_e, \omega, \tau \) denote electron mass, charge, laser frequency, and electron collision time, respectively. In air [19], \( \tau = 350 \) fs, \( \sigma = 5.1\times10^{-24} \) m\(^2\). The electron-ion recombination process on the third term has been investigated in the plasma decay experiment via time-resolved diffraction


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measurement \cite{21}. The recombination coefficient is determined as \(a = 5 \times 10^{-13} \text{ m}^3/\text{s}\).

In the process of a laser beam ionizing gas, the laser field is affected by nonlinear self-focusing, ionization absorption, and plasma defocusing \cite{22}. The nonlinear optical Kerr effect that increases the refractive index in the presence of intense radiation does lead to making an initially collimated beam convergent, and is expressed as \(n^2 I \sim 3.2 \times 10^{-19} \times 10^{13} = 3.2 \times 10^{-6}\). At the same time, the high density plasma generated in the intense power area can prodigiously decrease the refraction index according to the law \cite{19}: \(-n_e/2n_c \sim -3 \times 10^{19}/2 \times 10^{21} = -0.015\) (the critical density \cite{23} \(n_c\) of Nd laser is \(10^{21} \text{ cm}^{-3}\)). The self-focusing is much weaker than plasma defocusing so that it is ignored in the theoretical calculation. In addition, the group-velocity-dispersion (GVD) is likely to have a great influence on the short pulse \cite{18}. Considering that the laser beam irradiating gas is ns order in our schema, the GVD is dismissed from the theoretical simulation. The laser pulse evolution in gas is described by a three-dimensional \((2D+1)\) Maxwell’s wave equation \cite{24}

\[
\nabla^2 E(r, z, t) = \frac{1}{c^2} \frac{\partial^2 E(r, z, t)}{\partial t^2} = \frac{\mu_0}{c} \frac{\partial J(r, z, t)}{\partial t} + \frac{\omega_0^2}{c^2} (1 - n_{\text{eff}}^2) E(r, z, t),
\]

where \(E(r, z, t)\) is the transverse electric field of laser beam with central frequency \(\omega_0\), and \(z\) is the axial propagation direction. The first part of the right source term describes the absorption loss due to ionizing gas. The dissipative current density is described by a formula \cite{25}

\[
J(r, z, t) = \frac{W(t)n_e(t)UE(r, z, t)}{|E(r, z, t)|^2},
\]

The ionizing rate \(W(t)\) is calculated by multiphoton theory for \(I \sim 10^{13} \text{ W/cm}^2\) or Ammosov-Delone-Krainov (ADK) theory for higher intensities \cite{26}. The effective refractive index \(n_{\text{eff}} \sim n_e - n_c/2n_c\), where the refraction and absorption effect of the neutral atoms \(n_0 \sim 1\).

The formation of plasma is able to be accomplished in the initial several picoseconds, and the rest of the ns laser beam can uninterruptedly heat the plasma through inverse bremsstrahlung till the laser is over. After that, the intense hot plasma will expand into the outward environment. The expansion into a vacuum environment is treated as a simple adiabatic process that can be fully predicted by the fluid model \cite{27,28}. The complicated plasma behavior into a background gas can be described by the full Navier-Stokes model containing convection, thermal conduction, viscosity, mass, and forced diffusion \cite{14}. However, evaluated results from Le et al. \cite{14} indicated that a simple Euler model with convection can adequately describe the dynamic phenomena in the expansion stage of \(t < 200 \text{ ns}\), in which the convective regime is dominated.

Additionally, since the velocity of the expanding is much larger than diffusion velocities of electrons and ions, the influences, which arise from mass and energy change caused by particles (ions and electrons) collision, are negligible on the strong convective. Thus we attempt to utilize the simple Euler model to describe the plume expansion into background air. In the initial conditions of our calculation, the background air is assumed to be static, i.e., fluid velocity is zero, the surrounding temperature is \(300 \text{ K}\), and the surrounding pressure is an atmospheric pressure. The 3D Euler equation of mass fluid conservation is written as:

\[
\frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \mathbf{v},
\]

\[
\frac{\partial \rho \mathbf{v}}{\partial t} = -\nabla \cdot \rho \mathbf{v} \mathbf{v} - \nabla P,
\]

\[
\frac{\partial E}{\partial t} = -\nabla \cdot \mathbf{v} E - \nabla \cdot \mathbf{v} P.
\]

Where the expansion time is denoted by \(t\), and the energy density \(E = P/(\gamma - 1) + \rho \mathbf{v} \cdot \mathbf{v}/2\). The fluid velocity is denoted by the sign \(\mathbf{v}\). The mass density \(\rho = (m_i/Z + m_e)n_e\), \(m_i\) is ion mass, \(Z\) is the average charge number. The pressure \(P = (1/Z + 1)P_e\).

According to the equation of state of the classical ideal gas, the electron pressure can be described as

\[
P_e = n_e k_B T_e,
\]

where \(k_B\) is Boltzmann constant, and \(T_e\) is electron temperature. It is obvious that the expanding rate has a strong correlation with the degree of the laser heating electrons \cite{29}.

Electron-ion collisions frequency can be calculated in the high-field limit \(U_p \gg \kappa_e T_e\), where the ponderomotive potential is given by

\[
U_p = \frac{1}{4} \frac{e^2 E_0^2}{m_e \omega^2} \approx 9.33 \times 10^{-14} I(W/cm^2)\lambda^2(\mu m),
\]

\(E_0\), \(I\), \(\omega\), and \(\lambda\) are amplitude, intensity, frequency, and wavelength of laser electric field, respectively. Yielding an effective collision frequency is expressed as

\[
\nu_{ei}(T_{\text{eff}}) \sim 4 \pi (Z)^2 N_e e^4 \ln \Lambda_{ei}/m_e^2 T_{\text{eff}}^{3/2},
\]

where \(T_{\text{eff}}, N_i, \) and \(\ln \Lambda_{ei}\) are effective temperature, ion density, and Coulomb logarithm. In our experiment, \(n_e \sim 10^19 \text{ cm}^{-3}, \lambda \sim 1053 \text{ nm}, Z \sim 1, \ln \Lambda_{ei} \sim 10^4, I \sim 10^{13} \text{ W/cm}^2\), so the heating time is \(t^* \sim (\alpha e)^{-1} \sim 10\) picosecond \((\text{ps})\). Because it is much less than the duration time of laser pulse \((\tau_p \sim 3 \text{ ns})\), the process of heating plasma is apprehended with long-pulse regime: \(\kappa_B T_e \sim U_p (\tau_p/t^*)^{1/5} \sim 60 \text{ eV}\).

## 4 Results and discussions

Since our primary interest is 2D spatial density distribution of the plasma created in gas, the authentic experimental data about the 2D spatial density distribution are presented first. For the earlier times of plasma expansion, the pattern of interference
fringes detected via optical interferometry will become distorted due to the high density layers of plasma refracting the probing beam. The probing beam is delayed 20 ns with respect to the main beam by an optical delay line. It is directed transversely cross plasma channels generated by 20 mJ, 50 mJ, 100 mJ main beam breakdown in air respectively. The non-distortion and clear interference fringes are imaged on CCD through an imaging system, and shown in Fig. 2. It can be seen from the figure, as the laser energy becomes strong, the plasma channel is longer and wider. In order to reveal features of electrical distribution visually, the 2D plasma density profiles are extracted from these interferograms via the Abel transformation technique. These measurement results reveal a similar feature of density distribution that the electron density in the center region is lower than in the border. To analyze the hollow-core feature of density distribution, we calculate the 2D density distribution of laser-gas plasma by the simplified theoretical model mentioned above.

In the simulation of the formation stage of the plasma, the electron density distribution is calculated with Eqs. (1) and (2). The fundamental laser field is assumed to be Gaussian both in space and time at the entrance of a gas. The Crank-Nicholson implicit method is used to construct the tridiagonal matrix of Eq. (2). The laser pulse intensities are $0.7 \times 10^{13}$ W/cm$^2$, $1.75 \times 10^{13}$ W/cm$^2$, $3.5 \times 10^{13}$ W/cm$^2$, respectively, for energies of 20 mJ, 50 mJ, 100 mJ. The pulse wavelength $\lambda=1053$ nm, and the evolution time is set as 4 ps. In the expansion stage of plasma, the 2D Euler equations of mass fluid conservation, i.e., Eqs. (4)–(6), are numerically solved by the LCPFCT algorithm $[30]$. The calculated results are compared with experimental results. Fig. 3(a) shows the electron density distribution along the main beam propagation direction $z$ and transverse direction $r$ extracted from Fig. 2(a), that for the laser energy of 20 mJ. The figure clearly displays a hollow-core distribution, the electrons in plasma are mostly located in the border of the profile. This can be explained qualitatively as follows. In the early stage of plasma formation, because the power of the pulse is the most intense in the center regions of the Gaussian laser beam, the gas is more easily ionized in these regions. The electron density in the center regions is higher than that in the border. However, after the plasma of the high density region is heated by electron-ion collisions under a long driven laser pulse, these hot electrons and ions in the center regions will diffuse into the border. The plasma expansion occurs in the form of a shock wave. Finally the hollow-core distribution that the density near the periphery is higher than that in the center is formed.

![Fig.2](image_url)

**Fig.2** Interferograms of laser breakdown in air at 20 ns after the main beam for three laser energies of (a) 20 mJ, (b) 50 mJ, (c) 100 mJ. The laser propagation direction is labeled out by a red arrow

![Fig.3](image_url)

**Fig.3** The experimental (a) and simulated (b) 2D electron density distribution along the main beam propagation direction $z$ and transverse direction $r$ for the laser energy of $\sim 20$ mJ and delay time of $\sim 20$ ns. (c) Simulated electron density profiles along $r$ versus expansion time $\tau_{\text{delay}}=5$ ns, 10 ns, 15 ns, 20 ns, the dashed line is experimental result for 20 ns for comparison

Fig. 3(b) shows the corresponding simulated result. The main features of measurement (the profile, size of plasma channel and maximum value of electron density) are properly reproduced in the simulation. In the calculation of plasma formation, if the ionization absorption and plasma defocusing are not considered, the electron density calculated must be higher than the experimental results. Compared with the well-known PIC simulation for calculating beam-plasma interaction, our model has the advantage in the larger spatio-temporal windows. What is more, our model
can be used to simulate the dynamic process of plasma expanding. In Fig. 3(c) we show the electron density profiles along transverse direction $r$ for expansion time $\tau_{\text{delay}}=5$ ns, 10 ns, 15 ns, 20 ns, for comparison we also show the experimental result for 20 ns. For the initial stage of expansion, i.e., $\tau_{\text{delay}}=5$ ns, plasma density reaches $6.4 \times 10^{19} \text{ cm}^{-3}$ and its width is only 100 µm. As the expansion time increases, the plasma density decreases fast and the plasma width becomes large. Finally, the density decreases to $1.7 \times 10^{19} \text{ cm}^{-3}$, while the width reaches about 300 µm. The comparison between simulation and experiment demonstrates again the validity of our model, especially in the border region.

Fig. 4(a) shows the 2D experimental electron density distribution from a laser energy of 50 mJ and delay time of 20 ns. Compared to the low energy of 20 mJ [Fig. 3(a)], the density reaches a higher value of about $2.5 \times 10^{19} \text{ cm}^{-3}$. The simulated results show the same change [Fig. 4(b)]. If the duration of pulse remains unchanged, the stronger the laser energy is, the higher its intensity is. The multiphoton process is able to provide more initial free electrons, and the avalanche process can occur more acutely. Obviously, this can result in a higher ionization of the gas target.

When the laser energy is increased to a more higher value of 100 mJ, as the simulated and experimental results show [seen in Fig. 5(a) and (b)], the electrical density and width of plasma are further increased to about $3.3 \times 10^{19} \text{ cm}^{-3}$ and 600 µm, respectively. The changes of electrical density have been illustrated in the previous paragraph. The changes of plasma width can be understood via heat expansion of plasma. The laser with high energy is able to generate a large number of free electrons in the plasma. The electron-ion collisions frequency will increase sharply with an upsurge of electron number. This will cause the plasma to become very hot. Its velocity of expansion is larger than these inferior hot plasma. The hotter plasma develops wider at the same time.
decreases continually with outward expansion. Because of neglecting the dynamics process of temperature compensated, the local temperatures are lower than in the real experiments. In the same amount of time, the calculated plasma regions with a lower temperature expand less than the experimental plasma regions with higher temperature. Understandably, the calculated results, in comparison with experiment results, show higher plasma densities near the \( z \) axis. If the duration of the laser beam is \( \sim 100 \) ps, the persistent heating to the center region of plasma can be restrained, the results similar to simulations are likely to be observed.

5 Summary

In conclusion, the 2D density distributions of laser-induced plasma channel in the air target are investigated both in experiment and theoretical simulation. Some clear interferograms versus 20 mJ, 50 mJ, 100 mJ laser breakdown in air are obtained by using optical interferometry. The 2D density distributions are extracted from the interferograms through an Abel transformation technique. Subsequently, the physical processes of laser creating plasma are analysed. The plasma formation and expansion are considered separately. The formation process is evaluated by combining the propagation model of pulse in the medium with the evolution model of electron density. The expansion process is investigated by the adiabatic dynamic model. We evaluate the plasma density distributions versus different laser pulse intensities. In order to clearly demonstrate the process of expansion, the density profiles along \( r \) at \( \tau_{\text{delay}} = 5 \) ns, 10 ns, 15 ns, 20 ns are also shown. The simulated results show good agreements with experiments as a whole. The laser-plasma process was considerably complicated due to its numerous physical regimes. Through a reasonable predigestion and based on the authentic experiment result, our two-step model could provide a quantitative simulation with regard to the 2D density distribution of the early plasma expansion stage.

Many applications based on plasma need to determine the 2D density data of laser-induced plasma plume. In the case of the plasma waveguide, the hollow core, long plasma pipe is able to guide an intense pulse propagating over many Rayleigh lengths with a small spot. This plasma condition is capable of generation in the late stage of expansion. But the extremely high density plasma, which is suitable for backward Raman amplification, appears in the early stage of expansion. Our work can provide a theoretical basis for predicting the expected plasma conditions required for some applications.

References


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