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Cite as: AIP Advances 11, 075313 (2021); https://doi.org/10.1063/5.0054582
Submitted: 09 June 2021. Accepted: 25 June 2021. Published Online: 09 July 2021

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ABSTRACT
A gas jet produced by adiabatic expansion of gas through a slit nozzle into a vacuum has been served as a target in the study of high harmonic generation or laser wakefield electron acceleration. In this work, Mach–Zehnder interferometry was utilized to obtain the gas density distribution in an argon cluster gas jet produced from a supersonic slit nozzle. The interference fringe distortion caused by the gas jet along the slit width under high backing pressure was recorded and inverted to a gas density profile. The gas backing pressure was up to 80 bars to obtain a gas jet with a higher density. It is found that the gas density in the jet is not uniform along the width direction of the slit nozzle and is the highest at the center of the jet. Along the gas jet, the highest gas density roughly decreases linearly. However, a steep density gradient is observed at \( P_0 = 60–80 \) bars. Meanwhile, the highest gas density depends linearly on the gas backing pressure and the degree of dependence gradually decreases along the gas jet.

I. INTRODUCTION
The clustered-gas jet, which is produced by adiabatic expansion of gas under a high backing pressure through a nozzle into a vacuum, has the average density of gas and the local density of solid or liquid in individual clusters.1 The unique density characteristic of the clustered-gas jet makes it a special interaction target in the study of intense laser interaction. For example, the intense laser pulse interaction with a clustered-gas jet generates high-energy ions,2-4 x rays,4 table-top nuclear fusion,5,6 and so on. Meanwhile, the clustered-gas jet, as another medium of high-order harmonic generation (HHG), has also attracted the interest of many research groups.8-10 HHG resulting from the interaction of an intense laser pulse with an atom is well described by the “three-step model.”11,12 However, HHG resulting from the interaction of an intense laser pulse with a cluster is not well understood and identified.8-10 It is well known that phase matching in HHG between the fundamental field and harmonics in a medium is influenced by the density and length of the medium due to the medium dispersion. Therefore, the gas density distribution in a gas jet is an important factor for HHG efficiency.15,16 Considering that in a clustered-gas jet, the cluster density distribution is related to gas density distribution, knowledge of gas density distribution is helpful to clarify the effect of the cluster density distribution on HHG efficiency. Thus, the investigation of gas density in a clustered-gas jet is useful for further understanding of the HHG mechanism underlying in a cluster. Compared with a conical nozzle, the slit nozzle can be used to produce a gas jet with higher gas density on the one hand and to produce a jet with a long dimension (length) and a short dimension (width) on the other hand, which is widely used in HHG research.
an intense laser pulse interacts with the jet along the length, the interaction dimension is long, which could generate a long plasma waveguide to achieve phase matching and increase harmonic yield. For example, Geng et al.\textsuperscript{12} used femtosecond laser pulses to interact with Ar gas cluster jets along the length and demonstrated the enhancement of the 27th harmonic yield. While an intense laser pulse interacts with the jet along the width, the interaction dimension is short. The influence of phase matching on harmonic yield is weakened, which is beneficial to study the harmonic generation mechanism.\textsuperscript{13} Meanwhile, the slit nozzle is widely used to produce a structured gas jet target for the laser wakefield electron acceleration experiments.\textsuperscript{14–16} Because the spatial distribution of gas density in the jet depends on the nozzle configuration,\textsuperscript{17,18} it is necessary to investigate the gas density distribution in the jet formed by a slit nozzle.

In this work, Mach–Zehnder interferometry\textsuperscript{22,23} and the method of interferometric data evaluation algorithms (IDEA)\textsuperscript{24} were used to investigate the spatial distribution of gas density in the jet formed by a supersonic slit nozzle along the width. The distributions at different distances from the nozzle outlet under different backing pressures were investigated experimentally. The results show that the spatial distribution of gas density along the width is non-uniform. The full width at half maximum (FWHM) of the distribution profile gradually increases along the gas jet and is approximately close to the slit width in the range of 2 mm far away from the nozzle outlet. The gas density at the center of the jet is the highest, and the highest density increases linearly with the gas backing pressure. Along the gas jet, however, the linear dependence gradually becomes weak. It is noted that a steep density gradient is observed at $P_0 = 60$–80 bars.

II. EXPERIMENTAL SETUP

The schematic diagram of the experimental setup is shown in Fig. 1. The clustered-gas jet was produced by the adiabatic expansion of argon gas through a supersonic slit nozzle into a vacuum. The nozzle (its configuration is shown in the lower panel of Fig. 1) was connected with a pulsed solenoid valve (Parker series 99). The throat diameter of the nozzle is 0.5 mm, and the nozzle outlet is rectangular with a size of $5 \times 0.5$ mm$^2$ (i.e., the slit length is 5 mm along the y-axis and the slit width is 0.5 mm along the z-axis). The nozzle depth is 5 mm along the x-axis direction (i.e., the gas jet direction). A Mach–Zehnder interferometer was set up in a vacuum chamber, in which the background pressure was maintained at $10^{-5}$ Torr using turbo molecular pumps and mechanical pumps. The on-time of the pulsed solenoid valve was set to be 5 ms, which ensures the formation of a steady-state clustered-gas jet. A He–Ne laser (Uniphase 1507P-0; wavelength, 632.8 nm; output power, 4 mW) was used in the Mach–Zehnder interferometer. The laser beam was first expanded and shaped to be a collimated beam with a spot diameter of about 4 mm and then was split into the probe beam and the reference beam by a beam splitter (BS1). The probe beam passed through the gas jet along the slit length (y-axis in Fig. 1) and was combined with the reference beam, and then, the interference pattern of the two beams was imaged using a CCD camera (Spiricon SP620U) with a lens. The spatial resolution of the CCD imaging system is about 7.1 μm/pixel. The CCD was triggered by the signal from the control box of the pulsed solenoid valve (Parker-lo-to-One) to realize the synchronization of the CCD and the pulsed solenoid valve. In this work, the interference fringes were recorded under gas backing pressures of 20, 30, 40, 50, 60, 70, and 80 bars (the interference fringes were along the z-axis, that is, along the slit width).

III. METHODS

Because the phase shift $\Delta \phi$ induced by a gas jet results in the fringe distortion in Mach–Zehnder interferometry, the interferogram encodes the distribution of the phase shift. In order to obtain the density distribution, the phase shift distribution is first inverted by comparing the interferograms obtained with and without a gas jet using the IDEA method. Then, the gas density distribution can be calculated using Eq. (1). $\Delta \phi$ can be expressed as

$$\Delta \phi = \frac{2\pi}{\lambda} \cdot \Delta n \cdot L,$$  \hspace{1cm} (1)

where $\lambda$ is the wavelength of the He–Ne laser (632.8 nm), $\Delta n = n + 1$ is the change of refractive index ($n$ is the refractive index of a gas jet), and $L$ is the dimension in a gas jet where the probe beam passed through. Since the supersonic slit nozzle has an opening angle along the x-axis, the jet dimension will gradually become wider. According to the geometric shape of the supersonic slit nozzle, $L$ can be approximately expressed as $0.5 + 0.9(5 + x)$ (mm), where $x$ is the distance from the nozzle outlet along the jet direction (as shown in Fig. 1). It is noted that this assumption is in good agreement with the experimental result, in which the jet dimension is about 7.3 mm at $x = 2.5$ mm for a supersonic slit nozzle.\textsuperscript{25} Based on the Lorentz–Lorenz relation, the polarizability $\chi$ of the Ar atom can be determined using the following equation:

$$\chi = \frac{3}{4\pi \rho} \frac{n^2 - 1}{n^2 + 2},$$  \hspace{1cm} (2)

where $\rho$ is the gas density. Using the approximate relation\textsuperscript{26}

$$\frac{n^2 - 1}{n^2 + 2} = \Delta n,$$  \hspace{1cm} (3)
IV. RESULTS AND DISCUSSION

In this work, the interferograms under gas backing pressures of 20, 30, 40, 50, 60, 70, and 80 bars were investigated. Figures 2(a) and 2(b) show the typical interferograms obtained with a gas jet under a backing pressure ($P_0$) of 80 bars. The fringe distortion induced by the gas jet can be seen clearly in Fig. 2(b). Obviously, the region with the fringe distortion corresponds to the area where the gas jet exists. Using the IDEA method, the phase shift distribution corresponding to Fig. 2(b) can be inverted and is shown in Fig. 2(c).

Based on the obtained phase shift distribution in Fig. 2(c) and Eqs. (1) and (4), the spatial gas density distribution under 80 bars was calculated. As examples, Fig. 3 shows the gas density distributions at three different $x$ values (i.e., 0.5, 1.0, and 1.5 mm) from a single shot. It can be seen that the gas density at the center of the jet $\rho_{\text{peak}}$ is the highest and it decreases as $x$ increases. For example, when $x$ is 0.5, 1.0, and 1.5 mm (that is, the distance from the nozzle throat is 5.5, 6.0, and 6.5 mm, respectively), the corresponding $\rho_{\text{peak}}$ value is $1.4 \times 10^{19}$, $1.2 \times 10^{19}$, and $8.6 \times 10^{18}$ cm$^{-3}$, respectively. Meanwhile, it can be seen that the density distribution is not uniform and its spatial width is larger than the slit width. The full width at half maximum (FWHM) of the density distribution profile corresponding to the three $x$ values is 0.34, 0.39, and 0.63 mm, respectively. That is, the FWHM is roughly close to the slit width. The non-uniform spatial distribution of density should be considered in the study of intense laser pulse interaction with the gas jet from a supersonic slit nozzle.

In order to investigate the evolution of $\rho_{\text{peak}}$ along the jet direction ($x$-direction), the $\rho_{\text{peak}}$ values under gas backing pressures $P_0 = 20$–80 bars were calculated. The results are shown in Fig. 4. The average SD at all $P_0$ values is about $3.4 \times 10^{17}$ cm$^{-3}$. It can be seen that at a given $x$ value, the higher the $P_0$ value is, the higher the $\rho_{\text{peak}}$ value is. At a given $P_0$ value, the $\rho_{\text{peak}}$ value decreases as $x$ increases. Meanwhile, the $\rho_{\text{peak}}$ value at different $P_0$ values indicates the same evolution trend with $x$, i.e., the $\rho_{\text{peak}}$ value gradually decreases. For example, the $\rho_{\text{peak}}$ values at both $P_0 = 20$ and 80 bars are the highest at the nozzle outlet ($x = 0$ mm), which are about $0.4 \times 10^{19}$ and $1.6 \times 10^{19}$ cm$^{-3}$, respectively. However, at $x \approx 2$ mm, the corresponding $\rho_{\text{peak}}$ value decreases to be $0.09 \times 10^{19}$ and $0.6 \times 10^{19}$ cm$^{-3}$, respectively. In general, the $\rho_{\text{peak}}$ value decreases with $x$ approximately linearly at all $P_0$ values.

It is noted that the linear dependence of $\rho_{\text{peak}}$ on $x$ is different from the case where a circular hole nozzle is used and the hydrogen molecule density exponentially decays as the distance increases away from the nozzle in Ref. 27. This result can be understood as below. As the distance increases, the cross section $S$ of the gas jet increases approximately with a square law due to the configuration of the circular nozzle. According to the mass conservation law of fluid ($\rho v S = \text{constant}$, where $\rho$ is the fluid density and $v$ is the flow velocity. For a stable gas flow, at a distance of a few nozzle-orifice diameters downstream away from the nozzle inlet, the flow velocity $v$ will reach a constant value, $v_0$), the fluid density decreases inversely proportional to $S$, i.e., the square of the distance. In our case, the supersonic slit nozzle is used. The increase in $S$ with $x$ mainly results

![Fig. 2](image-url)

![Fig. 3](image-url)
from the increase in the jet dimension in the \( y \)-direction due to an opening angle of the nozzle. In the \( z \)-direction, the FWHM of the jet density distribution profile is close to the nozzle width (as discussed above). Therefore, the linear dependence of \( \rho_{\text{peak}} \) on \( x \) in our case is reasonable, which is in agreement with the reported results.\textsuperscript{25,29,30} It should be noted that in Fig. 4, there is an inflection point at \( P_0 = 60–80 \) bars, where \( \rho_{\text{peak}} \) decreases rapidly and a steep density gradient is observed. The higher the \( P_0 \) value, the more obvious the inflection. The steep density gradient could be the shock front. The corresponding positions of the inflection \( x_{\text{inf}} \) at \( P_0 = 60, 70, \) and 80 bars are about 0.6, 0.8, and 1.0 mm, respectively, which increase further as \( P_0 \) increases. Obviously, the inflection at \( P_0 \) values of 60 and 70 bars leads to the partial overlap of the density curves (\( x > 1.0 \) mm, as shown in Fig. 4). The formation of the steep density gradient needs further research.

In order to further investigate the variation of \( \rho_{\text{peak}} \) with \( x \), the \( \rho_{\text{peak}} \) values corresponding to three \( x \) values (0.5, 1.0, and 1.5 mm, respectively) at different \( P_0 \) values were evaluated. The results are shown in Fig. 5. It can be seen that for a given \( x \) value, \( \rho_{\text{peak}} \) basically increases linearly with \( P_0 \). However, the dependence of \( \rho_{\text{peak}} \) on \( P_0 \) varies for different \( x \) values. For a large \( x \) value, the dependence of \( \rho_{\text{peak}} \) on \( P_0 \) slightly becomes weak. This is because the cross section \( S \) of the gas jet also increases as the distance \( x \) increases along the jet direction, which causes the decrease in density and weakens the influence of \( P_0 \) on the density. For example, at \( x = 0.5 \) mm, \( \rho_{\text{peak}} \) increases from \( 2.7 \times 10^{18} \) to \( 1.4 \times 10^{19} \) \( \text{cm}^{-3} \) when \( P_0 \) increases from 20 to 80 bars. The increment is about \( 1.1 \times 10^{19} \) \( \text{cm}^{-3} \). However, at \( x = 1.5 \) mm, \( \rho_{\text{peak}} \) increases from \( 1.5 \times 10^{18} \) to \( 8.6 \times 10^{18} \) \( \text{cm}^{-3} \), and the increment is \( 0.7 \times 10^{19} \) \( \text{cm}^{-3} \). Clearly, the increment is larger at \( x = 0.5 \) mm. It should be noted that when \( P_0 \) is changed 4 times, \( \rho_{\text{peak}} \) is increased 5.2 (\( x = 0.5 \) mm) and 5.7 (\( x = 1.5 \) mm) times. These results indicate the non-uniformity of the density distribution in the jet again. It is noted that at \( x = 1.0 \) mm, due to the inflection point of the density curve (as discussed above), \( \rho_{\text{peak}} \) at 70 and 80 bars indicates a little deviation from the trend at other \( x \) values.

It is noted that the spatial distribution along the slit length (i.e., \( xy \) plane in Fig. 1) is not involved in this work. Obviously, it is also important to study the spatial distribution of the gas density in the \( xy \) plane. Due to the spatial distribution, as shown in Fig. 4(d) in Ref. 25, the actual \( \rho_{\text{peak}} \) value could be higher than the calculated one. That is to say, the atom density could be underestimated in our calculation. To know the spatial distribution in the \( xy \) plane, however, on the one hand, the laser beam diameter should be further expanded due to the large dimension of the jet in the \( xy \) plane, which reduces the intensities of the probe and reference beams. On the other hand, because the probe beam is along the slit width, \( L \) is approximately equal to the width of the slit, in which the optical path of the probe beam is greatly reduced and the phase shift induced by the jet is weak. Therefore, the investigation of the spatial distribution of gas density along the slit length is challenging and demands more careful design.

V. CONCLUSIONS

In summary, Mach–Zehnder interferometry and the IDEA method were combined to investigate the gas density distribution in a clustered-gas jet produced by a supersonic slit nozzle along the slit width. It is found that the spatial distribution of gas density is not uniform. The study of gas density distribution under different back pressures (20–80 bars) shows that the gas density at the center of the jet basically increases linearly with gas backing pressure. Along the gas jet, the highest gas density decreases roughly linearly. However, the degree of the linear dependence gradually decreases. It is noted that a steep density gradient that could be the shock front is observed at the higher gas backing pressure. In the HHG experiment, the yield of high-order harmonics is related to the medium density and its spatial distribution; hence, the results could be helpful to the optimization for the yield of the high-order harmonics and the understanding of the HHG mechanism from a cluster in which a slit nozzle is used to produce the clustered-gas jet.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Paramita Deb for helpful discussion. This work was partly supported by the National Natural Science Foundation of China (Grant No. 51775327). Dong Eon Kim was supported by the National Research Foundation of
Korea (NRF) funded by the Ministry of Science and ICT (Grant No. 2016K1A4A4A01922028).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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