A Multi-Reflection Type Visible-Laser Interferometer for High Density Plasma Measurements

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In order to measure a high density plasma more than $10^{20}\,m^{-3}$ in the vicinity of a magneto-plasma-dynamic arcjet (MPDA), a visible-laser interferometer is fabricated using a He-Ne laser ($\lambda = 632.8$ nm). As it doesn't have enough phase shift when the light passes through the MPDA plasma once, we adopt a multi-reflection optical system in this interferometer to improve the phase sensitivity. We measured a plasma density by the interferometer and estimated the maximum value of line-integrated density of $4 \times 10^{19}\,m^{-2}$. These experimental results are consistent with that of electrostatic probe measurement in the downstream region.

Keywords: laser interferometer, multi-reflection, magnet-plasma-dynamic arcjet, high density plasma, electron density measurement

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1. Inroduction

A magneto-plasma-dynamic arcjet (MPDA) is utilized as a high-enthalpy plasma source not only for a plasma injection source for open magnetic confinements but for an electric propulsion and several applications. Detailed measurement of plasma density in the vicinity of an MPDA is important to evaluate its performance.

The interferometry method using electromagnetic waves is useful and convenient to obtain a line-integrated plasma density [1] and can be used in the high density plasma more than $10^{20}\,m^{-3}$, where it is difficult to measure the plasma density by an electrostatic probe. The MPDA plasma density had been measured by an interferometry method using a CO_2 laser [2] or a dual-beam laser [3]. However, the interferometer was not always used as an electron density measurement method and detail measurement has not been achieved yet.

The purpose of this research is to develop a laser interferometer for measurement of a high density plasma in the vicinity of an MPDA. The feature of this interferometer is to use a He-Ne laser ($\lambda = 632.8$ nm) and a multi-reflection optical system. A He-Ne laser is easily obtained and easy to handle as visible light. As it doesn't have enough phase shift when the light passes through the MPDA plasma once, we adopt a multi-reflection optical system in this interferometer to improve the phase sensitivity.

2. Interferometer System

A Schematic of the Michelson-type interferometer system is shown in Fig. 1, where a He-Ne laser (10 mW) is used as a light source. The laser beam is divided into a reference beam and a probe beam by a beam splitter (BS).

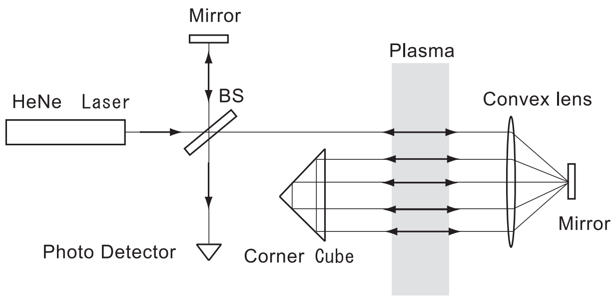

Fig. 1 Schematic view of the multi-reflection type laser interferometer.

The probe beam is reflected between a corner cube mirror and a flat mirror with a convex lens and passes through a plasma many times. The multi-reflection optical system was developed by D. Lee *et al.* for the purpose of a high accuracy displacement measurement [4]. One of the additional advantages in this system is that the number of reflection can be easily changed. We used the concept of the optical system to utilize the plasma measurement method. However, the spatial resolution is rather poor because the average values of the integrated line density along with an optical path is obtained.

A mockup experiment was attempted in order to confirm the performance of the system. We measured a phase shift when the light passes through air gas, since the refractive index is changed according to gas pressure. A pressurized vessel (0.11 m in diameter, 0.215 m in length with quartz window (0.095 m in diameter) on both sides), was set instead of the plasma. The phase shift($\Delta\phi$) and air gas

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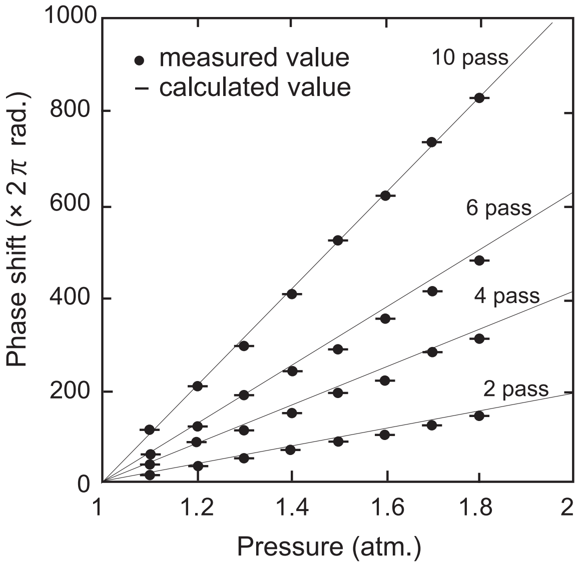


Fig. 2 Dependence of the phase shift on the air pressure for several numbers of reflection. The solid circle denotes measured value using the interferometer. The solid line denotes calculated value from Eq. (1).

pressure(Δp) are related to each other as

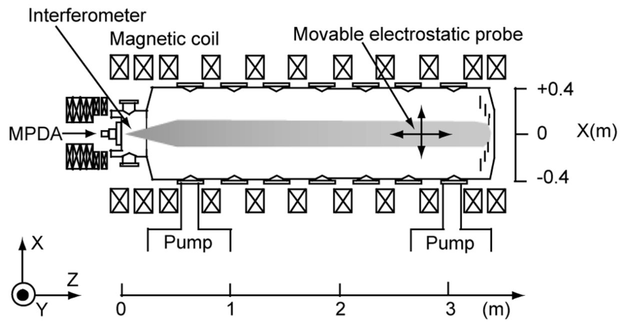
$$\Delta\phi = \frac{L \times 2.765 \times 10^{-4}(\Delta p - 1)}{\lambda}, \quad (1)$$

where L is optical path length in the pressurized vessel. λ is wavelength of the incident light [5]. The experimental results are shown in Fig. 2. The phase shift increases with the increase of the number of reflection. The experimental results are in good agreement with that of the calculated from Eq. (1).

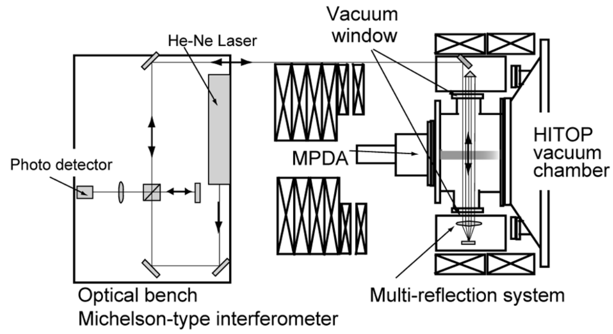
From various experimental researches in the MPDA plasma [2, 3], we can estimated the electron density is around 1×10^{21} m^{-3}, which corresponds to phase shift of 27 degrees even when the laser light passes 10 times through the plasma.

3. Experimental Setup and Results

The interferometer is attached to a HITOP device [6] as shown in Fig. 3. The HITOP consists of a large cylindrical vacuum chamber (0.8 m in diameter, 3.3 m in length) with eleven main and six auxiliary magnetic coils, which generate a uniform magnetic field up to 0.1 T. A high power quasi-steady MPDA is installed at one end-port of the HITOP. An MPDA has coaxial electrodes with a central cathode rod and an annular anode. The discharge current I_d up to 10 kA is supplied with a quasi-steady duration of 1 ms. A high density plasma (more than 10^{20} m^{-3}) is produced with helium as working gas and accelerated axially by an electromagnetic force generated by a radial discharge current and an azimuthal self-induced magnetic field. The MPDA plasma characteristics are measured by a several diagnostics installed on the HITOP. Spatial profiles



(a)



(b)

Fig. 3 Schematic views of (a) the HITOP device and (b) the multi-reflection type interferometer.

of electron temperature T_e and density n_e are measured by a movable electrostatic probe and a fast-voltage-scanning electrostatic probe at the downstream region. T_e and n_e are derived from a current-voltage characteristic line detected by the electrostatic probes [7]. Ion temperature and plasma flow velocity are measure by a spectrometer with an ICCD detector at the vicinity of the MPDA. Typical ion temperature is 10-20 eV, higher than electron temperature T_e (5-10 eV), and axial flow velocity is 3×10^4 m/s.

The vacuum windows, are made of fused-quartz with 0.11 m × 0.31 m, and located at the vicinity of the MPDA. The distance between the vacuum windows is 0.5 m. The center of the laser beam of the installed interferometer is set at $Z = 0.135$ m.

A mechanical vibration is one of the most serious problems for the interferometer. Many interferometers used on existing plasma experiments are two-color interferometers [8] that decouple the phase shift caused by mechanical vibrations. Mechanical vibrations are not so important because of the short duration (1 msec) of the HITOP discharge, since the mechanical vibration frequency in the system is several hundred Hertz.

Figure 4 shows time evolutions of an ion saturation current measured by an electrostatic probe set at $Z = 1.76$ m, and the phase shift obtained by the interferometer, where the light passes 6 times through the plasma at $Z = 0.135$ m. Although the diameter of a single laser beam at the plasma center was around 0.1 cm, the density mea-

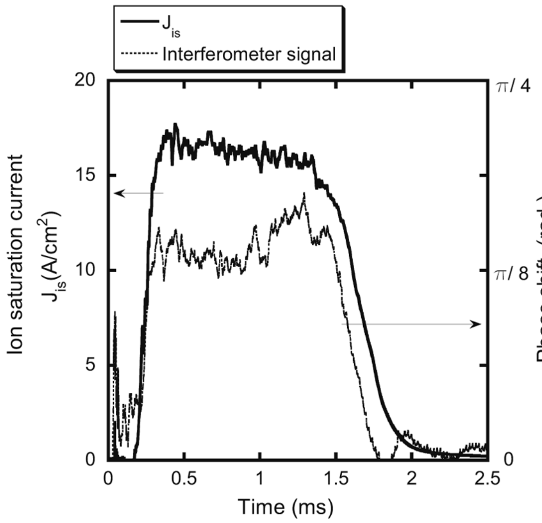


Fig. 4 Time evolution of (a) Ion saturation current measured by the electrostatic probe at downstream ($Z = 1.76$ m). and (b) Phase shift measured by the interferometer at upstream ($Z = 0.135$ m).

surement region was broadened to 3 cm in width due to the multi-reflection. As the spatial variation along the axial direction was weak, we set the multi-beam path shifting in axial direction to minimizing the error due to the change of n_e during the multi-reflection. As the number of beam reflection increased, the intensity of reflected laser light decreased. Due to the elimination of light intensity and increasing difficulty of beam path alignment, we adopted the beam reflection in three times, where the laser beam passed through the plasma in six times.

Temporal behaviors of these two signals are similar to each other, although the measurement positions by the interferometer and an electrostatic probe were different. We estimated a maximum value of line-integrated density of $4 \times 10^{19}\,\mathrm{m}^{-2}$ from the phase shift of the interferometer.

The axial profiles of the plasma density measured by the electrostatic probe is shown in Fig. 5. Plasma density decreases in the downstream region in the experiment.

The plasma density measured by the interferometer is the integrated density along a chord through the plasma. It is necessary to estimate a local density using the Abel inversion method. But, this system cannot be scanning to the radial direction of the plasma yet. We assumed the axis-symmetry cylindrical plasma with Gaussian density profile (3 cm in e-folding length). The estimated plasma density on axis at $Z = 0.1350$ m is also plotted in Fig. 5. Plasma density measured with the interferometer is in agreement with the plasma density measured by electrostatic probe.

Line-integrated density is measured as a function of a discharge current I_d and plotted in Fig. 6 for different values of operating gas pressure in MPDA discharge. The line-integrated density increases almost linearly with I_d. This tendency agrees with that of the electrostatic probe

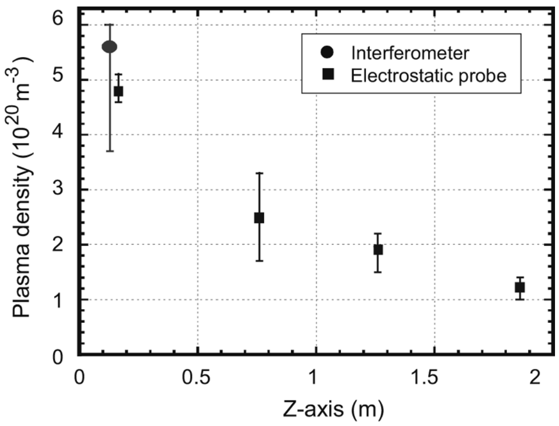


Fig. 5 Axial profile of the plasma density measured by the interferometer and the electrostatic probes. (Discharge current $I_d = 5.2$ kA, Uniform magnetic field strength = 0.087 T).

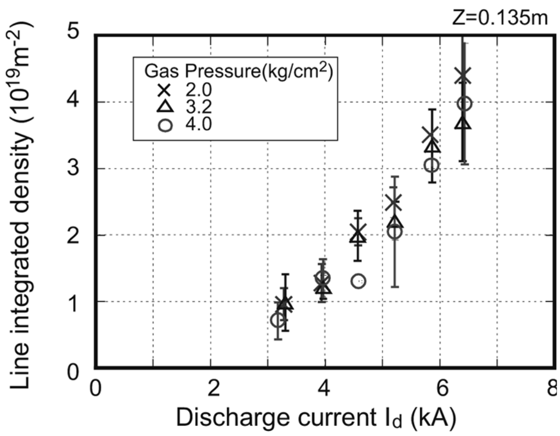


Fig. 6 Dependence of the line integrated density with the discharge current I_d.

measurement in the downstream region.

4. Summary

We have developed the Michelson-type interferometer with a multi-reflection optical system. A He-Ne laser ($\lambda = 632.8$ nm) is used as a light source .As the wavelength of the laser is short, the phase shift is magnified by a multi-reflection optical system. A mockup experiment was performed using a pressurized air where the refraction index of air is varied according to the atmospheric pressure. The experimental results are in good agreement with that of the predicted one.

The interferometer system is adopted to measure the MPDA plasma. The maximum value of line-integrated density in the vicinity of the MPDA is estimated to be $4 \times 10^{19}\,\mathrm{m}^{-2}$ at $I_d = 6.5$ kA. These experimental results are consistent with that of electrostatic probe measurement in the downstream region.

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