Influence of Suprathermal Electrons Kinetics on Cyclotron Radiation Transport in Hot Toroidal Plasmas

K.V. Cherepanov, A.B. Kukushkin,
NFI RRC "Kurchatov Institute", Moscow, 123182, Russia

e-mail: kuka@nfi.kiae.ru

Abstract. Numerical studies of the contribution of suprathermal electrons to electron cyclotron radiation (ECR) transport in hot (Te > 10 keV) plasmas confined by a strong toroidal magnetic field (B > 5 T) are reported. The respective code (Proc. 14th IAEA Conf. PPCF, Wuerzburg, 1992, v.2, p.35) which, for maxwellian electron velocity distribution (EVD) with inhomogeneous temperature/density, has been tested against well-known numerical and semi-analytical codes by S. Tamor, is now applied to solving the following two problems for ITER-like conditions. (1) Spatial profile of the net radiated power density, $P_{EC}(r)$, is found to be strongly sensitive to the presence of suprathermal electrons. This enables us to evaluate allowable limits for local rise of effective temperature/density of suprathermal electrons (in terms of bi-maxwellian EVD). (2) Self-consistent modeling of the ECR transport and the kinetics of suprathermal electrons gives spatial profile of deviations from maxwellian EVD, caused by the transport of plasma's self EC radiation. These kinetic effects work ultimately for the global flattening of the $P_{EC}(r)$ profile: a lowering, in the core, and a rise, in the periphery. For ITER-like conditions, these effects upon $P_{EC}(r)$ appear to be small. The results of treating the above two tasks suggest the necessity of solving self-consistently the problems of (i) ECRH and ECCD optimization and (ii) ECR transport in the entire range of radiation frequency, when strong enough suprathermals may be produced.

1. Introduction

The transport of electron cyclotron radiation (ECR) in hot (T_e > 10 keV) toroidal plasmas confined by a strong magnetic field (B_T > 5 T) is known, for highly reflecting walls, to exhibit the following features [1,2(A),3]:

- the escaping radiation spectrum is dominated by the high harmonics of fundamental electron cyclotron frequency;
- peripheral plasma appears to be a net absorber of the ECR, thus attenuating the radiation emitted by the hot core;
- spatial profile of the net radiated power density, $P_{EC}(r)$, strongly depends on the temperature and density profiles;
- concentration of $P_{EC}(r)$ in the core (i.e. the peaked profile) may influence the ignition conditions even for not so large *total* ECR power loss.

Here we report on numerical studies of the contribution of suprathermal electrons to $P_{EC}(r)$ in toroidal magnetically confined plasmas. The respective code CYNEQ (electron CYclotron radiation transport in Non-EQuilibrium hot tokamak plasmas) is based on the approach [2] which allowed, via extending the *escape probability* methods developed in the theory of nonlocal transport, to solve semi-analytically the transport problem in the case of a strong enough reflection of EM waves from the wall. This approach simplifies the semi-analytic approach of the code CYTRAN [1(B)] (developed for hot *maxwellian* toroidal plasmas of non-circular cross-section, not too large aspect ratio, multiple reflection of waves from the wall) and retains the CYTRAN's accuracy of approximating the results of the Monte Carlo code SNECTR [1(A)]. CYNEQ was also tested [2(A)] against well-known benchmark -- numerical results, and respective analytic fit [4], for *total* ECR power loss for *maxwellian* electron plasmas of *homogeneous* profiles of temperature and density.

The modeling carried out enables us to solve the following two tasks. First, modeling of $P_{EC}(r)$ for bi-maxwellian electron velocity distribution (EVD) calculates the impact of suprathermal electrons on $P_{EC}(r)$ for ITER-like conditions (Sec. 2) and allows to evaluate allowable limits for density/temperature of suprathermals. Second, the revealed sensitivity of $P_{EC}(r)$ to suprathermal electrons suggests the necessity of a self-consistent treatment of (i) kinetics of suprathermal electrons and (ii) ECR transport. In such a frame, we calculate the deviations of EVD from the maxwellian, which are caused by the transport (i.e. emission, propagation, and absorption) of plasma's self ECR, and the respective changes of $P_{EC}(r)$ (Sec. 3).

2. Spatial Profiles of ECR Power Balance in Non-Maxwellian Tokamak Plasma

An analysis of $P_{EC}(r)$ is carried out for a model bi-maxwellian electron velocity distribution (EVD) function which *qualitatively* describes the presence of suprathermal electron under condition of auxiliary heating (either central or off-axis ones):

$$f_e(\vec{p},\vec{r}) = n_{e0}(\vec{r})\left\{\left[1-\delta_{ne}(\vec{r})\right] f_{MAXW}(\vec{p},T_e(\vec{r})) + \delta_{ne}(\vec{r})\, f_{MAXW}(\vec{p},T_e^{(hot)}(\vec{r}))\right\}, \quad (1)$$

$$\delta_{ne}(\rho) \equiv n_e^{(hot)}/n_e = (\delta_{ne})_{\max} EXP\left[-(\rho-\rho_0)^2/(\Delta\rho)^2\right] \quad (2)$$

$$T_e^{(hot)}(\rho) = (T_e^{(hot)})_{\max} EXP\left[-(\rho-\rho_0)^2/(\Delta\rho)^2\right] \quad (3)$$

where ρ = r/a is the normalized radial coordinate in the reduced 1D problem [1] for ECR transport in a non-circular toroidal plasma; relativistic maxwellian distribution f_{MAXW} is normalized in momentum space; other parameters in Eqs. (2),(3) characterize the density and temperature of suprathermal electrons, and the location and width of their spatial distribution. The profiles of background plasma were taken close to those for one of ITER-FEAT regimes predicted by the ASTRA code 1D simulations [5] (major/minor radius 6.2/2 m, B_T=5.3 T):

$$n_e(\rho) = n_e(1) + \left(n_e(0)-n_e(1)\right)\left[1-\rho^2\right]^{0.1}, \quad n_e(0) = 10^{20}\,m^{-3}, \quad n_e(1) = 0.5*10^{20}\,m^{-3},$$

$$T_e(\rho) = T_e(1) + \left(T_e(0)-T_e(1)\right)\left[1-\rho^2\right]^{1.5}, \quad T_e(0) = 25\,keV, \quad T_e(1) = 2\,keV\,. \quad (4)$$

The results of calculations for two types of suprathermal electron velocity distrubution are given in Figs. 1,2 in comparison with the case of maxmellian background plasma only. These two regimes are described by the following set of parameters (cf. Eqs. (2), (3)):

"bi-maxwellian core": $\rho_0 = 0$, $\Delta\rho = 0.2$, $(\delta_{ne})_{max} = 0.1$, $(T_e^{(hot)})_{max} = 50$ *keV*, (5)

"bi-maxwellian off-axis": $\rho_0 = 0.5$, $\Delta\rho = 0.1$, $(\delta_{ne})_{max} = 0.1$, $(T_e^{(hot)})_{max} = 30$ *keV.* (6)

The functions (5), (6) correspond to local enhancement of temperature by a factor of 2 for a 10% fraction of electrons. Note that the respective profile effects practically do not disturb the value of *total* EC power loss.

In Fig. 1, we compared spatial profiles of the CYNEQ's net radiated power density, $P_{EC}(r)$, with the "localized" Trubnikov's formula (LTF), which is based on interpreting the fit formula [4] for *volume-integrated* EC loss as a *local* value for net power loss (sometimes LTF

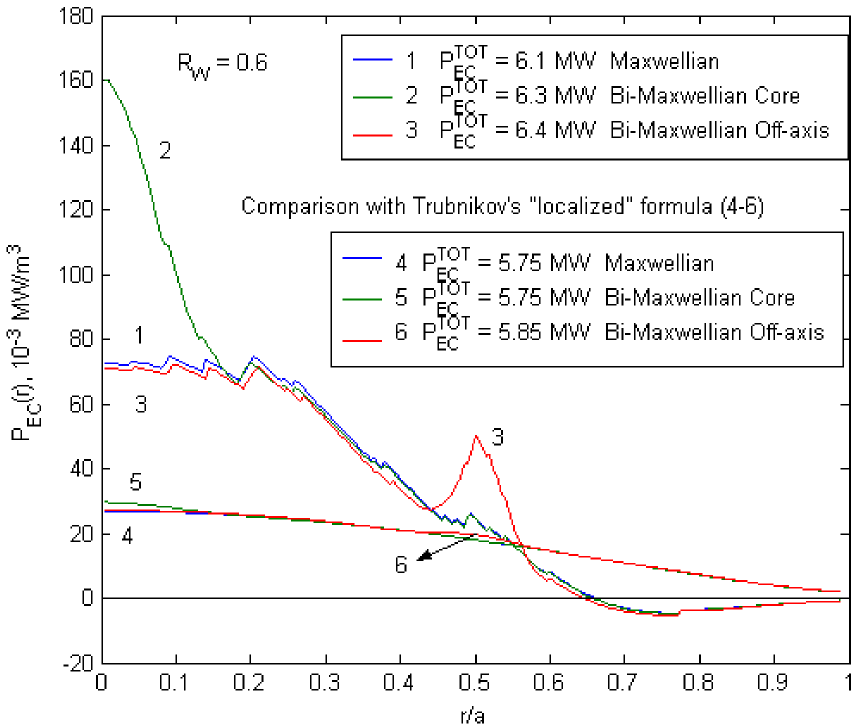

FIG. 1. Comparison of radial profiles of net ECR power loss for three cases -- two regimes of bi-maxwellian electrons (5) (6) and maxwellian background plasma -- for wall reflection coefficient R_W = 0.6. (The jumps in the curves stem from the calculation procedure -- these illustrate the accuracy of calculation procedure's transition from optically thick core to optically thin periphery in the frequency-radius space -- and have to be smoothed). The curves (1)-(3) are computed with the code CYNEQ, while the curves (4)-(6) correspond to the "localized" Trubnikov's formula.

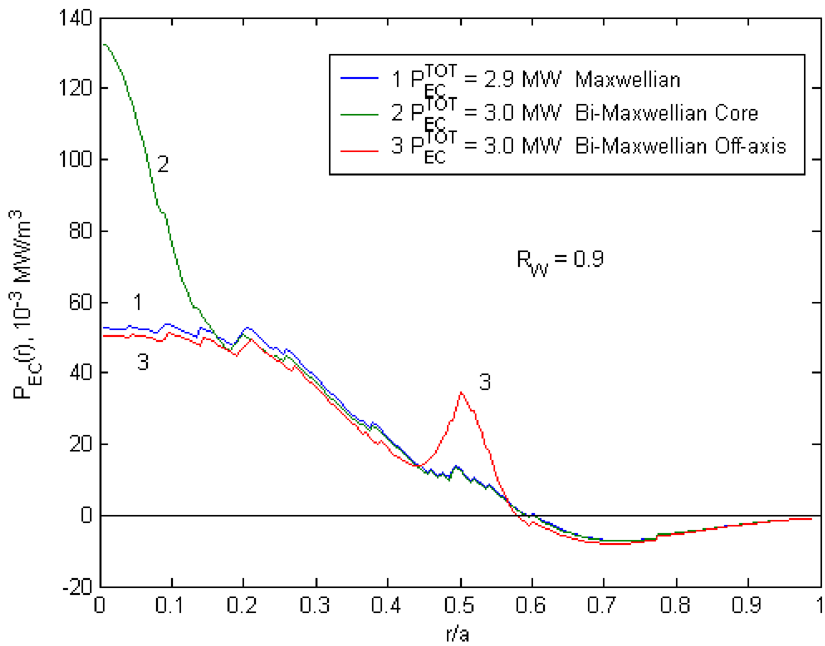

FIG. 2. The profiles similar to those in Fig. 1, for wall reflection coefficient R_W = 0.9 [6].

is used as a simplest approximation of $P_{EC}(r)$ in the global transport codes). Note that the LTF prescribes the $P_{EC}(r)$ to strictly follow the profile of electron pressure that seems to be a reasonable assumption but has obviously a quite limited accuracy. The comparison shows that (i) LTF provides good enough accuracy for total EC loss for not large R_W (cf. the respective comparison in Fig. 7 in [3]); (ii) LTF, because of its complete neglect of the effect [1] of a net power absorption by the relatively cold and dense periphery of the plasma column, may substantially underestimate the power loss in the core (by a factor of 2-3, in the maxwellian case, and even larger, in the non-maxwellian case) and overestimate it in the periphery, where it may differ from exact results even by sign.

3. Self-Consistent Simulation of ECR Transport and Suprathermal Electron Kinetics

The revealed sensitivity of $P_{EC}(r)$ to suprathermal electrons suggests -- in the case of developing the instabilities and appearance of strong enough «tails» in the EVD -- the necessity of a self-consistent treatment of (i) plasma electron kinetics and (ii) ECR transport problem with a proper allowance for deviations of the EVD from a maxwellian.

Such a self-consistency implies the feedback between the ECR losses and the EVD. To evaluate kinetic effects we use a numeric code CYNEQ-KIN based on the general semi-analytic approach (for the formalism see Sec. 2 in [2(A)]), which has been formerly applied to evaluating the feedback between $P_{EC}(r)$ and EVD in tokamaks with very strong magnetic field (B_T ~ 10 T -- APOLLO, IGNITOR), in which case the ECR losses would dominate in the total power losses. The solution of kinetic equation for suprathermal electrons with their isotropic distribution in pitch angles has the form [2(A)]:

$$f(\varepsilon) = f_{\max w}(\varepsilon) A \exp\left[\int_0^{\varepsilon}\left(1 - \frac{Q_{em}^c + Q_{em}}{Q_{abs}^c + Q_{abs}}\right)\frac{d\varepsilon}{T_e}\right] \tag{7}$$

where Q_{em} (Q_{abs}) is the rate of energy loss (gain) by an electron of energy ε due to wave emission (absorption); each Q is a sum over all the emission/absorption mechanisms and is averaged in pitch angles (in the present calculations, we allowed only for the EC emission/absorption and the Bremsstrahlung emission for homogeneous space distribution of ion effective charge, Z_{eff} =3); Q^c – similar rates of energy loss/gain caused by the pair Coulomb collisions (for collisions of an electron with the maxwellian background, one has $Q^c_{em} = Q^c_{abs}$); f_{maxw} - maxwellian EVD; A - normalization constant. Equation (7) gives transparent description to competition of the following three effects:

a) flattening of the EVD in a strong enough radiation field, and the respective partial enlightenment of an optically thick medium;
b) depletion of the EVD's «tail» due to intense radiation emission by the fast particles (in particular, EC emission by an electron in a strong magnetic field);
c) relaxation of EVD to a maxwellian, due to the pair Coulomb collisions in plasmas.

Approximate analytic solutions of each separate problem -- (i) the problem of energy transport by EM waves, in the case of dominance of non-locality of transport [2], and (ii) the kinetics of suprathermal electrons (see Eq. (7)) -- allow us to reduce the original system of integro-differential equations to a couple of integral equations. Numerical solution of this system of equations by an iterative procedure appears to be converging very fast. This is illustrated with Figs. 3 and 4, which show a dramatic drop, by more than three orders of magnitude, of relative deviations of the effective temperature $T_{ef}(E) \equiv -E/\ln[f(E)]$ from the respective value for previous iteration.

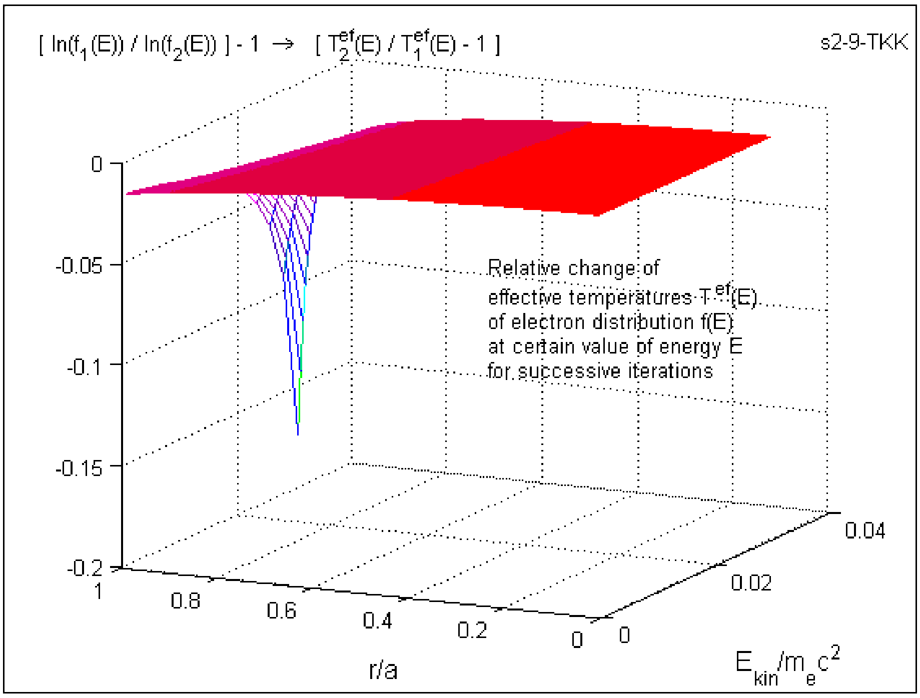

FIG. 3. Relative change of effective temperature, for electron velocities v/c<0.25 (c is the speed of light), for the maxwellian EVD (n=1) and the EVD calculated in the first iteration (n=2).

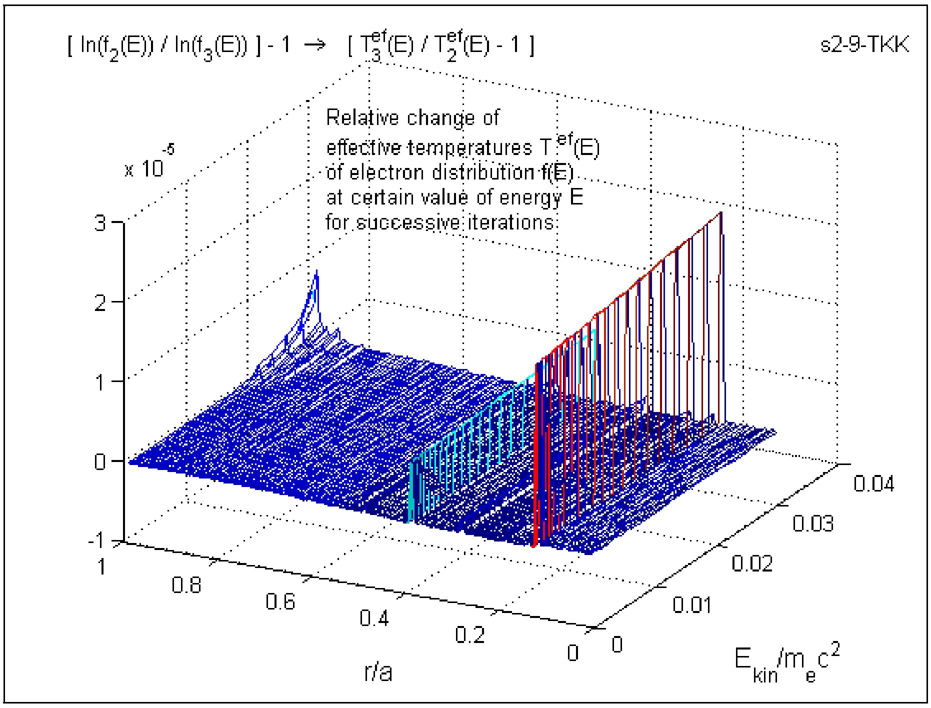

FIG. 4. Similar comparison of EVD for first (n=2) and second iterations (n=3). The spikes stem from the discontinuity in the spatial profile of radiation intensity (cf. caption to Fig. 1).

Such a fact convergence is caused by the low sensitivity of the radiation spectrum (and, consequently, of the volume-integrated power loss, see Figs. 5 and 6) to redistribution of spatial profile $P_{EC}(r)$ caused by the local deviations from a maxwellian.

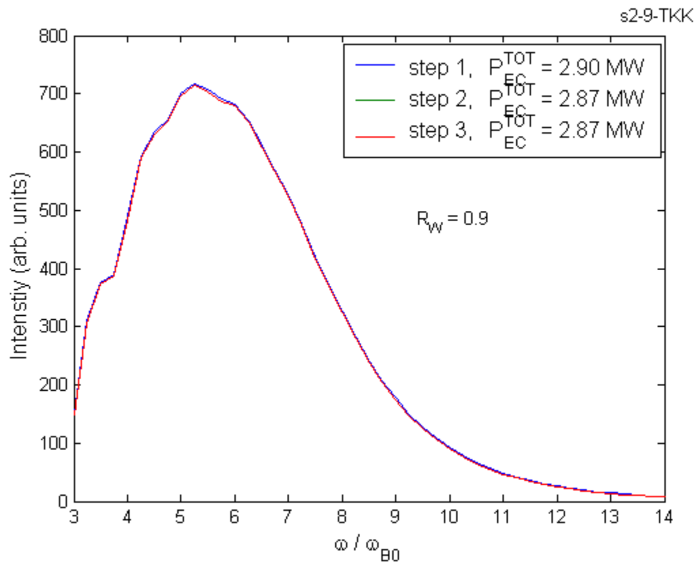

FIG. 5. Spectral distribution of EC radiation escaping the tokamak vacuum chamber for maxwellian EVD (step 1) and two iterations (steps 2 and 3), for wall reflection coefficient R_W =0.9. Respective values of volume-integrated power loss are indicated. The frequency is given in the units of fundamental electron cyclotron frequency ω_{B0}. This figure illustrates the role of high harmonics of the frequency ω_{B0} in the EC transport for ITER-like conditions.

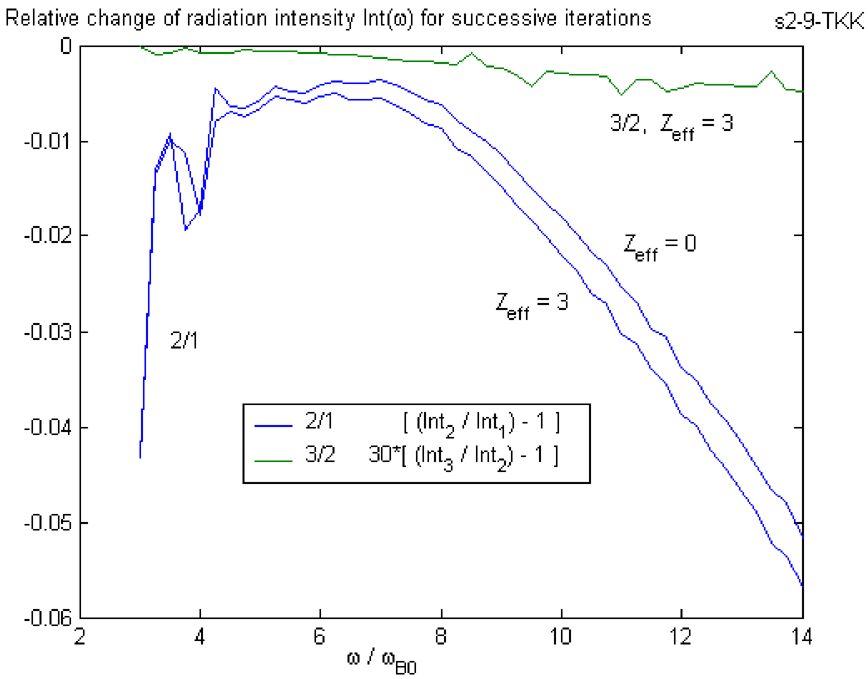

FIG. 6. Relative change of the escaping radiation intensity for maxwellian EVD (I_1) and two iterations (I_2 and I_3). Ratio of spectra for step 2 and step 3 is multiplied by the factor 30. A comparison with the case of Bremsstrahlung radiation switched off (Z_{eff} = 0) is shown, for the case "2/1".

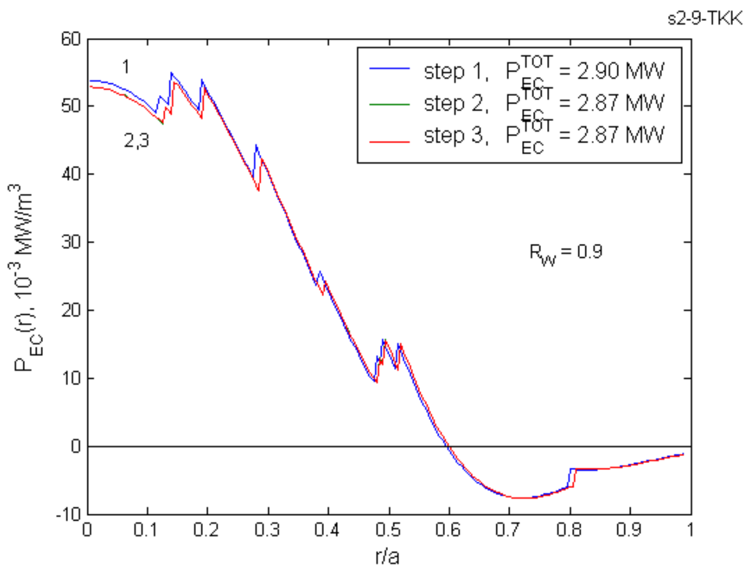

FIG. 7. The profiles of radiated power, $P_{EC}(r)$, for wall reflection coefficient R_W =0.9.

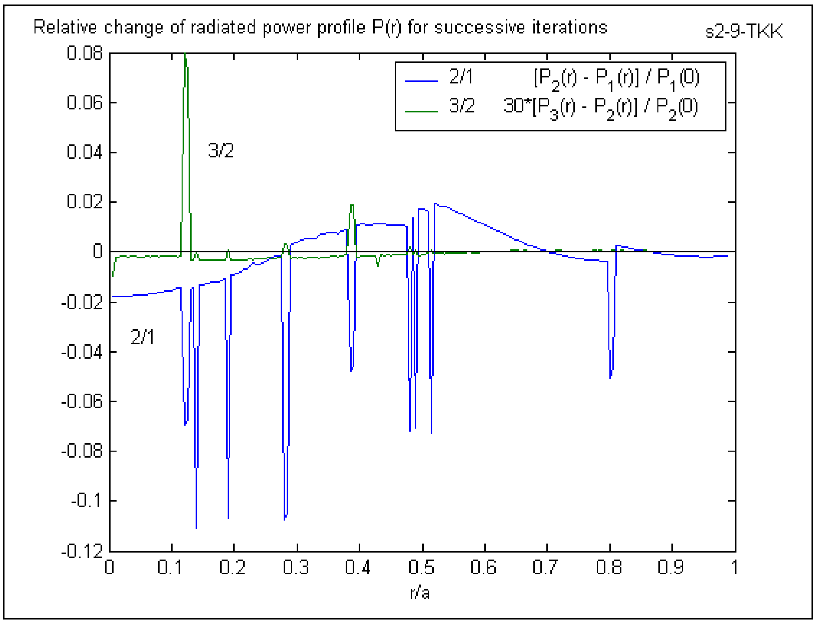

FIG. 8. Relative change of $P_{EC}(r)$ for maxwellian EVD (n=1) and two iterations (n=2 and n=3). Ratio of profiles for step 2 and step 3 is multiplied by the factor 30.

4. Conclusions

The items a) and b) stem from calculations of the contribution of suprathermal electrons with a fixed, "frozen" electron velocity distribution (EVD). The items c), d) and e) stem from self-consistent modeling of (i) transport of plasma's self ECR and (ii) kinetics of suprathermal electrons. And finally, the item f) is an implication of all the items, from a) to e).

a) Strong absorption of ECR in the relatively cold and dense peripheral plasma (Figs. 1,2) is capable of compensating the enhancement of ECR source, which is caused by the presence of suprathermal electrons, to give almost the same value of volume-integrated ECR power loss. This is true for suprathermals both in the core and off-axis regions.

b) For ITER-like conditions, local rise of the net ECR power loss $P_{EC}(r)$, caused by the suprathermal electrons in the core (e.g., by the 10% fraction with a locally doubled temperature), makes the value $P_{EC}(0)$ a noticeable part of the fusion power in the core (cf. [5]). This qualitatively agrees with the ASTRA code-based analysis [7] of contribution of ECR to the local energy balance for regimes with purely maxwellian EVD of somewhat higher temperatures, namely $T_e(0) \sim 35$ - 45 keV.

c) The revealed sensitivity of $P_{EC}(r)$ to suprathermal electrons suggests the necessity of a self-consistent treatment of (i) kinetics of fast electrons and (ii) ECR transport. Numerical solution of such a problem under reasonable assumptions (isotropicity of EVD in pitch angles, etc.) by an iterative procedure appears to be converging very fast (see Figs. 3,4,6,8) due to a low sensitivity of the radiation spectrum (Fig. 6) (and, consequently, of the volume-integrated power loss) to reshaping of the spatial profile $P_{EC}(r)$ (Fig. 8), which is caused by the deviations of EVD from a maxwellian.

d) In the core of the plasma column, the depletion of EVD's "tail" is found to be stronger than its growth/flattening, while in the periphery the flattening may compete with the depletion and even exceed it. These kinetic effects work ultimately for the global flattening of $P_{EC}(r)$ profile: a lowering, in the core, and a rise, in the periphery (Fig. 8).

e) For ITER-like conditions, the contribution of deviations of EVD from Maxwellian caused by the transport of plasma's self EC radiation (rather than by the injected waves of high intensity, used for EC auxiliary heating or EC current drive) appears to be small even for high values of the wall reflection coefficient (R_w=0.9) (Figs. 6,8).

f) The results of items a)-e) suggest the necessity, for ITER-like conditions, of solving self-consistently the problems of (i) ECRH and ECCD optimization and (ii) ECR transport in the entire range of radiation frequency, when strong enough suprathermals may be produced.

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