CHARACTERISATION AND ANALYSIS OF SUPERSONIC GAS JETS USING INTERFEROMETRIC MEASUREMENT METHODS*

A. Webber-Date[1†], C. Swain, J. Wolfenden, H. Zhang, C. Welsch
University of Liverpool and Cockcroft Instutute, Daresbury, Warrington, UK

Abstract

Supersonic gas jets are useful tools in particle accelerators used in both scientific and medical applications. They can provide real-time, longitudinal and transverse beam profile measurements for charged particle beams in accelerators and are also being used as a plasma source in wakefield accelerators. For gas jets to be used effectively as beam profile monitors, the density profile of the jet must also be well-known. This can be calculated by measuring the phase shift produced by the gas jet inside a laser beam due to the difference in density between the gas and the surrounding vacuum environment from the Lorentz-Lorenz relation.

Using a 532 nm laser with a gas jet backing pressure of 7 bar, multiple techniques for measuring gas jet profile and density will be compared and analysed; Mach-Zehnder and Nomarski interferometry. Multi-pass interferometry will also be discussed as a method of increasing the measurable phase shift making the technique suitable for lower density gas jets.

INTRODUCTION

Gas jets are a tool used in a range of scientific applications. They are used as sources in plasma experiments and have been used in accelerators as beam profile monitors [1] and plasma sources for wakefield acceleration citeCOUPERUS2016504.

Measurement of the characteristics of these gas jets can be done using interferometric techniques, taking advantage of the phase shift caused by the change in refractive index as light passes through the jet. The most common method to achieve this is through the use of a Mach-Zehnder interferometer [2]. This technique typically requires one of the arms of the interferometer to be passed through the jet, with another passing unimpeded through a vacuum. It has also been shown that by imparting a polarisation on the beam, the initial beam can carry the phase information of the gas jet before being split and recombined to produce an interference pattern [3]. This setup still requires the use of two beam splitters and two mirrors to create the Mach-Zehnder interferometry scheme.

The set-up can be simplified through the use of a Nomarski interferometer. This uses a Wollaston prism to produce the two interferometry arms which are recombined using a lens and a polariser [4]. This system simplifies the set-up by using fewer components reducing the complexity of the system. The alignment becomes easier, and the interferometer is less susceptible to vibrations within the system.

Using interferometry, the density and profile of the gas jet can be characterised. These factors are important for the running of the gas jets when utilised as a beam profile monitor or as a plasma source for wakefield acceleration. Using interferometry these characteristics can be measured in real-time as the gas jet is running, without perturbing the gas jet outside of the vacuum. This can reduce downtime in the experiments and the complexity of the diagnostic tools. In this paper, we will discuss both the Mach-Zehnder and Nomarski interferometric schemes and compare the performance of both methods in terms of analysing pulsed gas jets.

THEORY

The density of a gas can be related to its refractive index by the Lorentz-Lorenz equation:

$$\frac{n^2-1}{n^2+2} = \frac{4\pi}{3} N\alpha_m, \tag{1}$$

where n is the refractive index, N is the number of molecules per unit volume and α_m is the mean polarisability of the gas [5]. This can be simplified to form the Gladstone - Dale equation:

$$n - 1 = K\rho, \tag{2}$$

where K is the Gladstone - Dale coefficient and ρ is the density.

As the beam passes through the gas jet, the phase accumulates in the direction of propagation of the laser beam. This accumulated phase difference is given by the Abel transform [6]:

$$\Delta\Phi(y) = \frac{4\pi}{\lambda}\int_y^{r_0} \frac{(n(r)-1)r}{\sqrt{r^2-y^2}}\, dr, \tag{3}$$

where r_0 is a radius far outside the influence of the jet and y is the coordinate perpendicular to the direction of the laser beam.

Assuming axisymmetric geometry of the gas jet, the density can then be calculated using the Abel inversion:

$$\frac{2\pi}{\lambda}(n(r)-1) = \frac{1}{\pi}\int_r^{r_0} \frac{d}{dy}\frac{\Delta\Phi(y)}{\sqrt{y^2-r^2}}\, dy. \tag{4}$$

This forms the basis of how the density of the gas jets can be calculated using the measured phase shift from the interferograms.

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* Work supported by HL LHC.

† a.webber-date2@liverpool.ac.uk

METHOD

The nozzle used for testing both methods of interferometry was a Parker 009-1671-900 pulse valve with straight nozzle geometry and an opening size of 0.79 mm. This was backed by Nitrogen gas at a pressure of 7 bar. Recording the images was done by setting the camera to trigger every 10 seconds, taking a total of 10 images. The first image would record the interferogram of the background. Another photo was taken of the interferogram with the gas jet on 2 ms later. The short time delay between the background and jet on images was to reduce the background caused by jitter in the fringes of the interferogram. The pulse valve was opened for 3 ms, with the camera taking an image 2 ms into the pulse, with a 3 ms exposure time.

The Mach-Zehnder system was implemented using a Thorlabs CPS532-C2 compact laser diode module which outputs a beam with diameter 3.5 mm. This was followed by a linear polariser to manipulate the polarisation of the laser source. The beam diameter was doubled using a beam expander consisting of a -50 mm FL lens and a +100 FL lens to ensure that the beam fully encompassed the gas jet. The beam was then passed through the vacuum chamber containing the gas jet, split using a beam splitter, reflected by two mirrors, and then recombined by another beam splitter. There is then another polariser with the interferogram image being detected with a Thorlabs CS135MU CMOS camera. The schematic of this can be seen in Fig. 1

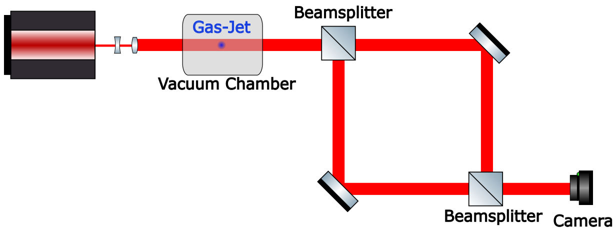

Figure 1: Schematic of a Mach-Zehnder style interefrometer being used to measure the density of a gas get. With this set-up, only the initial beam needs to pass through the jet.

For the Nomarski set-up, seen in Fig. 2, the initial laser, polariser and beam-expanding optics were kept the same. After the beam is passed through the vacuum chamber in this scheme the light passes through an 80 mm FL lens before passing through the Wollaston prism. The prism separates the ordinary and extraordinary polarisation of the laser beam by 1 degree. The lens causes a path difference and allows this separation to increase so that the jet projections are spaced far enough apart so as to not interfere with each other. The same camera is used to capture the interferograms.

RESULTS

Both methods produce similar phase maps of the gas jet. The most noticeable initial difference in the setups are the differences in the background jitter caused by vibrations transferring to the interferogram images. The Nomarski set-up was much more stable and robust against vibrations compared with the the Mach-Zehnder set-up. This is likely due to the reduced complexity of the Nomarski system since it does not rely on two independent reflecting mirrors and two separate beam splitters. The Mach-Zehnder and Nomarski interferometer phase maps can be seen in Fig. 3.

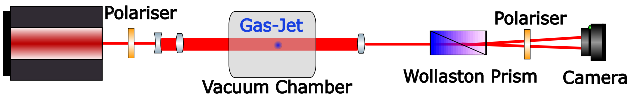

Figure 2: Schematic of a Nomarski style interefrometer being used to measure the density of a gas get. The laser is split using the Wollaston prism and an interference pattern is produced at the camera.

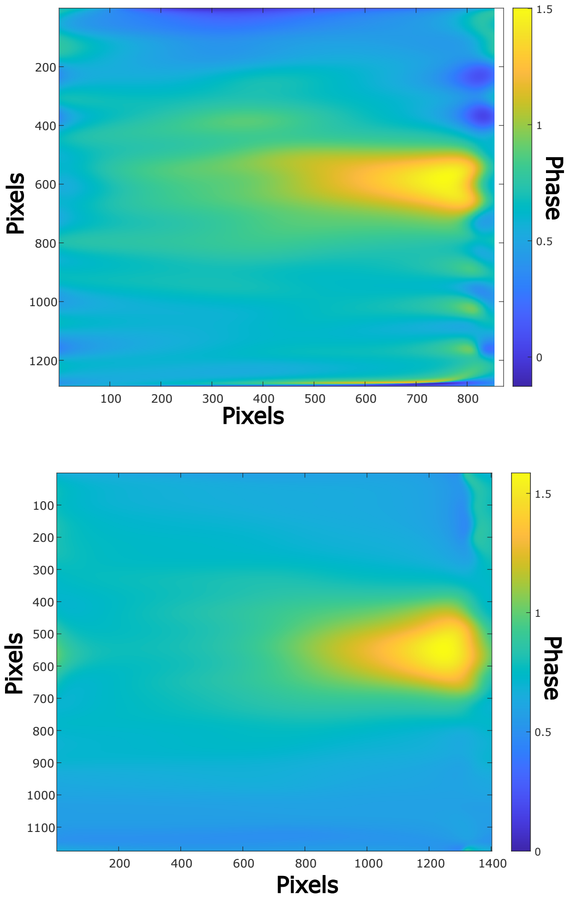

Figure 3: Top: Phase map of Mach-Zehnder interferometer with the gas jet coming from right to left. Bottom: Nomarski interferometer phase map.

In order to obtain the density profiles from these phase maps, an inverse Abel transformation can be performed assuming the gas jet is axisymmetric. The inverse Abel transformation is done numerically, using the Backus-Gilbert algorithm [7]. The implementation of this algorithm was performed using the IDEA software [8]. The solution to the Abel inversion is multiplied by a constant to give the density.

The density of the gas jet can be seen at 0.1 mm, 0.4 mm. 0.7 mm and 1 mm from the exit of the gas jet in Fig. 4.

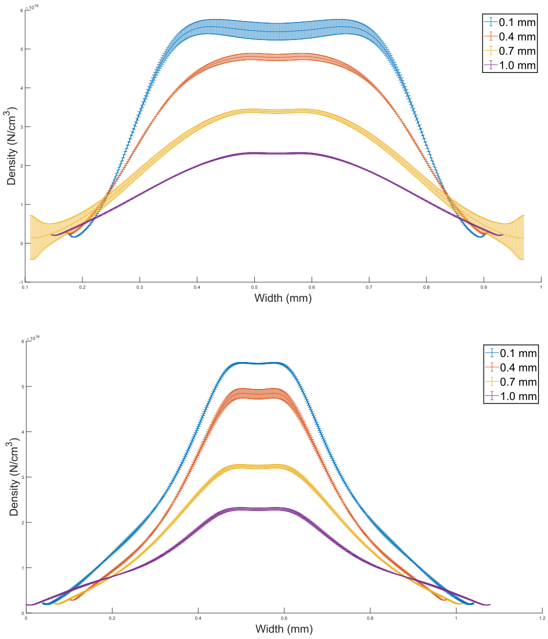

Figure 4: Top: Density measurements using the Mach-Zehnder interferometer. Bottom: Density measurements using the Nomarski system. Pixels are converted to mm by using a captured reference image of an object of known thickness. This was found to be 350 pixels/mm.

The peak density of the gas jet 0.1 mm from the nozzle exit is ~ 6×10^{19} molecules/cm^3 with the density decreasing as the jet expands. The densities for the Nomarski and Mach-Zehnder interferometers are consistent with one another with a slight decrease in background jitter for the Nomarski interferometer. The difference in scale on the x axis when comparing the two systems is due to this decrease in background. With the Mach-Zehnder interferometer the lower density jet phase shifts were washed out by the background jitter, so a smaller spatial range of the jet could be detected.

FUTURE WORK

Interferometry analysis is very useful for measuring gas jets of relatively high densities close to nozzle exits. The measurement of the density is however related to the phase shift caused by a change in refractive index. In lower density jets, where the refractive index is much closer to 1, the phase shifts caused by this change in refractive index will be undetectable using this method. One solution to this would be to increase the relative phase shift by passing the beam through the jet multiple times [9]. This will allow the phase shift to accumulate over each pass, increasing proportionally to the number of passes. Upgrading to a 2x or 4x pass with the Nomarski interferometer is relatively simple and involves the use of additional beam splitters and polarisation optics. A potential set-up for this system can be seen in Fig. 5. Although this may reduce the robustness and simplicity of the Nomarski interferometer, the increase in phase shift could be used to measure lower density jets.

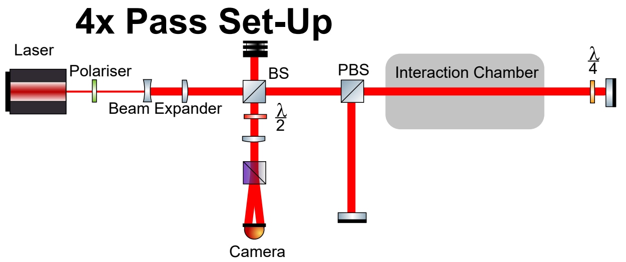

Figure 5: Schematic of a Mach-Zehnder style interefrometer being used to measure the density of a gas get. With this set-up, only the initial beam needs to pass through the jet.

CONCLUSION

Both Mach-Zehnder and Nomarski interferometers can measure gas jets with a density of around 6×10^{19} molecules/cm^2. Compared with the Mach-Zehnder system the Nomarski interferometer is more simple, robust to background vibrations and is upgradeable to a multi pass system. The uncertainties in the two interferometers are comparable with the Nomarski interferometer performing slightly better, 0.7% for the Nomarski and 1.6% for the Mach-Zehnder at peak density. This system could be used on wakefield accelerators for plasma density measurements of aon gas jet beam profile monitors near the nozzle of the jet to monitor gas density and output. A Nomarski interferometer presents a simple, easily implementable diagnostic for gas jet and plasma experiments.

ACKNOWLEDGEMENTS

This work is supported by the UKRI STFC Cockcroft Core grant and the HL-LHC phase II grant.

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ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPL068

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