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GENERAL AND APPLIED PHYSICS

Plasma Core Electron Density and Temperature Measurements Using CVI Line Emissions in TCABR Tokamak

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Abstract In this work, we present results of electron temperature (T_e) and density (n_e) measurements obtained in Tokamak Chauffage Alfvén Brésilien (TCABR) tokamak using visible spectroscopy from CVI line emissions which occurs mainly near the center of the plasma column. The presented method is based on a well-known relationship between the particle flux (Γ_{ion}) and the photon flux ($\o_{\text{ion}}$) emitted by an ion species combined with ionizations per photon atomic data provided by the atomic data and analysis structure (ADAS) database. In the experiment, we measured the photon fluxes of three different CVI spectral line emissions, 4685.2, 5290.5, and 6200.6 Å (one line per shot). Using this method it was possible to find out the temporal evolution of T_e and n_e in the plasma. The results achieved are in good agreement with T_e and n_e measurements made using other diagnostic tools.

Keywords Plasma diagnostics · Plasma spectroscopy · Tokamak · Electron temperature · Electron density

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1 Introduction

The development of diagnostic tools and methods for measurements of plasma parameters, like temperatures, densities, and confinement times, is an important matter in plasma physics. In previous works [1–3], we have used spectral emissions originating from neutral hydrogen and C^{1+} (CII) ions in order to measure the electron densities and temperatures at the edge of NOVA-UNICAMP tokamak plasma [4]. The method developed in [3] uses a well-known relationship between the particle flux and the photon flux emitted by an ion species [5–7] combined with ionizations per photon atomic data provided by the atomic data and analysis structure (ADAS) database [8]. In that work, we measured the photon fluxes of three different CII spectral line emissions during a single tokamak discharge and then established the basic ideas to start the studies on the use of different impurity spectral line emissions for the measurements of T_e and n_e in tokamak plasmas.

Now we present some results of plasma core T_e and n_e measurements obtained in Tokamak Chauffage Alfvén Brésilien (TCABR) tokamak plasma [9, 10], which is a machine with major radius R=0.61 m, minor radius a=0.18 m, discharge current I_P=100 kA, toroidal magnetic field BT= 1.1 T, maximum average density n_e (1–4.5)×10^{19} m^{-3}, Te (0)≈500, Ti (0)≈200 eV, duration of the stationary phase of the discharge 60 ms. The results were achieved using visible spectroscopy of highly ionized carbon emission lines, C^{5+} (CVI), combined with the method that we have developed. The experimental data were taken in three different tokamak shot discharges using one absolutely intensity calibrated monochromator equipped with a photomultiplier.

Using this method it was possible to determine the temporal evolution of density and temperature of the electrons at the central region of the plasma column. The results achieved are in good agreement with the expected values for the plasma region where occurs the largest probability of CVI emissions [11] and also with measurements made using other diagnostic tools [12, 13].

2 Theoretical Model

The method used in this work for measurements of density and temperature of electrons is based on a well-known relationship between the particle flux (Γ_{ion}) and the photon flux ($\phi^{[\lambda]}_{\text{ion}}$) emitted by an element (or an ion), at a given wavelength (λ) [5]:

$$\Gamma_{\text{ion}}[\lambda] = \left(\frac{S}{XB}\right)^{[\lambda]} \phi^{[\lambda]}_{\text{ion}} \quad (1)$$

where the (S/XB) factor is known as ionization per photon coefficient, and depends on local T_e and n_e. In a plasma in the equilibrium condition, we can assume that the particle flux of a given ion species, at a fixed ionization stage, is constant [14]. Then, for an ion emitting in various different wavelengths' we have:

$$\Gamma_{\text{ion}}[\lambda_1] = \Gamma_{\text{ion}}[\lambda_2] = \cdots = \Gamma_{\text{ion}}[\lambda_n] = \ldots \quad (2)$$

We can take the ratios between particle fluxes obtained using different wavelengths emitted by the ion in order to write:

$$\frac{\Gamma_{\text{ion}}[\lambda_1]}{\Gamma_{\text{ion}}[\lambda_2]} = \frac{\Gamma_{\text{ion}}[\lambda_2]}{\Gamma_{\text{ion}}[\lambda_3]} = \cdots = \frac{\Gamma_{\text{ion}}[\lambda_{n-1}]}{\Gamma_{\text{ion}}[\lambda_n]} = 1 \quad (3)$$

Combining Eq. (1) and (3) with measurements of photon fluxes emitted by three CVI lines, we have a system with two equations and two undetermined parameters (T_e and n_e):

$$\frac{\Gamma_{\text{ion}}[\lambda_1]}{\Gamma_{\text{ion}}[\lambda_2]} = \frac{(S/XB)^{[\lambda_1]}\phi^{[\lambda_1]}_{\text{ion}}}{(S/XB)^{[\lambda_2]}\phi^{[\lambda_2]}_{\text{ion}}} = 1 \quad (4-\text{a})$$

And

$$\frac{\Gamma_{\text{ion}}[\lambda_2]}{\Gamma_{\text{ion}}[\lambda_3]} = \frac{(S/XB)^{[\lambda_2]}\phi^{[\lambda_2]}_{\text{ion}}}{(S/XB)^{[\lambda_3]}\phi^{[\lambda_3]}_{\text{ion}}} = 1 \quad (4-\text{b})$$

Table 1 List of CVI transitions [15, 16] used with their respective wavelengths

Label	Wavelength (Å)	Transition
CVI1	4685.2	n=12 → n=9
CVI2	5290.5	n=8 → n=7
CVI3	6200.6	n=11 → n=9

The system formed with these two equations allows us to perform an interactive method in order to find correct values of local T_e and n_e that satisfy the Γ_{ion} constancy.

3 Experimental Setup and Analysis Method

The spectroscopic data of CVI line emissions were acquired using the scheme shown in Fig. 1. In this experimental setup, the light emitted by the plasma is collected using an achromatic telescope (f=100.1 mm) and transmitted to the entrance slit of the monochromator through an optical fiber with diameter 1.74 mm.

The monochromator used in this experiment was a THR1000 Jobin Yvon, which has a focal length 1000 mm and a reciprocal linear dispersion of 8.0 Å/mm. The monochromator was equipped with a R943-02 photomultiplier tube manufactured by Hamamatsu.

The ionization per photon coefficient used in these experiments was obtained from the ADAS database [8] that provides S/XB for CVI transitions listed in Table 1 for a wide range of electron temperatures and densities. The ADAS data were interpolated in a finest way in order to improve the precision of our measurements.

Since the temporal evolution of photon flux of CVI spectral lines was obtained experimentally and S/XB coefficients are available in the ADAS database, using Eq. 1, we can calculate the ratio of particle flux for two different lines as function of electron density for a fixed electron temperature. The particle flux ratio curve as function of electron density for a pair of spectral lines should intercept the curve of particle flux ratio for another pair at some density value. The electron density value for each cross point should be different for different electron temperature value. This calculation procedure should

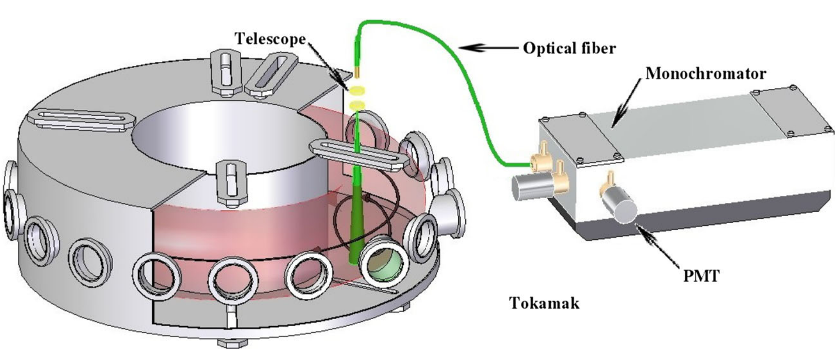

Fig. 1 Experimental setup used for temporal evolution of density and temperature of electrons in TCABR tokamak

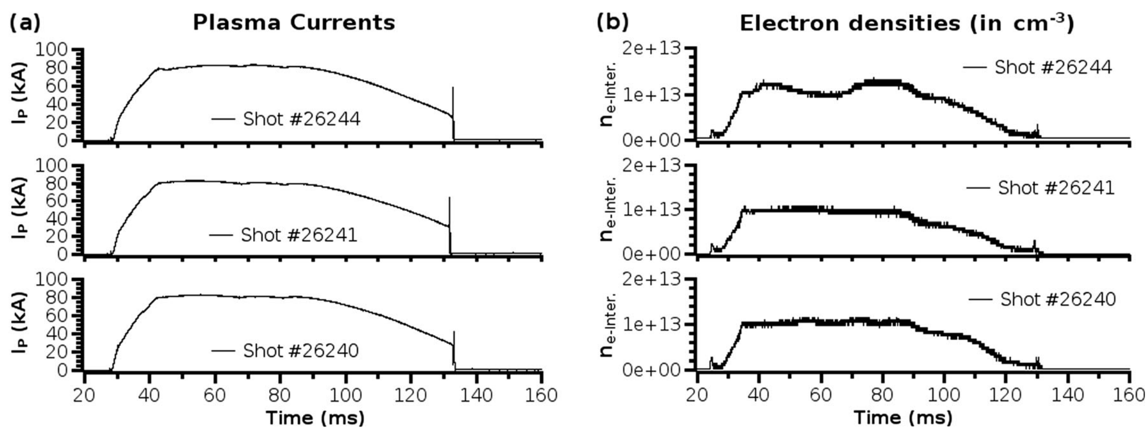

Fig. 2 Plasma current and line integrated electron density signals from three distinct discharges used for spectroscopic analysis

continue until a pair of T_e and n_e values that satisfy the condition 4-a was found out. Once the values of n_e and T_e that satisfies condition 4-a for a given time instant were found out, this procedure should be repeated for another instant. The complete description of the analysis method, with an application for CII ions, can be found in [3].

The procedure described above must be performed for each time instant of the plasma discharge in order to get the temporal evolution of T_e and n_e.

4 Results and Conclusions

Due to the high level of energy needed in order to get five times ionized carbon ions, the plasma region where the CVI line emissions have the higher probability of occurrence is near the core of the plasma column. Using the method previously described, we have determined the temporal evolution of the electron temperature and density at the central region of TCABR tokamak plasma.

Figure 2a shows the plasma currents of the three discharges, labeled as #26240, #26241, and #26244, used to measure the CVI emission signals (Fig. 3a). Figure 2b shows a central chord of the electron densities of each discharge using microwave interferometry.

Figure 3 shows the T_e and n_e results achieved using the method we have developed.

The discharge time interval, which can be used to perform our analysis, is between 50–90 ms, where plasma current and electron density are stable. At about 75 ms, we can observe a slight increase of electron density on shot #26244 in Fig. 2b.

Figure 3a shows the emission spectra from CVI of discharges shown in Fig. 2. The signal obtained have been slipped up for the sake of viewing facility. The values of emission signals used in calculation are taken from a baseline where the signal must be zero.

Figure 3b shows the time evolution of electron temperature and density from 60 to 85 ms of the set of tokamak discharges #26240, #26241, and #26244; the uncertainties in T_e measurements are all of the same order of magnitude of the uncertainty in the first data point. Slight increase of electron density at around 75 ms of the discharge may be related to the increase observed in microwave interferometry.

The electron temperatures obtained in the combination of the set of three tokamak discharges are around 480 eV. This result is in good agreement with the T_e values predicted in [12]

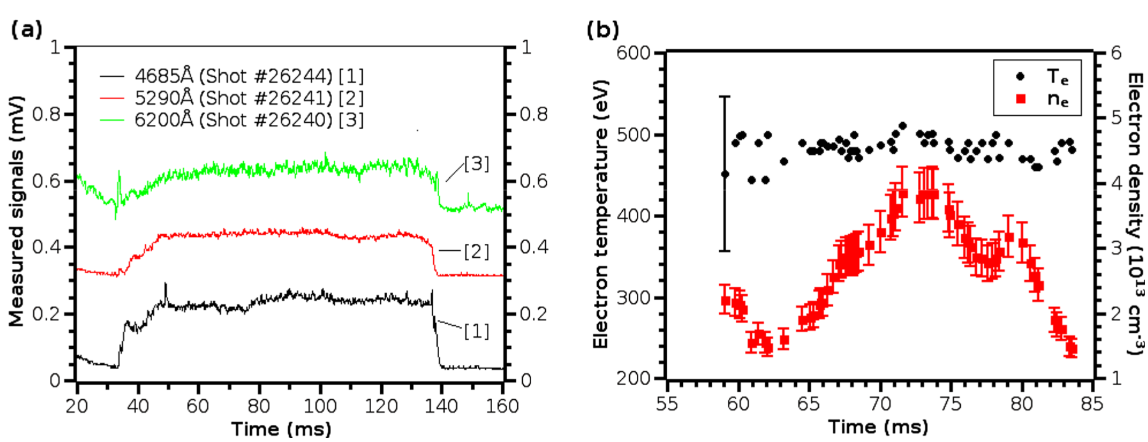

Fig. 3 Spectroscopic data of CVI emission lines (**a**), and T_e and n_e (**b**), obtained for the set of tokamak discharges #26240, #26241, and #26244

and [13], and also for the plasma region where the higher probability of CVI emissions in the TCABR tokamak occurs. The electron density that was obtained oscillates between 1 and 4×10^{13} cm^{-3} and is in good agreement with the values measured using microwave interferometry. This indicates that the proposed diagnostic method can be used to monitor the temporal evolution of electron densities and temperatures at the center of tokamak plasmas or outer radial positions, according to the impurity ionization level and provided that at least three independent line emissions for each ion species can be measured. It also suggests that the method can be applied not only to other impurity ions with different ionization levels present in the plasma but also at lower wavelengths, as in vacuum ultraviolet region, where higher energy ions are more frequent, as fin the case of large tokamaks.

The absence of T_e and n_e results in other time intervals of the discharges is due to the fact the CVI line emission measurements were made in distinct tokamak discharges, which lead to the impossibility to satisfy the conditions 4-a and 4-b or differences in the values of plasma parameters. It is highly recommended to perform the measurements simultaneously, in the same tokamak shot discharge, to obtain the three line emissions in order to avoid possible differences among distinct discharges as in references [2, 3].

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