Influence of Plasma Equilibrium on Scaling Laws for Local and Total Electron Cyclotron Power Losses in Tokamak-Reactors

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1. Introduction. Electron cyclotron (EC) wave emission can significantly contribute to the local electron power balance in central part of plasma column for high temperatures expected in DEMO and steady-state regimes of ITER operation (see, e.g., [1,2]). In this view it is very important to develop the fast and accurate routines for calculating of the 1D distribution, over magnetic flux surfaces, of the net radiated power density, $P_{EC}(\rho)$. Benchmarking of codes for the $P_{EC}(\rho)$ profile (SNECTR [3], CYTRAN [4], CYNEQ [5], EXACTEC [6]) in a wide range of temperature and density profiles expected in reactor-grade tokamaks was carried out in [7] for homogeneous profile of magnetic surface-averaged magnetic field, $B(\rho)$=const. The similarity of the $P_{EC}(\rho)$ profile, normalized to total (i.e. volume-integrated) power loss, for identical profiles of normalized electron temperature and density has been found in [8] again for $B(\rho)$=const. The above similarity of the $P_{EC}(\rho)$ profiles was shown to be a measure of numeric code's accuracy. The benchmarking [7] was extended in [2,[9] (including the results from new code RAYTEC [10] and from CYTRAN, EXACTEC, and modified CYNEQ [9],[11] codes in the frame of self-consistent 1.5D transport simulations) to the case of inhomogeneous magnetic field profile $B(\rho)$ calculated with account of the plasma equilibrium (Shafranov shift, 2D plasma shape).

Here we analyze the influence of plasma equilibrium effects such as the Shafranov shift, elongation and triangularity of the plasma on the above similarity of the normalized $P_{EC}(\rho)$ profiles and on the possibility of using this scaling law as an additional method of benchmarking the numeric codes for spatial profiles and total power of the EC losses.

2. Universal shape of the spatial profile of power loss. The similarity of the shape of the $P_{EC}(\rho)$ profiles is formulated as follows:

$$P_{EC}^{norm}(\rho) \equiv \frac{P_{EC}(\rho)}{P_{EC}^{tot} / V_{tot}} = f\left(\rho, \left[\frac{T_e(\rho)}{< T_e >_V}\right], \left[\frac{n_e(\rho)}{< n_e >_V}\right]\right), \tag{1}$$

where P_{EC}^{tot} is total (volume integrated) EC radiation losses, V_{tot} is the plasma volume, $< >_V$ is a volume-average value, and the brackets [ ] stand for a functional dependence. This scaling law appears to be valid for the results of calculations of all existing codes for the EC power losses. First, we illustrate this in figs. 1, 2 for the case of a given homogeneous magnetic field, i.e. without taking into account the plasma equilibrium effects and for different temperature profiles, given by the formula:

$$T_e(\rho) = T_e(1) + (T_e(0) - T_e(1))(1-\rho^{\beta T})^{\gamma T} \tag{2}$$

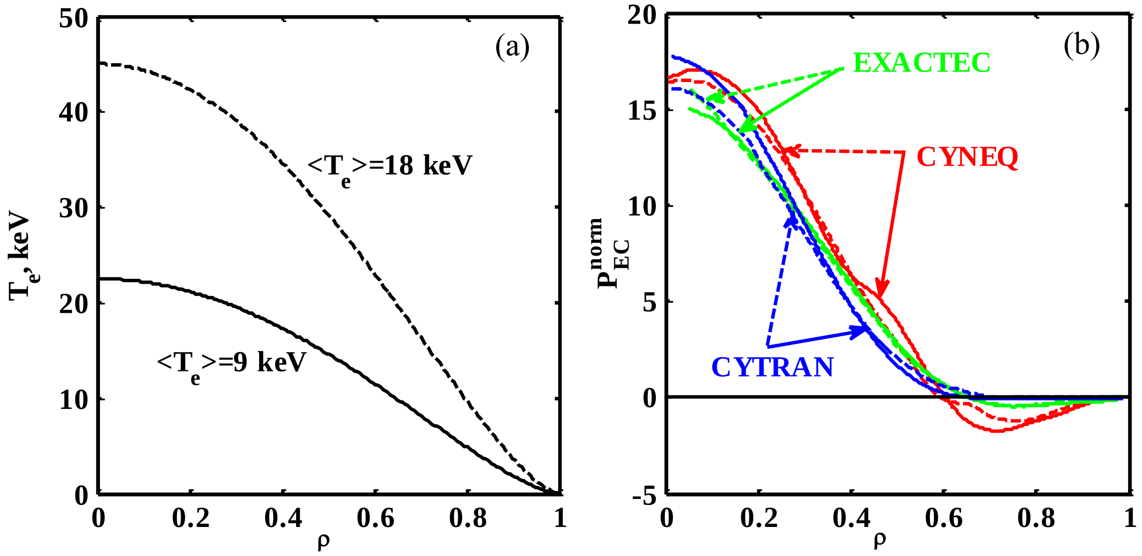


Fig. 1. (a) Parabolic electron temperature profiles, calculated by the formula (2) with $T_e(1)$=0.01 keV, βT=2, γT=1.5 and substantially different values of central temperature, $T_e(0)$, 45 keV (dashed line), 22.5 keV (solid line) (the volume averaged temperatures shown on the figure). (b) Similarity of the shape of the $P_{EC}^{norm}(\rho)$ profiles Eq. (1) predicted by the CYNEQ, CYTRAN and EXACTEC codes for temperature profiles in fig. 1a (dashed line corresponds to the case $T_e(0)$=45 keV, solid line, $T_e(0)$=22.5 keV), R_0=6.2 m, a=2 m, B_0=5.3 T, R_w=0.8. Electron density profile is given by the same equation as temperature profile and other parameters $n_e(0)=1.1\ 10^{20}\ m^{-3}$, $n_e(1)$=0, βn=2, γn=0.1.

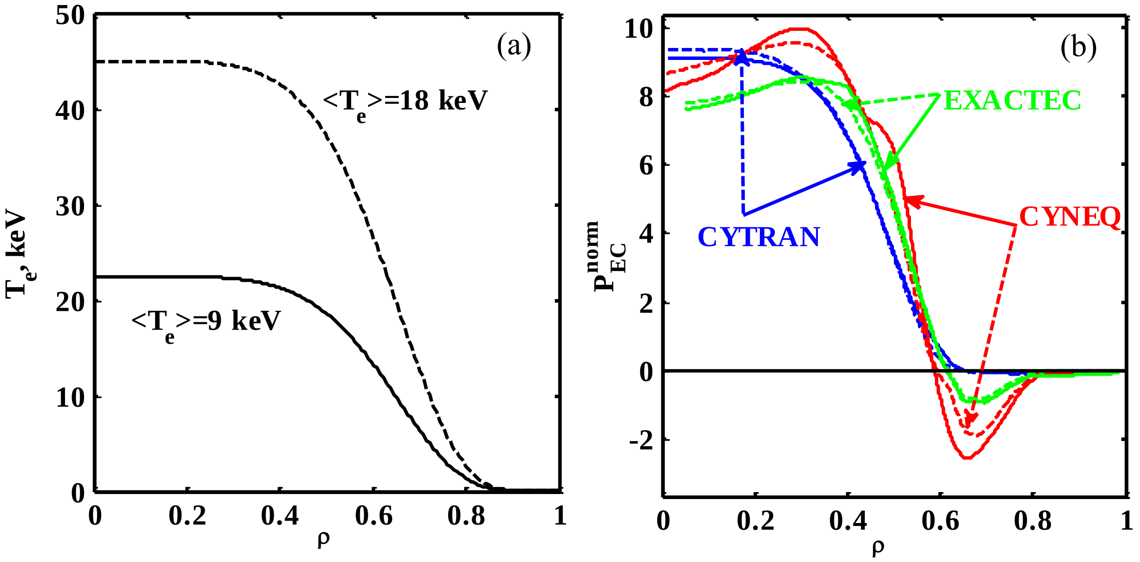
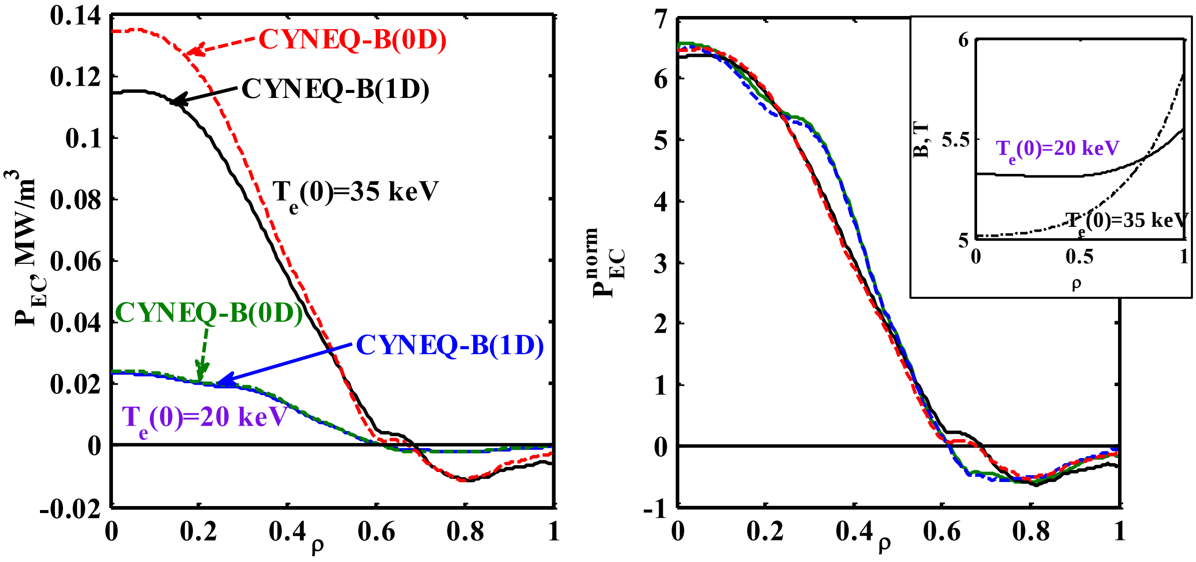


Fig. 2. The same as in fig. 1 but for an "advanced" T_e profile (Eq. (2) with βT=5.4, γT=8).

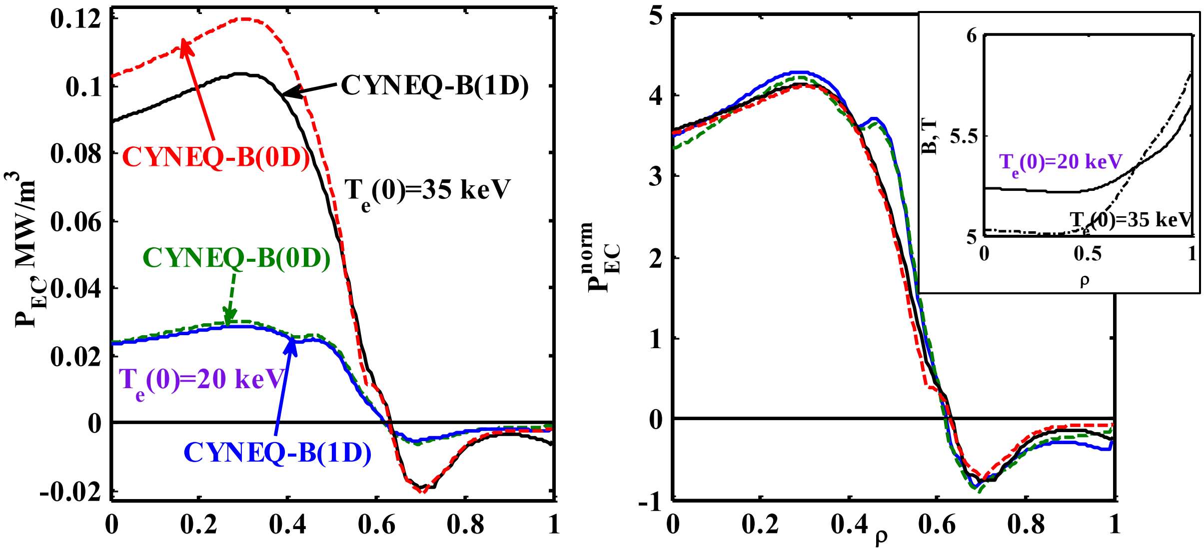
One can see the correlation between the degree of similarity of the shape of the $P_{EC}(\rho)$ profiles and the accuracy of the numeric code: the similarity is highest for the EXACTEC code which is based on the exact solution of the radiative transfer problem for plasmas in a cylinder with circular cross section [6].

3. Account of the plasma equilibrium effects. The influence of plasma equilibrium on the scaling law (1) for the P_{EC}^{norm} profiles can be analyzed with the help of the modified code CYNEQ [5]. The CYNEQ-B(1D) version of the code takes into account the effects of the magnetic field inhomogeneity with allowance for plasma equilibrium which is calculated in the frame of the ASTRA code [12], while the CYNEQ-B(0D) version uses homogeneous magnetic field $B(\rho)=\langle B\rangle_V$ (see fig. 3, 4).



(a) (b)

Fig. 3. (a) Profiles of the power density loss, $P_{EC}(\rho)$, calculated by the CYNEQ-B(1D) and CYNEQ-B(0D) versions of the code for parabolic electron temperature profile (Eq. (2) with $\beta T=2$, $\gamma T=1.5$) for substantially different values of central temperature, $T_e(0)=$ 20 keV, $T_e(1)=$ 1 keV ($n_e(0)=0.7\ 10^{20}$ m^{-3}, $n_e(1)=0.1\ 10^{20}$ m^{-3}, $\beta n=2$, $\gamma n=0.1$) and $T_e(0)=$ 35 keV, $T_e(1)=$ 3 keV ($n_e(0)=1.0\ 10^{20}$ m^{-3}, $n_e(1)=0.6\ 10^{20}$ m^{-3}, $\beta n=2$, $\gamma n=0.1$), and ITER-like parameters $R_0=6.2$ m, $a=2$ m, $k_{elong}=1.8$, $R_w=0.8$, plasma current $I_p=10$ MA. For CYNEQ-B(1D) calculations (solid lines) the magnetic field and plasma equilibrium are taken from the calculations of the ASTRA code [12], while for CYNEQ-B(0D) calculation we use $B(\rho)=\langle B\rangle_V$ (dashed lines) (b) Similarity of the shape of the $P_{EC}^{norm}(\rho)$ profiles calculated from the curves in fig. 3a. Inset: profiles of magnetic field obtained from plasma equilibrium calculated with the ASTRA code (Shafranov shift equals to $\Delta(0)=0.4$ m for $T_e(0)=$ 35 keV, and $\Delta(0)=0.3$ m for $T_e(0)=$ 20 keV).



(a) (b)

Fig. 4. The same as in fig. 3 but for an “advanced” T_e profile (Eq. (2) with βT=5.4, γT=8).

4. Conclusions. Spatial profiles of the ECR power losses normalized to the total (volume integrated) ECR power losses per unit volume, $P_{EC}^{norm}(\rho) = \dfrac{P_{EC}(\rho)}{P_{EC}^{tot} / V_{tot}}$, are shown to be identical functions for the same normalized profiles of electron temperature and density. This scaling law is valid for the results of calculations of all existing codes for the ECR losses in tokamak-reactors. The degree of similarity of P_{EC}^{norm} correlates with the accuracy of these codes. The effects of plasma equilibrium (e.g., Shafranov shift) do not affect the above similarity of the $P_{EC}(\rho)$ profiles.

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