CHARACTERISATION OF NITROGEN CLUSTERS AND GAS JET TARGETS UNDER VARIED NOZZLE GEOMETRIES

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Abstract

Gas jets are widely used for targets in laser-plasma driven article acceleration experiments. Optimising the mechanism requires tailored gas jet density profiles. Therefore, high density gas profiles have been investigated and characterised using different types of nozzles: sonic, supersonic, slit and supersonic slit. Gas jet profile optimisation was examined using nozzles of different diameters while varying gas pressure between 0 and 100 bar and valve opening duration. Gas jets produced by the nozzles were characterised using an optical probe laser. The gas jet density profile was measured through interferometry which was captured using a CCD camera. A second camera was used to record the Rayleigh scattering from the laser to confirm the presence clustering in nitrogen at high pressures.

INTRODUCTION

Recent research into laser-plasma ion acceleration has demonstrated beams with various characteristics from a number of different target types. The use of solid targets presented two widely investigated mechanisms: target normal sheath acceleration (TNSA) and radiation pressure acceleration (RPA) [1]. For applications that require high energies and monoenergetic beams, RPA is seen as the more desirable mechanism for acceleration due to the characteristics of the accelerated beams, though has been difficult to achieve in experiments [2][3]. Solid targets can add complications to the ion source as they require very high laser contrast to avoid their destruction, create debris, result in multispecies beams, and may cause difficulty for high repetition rate systems for applications.

Gas jet targets have been seen to offer a solution to these issues. Gas jet targets have been widely used for laser wakefield electron acceleration [4], and some more recent studies for ion acceleration. For example, recent experiments have demonstrated monoenergetic proton beams from the interaction of a CO2 laser with gas jets [5], generated from the laser radiation pressure acting on a low density, but opaque, plasma. Interest in gas targets has led to the development and subsequent optimisation. The acceleration mechanism can be optimised via tailored gas jet density profiles through altering nozzle geometry (Figure 1).

Under high pressure and specific conditions a range of gases have been found to form small grouping of atoms which are loosely bound to each other through their Van der Waals forces. These are known as gas clusters. The formation of clustering in supersonic gas jets is a concept that has been observed for many years, along with their dependency on pressure and nozzle size [6]. Clustering gases are of interest in targetry mainly in relation to high intensity laser-plasma interaction as they provide very high absorption of laser energy [7]. It has also been shown that high pressure gas clustering can be utilised as targets in ion acceleration [8]. More recently, an experiment has been reported investigating a selection of nozzle geometries: sonic, supersonic, slit and supersonic slit (Figure 2).

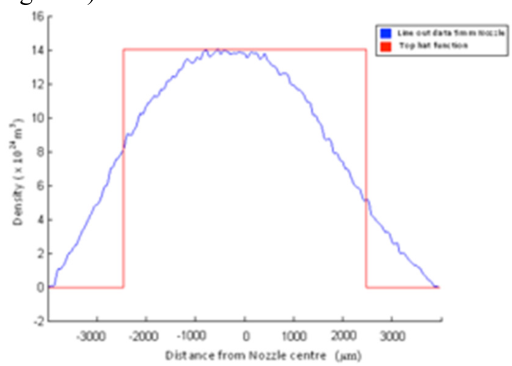

Figure 1: Ideal gas jet would possess a density profile that follows the shape of a top hat function. Actual jets do not produce such a steep density gradient.

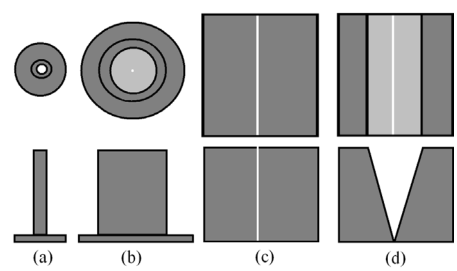

Figure 2: Examples of nozzle geometries for (a) sonic nozzle (b) conical nozzle (c) slit nozzle (d) supersonic slit nozzle.

EXPERIMENTAL SET-UP

Nozzles

A selection of nozzles was used to produce gas jets bearing different characteristics due to their geometries. Additionally, the effect of placing an insulator before the nozzles was investigated (Figure 3). These included a 10 mm diameter conical supersonic nozzle with an entrance aperture of 2 mm, a 2 mm diameter conical sonic nozzle and a slit nozzle. The slit nozzle was shaped with pliers from a 2 mm sonic nozzle to approximate the properties for this geometry. The slit dimensions were verified the CCD camera. This set up was found to be able to observe clusters in argon gas through a probing laser and the resulting Rayleigh scattering [9].

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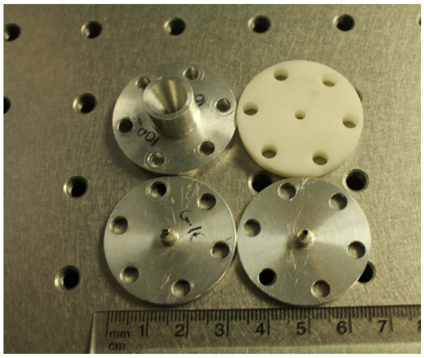

Figure 3: Nozzles used (diameters given). From left: (top) 10 mm conical nozzle, insulator (bottom) 2.5 mm by 1 mm slit nozzle, 2 mm conical nozzle.

The introduction of an insulator should reduce the likelihood of discharge onto the nozzle from the laser-plasma area. Discharge can lead to degradation of the nozzle or could obscure or completely obstruct the plasma feature that is being observed or, potentially, influence laser-plasma interactions differently.

Mach-Zehnder Interferometry and Rayleigh Scattering

High-pressured nitrogen gas was passed through nozzles inside a controlled vacuum chamber where the gas was then characterised using an optical probe laser. The laser used was a ~1 mW CW Helium-Neon 632.8 nm laser .The gas jet density profile was measured using a Mach-Zehnder interferometer (see Figure 4). After both paths were recombined, the fringe shift was captured using a high frame rate CCD camera, allowing measurement of the time evolution of the gas jet as well as the spatial properties. A second camera (Qimaging camera) was used to record the Rayleigh scattering from the laser to confirm the presence clustering.

For each of the nozzles, pressure, valve opening duration and gas jet-time evolution were investigated. Gas jet pressure was varied between 0 and 100 bar and valve opening duration between 6 ms and 150 ms with the fringe shift being taken at a time where the jet was deemed stable. The gas jet evolution to reaching this point of stability and after was also viewed.

Image Processing

Images produced through interferometry were analysed using a method earlier used to review gas jet density profiles of needle nozzles [10]. The processing script was written using Matlab.

Phase shift maps were compared with a reference (control) image to obtain the net phase shift experience under the gas evolution. Region containing shift - found above the nozzle - was then selected to reduce redundant processing and thus reduce computing time. The sampled region selected was Fourier filtered around the frequency space of the interferometry fringes to remove noise. This is then used to produce a 2D image of the phase shift as a function of space. Lastly, the geometrical conditions are applied resulting in a density profile that accounts for nozzle shape and symmetry. The Abel inversion was used for nozzles which possessed cylindrical symmetry (conical nozzles). Gaussian smoothing is also applied to remove noise and achieve main characteristic.

The area of interest from the density profiles was selected as 0.7-1 mm height above the nozzle exit, which is where the laser will be focussed on the high intensity laser experiments the gas targets, will be used for. This position is a chosen compromise between achieving the best density profile at the nozzle exit while avoiding any possibilities of ablating or melting of the nozzle caused by intense laser contact.

Scattered light from clusters will be visible in the images without any processing [9].

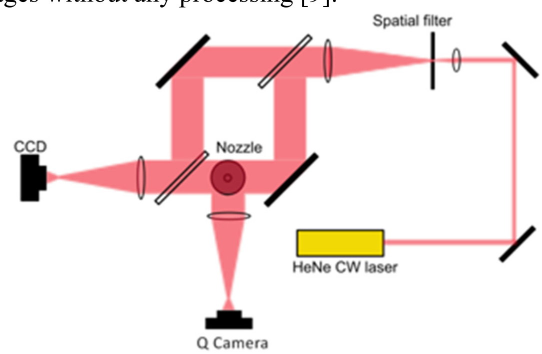

Figure 4: Experimental set up used. Combining Mach-Zehnder interferometry with an additional focussing lens and camera to image Rayleigh Scattering from the probing laser due to clusters within the gas medium.

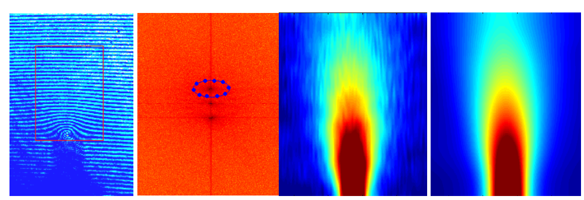

Figure 5: Interferometry image processing (from left): 1 showing region selected for transforming (red box), 2 showing Fourier transformed phase map with sample area highlighted (blue ring), 3 gas jet density profile, 4 smoothed density profile with geometric compensations.

CLUSTER FORMATION

From analysing the images taken by the Qimaging camera, Rayleigh scattering from the probing laser was not observed. This is believed to be resulting from: low camera resolution, light lost in path to camera and the intensity of the laser not being high enough to produce a measureable scatter when accounting for losses. The experimental set up will be amended to resolve these issues.

Density Profiles of Nozzles

Analysis of the phase maps indicates that both transverse (Figure 7) and parallel (Figure 8) of the slit nozzle have a different characteristic shape to that of the sonic nozzle (Figure 6) across the range of pressures. Throughout the phase line outs for the transverse slit, a plateau is visible around the region of highest phase shift, on the axis of the nozzle centre. This accounts for the wider diameter of the nozzle. A distinct, sharp peak is visible where the phase shift is at maximum for those when the slot nozzle is parallel to the probing laser (Figure 8). This was also expected due to its decreased diameter.

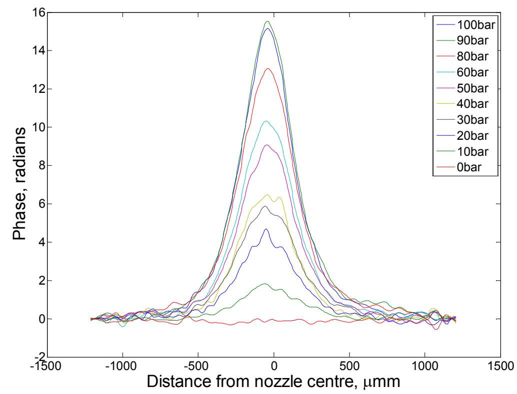

Figure 6: Phase line out 1 mm above nozzle normal to laser and gas jet for 2 mm diameter sonic nozzle.

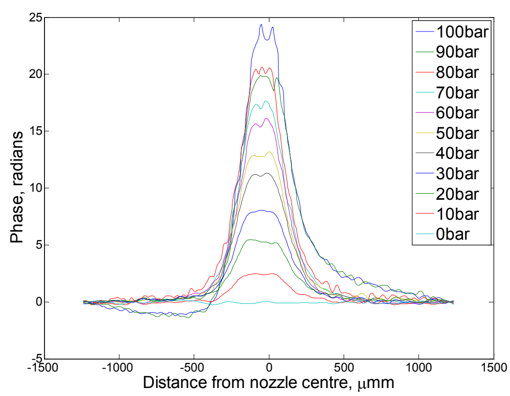

Figure 7: Phase line out 1 mm above nozzle normal to laser and gas jet for 2.5 mm x 1 mm slit nozzle at normal incidence.

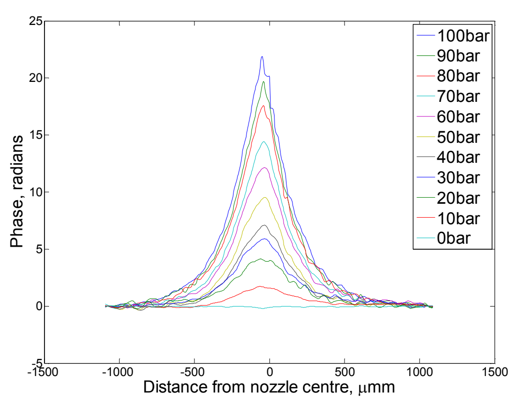

Figure 8: Phase line out 1 mm above nozzle normal to laser and gas jet for 2.5 mm x 1 mm slit nozzle at normal incidence.

Both orientations of the slit nozzle achieved higher phase shift than those achieved at the same pressures for sonic nozzle. This is a result of the decreased area at the exit of the nozzle.

The phase shift at the centre of the nozzle was found to be higher throughout the range of pressures when the slit was orientated normal to the laser. It was expected that greater phase shift would be observed when the slit of placed parallel as this would present a longer gas medium, more laser interaction and thus, greater phase shift. This could be a result of the experimental set up, i.e. slit on parallel to incidence or may suggest that the gas diverges differently from the slit nozzle to predictions.

CONTINUATION OF THE EXPERIMENT

A higher power laser will be incorporated in the set up. This should lead to a greater amount of Rayleigh scattering from the laser which should be detectable by the camera. An improved imaging system will be introduced to increase the scattering solid angle being captured by the imaging system. Coning and casing around the path between nozzle and camera may be added to reduce noise. Lastly, a lens will be placed before the nozzle to focus down the laser at the gas jet-laser interface.

New slit and supersonic slit nozzles have been designed (Figure 9) and these will be tested, following the same method and experimental set up as before.

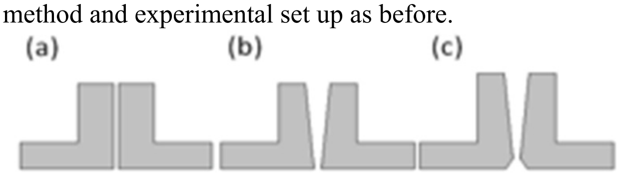

Figure 9: Supersonic slits: These are formed from two pieces as opposed to the single piece structure of the originals allowing the entrance aperture and nozzle diameter to be varied. Shown are the prism faces of each and all have a depth of 35 mm: (a) 15 mm x 15 mm (b) 15 mm x 15 mm with wall angle of 2° (c) 18 mm x 15 mm with wall angle 2° and lower of 65°.

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