29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. ***26B****, P-4.048 (2002)*

Measurements and Modelling of Neutral Helium Populations on the Actively Cooled Modular Limiter of Tore Supra

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The behaviour of helium, and in particular its recycling on the plasma facing components, is an issue for future fusion devices such as ITER. A spectroscopic line of sight with a perpendicular view of the new actively cooled limiter surface has been used for He recycling studies on Tore Supra (TS). The line of sight is connected to a high resolution visible spectrometer with typical space and time resolutions of 10 cm and 100 ms, respectively. The spectral profiles of several He I transitions indicate the existence of at least two atomic populations, whose origin is discussed. The line ratios are compared to 1D modelling predictions in order to estimate the plasma edge electron density and temperature in a series of He discharges, with a density ramp between two stationary density phases.

1. Characteristics of the neutral helium populations.

Three observed line spectra are shown in Fig. 1. Reflections at Brewster angle of the incident light on two successive mirrors change the line shape from the usual Zeeman pattern to the shape shown on Fig. 1 due to partial suppression of the π components. This effect is taken into account in the following.

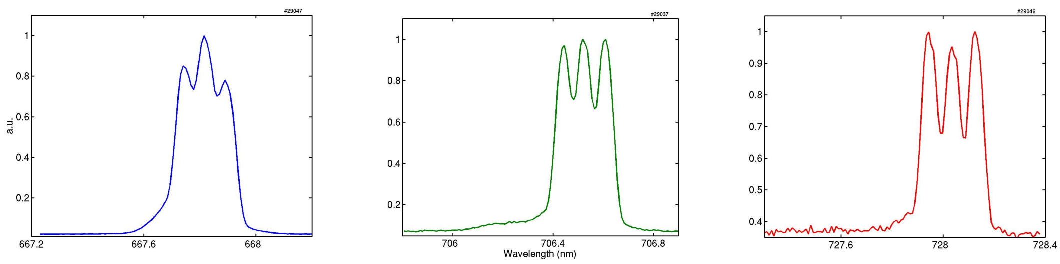

Figure1: Experimental He I spectra observed on the limiter (left) 6678.1 nm, 2p $^1P^0$ - 3d ^1D, (center) 706.5 nm, 2p $^3P^0$ - 3s ^3S, (right) 728.1 nm, 2p $^1P^0$ - 3s ^1S. The Zeeman effect is distorted by reflection at an angle close to Brewster

The first expected neutral helium population is that of cold atoms desorbed at thermal energy (0.05 eV in the present case) with a narrow velocity distribution function. This population will give rise to a Zeeman pattern of features with a FWHM close to the Gaussian instrument function width. However, as can be seen on Fig. 1, in addition to these partly resolved Zeeman patterns all lines exhibit an extended blue wing particularly clear in the case of the 3s $^3S \rightarrow$ 2p ^3P transition at 7065 Å. It has been checked that no species other than He I can be the emitter of such features, which indicates the existence of more than one He atom population. Direct

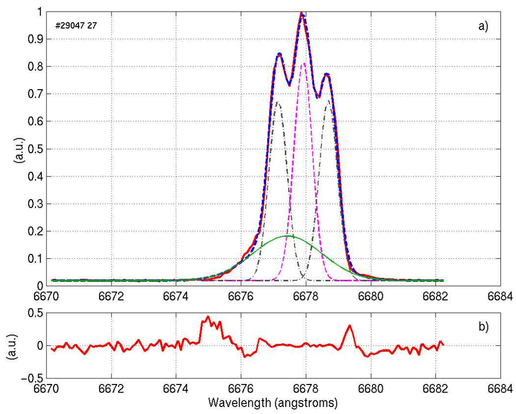

Figure 2: (top) an experimental spectrum (in red) with the fitted sum of Gaussians (dashed blue): a cold triplet (dashed lines) and a blue shifted component (green) ; (bottom) residue

reflection of light on the CFC tiles of the limiter can be ruled out because this process would have no effect on the wavelength.

In the following we fit to the experimental spectra a sum of three Gaussian curves for the resolved Zeeman triplet and a fourth Gaussian for the additional feature, assuming that only two He atom populations are present. In the case of the 3s $^3S \rightarrow 2p\ ^3P$ transition we take into account the fine structure of the atomic levels. It is found that for all spectral lines the width of the narrower pattern is too close to the instrument function width to estimate the corresponding energy distribution width, thus indicating a temperature lower than 1000 K. This confirms the presence of the desorbed population. In the following we use the central position of this narrow pattern as the wavelength reference. It must be kept in mind that the choice of a Gaussian curve to fit the broad feature is arbitrary as long as we do not know its physical origin (in particular, the broad feature is expected to be Zeeman-splitted; it will be taken into account in our future studies). And indeed, the broad feature wings are not exactly fitted by a Gaussian, as illustrated in Fig. 2. The figures quoted in Table 1 should thus be taken with care. The width and the wavelength shift of the broader feature depend very much on the considered transition. The results of the fitting procedure for two spectral lines (2p $^1P^0$ - 3d ^1D at 6678.15 Å and 2p $^3P^0$ - 3s ^3S at 7065.19 Å) are shown on Table 1 as a function of $\langle n_e \rangle$.

$\langle n_e \rangle$ (10^{19} m^{-3})	E_{eV} (6678 Å)	$FWHM_Å$ (6678 Å)	E_{eV} (7065 Å)	$FWHM_Å$ (7065 Å)
1.5	28 ± 12	1.95 ± 0.5	294 ± 40	1.6 ± 0.5
2	17	1.65	284	1.5
2.5	10.5	1.55	96	2.7
3	8.9	1.5	96	2.65
3.2	8.5	1.5	96	2.65

Table 1: Dependence on $\langle n_e \rangle$ of the mean kinetic energy (E_k) and the FWHM of the second population deduced from the wavelength shift and the width of two observed transitions.

The uncertainties are due to the fitting procedure as much as to the variations between successive spectra. They are estimated to be 0.2 Å for the position and 0.5 Å for the width. The statistical error is negligible due to the strong intensity of the observed lines in the cases presented here. It can be seen on the table that the mean kinetic energy for both lines tend to decrease when the density is increased. Note the surprisingly high kinetic energy corresponding to the transition at 7065 Å. The relative contribution of the broad feature compared with the "cold" triplet increases with $\langle n_e \rangle$ in the case of the 6678 Å line, whereas the effect is less obvious for the 7065 Å line. The use of lower hybrid power roughly doubles the broad feature contribution. There are also indications that the D content of the wall influences the broad feature relative intensity.

A possible explanation is the existence of a population of fast reflected atoms. The contribution to the He I spectrum due to reflected particles has been simulated with the BBQ scrape-off layer impurity transport code [1]. Using a model for the limiter geometry the code calculates the physical- and velocity-space distributions of neutral helium. The incident

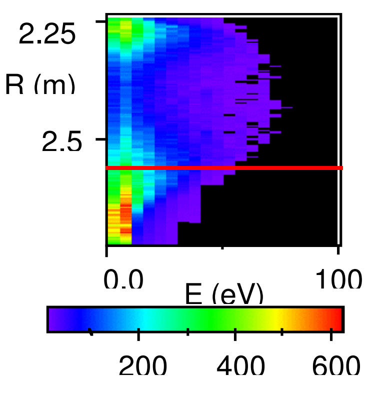

Figure 3: Kinetic energy distribution of reflected He atoms calcualted by BBQ-TRIM; color scalestands for number in population

He^+ distribution, an input to the calculation, results from use of the CASTEM-2000 [2] results for the distribution of incident flux on the limiter surface, which is then mapped to the BBQ grid. The reflected fraction is then calculated using the TRIM database [3]. The He I velocity space distribution is shown as a function of major radius in Fig. 3, in which the density is averaged over the toroidal direction. A relatively high energy component (10-50 eV) can be seen at the major radius corresponding to the spectroscopic line of sight (indicated by a red line on Fig. 3). However, a dependence of the energy and particle reflection coefficients on the reflected atom excitation state is not predicted. Another explanation would be the charge exchange (CX) reaction $He^+ + D^0 \rightarrow He^* + D^+$, which is expected to depend on the final excitation state and also on T_e; the difference in the measured widths could then be explained. As for the wavelength shift, the CX He atoms are produced with an isotropic velocity distribution but those with a velocity directed toward the limiter have a lower photon emission probability due to their short lifetime, hence a possible blue wavelength shift. A mixed explanation can be given, in which fast reflected He atoms are ionised further in the plasma and enhance the CX contribution. Unfortunately, at the moment there are no data describing the He^+-D^0 CX process at thermal energies.

2. Measurements and modelling of the line brightness ratios

A technique commonly used to measure the electron density and temperature is based on the observation of three He I lines (667.8 nm, 706.5 nm and 728.1 nm) emitted by a He atom beam [4]: the 728.1 nm to 667.8 nm and 728.1 nm to 706.5 nm emissivity ratios are sensitive to n_e and T_e, respectively. No n_e or T_e measurement being available on the limiter, and no He beam being available on TS, we have tried to use the corresponding brightness ratios to obtain estimates of these quantities. Although the characteristics of the broad feature are not known precisely, it is possible to subtract its contribution from the measured spectra to obtain the absolute brightnesses emitted by the desorbed atoms and their ratios with an uncertainty below 5% (Fig. 4). The first ratio decreases slightly when $\langle n_e \rangle$ is increased, indicating a possible increase of the edge density. The second ratio decreases by a factor of 2 on the experimental $\langle n_e \rangle$ range, which corresponds to a T_e decrease.

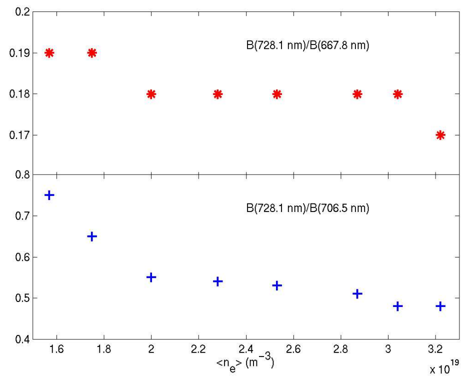

Figure 4: Measured brightness ratios

In order to evaluate n_e and T_e from the line brightness ratios we have built a 1D fluid model which calculates self-consistently the edge values of n_e and T_e and the He I line brightnesses ratios. The n_e profiles inside the last closed flux surface (LCFS) are constructed using the interferometric measurements along a set of vertical chords, the measurements of a reflectometer in the midplane and of a reciprocating Langmuir probe at the top of the plasma. We kept in mind that, at the edge, the electron density is undoubtedly poloidally asymmetric because of the limiter. The density at the limiter n_e^{lim} is a free parameter. For T_e, we use ECE measurements and again the T_e value at the limiter T_e^{lim} is a free parameter. The kinetic energy distribution function of the helium atoms is assumed to be a Maxwellian, whose mean W and width ΔW are adjusted by hand (in the present study $0.05 < W < 0.3$ eV and $0.01 < \Delta W < 0.1$ eV). Using the ADAS [5] collisional-radiative coefficients, we calculate the radial atom penetration profile neglecting recombination and we deduce the radial emissivity profile for the transitions of interest. Note that, with the assumption that the singlet and triplet populations are completely decoupled, it was impossible to reproduce the experimental B(728.1 nm)/B(706.5 nm) brightness ratio because of the short triplet population decay length (except by assuming a factor of 4 increase of the triplet population relatively to the singlet). The emissivity profiles are then integrated along the line of sight to obtain the brightnesses. For the tested energy distributions and the experimental $\langle n_e \rangle$ values, n_e^{lim} and T_e^{lim} are adjusted so that the modelled brightness ratios match the measured ones.

As expected, the modelled n_e^{lim} and T_e^{lim} values are found to decrease when the atom energy is increased. In all cases these values are significantly higher than the corresponding reciprocating Langmuir probe measurements (see Fig. 5). As far as n_e is concerned this can be explained by the proximity of the limiter on which most of the particle production (D recycling and impurities) and ionisation take place. It should be added that not only the Langmuir probe diagnostic but also possibly the reflectometric measurements cannot be used directly to reproduce the density profiles on the limiter. This problem might be solved in the next campaign, for which pop-up probes have been installed on the limiter surface. As for the temperature the high values might indicate the existence of a non thermal electron population, a hypothesis supported by the enhancement of the energetic atomic population during LH power injection. A modification in the triplet to singlet equilibrium balance would allow for the simulation to fit the data. Note also that a measurement of the wavelength of the spectral feature emitted by desorbed atoms would improve the accuracy of the model predictions.

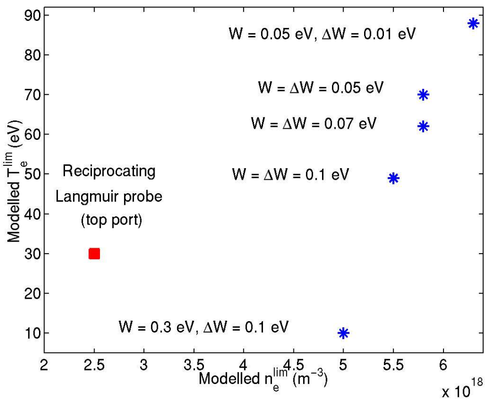

Figure 5: modelled n_e^{lim} and T_e^{lim} as functions of the energy distribution parameters

Conclusions

Production of fast helium atoms has been observed on the modular version of the actively cooled limiter of Tore Supra. These atoms leave the limiter surface with a mean velocity of 20 to 200 eV which indicates that it may come from He^+ ion reflection on the limiter. The fast atom energy distribution depends on the atomic excitation state, an indication that charge exchange is also involved. Systematic experiments are needed to improve our knowledge of the phenomenon, in particular to address the role of the wall content in the broad feature behaviour, a hint to the link between the wall status and He recycling.

The visible emission of the thermally desorbed atoms has been used to gain some information on n_e and Te at the plasma edge. A 1D model shows that the brightness ratios can be used to estimate n_e and T_e 2 to 3 cm outside the last closed flux surface. The modelled n_e values on the limiter are larger (by a factor 2 to 3) than the coresponding reciprocating Langmuir probe at the top of the plasma, pointing to the need for a dedicated n_e and T_e diagnostic on the limiter. The modelled T_e^{lim} values are also higher than the expected ones, due either to an incorrect triplet-singlet population equilibrium or to a non-thermal electron population.

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