Numerical and Experimental Study of High-Pressure Gas-Jet Targets for Ion Acceleration in the Near-Critical Density Regime

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Abstract*. Ion acceleration in the near-critical density regime is a captivating research area in high-energy physics and plasma physics. High-pressure gas jets have gained popularity as targets for ion acceleration experiments, due to their potential to offer debris-free ion sources that support high repetition rates. The purpose of this research is the design and fabrication of such gas targets for future ion acceleration experiments in the near-critical density regime. The optimization of two nozzle geometries has been studied using the ANSYS Student simulation program. The Computational Fluid Dynamics (CFD) problem is efficiently solved, and the determination of their cubic particle density maps is achieved. In addition, these nozzle geometries were fabricated using 3D printing and characterized in a vacuum environment, using Mach-Zehnder interferometry. These results make a significant contribution to the production of high-pressure gas targets for ion acceleration experiments and offer valuable insights for the design of future experiments.*

Keywords. Near-critical density regime, ion acceleration, 3D printing, CFD simulations, high-pressure gas-jet targets

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1 Introduction

Laser-induced ion acceleration is achieved by the interaction of a laser beam with a solid target. After each irradiation, these targets are destroyed, and replacement is required. As a result, they are not able to support high repetition rates. Near-critical density targets are considered a promising alternative for high-repetition-rate and debris-free ion sources. Several methods have been explored for the creation of near-critical density plasmas, including carbon nanotubes, liquids, water droplets, or gas jets [1]. Among these options, high-pressure gas targets have gained significant attention in ion acceleration experiments due to their numerous advantages [2].

The purpose of this study is to conduct an interferometric characterization of one cylindrical and one conical nozzle geometry within the vacuum. This parametric investigation initiates with the design and simulation of these two nozzle geometries to assess their potential as near-critical density targets. To experimentally validate the simulation findings, an experimental setup was developed to generate the consequent particle densities. The study finishes by presenting significant findings and drawing important insights.

2 Computational modelling

In laser-plasma interaction experiments, achieving the optimal density profile is crucial [3]. Two nozzle geometries, one cylindrical nozzle with $800\mu m$ diameter throat and one conical nozzle with $400\mu m$ minimum diameter demonstrated interesting characteristics [2, 4]. The CFD problem was efficiently solved using ANSYS Student, and its associated processor, ANSYS Workbench.

When determining the geometry for the flow analysis, the proper computational mesh was chosen. The mesh was divided into three distinct areas, as illustrated in Fig. 1 for the $800\mu m$ cylindrical nozzle. Fig. 1 depicts the computational design of the nozzle along with a reservoir and a $6mm \times 6mm$ chamber for gas expansion. The triangular mesh was employed, and the inflation-layer meshing was implemented near the walls.

Once the computational mesh was generated, the CFD analysis was set up. Its set of governing equations was chosen to be solved until a steady-state solution is achieved. Helium (as an ideal gas) was selected, and appropriate boundary conditions were specified. The inlet pressure was set to be $55 \times 10^5 Pa$, while the outlet pressure was set to be $25Pa$. The adiabatic expansion was assumed. By following this procedure for both nozzle geometries, numerous simulation results were obtained.

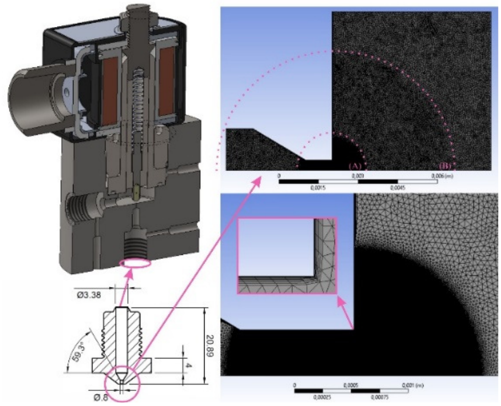

Figure 1. Each nozzle geometry is placed within the inner section of the solenoid valve. The computational mesh contained a reservoir positioned at the back of the nozzle, along with a chamber for gas expansion. The three distinct regions, that the mesh was separated into, are visible, along with the inflation-layer meshing near the walls.

3 Numerical simulations of the flow

By defining the key parameters, the prediction of the particle densities and velocity magnitudes was achieved. The program computed the helium particle densities across the whole domain for the case of the $800\mu m$ cylindrical nozzle, and at the exit of the nozzle the particle density was approximately $8.3 \times 10^{20} cm^{-3}$ (which corresponds to electron density $n_e = 0.48 n_{cr}$ for a $800nm$-wavelength laser system, where n_{cr} is the critical density). As far as the $400\mu m$ conical nozzle is concerned, the maximum helium particle density at the exit was determined to be approximately $9.3 \times 10^{20} cm^{-3}$ ($n_e = 0.55 n_{cr}$ for a $800nm$-wavelength laser system).

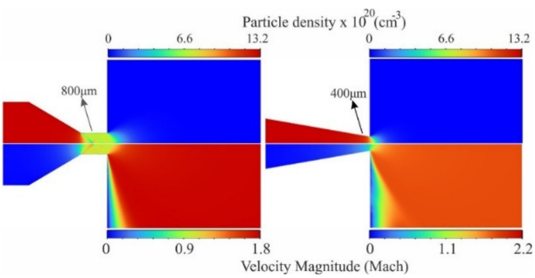

Figure 2. The particle density (top line) and the velocity magnitude contour maps (bottom line) at the exit of the nozzle for the $800\mu m$ cylindrical (left row) and the $400\mu m$ conical nozzle (right row), at inlet pressure of $55bar$, using helium expanding inside the vacuum.

During the setup process, a steady-state solution was chosen for each velocity contour map, in order to depict the final, unchanging pattern of flow. At the exit of the nozzle, for the $800\mu m$ cylindrical nozzle, the velocity is approximately $1 Mach$. For the case of the $400\mu m$ conical nozzle, the velocity magnitude at the exit of the nozzle is approximately $0.9 Mach$.

4 Methodology of the interferometric analysis

Following the simulation of the cubic density profiles, an experimental setup was developed. This experiment was conducted inside the laboratories of the Institute of Plasma Physics and Lasers (IPPL), in Rethymnon, Greece. The Mach-Zehnder interferometry was employed and the experimental configuration is depicted in Fig. 3. Upon employing the necessary experimental apparatus, the interferometric characterization of the gas-jet targets was successfully executed.

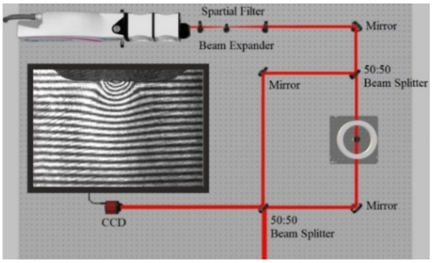

Figure 3. Schematic of the experimental setup that was employed for the interferometric characterization of the gas-jet targets.

5 Experimental results and analysis

The cubic particle density maps were calculated for both helium, and nitrogen, expanding within the vacuum, for each of the two nozzle geometries. Simulation investigation using nitrogen was not carried out due to limitations of ANSYS Student. The first experimental measurements were conducted using the $800\mu m$ cylindrical nozzle. Fig. 4(a) and (b) illustrate the cubic particle density contour maps for the case of helium and nitrogen respectively. The maximum particle density using helium was calculated to be $5.91 \times 10^{20} cm^{-3}$ ($n_e = 0.35 n_{cr}$ for an $800nm$-central-wavelength laser system), at the edge of the nozzle. Correspondingly, when nitrogen was employed, the maximum particle density was $3.66 \times 10^{20} cm^{-3}$ ($n_e = 0.21 n_{cr}$ for an $800nm$-central-wavelength laser system) at the exit of the nozzle.

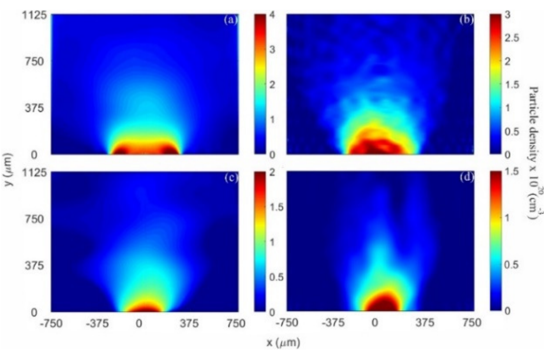

Figure 4. Cubic particle density contour maps for the $800\mu m$ cylindrical nozzle ((a) and (b)) and the $400\mu m$ conical nozzle ((c) and (d)), using helium ((a) and (c)) and nitrogen ((b) and (d)) expanding within a vacuum of $200mTorr$, at a static pressure of $55bar$.

An analytical investigation was carried out for the $400\mu m$ conical nozzle, as depicted in Fig. 4(c) and (d). The maximum particle density in this situation is equal to $2.41 \times 10^{20} cm^{-3}$ at the edge of the nozzle ($n_e = 0.14 n_{cr}$ for an $800nm$-central-wavelength laser system). As far as nitrogen is concerned, the calculated maximum particle density equals to $1.86 \times 10^{20} cm^{-3}$ (corresponding to $n_e = 0.11 n_{cr}$ for an $800nm$-central-wavelength laser system).

In these experimental findings, helium exhibited higher particle densities compared to nitrogen, for all nozzle shapes. However, nitrogen possesses more electrons compared to helium, making it a better donor of electrons. For full ionization of nitrogen, which can be achieved with the Zeus laser system (critical density $1.7 \times 10^{21} cm^{-3}$, and intensity $4.5 \times 10^{20} W/cm^2$) which is located inside the laboratories of the IPPL, the consequent plasma electron density equals to $1.51 n_{cr}$. For the same experimental conditions, for full ionization of helium, the consequent plasma electron density equals to $0.35 n_{cr}$. Taking these factors into consideration, the selection of the ideal gas for an experiment should be based on its specific requirements.

6 Comparison of the simulation and experimental results

Following the acquisition of the experimental and the simulation contour maps illustrating the helium particle density, a comparative analysis was conducted for both nozzle geometries. Specifically, a density lineout comparison between the experimental and simulation results was performed at a distance of $100\mu m$ from the exit of each nozzle. The results of this comparison are presented in Fig. 5, with the particle density axis being in a logarithmic scale.

It is clear that the simulation and experimental semilogarithmic particle density lineouts follow the same trend for each of the nozzle geometries. In the case of the $800\mu m$ cylindrical nozzle (left), the gas has a top-hat density profile, while for the $400\mu m$ conical nozzle, the gas exhibits a Gaussian-type density profile. Depending on the demands of the experiment, each nozzle geometry can be selected.

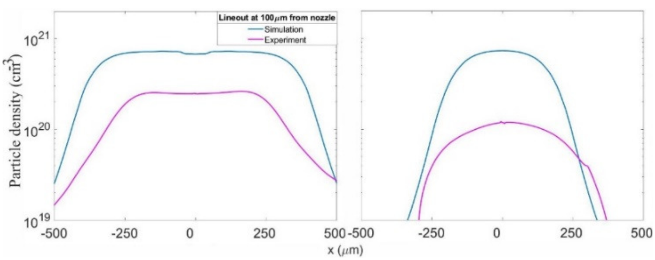

Figure 5. Semilogarithmic density lineout comparison at a distance of $100\mu m$ from the exit of the nozzle between simulation and experiment for the cylindrical (left) and the conical (right) nozzle, using helium expanding within a vacuum of $200mTorr$, and an inlet pressure of $55bar$.

Another interesting observation is that the peak particle densities for the $800\mu m$ cylindrical and the $400\mu m$ conical nozzles are lower in the experimental data than in the ANSYS Student calculations. This is attributed to the fact that the particle density lineout in the experimental data does not correspond to the actual distance of $100\mu m$ above the exit of the nozzle. This is due to the tilt of the system, especially the gas jet, that caused shadows to the experimental data. Nonetheless, the simulated and the experimental results are in agreement.

7 Concluding remarks

In this study, the simulation of two nozzle geometries, one cylindrical and one conical, was performed with the use of ANSYS Student. The aim was to investigate the resulting particle densities and profiles. Subsequently, these nozzle geometries were 3D printed and characterized within the vacuum using the Mach-Zehnder interferometry.

The most significant outcome of this study is that these gas-jet targets can be provided as near-critical density gas targets for dynamic ion acceleration experiments using a laser of $800nm$ central wavelength. For an $800nm$-wavelength laser system, the critical zone is from $1.72 \times 10^{20} - 1.72 \times 10^{22} cm^{-3}$. These peak particle densities were achieved using both types of nozzles and gases, at a static pressure of $55bar$. Consequently, the next step involves the further optical tailoring of these gas-jet targets, i.e., their optical shaping with ns laser pulses, for future ion acceleration experiments.

References

[1] Tazes, I., et al. "A computational study on the optical shaping of gas targets via blast wave collisions for magnetic vortex acceleration." *High Power Laser Science and Engineering*, vol. 10, e31, p. 1, 2022, DOI: 10.1017/hpl.2022.16

[2] Malka, Victor, et al. "Characterization of neutral density profile in a wide range of pressure of cylindrical pulsed gas jets." *Review of Scientific Instruments*, vol. 71, p. 1-2, 2000, DOI: 10.1063/1.1150619

[3] Semushin, S., and Victor Malka. "High density gas jet nozzle design for laser target production." *Review of Scientific Instruments*, vol. 72, p. 1-2, 2001, DOI: 10.1063/1.1380393

[4] Pilar Puyuelo Valdes. “Laser-driven ion acceleration with high-density gas-jet targets and application to elemental analysis.” Université de Bordeaux; Institut national de la recherche scientifique (Québec, province), Dec. 2020.