Analytical Models for Spatial Profile and Total Electron Cyclotron Power Loss in Tokamak Reactors

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1. Introduction. For the next generation of tokamaks like ITER and DEMO, in contrast to all previous devices, the electron cyclotron radiation (ECR) power loss will play an important role because of expected high temperatures in central plasma and high magnetic field [1]. The modelling of the steady state regimes of ITER operation predicts the significant contribution of the ECR power loss to the local electron power balance [1], [2], [3]. The ECR power loss can also limit the fusion power temperature excursions in ITER and DEMO for central electron temperature $T_e(0)>35$ keV [4]. The above demanded the development of numerical codes for more accurate ECR transport calculations (especially in central plasma).

According to the benchmarking of the ECR transport codes carried out in [5] for the flat profile of flux surface-average magnetic field, $B(\rho)$=const, and updated in [6] for self-consistent 2D plasma equilibrium (also the new code RAYTEC [7] was included), the modified CYNEQ code [8] is the most appropriate code for using in the global transport codes (like ASTRA [9]) for self-consistent 1.5D transport simulations of plasma evolution in tokamak reactors because it provides good approximation and computational efficiency. However, for simple transport models it is of interest to have analytical models for the spatial ECR power loss profile, $P_{EC}(\rho)$ (1D distribution, over magnetic flux surfaces, of the net radiated power density), and total power loss, P_{tot} (the ECR power loss, integrated over the plasma volume).

Here we give a brief review of the existing analytical models for the ECR spatial loss profile and total power loss. We also analyze the possibility of using these models under conditions of ITER and DEMO.

2. Analytical models for spatial EC power loss profile. Under conditions of reactor-grade tokamaks (hot Maxwellian plasma with volume-average temperatures $\langle T_e \rangle_V \geq 10$ keV, toroidal plasma with noncircular cross-section and moderate aspect ratio, multiple reflection of radiation from the vessel wall) the transport of the EC radiation is characterized by its nonlocal (non-diffusive) nature, i.e. most of the EC radiation energy carried by the photons is related to the frequencies for which the plasma is optically thin. Nonlocal transport of plasmaproduced EC radiation in tokamak reactors has the following properties: (a) the ECR transport depends on the angle-averaged spectral distributions for the emission and absorption coefficients (for a Maxwellian plasma these coefficients are the functions of temperature and normalized frequency), (b) the intensity of the EC radiation is an isotropic function of frequency and EC wave's type, (c) for a wide range of frequencies, for which the spectral energy balance gives major contribution to the $P_{EC}(\rho)$ profile, the outer optically thin region (where the nonlocal transport dominates) can cover almost the entire volume of the plasma. These properties of the ECR transport in a tokamak reactor allow to obtain an analytical description of the profile $P_{EC}(\rho)$.

There are several approaches for the analytical description of the ECR transport problem in tokamaks. (**A**) Semi-analytical models: analytical solution of the ECR transport equation + approximate formulas for the EC absorption and emission coefficients (CYTRAN code [10], EXACTEC code [11], parameterization of the $P_{EC}(\rho)$ profile [12] – CYNEQ Simulator) (see also benchmarkings [5], [6]). (**B**) Modification and intuitive generalization of the approximate expressions for the total EC loss (generalization of the famous Trubnkiov formula [13] for the ECR loss in a homogeneous plasma slab – LATF [Locally Applied Trubnikov Formula] [7], or localization of the total power loss [14] – LNONLOC). (**C**) The use of scaling laws of the ECR transport in tokamak reactors [15], [16]. Figure 1 shows a comparison of analytical models for $P_{EC}(\rho)$ profile with calculations of the numeric codes CYNEQ and CYTRAN for steady state regimes of ITER and DEMO operation.

3. Analytical models for total EC power loss. Total EC power loss, P_{tot}, can be calculated as the volume integral of spatial ECR loss profile, $P_{EC}(\rho)$. The existing formulas for P_{tot} have been obtained by approximating the numerical calculations ([17], [18]) or by a generalization of the Trubnikov formula for a homogeneous plasma slab [13] for the case of inhomogeneous plasmas in tokamak reactors ([15]). Figure 2a shows a comparison of the existing analytic approximations of the total ECR power loss with calculations by the CYNEQ code. Figure 2b shows the scaling law of the ECR transport in tokamak reactors – universal shape of the normalized profiles $P_{EC}(\rho)/P_{tot}$ for identical normalized temperature and density profiles [15].

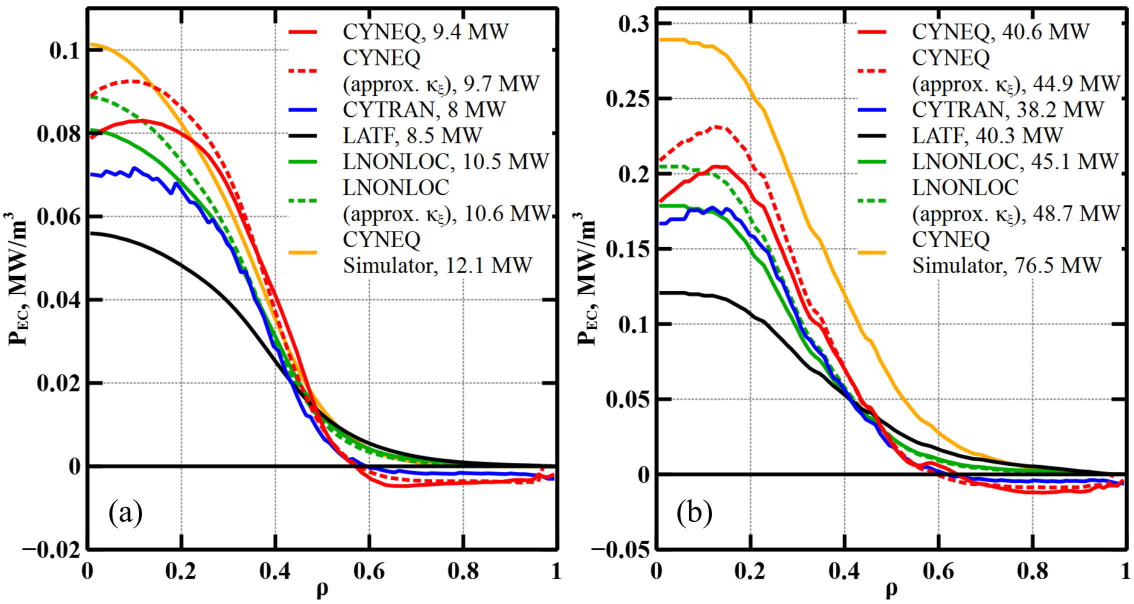

Fig. 1. Comparison of analytical models for $P_{EC}(\rho)$ profile with calculations of numeric codes CYNEQ and CYTRAN, for (a) steady state regime of ITER operation [19] (R_0=6.2 m, a=2 м, k_{elong}=1.76, reflection from the wall R_w=0.6, B_0=5.3 T, $T_e(0)$=30 keV, $T_e(1)$=1 keV, $n_e(0)$=0.75 10^{20} m^{-3}, $n_e(1)$=0,4 10^{20} m^{-3}, I_p=9 MA) and (b) steady state regime of DEMO operation with ECH and ECCD [3] (R_0=7.5 m, a=2,5 m, k_{elong}=1.9, R_w=0.7, B_0=6 T, $T_e(0)$=35 keV, $T_e(1)$= 0.7 keV, $n_e(0)$= 1.27 10^{20} m^{-3}, $n_e(1)$= 0.5 10^{20} m^{-3}, I_p=19 MA). The calculations by the modified CYNEQ code [20] carried out for the 1D approximation of the flux-surface-average magnetic field. In calculations labeled as *approx.* κ_ξ the approximate formulas for absorption coefficients are used (obtained by Tamor in [10] and improved by Bateman (see ref. in [5])).

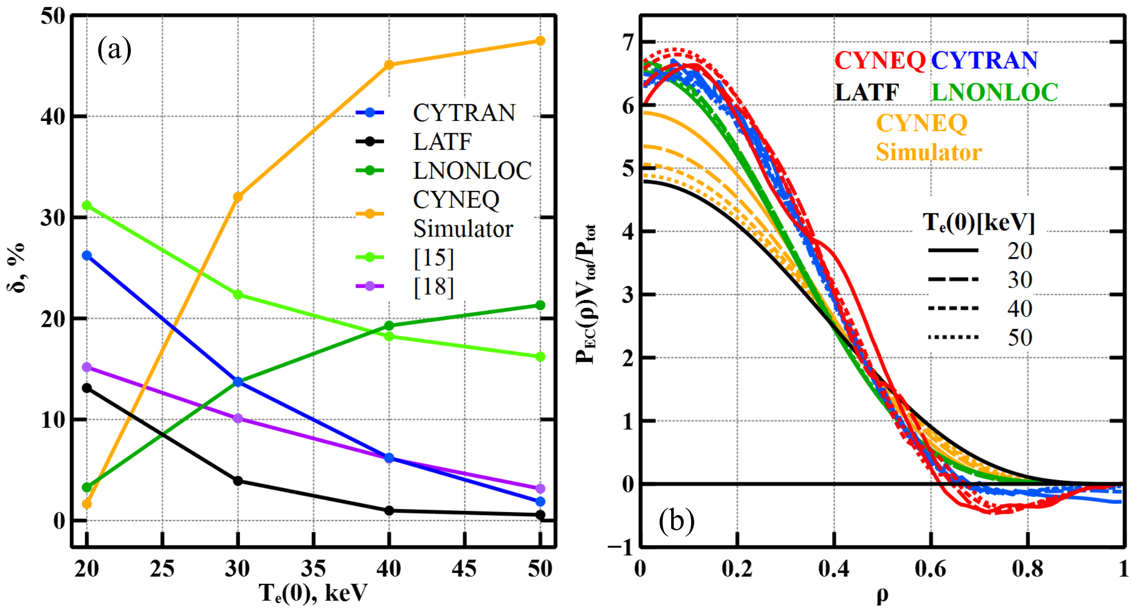

Fig. 2. (a) Relative deviation, δ, of total EC power loss given by analytic formulas from calculations by CYNEQ code: CYTRAN calculations (blue), LATF [7] (black), LNONLOC (green), CYNEQ Simulator (orange), formula [15] (light green), formula [18] (purple). Calculations are carried out for ITER-like conditions: parabolic T_e profile $T_e(\rho)=T_e(0)(1-\rho^2)^{1.5}$, R_0=6.2 m, a=2 m, k_{elong}=1.9, B_0.=5.3 T, R_w=0.6, $n_e(\rho)=(1-\rho^2)^{0.1}$ 10^{20} m^{-3}. (b) Similarity of the $P_{EC}(\rho)$ profiles corresponding to calculations in figure 2a.

4. Conclusions. The paper presents a brief review of existing analytical models for the ECR spatial loss profile and total power loss in tokamak reactors. The applicability of these models for the conditions of tokamak reactors ITER and DEMO is analyzed. It is shown that for DEMO none of the existing scaling formulas can properly describe the P_{EC}-profile in the center of plasma column. The total ECR power losses can be described with a good accuracy by the approximate formulas [18], [15].

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