Limit of Electron Cyclotron Radiation in ITER Long Pulse Operation

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1. Introduction. Electron cyclotron radiation (ECR) loss strongly increases with the electron temperature, $P_{EC} \sim n_e^{0.5}T_e^{2.5}$ [1], meanwhile heating from fusion alphas saturates with the temperature increase, $P_\alpha \sim n_e^2\ T_e^\gamma$, $\gamma < 2$ [2]. For the case of high electron temperatures, $T_e > 30$ keV, and moderate electron densities, $n_e \sim 7\text{-}6\ 10^{19}\ m^{-3}$, optimal for the maximal current drive (CD) efficiency in the long pulse operation, the role of the EC radiation becomes more pronounceable in comparison with the heating from fusion alphas. It is clear that temperature excursion has a natural radiative limit, $T < T_{cr}(n)$ at $P_{EC}(T_{cr}) = P_\alpha(T_{cr})$, and this limit reduces with the density reduction. Here we assess the role of the ECR for the range of plasma parameters, required for long pulse operation in ITER [3] with current drive by 33 MW of the neutral beam (NBCD) and by 20 MW of the electron cyclotron waves (ECCD).

2. Role of ECR power losses. To assess the effect of temperature excursions on plasma parameters, we carried out self-consistent 1.5D transport simulations. The ECR losses were calculated using the CYNEQ code [4],[5] extended to a full account of the 2D inhomogeneity of the magnetic field [6], assuming the wall reflection coefficient, $R_w = 0.6$. For moderate densities, $n_e \sim 6\ 10^{19}\ m^{-3}$, and high temperatures, $T_e(0) \sim 25$ keV, required for long pulse operation, the volume-integrated ECR loss is relatively small, $f_{ECR} \equiv Q_{EC}/(Q_\alpha + Q_{aux}) \sim 9\%$ (Fig. 1a). With temperature excursion (Fig. 1b) it reaches the radiative limit for electrons in the hot core, $P_{EC}(0) = P_{\alpha,e}(0)$ (Fig. 1a), simultaneously with the ideal MHD stability limit, $\beta_N = 4\ l_{i3} \sim 3$ (Fig. 1b). Meanwhile the relative loss fraction remains moderate at this limit, $f_{ECR} < 18\%$ (Fig. 1a), it helps to keep power loss to divertor in the moderate range, $Q_{loss} < 110$ MW. Fusion power excursion also remains moderate, $Q_{fus} < 500$ MW (Fig. 1c).

For the analyzed case the central value of the ECR loss is about 30% of heating from fusion alphas and almost equal to the central heating from on-axis NBI (see Fig. 5 of [6]). Qualitatively, the latter agrees with the results obtained in [7] by self-consistent 1.5D transport simulations of ITER steady-state scenarios with the CYTRAN module in the frame of the Automated System for Transport Analyses (ASTRA).

For $T_i = T_e = T$, $n_e \sim 6\ 10^{19}\ m^{-3}$, $B_0 = 5.3$ T the central heating of electrons by the fusion alphas starts to decrease with increasing central temperature, $d(P_\alpha - P_{rad})/dT < 0$, at $T_e(0) \geq 35$ keV (Fig. 1d), the EC loss starts to dominate and requires accurate assessment.

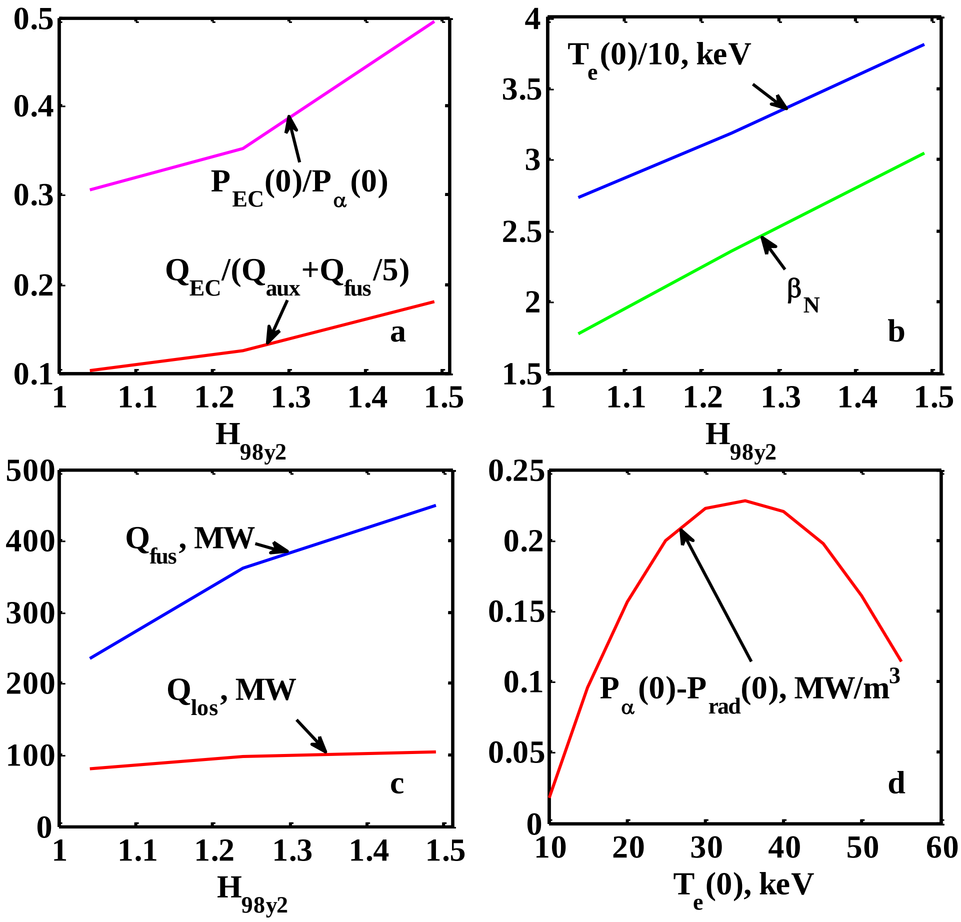

Fig. 1. (a) Local, $P_{EC}(0)/P_\alpha(0)$, and total, $Q_{EC}/(Q_{aux}+Q_{fus}/5)$ fraction of EC loss, (b) central electron temperature and normalized beta, (c) fusion power, Q_{los} and loss to the SOL, $Q_{los} = Q_\alpha + Q_{aux} - Q_{rad}$ from 1.5D simulations of scan of plasma confinement, H_{98y2}. The scan is started from plasma parameters required for long pulse operation in ITER at low density [3], I_p = 15 MA, <n> ~ $6\ 10^{19}\ m^{-3}$. (d) Central power balance from 1.5D simulations of temperature scan with $T_i=T_e$ at low density, <n> ~ $6\ 10^{19}\ m^{-3}$ in ITER-like configuration [6].

3. Comparison of codes for EC power loss. The importance of EC power loss in fusion reactor-grade tokamaks makes it reasonable to extend the benchmarking [8], comparing the results of CYNEQ simulations with predictions by the CYTRAN [7], EXACTEC [9], RAYTEC [10] codes for ITER and DEMO cases. Short description of the CYNEQ code for various dimensionality of magnetic field approximation is given in [6]. The EC power density profiles, $P_{EC}(\rho)$, are shown in Figs. 2-4. Volume-integrated losses are shown in histograms. Temperature and density profiles are prescribed as follows:

$$F(\rho)=F(1)+(F(0)-F(1))(1-\rho^{\beta_F})^{\gamma_F}, \quad F=\{T_e,n_e\}, \tag{1}$$

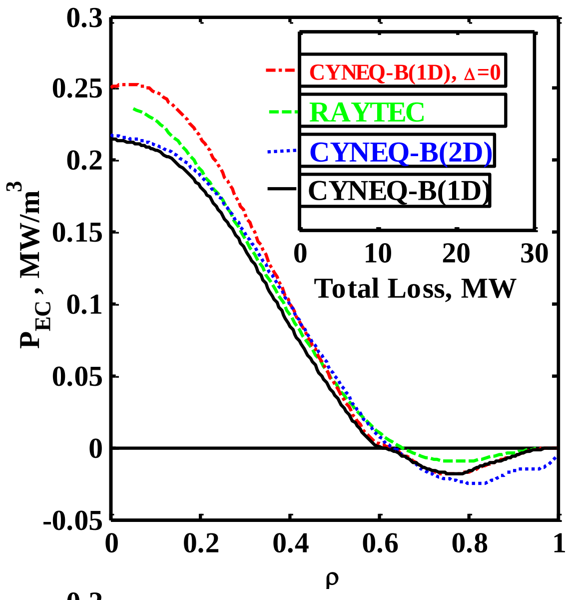

Fig. 2. EC power density, $P_{EC}(\rho)$ predicted by RAYTEC [10] and CYNEQ codes for major/minor radii R_0=6.2 m, a=2 m, plasma elongation k=1.7, triangularity δ=0, wall reflection coefficient R_w=0.8, I_p=11 MA, $T_e(0)$=45 keV, $T_e(1)$=0.01 keV, β_T=2, γ_T=1.5, $n_e(0)$=1.1 10^{20} m^{-3}, $n_e(1)$=0, β_n=2, γ_n=0.1, , Z_{eff}=2, T_i=T_e. Magnetic surfaces are taken to be concentric ellipses. CYNEQ calculations are carried out for 1D and 2D magnetic field, calculated from plasma equilibrium for prescribed temperature, density and current density profiles with calculated Shafranov shift, $\Delta(0) \cong 0.4$ m.

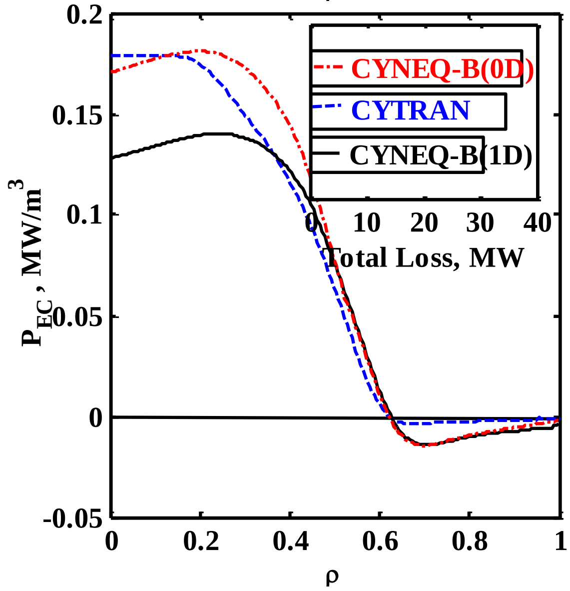

Fig. 3. Predictions of the CYNEQ and CYTRAN codes for the ITER steady-state scenario [7] with R_0=6.4 m, a=1.9 m, k=1.9, δ=0.4, R_w=0.6, B_0=5.2 T, I_p=9 MA, Z_{eff}=2.3, $T_e(0)$=43 keV, $T_e(1)$ = 3.3 keV, $n_e(0)$=0.7 10^{20} m^{-3}, $n_e(1)$ = 0.1 10^{20} m^{-3}, β_n =2, γ_n=0.1. The CYNEQ-B(1D) case corresponds to 1D magnetic field, $B(\rho)$, calculated from plasma equilibrium for temperature, density and current density profiles of [7] ($\Delta(0) \cong 0.4$ m). The CYNEQ-B(0D) loss is calculated for homogeneous magnetic field, $B = \langle B \rangle_v$ = 5.26 T, similarly to CYTRAN.

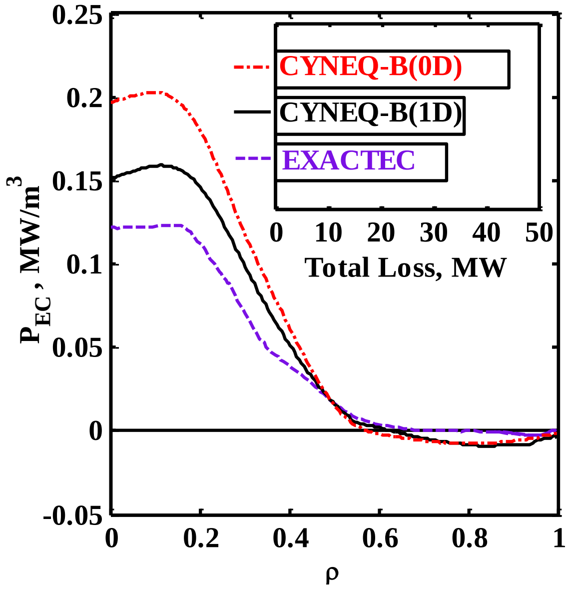

Fig.4. Predictions of the CYNEQ and EXACTEC codes for steady state scenario in DEMO with ECH/ECCD [9] (R_0=7.5 m, a=2.5 m, k=1.9, δ=0.47, R_w=0.7, B_0=6 T, I_p=19 MA, Z_{eff}=2.2). The EXACTEC's $P_{EC}(\rho)$ profile is taken from figure 11 of [9]. The CYNEQ-B(1D) case corresponds to 1D magnetic field, $B(\rho)$, with $\Delta(0) \cong 0.3$ m. The CYNEQ-B(0D) loss corresponds to $B(\rho) = \langle B \rangle_v$=6.28 T.

4. Conclusions. (i) The EC power loss can play noticeable role in the local power balance near the center for $T_e(0) > 30$ keV at moderate densities, $n_e \sim 6\ 10^{19}\ m^{-3}$. In the global power balance it remains relatively small, but helps to keep fusion power and divertor loads at moderate level for all imaginary temperature excursions up to the MHD limit, $\beta_N = 4l_{i3}$. (ii) Benchmarking of the CYNEQ-B(2D) and CYNEQ-B(1D) vs. CYTRAN, EXACTEC, RAYTEC is carried out with the same assumptions of plasma configuration used for each of the codes. Good agreement with the full 2D code RAYTEC [10] is demonstrated for ITER-like configuration with both the CYNEQ-B(2D) and CYNEQ-B(1D) approximations. The CYTRAN predictions [7] are close to the CYNEQ-B(0D) with zero Shafranov shift. If the shift is calculated consistently from plasma equilibrium the difference increases to 30% in the hot center where the local loss is the most pronounceable. In the case of DEMO steady-state scenario [9] the difference of EXACTEC from CYNEQ-B(0D) is about 40% in the central plasma while in the case of CYNEQ-B(1D) the difference reduces to ~20%.

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