31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-4.171 (2004)

Electron Cyclotron Radiation Transfer in Fusion Plasmas: Use of 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*

Whereas Electron Cyclotron (EC) radiation losses are weak in present-day magnetically confined plasmas, these effects tend to become important for reactor-grade tokamaks in steady-state operation. For a satisfactory modelling of EC wave losses then the non-local properties of EC wave transport must be taken into account. Therefore the CYTRAN routine was coupled with the ASTRA transport code. The modelling performed for ITER-like parameters shows that EC wave emission is an important cooling mechanism for electrons in the plasma core when the peak temperature exceeds about 30 keV.

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 ($\gtrsim 5$), 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 (cf. Ref. [1]).

In the present study, we concentrate on ITER-like steady-state operation conditions (see Ref. [2,3]). Since it has been shown earlier [4,5] that the CYTRAN routine [6] provides a reasonable approximation to more exact approaches to describing non-local effects, this routine was coupled to the ASTRA transport code [7] 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, the phenomenological model of Ref. [8] was used, which allows to reduce the thermal diffusivities to the neoclassical value of the ions in the plasma core (where the magnetic shear is small or reversed) and at an H-mode edge.

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, $\kappa = 1.85$ and 2.0, $\delta = 0.4$ 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 $Z_{eff} \approx 2$. The impurity fractions are supposed to be constant for the two impurity species considered, Beryllium and Argon, with $f_{Be} = 2\%$ and $f_{Ar} = 0.3\%$. The reference effective wall reflection coefficient is taken to be $R_w = 0.6$, polarization scrambling is disregarded and a fixed external power of $P_{ext} = 68$ MW having a Gaussian radial distribution with a characteristic width $\sigma = 1.2$ m is, respectively, fully coupled to the electrons ($\kappa = 1.85$) or transferred in the proportion 4:1 to electrons and ions ($\kappa = 2.0$). The current density profile is taken to fit the current distribution resulting from the current-drive calculations of Ref. [2], corresponding to a total current $I_p = 9$ MA. The two slightly different elongations κ and external heating conditions (referred to as cases I and II) allow to generate somewhat different plasma temperatures for otherwise identical discharge parameters.

The global characteristics of the two cases are summarised in the following table:

Case	**I**	**II**	***Case***	**I**	**II**
T_{e0} (keV)	45	35	Z_{eff}	2.2	2.2
$\langle T_e \rangle$ (keV)	18	15	f_{He} (%)	6.0	6.0
T_{i0} (keV)	48	37	P_α (MW)	84	80
$\langle T_i \rangle$ (keV)	18	15	P_{ext} (MW)	68	68
n_{e0} (10^{19} m^{-3})	7.0	7.0	P_{EC} (MW)	29	17
$\langle n_e \rangle$ (10^{19} m^{-3})	6.3	6.3	P_B (MW)	15	15
W_{tot} (MJ)	390	360	P_{con} (MW)	108	116
τ_E (s)	3.6	3.1	Q	6.2	5.9

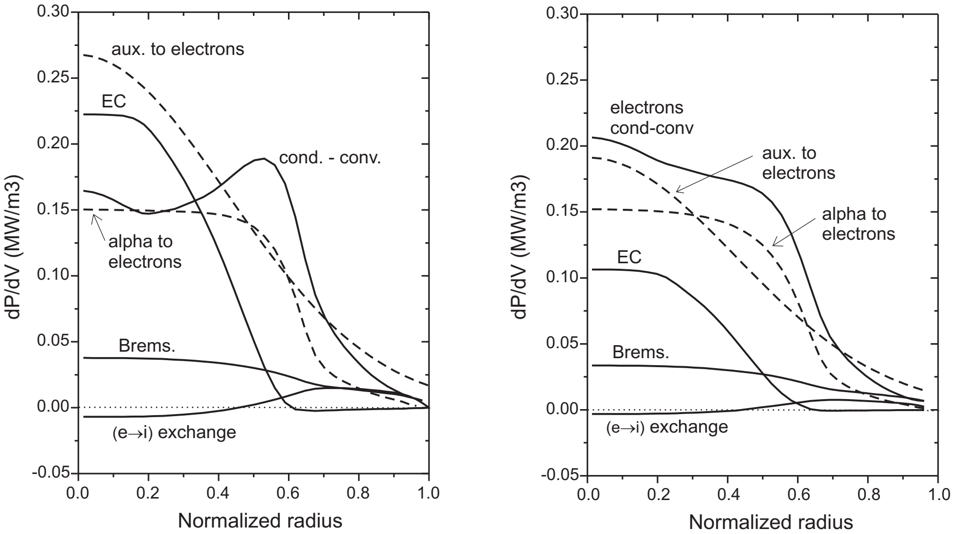

Figure 1: Local power balance of the electrons: cases I (left) and II (right); $\rho = r/a$ is the normalized plasma radius and dP/dV refers to the respective power densities.

Figure 1 shows that effectively the net EC radiation losses may provide the most important cooling mechanism for electrons in the plasma core, keeping $T_{e0} < T_{i0}$, if T_{e0} is larger than 40 keV. However, the importance of EC wave cooling depends sensitively on the level of T_{e0}. Anyway, the net power loss due to EC waves dP_{EC}/dV, in a wide parameter range, is larger than the bremsstrahlung losses dP_B/dV.

A study of the impact of the strength of wall reflection shows that for increasing R_w the effect of increased self-absorption of EC waves (equivalent to reduced cooling of the core electrons and a tendency towards enhanced heating where the electron temperature gradient is strong) makes the core electron temperature increase. The effect is sizeable, however, only for $R_w \gtrsim 0.6$.

CYTRAN versus Trubnikov approach

The results obtained using the CYTRAN routine were compared with those following from locally applying Trubnikov's global formula [9]. 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. 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.

Conclusions and Discussion

In conclusion, for next-step and reactor-grade tokamaks in steady-state operation the net EC wave emission tends to provide an effective (and at core temperatures above 40 keV 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 $R_w \gtrsim 0.6$.

On the other hand, for next-step devices operating at core temperatures in the range of 25 keV or less (ITER in the inductive regime, FIRE, IGNITOR), EC wave losses do not exceed (or even are much smaller than) bremsstrahlung losses. In fact, as indicated by the quasi-dimensionless global scaling of the ratio of EC and bremsstrahlung losses,

$$P_{EC} / P_B \sim \left(\frac{n}{n_{Gw}} \right)^{-3/2} (aB_t) \left(\frac{Rq}{a} \right)^{3/2} T_e^2 ,$$

with n_{Gw} the Greenwald density, high electron temperature is most effective in making EC wave losses important, followed by the “size” (aB_{t}) of the confinement device.

References

[1] F. Albajar et al., Proc. of the 13th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Heating, Nizhny Novgorod, Russia (2004).

[2] B.J. Green et al., Plasma Phys. Control. Fusion, 2003, **45**, 687.

[3] M. Shimada et al., Nucl. Fusion, 2004, **44**, 350.

[4] F. Albajar, M. Bornatici, and F. Engelmann, Nucl. Fusion, 2002, **42**, 670.

[5] S. Tamor, Nucl. Technology/Fusion, 1983, **3**, 293.

[6] 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).

[7] G. Pereverzev, et al., Report IPP 5/42 (1991).

[8] 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.

[9] B.A. Trubnikov, Reviews of Plasma Physics (Leontovich, M.A., Ed.) Vol. 7, Consultants Bureau, New York, 345 (1979).