Electron Cyclotron Power Losses in ITER for 2D Profile of Magnetic Field

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Abstract. Potential importance of electron cyclotron (EC) wave emission in the local electron power balance in the steady-state regimes of ITER operation with high temperatures and DEMO reactor suggested accurate calculations of the local net radiated power density, $P_{EC}(\rho)$. When central temperature increases to ~30 keV the local EC power loss becomes a substantial part of heating from fusion alphas and is close to the total auxiliary heating, $P_{EC}(0) \cong 0.3 \cdot P_{\alpha}(0) \cong P_{aux}(0)$. Here with the help of the modified code CYNEQ we analyze the influence of the inhomogeneity of the magnetic field, $B(\rho,\theta)$ on the profile $P_{EC}(\rho)$, intensity of the outgoing radiation and total power losses. It is demonstrated that for reactor scale parameters B, T_e and wall reflection coefficient R_w, expected in ITER and DEMO, accurate simulation of non-local transport of EC-waves requires self-consistent 1.5D simulation (1D plasma transport with 2D equilibrium). It is shown that the EC transport with good accuracy is described by the 1D approximation of the total magnetic field, averaged over the magnetic surface $B(\rho) = < B(R,Z) >_{ms}$, derived from the self-consistent 1.5D simulation.

1. Introduction

Electron cyclotron radiation (ECR), P_{EC} can significantly contribute to the local electron power balance in central part of plasma for high temperatures, T_e expected in DEMO and steady-state regimes of ITER operation (see, e.g., [1]). Therefore, the magnetic surface averaged power density, $P_{EC}(\rho)$ should be determined with a sufficient accuracy self-consistently with 1.5D time dependent transport simulations. Comparison of accuracy of the ECR predictions by codes CYTRAN [2], CYNEQ [3] and EXACTEC [4] was carried out for homogeneous magnetic field in a wide range of temperature and density profiles, $T_e(\rho)$, $n_e(\rho)$, expected in reactor-grade tokamaks [5]. The results were benchmarked versus predictions of the most comprehensive, but the slowest code SNECTR [6], based on Monte Carlo simulation of the ECR emission and absorption processes in axisymmetric toroidal plasmas with mirror or diffuse reflection of waves from the vacuum vessel. Good agreement between CYNEQ and SNECTR predictions was demonstrated [5].

The inhomogeneity of magnetic field affects the spatial distribution of the radiation. In section 2 of this paper we consider the new version of the CYNEQ code, extended to full account of the inhomogeneity of the magnetic field, B in axisymmetric approximation. We analyze the influence of this inhomogeneity on the profile $P_{EC}(\rho)$, spectral intensity of outgoing radiation, $J(\omega)$, and total volume-integrated power losses, P_{EC}^{tot}.

However, the detailed multi-dimensional calculations become time consuming. Meanwhile for self-consistent time dependent transport simulations fast algorithms are preferable. In section 3 we compare the accuracy of ECR predictions by CYNEQ for the cases of the homogeneous (0D), 1D and 2D magnetic field approximations and choose approximation appropriate for the self-consistent time dependent analyses. The results of application of CYNEQ for self-consistent 1.5D transport simulations in the framework of ASTRA [7] are discussed.

2. CYNEQ code modification

The code CYNEQ [3] (Electron **CY**clotron radiation transport in **N**on-**EQ**uilibrium hot plasmas), developed for calculation of EC radiation transport in plasma with arbitrary non-equilibrium electron distribution function and high enough reflection of EC waves from the walls , is based on the approach [8], which allowed to semi-analytically solve the transport problem for the case of large coefficient of EC waves reflection from wall ($(1-R_W) \ll 1$), via extending the escape probability methods developed in the theory of nonlocal transport of radiation in atomic spectral lines. Method [8] modifies and improves semi-analytic approach of the code CYTRAN [2], developed for the typical conditions of tokamak-reactor:

- hot maxwellian plasma with the volume-averaged temperature of electrons $<T_e>_V \geq 10$ keV,
- toroidal plasma with noncircular cross-section and moderate aspect ratio, A~3,
- multiple reflection of radiation from the walls.

The assumption of the angle-isotropy of radiation intensity, suggested from the results of SNECTR calculations, allows to simplify the problem of ECR transport by making EC power loss profile one-dimensional, dependent only on the magnetic surfaces in toroidal plasma.

The total magnetic field in the plasma column, derived from plasma equilibrium as a sum of toroidal magnetic field B_{tor}, and poloidal field, B_{pol}, may be considered in the following three representations:
B(2D) – two-dimensional profile of magnetic field $B(\rho,\theta)$, as a function of normalized toroidal flux through the magnetic surface, ρ, and poloidal angle, θ,
B(1D) – one-dimensional profile $B(\rho)$, derived through averaging the field $B(\rho,\theta)$ over magnetic surface,
B(0D) – homogeneous profile, $B(\rho)=\text{const}=B_{tor}(R_0)\equiv B_0$, where B_0 – vacuum toroidal magnetic field on the toroidal axis of vacuum vessel.
In the modified code CYNEQ, plasma equilibrium geometry is described in 3-moment approximation (see FIG. 1):

$$\begin{cases} R(\rho,\theta) = R_0 + \Delta(\rho) + a_{metr}(\rho)(\cos\theta - \delta(\rho)\sin^2\theta), \\ Z(\rho,\theta) = a_{metr}(\rho)\lambda(\rho)\sin(\theta). \end{cases}, \tag{1}$$

where R_0 – major radius of torus, $a_{metr}(\rho)$ – transverse radius of magnetic surface in the torus equatorial plane (conventional minor radius of torus, $a=a_{metr}(1)$), $\Delta(\rho)$ is Shafranov shift, $\lambda(\rho)$ and $\delta(\rho)$ are vertical elongation and triangularity of magnetic surface (see FIG. 1). These momenta and two-dimensional magnetic field are taken from plasma equilibrium calculated self-consistently in 1.5D transport simulations (FIGS. 2, 3).

In the formalism of EC radiation transport [2-3, 8], we use the following averaging over magnetic surface:

$$F(\rho) \equiv < F(\rho,\theta) >_{ms} = \left[\int_0^{2\pi} F(\rho,\theta)\, g(\rho,\theta) d\theta\right] \cdot \left[\int_0^{2\pi} g(\rho,\theta) d\theta\right]^{-1}, \tag{2}$$

where $g(\rho,\theta)$ is plasma volume within the surfaces $\{\rho \div \rho + d\rho\ ,\ \theta \div \theta + d\theta\}$, so that the total plasma volume and the volume-averaging are as follows:

$$V_{tot} = \int_0^1 \int_0^{2\pi} g(\rho,\theta) d\rho d\theta, \tag{3}$$

$$F_v \equiv \langle F(\rho,\theta) \rangle_v = V_{tot}^{-1} \int_0^1 \int_0^{2\pi} F(\rho,\theta)\, g(\rho,\theta) d\rho d\theta \equiv V_{tot}^{-1} \int_0^1 \langle F(\rho,\theta) \rangle_{ms} \frac{dV(\rho)}{d\rho} d\rho \qquad (4)$$

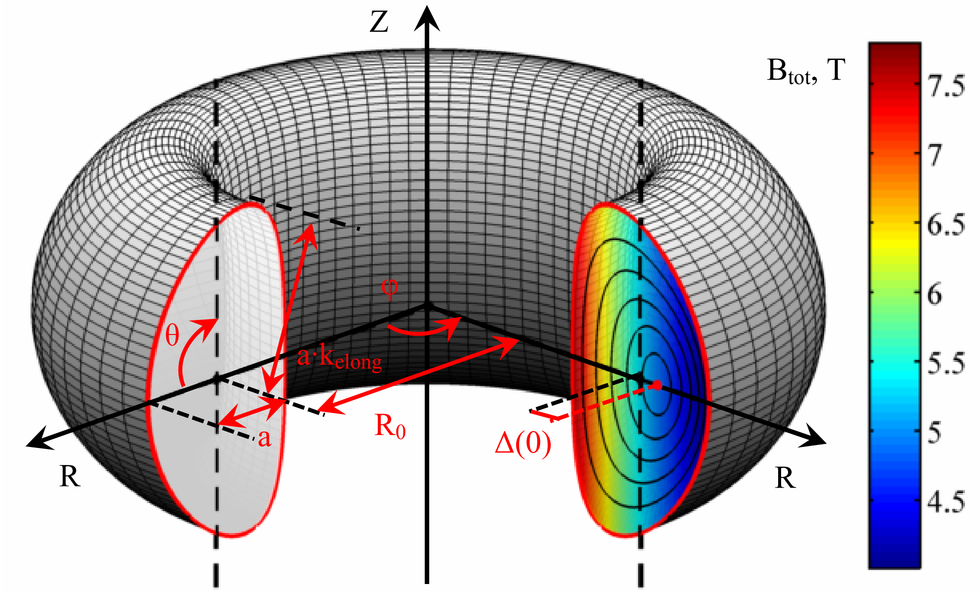

FIG. 1. Geometrical parameters, magnetic surfaces structure and total magnetic field profile. R_0, a – major and minor radii of the plasma column, k_{elong} – elongation, θ, φ – poloidal and azimuthal angles, Δ(0) – the shift of magnetic axis with respect to vessel's toroidal axis. Magnetic surfaces are calculated with Eq. (1) for given moments: magnetic surface radius, $a_{metr}(\rho)$, Shafranov shift, Δ(ρ), triangularity, δ(ρ), and vertical elongation, λ(ρ), taken from the ASTRA code calculations of ITER steady-state operation [9].

In the models [2] and [8], the ECR transport depends only on the angle-averaged coefficients of absorption, $\kappa(\vec{r},\Phi)$, and emission, $q(\vec{r},\Phi)$:

$$\kappa_\xi(\vec{r},\omega) \equiv \int \frac{d\Omega_{\vec{n}}}{4\pi} \kappa(\vec{r},\Phi), \quad q_\xi(\vec{r},\omega) \equiv \int \frac{d\Omega_{\vec{n}}}{4\pi} q(\vec{r},\Phi), \qquad (5)$$

where $\Phi = (\omega, \vec{n}, \xi)$, ω и $\vec{n} = \frac{\vec{k}}{k}$ – frequency and direction of wave, $\vec{k}$ – wave vector, ξ labels the ordinary or extraordinary EC wave mode. In the tokamak reactor geometry (FIG. 1) absorption and emission coefficients are the following functions of normalized radius ρ, wave mode ξ, dimensionless frequency $\tilde{\omega} = \omega / \omega_B$ (ω_B – local fundamental EC frequency, dependent on the local magnetic field B(ρ,θ), τ – characteristic optical thickness):

$$\kappa_\xi(\rho,\, \theta,\, \tilde{\omega}) = \frac{\omega_{pe}^2}{c\omega_B} \chi_\xi\left(\frac{\tilde{\omega} B_0}{B(\rho,\, \theta)}, T_e(\rho)\right) \equiv \frac{\tau}{a} \chi_\xi\left(\frac{\tilde{\omega} B_0}{B(\rho,\, \theta)}, T_e(\rho)\right), \qquad (6)$$

$$q_\xi(\rho,\, \theta,\, \tilde{\omega}) = \kappa_\xi(\rho,\, \theta,\, \tilde{\omega}) \frac{\tilde{\omega}^2 \omega_B^2 T_e(\rho)}{8\pi^3 c^2}. \qquad (7)$$

In the framework [8] for ECR transport in toroidal plasmas the formalism used in code CYNEQ [3] to describe spectral intensity of the outgoing radiation J(ω) and profile $P_{EC}(\rho)$ for B(0D) magnetic field is extended here to the case of B(ρ,θ) magnetic field. The phase space $\Gamma = \{\vec{r}, \omega, \xi\}$, with coordinate $\vec{r}$ and wave (ω,ξ) parts, is still divided into two parts by the type of ECR transport: (i) optically thin outer plasma layer (where the transport is nonlocal), which, for a wide range of frequency, may cover the entire plasma column:

$$\Gamma_{esc} = \left\{ (\rho, \theta, \omega, \xi) : \int_{\rho}^{1} d\rho\ a \cdot \kappa_{\xi}(\rho, \theta, \omega) \leq \tau_{crit} \cong 1 \right\} \tag{8}$$

(ii) residual part of phase space, which is an optically thick inner part of plasma (here the diffusion transport dominates). Formula (8) defines the border between these parts – the function $\rho_{cut}(\omega,\theta,\xi)$, dependent, unlike [3], from poloidal angle (cf. [10]). Note that the function $\omega_{cut}(\rho,\theta,\xi)$, also defined by Eq. (8), is a two-valued function, that should be taken into account when integrating by frequency. Intensity of the outgoing EC radiation is determined by the nonlocal part of the phase space:

$$J_{esc}(\omega, \xi) = \frac{\left\langle q_{\xi}(\rho, \theta, \omega) \right\rangle_{V_{esc}}}{\int \frac{d\Omega_{\vec{n}}}{4\pi} \int \left(\vec{n}, \frac{d\vec{S}_w}{V_{esc}} \right) (1 - R_w) + \left\langle \kappa_{\xi}(\rho, \theta, \omega) \right\rangle_{V_{esc}}}, \tag{9}$$

where V_{esc} is a projection of phase space of Eq. (8) to its coordinate part, $< >_{Vesc}$ is an averaging over volume V_{esc} with the formula (4), S_w is an internal surface of vacuum vessel, R_w is a coefficient of wave reflection from the vacuum vessel wall, which generally is a function of frequency ω and wave direction $\vec{n}$. Profile $P_{EC}(\rho)$ is calculated by the ordinary balance of ECR absorption and emission, averaged over magnetic surface:

$$P_{EC}(\rho) = \left\langle \sum_{\xi} \int d\omega \left[q_{\xi}(\rho, \theta, \omega) - \kappa_{\xi}(\rho, \theta, \omega) J(\omega, \xi, \rho, \theta) \right] \right\rangle_{ms} . \tag{10}$$

In the region defined by Eq. (8), intensity is described by Eq. (9), while in the optically thick region one can neglect the diffusion transport and for the case of maxwellian electron distribution function take the spectral intensity equal to the local Planckian (black body) value, $J_{BB,}$. Thus, in Eq. (10) the net form of the intensity is as follows:

$$J(\omega, \xi, \rho, \theta) = J_{esc}(\omega, \xi) \eta(\rho - \rho_{cut}(\omega, \theta, \xi)) + J_{BB}(\omega, T_e(\rho)) \eta(\rho_{cut}(\omega, \theta, \xi) - \rho), \tag{11}$$

where η – Heaviside function. This gives in the optically thick region the equality $P_{EC}(\rho) = 0$. Note that intensity (11) differs from that in CYTRAN because of neglect of the energy exchange between optically thick internal and optically thin outer regions. This approach gives an alternative to CYTRAN formalism in the optically thick region, eliminating thus the shortcomings of CYTRAN (namely, formal divergence in the center, $P_{EC}(0) \rightarrow \infty$, and overestimation of $P_{EC}(\rho)$ in the central plasma). Formulas (9)-(10) work good for CYTRAN's value of τ_{crit}=1.5 and retain CYTRAN's accuracy of approximating the results of the Monte Carlo code SNECTR. The accuracy may be improved by a simple interpolation of the intensity between the above-mentioned expressions in the optically thin and optically thick regions, within a layer of the unit optical thickness.

CYNEQ calculates the angle-averaged absorption coefficients by the direct numerical integration of the well-known expressions in the vacuum limit (for arbitrary distribution in electron energy and isotropic one in pitch angles). The use of absorption coefficients without refraction and slowing down of the waves is justified [11] because for tokamak-reactor conditions high harmonics of the fundamental EC frequency, ω_B, dominate in the EC transport.

3. ECR modeling in self-consistent 1.5D time dependent transport simulations

CYNEQ module was implemented in the 1.5D transport code in the frame of ASTRA and applied for calculations of ITER steady-state scenario outlined in [9] (see FIGS. 2, 3). The influence of magnetic field approximation on the profile $P_{EC}(\rho)$, intensity, $J(\omega)$, and total power losses is illustrated with FIGS. 4, 5. Also, we compare the ECR profiles predicted by codes CYNEQ-B(2D), CYNEQ-B(1D), CYNEQ-B(0D) and simulator [12], which is a simple semi-analytical approximation of CYNEQ-B(0D).

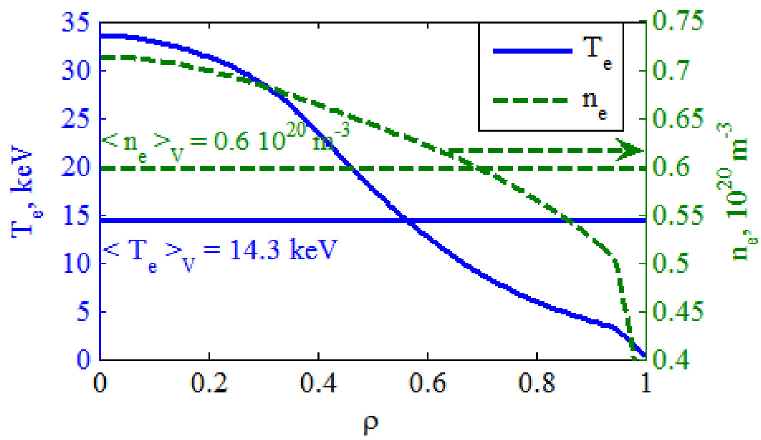

FIG. 2. Electron temperature and density profiles for the steady-state regime of ITER operation [9], used for comparison of EC power loss profile predictions (see FIG. 4).

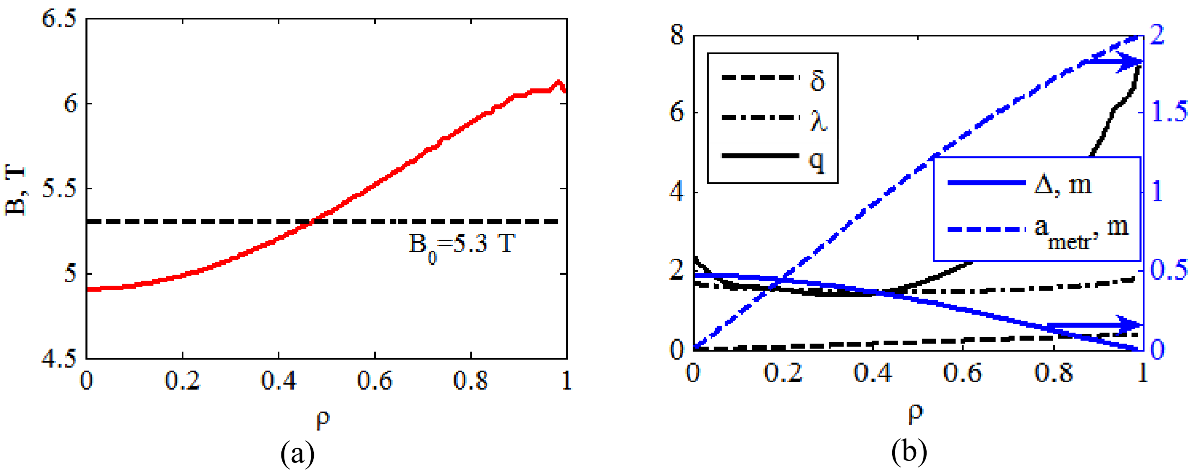

FIG. 3. (a) Comparison of radial distribution of total magnetic fields used in different approximations: dashed line - 0D (homogeneous) case, solid line – surface averaged 2D field used in 1D approximation. (b) Profiles of safety factor, $q(\rho)$, and magnetic flux surface moments: triangularity, $\delta(\rho)$, elongation, $\lambda(\rho)$, Shafranov shift, $\Delta(\rho)$, and magnetic surface minor radius, $a_{metr}(\rho)$. In both figures, parameters are taken from 1.5D self-consistent calculations for steady-state ITER operation [9]. Radial variable ρ is a square root of the normalized toroidal magnetic flux.

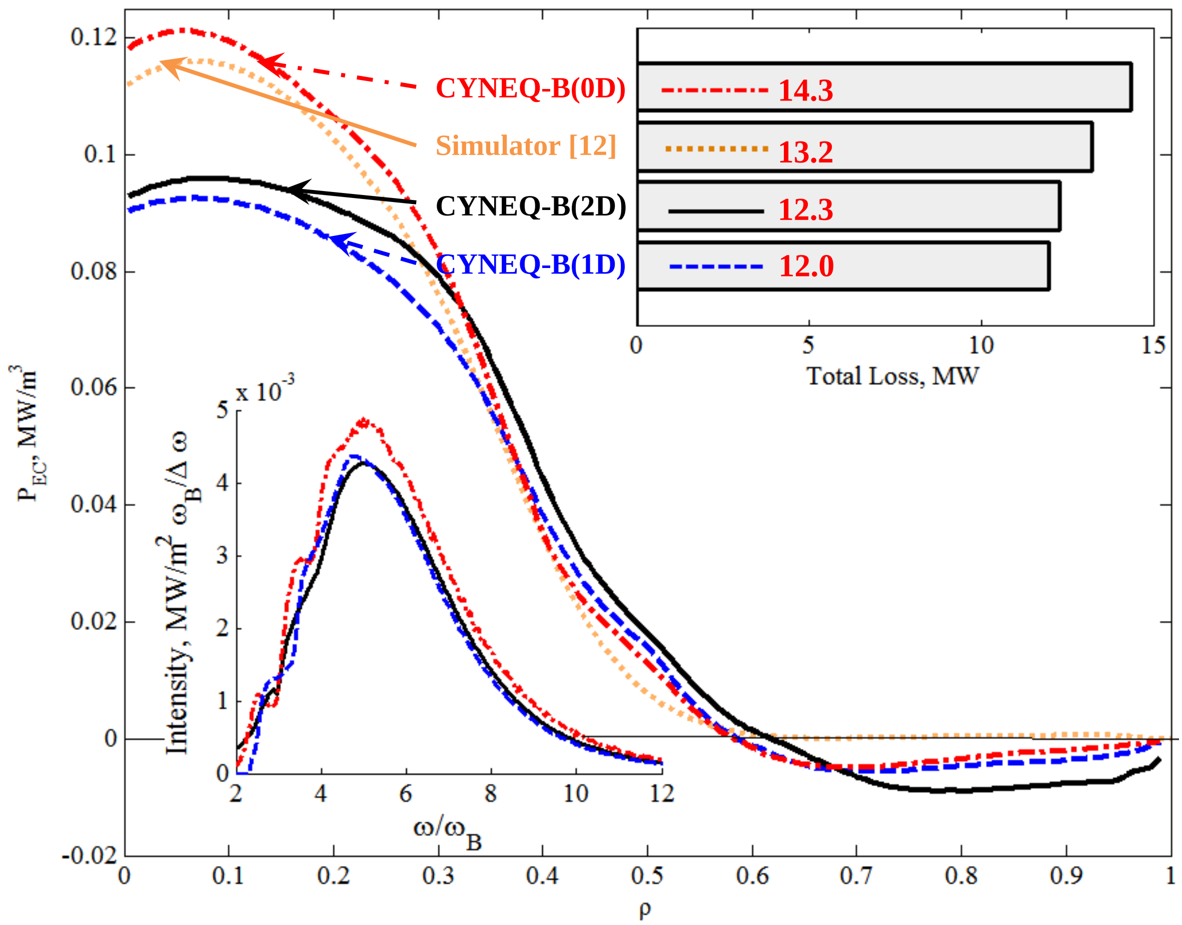

FIG. 4. Profiles of EC power density losses, $P_{EC}(\rho)$, predicted by CYNEQ, for three different cases of magnetic field approximation for self-consistent 1.5D transport simulations [9] for temperature and density profiles displayed in FIG. 2. Volume-integrated total outgoing ECR losses are shown in the legend. Inset: respective intensities of outgoing radiation as a function of frequency normalized to fundamental gyrofrequency for vacuum toroidal field on the vessel's axis.

The difference between ECR predictions by CYNEQ-B(1D) and CYNEQ-B(2D) appeared to be about 5% in the hot central plasma meanwhile 2D calculations are 25 times slower than 1D. Therefore, the 1D approximation of magnetic field looks sufficient and more appropriate for time dependent analyses giving noticeable advantage in the speed of computations.

The relative role of the ECR in power balance for this scenario is visible from FIG. 5. For the analyzed case the central value of ECR losses is about 30% of heating from fusion alphas and almost equal to the central heating from on-axis NBI. Fast increase of the ECR in the center with temperature has a positive impact on stabilization of fusion burning in the case of non-stiff transport coefficients near the plasma center. E.g., for T_i=T_e=T the central heating starts to decrease with increasing central temperature, $d(P_\alpha-P_{rad})/dT < 0$, at T(0) ~ 35 keV. Thus, EC power can slow down the temperature runaway near the center.

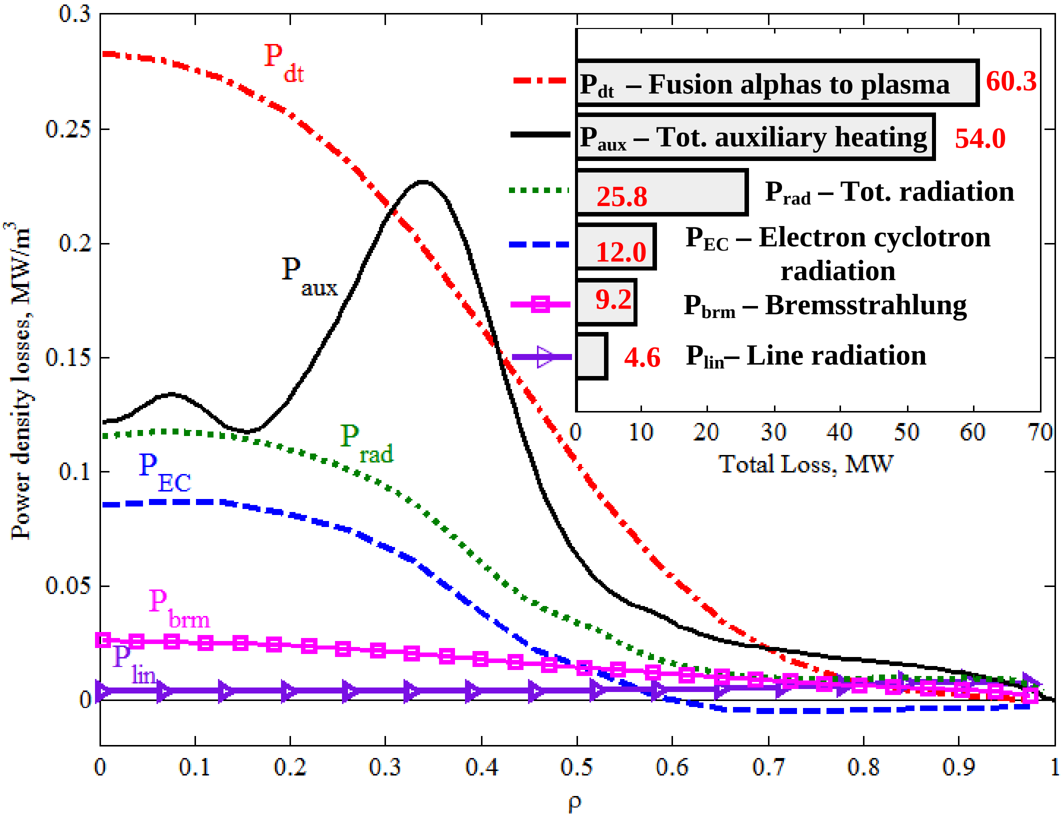

FIG. 5. Comparison of components of the local energy balance for scenario [9] with T_e and n_e profiles from FIG. 2. Inset: comparison of total power losses.

4. Conclusions

The numerical code CYNEQ was modified to take into account the inhomogeneity of the magnetic field in 1D and 2D approximations of magnetic field spatial profile for calculation of the electron cyclotron radiation transport. The dominant effect appeared to be caused by the reduction of the local magnetic field in the hot core due to Shafranov shift. Thus, for reactor scale parameters, accurate simulations of nonlocal heat transport by EC waves requires self-consistent 1.5D calculations of plasma parameters with 2D equilibrium. For parameters expected in ITER steady state scenario the difference between ECR predictions in 1D and 2D approximations of magnetic field appeared to be small. Meanwhile 2D calculations are 25 times slower than 1D. Therefore, the 1D approximation of magnetic field spatial profile looks sufficient and more appropriate for time dependent analyses giving noticeable advantage in the speed of computations.

When central temperature increases to $T_e(0)$ ~30 keV the local EC power loss becomes a substantial part of heating from fusion alphas and is close to the total auxiliary heating. For $T_i \cong T_e$ the fast increase of $P_{EC}(0)$ with temperature has a positive impact on stabilization of fusion burning provided the transport coefficients are not stiff in the central region.

Acknowledgements. This work is supported by the State Corporation ROSATOM under the contract №H.4a.52.03.10.1001 dated 11.01.2010.

References

[1] ALBAJAR, F., BORNATICI, M., CORTES, G., DIES, J., ENGELMANN, F., GARCIA, J., IZQUIERDO, J., "Importance of electron cyclotron wave energy transport in ITER", Nuclear Fusion 45 (2005) 642-648.

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

[3] (A) KUKUSHKIN, A.B., "Heat transport by cyclotron waves in plasmas with strong magnetic field and highly reflecting walls", Proc. 14th IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research, Wuerzburg (1992) 2 35-45; (B) CHEREPANOV, K.V., KUKUSHKIN, A.B., "Influence of suprathermal electrons kinetics on cyclotron radiation transport in hot toroidal plasmas", Proc. 20th IAEA Fusion Energy Conference, Vilamoura, Portugal (2004) P6-56.

[4] ALBAJAR, F., BORNATICI, M., ENGELMANN, F., "Electron cyclotron radiative transfer in fusion plasmas", Nuclear Fusion 42 (2002) 670-678.

[5] ALBAJAR, F., BORNATICI, M., ENGELMANN, F., KUKUSHKIN, A.B., "Benchmarking of Codes for Calculating Local Net EC Power Losses in Fusion Plasmas", Fusion Science and Technology 55 (2009) 76-83.

[6] TAMOR, S., Nuclear Technology/Fusion 3 (1983) 293.

[7] PEREVERZEV, G.V., YUSHMANOV, P.N., "ASTRA - Automated System for TRansport Analysis in a Tokamak", Report IPP 5/98 (2002).

[8] KUKUSHKIN, A.B., "Analytic description of energy loss by a bounded inhomogeneous hot plasma due to the emission of electromagnetic waves", JETP Letters 56 (1992) 487.

[9] POLEVOI, A.R., MEDVEDEV, S.Y., CASPER, T., GRIBOV, Y.V., IVANOV, A.A., SNIPES, J.A., CAMPBELL, D.J., CHUYANOV, V.A., "Assessment of Operational Space for Long-pulse Scenarios in ITER", Proc. 37th EPS Conference on Controlled Fusion and Plasma Physics, Dublin, Ireland (2010) P2.187.

[10] CHEREPANOV, K.V., KUKUSHKIN, A.B., MINASHIN, P.V., NEVEROV, V.S., "Nonlocal vs. Diffusion mechanisms of electron cyclotron radiation transport in fusion reactor-grade tokamaks", Proc. 34th EPS Conference on Controlled Fusion and Plasma Physics, Warsaw, Poland (2007), ECA 31F P4.133.

[11] TRUBNIKOV, B.A., Plasma Physics and the Problem of Controlled Thermonuclear Reactions Series, ed. M.A. Leontovich, New York: Pergamon Press (1959) 122.

[12] (A) CHEREPANOV, K.V., KUKUSHKIN, A.B., "Parameterization of Radial Profile of Electron Cyclotron Radiation Power Loss in Fusion Reactor-Grade Tokamaks", Proc. 33rd EPS Conference on Controlled Fusion and Plasma Physics, Rome, Italy (2006) P1.169; (B) KUKUSHKIN, A.B., ZHOGOLEV, V.E., "Fast routine for calculating the electron cyclotron powerloss profile in tokamak-reactors", Preprint Russian Research Centre "Kurchatov Institute" IAE-6507/8 (2008).