Laser Absorption Spectroscopy for Diagnostics of a Neutral Helium Beam

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The density resolution of a measurement system using laser absorption spectroscopy is evaluated in order to diagnose a fraction of metastable helium atoms ($2\ ^3S_1$) in a neutral helium beam. Experiments performed in a hollow cathode device show that the density resolution of the present system is about $5 \times 10^{13}\,\mathrm{m}^{-3}$ for a 1 m absorption length. Optimization of absorption scheme and improvements of signal detection are suggested, which shows that laser absorption spectroscopy is a promising diagnostic method for a neutral helium beam.

Keywords: laser absorption spectroscopy, neutral beam, helium atom, metastable state, hollow cathode discharge

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1. Introduction

A diagnostic neutral beam using helium atom is proposed to measure the spatial and energy distributions of alpha particles in fusion plasmas [1, 2]. For burning plasmas in the international thermonuclear fusion experimental reactor (ITER), an approximately 1-2 MeV helium neutral beam has been designed [3–5]. The diagnostic neutral beam is required to be well controlled regarding the population of helium atoms in a metastable state as well as beam divergence and other beam parameters. Since a neutral beam that includes considerable amount of metastable atoms causes undesired beam attenuation, quantitative evaluation of alpha particle distribution becomes difficult and measurement itself might be impossible near the magnetic axis. Therefore, the helium neutral beam is produced not directly from the charge exchange of a positive beam but from an autodetachment of a negative ion beam, where the negative ion beam is converted from a positive ion beam through an alkali vapor cell [6, 7]. In this method almost all neutral helium atoms are expected to be in a ground state [2]. However, few reports have experimentally verified a metastable fraction after autodetachment. Experimental research has recently been started in which a helium neutral beam is produced using the above-described method for proof of principle [8, 9]. The current of the helium neutral beam produced in the proof of principle experiment is about $10\,\mu$A at a beam energy of 100 keV. Then the beam density is about $5 \times 10^{11}\,\mathrm{m}^{-3}$. Thus a measurement system aimed at ultra-low density metastable atoms is required. The density resolution of such a system should be about one order less than the beam density.

In this paper, a method of measuring the population density of a metastable state in a neutral beam is described. We propose a measurement system using laser absorption spectroscopy, which is a popular method to measure atomic density in laboratory plasmas [10, 11]. On the other hand, applying the method to beam diagnostics could be regarded as ambitious since the beam density is much lower than that of the plasma. Thus we have constructed a prototype measurement system and have checked its performance using a hollow cathode plasma. In section 2, principle of the measurement and the estimation of density resolution is described. The experimental setup and results are shown in section 3, followed in section 4 by discussion regarding the improvement of density resolution for the beam diagnostics. A summary is provided in section 5.

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2. Measurement of Metastable Atoms

When a laser light with a frequency ν passes through a length l of a swarm of metastable atoms, the population density n of metastable atoms is obtained by

$$nl\sigma(\nu) = -\ln(I(\nu)/I_0), \tag{1}$$

where $I(\nu)$ and I_0 are the intensities of the transmitted and the incident laser, respectively. If broadening of the absorption spectrum is determined mainly by Doppler broadening, the absorption cross section $\sigma(\nu)$ is described as follows:

$$\sigma(\nu) = \frac{h\nu}{c}\frac{B_{ij}}{\Delta\nu\sqrt{\pi}}\exp\left[-\left(\frac{\nu-\nu_0}{\Delta\nu}\right)^2\right], \tag{2}$$

where h and c are the Planck constant and light speed, respectively. Transition probability for absorption B_{ij} is related to Einstein's A coefficient A_{ji} using lower (g_i) and upper (g_j) statistical weights:

$$B_{ij} = \frac{g_j}{g_i}\frac{c^3}{8\pi h\nu^3}A_{ji}. \tag{3}$$

Excited states of helium atoms, $n\ ^3P_J$, ($n = 2, 3, 4\dots$,

Table 1 Absorption schemes for helium metastable atoms. g_j indicates the statistical weights of the upper state; B_{ij}, transition probability for absorption. $\sigma(\nu_0)$ is the cross section of the center wavelength with the assumption of room temperature. These data are deduced from the Atomic Spectra Database [12].

Transition	wavelength [nm]	g_j	$B_{ij}[J^{-1}s^{-2}m^{-3}]$	$\sigma(\nu_0)[m^2]$
$2\,^3S_1 \rightarrow 2\,^3P_0$	1082.909	1	2.60×10^{20}	8.71×10^{-17}
$2\,^3S_1 \rightarrow 2\,^3P_1$	1083.025	3	7.80×10^{20}	2.61×10^{-16}
$2\,^3S_1 \rightarrow 2\,^3P_2$	1083.034	5	1.30×10^{21}	4.35×10^{-16}
$2\,^3S_1 \rightarrow 3\,^3P_0$	388.861	1	1.12×10^{19}	3.74×10^{-18}
$2\,^3S_1 \rightarrow 3\,^3P_{1,2}$	388.865	8	8.92×10^{19}	2.99×10^{-17}
$2\,^3S_1 \rightarrow 4\,^3P_0$	318.773	1	3.27×10^{18}	1.10×10^{-18}
$2\,^3S_1 \rightarrow 4\,^3P_{1,2}$	318.774	8	2.62×10^{19}	8.78×10^{-18}

$J = 0, 1, 2$), are produced by photon absorption from metastable helium ($2\,^3S_1$). The absorption cross section for each scheme as well as the transition level and wavelength are shown in Table 1. It is difficult to distinguish the fine structure in $n \geq 3$ states, especially between $J = 1$ and $J = 2$ states, while the energy levels of the fine structure should be treated individually in $n = 2$ states. For the purpose of ultra-low density measurement of a metastable state in a beam, the largest absorption cross section is suitable. The transition, $2\,^3S_1 \rightarrow 2\,^3P_2$, has an advantage for measurement in an actual beam, while using an excited state, $2\,^3P_0$, has advantages for testing a measurement system. The latter is in a more severe (less sensitive) condition than that of the actual beam diagnostics, but the same optical components can be tested because these two transitions have the same wavelength region. In the present experiment, hence, the absorption scheme $2\,^3S_1 \rightarrow 2\,^3P_0$ is used. In terms of the availability of a light source of about 1083 nm, this absorption scheme is also attractive, because of the availability of low-cost, narrow-linewidth diode lasers.

The minimum measurable density of the metastable atom (density resolution) is determined by the dynamic range of a detector. The range's lower limit depends on the noise level, while the upper limit is determined by the saturation of the detector and that of the absorber. Due to these saturations, a low power laser can provide a sufficient light source for absorption spectroscopy. If the dynamic range is about 10^{-3}, the line-density resolution is about 1×10^{13} m^{-2} as determined by Eq. (1). Thus, about 200 m of absorption length is required to achieve 5×10^{10} m^{-3} of density resolution for the beam measurement. The absorption length described above is impractical. However, if less than 10^{-5} of the dynamic range is obtained, the required absorption length can be shortened by about one meter.

3. Experiment

The experiments were performed in a hollow cathode device for the production of metastable atoms (PROMESTA device) in Tohoku University [13]. A schematic of the experimental setup is shown in Fig. 1. A cylindrical cathode and two cylindrical anodes positioned

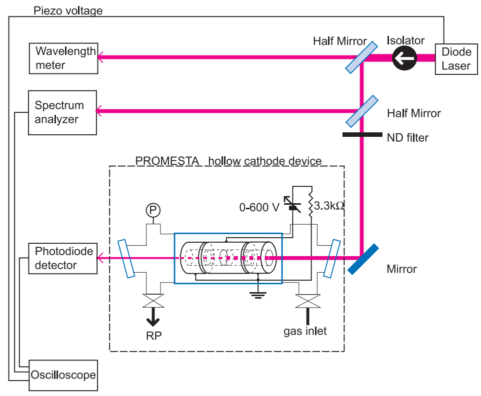

Fig. 1 Schematic of the experimental setup.

at both ends of the cathode with 2 mm gaps are made of aluminum and are contained in a Pyrex glass tube. Inner diameter of the cathode is 10 mm and its length is 40 mm. The two anodes have the same inner diameter as the cathode. Both ends of the vacuum chamber contain a window to allow a laser beam to pass through the PROMESTA device. In this experiment, the discharge current was varied from 3 mA to 50 mA at about 200 Pa of helium gas pressure. The discharge voltage was kept at about 170 ± 10 V.

An external cavity-stabilized diode laser (DL100, Toptica photonics) was used for laser absorption in metastable ($2\,^3S_1$) helium atoms. When the wavelength is scanned using a piezo actuator placed in the external cavity, the wavelength and longitudinal modes are monitored by means of a multi-wavelength meter and an optical spectrum analyzer. The spectrum analyzer is composed of a photodetector and a confocal Fabry-Perot interferometer, which has a free spectrum range of 1.5 GHz. When the scan-speed of the piezo-voltage is smaller than 4 V/s, a single mode laser beam without mode hop is emitted. The scanning range of the single mode laser is about 5 GHz (0.02 nm), which is sufficiently wider than the Doppler broadening (1 GHz) at a room temperature. The laser light passing through the plasma is detected by a silicon photodiode. A digital oscilloscope (12 bit, 2000 samplings/s) was used to acquire the signals. The signal was then averaged in every 100 points to reduce high frequency noise. The averaged data consist of about 20 samplings/GHz in

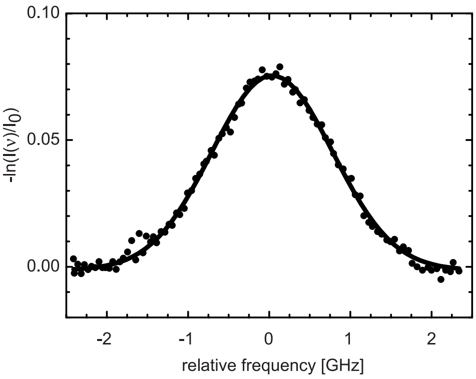

Fig. 2 Absorption spectrum of metastable helium atoms, obtained in a discharge current, $I_{dis} = 50\,mA$. Plots represent experimental data; solid line, the Gaussian fitting curve. A temperature of 315 ± 9 K and a line density of $9.03 \pm 0.19 \times 10^{14}\,m^{-2}$ are obtained.

the laser frequency scale. This is sufficient for Gaussian fitting based on the Doppler broadening.

A typical absorption spectrum obtained in a discharge current, $I_{dis} = 50\,mA$, is shown in Fig. 2, where the vertical axis is a quantity represented by Eq. (1). The solid line well-fitted to the experimental plot in Fig. 2 represents a Gaussian fitting curve, the temperature of the metastable helium is then 315 ± 9 K, which is very close to room temperature and is a reasonable value in glow discharges, while line density of the metastable helium obtained from this spectrum is $9.03 \pm 0.19 \times 10^{14}\,m^{-2}$. The errors of the temperature and the line density are evaluated based on the curve-fitting procedure.

The measured line density depends on the laser power, even under the same discharge condition, as shown in Fig. 3. Although higher laser power improves the signal to noise (S/N) ratio, it cause saturation of absorption, resulting in under-estimation of the line density. In high power region (≥ 100 μW), it is also noted that the temperature obtained from the width of the spectrum gradually increases with the laser power. At under 50 μW of laser power, the line density is safely measured in discharge currents of both 30 mA (open square) and 50 mA (filled circle). However, lower power degrades the S/N ratio as seen in the larger error bars. Thus, limited laser power (~ 50 μW) is used in this experiment.

Dependence of the line density of the metastable helium on the discharge current is shown in Fig. 4. The line density increases linearly with the discharge current up to $9.03 \pm 0.19 \times 10^{14}\,m^{-2}$, while in the case of the lowest discharge current a line density of $8.4 \pm 4.8 \times 10^{13}\,m^{-2}$ is obtained. The temperature of the metastable helium atoms remains constant near room temperature, except for the under 10 mA case. While the width of Gaussian fitting-function is sensitive to the shape of the spectrum, the area of the Gaussian function is barely influenced by the shape. The line density can thus be precisely measured even in the weak discharge condition, although the temperature not.

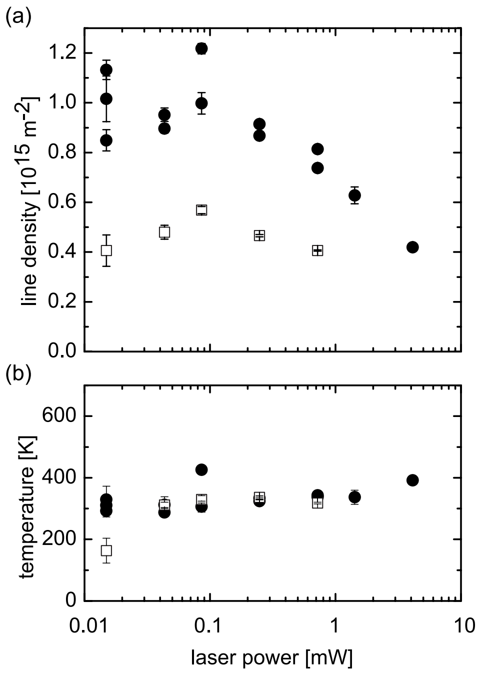

Fig. 3 Laser power dependence of measured line density (a) and temperature (b). Filled circle (•) is obtained at $I_{dis} = 50\,mA$, while the open square (□) at $I_{dis} = 30\,mA$

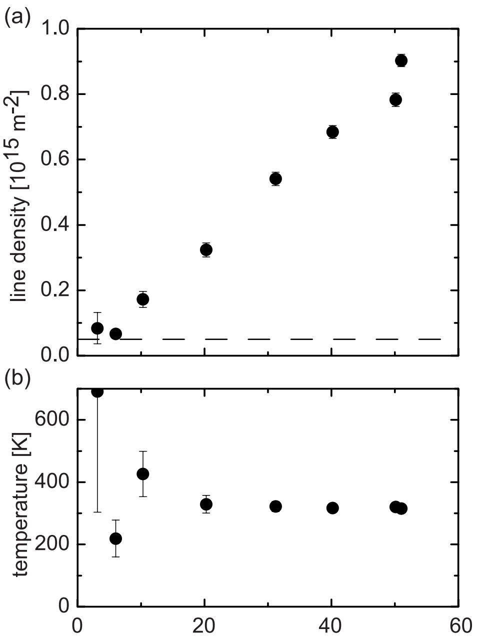

Fig. 4 Dependence of line density (a) and temperature (b) of metastable helium atoms on discharge current. Measurable line density ($5 \times 10^{13}\,m^{-2}$) is shown by a broken line in (a).

This suggests that a line density more than $5 \times 10^{13}\,m^{-2}$ can be accurately measured by the present measurement system.

4. Discussion

Here we discuss the applicability of the measurement system to the diagnostics of a neutral helium beam. The current of the helium neutral beam produced for the proof of principle experiment [8, 9] is about 10 μA at a beam energy of 100 keV. The beam density is then $5 \times 10^{11}\,\mathrm{m}^{-3}$. A less than 10 % metastable fraction resolution is required for diagnostics of the helium neutral beam. Thus a density resolution of $5 \times 10^{10}\,\mathrm{m}^{-3}$ is required.

When a 1 m absorption length is configured, the density resolution in the present measurement system is about $5 \times 10^{13}\,\mathrm{m}^{-3}$. This is three orders higher than the required density resolution. However, this discrepancy is overcome by the following improvements of the measurement system. It is again noted that an increase of laser power brings no improvement in density resolution but leads to an underestimation of density due to absorption saturation. Thus, the absorption scheme and signal detecting technique are key areas for improvement.

(i) Applying larger statistical weights of the upper state (g_j) results in much greater sensitivity as seen in Eq. (3). By applying laser absorption excitation to the $2\,^3P_2$ state leads to a level of sensitivity five times higher than the present excitation scheme wihch utilize the $2\,^3P_0$ state. The wavelength difference between these two absorptions is 0.125 nm (Table 1), which is beyond the mode hop-free scanning range of the laser diode but still in a stable operation range. Laser absorption to the $2\,^3P_2$ state can be realized by tuning the laser diode, resulting in improvement of the absorption coefficient.

(ii) Using a more sensitive detector is required and planned for the diagnostics in the beam experiment. The wavelength, 1083 nm, used in the present experiment is almost the upper limit of the sensitivity curve of the silicon photodiode. Hence, the detector is less sensitive and may suffer from large individual differences. The sensitivity of the actually used detector is 0.1 A/W. A photodiode suitable for the infrared telecommunication band, for example an InGaAs photodiode, is more sensitive than silicon's one at 1083 nm. The typical sensitivity of InGaAs photodiodes at 1083 nm is about 0.7 A/W, and has less piece-to-piece variations. Thus, an approximately seven-fold improvement is expected by changing the photodiode detector.

(iii) Noise reduction is also available. Because the detector emits white noise, applying lock-in detection is the most effective method. Commercial lock-in amplifiers, for example, have a −60 to −100 dB dynamic reserve, while data averaging applied to the present experiment equivalently has less than −20 dB.

To reduce the noise caused by the fluctuation of laser power, another detector intended to obtain a reference signal will be added in the system. Then the noise produced by the fluctuations in laser power will be canceled by the absorption signal and the reference signal.

With these improvements in the detection system, the density resolution is expected to be three to five orders higher than that of the present system. Hence, the measurement of a metastable fraction of the helium neutral beam produced in the proof of principle experiment will be easily achieved.

5. Summary

The density resolution of a measurement system using laser absorption spectroscopy is evaluated in order to diagnose a fraction of metastable helium atom ($2\,^3S_1$) in a neutral helium beam. The line densities of metastable helium atoms are measured by means of laser absorption spectroscopy in a hollow cathode plasma, from which the density resolution of the present measurement system, $5 \times 10^{13}\,\mathrm{m}^{-2}$, is obtained. A more efficient absorption scheme and signal detecting technique are suggested, which shows that the density resolution will improve by more than three orders. It is expected that laser absorption spectroscopy will become a suitable method to measure the metastable population in a neutral helium beam.

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