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Hydrogen Gas Density Measurement by using Interferometry and Shadography with Pulsed Gas Jet Nozzles

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Abstract.

We measured the electron density of the *neutral(not plasma)* hydrogen gas jet which is emitted from the solenoid valves with/without an external diverging nozzle. By using a Michelson interferometer with a 635 nm laser, we measured the hydrogen electron density of 1.9 x 10^{19} cm^{-3}, which corresponds to 0.4 x 2π fringe shift, at 3 mm from the exit of the external nozzle, with the gas jet pulse width of 100 ms and with the backing pressure of 1000 psi. The shadow graph of the hydrogen gas jet from the external diverging nozzle showed a half opening angle of 3 degrees at 10 mm from the exit of the external nozzle. We observed good linear correlation between the hydrogen density and the backing pressure in the range of 0 - 1000 psi.

Without an external diverging nozzle (with a conical cap of the solenoid valve), we measured the hydrogen electron density of 3 x 10^{18} cm^{-3} (which is lower by a factor of 5 than that with the external nozzle) at 3 mm from the exit of the nozzle with the gas jet pulse width of 100 ms and with the backing pressure of 880 psi. The half opening angle at 10 mm from the exit of the nozzle was measured to be 23 degrees by the shadow graph.

In the Plasma Lens Experiment at the FFTB(Final Focus Test Beam) at SLAC, we plan to measure the plasma density (hydrogen electron density) by using the blue shift and the interferometry, where we expect better sensitivity of the fringe shift compared with that of neutral hydrogen.

I SET UP

Figure 1 shows the overview picture of the set up of the Michelson Interferometer. A half mirror is placed at an angle of 45 degrees with the incoming laser beam of the wave length 635 nm. Continuous laser beam was used in this measurement, which limited the practical gas jet pulse width longer than around 100 ms which is comparable to the updating interval of the CCD camera. Figure 2 shows a schematic of the set up. The gas jet volume that the laser beam goes through is 3 mm deep, so the total path length of the laser light through the gas volume is 6 mm. The laser through the gas is then deflected by the half mirror to a CCD camera which is connected to a frame grabber. The frame grabber was a product of SPRICON LBA 100A and is triggered by the TTL edge which is synchronized with the trigger of the gas jet pulse.

The vacuum chamber volume is 0.65 litter and the chamber is pumped by a roots vacuum pump with the pumping speed of 110 litter/s which gives 0.07 torr without any gas jet emission. The vacuum pressure is monitored by a capacitance manometer.

In this density measurement of the neutral hydrogen gas jet, we used two kinds of nozzles of the solenoid valves :

- a set of an diverging external nozzle and a flange type internal solenoid cap (Parts number 9-381). The external nozzle has a cross section of parabolic ally diverging shape with the hole diameters of the upstream end and downstream end of 0.8 mm and 3.0 mm respectively. The external nozzle is made of 5 mm thick Aluminum plate. The solenoid cap has a 1.8 mm long straight through internal nozzle with a diameter of 0.8 mm. Figure 3a and 3b show a side view of the external diverging nozzle, the flange type solenoid cap of the solenoid valve, and a drawing of the cross section. Downstream end of the external nozzle and the solenoid cap will be trimmed for the access of the wire scanner to the plasma.

- a conical solenoid cap (Parts number 91-222) with a 3.6 mm long straight through nozzle with a diameter of 0.8 mm. Figure 4a and 4b show a side view of the conical solenoid cap, and a drawing of the cross section.

II TEST RESULTS

Figures 5a and 5b show the interferometer fringe patterns at hydrogen backing pressure of 880 and 440 psia with a pulse width of 100 ms. Figure 5c shows a picture of the background fringe pattern with a hydrogen backing pressure of 0 psia.

FIGURE 1. Interferometer set up with an author

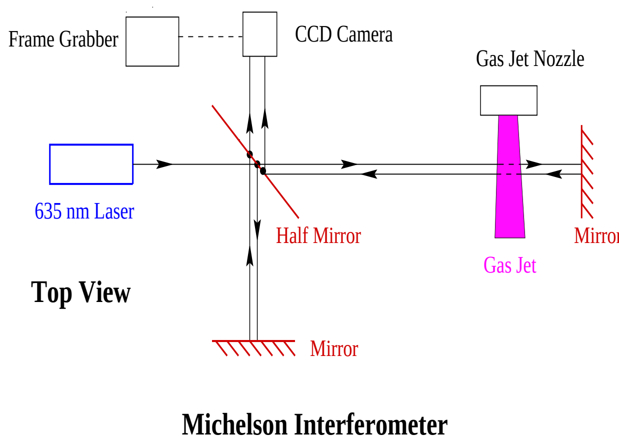

FIGURE 2. Schematic diagram of the Interferometer

Figures 6a and 6b show a fringe pattern with a backing pressure of 1000 psia and the background fringe pattern with a pulse duration of 100 ms. The fringe shift at 3 mm from the exit of the external nozzle was measured to be 0.4 x 2π which corresponds to the hydrogen electron density of 1.9 x 10^{19} cm^{-3}.

The densities of hydrogen gas were calculated by assuming that the measured phase shift, $\Delta\phi$ was caused by the decrease of the laser light (wave length λ nm)travel speed through the hydrogen gas jet volume with the total path length of L (mm). We used the molecular refractive index, n_g, of (1.0 + 1.32 x 10^{-4}) for the hydrogen gas at 1.0 atmospheric pressure at 273 degree Kelvin for the Na D lines. Assuming the (molecular refractive index - 1.0) is proportional to the uniform instantaneous pressure, p (atm. pressure), inside the hydrogen gas volume at T (degree Kelvin), we obtain the following equation which gives the pressure p:

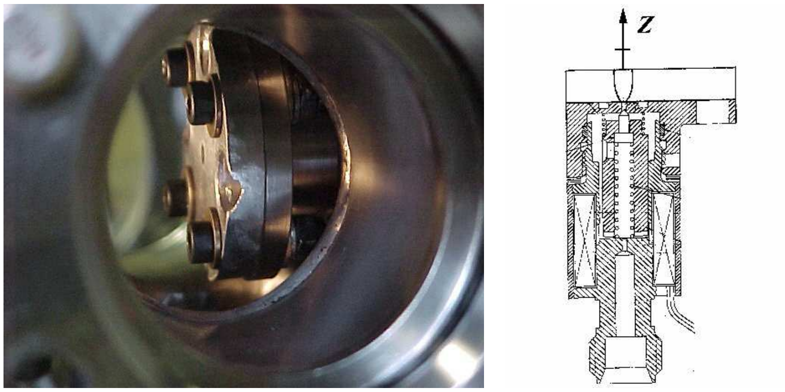

FIGURE 3. (a) Diverging external nozzle picture (b) Cross section of the solenoid valve with an external nozzle and a flange type solenoid cap

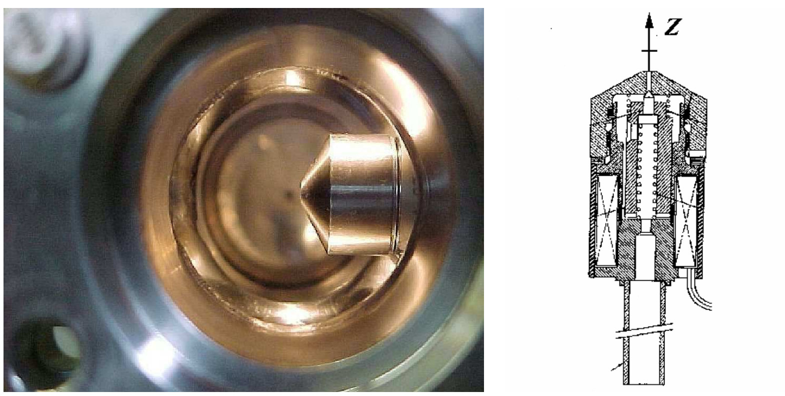

FIGURE 4. (a) Conical nozzle picture (b) Cross section of the solenoid valve with a conical solenoid cap

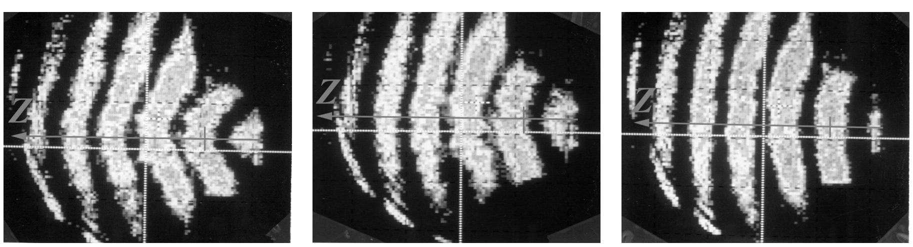

FIGURE 5. (a)Fringe shift at 880 psia for the diverging external nozzle (b)Fringe shift at 440 psia (c)Background fringe pattern at 0 psia

$\frac{\Delta\phi}{2\pi} = (n_g \text{ -}1)\cdot p\cdot \frac{273}{T} \cdot \frac{L\cdot 10^{-3}}{\lambda\cdot 10^{-9}}$

The hydrogen electron density d (cm^{-3}) is then given by:

d (cm^{-3}) = 4.41 x 10^{19} x $\frac{\Delta\phi(rad)}{L(mm)}$

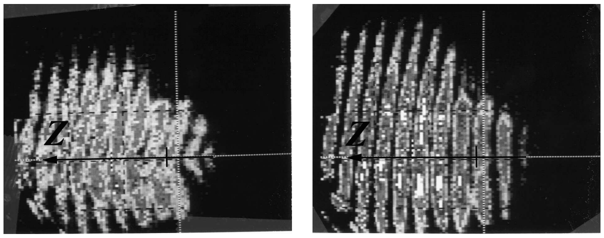

FIGURE 6. (a)Fringe shift at 1000 psia for the diverging external nozzle (b)Background fringe pattern at 0 psia

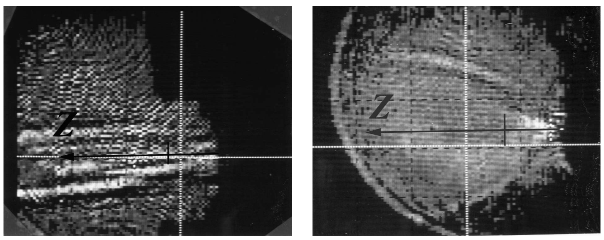

FIGURE 7. (a)Shadowgraph image of the H_2 gas jet from the diverging external nozzle (b)Shadowgraph image of the H_2 gas jet from the conical nozzle

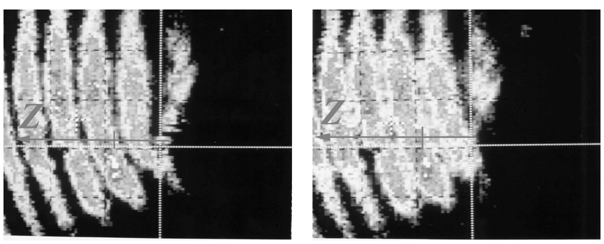

FIGURE 8. (a)Fringe shift at 880 psia with the conical nozzle (b)Background fringe pattern at 0 psia

We estimated the depth of the gas jet volume along the laser beam to be 3 mm, based on the shadow graph measurement of the geometrical shape of the gas jet with the backing hydrogen pressure of 1000 psi and the pulse duration of 100 ms, which is shown in Figure 7a.

Shadowgraphy was done by blocking one of the laser paths in the Michelson interferometer and subtracting the background image from the shadowgraph image at 1000 psia in the frame grabber.

Figure 7b shows the shape of the gas jet in the case of using conical nozzle which is very divergent as compared to that with the diverging external nozzle. The half broadening angle for the diverging nozzle was measured to be 3 degrees at 10 mm from the exit of the external nozzle, whereas with the conical nozzle it was measured to be 23 degrees at 10 mm from the exit of the nozzle of the conical solenoid cap.

Figure8a shows the fringe pattern with the hydrogen backing pressure of 880 psia with the gas jet pulse duration of 100 ms. Figure8b shows the background fringes at 0 psia. The fringe shift was measured to be 0.067 x 2π which corresponds to

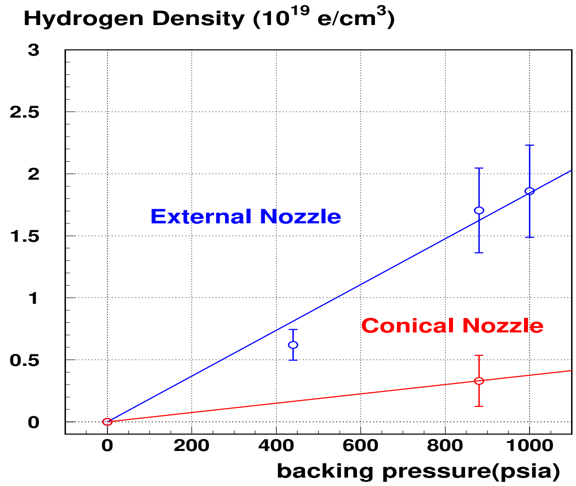

FIGURE 9. Density at 3mm along the z axis as a function of backing pressure for both the diverging external nozzle and the conical external nozzle

the hydrogen electron density of 3.2 x 10^{18} electrons cm^{-3}. The measured neutral hydrogen density with the conical solenoid cap is lower by a factor of 5 than that with the external diverging nozzle at the hydrogen backing pressure of 880 psia with the pulse duration of 100 ms. We assumed the depth of the gas volume at 3 mm from the exit of the nozzle to be 2.5 mm, which was extrapolated from the measurement data by the LBNL experiment (*Reference 3*). The FWHM width of the gas jet was 2 mm at 2.4 mm from the nozzle exit.

Figure 9 shows the hydrogen density as a function of the backing pressure with the external nozzle and the conical solenoid cap. This figure illustrates the linearity of the instantaneous density with the backing pressure. The observed linearity is consistent with our earlier result of the linearity of integrated mass flow of hydrogen with the backing pressure for a pulse width of 800us.(*Reference 3*)

III CONCLUSION

A external diverging nozzle creates the ideal hydrogen gas jet density for the plasma lens experiment (E150) at FFTB with the depth of around 3 mm and the maximum hydrogen electron density of 2 x 10^{19} cm^{-3} at 3 mm from the exit of the external nozzle with the backing pressure of 1000 psi. We observed the linearity of the hydrogen density with the backing pressure in the range of 0 - 1000 psia with the gas jet pulse width of 100 ms. The shadow graph of the hydrogen gas jet from the external diverging nozzle shows a half opening angle of 3 degrees at 10 mm from the exit of the external nozzle.

Without an external diverging nozzle (with a conical nozzle of the solenoid valve), we measured the hydrogen electron density of 3 x 10^{18} cm^{-3} (which is lower by a factor of 5 than that with the external nozzle) at 3 mm from the exit of the nozzle with the gas jet pulse width of 100 ms and with the backing pressure of 880 psi. The half opening angle at 10 mm from the exit of the nozzle was measured to be 23 degrees by the shadow graph.

IV ACKNOWLEDGMENTS

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