Development of electron-density diagnostics in high-pressure plasmas using phase-modulated dispersion interferometry

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Phase-modulated dispersion interferometry (PMDI) is a laser interferometry technique that was first developed for electron-density measurement of plasmas generated in large fusion reactors. We have demonstrated the potential of the PMDI for the diagnostics of low-temperature plasmas generated at high pressures. Most of refractive-index variation induced by the change of gas number density is eliminated in signal processing of the PMDI, and this feature contributes to accurate electron-density determination in high-pressure plasmas. In this paper, we introduce characteristics of the PMDI at NIFS in high-pressure plasma diagnostics and electron-density measurement of atmospheric-pressure plasmas by cross-check experiments using the PMDI and laser Thomson scattering spectroscopy at Kyushu Univ.

1. Introduction

Laser interferometry is a useful technique to diagnose electron density \( n_e \) in plasmas measuring phase shift of probing laser beam induced by variation of refractive index due to the generation of electrons [1]. Recently it has been applied to diagnostics of high-pressure plasmas using MIR \( \text{CO}_2 \) and NIR diode lasers [2,3]. In the measurement of high-pressure plasmas, the separation of the \( n_e \) and gas number density \( n_g \) components mixed in the total phase shift generates uncertainty in the \( n_e \) determination, because the \( n_g \) variation is significant in high-pressure plasmas due to frequent collisions.

In this study, we applied phase-modulated dispersion interferometry (PMDI), which has been developed for the \( n_e \) monitoring in a Large Helical Device (LHD at National Institute for Fusion Science, Japan) [4], to high-pressure low-temperature plasma diagnostics. Dispersion interferometry [5] is considered as a promising tool for determining \( n_e \) in fusion plasmas, since it automatically cancels influence of mechanical vibrations during the measurement. We found that it is also possible to cancel the phase shift induced by the \( n_e \) variation in and around the high-pressure plasma using the cancelling analogy of mechanical vibrations in the PMDI [6].

2. Phase-modulated dispersion interferometry

The PMDI method determines \( n_e \) along the probing laser path from following relationship.

\[
\arctan \left( \frac{I_{1m}}{I_{2m}} \right) = \frac{3e^2 \lambda A_{e,0}}{8 \pi m_e e_0} \int n_e dl + \frac{12 \pi A B}{3 \lambda n_{g,0}} \int \Delta n_g dl
\]

where \( I_{1m} \) and \( I_{2m} \) are the frequency elements in the measured signal at the fundamental and second harmonic of the phase modulation frequency \( \omega_m \). \( e \) is the charge of an electron, \( \lambda \) is the probing laser wavelength, \( e_0 \) is the speed of light in vacuum, \( m_e \) is the mass of an electron, \( e_0 \) is the permittivity of vacuum, \( A \) and \( B \) are specific constants that depend on the gas species, and \( n_{g,0} \) is the gas number density at STP (standard temperature and pressure) condition. Details of the PMDI theory are explained in Refs [4,6]. Compared with the heterodyne interferometry (HI) [2,3], the PMDI has similar \( n_e \)
sensitivity and much less sensitivity to \( n_e \) variation. This means that the effect of \( n_e \) variation in the total measured signal and the minimum detectable \( n_e \) in high-pressure plasma diagnostics become small in the PMDI compared to the HI.

Figure 1 is an example result of PMDI measurement of atmospheric-pressure pulsed dc microdischarge [6]. From the results, it was revealed that the \( n_e \) in the microdischarge was 9×10^{13} \, \text{cm}^{-3}, and line-integrated \( n_e \) sensitivity and temporal resolution of the PMDI system at NIFS are 7×10^{11} \, \text{cm}^{-2} and of 110 \, \mu\text{s} respectively.

3. Diagnostics of discharge with liquid electrode

Similar to the \( n_e \) diagnostics of fusion plasmas, we are now measuring \( n_e \) in high-pressure plasma sources using the PMDI and laser Thomson scattering spectroscopy [7] under the same discharge conditions. This cross-check experiment enables us to assure the \( n_e \) measurement results and discuss the data obtained in each measurement in more details.

For the cross-check experiments, in addition to plasmas generated in a gap between two metal electrodes, we measured \( n_e \) in a discharge using metal tube and liquid electrodes [8] with a continuously liquid-flowing system. Plasmas with the liquid electrode have attracted interests in recent years since they have potentials to be applied to for example nanomaterials synthesis [9] and plasma medicine [10]. In the presentation, experimental results of the \( n_e \) measurement in a pulsed dc microdischarge with the liquid electrode are introduced and we discuss the effect of liquid electrode on the discharge behaviors comparing with a case of the metal electrodes.

4. Summary

From a viewpoint of eliminating the \( n_e \) component in the measured signal, the PMDI method is advantageous over the conventional HI method. This feature improves the \( n_e \) resolution in the PMDI measurement particularly for plasmas generated under high-pressure conditions. The minimum limit of \( n_e \) detection in PMDI is comparable to that in Thomson scattering; therefore, we can proceed our research to cross-check experiments of \( n_e \) measurement for various low-temperature plasma sources such as atmospheric-pressure microdischarge with the liquid electrode.

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