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Comparative study of recombining He plasmas below 0.1 eV using laser Thomson scattering and spectroscopy in the divertor simulator MAP-II

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ABSTRACT

The recent upgrades of the MAP-II Laser Thomson Scattering (LTS) system and the development of a new Hetero-Tandem Double Monochromator, allowed detectable electron temperatures as low as 0.05 eV and electron densities as low as 10^{12} cm^{-3}. This enabled the study of He Electron Ion Recombining (EIR) plasmas and the comparison with optical emission spectroscopy for He I Rydberg states in partial local thermal equilibrium (p-LTE). $2^1P - n^1D$ and $2^3P - n^3D$ series with transitions from principal quantum numbers $n = 9-16$ were used for the T_e derivation. Results from both Boltzmann plot and Collisional Radiative model fitting are consistent with those from LTS. The very low temperature of 0.06 eV, usually obtained by the Boltzmann plot for He EIR states, is confirmed.

1. Introduction

In modern magnetic fusion devices, the magnetic field geometry diverts plasma fluxes onto the divertor plates in order to localize the plasma–wall interaction far away from the core plasma. Due to the plasma flow along the magnetic field lines intersecting the divertor plates, the peak value of the heat load onto the target could be unacceptably high. Considering the materials life-cycle in a possible steady state regime, the heat load should be mitigated to less than 5 MW/m^2. To this end, the achievement of a detached plasma regime and the enhancement of volumetric recombination processes can have a crucial impact for the reduction of power loads on material surfaces [1].

The effectiveness of conventional electron–ion recombination processes (EIR) as well as molecular assisted/activated recombination processes (MAR) induced by hydrogen molecules strongly depends on the plasma parameters such as electron temperature T_e and electron density n_e [2]. Very low electron temperatures are required for the recombination processes to be effective: $T_e < 1$ eV for EIR and T_e between 1 and 3 eV for MAR processes. Reliable low temperature plasma diagnostics are thus needed for the control and the optimization of the plasma detachment. Langmuir probes, optical emission spectroscopy and laser Thomson scattering have been widely applied in divertor plasmas. Since alpha particles are produced by fusion reactions and the density may be up to 5–10% of the total particle density in the divertor region, helium spectroscopy could be applicable for measuring plasma parameters [3].

In a He plasma, for high electron densities ($n_e > 10^{13}$ cm^{-3}) and very low electron temperatures ($T_e < 1$ eV), electron–ion recombination processes, both radiative and three body, dominate over ionization processes (EIR regimes) as evaluated in Fig. 5 in Ref. [2]. These EIR regimes are characterized by the appearance of the emission from higher excited states, the so-called Rydberg series spectra. As the principal quantum number n for the upper state increases, the emission tends to converge to that from partial local thermal equilibrium (p-LTE) states. This can be seen from the atomic Boltzmann plot method. A linear behavior of the logarithm of the excited states populations with respect to the excitation energy represents the achievement of the LTE with free electrons. Thus, if the plot lies on the straight line for a certain value of n, T_e can be determined from the reciprocal of the slope of the Boltzmann plot. Kado et al. reported in Ref. [4] that, in He EIR plasmas in which the Rydberg series can be observed, p-LTE may be a substantially good approximation provided $n_e \geqslant 10^{12}-10^{13}$ cm^{-3}.

An alternative method to the Boltzmann plot is the application of a collisional radiative model to spectroscopic data. The Collisional Radiative model (CR model) for the neutral helium lines (He I), developed by Fujimoto [5] and updated by Goto [6], has been widely applied with success. The application of the CR model to recombining plasmas, fitting He I ($n = 2$) series, gave results consistent with those obtained by the Boltzmann plot method, namely, T_e of about 0.06 eV in the He EIR regimes [7].

Although there is a difficulty in the determination of the lowest usable n for the fitting procedure, the merit in the Boltzmann plot method is that T_e can be determined using every term in the series spectra. In the CR model, on the other hand, the atomic data for states higher than $n = 10$ are state averaged.

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It must be noted that in recombining plasma regimes, the Langmuir probe method, due to the so-called 'anomalous current–voltage probe characteristic', gives overestimated values for the electron temperature (1–2 eV) [8,9].

Laser Thomson Scattering (LTS) systems for low temperature plasmas have been developed and successfully applied in recent years [10,11]. LTS has been employed in order to try to confirm the very low T_e values given by spectroscopy in He EIR regimes [12]. Due to limitations in the lowest measurable temperature of the LTS system, only measurements at the entrance of the He plasma recombining regime were possible, giving T_e of about 0.15 eV.

Therefore, in this paper, we describe an upgraded spectrometer for LTS aiming at measuring the T_e values observed using the CR-model and Boltzmann plot, namely 0.05–0.06 eV. Then we verify the reliability of the spectroscopic results in the EIR regime.

2. Experimental setup and method

The experiments were performed in the steady-state linear divertor simulator MAP-II (Material and Plasma-II) at the University of Tokyo. The detailed setup is reported in Ref. [4]. MAP-II consists of two chambers: a source chamber attached to the plasma source region where an arc discharge between a LaB_6 cathode and an anode pipe produces a high density plasma, and a target chamber where the plasma flows and terminates onto a target. In addition to the He gas puffed into the source region, additional puffing in the second chamber can help increase the neutral pressure in the first chamber. This mode of operation can activate EIR processes in the first chamber where the LTS system is installed (at lower pressures EIR processes are present only in the proximity of the target plate). By controlling the gas puffing rate in the second chamber it is possible to longitudinally move the plasma column without changing the discharge conditions [13].

The previous LTS system on MAP-II is described in Refs. [13,14]. The laser source is a frequency doubled Nd:YAG laser (532 nm in wavelength, 460 mJ in pulse energy, 7 ns in pulse duration, 10 Hz in repetition rate). The previous setup led to a lowest measurable temperature of 0.13 eV. The EIR temperatures usually reported by spectroscopy were thus still below the capabilities of the old LTS system. For this reason, a new double monochromator system was developed in 2007.

The present double monochromator system shown in Fig. 1, the Hetero-Tandem Double Monochromator (HTDM), is composed of two non-symmetric stages. Bright achromatic lenses F/2 ($f = 200$ mm in the first stage and $f = 100$ mm in the second stage) were used to collimate input light onto the gratings and focus it onto the Rayleigh block (first stage) and then onto the ICCD chip (second stage). Holographic gratings 1800 grooves/mm were used, having dimensions of $100 \times 135\ \mathrm{mm}^2$ for the first stage and $50 \times 50\ \mathrm{mm}^2$ for the second stage. This setup allows a theoretical lowest measurable T_e of 0.03 eV [11] and twice the number of acquired photons (limited, in our setup, by the numerical aperture of the optical fibers, 0.2). The wavelength resolution is 0.19 nm in FWHM for a slit width of 45 μm, optimized for the T_e measurement. The total reciprocal linear dispersion is 1.37 nm/mm, the practical lowest measurable T_e is about 0.05 eV [13] and the highest measurable T_e is 40 eV.

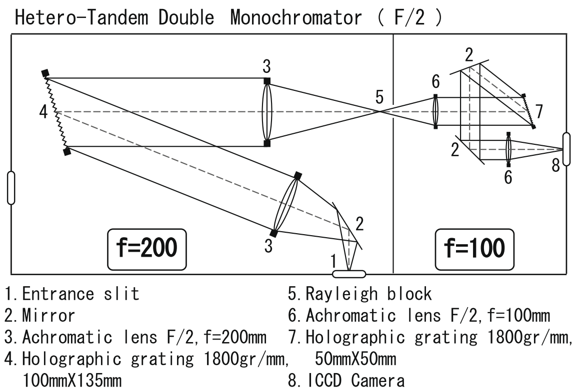

Fig. 1. Design of the upgraded double monochromator system (Hetero-Tandem Double Monochromator, HTDM).

It has been pointed out in Ref. [15] that possible effects leading to an error in the estimation of the parameters in a very low temperature plasma, such as plasma heating by high power laser absorption and photoionization of the excited states, are negligible. In particular, with regard to plasma heating, which is of more concern in the present experiment, the convex lens focusing the laser beam at the center of the plasma column has been replaced with a cylindrical lens of the same focal length, thus completely avoiding the problem.

A 1 m Czerny–Turner scanning monochromator with a 2400 grooves/mm holographic grating, which has a resolution of less than 0.03 nm in FWHM, was used for spectroscopic measurements. The monochromator was equipped with a Photo-Multiplier Tube (HAMAMATSU R928) for photon efficiency over UV and visible regimes.

Spectroscopic data were analyzed based on the Goto's CR model code [6], recently modified by Iida (for the application to MAP-II) in order to take into account the radiation trapping of the resonant states in Otsuka's formulation [7]. In recombining plasmas, the contribution to the excited state population from ground 1^1S, meta-stable 2^1S and meta-stable 2^3S states becomes negligible and only the contribution from the ionic state is necessary.

3. Experimental results and discussion

The lower electron temperatures accessible by means of the HTDM system allowed for the full investigation of the recombining front of the He EIR plasma. In our discharge conditions, the recombining front in the He discharge covers the cone-shaped ionizing plasma stream and is separated from it by means of a dark transition layer [13]. Starting from the tip (the brightest point) in the recombining front, its spatial profile for T_e and n_e along the magnetic field axis has been measured moving towards the colder and lower density plasma. This was possible by controlling the neutral pressure, increasing the gas puffing from the second chamber and thus moving the plasma towards the source across the laser beam. As already discussed in Ref. [13], the increase in the pressure mainly affects the ionizing region of the plasma column (dominated by electron elastic collisions with neutrals). The result is a simple translation of the recombination front.

A Baratron gauge in the first chamber was used to measure the neutral pressure. The discharge conditions were as follows: discharge voltage $V_{dis} = 64$ V and discharge current $I_{dis} = 30$ A with He as the fueling gas. The laser pulse energy was $P_{LAS} = 460$ mJ and the acquisition time was 30 min. The neutral pressure ranged from 13 to 28 Pa. In Fig. 2, LTS spectra for two different plasma conditions are shown.

In the same positions as the LTS measurements, spectroscopic data were acquired, by means of the Czerny–Turner spectrometer, between 330 and 390 nm. Among the He I ($n = 2$) series, the brightest $2^3P - n^3D$ and $2^1P - n^1D$ were used both for the Boltzmann plot and for the CR model fitting, including transitions from excited states with $9 \leqslant n \leqslant 16$. Atomic level populations were fitted against the excitation energy. From the slope, T_e was derived separately for the two above mentioned transition series. In Fig. 3, the Boltzmann plots for two different plasma conditions are reported.

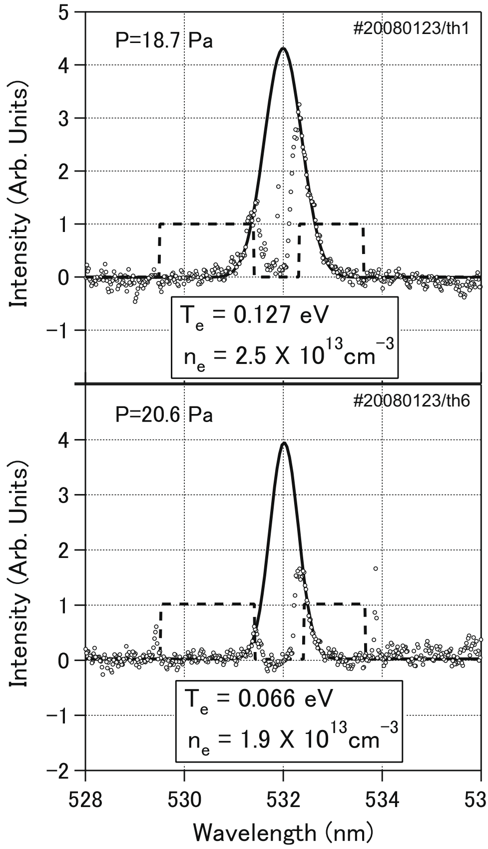

Fig. 2. Laser Thomson scattering spectra (circles) for neutral pressures of $P = 18.7$ Pa (top) and $P = 20.6$ Pa (bottom). In the same graphs the Gaussian fitting (solid line) and the fitting mask (dashed line) are reported.

It must be noted that in these relatively high neutral pressure conditions, radiation trapping may significantly modify the population of the resonant states. As suggested by Kado and Iida in Ref. [16], the measured ratio of the populations of the excited levels 3^1P and 4^1P was fitted by means of the CR model in order to determine the radiation trapping radius, L. The applicable regimes can be evaluated based on the CR model for a given neutral density. In ionizing plasmas, for $2 < T_e < 10$ eV, the ratio for 3^1P and 4^1P depends on n_e and L, while it exhibits almost no dependence on T_e. Therefore, using the n_e measured by alternative diagnostics, such as Langmuir probes or LTS, one can determine L from the measured intensity ratio of the ^{1}P series. This is also true for T_e below 0.2 eV. Therefore, the same scheme can be applied to the EIR regimes. Here it should be mentioned that the value of L loses its physical meaning and does not reflect the real absorption length since it is calculated assuming a constant spatial profile for the excited state population and the atomic temperature [7]. The fitting of the experimentally measured ratio for 3^1P and 4^1P in the EIR regimes (using T_e and n_e from LTS) showed that the effect of absorption of photons emitted from the recombining plasma column on the CR processes in the line-integrated observation chord is equal to that in the small region ($\leqslant 1$ cm) around the center of the plasma column having the uniform upper state population at 400 K. The fitting of Rydberg states for the singlet and triplet D series ($n = 9$—16) showed no difference whether using $L = 1$ cm or the conventionally used plasma column radius $L = 2.5$ cm, that was thus adopted in the fitting throughout the present experiment.

The main results of the experiment are summarized in Fig. 4 with the dependence on the neutral pressure. As shown in Fig. 4, LTS measurements could not be obtained in the highest pressure conditions due to the low n_e. The electron density was measured

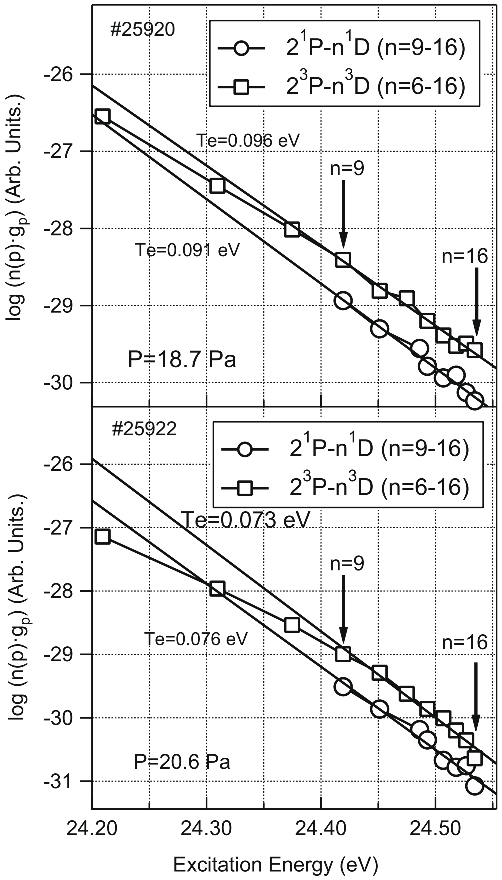

Fig. 3. Examples of Boltzmann plot (not divided by g_p) for neutral pressures of $P = 18.7$ Pa (top) and $P = 20.6$ Pa (bottom). The linear fitting of the Rydberg states $n = 9$—16 and the obtained electron temperature are reported on the graph.

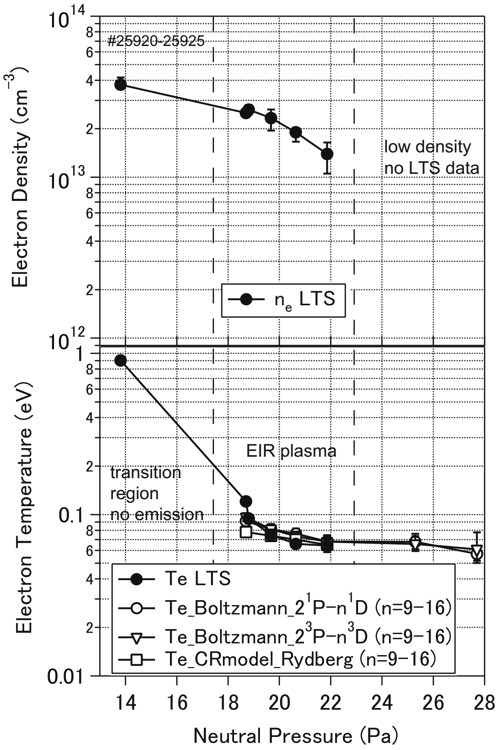

Fig. 4. Electron density and electron temperature profiles as a function of He neutral pressure in the following discharge conditions: $V = 64$ V, $I = 30$ A.

only by means of LTS. In the T_e plot, the values obtained by LTS, Boltzmann plot for $2^3P - n^3D$ and $2^1P - n^1D$ and CR model fitting for the Rydberg states are shown.

One data point from LTS was measured also in the transition region between the ionizing and recombining regimes at approximately 14 Pa. The absence of emission from the central point of the plasma column did not allow any spectroscopic measurement. The T_e was 0.9 eV, which is consistent with the values reported in our previous work in the same regimes [13].

As reported in Fig. 4, a decrease of n_e for increasing pressure due to both diffusion and volumetric recombination effect was observed. T_e decreases along the plasma column, mainly due to elastic scattering with ions and neutrals. In the brightest point of the EIR recombination front, LTS gives a T_e value of 0.12–0.13 eV, which is higher than those obtained by Boltzmann plot and CR model (0.08–0.09 eV). This may be due to the fact that the spectroscopic data are weighted by the emission intensity profile. The integration effect becomes less important moving along the plasma column, with all the diagnostics giving the same results, converging to a constant value at about 0.06–0.07 eV. Results from the Boltzmann plot also give the same T_e at 25 and 28 Pa. These results are also consistent with previous experiments in similar and lower density conditions which reported T_e values of 0.06 eV [7,4]. Since the same analysis scheme is applied over the whole data points from 0.9 to 0.06 eV, the reliability of such a low temperature measurement can be regarded as valid.

4. Summary and conclusion

We have developed an LTS system intended for the study of low temperature recombining plasmas. The development of the Hetero Tandem Double Monochromator allowed T_e measurement as low as approximately 0.05 eV. Electron temperatures in the He EIR regimes are confirmed to be about 0.06–0.07 eV, a value obtained also from Boltzmann plot and Collisional Radiative model fitting of the Rydberg states.

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