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Development of Low-Dispersion High-Throughput Visible Spectrometer System for Atomic He Line Intensity Ratio Method in Heliotron J

ヘリオトロンＪにおけるHe原子線強度比法のための低分散・高スループット可視分光計測システムの開発

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We are developing a low-dispersion high-throughput visible spectrometer system in order to observe many lines and continuous spectra simultaneously, and to apply to the measurement of the plasma parameters in Heliotron J. This system is supposed to measure the electron temperature T_e and the electron density n_e by the atomic He line intensity ratio method, and the objective wavelength range is 390-730 nm. We found that a 600 lines/mm transmission grating and a focus length 85 mm camera optics achieve F/1.4 and the observed wavelength range of 465-710 nm. We evaluated the reciprocal linear dispersion in the prototype optical arrangement and the error between the measured and theoretical values was as small as 0.17%.

1. Introduction

The temperature gradient in magnetically confined fusion plasma is typically steep in the boundary region where the electron temperature T_e is several eV - 100 eV. Therefore, in Heliotron J, a helical axis heliotron [1], the measurement of T_e, the electron density n_e and their spatial distributions in this area can provide a significant indicator of the confinement. In such low temperature area, the measurement of T_e and n_e by the atomic He line intensity ratio method has been noticeable [2].

The line intensity ratio method determines T_e and n_e by the comparison of the line intensity ratio obtained from the collisional-radiative (CR) model [3] with the one from the actual plasma measurement. The CR model is the plasma model which describes the rate balance equations in the excitation level populations as the efflux and influx due to the processes of the electron collision and the radiation. The quasi-steady state solution provides the population density in level p, $n(p)$, as the recombining and ionizing components [4] as:

$$n(p) = R_0(p\,,T_e\,,n_e)n_e n_i + R_1(p\,,T_e\,,n_e)n_e n_{1^1s}, \quad (1)$$

where the first term in the right hand side is the recombining component and the second term is the ionizing component, characterized by the so-called reduced population coefficient $R_0(p, T_e, n_e)$ and $R_1(p, T_e, n_e)$, respectively; n_i is the ion density and n_{1^1s} is the ground level density.

Therefore, in this study, in order to employ the atomic He line intensity ratio method, we develop a low-dispersion high-throughput visible spectrometer system which can simultaneously observe the atomic He lines with high temporal resolution in a broad wavelength region.

2. Selection of the Measuring Wavelength Range

The line intensity I_{pq} of the electron transition from the higher level p to the lower level q is represented by the following formula:

$$I_{pq} = hcn(p)A_{pq}/\lambda_{pq}, \quad (2)$$

where h is the Planck constant, c is the velocity of light, A_{pq} and λ_{pq} are Einstein's A coefficient and the wavelength of this transition, respectively. All of them are the known constants so that I_{pq} depends only on $n(p)$ and the population density ratio can be interpreted by the line intensity ratio.

Figure 1 shows the He discharge lamp spectra measured using a low-dispersion compact spectrometer (StellarNet EPP2000C UV-VIS). A considerable number of atomic He spectra, which correspond to the transitions to the principal quantum number n = 2, exist in the visible region. Thus, we decided the objective wavelength range to be 390-730 nm.

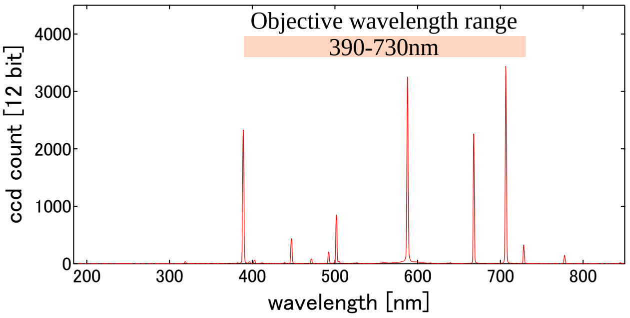

Fig.1. He discharge lamp spectra

3. Optical Design and Evaluation of the Visible Spectrometer System

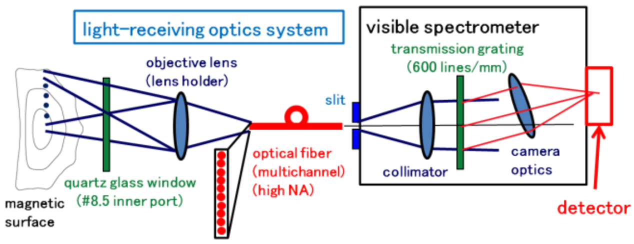

Fig.2. Schematic of the visible spectrometer system

Figure 2 shows the schematic of the visible spectrometer system which is being developed in this study. The upper half area of the poloidal cross-section is focused onto the end surfaces of the multichannel high-NA optical fibers using an objective lens, and the photons transmitted in the fibers are introduced to the visible spectrometer. In the early stage of the design, we assume that the detector has the area of 13×13 mm^2. The visible spectrometer employs two photographic lenses as the collimator and the camera optics, and a transmission grating to reduce vignetting by minimizing the distance between these lenses [5]. Table I shows the specifications of the photographic lenses for the collimator and the camera optics including the effective F-number (F/#) and the measurement wavelength range.

We evaluated the reciprocal linear dispersion by measuring the He discharge lamp in the prototype optical arrangement using the digital camera (Nikon D90). The result was 18.19 nm/mm. The theoretical value is 18.16 nm/mm, so that the error was as small as 0.17%. Thus, we found that we can implement the optical arrangement based on the designed configuration.

Table I. The specifications of the photographic lenses and the resultant optical features

	collimator	camera optics (both available)	
f [mm]	85	50	85
F/# [-] (effective F/#)	1.4	1.2 (2.04)	1.4 (1.4)
measurement wavelength range [nm]	-	390 - 730	465 - 710

4. Summary and Future Plans

We have completed the optical design of the visible spectrometer system for the atomic He line intensity ratio method. The reciprocal linear dispersion in the prototype optical arrangement agreed with the theoretical design with the error of 0.17%. In order to apply to the plasma discharge experiments in Heliotron J, we are planning to use EMCCD (electron multiplying charge coupled device). This enhances the detection efficiency because of the high quantum efficiency, which enables the synchronizing acquisition with the discharge pulse of about 150 msec. The manufacturing is now under way.

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