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First EIRENE modelling of a He plasma. Simulation of emission profiles in a TJ-II ECRH plasma

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Introduction

The emission profiles of the three neutral He lines typically used in the supersonic He beam diagnostic were recently recorded in ECRH helium plasmas of the TJ-II stellarator, with minor contamination from H [1]. In the present investigation the Eirene code [2], which we had previously adapted to the fully 3D TJ-II geometry, has been used for the first time to obtain He emission profiles, and its predictions have been compared with the line integrated values measured at the plasma edge. While the central values of the density and temperature profiles corresponding to the Thomson Scattering data for the analysed discharges have been used in the simulation, some freedom on the corresponding values at the edge has been allowed, and the values measured in similar H plasmas by the supersonic He beam have been used as starting guess. For these simulations the original Eirene default set of reactions has been completed with the He emissivities at the selected wavelengths and with CX processes for He.

Experimental input

The relative He emissivities for the 667 and 728 singlet and the 706 nm triplet lines from the $n = 3$ excited He atoms were measured in a purely ECRH helium discharge with boronised wall. These measurements were line integrals along 13 peripheral chords, 6 of which we have used in the simulation (Fig. 1). As no absolute values were known in this phase, for the initial comparison with the Eirene calculations we have taken the ratio of all the signals (18 in total) to the 728 line corresponding to the first chord, the most internal one.

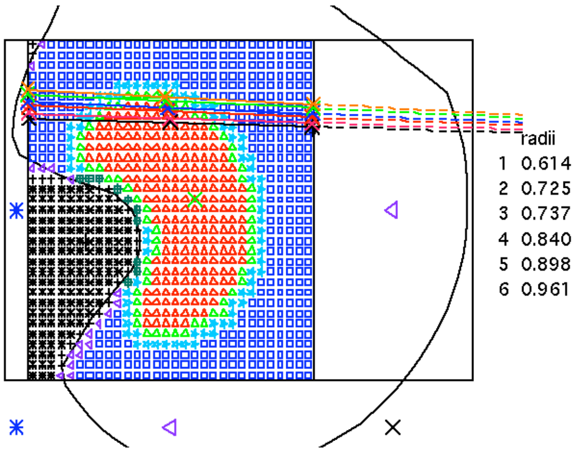

Figure 1: Poloidal section of the grid used for Eirene, with the 6 peripheral chords used in the Eirene simulation.

For the electronic density and temperature radial profiles (Fig. 2) we have basically used the symmetrised and smoothed Thomson scattering profiles [3]. Near the border these profiles have been complemented with data taken from the He beam for a similar hydrogen discharge. The values at the border were $n_e = 1.2^{+0.4}_{-0.4} \times 10^{18}$ m^{-3}, $T_e = 37^{+6}_{-9}$ eV. For T_i, which was not measured, we have estimated 80 eV at the center and 25 eV at the border.

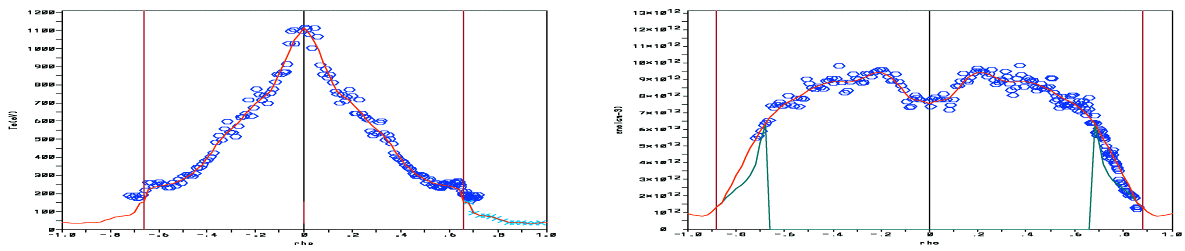

Figure 2: T_e (left, vertical scale from 0 to 1200 eV) and n_e (right, vertical scale from 0 to 13×10^{18} m^{-3}) radial profiles. Between the red vertical bars they are the symmetrised and smoothed Thomson scattering profiles. Beyond, the data are taken from a different, hydrogen discharge.

Eirene simulations

In the simulations with Eirene 9.6 million trajectories of neutral He atoms were followed. This large number was chosen in order to attain a statistical uncertainty not higher than 3% for the line ratios (most of the other results have an uncertainty level of half that value). One single run takes around 15 minutes with 24 processors on the Altix-3700 computer at Ciemat.

The source for the neutrals is located on the vacuum vessel wall and the two limiter surfaces. They are produced by the impact of He ions which escape the plasma. The energy of these ions is calculated by Eirene assuming a drifting Maxwellian flux with an average energy equal to $3T_i + 0.5T_e$, of which $2.5T_i$ is thermal and $0.5T_i + 0.5T_e$ is in the directed motion, and taking into account the effect of the sheath potential acceleration [2]. These ions are reflected at those surfaces and, in the Eirene model, are immediately neutralised, giving rise to He atoms. The trajectories of these atoms are followed while they collide and react with other particles and are reflected, reemitted or absorbed by the different surfaces. The trajectory tracking ends when the atom is ionised or absorbed. To manage all these processes we have used the Eirene default set of reactions, with inclusion of the He emissivities at the selected wavelengths and the charge exchange processes for He [4], as well as the reflection and thermal surface models of the TRIM database [5] [6]. In the calculations all the walls were assumed to be boronised.

In order to find the Eirene parameters that produce results closer to the experimental data, it is necessary to run the code repetitively many times using some minimization process. But since it would be extremely costly to perform such a minimization search blindly, involving a large number of parameters over large variation ranges, we previoulsy make scans of parameters in order to show trends or to reveal the sensitivity to variation of the different parameters. This means that the full finding process can take a lot of computer time, days in fact. For example a scan on a single parameter for 25 points takes more than 6 hours in the same Altix computer.

From the start it was clear that the line ratios were very insensitive to most of the model parameters (wall and limiter surface temperatures, ion temperature, etc.). Instead the results were very sensitive to the shape of the density and temperature profiles near the border. Also, but in a much lesser measure, some dependence was observed with respect to the relative population He^+/He^{++}. Hence, the optimization was mostly centered in modifying the shape of the plasma profiles, although even with the unmodified profiles, the agreement between the measurements and the Eirene results was quite good, with a maximum difference of -28.7% (Fig. 3, left). The change of profiles near the border is made by substituting a certain polynomial for the original profile beyond a certain value of r/a. The results for the best fit are shown in Fig. 3, right.

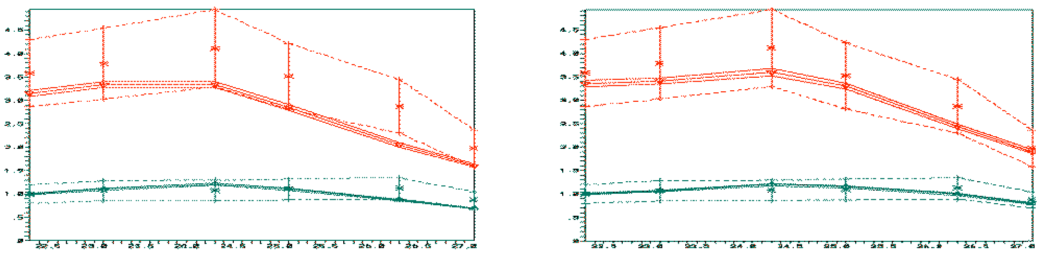

Figure 3: Emission profile rates for the 667 line (red) and the 728 line (green), obtained dividing the emission profiles by the 728 emission at the innermost chord (left end of the abscissas axis). The plots on the left correspond to the unmodified plasma density and temperature profiles, and those on the right to the plasma profiles modified to obtain the best fit. The discontinuous lines mark the $\pm 20\%$ experimental error limits, and the continuous ones correspond to the $\pm 3\%$ statistical uncertainty of the Eirene results. When the continuous band is fully contained inside the discontinuous one we consider that the optimization has been achieved. With the unmodified plasma profiles the maximum difference between the measured emission rate and the calculated one for each of the three lines is -28.7% for the 667 line (red), -21.9% for the 706 line (not shown), and -12.9% for the 728 line (green). With the optimized plasma profiles the corresponding values are -15.0%, +15.3%, and -11.4%.

In a second phase of the calculations we have determined the absolute calibration of the 667 nm line and added this absolute value of emissivity as a supplementary parameter to adjust, with an estimated uncertainty of $\sim 50\%$. For the former optimal fitting, the discrepancy of the absolute emissivity is -19.4%, well inside the uncertainty range. Nevertheless we can modiy the value of the particle confinement time τ_p, experimentally estimated at $\tau_p = (7 \pm 2)$ ms, from 7 to 5.6 ms, so that the absolute emissivity value is exactly matched. As the relative emissivity rates remain invariant when changing τ_p, the results obtained previously remain unchanged. The final set of parameters adopted is: $n_e(a) = 1.09 \times 10^{18}$ m^{-3} ($\pm$8%), $T_e(a) = 41$ eV ($\pm$4%), $T_i(0) = 80$ eV ($\pm$24%), $T_i(a) = 25$ eV ($\pm$32%), He$^+$/He^{++} = 90% ($\pm$10%), $\tau_p = 5.6$ ms ($\pm$20%).

For this optimal set of parameters, Fig. 4, left, shows the n_{He} radial profile inside the plasma (red line; the blue and green lines are exponential fits). For this profile $n_{He}(a) = 9.3 \times 10^{16}$ m^{-3}, $n_{He}(0) = 1.8 \times 10^{15}$ m^{-3}, $n_{He}(0)/n_{He}(a) = 51$, penetration length = 2.9 cm. Fig. 4, right, shows the n_{He} distribution along the most external chord. n_{He} is minimum (8.5×10^{16} m^{-3}) at the point of plasma contact and maximum (2.2×10^{17} m^{-3}) near the vacuum vessel.

In all the torus the neutrals have an average density $\langle n_{He} \rangle_{\rm tot} = 1.25 \times 10^{17}$ m^{-3} and an average energy $\langle E_{He} \rangle_{\rm tot} = 1.5$ eV. Thus, the bulk of the neutrals constitute a cold cloud surrounding the plasma. Inside the plasma $\langle E_{He} \rangle_{\rm plasma} = 8$ eV, and along the magnetic axis $\langle E_{He} \rangle_{\rm axis} = 83$ eV.

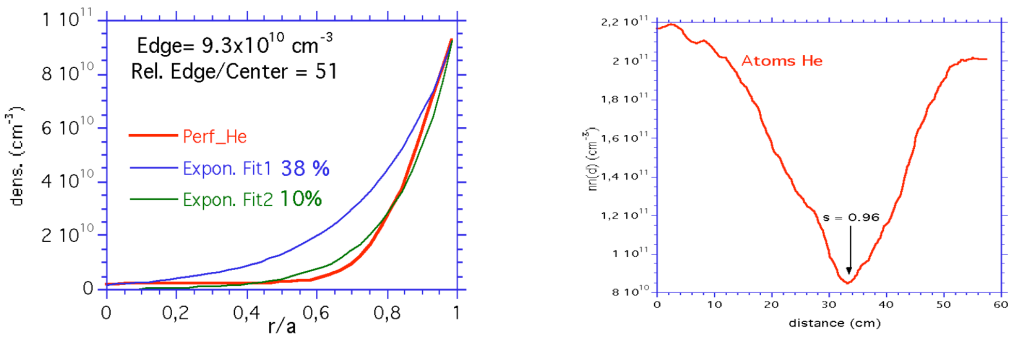

Figure 4: Neutral density profiles: radial profile inside the plasma, averaged over each magnetic surface (left); distribution along the 6$^{\rm th}$ chord, the most external one (right).

Conclusions

A search for the Eirene parameters that produce agreement between the experimental data for three He emission lines in TJ-II has been carried out. Absolute calibrated emissivity values, as well as signal ratios, have been used in the fits. The most sensitive parameters correspond to the shape of the radial profiles near the plasma border. Optimal values, well within the experimental error limits and the Monte Carlo statistical uncertainty, have been found (maximum difference 15%, average 9%), and the corresponding neutral profiles have been obtained and analysed.

References

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