ELSEVIER

Journal of Nuclear Materials 241–243 (1997) 528–531

journal of nuclear materials

Effect of magnetic field stochastization on impurity behavior in a tokamak

M.Z. Tokar' [a,*], H. Lasaar [b], W. Mandl [c], W.R. Hess [c], C. De Michelis [c], A. Grosman [c], U. Samm [a]

[a] *Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, Ass. Euratom-KFA, P.O. Box 1913, D-52425, Jülich, Germany*
[b] *Heinrich-Heine-Universität, Düsseldorf, Germany*
[c] *Ass. Euratom-CEA sur la Fusion, DRFC / SPPF-Centre d'etudes de Cadarache, St-Paul-lez-Durance, France*

Abstract

Magnetic field stochastization at the plasma edge in Tore-Supra with the ergodic divertor (ED) results in a significant reduction of the impurity concentration and a simultaneous increase of the edge radiation. This behavior is modelled by the codes RITM and CNET by taking the enhancement of the energy and particle transport with ED into account. A qualitative explanation of the influence of stochastization on different charge states of impurities is proposed.

Keywords: Tore Supra; Ergodic divertor; Impurity transport; Impurity radiation; 1D model

1. Introduction

Enhancement of the particle and energy transport by the magnetic field stochastization at the plasma edge should lead to a reduction of the impurity content in tokamak plasmas. On the one hand, impurity ions generated by ionization of atoms released from the walls leave more promptly the plasma [1]. On the other hand, recycling of main particles increases as well [2] and this leads to a decrease of the edge plasma temperature [3] and of the wall erosion by physical sputtering [4].

Experiments on Tore-Supra with the ergodic divertor (ED) confirm such expectations. The measurements [5–7] demonstrate that activation of the ED leads to a significant diminution of the concentration of intrinsic impurities (carbon, oxygen, iron). Conversely, the impurity radiation from the plasma edge is enhanced noticeably [5,6].

These findings manifest that stochastization acts differently on the charge states which make the main contribution to the total impurity density (nuclei, H- and He-like particles) and on ions which contribute dominantly to the edge radiation (Li-like and lower ionized ions). Such a selective effect on impurities of different charges has been demonstrated directly by spectroscopic measurements of line radiation from carbon ions [8,9].

An interpretation of these experimental results is of importance for a deeper understanding of mechanisms of impurity behavior and for optimization of the methods to control this behavior in thermonuclear devices. In this paper the results of a one-dimensional modelling of the plasma and impurity transport in Tore-Supra with and without ED are presented. This modelling is done by the numerical codes RITM and CNET, which are described in the next section. Section 3 is a comparison between numerical simulations and experimental results. A qualitative interpretation of the influence of stochastization on impurity ions of different charges is proposed in Section 4.

2. Numerical models

2.1. Code RITM

The influence of stochastization on transport processes requires a coherent approach to modelling. Such an approach underlies the transport code RITM [10] which

* Corresponding author. Tel.: +49-2461 612 784; fax: +49-2461 612 970.

PII S0022-3115(96)00558-2

describes self-consistently changes in transport coefficients, the effect of impurity radiation on the electron heat balance and dilution of the ion component. RITM solves time-dependent one-dimensional equations for the radial variation of the densities and temperatures of neutral and charged particles inside the last closed magnetic surface (LCMS). Without the ED the LCMS is determined by the position of the limiter and with ED — by the inner border of the 'laminar' layer (where the lines of force can hit the wall elements). Impurities are described in a non-corona approximation taking into account ionization, recombination, charge-exchange with hydrogen neutrals, anomalous diffusion and neo-classical convection. The boundary conditions at the LCMS prescribe the percentages of molecules and atoms in the hydrogen neutral influxes, their velocities, the influxes of impurity neutrals, e-folding lengths of densities and temperatures of charged particles.

2.2. Code CNET

The code CNET [8] solves the transport equations for impurity ions for prescribed profiles of the plasma parameters (for the present calculations the profiles of the electron and ion densities and temperatures found by RITM were used). As distinct from RITM a detailed collisional radiative model for transitions in carbon ions is incorporated in CNET, which allows to compare the results of calculations with the data of spectroscopic measurements.

2.3. Transport coefficients

Without ergodic divertor in ohmic discharges the particle and electron heat diffusivities are modelled by the Alcator-like scaling: $D_\perp = A_D/n_e$ and $\chi_\perp^e = \alpha_\chi D_\perp$, respectively. The parameters A_D and α_χ were determined from the comparison of measured and calculated particle and energy confinement times. The pinch velocity of the main ions is defined by the relation $V_\perp = \alpha_V D_\perp r/a^2$ with α_V chosen to reproduce the experimental peaking factor of the electron density n_e; for impurities $V_\perp$ is calculated from the neo-classical theory [11]. For additionally heated plasmas $\chi_\perp^{e,i}$ are determined from the Rebut-Lallia model [12] and $D_\perp$ is the OH scaling increased up to Bohm diffusion at the plasma edge [10].

The transport coefficients with ED are calculated on basis of the physical picture proposed in Refs. [5,13,14]. The following general formula has been found for the effective heat and particle diffusivities across the stochastic layer:

$$\left\{\begin{matrix} \chi_\perp^{eff} \\ D_\perp^{eff} \end{matrix}\right\} \approx \left\{\begin{matrix} \chi_\perp \\ D_\perp \end{matrix}\right\} \cdot \left[1 + \sqrt{\frac{L}{L_c}} \cdot \exp\left(\frac{2L}{L_c}\right)\right] \qquad (1)$$

where L is the characteristic dimension of the corresponding parameter (temperature, density) change along the line of force and L_c is the length of correlation between the components of the magnetic field perturbation.

In the case of the heat transport L is determined by the equation $\exp(2L/L_c) = \chi_\parallel/\chi_\perp \cdot D_{Fl}/(L + \chi_h)$, with $\chi_\parallel$ being collisional heat diffusivity [15], D_{Fl} the diffusivity of magnetic field lines, and χ_h the path length between Coulomb collisions of electrons which carry heat. For $\lambda_h = 0$ these formulas recover in principle details the results of Refs. [5,13]; distinction of λ_h from zero takes into account non-local effects in the parallel heat transport [16] which are important for λ_h comparable with L_c. For typical magnitudes of parameters this correction leads to reduction of χ_{eff} by an order of magnitude in comparison with the estimate of Ref. [5].

For diffusion of the main ions $L \approx L_c \cdot \ln[D_{Fl}/D_\perp \cdot (T_i/m_i)^{1/2}]/2$. In the case of impurity particles their thermal motion along field lines is superimposed with the friction with the background ones. Electric field and thermal force arise due to parallel gradients of the plasma density and temperature. Thus, in addition to diffusion a convection with a flow proportional to the particle density can be generated. In the present consideration we do not distinguish these flow components and it is assumed that stochastization leads only to a modification in the diffusivity of impurity particles. In this case $L = L_c \cdot \ln[D_{Fl}/D_\perp \cdot (T_i/m_I)^{1/2} \cdot f_I]/2$, where m_I is the impurity mass and the factor f_I depends on the frequency of collisions with the background ions. In the case of high collisionality f_I approaches $(m_I/m_i)^{1/2}$, so the diffusivities of the main ions and impurity particles coincide.

The radial profiles of L_c and D_{FL} which are needed for computation of the transport coefficients in the stochastic layer were taken from Ref. [17].

3. Results of calculations and comparison with experimental data

In this Section we present the results of computations by the codes RITM and CNET performed for conditions of ohmic discharges in Tore-Supra with the following main characteristics: the major and minor radii of the LCMS are $R_0 = 2.4$ m and $a = 0.75$ cm, respectively, the toroidal magnetic field $B_T = 3.8$ T, the plasma current $I_p = 1.6$ MA.

RITM has been run to model the conditions of shots #19807 (w/o ED) and #19808 (w ED) at $t = 9$ s with roughly the same volume mean electron density $\langle n_e \rangle = 2.85 \cdot 10^{13}$ cm^{-3}. Comparison of the results of computations and measurements shows that a reasonable agreement is achieved for $A_D = 5 \cdot 10^{16}$ cm^{-3}, $\alpha_\chi = 3.5$ and $\alpha_V = 0.5$. Fig. 1 shows the radial profile of the electron heat diffusivity and particle diffusivity of the main ions for cases with and without ED. The calculated and the measured temperature profiles are given in Fig. 2.

The influxes of carbon and oxygen neutrals were chosen to reproduce the measured level of the total radiation

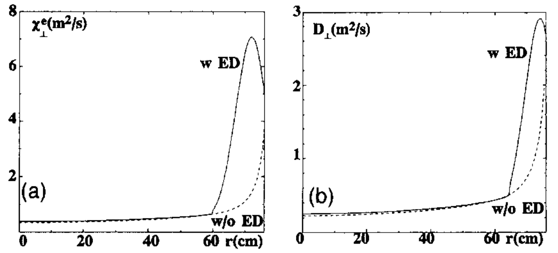

Fig. 1. Radial profiles of the electron heat diffusivity (a) and diffusivity of the main ions (b) in plasmas without and with ergodic divertor as calculated by RITM.

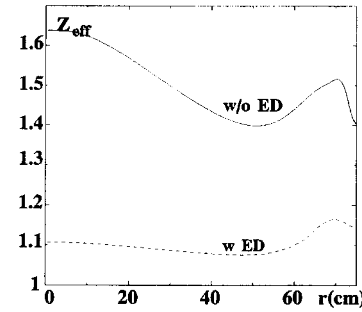

Fig. 3. Radial profiles of the plasma effective charge as calculated by RITM.

losses, being, respectively, 34 and 40% of the ohmic power without and with ED, and of the ratio of viewing-line integrated intensities of L_y–α lines of *C* and *O* hydrogen-like ions. The spectroscopic measurements are taken with XUV spectrometer with a radial viewing line in the midplane of the plasma. Without ED this requires influxes of carbon and oxygen atoms of 0.033 and 0.003 of the outflow of deuterons, respectively. Under ED conditions the relative influxes into the well confined bulk plasma should be 0.016 and 0.0035, respectively. Such a change of the carbon yield is in an agreement with the diminution of the physical sputtering with decreasing temperature at the LCMS; according to calculations it drops from 18 to 10 eV. The increase of the oxygen yield with activation of the ED could be explained by a stronger interaction of the plasma with the liner being the main reservoir of oxygen molecules.

Fig. 3 shows the radial profiles of the effective plasma charge Z_{eff}. It can be seen that the activation of the ED leads to a significant plasma purification. The calculated magnitudes of Z_{eff} are in qualitative agreement with the data of measurements which give $Z_{eff} \approx 1.65$ and 1.34 without and with ED, respectively. The densities of carbon ions with different z and the radiated power density are presented in Fig. 4.

The results of the modelling reproduce the selective influence of stochastization on different impurity charge states. The profiles of densities of the radiating ions with $z = 2, 3$ become significantly broader. Although their amplitudes decrease slightly the total amount of these particles and radiation losses from them increase. Conversely, the densities of ions of higher charges reduce significantly and one can distinguish two different effects: reduction of the density at the edge due to diminution of the impurity source and reduction of the peaking factor in the plasma core due to changes in the neo-classical transport.

The code CNET was run to calculate the so called 'r-ratio' of the line integrated intensities of the L_y–α line (33.74 Å) of C V ions and of the resonance line (40.73 Å) of C V ions. The radial profiles of these signals, computed for plasma profiles found by RITM for conditions of the ohmic shot #14342 at $t = 4$ s (w/o ED) and at $t = 7$ s (w ED), are presented in Fig. 5. The corresponding 'r-ratio'

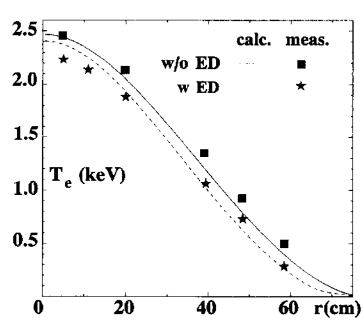

Fig. 2. Calculated by RITM and measured radial profiles of the electron temperature.

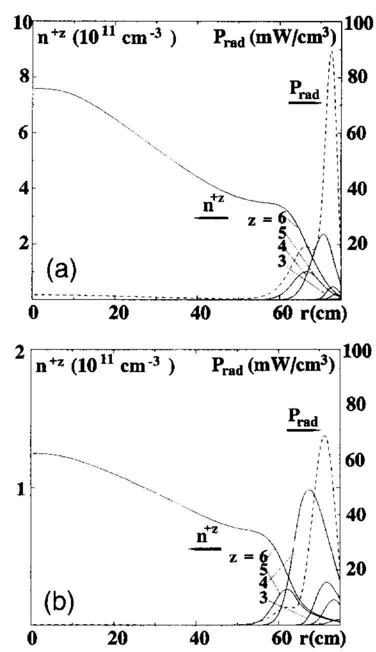

Fig. 4. Radial profiles of the densities of different carbon charge states and of the power density of impurity radiation without (a) and with (b) ergodic divertor as calculated by RITM.

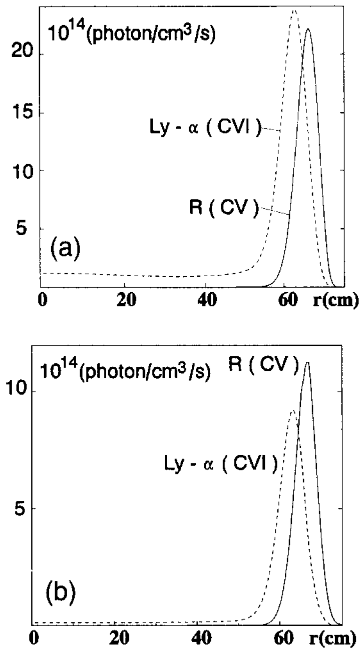

Fig. 5. Radial profiles of intensities of $L_y - \alpha$ (CVI) and R (CV) lines calculated by CNET without (a) and with ED (b).

changes from 1.71 to 1.01 in a agreement with the measurements of 2–2.5 and 1–1.5, respectively. The 'r-ratio' gives a measure of the ratio of the integrated line densities of C^{+5} and C^{+4} ions and its variation manifests that stochastization leads to a redistribution of carbon particles in favor of lower charges.

4. Discussion and summary

The results of numerical modelling show in agreement with measurements a different influence of stochastization on the different charge states of impurities. This can be interpreted on the basis of the following consideration. For each charge state Z one can introduce the characteristic width l_z of the region where these particle are mainly localized. This width is estimated by the distance which the ions diffuse into the plasma before further ionization. Ionization takes place in a time of $1/(k_z n_e)$, where k_z is the ionization rate coefficient, and $l_z \approx (D_\perp / k_z / n_e)^{1/2}$ [18].

The intensity of a particular spectral line or the total radiation losses from a given charge state are determined by the total number N_z of particles with charge z which is proportional to l_z and by their cooling rate. Stochastization leads to changes in the particle diffusivity and in the ionization rate which determine l_z: k_z decreases with decreasing temperature and $D_\perp$ increases. At the same time the edge temperature remains high enough ($T_e > 10$ eV) for effective excitation of transitions being of most importance for radiation losses. Thus l_z and N_z grow, but the closer the region of localization to the coils of ED is and the larger the magnetic field perturbations are the stronger is this effect. Therefore, it is strongest for the radiating ions of low Z which are localized at the very periphery. This explains why the total radiation losses increase and the 'r-ratio' decreases by stochastization. Thus the different strength of the perturbation in the regions of localization of the different charge states is the cause of the selective influence of stochastization on impurities.

It is interesting to analyze what of the effects of stochastization, decrease of the edge temperature and increase of the particle transport, is more important for changes in impurity behavior. For this purpose calculations have been done with a selective turn on of the alterations in transport coefficients due to ED. The results predict that the changes in the temperature profile are of most importance for radiating ions of low Z and conversely the alteration of the particle transport is responsible for reduction of the central impurity concentration.

Acknowledgements

A part of this work has been done as a part of the Ph.D. thesis of H.L.

References

[1] W. Engelhardt and W. Feneberg, J. Nucl. Mater. 76–77 (1978) 518.
[2] M.Z. Tokar', Fiz. Plasmy 5 (1979) 454.
[3] N.N. Vasilyev et al., in: Proc. 8th Europ. Conf. on Controlled Fusion and Plasma Physics, Vol. 1 (1977) p. 164.
[4] A.V. Nedospasov and M.Z. Tokar', J. Nucl. Mater. 93–94 (1980) 248.
[5] Ph. Ghendrih et al., Plasma Phys. Controlled Fusion 34 (1992) 2007.
[6] C. Breton et al., Nucl. Fusion 31 (1991) 1774.
[7] C. de Michelis et al., Nucl. Fusion 35 (1995) 9.
[8] M. Mattioli et al., Nucl. Fusion 35 (1995) 807.
[9] W.R. Hess et al., Plasma Phys. Controled Fusion 37 (1995) 951.
[10] M.Z. Tokar', Plasma Phys. Controlled Fusion 36 (1994) 1819; Phys. Scr. 51 (1995) 665.
[11] K.W. Wenzel and D.J. Sigmar, Nucl. Fusion 30 (1990) 1117.
[12] P.H. Rebut et al., Phys. Fluids B 3 (1991) 2209.
[13] A.B. Rechester and M.N. Rosenbluth, Phys. Rev. Lett. 40 (1978) 38.
[14] H. Capes et al., Contrib. Plasma Phys. 32 (1992) 192.
[15] S.I. Braginskii, in: Review of Plasma Physics, ed. M.A. Leontovich, Vol. 1 (Consultants Bureau, New York, 1965) p. 205.
[16] J.F. Luciani et al., Phys. Rev. Lett. 51 (1983) 1664.
[17] A. Grosman et al., in: Proc. 2nd Eur. Fusion Programme Workshop (Royal Military Academy, Bruxelles, 1994) p. 236.
[18] M.Z. Tokar', Nucl. Fusion 34 (1994) 853.