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Development of electron-density diagnostics in high-pressure plasmas using phase-modulated dispersion interferometry
位相変調２倍高調波干渉計を用いた高気圧プラズマ
電子密度度診断研究とその展開

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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 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 promissing 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_g 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.

$$\arctan\left(I_{\omega_m} \middle/ I_{2\omega_m} \right) = \frac{3e^2\lambda}{8\pi c_0^2 m_e \varepsilon_0}\int n_e \mathrm{d}l + \frac{12\pi AB}{\lambda^3 n_{g0}}\int \Delta n_g \mathrm{d}l$$

where I_{ω_m} and $I_{2\omega_m}$ are the frequency elements in the measured signal at the fundamental and second harmonic of the phase modulation frequency ω_m, e is the charge of an electron, λ is the probing laser wavelength, c_0 is the speed of light in vacuum, m_e is the mass of an electron, ε_0 is the permittivity of vacuum, A and B are specific constants that depend on the gas species, and n_{g0} 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

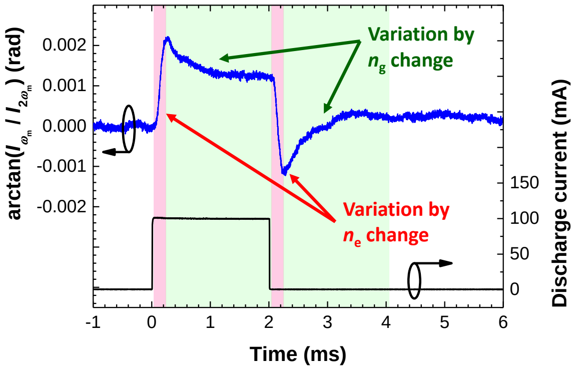

Fig.1. Measured signal waveform in the PMDI with the discharge current. Fast signal variations just after on and off timings of the discharge are induced by n_e variation in the atmospheric-pressure plasma [6].

sensitivity and much less sensitivity to n_g variation. This means that the effect of n_g 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} cm^{-3}, and line-integrated n_e sensitivity and temporal resolution of the PMDI system at NIFS are 7×10^{11} cm^{-2} and of 110 μs 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_g 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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