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The radial dimension of a supersonic jet expansion from conical nozzle

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In a laser-cluster interaction experiment, the radial dimension of a supersonic gas jet is an important parameter for the characterization of interaction volume. It is noted that due to the lateral gas expansion, the diameter of a supersonic gas jet is larger than the idealized diameter of a gas jet from a conical nozzle. In this work the effect of the lateral expansion on the radial dimension of gas jet was investigated by simulations. Based on the simulation results, the diameter of gas jet l was compared in detail with the corresponding diameter l_T in the idealized straight streamline model and the diameter l_H at a half of maximum atom density of gas jet. The results reveal how the deviation of l from l_T (l_H) changes with respect to the opening angles of conical nozzles, the heights above the nozzle, the nozzle lengths and the gas backing pressures. It is found that the diameter of gas jet l is close to the idealized diameter l_T and l_H in the case where a long conical nozzle with a large opening angle is used under a low gas backing pressure. In this case, the effect of the lateral expansion is so weak that the edge of gas jet becomes sharp and the radial distribution of atom density in gas jet tends to be uniform. The results could be useful for the characterization of a supersonic gas jet. [http://dx.doi.org/10.1063/1.4967782]

I. INTRODUCTION

A clustered-gas jet has been widely used in the studies of laser pulse interaction with matter, e.g., table-top nuclear fusion experiment[1,2] plasma waveguide generation.[3,4] The production of a gas jet and its characterization have attracted interests and been extensively studied.[5–19] Usually, a supersonic clustered gas jet can be produced by the adiabatic expansion of gas under a high backing pressure through a conical nozzle into vacuum. The dimension of a gas jet is an important parameter for the determination of interaction length.[4,20] Based on the idealized straight streamline model, the expansion angle of a supersonic gas jet is equal to the opening angle of a conical nozzle. Thus the idealized diameter of gas jet from a conical nozzle can be obtained by following the nozzle's geometric structure. Unfortunately, due to the lateral gas expansion into vacuum, the diameter of a gas jet will be larger than the idealized one.[8,21,22] Thus it is important to know how the lateral gas expansion makes effects on the radial dimension of a supersonic gas jet. In this work, a large number of simulations about supersonic gas jet in case of a conical nozzle with a throat diameter of 0.5 mm were made using the Boldarev's 2D model.[18] Eighteen cases were considered in simulations: six

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nozzle lengths L of 5, 10, 15, 20, 25 and 30 mm, and three opening angles for each nozzle length. For each nozzle the diameters of gas jets at sixteen different heights above the nozzle exit were investigated under five different gas backing pressures (P_0=10, 20, 30, 40 and 50 bars). Firstly we made detailed comparisons between the idealized diameter l_T and the simulated diameter l of gas jet for all conical nozzles. To further investigate the effect of the lateral expansion on gas jet, the diameter l_H of gas jet at a half of its maximum atom density is also compared with the diameter of gas jet. In this work, the ratio of simulated diameter to that from the straight streamline model of gas jet is introduced to denote the deviation between them. Furthermore the ratio of the diameter at a half maximum atom density to the diameter of gas jet was calculated to investigate the radial density distribution of gas jet. It is interesting to find that both the ratios are related to the nozzle length and the gas backing pressure besides the opening angle of conical nozzle and the height above the nozzle. The dependence of the diameter ratio on these parameters is similar to that of the on-axis atom density on these parameters.[21,22] Due to the lateral expansion, the diameters l, l_T and l_H are usually different. They tend to be the same only when the conical nozzle with a long nozzle length and a large opening angle is used under a low backing pressure. In other words, a long conical nozzle of a large opening angle could be used to produce a supersonic gas jet with the uniform radial atom density distribution, even at high gas backing pressure. The results could be helpful for the characterization of a gas jet in the study of laser-cluster interaction.

II. THE RADIAL DIAMETER RATIO OF GAS JET

Because there is no effect of the lateral gas expansion in the straight streamline model, the ratio of the gas jet dimension from simulation to that in the straight streamline model can be used to study the effect of the lateral expansion. Firstly the diameter ratio η is defined as $\eta = l/l_T$, where l is the simulation diameter of gas jet and l_T is that expected by the straight streamline model. Also the other diameter ratio η_H is defined as $\eta_H = l_H/l$, where l_H is the diameter of gas jet, at which the atom density is a half of the maximum atom density. This work mainly concerns about the variation of these two diameter ratios for eighteen conical nozzles.

The idealized diameter of a gas jet from a conical nozzle can be obtained based on the idealized straight streamline model. Figure 1 shows its schematic diagram for the streamline of a gas jet into vacuum from a conical nozzle. Form Fig. 1, the idealized diameter of gas flow l_T can be given by the expression $l_T = 2\,(L + h)\tan\alpha + d$, where L is the length of the conical nozzle, h the height above the nozzle exit and d, α the throat diameter and the half opening angle of the conical nozzle, respectively. It is clear that the idealized diameter is related to the opening angle, the height and the nozzle length.

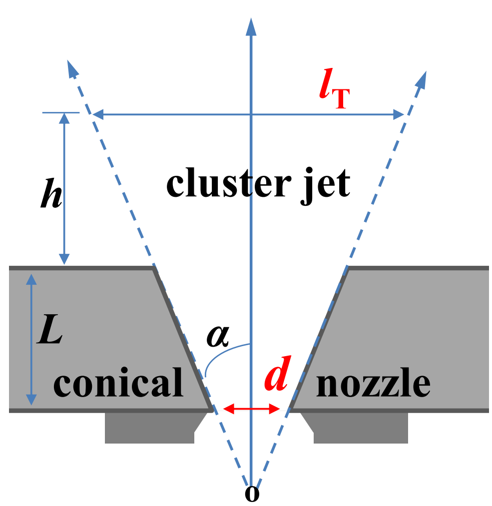

FIG. 1. The schematic diagrams for the streamline of a gas jet into vacuum from a conical nozzle based on the idealized straight streamline model.

The simulation diameter of gas jet is obtained from the simulation results about argon gas flow using e 2D hydrodynamic model described in detail in Ref. 18. The capability of this model for the spatial distribution of gas density has been demonstrated.[16,18,19] The 2D hydrodynamic model reproduces the spatial structure of the gas jet, including the rarefaction waves at the edges of the jet, and it is possible to evaluate the diameter on the base of the simulated results by introducing a threshold density value. Similarly to the definition of gas diameter in Ref. 22, the calculated diameter of gas jet, l, is, in this work, defined as that of the region where the atom density is higher than 3% of the maximum atom density. The diameters of a gas jet at sixteen heights above the nozzle are obtained. Meanwhile, the diameter of the gas jet l_{H}, at which the atom density is a half of the maximum atom density, is also obtained based on the simulation results.

III. RESULTS AND DISCUSSIONS

For analysis of the diameter of a gas jet, we calculated all the diameters from the atom density profiles based on the simulation results. As expected, it is found that the bigger the opening angle or the higher the height is, the larger the diameter of gas jet is for a given nozzle length. Moreover, it is also noted that the diameter increases with the increase of the nozzle length L for a given opening angle. For example, the diameter is about 2.8 mm at h =3.0 mm for the conical nozzle of L=5mm, $\alpha = 8.5°$, while it is about 6.2 mm for the conical nozzle of L=30 mm, $\alpha = 8.5°$. All these results can be easily understood based on the geometrical structure of conical nozzles. For a conical nozzle, the diameter of nozzle exit will become larger when the opening angle and the nozzle length increase. The diameter of a gas jet should then increase, which is in agreement with the results from the idealized straight streamline model.

The detailed comparison between the simulation diameter and the diameter in the straight streamline model is made. The diameter ratios η for all conical nozzles and for all heights are calculated and listed in Table I. From Table I, it is clearly found that for any nozzle length, (1) the diameter ratio is always larger than 1. That is to say, due to the lateral gas expansion, the diameter of a gas jet

TABLE I. The diameter ratio η of gas jet at the heights from 1.8 mm to 4.8 mm for the eighteen conical nozzles under the backing pressure of 50 bars.

		Height (mm)															
		1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.8
	8.5°	1.67	1.73	1.78	1.83	1.88	1.92	1.96	2.01	2.05	2.08	2.12	2.15	2.19	2.22	2.26	2.29
L=5 mm	14.0°	1.46	1.49	1.52	1.56	1.59	1.62	1.65	1.68	1.70	1.73	1.76	1.76	–	–	–	–
	19.3°	1.31	1.34	1.36	1.39	1.39	1.40	1.42	1.44	–	–	–	–	–	–	–	–
	8.5°	1.39	1.42	1.46	1.49	1.52	1.56	1.59	1.62	1.65	1.68	1.71	1.74	1.76	1.79	1.81	1.84
L=10 mm	14.0°	1.23	1.25	1.27	1.29	1.30	1.32	1.34	1.37	1.38	1.40	1.42	1.44	1.45	1.47	1.48	1.49
	19.3°	1.15	1.17	1.18	1.19	1.21	1.22	1.23	1.24	1.26	1.27	1.28	1.29	1.31	1.32	1.33	1.34
	8.5°	1.26	1.28	1.30	1.32	1.34	1.37	1.39	1.41	1.43	1.45	1.48	1.50	1.52	1.54	1.56	1.57
L=15 mm	14.0°	1.15	1.16	1.17	1.19	1.20	1.21	1.23	1.24	1.25	1.26	1.27	1.29	1.30	1.31	1.33	1.34
	19.3°	1.10	1.11	1.12	1.12	1.13	1.14	1.14	1.15	1.15	1.16	1.16	1.17	1.18	1.18	1.19	1.19
	8.5°	1.19	1.21	1.23	1.24	1.26	1.28	1.30	1.31	1.33	1.35	1.37	1.38	1.40	1.42	1.44	1.45
L=20 mm	14.0°	1.11	1.12	1.13	1.13	1.14	1.15	1.16	1.17	1.18	1.19	1.20	1.20	1.21	1.22	1.23	1.24
	19.3°	1.07	1.07	1.08	1.08	1.08	1.09	1.09	1.10	1.11	1.11	1.11	1.11	1.12	1.12	1.12	1.13
	8.5°	1.14	1.15	1.17	1.19	1.20	1.21	1.23	1.24	1.26	1.27	1.28	1.30	1.31	1.32	1.34	1.35
L=25 mm	14.0°	1.08	1.09	1.10	1.10	1.11	1.12	1.12	1.13	1.14	1.15	1.15	1.16	1.17	1.17	1.17	1.18
	19.3°	1.05	1.05	1.06	1.06	1.06	1.06	1.06	1.07	1.07	1.07	1.08	1.08	1.08	1.08	1.09	1.09
	8.5°	1.12	1.13	1.14	1.15	1.16	1.17	1.19	1.19	1.21	1.22	1.23	1.24	1.25	1.27	1.27	1.28
L=30 mm	14.0°	1.06	1.07	1.06	1.08	1.09	1.09	1.09	1.10	1.10	1.11	1.11	1.12	1.13	1.13	1.13	1.14
	19.3°	1.03	1.04	1.04	1.04	1.04	1.04	1.04	1.05	1.05	1.05	1.06	1.06	1.05	1.05	1.05	1.06

is always larger than the one predicted by the idealized straight streamline model. (2) The diameter ratio generally increases with the increase of the height and (3) the diameter ratio generally decreases with the increase of the opening angle. For example, the diameter ratios are 1.39, 1.23, and 1.15, for the opening angle of 8.5°, 14.0°, and 19.3°, respectively, at a height of 1.8 mm and for a nozzle length of 10 mm, while the diameter ratios are 1.84, 1.49, and 1.34 at the height of 4.8 mm for the same nozzle. These observations clearly say that both the diameter and the diameter ratio are related to the height and the opening angle for any nozzle. These results are similar to the experimental results discussed for the conical nozzle with L = 5 mm in Ref. 22. It is also interesting to find from Table I that the diameter ratio is related to the nozzle length: it decreases with the increase of the nozzle length for the same height and opening angle. For example, the diameter ratios are 1.88, 1.52, 1.34, 1.26, 1.20 and 1.16 for a nozzle length of 5, 10, 15, 20, 25 and 30 mm, respectively at a height of 2.6 mm and a opening angle of 8.5°. Because the diameter ratio indicates the deviation from the prediction by the streamline model, it is concluded that the deviation of diameter becomes small for the conical nozzle with a big opening angle and a long nozzle length at a low height.

To more clearly show the radial spatial structure of the supersonic gas jet, the diameter ratios η_H for all conical nozzles and for all heights were calculated and listed in Table II. Table II, clearly shows that, similar to the diameter ratios η, η_H is also related to the height, the opening angle and the nozzle length for any nozzle. However, it is noted that η_H shows a different dependence from η. It generally increases with the increase of the opening angle and the nozzle length, but decreases with the increase of the height. For example, η_H are 0.69, 0.80, and 0.84 for an opening angle of 8.5°, 14.0°, and 19.3° respectively, at a height of 1.8 mm and a nozzle length of 10 mm, while the diameter ratios are 0.47, 0.62, and 0.69 at a height of 4.8 mm for the same nozzle. Meanwhile, it is noted that the diameter ratios are 0.89 at a height of 1.8 mm and for a nozzle length of 30 mm with an opening angle of 8.5°. It is noted that the dependence of η_H on the height is similar to the experimental result for the nozzle with L =5 mm in Fig.4 of Ref. 22. Because the ratio η_H denotes the deviation of l_H from l, the smaller η_H corresponds to the weaker lateral expansion and the sharper edge of gas jet.

TABLE II. The diameter ratio η_H of gas jet at the heights from 1.8 mm to 4.8 mm for the eighteen conical nozzles under the backing pressure of 50 bars.

		Height (mm)															
		1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.8
	8.5°	0.52	0.50	0.48	0.46	0.45	0.43	0.42	0.41	0.40	0.38	0.37	0.36	0.34	0.33	0.32	0.32
L=5 mm	14.0°	0.63	0.62	0.60	0.58	0.56	0.55	0.54	0.53	0.51	0.50	0.49	0.49	–	–	–	–
	19.3°	0.70	0.68	0.66	0.64	0.63	0.61	0.60	0.58	–	–	–	–	–	–	–	–
	8.5°	0.69	0.67	0.65	0.63	0.62	0.60	0.58	0.57	0.56	0.54	0.53	0.52	0.51	0.49	0.48	0.47
L=10 mm	14.0°	0.80	0.78	0.77	0.75	0.74	0.73	0.71	0.70	0.69	0.68	0.66	0.66	0.65	0.64	0.63	0.62
	19.3°	0.84	0.83	0.82	0.80	0.79	0.78	0.77	0.76	0.75	0.74	0.73	0.72	0.72	0.71	0.70	0.69
	8.5°	0.78	0.77	0.75	0.74	0.72	0.70	0.69	0.68	0.66	0.65	0.64	0.63	0.62	0.61	0.60	0.59
L=15 mm	14.0°	0.86	0.85	0.83	0.82	0.81	0.80	0.79	0.78	0.77	0.76	0.75	0.74	0.74	0.73	0.72	0.71
	19.3°	0.89	0.89	0.88	0.87	0.87	0.86	0.85	0.85	0.84	0.84	0.83	0.83	0.82	0.82	0.81	0.81
	8.5°	0.83	0.81	0.80	0.78	0.77	0.76	0.75	0.73	0.72	0.71	0.70	0.69	0.68	0.67	0.66	0.65
L=20 mm	14.0°	0.89	0.89	0.88	0.87	0.86	0.85	0.84	0.84	0.83	0.82	0.81	0.81	0.80	0.80	0.79	0.78
	19.3°	0.93	0.92	0.92	0.91	0.91	0.91	0.90	0.89	0.89	0.88	0.88	0.88	0.88	0.87	0.87	0.86
	8.5°	0.86	0.85	0.84	0.82	0.82	0.80	0.79	0.78	0.77	0.76	0.75	0.74	0.73	0.72	0.71	0.70
L=25 mm	14.0°	0.92	0.91	0.90	0.90	0.89	0.88	0.88	0.87	0.86	0.86	0.85	0.84	0.84	0.84	0.83	0.83
	19.3°	0.95	0.94	0.94	0.94	0.94	0.93	0.93	0.92	0.92	0.92	0.92	0.91	0.91	0.91	0.90	0.90
	8.5°	0.89	0.88	0.87	0.85	0.85	0.84	0.82	0.82	0.81	0.80	0.79	0.78	0.77	0.76	0.76	0.75
L=30 mm	14.0°	0.94	0.93	0.93	0.92	0.91	0.91	0.91	0.90	0.90	0.89	0.89	0.88	0.87	0.87	0.87	0.86
	19.3°	0.97	0.96	0.96	0.96	0.95	0.96	0.95	0.95	0.94	0.94	0.94	0.93	0.94	0.94	0.94	0.93

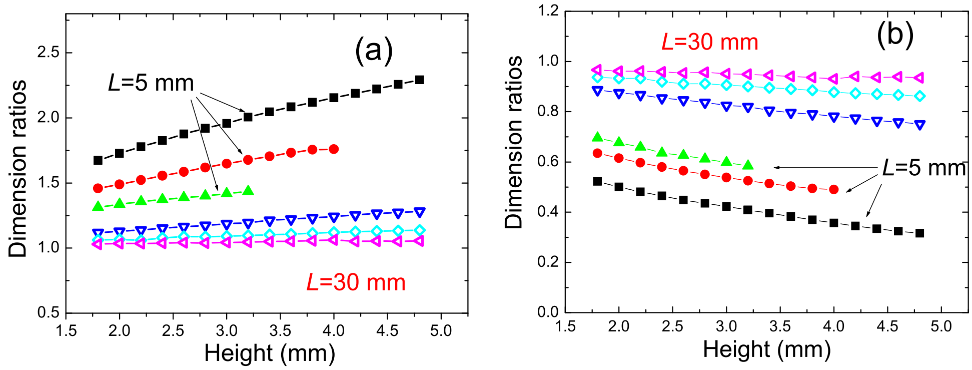

FIG. 2. Comparison of diameter ratios η (a) and η_H (b) at different heights above the nozzle for two nozzle lengths (L=5 mm and 30 mm) and three opening angles ($\alpha = 8.5°$, 14.0°and 19.3°), respectively.

From Table I and Table II, it can be found that η and η_H are close to 1 only when the height is low for a nozzle with a long length and a big opening angle. The small η indicates that the deviation of l from l_T is small, which mean the weaker rarefaction waves at the edge of jet. Meanwhile, when the diameter ratio η_H is close to 1, l_H will be equal to l, which means a sharp edge of the jet profile, i.e., the atom density in gas jet could be radially uniform. Thus it can be concluded that a conical nozzle with a long length and a big opening angle could be helpful to produce a supersonic gas jet with a radially uniform distribution of atom density, especially at a low height. These results can be understood as below: Because the lateral expansion becomes weak with the increase of the nozzle length and the opening angle,[21] it is reasonable that the l_H become to be close to l, and the radial distribution tend to be uniform for a nozzle with a long length and a big opening angle at a given height. Meanwhile, as for the height dependence, because the increase of the height results in the

TABLE III. The diameter ratios η of a gas jet at the height of 2.4 mm under five gas backing pressures for the eighteen conical nozzles.

		P_0 (bars)				
		10	20	30	40	50
	8.5°	1.49	1.53	1.62	1.79	1.83
L=5 mm	14.0°	–	1.31	1.30	1.57	1.56
	19.3°	1.12	–	–	1.38	1.39
	8.5°	1.25	1.44	–	1.49	1.49
L=10 mm	14.0°	1.14	1.14	1.18	1.29	1.29
	19.3°	1.09	1.10	1.10	1.18	1.19
	8.5°	1.16	1.17	1.25	1.32	1.32
L=15 mm	14.0°	1.09	1.09	1.12	1.18	1.19
	19.3°	1.07	1.07	–	1.11	1.12
	8.5°	1.12	1.12	1.23	1.24	1.24
L=20 mm	14.0°	1.07	1.07	1.10	1.13	1.13
	19.3°	–	–	1.05	1.08	1.08
	8.5°	1.09	1.09	1.16	1.19	1.19
L=25 mm	14.0°	1.05	1.05	1.07	1.10	1.10
	19.3°	–	–	1.04	1.06	1.06
	8.5°	1.08	1.08	1.15	1.15	1.15
L=30 mm	14.0°	–	1.05	1.06	1.08	1.08
	19.3°	–	–	1.03	1.04	1.04

increase of the lateral expansion time, the deviation of l_H from l or the deviation of l from l_T will increase as the height.

It is necessary to note that though the ratio is related to the height and the opening angle, the dependence is different for different nozzle lengths. To illustrate the dependence more clearly, both η and η_H for the nozzles with L=5 mm and 30 mm were plotted together in Figs.2(a) and (b). From Fig.2(a), it is clearly seen that for the nozzle with L=30 mm, the dependence of η on the height and the opening angle is weaker and the change of the ratio is not so large as that for the nozzle with L=5 mm. From Fig.2(b), the similar results about η_H can be found. This means that the diameter of gas jet is close to that predicted by the idealized model or the dimension at a half maximum for the nozzle with a longer length, even though the nozzle has the small opening angle. It can be understood from the fact that the lateral expansion would become weaker with respect to the axis expansion with the increase of the nozzle length.

To investigate the dependence of the diameter ratios on a gas backing pressure, we calculated the diameter ratios for eighteen nozzles under a backing pressure of 10, 20, 30, 40 and 50 bars, respectively. As examples, the results about η and $\eta_{H,}$ at a height of 2.4 mm are listed in Table III and Table IV. From Table III and Table IV, it is found that (1) the behavior of the diameter ratio under other backing pressures is similar to that under a backing pressure of 50 bars, i.,e., the diameter ratio is bigger (η) or smaller (η_H) for nozzles with smaller opening angles and shorter nozzle lengths. (2) The diameter ratio increases (η) or decreases (η_H) when the gas backing pressure changes from 10 bars to 50 bars for any nozzle. This means that the diameter ratio is dependent on the gas backing pressure. (3) The diameter ratio indicates the smaller variation for a long nozzle when the gas backing pressure increases. For example, the ratio η (η_H) changes from 1.49 (0.61) to 1.83 (0.47) for a nozzle length of 5 mm, while it only changes from 1.08 (0.93) to 1.15 (0.86) for a nozzle length of 30 mm when the opening angle is 8.5°. This results from the fact that the lateral expansion becomes strong as the gas expands from a conical nozzle under the high backing pressure.[21] This fact cannot be explained in the frames of the idealized straight streamline model, since this model provides a fixed structure of the jet for a given nozzle geometry (and a given gas species), which is independent of a gas backing pressure.

TABLE IV. The diameter ratios η_H of a gas jet at the height of 2.4 mm under five gas backing pressures for the eighteen conical nozzles.

		P_0 (bars)				
		10	20	30	40	50
L=5 mm	8.5°	0.61	0.59	0.59	0.45	0.47
	14.0°	–	0.70	0.78	0.59	0.58
	19.3°	0.84	–	–	0.67	0.64
L=10 mm	8.5°	0.79	–	–	0.64	0.63
	14.0°	0.87	0.87	0.84	0.75	0.75
	19.3°	0.91	0.90	0.89	0.81	0.80
L=15 mm	8.5°	0.86	0.83	0.78	0.74	0.74
	14.0°	0.91	0.91	0.89	0.83	0.82
	19.3°	0.93	0.93	–	0.88	0.87
L=20 mm	8.5°	0.90	0.89	0.80	0.79	0.79
	14.0°	0.93	0.93	0.91	0.86	0.87
	19.3°	–	–	0.94	0.91	0.91
L=25 mm	8.5°	0.92	0.91	0.85	0.83	0.83
	14.0°	0.95	0.95	0.93	0.90	0.90
	19.3°	–	–	0.95	0.93	0.94
L=30 mm	8.5°	0.93	0.92	0.86	0.86	0.86
	14.0°	–	0.94	0.94	0.92	0.92
	19.3°	–	–	0.96	0.95	0.96

It is noted that the relation between l_T and l_H can be obtained using η and η_H. From discussion above, the l_H is close to l_T at a low height and low gas backing pressure for a long conical nozzle and a big opening angle. This result implies that l_T can be used to estimate l_H in this case.

IV. CONCLUSIONS

In conclusions, by simulations, we investigated the dependence of the diameter ratio of a gas jet on the opening angle, the nozzle length of a conical nozzle, the height above the nozzle and the gas backing pressure. All the results indicate that the diameter ratio is related to these parameters. Because the diameter ratio indicates the deviation of the diameter of a gas jet from that predicted by the idealized diameter or the diameter at half maximum atom density, we can conclude that the three diameters trend to be equal to each other (i.e., the diameter ratio is close to 1.0) only when long conical nozzles with a large opening angle are used under a low gas backing pressure and a small height. In this case, a supersonic gas jet with a uniform radial distribution of an atom density could be produced, i.e., the supersonic gas jet has a relative sharp edge, in which the idealized diameter (l_T) in straight streamline model can be almost equal to the diameter l or the diameter l_H of gas jet. This kind of gas jet with a uniform radial atom density distribution will be useful in the laser-cluster interaction experiments.

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