Development of dispersion interferometer for magnetic confinement plasmas and high-pressure plasmas

T. Akiyama,\textsuperscript{a,1} R. Yasuhara,\textsuperscript{a} K. Kawahata,\textsuperscript{a} K. Nakayama,\textsuperscript{b} S. Okajima,\textsuperscript{b} K. Urabe,\textsuperscript{c,d} K. Terashima\textsuperscript{c} and N. Shirai\textsuperscript{e}

\textit{National Institute for Fusion Science}
Toki, 509-5292, Japan
\textit{Chubu University}
Kasugai, 487-8501, Japan
\textit{The University of Tokyo}
Kashiwa, 277-8561, Japan
\textit{Japan Society for the Promotion of Science}
Chiyoda, 102-0083, Japan
\textit{Tokyo Metropolitan University}
Hachioji, 192-0397, Japan

E-mail: takiyama@nifs.ac.jp

ABSTRACT: A CO$_2$ laser dispersion interferometer (DI) has been developed for both magnetically fusion plasmas and high pressure industrial plasmas. The DI measures the phase shift caused by dispersion in a medium. Therefore, it is insensitive to the mechanical vibrations and changes in the neutral gas density, which degrade the resolution of the electron density measurement. We installed the DI on the Large Helical Device (LHD) and demonstrated a high density resolution of 2\times10^{17} m$^{-3}$ without any vibration-free bench. The measured electron density with the DI shows good agreement with results of the existing far infrared laser (a wavelength of 119 $\mu$m) interferometer. The DI system is also applied to the electron density measurement of high-pressure small-scale plasmas. The significant suppression of the phase shift caused by the neutral gas is proven. The achieved density resolution was 1.5\times10^{19} m$^{-3}$ with a response time of 100 $\mu$s.

A shorter version of this contribution is due to be published in PoS at:

\textit{1$^{st}$ EPS conference on Plasma Diagnostics}

KEYWORDS: Nuclear instruments and methods for hot plasma diagnostics; Plasma diagnostics - interferometry, spectroscopy and imaging

\textsuperscript{1}Corresponding author.
1 Introduction

An interferometer is a conventional tool for measuring the electron density of a plasma [1]. Since the interferometry is a mature technique, it is widely used for various plasmas with various light sources or oscillators. In principle, the phase difference depends on not only the electron density, but also the change in the optical path length due to mechanical vibrations, and the changes in the neutral gas density. Since the phase shifts caused by the above three terms cannot be distinguished in the conventional interferometer, the latter two terms lead to measurement errors in the electron-density measurement. For example, the phase shift caused by the mechanical vibrations cannot be neglected in the case of the laser light such as a CO$_2$ laser (a wavelength of 10.6 $\mu$m) and a Nd:YAG laser (a wavelength of 1.064 $\mu$m). This is because mechanical vibrations can cause changes in an optical path length typically with an order of micron or submicron. In the cases of plasmas which are generated under low pressure conditions, such as fusion plasmas, mechanical vibrations are a dominant error source because changes in the neutral gas density in and around the plasma are negligible. On the other hand, changes in the neutral gas density cannot be negligible in the case of high-pressure, including atmospheric pressure, plasmas, in addition to mechanical vibrations. When the neutral gas is heated by the plasma, the gas density changes. That results in changes of the refractive index of the gas and causes changes in the phase shift. In the case of the high-pressure plasma, the phase shift is often larger than that due to the electron density because the absolute value of the neutral gas density change is significant.

Use of a vibration-free bench is preferable for reducing the mechanical vibrations. A two-color interferometer [1] is a typical method to separate the phase shift due to the electron density from the phase shifts due to mechanical vibrations. It consists of two interferometers with different wavelengths. While the phase shift due to the plasma is proportional to the wavelength, the other
phase shifts caused by mechanical vibrations are inversely proportional. From the different dependencies on the wavelength, we can evaluate the electron density by solving simultaneous equations. Hence, the two-color technique is widely used on fusion devices [1]. However, the separation is sometimes not perfect because of slight differences in the optical paths of the two interferometers. In addition, the optical system becomes somewhat complicated because of the combination of two interferometers with different wavelengths.

A dispersion interferometer (DI) measures the phase shift which arises from dispersion of mediums. While the DI is basically an interferometer, it is insensitive to mechanical vibrations. At first, the DI was used for transmission tests of semiconductors and for contouring the surface [2]. Since a plasma has dispersion, the phase shift can be measured with the DI. The DI was implemented to measure the electron density of a plasma of laser spark [3]. Then, the DI was introduced to a magnetically confined plasma in 90s [4]. At present, some fusion plasma devices are equipped with the dispersion interferometers [5–7]. The DI is now one of the candidates for density diagnostics on future large fusion devices [8, 9] due to its insensitivity to mechanical vibrations and the simplicity of the optical configuration.

In this paper we describe the DI installed on a fusion plasma device, the Large Helical Device (LHD) [10]. We also applied the DI system to high-pressure plasma [11] and demonstrated that the DI can reduce the phase shift caused by the neutral gas. In section 2, the principle of suppression of components of vibrations and the neutral gas density is described. Following the description of the optical system on LHD in section 3, the measurement results of fusion and high-pressure plasmas are shown in section 4. Finally the conclusion is given in section 5.

2 Principle of dispersion interferometer

2.1 Conventional dispersion interferometer

Figure 1 shows a comparison between a conventional interferometer and a dispersion interferometer. In both interferometers, the interference signal $I$ is given by

\[ I(t) = I_{DC} + I_{AC} \cos \{ \varphi_2(t) - \varphi_1(t) \} \]

\[ I_{DC} = I_1 + I_2, \quad I_{AC} = 2 \sqrt{I_1 I_2} \]

where $\varphi$ and $I$ are the phase and the intensity of each beam, respectively. The refractive index $N$ of weakly ionized plasmas depend on the density of the neutral gas and the density of the electron density as given by [12]

\[ N = 1 + A \left( 1 + B \left( \frac{\omega}{2 \pi c} \right)^2 \right) \left\{ \frac{n_{g0} - \Delta n_g(l,t)}{n_{gSTP}} \right\} - \frac{1}{2} \frac{n_e(l,t)}{n_c} \]

where $n_{g0}$, $\Delta n_g(l,t)$, $n_{gSTP}$, $n_c$ are the initial neutral gas density along the beam path, changes in the neutral gas density near the plasma, the gas density in the standard condition, and the cut-off density described by $\frac{e^2}{2 \pi m_e c^2}$, respectively. $A$ and $B$ are constants which depend on gas species [13]. In the case of the conventional interferometer shown in figure 1 (a), phases of probe (denoted as
and reference (denoted as “2”) beams are as follows.

\[
\phi_1^f (t) = \omega t + \frac{\omega}{c} \int_0^{L_1(t)} \left[ 1 + A \left\{ 1 + B \left( \frac{\omega}{2\pi c} \right)^2 \right\} \left\{ \frac{n_{g0} - \Delta n_e(l,t)}{n_{gSTP}} \right\} - \frac{1}{2} \frac{n_e(l,t)}{n_c} \right] \, dl \tag{2.4}
\]

\[
\phi_2^f (t) = \omega t + \frac{\omega}{c} \int_0^{L_2(t)} \left[ 1 + A \left\{ 1 + B \left( \frac{\omega}{2\pi c} \right)^2 \right\} \left\{ \frac{n_{g0} - \Delta n_e(l,t)}{n_{gSTP}} \right\} - \frac{1}{2} \frac{n_e(l,t)}{n_c} \right] \, dl \tag{2.5}
\]

\[
L_{1.2}(t) = L_{pg} + L^y_{1.2}(t) \tag{2.6}
\]

where \(L_{1.2}(t)\), \(L_{pg}\), and \(L^y_{1.2}(t)\) are the total path length, the length near the plasma where the neutral gas density possibly changes, and the path length including mechanical vibrations except the vicinity of the plasma, respectively. The phase of the interference signal is

\[
\phi_2^x (t) - \phi_1^x (t) = \frac{\omega}{c} \int_0^{L_2(t)} \left[ 1 + A \left\{ 1 + B \left( \frac{\omega}{2\pi c} \right)^2 \right\} \left\{ \frac{n_{g0} - \Delta n_e(l,t)}{n_{gSTP}} \right\} - \frac{1}{2} \frac{n_e(l,t)}{n_c} \right] \, dl - \frac{\omega}{c} \int_0^{L_1(t)} \left[ 1 + A \left\{ 1 + B \left( \frac{\omega}{2\pi c} \right)^2 \right\} \left\{ \frac{n_{g0} - \Delta n_e(l,t)}{n_{gSTP}} \right\} - \frac{1}{2} \frac{n_e(l,t)}{n_c} \right] \, dl
\]

\[
= \frac{\omega}{c} \int_0^{L_2(t)} \left[ 1 + A \left\{ 1 + B \left( \frac{\omega}{2\pi c} \right)^2 \right\} \left\{ \frac{n_{g0} - \Delta n_e(l,t)}{n_{gSTP}} \right\} \right] \, dl - \frac{\omega}{c} \int_0^{L_1(t)} \left[ 1 + A \left\{ 1 + B \left( \frac{\omega}{2\pi c} \right)^2 \right\} \left\{ \frac{n_{g0} - \Delta n_e(l,t)}{n_{gSTP}} \right\} \right] \, dl
\]

\[
+ \frac{\omega}{c} \int_0^{L_{pg}} \left[ A \left\{ 1 + B \left( \frac{\omega}{2\pi c} \right)^2 \right\} \frac{\Delta n_e(l,t)}{n_{gSTP}} \right] \, dl + \frac{\omega}{2cn_c} \int_0^{L_{pg}} n_e(l,t) \, dl \tag{2.7}
\]

The first and the second terms can vary due to the mechanical vibrations \(L^y_{1.2}(t)\) and \(L^y_{1}(t)\). The third term changes when the neutral gas is heated by a plasma and the composition of the gas (A and B) changes. Hence, they can lead to error terms when the line averaged electron density is evaluated from the forth term.

To date, some techniques have been proposed and attempted in order to reduce the error terms: rigid structure, vibration isolation system, two-colour system, and others. While they are effective for reducing the errors, the measurement system tends to be larger and more complex. One of the fundamental solutions is a DI. Figure 1(b) shows the schematic view of the DI. A laser beam is injected into a nonlinear crystal in order to generate the second harmonic component. Although beam paths are slightly displaced due to “walk-off” in the crystal, it can be negligible compared to the beam radius. After passing through a plasma, the other nonlinear crystal generates the second harmonic again. Following a filter to eliminate the residual fundamental component, an interference signal of two second harmonic beams is detected. Even if there are mechanical vibrations, changes in the neutral gas density, and changes in the gas composition, the non-dispersive components are
cancelled optically and the dispersion component only is measured as follows. The phases of two second harmonic components are given by

\[
\phi_d^f(t) = 2 \left[ \omega t + \frac{\omega}{c} \int_0^{L_1(t)} \left[ 1 + A \left( 1 + B \left( \frac{\omega}{2\pi c} \right)^2 \right) \left\{ n_{g0} - \Delta n_g(l,t) \right\} \frac{1}{n_{gSTP}} - \frac{1}{2} \frac{n_c(l,t)}{n_c} \right] dl \right] (2.8)
\]

\[
\phi_d^s(t) = 2 \omega t + \frac{2\omega}{c} \int_0^{L_1(t)} \left[ 1 + A \left( 1 + B \left( \frac{2\omega}{2\pi c} \right)^2 \right) \left\{ n_{g0} - \Delta n_g(l,t) \right\} \frac{1}{n_{gSTP}} - \frac{1}{2} \frac{n_c(l,t)}{4n_c} \right] dl. (2.9)
\]

Then the phase of the interference single is

\[
\phi_d^f(t) - \phi_d^s(t) = \frac{3}{2\pi^2} \left( \frac{\omega}{c} \right)^3 \frac{AB}{n_{gSTP}} \int_0^{L_1(t)} \{ n_{g0} - \Delta n_g(l,t) \} dl - \frac{3}{2} \frac{c}{2 \omega n_c} \int_0^{L_{pe}} n_c(l,t) dl
\]

\[
= \frac{3}{2\pi^2} \left( \frac{\omega}{c} \right)^3 \frac{ABn_{g0}}{n_{gSTP}} L_1^t(t) + \frac{3}{2\pi^2} \left( \frac{\omega}{c} \right)^3 \frac{AB}{n_{gSTP}} \int_0^{L_{pe}} \Delta n_g(l,t) dl - \frac{3}{2} \frac{c}{2 \omega n_c} \int_0^{L_{pe}} n_c(l,t) dl
\]

(2.10)

The first two terms originate from the dispersion component of the neutral gas. While they are still error terms, they are much smaller than the non-dispersive component. For example, \( A = 28.71 \times 10^{-5}, B = 5.67 \times 10^{-3} \) (unit of \( \frac{\omega}{2\pi c} \) is \( \mu \)m should be \( \mu \)m) for air at standard temperature and pressure (STP) for a wavelength of 589.3 nm [13]. Supposing that the constants \( A \) and \( B \) at 10.6 \( \mu \)m are the same as these at 589.3 nm, the error terms of \( A \left( \frac{\omega}{2\pi c} \right)^2 \) should be \( 2.87 \times 10^{-4} \) in eq. (2.6) can be reduced down to \( AB \left( \frac{\omega}{2\pi c} \right)^2 = 1.45 \times 10^{-8} \) in eq. (2.9). Even when \( L_1^t(t) \) varies due to the vibrations, the first term in eq. (2.9) becomes much smaller than that of the conventional interferometer. The vibration does not change the path length in a plasma (determined by the plasma size), the second term is also independent to the total path length. In this way, the DI is much less sensitive to the mechanical vibrations than other types of interferometers and can significantly reduce the phase shift caused by changes of neutral gas density.

### 2.2 Phase modulation and phase extraction method

Since the DI is basically a homodyne interferometer, it has the same disadvantages of the homodyne interferometer. The interference signal of the conventional interferometer is given by eq. (2.1), and the measurable range of the phase shift is limited less than \( \pi \). If the phase exceeds \( \pi \) by \( \alpha \), it is impossible to distinguish whether the phase increases or decreases from the interference signal because \( \cos(\pi + \alpha) = \cos(\pi - \alpha) \). In addition, the \( I_{DC} \) and \( I_{AC} \) are necessary to extract the phase. \( I_{DC} \) and \( I_{AC} \) are determined by the detected intensities, as shown in eq. (2.2), and are measured by a calibration experiment without plasma. However, \( I_{DC} \) and \( I_{AC} \) easily vary during plasma discharges by reflection of the beams, temporal variations of the laser oscillation, and electrical noises. Since both the phase shift and the variations of \( I_{DC} \) and \( I_{AC} \) can change the envelope of the interference signal, the latter leads to measurement errors.

In order to solve this problem, we introduced the phase modulation and the phase extraction method using a ratio of modulation amplitudes [14]. The phase modulation technique had been
already introduced to the DI [15]. In addition, we proposed the phase extraction method which needs no information of $I_{DC}$ and $I_{AC}$.

A phase modulator such as a photoelastic modulator (PEM) or an electrooptic modulator (EOM) is placed between two nonlinear crystals and adds the phase retardation $\delta = \rho \sin(\omega_m t)$ for either the fundamental or the second harmonic components, where $\rho$ is the maximum retardation and $\omega_m$ is the drive frequency of the modulators. In the case of the type-I nonlinear crystal, the polarization of the fundamental and the second harmonic components is perpendicular to each other, and both the PEM and the EOM can add the phase modulation to either of the two components. When the retardation is added to the second harmonic component, the resultant interference signal is given by

$$I(t) = I_{DC} + I_{AC} \cos \{ \rho \sin(\omega_m t) + \varphi(t) \}$$  \hspace{1cm} (2.11)

$$\varphi(t) = \varphi_2 (t) - \varphi_1 (t).$$ \hspace{1cm} (2.12)

Eq. (2.11) can be expanded by the harmonics of $\omega_m$. Amplitudes of fundamental $I_{\omega_m}$ and second harmonic $I_{2\omega_m}$ are:

$$I_{\omega_m} (t) = -2I_{AC} J_1 (\rho) \sin \{ \varphi (t) \}$$  \hspace{1cm} (2.13)

$$I_{2\omega_m} (t) = 2I_{AC} J_2 (\rho) \cos \{ \varphi (t) \}$$ \hspace{1cm} (2.14)

where $J_1 (\rho)$ and $J_2 (\rho)$ are the Bessel function of the order of first and second. Setting the maxi-
mum retardation $\rho = 2.6$ rad. to satisfy $J_1(\rho) = J_2(\rho)$, the phase shift can be extracted as

$$\varphi(t) = -\tan \left\{ \frac{I_{ac}(t)}{I_{2ac}(t)} \right\}. \quad (2.15)$$

This method can extract the phase shift without information of $I_{AC}$ and $I_{DC}$.

### 3 Optical system

The wavelength of a laser of the DI on LHD is selected as follows. One of the key issues of the DI is the generation of the second harmonic component. The nonlinear crystal for shorter wavelength than the infrared region is commercially available at present. In the near infrared region, a variety of laser sources and nonlinear crystals are fabricated. However, the returned power of laser light from a vacuum vessel tends to become smaller due to degradation of surface specularity caused by impurity deposition and erosion by plasma particles. This is significant especially for wavelengths shorter than 10 $\mu$m on LHD [16]. Although many efforts have been expended to suppress the reflectivity degradation, the optimum wavelength is longer than 10 $\mu$m at present. A CO$_2$ laser whose wavelength is 10.6 $\mu$m is widely used and large output power is available. For the above reasons, the CO$_2$ laser is adopted for the DI on LHD. From the viewpoint of the measurement of high-pressure plasmas, a wavelength should be short enough to meet the conditions [17]

\begin{align}
    \omega_{pe} & \ll \omega \\
    \nu_m & \ll \omega
\end{align}

where $\omega_{pe}$, $\nu_m$, $\omega$ are the electron plasma frequency, the electron collision frequency, and the angular frequency of the laser light. Eq. (3.1) is necessary to avoid the cut off of the laser light by plasmas. Eq. (3.2). As discussed in ref. [11], since $\nu_m = 1.5$ THz at atmospheric pressure helium and $\omega_{pe} = 0.56$ THz for an electron density of $1 \times 10^{20}$ m$^{-3}$, the CO$_2$ laser whose frequency of 30 THz satisfy the requirements of eqs. (3.1) and (3.2).

Arrangement of the optical system and optical bench are shown in figure 2. Most optical components are placed on the optical plates of the optical bench whose dimension is $1.9 \times 0.8 \times 2.1$ m. The CO$_2$ laser placed on the upper plate. The wavelength and the power are 10.6 $\mu$m and 8 W, respectively. The laser light is focused at the nonlinear crystal AgGaSe$_2$ to increase the conversion efficiency of the second harmonic component. The polarization of the generated second harmonic wave is perpendicular to the fundamental wave and its power is about 50 $\mu$W. The mixture of the fundamental and the second harmonic components as a probe beam is transmitted to LHD. A retroreflector is installed inside the vacuum vessel of LHD and the probe beam returns to the lower optical plate. The phase modulation is added to the second harmonic component only by arranging the modulation direction parallel to the polarization of the second harmonic component. The maximum retardation $\rho$ is 2.6 rad. and the drive frequency $\omega_b$ is 50 kHz. The probe beam is injected into the nonlinear crystal again and the second harmonic component is generated again. The fundamental component only is reflected with a sapphire plate and is dumped. The interference between two second harmonic components is detected. In the case of measurements of the atmospheric pressure plasmas, a plasma source [18, 19] is placed on the path to LHD. The probe beam does not go to LHD and takes a shortcut to the PEM.
The detected interference signal eq. (2.11) is input into lock-in amplifiers to obtain the amplitudes of the fundamental $\omega_m$ and second harmonic components $2\omega_m$, described by eq. (2.13) and eq. (2.14). The reference signals which are input into the lock-in amplitudes are provided by a controller of the PEM. The amplitude signals $I_{\omega_m}(t)$ and $I_{2\omega_m}(t)$ from the lock-in amplitudes are digitized and are processed to evaluate the phase shift eq. (2.15) and the resulting line averaged electron density.

![Experimental setup diagram](image)

**Figure 2.** The optical bench of the DI on LHD and arrangements of optical components.

### 4 Measurement results

#### 4.1 Fusion plasma

The density (phase) resolution is determined by the zero-line drift of the phase signal on LHD. The variations of the zero-line for 3 s and 1800 s are $\pm 1.5$ deg. (corresponds to $\pm 6 \times 10^{17}$ m$^{-2}$) and $\pm 2$ deg. ($\pm 8 \times 10^{17}$ m$^{-2}$), respectively. These variations of the phase shift correspond to line averaged electron density of $2 \times 10^{17}$ m$^{-3}$ and $2.4 \times 10^{17}$ m$^{-3}$, respectively on LHD due to a double-pass path length of 3.28 m in a plasma [10]. In this paper, we define the width of the zero-line drifts as the electron density resolution. Since the typical range of the electron density is from $10^{19}$ to $10^{20}$ m$^{-3}$, a signal to noise ratio of more than 50 is obtained. These density resolutions are achieved without any vibration isolation systems. It is speculated that the phase variations in the short time (3 s) might be caused by the uncancelled vibrations. If wavefronts of two second harmonic components are not overlapped perfectly or wavefronts are differently distorted, a small amount of the vibration components will remain and can lead to variations of the zero-line. On the other hand, long time drifts of the zero-line might be caused by temperature changes. It is possible that gradual temperature changes cause changes in the refractive index in the transmission optical
components, such as lens and a window made of ZnSe. If the dependences on the temperature of the refractive index at the fundamental and second harmonic components are different, temperature changes lead to variations of the zero-line. As for the time resolution, the response time and the latency are 100 $\mu$s and 80 $\mu$s, respectively, as discussed in section 4.2.

Figure 3 shows one of the measurement results of LHD plasmas. The line averaged electron density measured with the DI shows good agreement with that with the existing far infrared (FIR) laser interferometer [20], whose wavelength is 119 $\mu$m, as shown in figure 3. In this discharge, fishbone-like instabilities are observed during $t = 1.38 - 2.0$ s. Responses of the electron density to the instabilities are also measured.

![Figure 3](image)

**Figure 3.** One of the measurement results of LHD plasmas with the DI and the existing FIR laser interferometer. The DI and the FIR laser interferometer measure the line averaged electron density in the horizontally and vertically elongated cross section, respectively. Since the measurement chord of the DI passes through the plasma center [10], the line averaged electron density is compared with the plasma central chord (ch5) of the FIR laser interferometer. A signal of a Mirnov coil is also shown.

As discussed above, the reliability of the interferometer degrades by fringe jump errors. In the case that the phase signal cannot be tracked due to fast density changes or the interference signal disappears due to beam bending in a plasma, information of the total phase shift may be lost due to ambiguity of $2\pi$. Therefore, fringe jump errors tend to occur in high density plasmas. By using the CO$_2$ laser, the total phase shift and the beam bending can be reduced because they are proportional to the wavelength. Hence, the CO$_2$ laser DI can suppress fringe jump errors, as shown in figure 4 (a). In this discharge (#125835), the electron density is increased up to a high density of $2 \times 10^{20}$ m$^{-3}$ by repetitive injection of pellets of solid hydrogen [21]. While the FIR laser interferometer suffered from a fringe jump error at $t = 3.95$ s, the CO$_2$ laser DI could continue measurement. One exception, in which a fringe jump error occurred for the DI only in a low density plasma, was found, as shown in figure 4 (b). The DI suffered from a fringe jump error at a rapid density increase at $t = 4.55$ s due to an injection of a small impurity pellet [22]. The density of this discharge (#128568) is about one-tenth of that of the discharge #125835. This means that the displacement of the laser beam path due to the beam bending effect is also one-tenth. As
shown in the bottom figures of figure 4 (a) and 4 (b), the density change rate during #128568 was also about one-tenth of that during #125835. This suggests that changes in the density of #128568 were slow enough to be tracked by the DI. It is expected that the ablation cloud of the impurity pellet caused the fringe jump error even in such a low density plasma. An extremely high density up to $10^{20}-10^{22} \text{m}^{-3}$ is evaluated locally in the ablation cloud [23], and the steep density gradient is formed in the peripheral region of the cloud. The impurity pellet injector locates near the DI on LHD and the distance between the probe beam chord and the trajectory of the impurity pellet is close, at about 10 cm. Since the ablation cloud expands along the magnetic field line and deviates from the injection trajectory due the impact of the fast ions [24], it is possible that the ablation cloud causes a phase shift larger than $2\pi$ across the cross section of the probe beam because of strong density gradient. Such a homogeneous phase shift in the beam cross section would lead to perturbation of the phase measurement. Since the far infrared laser interferometer is located far from the pellet injector, it does not suffer the perturbations by the impurity pellets. Hence, even if it is the DI, measurement chords should be aligned with a sufficient longer distance than the deviation of the ablation cloud from trajectory of pellets.

Figure 4. (a) A high density discharge with repetitive hydrogen pellet injection. The far infrared laser interferometer suffers from a fringe jump error. (b) A low density discharge with an impurity pellet injection. The dispersion interferometer suffers from a fringe jump error.

4.2 High-pressure plasma

Since fusion plasmas are generated under ultrahigh vacuum condition around $10^{-6} \text{Pa}$, measurement errors caused by changes in the neutral gas density included in eq. (2.7) can be negligible. Hence, the dominant error source is mechanical vibrations. On the other hand, the phase shift caused by changes in the neutral gas density cannot be neglected in the case of high-pressure plasmas at several times higher than the atmospheric pressure [17]. So far, great efforts have been expended to exclude the phase shift due to the neutral gas density from a heterodyne interferometer [18, 25, 26].
As described in section 2.1, the DI can reduce the phase shift due to the neutral gas density by the order of $B$ in eq. (2.10). For the demonstration, an atmospheric-pressure small-scale plasma source [11, 19] was placed on the upper optical plate and density measurements were implemented with the DI. A photograph and a schematic view of one of the plasma sources is shown in figure 5. Helium gas is supplied through a tube anode made of stainless steel with an inner diameter of 0.5 mm. The distance between the anode and a cathode made of brass is 1 mm. The plasma is pulse-operated with a frequency of 100 Hz and the discharge duration is 1 ms. The discharge current is from 100 mA to 200 mA. In order to avoid perturbations by the surrounding air, nitrogen gas flows outside the plasma. The probe beam is focused at the plasma with a diameter of about 400 µm. For improvement of the spatial resolution, an aperture is put in front of the PEM and reduces the beam diameter by 40%. Then, the effective beam diameter for measurement is about 240 µm.

Figure 5. A photograph of the high pressure plasma source and a schematic view of its structure.

From the initial rise of the measured phase shift, the response time and the latency of this DI can be evaluated [11]. A phase resolution, which is defined from the variation of the zero-line, is $1.7 \times 10^{-2}$ deg. It is found that the signal delay and the response time are 80 and 100 µs since the response time of the electron density to the discharge current should be less than 1 µs [18]. The time constant of the lock-in amplifiers is 30 µs. The longer response time than that of the lock-in processing is expected to be determined by the response of the digital analog converter for output of the amplitude signal. The response time will be improved by the digital lock-in technique [27].

Figure 6 shows a radial profile of the phase shift at the beginning of the discharge, fitted with a Gaussian function. The position of a plasma was scanned by 100 µm each perpendicularly to the probe beam and the phase shift was measured at each position. Defining the diameter of the plasma as the 1/e$^2$ fall position of the peak phase shift, the diameter is about 700 µm and the above phase resolution corresponds to an electron density resolution of $1.5 \times 10^{19}$ m$^{-3}$.

The temporal behaviors of the phase shifts by 4096-times averaging of the discharges are shown in figure 7 (a). The discharge currents are scanned from 100 mA to 200 mA. The rapid
Figure 6. A radial distribution of the phase shift at the beginning of discharge. The beam diameter is determined to be 700 µm from the $1/e^2$ fall positions of the peak phase shift.

Figure 7. (a) Temporal behaviors of the phase shifts measured with the DI and the discharge current. (b) Dependences of the electron density evaluated from the rapid phase changes at the beginning (indicated by “•” in figure 7(a)) and at the end of discharges (▲). The increase in the phase shifts at the beginning (shown as • in figure 7 (a)) and the rapid decrease in the end (▲) of the discharge should be caused by the increase and decrease of the electron density, respectively. Increasing the discharge current from 100 mA to 200 mA, the electron density increases. Figure 7 (b) shows the dependence of the line averaged electron density evaluated from the phase shifts shown in figure 7 (a) on the discharge current. The electron densities which are evaluated from the increase and the decrease of the phase shift at the beginning and the end of the discharge are plotted with points • and ▲, respectively. Previously, the phase shift caused by the plasma and the neutral gas are separated by shortening the plasma duration much faster than the neutral gas density change [17]. Hence discharge conditions are quite limited. On the other hand, DI can evaluated the electron density without changing the discharge condition. Since the electron densities evaluated from data of the beginning and the end of the discharge are comparable, the electron density during the discharge is almost constant. The electron density was also measured with a Thomson scattering system [28] in another setting and the evaluated electron densities are
almost consistent with that with the DI [29]. The gradual change in the phase seems to be caused by the dispersion component (the first term in eq. (2.10)) of the neutral gas. After a plasma is ignited and the electron density and the electron temperature increase by the application of the rectangular voltage, the temperature of the neutral gas outside and inside the plasma increases. The neutral gas adiabatically expands and the neutral gas density decreases. The signs of the phase shifts are opposite between the increase in the electron density and the decrease in the neutral gas density as shown in eq. (2.10). Hence both behaviors can be distinguished easier than the conventional interferometer: the signs are the same as shown in eq. (2.7). The expansion of the gas starts from the beginning of discharges and continues even after termination of the discharge current. Then, the gas densities gradually return to the initial conditions.

5 Summary

It is demonstrated that a dispersion interferometer (DI) can significantly reduce the measurement errors caused by mechanical vibrations and changes in the neutral gas density, which are disadvantages of a conventional interferometer. The CO$_2$ laser DI which uses a ratio of modulation amplitudes for the phase extraction is applied to magnetically fusion plasmas on the Large Helical Device (LHD) and high-pressure plasmas. A density resolution of $5 \times 10^{17}$ m$^{-3}$ for 1800 s is achieved without any vibration isolation system on LHD. Due to the short wavelength laser light, the fringe jump errors can be avoided, except at an impurity pellet injection with the adjacent injector to the DI system. The ablation cloud with a steep density gradient seems to perturb the phase measurement of DI. The electron density of a high-pressure plasma is also successfully measured using the same DI system as the LHD measurement, reducing the phase shift due to the change in the neutral gas density. The achieved density resolution is $1.5 \times 10^{19}$ m$^{-3}$ by 4096-times averaging of the discharges with response time of 100 $\mu$s.

Acknowledgments

Authors appreciate the LHD Experiment group for supporting this project. This study is partially supported by Grant-in-Aid for Young Scientists (B) (20760584), Young Scientists (A) (24686104), and the National Institute for Fusion Science grant administrative budget, ULHH027.

References

[1] D. Veron, *Submillimeter Interferometry of High-Density Plasmas*, in *Infrared and Millimeter Waves*, Academic Press, New York, 1979, Vol. 2, p. 67-135.
[2] F.A. Hopf et al., *Second-harmonic interferometer*, Opt. Lett. 5 (1980) 386.
[3] K.P. Alum et al., *Nonlinear dispersive interferometer*, Sov. Tech. Phys. Lett. 7 (1981) 581.
[4] V.P. Drachev et al., *Dispersion interferometer for controlled fusion devices*, Rev. Sci. Instrum. 64 (1993) 1010.
[5] H. Dreier et al., *First results from the modular multi-channel dispersion interferometer at the TEXTOR tokamak*, Rev. Sci. Instrum. 82 (2011) 063509.
[6] F. Brandi et al., Electron density measurements of a field-reversed configuration plasma using a novel compact ultrastable second-harmonic interferometer, Rev. Sci. Instrum. 80 (2009) 113501.

[7] P. Kornejew et al., Comparison of dispersion interferometer and 2-colour interferometer for W7-X with respect to their sensitivity to mechanical vibrations, in Proceedings of the 39th EPS Conference on Plasma Physics, Stockholm, Sweden, 2-6 July 2012, P5.037.

[8] A. Sirinelli et al., Looking For An On-Line Backup Density Measurement For Iter, PoS(ECPD2015)089.

[9] T. Akiyama et al., Conceptual design of high resolution and reliable density measurement system on helical reactor FFHR-d1 and demonstration on LHD, Nucl. Fusion 55 (2015) 093032.

[10] T. Akiyama et al., Dispersion interferometer using modulation amplitudes on LHD (invited), Rev. Sci. Instrum. 85 (2014) 11D301.

[11] K. Urabe et al., Application of phase-modulated dispersion interferometry to electron-density diagnostics of high-pressure plasma, J. Phys. D-ApplPhys. 47 (2014) 262001.

[12] F. Leipold et al., Electron density measurements in an atmospheric pressure air plasma by means of infrared heterodyne interferometry, J. Phys. D-Appl. Phys. 33 (2000) 2268.

[13] J.J. Keady and D.P. Kilcrease, Radiation, in Allen’s astrophysical quantities, Springer, 2000, Chapter 5, p. 100.

[14] T. Akiyama et al., Conceptual Design of a Dispersion Interferometer Using a Ratio of Modulation Amplitudes, Plasma and Fusion Research 5 (2010) S1041.

[15] P.A. Bagryansky et al., Dispersion interferometer based on a CO₂ laser for TEXTOR and burning plasma experiments, Rev. Sci. Instrum. 77 (2006) 053501.

[16] T. Akiyama et al., Studies of reflectivity degradation of retroreflectors in LHD and mitigation of impurity deposition using shaped diagnostic ducts and protective windows, Nucl. Fusion 52 (2012) 063014.

[17] K. Urabe et al., Microscopic heterodyne interferometry for determination of electron density in high-pressure microplasma, Plasma Sources Sci. T. 23 (2014) 064007.

[18] K. Urabe et al., Development of Near-Infrared Laser Heterodyne Interferometry for Diagnostics of Electron and Gas Number Densities in Microplasmas, Appl. Phys. Express 6 (2013) 126101.

[19] N. Shirai et al., Influence of oxygen gas on characteristics of self-organized luminous pattern formation observed in an atmospheric dc glow discharge using a liquid electrode, Plasma Sources Sci. T. 23 (2014) 054010.

[20] T. Akiyama et al., Interferometer Systems on LHD, Fusion Sci. Tech. 58 (2010) 352.

[21] R. Sakamoto et al., Repetitive pellet fuelling for high-density/steady-state operation on LHD, Nucl. Fusion 46 (2006) 884.

[22] H. Nozato et al., A study of charge dependence of particle transport using impurity pellet injection and high-spatial resolution bremsstrahlung measurement on the Large Helical Device, Phys. Plasmas 11 (2004) 1920.

[23] M. Goto et al., Spectroscopic study of a carbon pellet ablation cloud, J. Phys. B-At. Mol. Opt. Phys. 43 (2010) 144023.

[24] S. Morita et al., Observation of ablation and acceleration of impurity pellets in the presence of energetic ions in the CHS heliotron/lorsatron, Nucl. Fusion 42 (2002) 876.
[25] F. Leipold et al., *Electron density measurements in an atmospheric pressure air plasma by means of infrared heterodyne interferometry*, J. Phys. D-Appl. Phys. 33 (2000) 2268.

[26] J.Y. Choi et al., *Measurement of electron density in atmospheric pressure small-scale plasmas using CO2-laser heterodyne interferometry*, Plasma Sources Sci. T. 18 (2009) 035013.

[27] Y. Shi, *Digital lock-in technique for the motional Stark effect diagnostic*, Rev. Sci. Instrum. 77 (2006) 036111.

[28] K. Tomita et al., *Two-dimensional Thomson scattering diagnostics of pulsed discharges produced at atmospheric pressure*, 2012 JINST 7 C02057.

[29] K. Urabe, *Laser diagnostics of microplasmas on metal and liquid electrodes*, in *Proceedings of 8th International Workshop on Microplasmas*, Newark, USA, 11-14 May 2015, p. 29.