Comparison between Laser Thomson Scattering and Spectroscopic Measurements in Low Temperature Helium Plasmas in Divertor/Edge Simulator MAP-II

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Electron temperature and density measurements of low temperature Helium plasmas are performed in the divertor/edge plasma simulator MAP-II, by means of Laser Thomson Scattering (using a ND:YAG Laser, a double monochromator and an ICCD detector) and optical emission spectroscopy (using a spectrometer and a CCD detector). The recent upgrades of our LTS system (reduction of the level of stray light and reduction of the band width of the notch filter) allowed the measurement of temperatures as low as 0.1 eV and the investigation of Electron Ion Recombination (EIR) processes in He plasma. Spatial profiles of electron temperature and density along the plasma column have been taken moving the plasma *recombination front* across the measurement point by controlling the gas pressure from 80 to about 145 mTorr. A comparison between LTS results and spectroscopic analysis based on a He I CR model including radiation trapping is shown in order to confirm the consistency of the diagnostics. CR model results, obtained fitting the excited state populations with principal quantum number n = 3,4, are consistent with those from LTS. The discrepancies are found to be attributable to the mixing of the ionization and recombination regimes over the line of sight of the optics.

Keywords: Thomson scattering, CR model, divertor, detached plasma, recombining plasma, electron ion recombination (EIR) process

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1. Introduction

The design of magnetically confined fusion devices employs a divertor configuration in order to reduce the influx of impurities to core plasma, with the reactor operational limit of heat flux onto the divertor plate. From this point of view, the volumetric recombination processes are regarded as key issue in order to reduce the particle flux onto the divertor plate. Electron temperature and density are important parameters for understanding the dynamic of plasmas in the divertor region. Specifically, the study of volumetric recombination processes in detached plasma regimes (Molecular Activated Recombination (MAR) processes induced by hydrogen puffing and Electron Ion Recombination (EIR) processes [1]), implies the necessity for reliable diagnostics in low temperature recombining plasmas, since their reaction rates strongly depend on the plasma parameters.

Electric probe, passive spectroscopy and Laser Thomson Scattering (LTS) methods have been used for parameters measurement in divertor plasmas. It should be noted that, in the application of the electric probe in recombining plasmas, there is an anomalous current-voltage characteristic of the single probe which disturbs the measurements of T_e and n_e [2]. Passive spectroscopy for the Rydberg series, on the other hand, in a partially local thermal equilibrium, such as EIR plasmas, always reflects the brightest point. Laser Thomson Scattering cannot avoid limitations due to the requirements of good port accessibility to the divertor region and of sufficient separation of the Thomson scattering signal from the stray light.

We have been applying Laser Thomson Scattering to MAR plasmas [3] and the recent upgrades are intended for the application to EIR plasmas [4]. The objective of this paper is a comparison of LTS results with those obtained from passive spectroscopy in combination with a collisional-radiative (CR) model for He I. This can give us information about the consistency of both measurements that is useful in using passive spectroscopy as a simple method for monitoring the divertor/edge plasmas from a limited observation chord.

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2. Experimental Setup and Analysis Method

Experiments were conducted in the divertor/edge simulator MAP-II [5]. MAP-II is a dual-chamber steady state linear device. The plasma is produced with a low-pressure arc discharge. In the present experiment the discharge conditions were as follows: $V = 65$ V, $I = 30$ A and pure Helium as discharge gas.

The detailed experimental setup is described in [4]. The laser source is a frequency doubled Nd:YAG laser (532 nm, 500 mJ, 7 ns, 10 Hz) and the Thomson scattered light, dispersed by a double monochromator system, is acquired by an ICCD camera. From the Doppler broadening of the scattered light T_e can be determined, while an intensity calibration, carried out by means of Rayleigh scattering from a known pressure of gas, allows the determination of n_e. A physical notch filter in the image plane of the first monochromator is used in order to block stray light at the laser wavelength that could swamp the true scattered light signal. The width of the block determines the lowest measurable Doppler broadening and thus the lowest determinable electron temperature. The recent upgrades of our LTS system, namely the reduction of the stray light level and of the stop-band width of the notch filter, have enabled the measurement of electron temperatures as low as 0.1 eV, allowing the investigation of Helium EIR plasmas. Using the same optics as the LTS system in the same plasma conditions, line-averaged spectroscopic data were acquired using a simple spectrometer equipped with a 2048 pixel linear CCD, having the typical resolution of 0.8 nm in full width at half maximum (FWHM).

In order to measure EIR regimes, the recombination of the plasma column had to be induced in the first chamber. The He neutral pressure was controlled by increasing the additional gas puff from the second chamber. The variation in the neutral pressure did not change the characteristics of the *recombination front* but just moved it across the measurement point, due to the effect of the increased pressure in the upstream part of the plasma column (about 1 m in length). Thus, the plasma can safely be regarded as having the same electron temperature and density, which emit the same spectra. As a consequence, we were able to measure a spatial profile of the plasma column varying the neutral pressure from 80 to 145 mTorr.

Passive spectroscopy data have been interpreted by using a CR model for He I excited states distribution. The CR model we applied in this study was developed by Fujimoto [6], upgraded by Goto [7] and recently modified by Iida taking into account a radiation trapping based on the Otsuka's formula [8]. The reliability has been verified in pure He discharge in MAP-II, with an effective absorption radius of 2.5 cm [9]. In regimes of higher electron temperature divertor plasmas, radiative transitions from excited states corresponding to the principal quantum number $n = 3$, have been reported to give consistent results for the determination of T_e and n_e [10]. In the plasma regimes of this experiment, the fitting of the experimentally obtained transitions from $n = 3$ alone wasn't able to give consistent results, as mentioned also in [11]. Specifically in the present conditions, intensity ratios from $n = 3$ are not sensitive enough to be applicable in the measurement. For this reason, transitions from n^1D and n^3S for $n = 3{,}4$ are used. T_e and n_e are swept and are simultaneously determined so as to obtain the best fit of the experimentally measured line ratios. Note that line 728 nm (2^1P-3^1S), cannot be used due to the low intensity so that line 447 nm (2^3P-4^3D) has been used as reference.

Specifically the lines that have been used are: 667 nm (2^1P-3^1D), 706 nm (2^3P-3^3S), 492 nm (2^1P-4^1D) and 471 nm (2^3P-4^3S), all normalized to the transition at 447 nm.

3. Experimental Results and Discussion

The plasma column appeared as can be seen in Fig. 1. In these conditions of electron temperature, density and neutral pressure, the electron collisions are dominated by elastic collisions with neutrals and ions with a total elastic mean free path decreasing along the plasma column from the order of 1 mm to the order of 0.1 mm. Taking into consideration only elastic collisions we can estimate an energy relaxation length of the order of 15 cm, which is comparable to the characteristic length in the cone shape at the tip of the ionizing plasma column. For this reason the decrease in the electron temperature can be understood as being mainly due to elastic collisions.

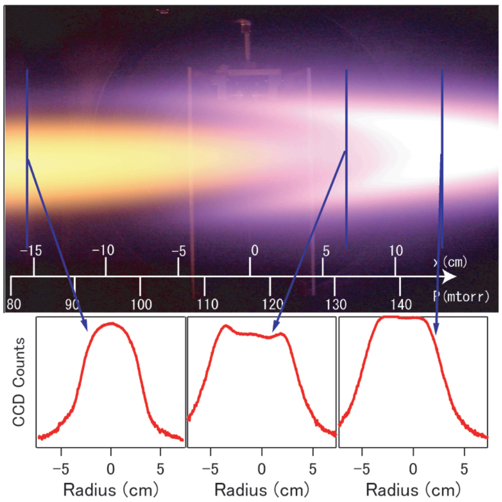

Fig. 1 Typical camera picture of the plasma column streaming from left to right, with the equivalent measured spatial position's dependence on the neutral pressure. Three emission intensity radial profiles at three different points are shown. One can see the recombining front covering the tip of the ionizing plasma.

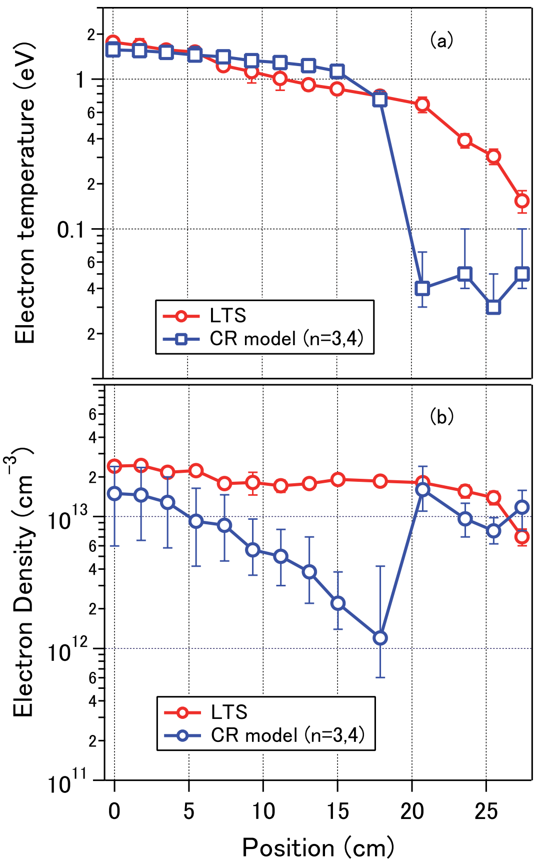

Fig. 2 Comparison of Laser Thomson Scattering and CR model results: (a) Electron temperature profile, (b) Electron density profile.

An objective of this paper is to give a comparison between LTS results and those obtained from spectroscopy. Thus, we have to consider the fact that while LTS diagnostic gives local measurements of the plasma parameters, spectroscopy offers results integrated over the line of sight of the optics. For this reason, spectroscopy always represents the brightest point which does not always coincide with the center of the plasma column in particular regarding, in our case, the transition region between ionizing and recombining plasma, as can be seen in Fig. 1. The results obtained from the two diagnostics are shown in Fig. 2 as a function of the position along the magnetic field axis.

The results for the electron temperature obtained from CR model are consistent with those from LTS, in particular in the ionizing region (80-100 mTorr, 0-10 cm) they are consistent within the error bars. On the other hand, the apparent discrepancy in the recombining region (≥ 130 mTorr, ≥20 cm), is due to the fact that the spectroscopic results represent the outer (brighter and colder) corona and not the central point. The results of the electron density are consistent within the error bars both at the beginning of the ionizing region and in the recombining region. However, in the ionizing region the discrepancy increases with the increase in the neutral pressure, reaching a factor of about 10 in the darkest point. The spatial profile obtained from spectroscopy gives an unjustified decrease-increase in the electron density before the recombining front.

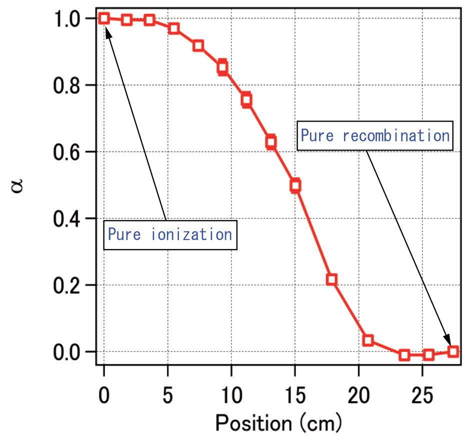

Fig. 3 Profile of the parameter α as obtained from the fitting of the line intensity ratios according to Eq. (1).

A plausible explanation of this discrepancy can be the mixing of the ionizing and recombining component due to the averaging over the line of sight of the measured line intensity ratios. The viewing chord crosses both the two regimes and the measured spectrum results from a linear combination of the ionizing and recombining spectra. Using the ratios $R(0\,\mathrm{cm};\ \mathrm{ion.})$ at the point $r = 0\,\mathrm{cm}$ (in ionizing regime) and the ratios $R(27\,\mathrm{cm};\ \mathrm{rec.})$ at the point $r = 27\,\mathrm{cm}$ (in recombining regime), the parameter α has been obtained fitting the intensity ratios R used in the CR model analysis, according to the following linear combination:

$$R = R(0\,\mathrm{cm};\ \mathrm{ion.}) \cdot \alpha + R(27\,\mathrm{cm};\ \mathrm{rec.}) \cdot (1 - \alpha). \tag{1}$$

The spatial profile obtained for α along the plasma column, shown in Fig. 3, supports the previous explanation.

By means of CR model, using plasma parameters obtained from each diagnostics, we can obtain the value of the intensity of visible light emitted from the plasma in every measured point from:

$$I = \sum_{vis} n(p) \left(\sum_{q<p} A(p, q) h\nu_{pq} \right). \tag{2}$$

Then, we compare qualitatively the brightness deduced from LTS and CR model results with the commercially-based 8-bit digital camera picture, which reflects the intensity profile in the visible region. Intensity of emission obtained using LTS parameters and camera intensities have been normalized in the ionizing region of the plasma and the scale of the relative intensity of the picture has been fitted to that obtained by LTS. Due to the limited dynamic range of the digital camera picture, the recombining region

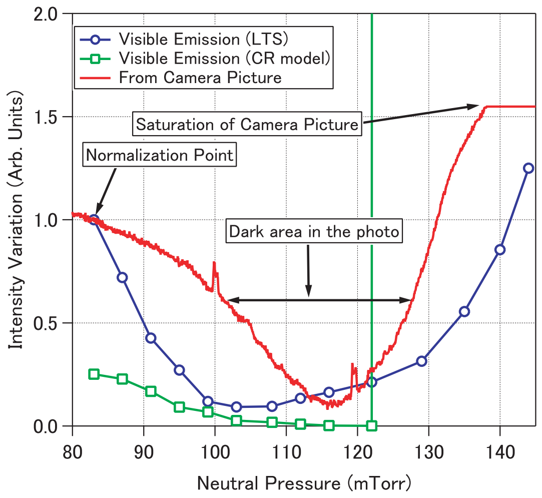

Fig. 4 Relative light emission intensity obtained from camera picture (continuous line), LTS results (circles), CR model results (squares).

is saturated. The results from LTS and CR model are scaled relating to each other. In Fig. 4 the three different profiles, obtained from the camera picture, from intensity of visible emission obtained from CR model and from LTS are shown. As we see the darkest region that can be seen in the camera picture results consistent with the decrease of the intensity of emitted visible light evaluated by means of LTS, confirming the consistency of the measurements. On the other hand, the emission intensity obtained from CR results is affected from the integration over the line of sight.

4. Summary and Conclusions

LTS measurements have been performed in low temperature recombining plasmas after the upgrades for the application to He EIR plasmas. Measurements of T_e and n_e spatial profiles in EIR plasmas have been carried out in MAP-II and a comparison with He I CR model including radiation trapping has been shown. The results of CR model using transitions from $n = 3,4$ agreed with LTS results in the ionizing and recombining region of the plasma column. The discrepancy in the measured density between LTS and CR model can be explained by the averaging of both the ionization and recombination regimes over the line of sight.

A qualitative comparison between the relative intensity of a camera picture and the profile of visible light emission intensity confirms the consistency of LTS measurements.

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[1] S.I. Krasheninnikov, A.Y. Pigarov and D.J. Sigmar, Phys. Rev. Lett. A **214**, 285 (1996).
[2] S. Kado, H. Kobayashi, T. Oishi and S. Tanaka, J. Nucl. Mater. **313-316**, 754 (2003).
[3] A. Okamoto, S. Kado, S. Kajita and S. Tanaka, Rev. Sci. Instrum. **76**, 116106 (2005).
[4] F. Scotti, S. Kado *et al.*, Plasma Fusion Res. **1**, 054 (2006).
[5] S. Kado, Y. Iida, S. Kajita *et al.*, J. Plasma Fusion Res. **81**, 810 (2005).
[6] T. Fujimoto, J. Quant. Spectrosc. and Radiat. Tranf. **21**, 439 (1979).
[7] M. Goto, J. Quant. Spectrosc. and Radiat. Tranf. **76**, 331 (2003).
[8] M. Otsuka, R. Ikee and K. Ishii, J. Quant. Spectrosc. Radiat. Transf. **21**, 41 (1979).
[9] Y. Iida, S. Kado *et al.*, J. Plasma Fusion Res. SERIES **7**, 123 (2006).
[10] B. Schweer, G. Mank, A. Pospieszczyk, B. Brosda and B. Pohlmeyer, J. Nucl. Mater. **196-198**, 174 (1992).
[11] S. Kajita, N. Ohno *et al.*, Phys. Plasmas **13**, 013301 (2006).