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On the determination of edge Ti profiles by a supersonic He beam in TJ-II

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ABSTRACT

In the present work, a new diagnostic for the simultaneous measurement of ne, Te and Ti profiles at the edge of a fusion plasma is proposed and tested. First, the propagation of a supersonic He beam is self-consistently simulated from the electron parameter profiles reconstructed from the line ratio method. The radial profile of excited HeII ions, measured simultaneously with the HeI lines, is then compared with the simulated profile and the total effective ion loss rate from the observation volume is deduced, which is function of Ti and the local plasma parameters. The values so obtained are normalized to those from passive CX measurements (NPA). Steeper gradients and lower values are found in the Ti profile compared to those in the Te profiles. The implication of these findings in ion transport at the edge of the TJ-II stellarator is addressed.

1. Introduction

Atomic beams from different sources have been traditionally used for edge characterization in fusion devices [1]. To date, they have provided information about electron density and temperature radial profiles. On the other hand, the toroidal dispersion of injected impurities has been analyzed in terms of local ion temperature and plasma rotation, but the electron parameter profiles need to be independently determined for the simulations [2]. More conventional methods for local Ti measurements, as passive Doppler-resolved spectroscopy or CXRS are of limited application to the edge region and are sensitive to other line-broadening mechanisms [3]. Moreover, electric probes such the retarding field analyzer (RFA) diagnostic are intrinsically perturbative if inserted beyond the LCFS. In the present work, a new potential diagnostic for the simultaneous measurement of ne, Te and Ti profiles at the edge of a fusion plasma is presented. It is based on the propagation of a supersonic He beam into the plasma edge. The simultaneous measurement of the radial profiles of excited HeI and HeII lines is simulated to provide ne and Te profiles from the line ratio method (HeI lines, [4]), thus allowing also for the estimate of the beam attenuation. The effective ion loss rate from the observation volume is then deduced from the continuity equation applied to the HeII profile. In the complex toroidal magnetic configuration of TJ-II, this method proves more reliable than the monitoring of toroidal dispersion, which was the diagnostic originally proposed for this type of analysis [5]. The values so obtained must be normalized to the central Ti values, obtained through passive CX measurements (NPA), or to Ti (a) values from the RFA diagnostic. Steeper gradients are found in the deduced Ti profiles compared to those in the Te profiles. The implications of these findings in ion transport at the edge of the TJ-II stellarator are addressed.

2. Experimental set-up

A brief description of the He beam is only given here as it has been done extensively in previous works [6,7]. The beam source consists of a fast-pulsed piezoelectric valve with a nozzle of 0.3 mm diameter and a parabolic profile skimmer with a diameter of 0.5 mm. For the experiments in TJ-II a nozzle-skimmer distance of 25 mm was chosen defining a divergence of 1.4. The mean beam velocity is 1500 m s^{-1} and the velocity distribution is defined by a speed ratio of 10–20, depending on the source pressure. The density of He atoms at the measurement region is estimated to be of the order of $<10^{11}$ cm^{-3}. The three He lines used for reconstruction of the edge temperature and density profiles (667.2, 706.5 and 728.1 nm) are simultaneously detected by means of a beam-splitter system and a set of three 16-channel photomultiplier arrays (Hamamatsu, model R5900U-20-L16) with interference filters (FWHM = 1 nm). The complete He emission profile is projected into the 16 channels of the array using a single lens with vertical displacements in order to match the region of interest. A typical toroidal resolution of 20 mm is given by a slit placed in front of the arrays and a radial resolution of 4 mm is chosen with a suitable object/image ratio to adjust the observation region to the different TJ-II plasma configurations. In the actual upgraded version of the supersonic helium beam a repetition rate up to 200 Hz can be achieved [7]. The pulse duration in the experiments was 1–2 ms and the He stagnation pressure was in the range 0.6–1.2 bar. The experimental set-up is shown in Fig. 1.

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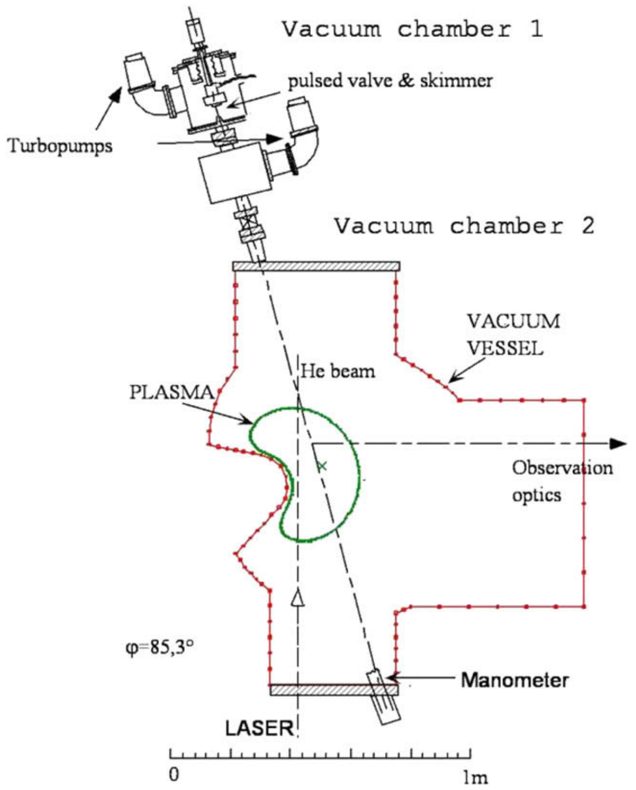

Fig. 1. Experimental set-up of the supersonic He beam in the TJ-II stellarator device. The laser (not used in the present experiments) can be crossed with the He beam for LIF measurements of excited He population (see 7) and validation of the CR model.

A Colisional Radiative (CR) model of emission intensities ratio is used in order to obtain diagnostic for the electron densities and temperature profiles. A set of differential equations provides the population of the levels that are included in the diagnostic [8]:

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = \left[\sum_{j\neq i}\langle\sigma v\rangle_{ji}n_e + A_{ji}\right]n_j - \left[\left(\sum_{j\neq i}\langle\sigma v\rangle_{ij} + \langle\sigma v\rangle_i\right)n_e + \sum_{j<i}A_{ij}\right]n_j. \quad (1)$$

In the steady state approach, the populations of the levels 3^1S, 3^1D and 3^3S are evaluated for a particular set of ne and Te values. The ratio of emission intensities from the two singlet levels, I ($\lambda = 667$ nm)/I ($\lambda = 728$ nm), provides a diagnostic for the electron density, while that from singlet D and the triplet, I ($\lambda = 728$ nm)/I ($\lambda = 706$ nm), provides a value of the electron temperature [8]. Electron density and temperature profiles, reconstructed from this comparison, are used in the simulation of the spatial distribution of the emission lines. Density profiles from some example shots are plotted in Fig. 2.

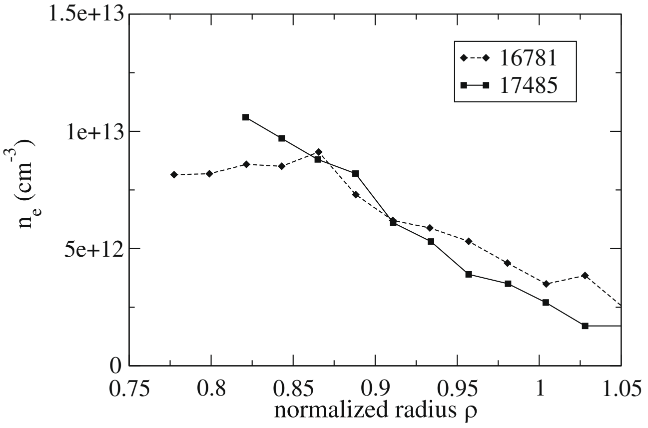

Fig. 2. Densities obtained from the intensity ratio CR diagnostic for the shots #16781 and #17485 (ECRH heating stage).

The central ion temperature of the plasma is obtained by two charge exchange neutral particle analyzers, NPAs. Both of them are Acord-12 [9] models that perform E||B analysis. Their lines of sight are perpendicular to the toroidal direction and can be varied poloidally to monitor different sections of the plasma to get the ion temperature profile in series of reproducible shots. Trapped particles are not expected to play any role in the interpretation of the NPA signal because of their collisionality ($\nu_i \approx 3.10^3\ \mathrm{s}^{-1}$ which gives $\nu^* = \nu_{ii}/\nu_{bounce} \approx 0.1$–1, being ν_{bounce} the bounce frequency).

3. Simple modeling of the He$^+$ radial profile

Simultaneously to the intensities of neutral He, the line of 468.6 nm corresponding to the transition between the levels $4^2F_{7/2}$–$3^2D_{5/2}$ of HeII is measured. A model of parallel transport of ions developed by Pitcher and Stangeby [5] is used in every radial position to rebuild the normalized intensity of this line. We use the assumption that the neutral He atoms are ionized and redirected along the magnetic field lines. The width of a pulse of ions diffusing in a magnetic flux tube is given by these authors as:

$$w(t) = w_0 + 2\left[\frac{\ln 2}{3}\right]^{1/2} c_{\mathrm{th}}\tau_{\mathrm{th}}g^{1/2}, \quad (2)$$

where w_0 is the initial width of the pulse, c_{th} is the thermal velocity, τ_{th} is the thermalization time and g is a function that depends on the time and the initial normalized temperature θ_0 of the **ions** in the pulse with respect to the plasma ions:

$$g(t) = \frac{t}{\tau_{\mathrm{th}}} - 2(1-\theta_0)[1 - e^{-t/\tau_{\mathrm{th}}}] + \frac{1}{2}(1-\theta_0)^2[1 - e^{-2t/\tau_{\mathrm{th}}}]. \quad (3)$$

Here, the typical values are $\theta_0 \approx 10^{-4}$ and thermalization times of $\tau_{\mathrm{th}} \approx 10^{-4}$ s depending of the ionic temperature.

The density of a pulse of ions of flux $\dot{N}$ (s^{-1}) released into a magnetic flux tube will be:

$$n = \frac{\dot{N}}{2A}\int_0^\infty \frac{e^{-t'/\tau_i}}{w(t')}\mathrm{d}t', \quad (4)$$

where A is the sectional area of the tube and τ_i is the ionization time obtained from:

$$\tau_i = \frac{1}{n_e\langle\sigma v\rangle^i_{\mathrm{HeII}}}. \quad (5)$$

Here, n_e is obtained from the CR model and $\langle\sigma v\rangle^i$ is given by [10]. This model has been applied for ionic temperature estimates through the monitoring of the ion emission along the toroidal coordinate in tokamaks. However, the twisting of the field surfaces in the magnetic configuration of the TJ-II stellarator, together with the restricted optical access in toroidal direction makes this diagnostic difficult to implement. Nevertheless, if we take into account the simple assumption that in each radial position the source He$^+$ ions is:

$$\frac{\dot{N}}{2Aw_0} = \frac{\mathrm{d}n}{\mathrm{d}t} = n_{\mathrm{HeI}}n_e\langle\sigma v\rangle^i_{\mathrm{HeI}}, \quad (6)$$

where n_{HeI} is the neutral helium stationary density and the rate coefficients has been obtained from the tabulated ones at [11], then it is possible to evaluate the radial profile of HeII density in terms of their characteristic diffusion time out of the observation volume. A simple balance equation from the radial density and temperature profiles plus the rate coefficient for HeII ($n = 4$) excitation [12] gives the intensity profile of the line $\lambda = 468.6$ nm. Competing processes as ionization from $n = 4$ level or direct excitation to the observed state from neutral He have been checked and dismissed in comparison to the proposed mechanism. Unless absolute calibration of the relevant magnitudes involved is available (photon flux, initial He density or full toroidal profile), an absolute value of the ionic temperature in some part of the profile must be known in order to normalize the reconstructed Ti profile.

4. Results

Measured normalized intensities are presented in Fig. 3 for some example shots in the ECRH heating phase. Plasma parameters are indicated in the corresponding captions. The attenuation of the He beam by the plasma is:

$$n_{\text{He}}(x) = n^0_{\text{He}} \exp\left[-\frac{x}{\lambda_{att}}\right] \qquad (7)$$

where the value $\lambda_{att} = \frac{v_{\text{HeI}}}{n_e \langle \sigma v \rangle^i_{\text{HeI}}} \approx 2$ cm is given by the experimental results and x is the radial coordinate along the penetration of the beam in the plasma. It must be pointed out here that a full collisional-radiative model of HeII excitation must be developed in the future in order to improve the accuracy of this simplified model. The corresponding Te (from the CR model) and preliminary results for Ti profiles are plotted in Figs. 4 and 5.

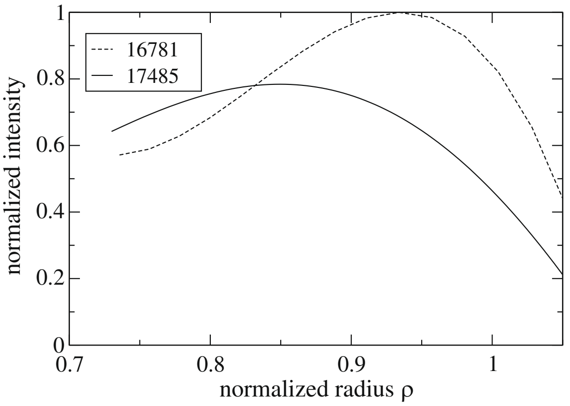

Fig. 3. Normalized intensities from HeII obtained for the two shots of Fig. 2.

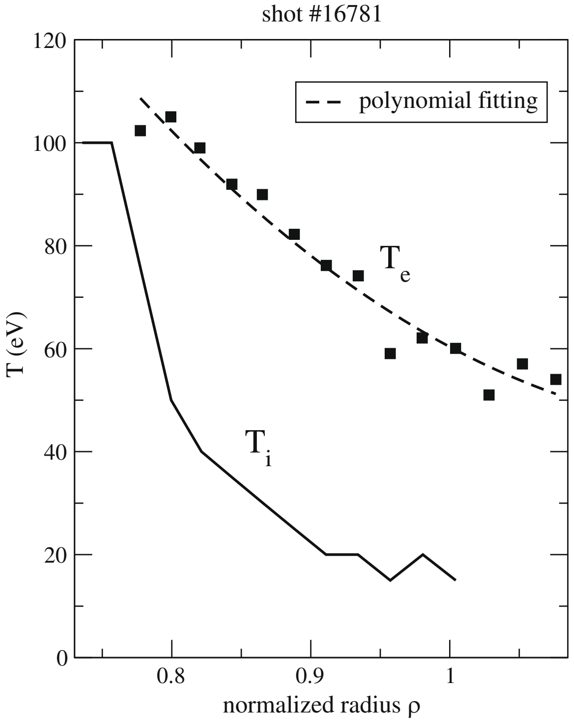

Fig. 4. Radial electronic and ionic temperature profiles for the shot #16781: $\langle n_e \rangle = 8.10^{18}$ m^{-3}, Ti (0) = 100 eV, coating: Li. The polynomial fitting for Te used in the calculation is also shown.

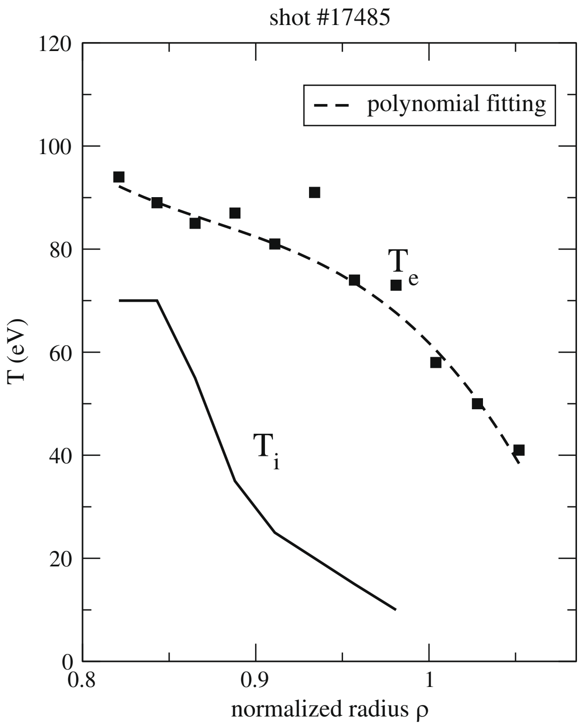

Fig. 5. Radial electronic and ionic temperature profiles for the shot #17485. <ne>= 6.2 10^{18} m^{-3}, Ti(0)= 90 eV, coating: B. The polynomial fitting for Te used in the calculation is also shown. The Ti values have been normalized to the value at $r/a = 0.83$ inferred form the NPA data.

Convergence of the model has been tested with different similar choices of the initial Ti value to check that similar profiles where obtained from the reconstruction of the normalized intensity. The Ti profiles have been cross-checked with the data from CXRS measurements where available and good agreement has been obtained [13]. So, values of ∼50 eV at $r/a = 0.8$ were measured by CXRS at electron densities of 0.9.10^{19} m^{-3}. Errors from the limited S/N ratio of the data are roughly estimated to be around ±10 eV from a preliminary parameter analysis. However, those associated to the model itself, are hard to evaluate until the C-R model for the recorded emission is developed.

5. Discussion and conclusions

Even when only a preliminary version of the technique is shown in the present work, the systematic trend of the results obtained here make them worth some comments. First, it should be pointed out that consistent profiles are obtained when the initial guess of the central Ti value is varied, so that we can conclude that steep, fast decaying Ti profiles seem to exist in TJ-II edge, with values of 10–20 eV at the LCFS. The fact that these values are as much as a factor of 3 lower than the electronic temperature must be understood from their different transport characteristics in the ECRH, low-density plasmas of TJ-II. Two main contributions are expected to contribute for comparative cooler ions. First, ion transport is characterized by larger orbits than electrons at the same temperature, thus comparatively worsening their confinement properties and leading to the development of negative electric fields at the edge [14]. Secondly, neutral hydrogen concentration at the periphery is maximal and enhanced charge exchange losses will contribute as a further ion energy loss channel.

Thus, in conclusion:

- An upgraded version of pulsed supersonic He beam with a high repetition rate has been implemented in TJ-II as a complete diagnostic for plasma edge. The self-consistency of the C-R model used in the profile reconstruction, which includes reproducing the attenuation pattern of the He beam, has been used for improved reliability of the results.
- A potential new diagnostic for edge ion temperature in fusion plasma has been developed. The modeling of parallel transport of injected impurities, describe in [9], was adapted to rebuild the normalized HeII radial profiles. Yet, a full collisional-radiative model of HeII excitation must be implemented in the future in order to improve the accuracy of the model.
- The deduced Ti values are systematically lower of than the corresponding Te at the same location in TJ-II. Larger ion transport losses and local CX processes are claimed for this finding.

Acknowledgment

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