ELECTRON CYCLOTRON RADIATION STUDIES USING THE ASTRA TRANSPORT CODE COUPLED WITH THE CYTRAN ROUTINE

F. Albajar[1], *M. Bornatici*[2], *G. Cortés*[1], *J. Dies*[1], *F. Engelmann*[3], *J. García*[1], *J. Izquierdo*[1]

[1]Fusion Energy Engineering Laboratoy, Departament de Física i Enginyeria Nuclear,
Universitat Politècnica de Catalunya, Barcelona, Spain
[2]INFM, Dipartimento di Fisica "A.Volta", Università di Pavia, Pavia, Italy
[3]Max-Planck-Institut für Plasmaphysik, Garching, Germany

e-mail: ferran.albajar@upc.es

Whereas Electron Cyclotron (EC) radiation losses are weak in present-day magnetically confined plasmas, these effects tend to become important in next step devices and fusion reactors if operated at high plasma temperature as, e.g., necessary in steady-state operation at high fusion gain Q (5) in a tokamak reactor. While in 1D transport studies, the calculation of the EC power loss is usually performed using locally applied global models, a more accurate analysis is then required owing to the non-local nature of the radiation transport. In order to be able to take EC radiation effects consistently into account, the ASTRA transport code has been coupled with the CYTRAN routine which accounts for essential parts of the non-local physics of the EC transport process including wall reflection and polarization scrambling and which was shown earlier to provide a reasonable approximation to an exact treatment. Modelling results for "advanced" transport regimes using different assumptions for the plasma transport properties are presented.

Introduction

In order to operate a next-step tokamak and a tokamak reactor in steady-state, using non-inductive current drive, and at high fusion gain Q (5), both good confinement properties (as obtained in "advanced" confinement regimes with low or weakly negative magnetic shear in the plasma interior) and high temperatures (typically above 30 keV) are required. In such regimes, the relative importance of radiative transport effects, and in particular, of those due to Electron Cyclotron (EC) waves, increases. Therefore, it is necessary for these regimes to describe radiative transfer effects of EC waves in sufficient detail to quantify them satisfactorily. This requires taking the essentially non-local character of EC wave transport, due to wall reflection and re-absorption and not covered by global models as usually applied, into account.

In the present study, ITER-like steady-state operation conditions (see Ref. [1,2]) are considered. Since it has been shown earlier [3,4] that the CYTRAN routine [5] provides a reasonable approximation to more exact approaches to describing non-local effects, this routine was coupled to the ASTRA transport code [6] for analysing the impact of EC wave radiative transfer in the local power balance and on the plasma electron temperature profile.

For the electron and ion thermal diffusivities, χ_e and χ_i, respectively, the phenomenological model of Ref. [7] was applied, viz.

$$\chi_e = \chi_i = C\, f(\rho)\left[1 - H(\rho - \rho_1)\right] F(s) + \chi_{i,\mathrm{neo}}, \tag{1}$$

where C is a constant taken to be 0.3 throughout this study, $f(\rho)=1+3\rho^2$ describes the overall radial dependence of the transport coefficients and the function $[1 - \mathrm{H}(\rho - \rho_1)]$ is equal to 1 up to the normalized radius $\rho \equiv r/a = \rho_1$ and is equal to 0 in the range $\rho_1 < \rho < 1$, the latter interval corresponding to that of reduced transport at an H-mode edge. In this study we take $\rho_1 = 0.95$. In Eq. (1) the factor $\mathrm{F}(s)$ takes account of the drop of the transport coefficients to neoclassical values of the ion thermal diffusivity, $\chi_{i,\mathrm{neo}}$, in the optimised and reversed shear zone, $\mathrm{F}(s) = 1/(1 + \exp(7(1 - s)))$, s being defined by $s = rq'/q \leq 1$.

Importance of EC radiation in an ITER-like steady-state scenario

We consider ITER-like parameters ($R = 6.35$ m, $a = 1.85$ m, $B_t = 5.18$ T, $\kappa = 1.85$, $\delta = 0.4$ in standard notation), an electron density profile $n_e = n_{e0}(1 - \rho^2)^{\gamma_n}$ with $n_{e0} = 7\times10^{19}$ m^{-3} and $\gamma_n = 0.1$, an alpha particle density consistent with an α-particle confinement 5 times better than energy confinement ($\tau^*_\alpha/\tau_E \approx 5$) and $Z_{\mathrm{eff}} \approx 2$. The impurity fractions are supposed to be constant for the two impurity species considered, Beryllium and Argon, with $f_{\mathrm{Be}} = 2\%$ and $f_{\mathrm{Ar}} = 0.3\%$. The reference effective wall reflection coefficient is taken to be $R_w = 0.6$, polarization scrambling is disregarded and a fixed external power of $P_{\mathrm{ext}} = 68$ MW having a Gaussian radial distribution with a characteristic width $\sigma = 1.2$ m is coupled to the electrons. The current density profile j is taken to fit the current distribution resulting from the current-drive calculations of Ref. [1], corresponding to a total current $I_p = 9$ MA.

With this input and with Eq. (1) for the (electron and ion) heat diffusivities the (electron and ion) temperatures profiles can be calculated from the (local) steady-state power balance,

$$\frac{dP_{\alpha,\mathrm{e}}}{dV} + \frac{dP_{\mathrm{ext}}}{dV} - \frac{dP_{\mathrm{e}\to\mathrm{i}}}{dV} = \frac{dP_{\mathrm{B}}}{dV} + \frac{dP_{\mathrm{EC}}}{dV} + \frac{dP_{\mathrm{con,e}}}{dV}, \tag{2}$$

$$\frac{dP_{\alpha,\mathrm{i}}}{dV} + \frac{dP_{\mathrm{e}\to\mathrm{i}}}{dV} = \frac{dP_{\mathrm{con,i}}}{dV} \tag{3}$$

where $dP_{\alpha,\mathrm{j}}/dV$ is the α-particle power density coupled to the electrons (j = e) and ions (j = i), respectively, dP_{B}/dV and dP_{EC}/dV are the Bremsstrahlung and the net EC radiative power losses, $dP_{\mathrm{e}\to\mathrm{i}}/\mathrm{dV}$ is the electron ion heat exchange due to Coulomb collisions, and $dP_{\mathrm{con,j}}/dV$ is the (local) conductive-convective loss of the electrons (j = e) and ions (j = i). The result obtained is shown in Figs. 1 and 2.

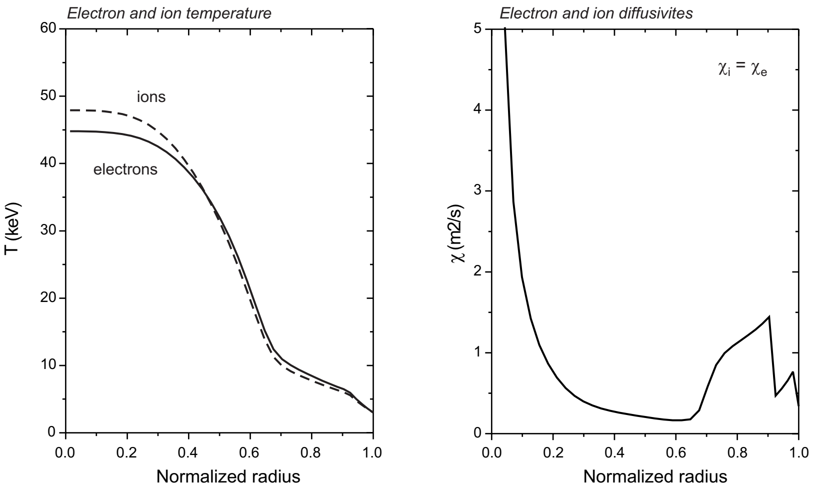

Figure 1: Electron (solid curves) and ion (dashed curves) temperature profiles for an ITER-like steady-state plasma with $R_w = 0.6$ (left); profile of the electron (and ion) diffusivity (right).

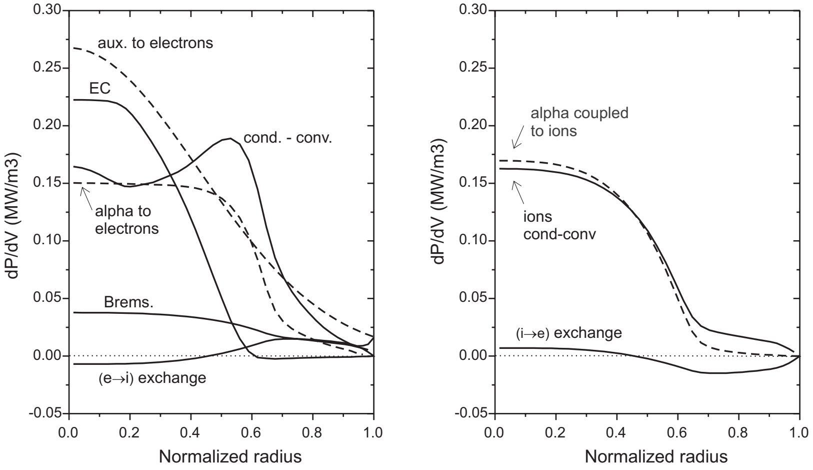

Figure 2: Radial distribution of the local power balance for the electrons (left) and ions (right) in an ITER-like steady-state plasma with $R_w = 0.6$.

From Fig. 2 it is seen that in this case the net EC radiation loss in the plasma core effectively provides the most important cooling mechanism for electrons: one has $(dP_{\mathrm{EC}}/dV)/(dP_{\mathrm{con,e}}/dV)$ 1.3 and $(dP_{\mathrm{EC}}/dV)/(dP_{\mathrm{B}}/dV)$ 6 for $\rho = 0$. As a consequence, the electron temperature is lower than the ion one in the plasma core, despite taking the external power to be coupled fully to the electrons and adopting the same heat diffusivity for electrons and ions. The temperature profile presents three well distinguished regions: the core region, ρ 0.3, with a high and almost flat temperature, the intermediate region, 0.3 ρ 0.65, with a strong T–gradient, and the edge region, 0.65 $\rho < 1$, with a low and steadily decreasing temperature.

The global characteristics of this scenario are summarised in the following table:

T_{e0} (keV)	44.8	Z_{eff}	2.2
T_e (keV)	18.2	f_{He} (%)	6
T_{i0} (keV)	47.9	P_α (MW)	84
T_i (keV)	18.1	P_{ext} (MW)	68
n_{e0} (10^{19} m^{-3})	7.0	P_{EC} (MW)	29
n_e (10^{19} m^{-3})	6.3	P_{B} (MW)	15
W_{tot} (MJ)	393	P_{con} (MW)	108
τ_E (s)	3.6	Q	6.2

Dependence of EC wave cooling on the wall reflection coefficient

The profiles of the net EC radiative loss and of the corresponding electron temperature are shown in Fig. 3 for different values of the wall-reflection coefficient (R_w = 0.0, 0.6, 0.8, 0.9, 0.98, 1.0). When the wall-reflection coefficient increases one observes that dP_{EC}/dV decreases due to the enhancement of the EC wave self-absorption. Also, the profile reversal of the net EC radiative power, due to EC power absorption becoming dominant in the cooler plasma range, tends to become stronger. As a result of this energy redistribution the strength of the electron temperature gradient increases in the net EC absorption region. Both these effects lead to an increase of the electron temperature at the plasma centre with increasing R_w, which, however, is sizeable only for strong wall reflection (R_w 0.6). It is to be emphasized that it is not the change of the α-particle heating power occurring due to the change of the plasma ion temperature when R_w is increased which is the dominant cause for the increase of the core electron temperature.

A comparison of the results obtained using the CYTRAN routine with those following from locally applying Trubnikov's global formula [8] is given in Fig. 4. As to be expected, Trubnikov's global model underestimates the spatial structure of the net EC radiative power density, yielding too low a power loss in the plasma core and overestimating it in the outer plasma, the deviation being the stronger the larger is R_w. (The profile reversal effect appearing at larger R_w obviously cannot be described at all by the locally applied global model.) For the electron temperature profile the difference between the two models is weaker because lower central cooling and higher power loss in the intermediate (high-temperature-gradient) range do counteract each other. For $R_w \approx 0.8$, this compensation is virtually complete, while for larger (smaller) R_w too high (low) a core temperature results from the global model.

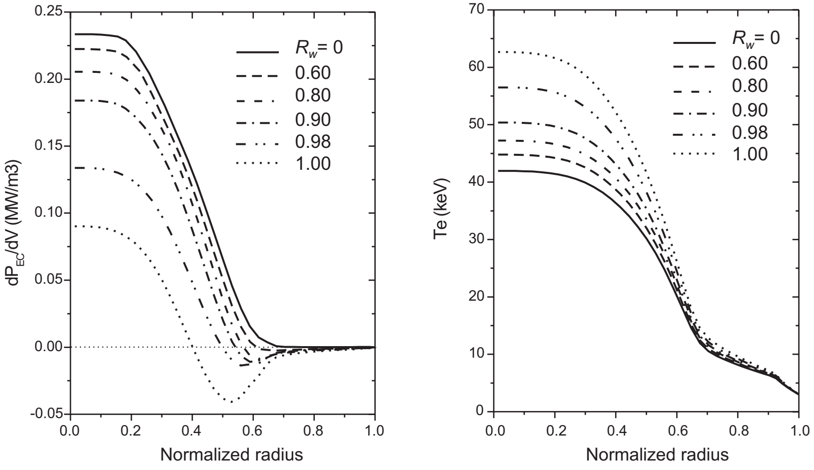

Figure 3: Profiles of the net EC radiative power density (left) and of the corresponding electron temperature (right) for various values of the wall-reflection coefficient R_w.

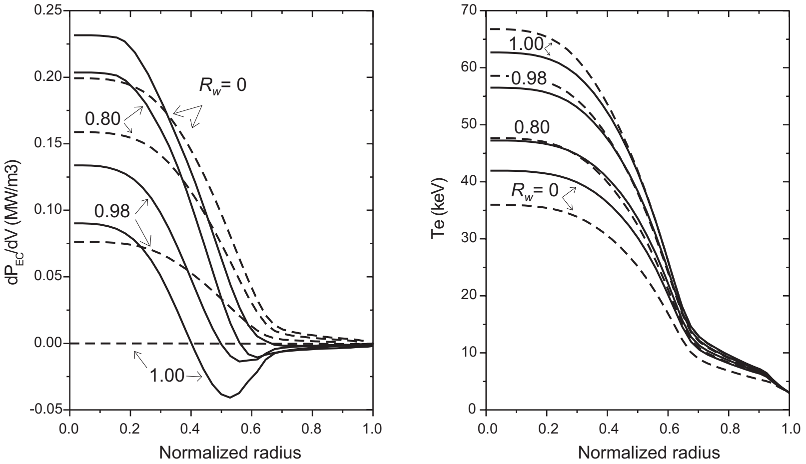

Figure 4: Comparison between a non-local model (CYTRAN routine) for EC radiative transfer (solid curves) and a local approach based on Trubnikov's formula (dashed curves) on the profile of the net EC radiative power density (left) and that of the electron temperature (right).

Conclusions

In conclusion, for next-step and reactor-grade tokamaks in steady-state operation the net EC wave emission tends to provide the most important cooling mechanism for electrons in the plasma core. Describing the EC wave power transfer with sufficient accuracy and, in particular, covering properly non-local effects deriving from wall reflection and re-absorption is therefore essential in modelling the plasma power balance. While the core electron temperature is quite sensitive to changes in electron heating and/or cooling in the regime in question, the dependence on the wall reflection coefficient is sizeable only for R_w 0.6.

References

[1] B.J. Green et al., Plasma Phys. Control. Fusion, 2003, **45**, 687.
[2] M. Shimada et al., Nucl. Fusion, 2004, **44**, 350.
[3] F. Albajar, M. Bornatici, and F. Engelmann, Nucl. Fusion, 2002, **42**, 670.
[4] S. Tamor, Nucl. Technology/Fusion, 1983, **3**, 293.
[5] S. Tamor, "A Simple Fast Routine for Computation of Energy Transport by Synchrotron Radiation in Tokamaks and Similar Geometries", Rep. SAI-023-81-189-LJ/LAPS-72 (La Jolla, CA: Science Applications, 1981).
[6] G. Pereverzev, et al., Report IPP 5/42 (1991).
[7] A.R. Polevoi et al., "Possibility of $Q > 5$ stable, steady-state operation in ITER with moderate β_N and *H*-factor", Proc. 19th Int. Conf. on Fusion Energy, Lyon, 2002.
[8] B.A. Trubnikov, Reviews of Plasma Physics (Leontovich, M.A., Ed.) Vol. 7, Consultants Bureau, New York, 345 (1979).