Importance of Electron Cyclotron Wave Energy Transport in ITER

F. Albajar 1), M. Bornatici 2), G. Cortes 1), J. Dies 1), F. Engelmann 3), J. Garcia 1), J. Izquierdo 1)

1) Fusion Energy Engineering Laboratory, Departament de Física i Enginyeria Nuclear, Universitat Politècnica de Catalunya, 08028 Barcelona, Spain
2) INFM, Dipartimento di Fisica 'A. Volta', Università di Pavia, 27100 Pavia, Italy
3) Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany

e-mail contact: javier.dies@upc.es

Abstract. Using the CYTRAN routine to cover non-local effects in electron cyclotron (EC) wave emission along with the ASTRA code, the importance of EC wave emission in the local electron power balance is analyzed for various ITER operation regimes, and, for comparison, for FIRE, IGNITOR and the reactor-grade ITER-EDA. As a result, EC wave emission is a significant contributor to core electron cooling if the core electron temperature is about 35 keV or higher as expected for ITER and tokamak reactor steady-state operation, and, in fact, becomes the dominant core electron cooling mechanism already at temperatures exceeding 40 keV, such affecting the core plasma power balance in an important way.

1. Introduction

Whereas, overall, electron cyclotron (EC) waves contribute comparatively little to the energy losses from a reactor-grade toroidal magneto-plasma, their role in determining the level of energy transport and, hence, the plasma electron and ion temperatures and temperature profiles in the plasma core may be quite important, especially in steady-state tokamak operation scenarios which are characterised by good energy confinement, modest peak plasma density ($n_0 \approx 10^{20}$ m^{-3}), and high peak plasma temperatures ($T_{e,0} \approx T_{i,0} \approx 40$ keV). In fact, in this case, energy transport by EC waves, from the plasma core, is found to be of the same order and sometimes even larger than the plasma electron heat transport [1]. This is due to the fact that net EC wave emission is strongest in the hot central region of the plasma while the cooler outer plasma layers are weak emitters or even net absorbers of EC waves. Therefore, in order to describe energy transport in a steady-state reactor-grade tokamak plasma properly, not only a reliable model for plasma heat transport by conduction and convection is required, but also transport by EC waves must be modelled satisfactorily. This implies that a description of EC wave transport is needed which takes the essentially non-local character of this transport mechanism, due to wave reabsorption and wave reflection, into account.

In the study of ITER operation conditions [2,3,4] that was performed, this was done by adopting the CYTRAN routine [5] for describing EC waves which has been tested earlier against more exact numerical [6] and analytical [7] models and found to be a reasonable approximation to the latter. This routine was coupled to the ASTRA transport code [8]. As ASTRA contains a local approach to electron cyclotron emission, based on Trubnikov's formula [9], a comparison between the results of the non-local and this usually applied local model could be made.

In this paper, in addition to ITER steady-state operation conditions, for comparison, ITER inductive operation, the working conditions of FIRE [10], IGNITOR [11], as well as steady-state operation of ITER-EDA [12] as an example of a device approaching fusion reactor conditions are also addressed.

2. ITER

The global characteristics of the operation scenarios considered for ITER are given in Table I. Here, the steady-state case 1 and the inductive case are modelled along the lines of the published ITER scenarios [2,3,4]. The steady-state scenario 2 has a slightly modified current profile, the current density in the core being slightly increased and that adjacent to the edge somewhat lower, at constant total current; consequently, the thermal heat conduction in the plasma core tends to be reduced.

	Steady-state 1	**Steady-state 2**	**Inductive**
Major radius R (m)	6.4	6.4	6.2
Minor Radius a (m)	1.9	1.9	2.0
Elongation/triangularity	1.9/0.40	1.9/0.40	1.7/0.33
B_t (T)	5.2	5.2	5.3
I (MA)	9.0	9.0	15
$n_{e,0}$ (10^{19} m^{-3})	7.0	7.0	11
$\langle n_e \rangle$ (10^{19} m^{-3})	6.4	6.4	10
$T_{e,0}$ (keV)	36	43	24
$\langle T_e \rangle$(keV)	17	19	8.5
$T_{i,0}$ (keV)	37	53	19
$\langle T_i \rangle$ (keV)	17	21	8.0
W_{tot} (MJ)	360	430	310
P_α (MW)/P_{ext} (MW)	82/68	97/68	76/40
P_{EC} (MW)/P_{Brems} (MW)	18/15	29/15	4.1/20
P_{con} (MW)/Q	120/6.0	120/7.1	92/9.5
Z_{eff}/f_{He} (%)	2.3/6.0	2.3/6.0	1.7/3.1
q_0/q_{95}	4.4/4.5	3.8/4.6	0.84/2.7

TABLE I: GLOBAL CHARACTERISTICS OF ITER OPERATION SCENARIOS; IT IS ASSUMED THAT THE EXTERNAL POWER P_{EXT} HAS A GAUSSIAN PROFILE AND IS DISTRIBUTED BETWEEN ELECTRONS AND IONS IN THE RATIO 80:20.

In figures 1, the electron temperature (T_e) profiles, for various wall reflection coefficients R_w of the EC waves (assumed to be constant over the relevant frequency range and over the wall surface), are given for the three scenarios. It is seen that the impact of varying R_w is weak as long as $R_w \leq 0.6$ for the steady-state scenarios 1 and 2 and negligible for any R_w for the inductive case. Since $R_w = 0.6$ also appears to be a reasonable effective value to be expected for next-step devices and reactors, this value is adopted generally in the following.

Figure 2 shows the ion temperature (T_i) profiles, in addition to those of the electron temperature (T_e), for the three scenarios at $R_w = 0.6$. Although the total heating power going to the electrons is much larger than that transferred to the ions and the heat conductivities of electrons and ions are assumed to be equal, T_i is larger than T_e in the plasma core in the steady-state cases. This is a consequence of the strong radiative cooling of the electrons when T_e is high ($T_e \geq 35$ keV). In the core, (T_i-T_e) increases with increasing T_e as then electrons are more efficiently cooled by radiation while collisional energy transfer between ions and electrons is reduced. Comparing the two steady-state scenarios, from figures 1 and 2 it is also seen that the actual core values of T_e and T_i in the high-temperature (steady-state) regime quite sensitively depend on the strength of electron heat transport.

The detailed local power balances for the plasma electrons are shown in figures 3. Note that the electron cyclotron power loss $(dP/dV)_{EC}$ is the effective one, given by the emitted power density reduced for the power density reabsorbed by the plasma from the EC wave field. For high core electron temperatures (and always for large $R_w \rightarrow 1$), adjacent to the plasma edge, this contribution effectively is a heat source as reabsorption becomes stronger than genuine emission there.

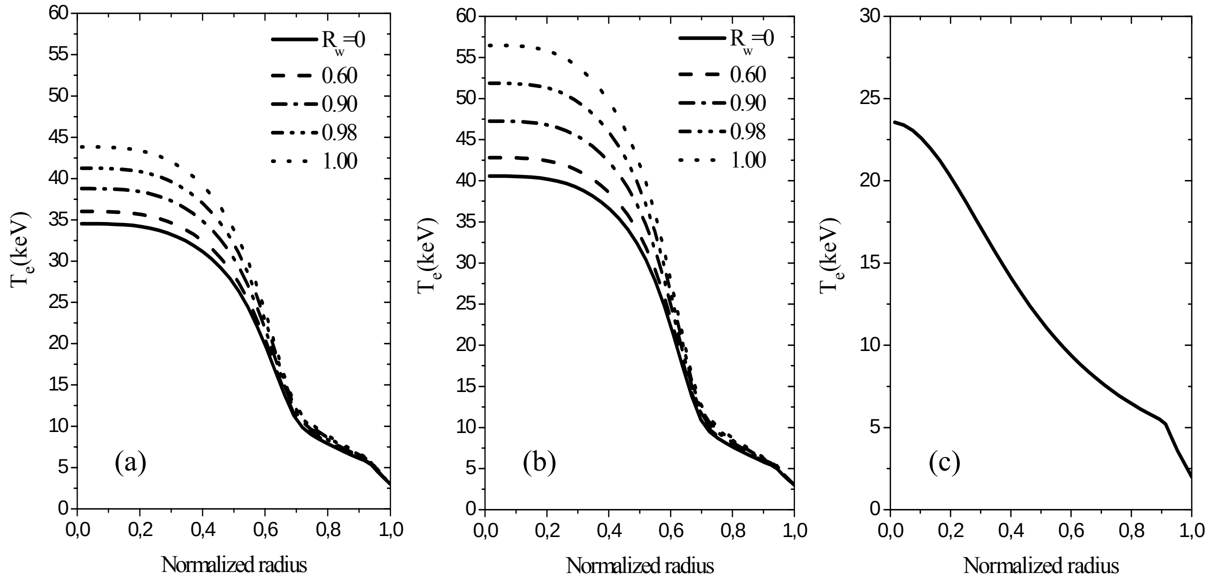

FIG. 1. Electron temperatures profiles $T_e(r/a)$ for various values of the wall reflection coefficient R_w: (a) steady-state 1, (b) steady-state 2, and (c) inductive, where the effect of varying R_w is negligible.

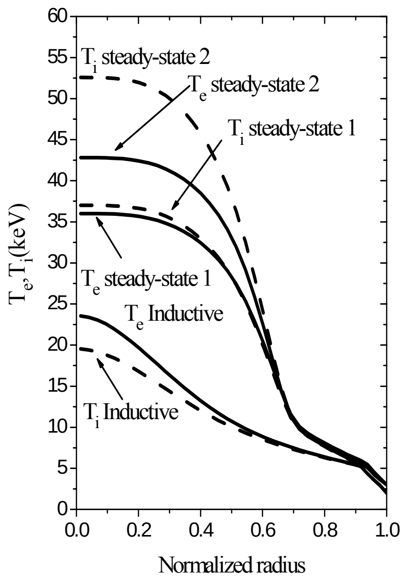

FIG. 2. Electron (T_e) and ion (T_i) temperature profiles for the ITER scenarios of Table I and for $R_w = 0.6$.

The main feature transparent from figures 3 is that the importance of the power loss of electrons by EC waves strongly increases with increasing electron temperature and, effectively, becomes the dominant electron cooling mechanism in steady-state operation of ITER in the core plasma if the core electron temperature exceeds about 40 keV (see figure 3 (b)). Such a situation, although the ITER reference steady-state regime (figure 3 (a)) does not quite reach such conditions, could well arise in practice, given the sensitivity of the core electron temperature to small changes of the heat transport and heating conditions. On the other hand, if the central T_e (T_{e0}, say) is below 25 keV, as happens in the reference inductive scenario, $(dP/dV)_{EC}$ is no longer an important contribution to the local electron power balance, of the order or even less important than bremsstrahlung. It should be noted that the predominant importance of the electron temperature for the strength of EC electron cooling is to be expected on the basis of simple scaling arguments [1].

A comparison between the non-local approach used here and the local one based on Trubnikov's formula [9] has been documented for the steady-state case 2 of Table I elsewhere [13]; see also [1]. The result is that the global model underestimates the spatial structure of the EC emission profile, 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 is less pronounced because of compensation effects.

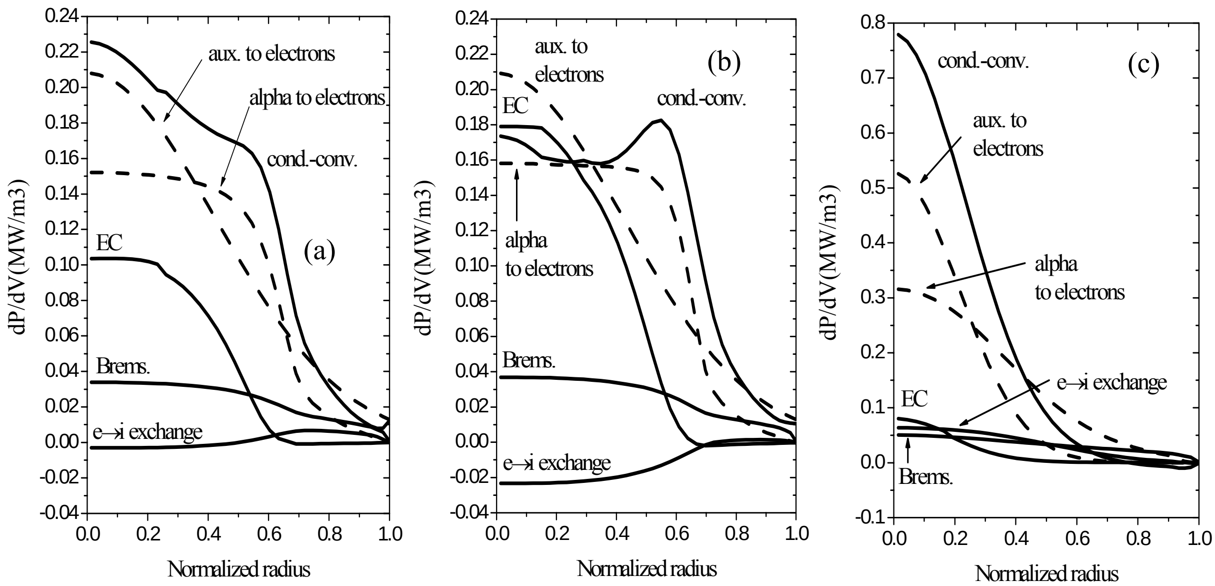

FIG. 3. Local electron power balance for the ITER scenarios of Table I and for R_w=0.6: (a) steady-state 1, (b) steady-state 2, and (c) inductive. The external power density coupled to the electrons ("aux to electrons"), the alpha particle power density coupled to electrons ("alpha to electrons") and the heat transfer from electrons to ions ("e→i exchange") in the steady-state case are source terms, while EC wave radiation ("EC"), at least in the core, as well as bremsstrahlung ("Brems") and conduction-convection ("cond-conv") are power density sinks.

3. FIRE and IGNITOR

Both FIRE and IGNITOR being high-field devices with a limited pulse duration, are supposed to work at comparatively high plasma density and low temperature (for the global characteristics of their working regimes, see Table II), the core electron temperature being as low as 17 keV for FIRE and 19 keV for IGNITOR. As a consequence, EC wave emission effects are comparatively small for these devices (see figures 4). In FIRE, they are less important than bremstrahlung, while in IGNITOR (due to the lower density and larger confinement capability, as measured by the product aB_t, see [1]), EC wave emission exceeds the power loss by bremstrahlung.

	FIRE	**IGNITOR**
Major radius R (m)	2.1	1.3
Minor Radius a (m)	0.59	0.47
Elongation/triangularity	1.8/0.55	1.8/0.40
B_t (T)	6.5	12
I (MA)	4.5	7.0
$n_{e,0}$ (10^{19} m^{-3})	35	47
$\langle n_e \rangle$ (10^{19} m^{-3})	22	29
$T_{e,0}$ (keV)	17	19

$\langle T_e \rangle$ (keV)	6.7	7.1
$T_{i,0}$ (keV)	16	18
$\langle T_i \rangle$ (keV)	6.1	6.0
W_{tot} (MJ)	20	11
P_α (MW)/P_{ext} (MW)/	20/30	13/8.0
P_{EC} (MW)/P_{Brems} (MW)	0.38/3.7	1.1/2.0
P_{con} (MW)/Q	46/3.3	18/8.1
Z_{eff}/f_{He} (%)	1.8/1.0	1.4/1.0
q_0/q_{95}	2.0/3.1	0.87/3.9

TABLE II: GLOBAL CHARACTERISTICS OF FIRE AND IGNITOR OPERATION SCENARIOS.

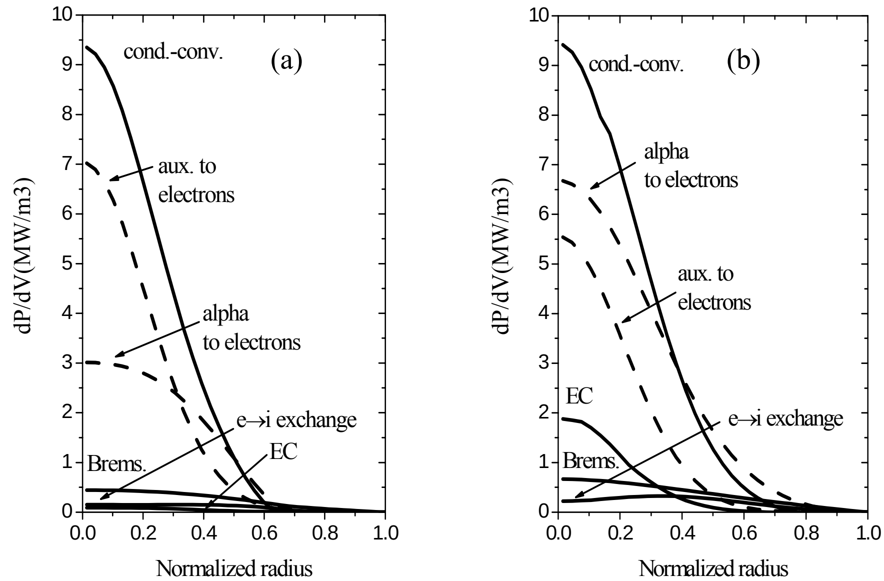

FIG. 4. Local electron power balance for (a) the FIRE and (b) the IGNITOR working scenarios of Table II.

4. ITER- EDA

In order to display the impact of the size (or, more precisely, of the confinement capability) of the device, steady-state operation of the larger ITER as considered earlier in the EDA ("ITER-EDA") and which approaches fusion reactor conditions, have also been analyzed, assuming the same transport model and current density profile as for the steady-state case 1 of ITER in section 2. To avoid the very high ion temperature arising under these conditions, a case in which ion heat transport is enhanced by a factor 1.5 ('steady-state 3') was treated in addition.

The global characteristics of these scenarios are given in Table III, whereas the electron and ion temperature profiles are shown in figure 5 (a) for a wall reflection coefficient R_w = 0.6.

The local power balances of the electrons are given in figures 5 (b) and (c). The main result is that, for a larger confinement capability aB_t, the importance of EC wave emission in cooling the core electrons is enhanced (as is, in fact, to be expected from the simple scaling argument given in [1]). It is, in fact, the dominant cooling mechanism for both ITER-EDA scenarios considered. Of course, the quite high electron temperatures attained in these scenarios are also essential for this.

	Steady-state 1	**Steady-state 3**
Major radius R (m)	8.1	8.1
Minor Radius a (m)	2.8	2.8
Elongation/triangularity	1.8/0.40	1.8/0.40
B_t (T)	5.7	5.7
I (MA)	15	15
$n_{e,0}$ (10^{19} m^{-3})	7.0	7.0
$<n_e>$ (10^{19} m^{-3})	6.4	6.4
$T_{e,0}$ (keV)	40	38
$<T_e>$ (keV)	19	17
$T_{i,0}$ (keV)	52	43
$<T_i>$ (keV)	23	18
W_{tot} (MJ)	1200	1100
P_α (MW)/P_{ext} (MW)	250/70	220/70
P_{EC} (MW)/P_{Brems} (MW)	67/46	62/44
P_{con} (MW)/Q	210/18	180/15
Z_{eff} /f_{He} (%)	2.3/5.9	2.3/5.9
q_0/q_{95}	4.7/5.6	4.8/5.4

TABLE III: GLOBAL CHARACTERISTICS OF ITER-EDA OPERATION SCENARIOS; STEADY-STATE 1: SAME TRANSPORT ASSUMPTIONS AS FOR THE CORRESPONDING ITER SCENARIO OF TABLE I; STEADY-STATE 3: ION HEAT TRANSPORT ENHANCED BY A FACTOR 1.5.

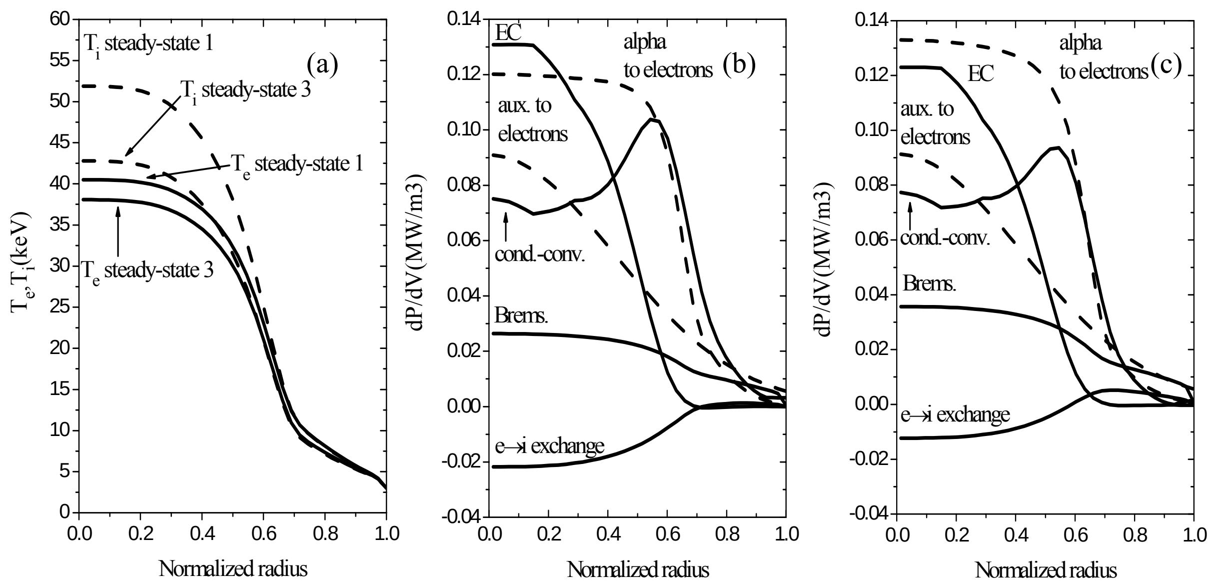

FIG. 5. Electron (T_e) and ion (T_i) temperature profiles for the ITER-EDA steady-state scenarios of Table III and for $R_w = 0.6$: (a). Local electron power balance for the ITER-EDA scenarios of Table III and for $R_w = 0.6$: (b) steady-state 1; (c) steady-state 3; for details, see caption of figures 3.

5. Summary and conclusions

The importance of electron cyclotron wave emission in the local electron power balance was analyzed, using the CYTRAN routine coupled to the ASTRA code which allows covering non-local effects in the wave emission, for typical operation regimes of ITER. For comparison, also FIRE, IGNITOR and steady-state ITER-EDA working conditions were considered.

In conclusion, the importance of electron cyclotron emission mainly depends on the electron temperature. It can become a significant cooling mechanism for the core electrons, exceeding bremsstrahlung, in ITER steady-state operation regimes when the core electron temperature is higher than about 35 keV, and tends to become the dominant one for core electron temperatures above 40 keV. On the other hand, for inductive operation of ITER where the core electron temperature is expected to be about 20 keV (and even more so for the still cooler FIRE and IGNITOR plasmas), also locally electron cyclotron power losses are small. Conversely, in steady-state operation of a device larger than ITER, approaching reactor conditions, such as the ITER-EDA, the relative importance of core electron cooling by electron cyclotron wave emission is enhanced.

The overall importance of wall reflection of electron cyclotron waves was shown to be small as long as $R_w \leq 0.6$. However, small changes in the transport properties may affect the core electron and ion temperatures significantly and may be decisive for which of the plasma species is hotter in the plasma core.

REFERENCES

[1] ALBAJAR, F., et al., Proc. of the 31st EPS Conference on Plasma Physics, London, June 2004, ECA Vol.28G, P-4.171 (2004)

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

[3] POLEVOI, A.R., et al., “Possibility of Q > 5 stable, steady-state operation in ITER with moderate β_N and H-factor”, Proc. of the 19th Fusion Energy Conference, Lyon, 2002, paper CT/P-08

[4] SHIMADA, M., et al., Nucl. Fusion **44** (2004) 350

[5] TAMOR, S., “A simple fast routine for computation of energy transport by synchrotron radiation in tokamaks and similar geometries”, Report SAI-023-81-189-LJ/LAPS-72 (La Jolla, CA : Science Applications, Inc., 1981)

[6] TAMOR, S., Nucl. Technology Fusion **3** (1983) 293

[7] ALBAJAR, F., BORNATICI, M., ENGELMANN, F., Nucl. Fusion **42** (2002) 670

[8] PEREVERZEV, G.V., et al., Report IPP 5/42 (Garching, Germany: Max-Planck-Institut für Plasmaphysik, 1991)

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

[10] MEADE, D., et al., “Advanced Tokamak Regimes in the Fusion Ignition Research Experiment (FIRE)”, Proc. of the 30th EPS, St Petersburg, July 2003

[11] COPPI, B., et al., “Critical Physics Issues for Ignition Experiments: Ignitor”, Report PTP 99/06, MIT (RLE), 1999.

[12] ITER Physics Basis Editors, et al., Nucl. Fusion **39** (1999), 2137

[13] ALBAJAR, F., et al., “Electron cyclotron radiation studies using the ASTRA transport code coupled with the CYTRAN routine”, Proc. of the 13th Joint Workshop on ECE and ECRH, Nizhny Novgorod, Russia, May 2004