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Self-Consistent Simulation of Electron Cyclotron Radiation Transport and Superthermal Electron Kinetics in Hot Tokamak Plasmas

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1. Introduction. Numerical studies [1(a)], with help of the code CYNEQ, of the contribution of superthermal electrons to electron cyclotron radiation (ECR) transport in hot plasmas (T_e > 10 keV) confined by a strong toroidal magnetic field (B > 5 T) revealed strong sensitivity of the net ECR power loss profile, $P_{EC}(r)$, to superthermal electrons. In particular, for conditions close to ITER Scenario 2 (“Inductive”, $T_e(0)$ ~ 25 keV [2]), local rise of $P_{EC}(r)$, caused by ~10% fraction with locally doubled temperature in the core, makes the value $P_{EC}(0)$ a noticeable part of the fusion power in the core (cf. [2]). This qualitatively agrees with {ASTRA + CYTRAN} code-based analysis [3] which showed significance of local/global contribution of ECR for purely maxwellian electron velocity distribution (EVD) in the ITER scenarios “Steady-State” which need somewhat higher temperatures ($T_e(0)$ ~ 35 - 45 keV). These results suggested the necessity of a *self-consistent* treatment of (i) kinetics of superthermal electrons and (ii) ECR transport. Numerical solution of such a problem under reasonable assumptions (isotropy of EVD in pitch angles, etc.) by an iterative procedure (the code CYNEQ-KIN) appeared to be converging very fast [1(b)].

Here we report on the major physics effect of the above self-consistent treatment –an impact of ECR transport on the increase/decrease of superthermal electrons fraction in hot magnetized plasmas -- and illustrate it with numeric results, in the case of transport of plasma’s self ECR only (i.e. without ECCD and/or ECRH), for ITER-like conditions.

2. Influence of ECR transport on superthermal electrons in hot magnetized plasmas. To evaluate these kinetic effects we use numeric code CYNEQ-KIN based on the general semi-analytic approach [4]. Solution of kinetic equation for superthermal electrons, under assumption of isotropy of EVD in pitch angles, has the form [4(A)].

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

where Q_{em} (Q_{abs}) is the rate of energy loss (gain) by an electron of energy ε due to the 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 (1) describes competition of three effects: (i) depletion of EVD's «tail» due to intense radiation emission by fast particles (term Q_{em}); (ii) flattening of EVD in a strong radiation field, and respective partial enlightenment of an optically thick medium (term Q_{abs}); (iii) relaxation of EVD to a maxwellian, due to the pair Coulomb collisions in plasmas (term Q^C).

The results of calculations of deviations of EVD from a maxwellian, ln(f) - ln(f_{maxw}), for ITER-like conditions, close to those in the regime "Inductive" [2] (cf. Fig. 1 in [1(a)]), for wall reflection coefficient R_W = 0.9 and 0.6, are given in Figs. 1-4. Recall that in our case, single iteration is sufficient to find the deviations (for R_W = 0.9, respective spectrum of ECR and the profile P_{EC}(r) see, respectively, in Figs. 5 and 7 in [1(b)]).

3. Conclusions. 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. It is this effect that works ultimately for, as found in [1(b)], a global flattening of P_{EC}(r) profile: a lowering, in the core, and a rise, in the periphery. For ITER-like conditions the latter effect is small for plasma's self ECR, but it may be important for stronger intensity of ECR (e.g. under ECRH and/or ECCD) or stronger tails produced by other kinetic mechanisms. On the whole, this vividly illustrates the capability of EM waves to couple the core and periphery via nonlocal mechanism of energy transport which is self-consistently sensitive to superthermal electrons.

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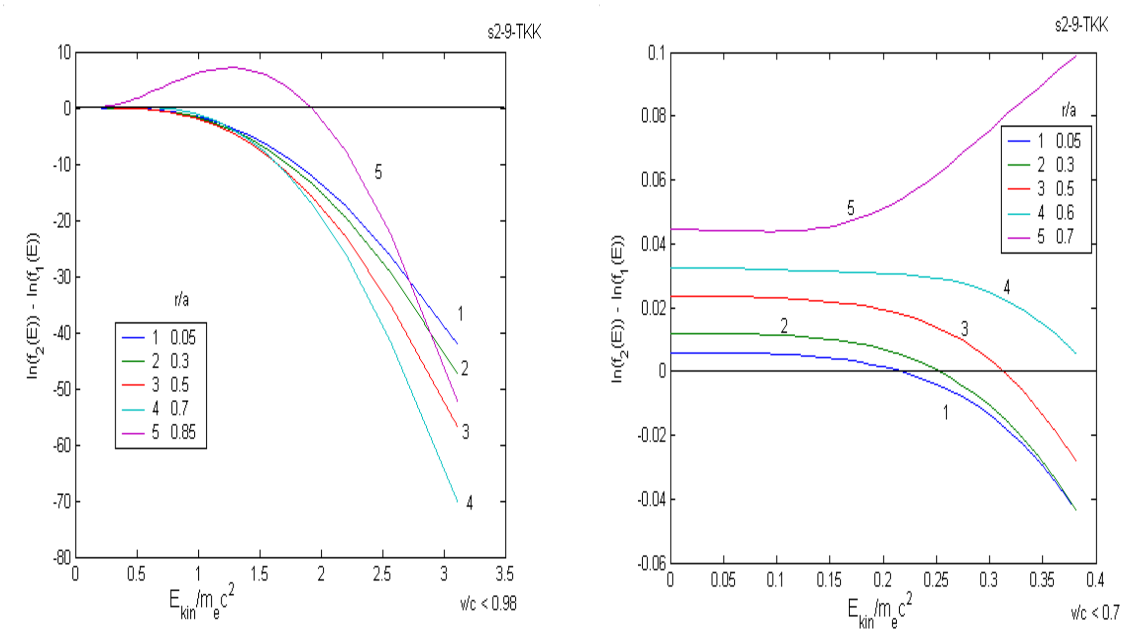

Fig. 1. Deviation of EVD from maxwellian, ln(f) - ln(f_{maxw}), at different magnetic surfaces as a function of electron kinetic energy, for velocities v/c <0.98 (left) and v/c <0.7 (right), and wall reflection coefficient R_W = 0.9. The onset of domination of tail's growth over its depletion (i.e. curve's rise vs. fall dawn) with increasing minor radius is seen on the curves 5 (left, r/a=0.85, and right, r/a=0.7).

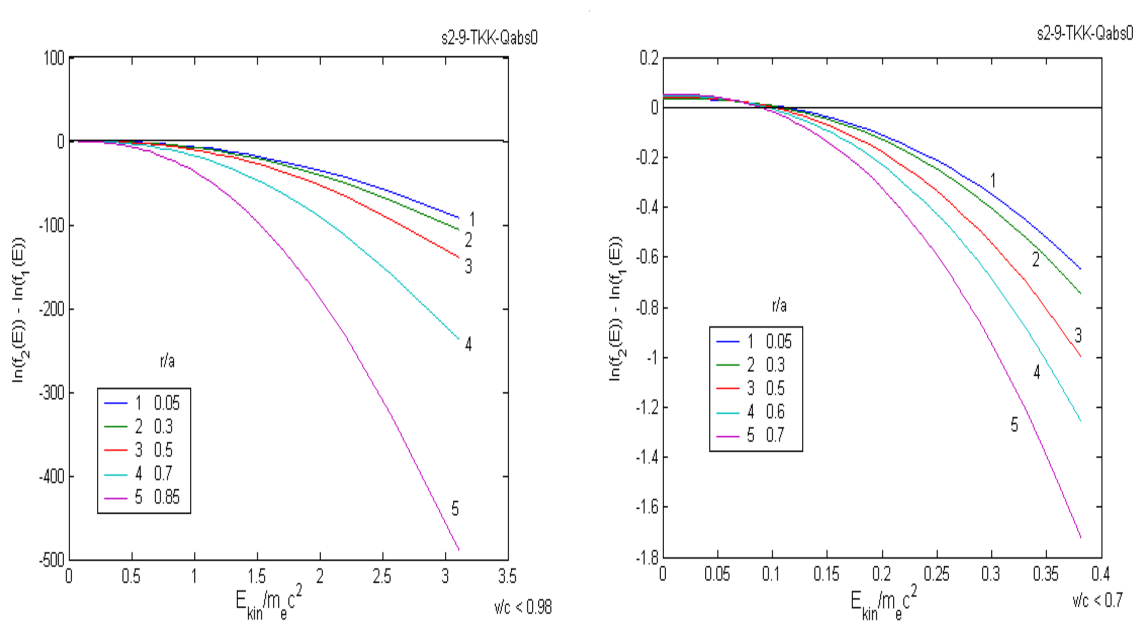

Fig. 2. The picture is similar to Fig. 1 with the absorption (and tail's growth) being switched off (i.e. Q_{abs}=0 in Eq. (1)). This illustrates the monotonic decrease, with increasing energy, of deviation from maxwellian in the case of ECR emission in optically thin media.

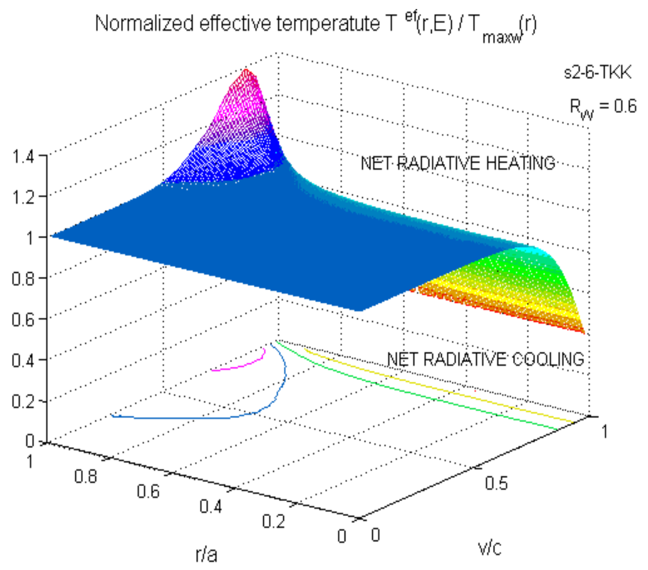

Fig. 3. The ratio of the effective temperature $T_{ef}(E) \equiv -\{\partial \ln[f(E)]/\partial E\}^{-1}$ of the disturbed EVD to the temperature of the undisturbed maxwellian background, as a function of normalized radius and velocity. The top and bottom regions correspond to, respectively, net radiative cooling and heating of electrons in the reduced phase space {r,v} in the process of emission and absorption of EC radiation. Here, wall reflection coefficient is $R_W = 0.6$, while the picture for $R_W = 0.9$ is similar, with the value of ~ 1.75 in the peak. Interestingly, the maximum of the function ($T^{eff}(r,E)/T_{maxw}(r)$ –1) is nearly proportional to the value of the ECR intensity inside the chamber, which is equal to 15 MW and 30 MW for, respectively, $R_W = 0.6$ and 0.9 (cf. Figs. 1 and 2 in [1(b)]).

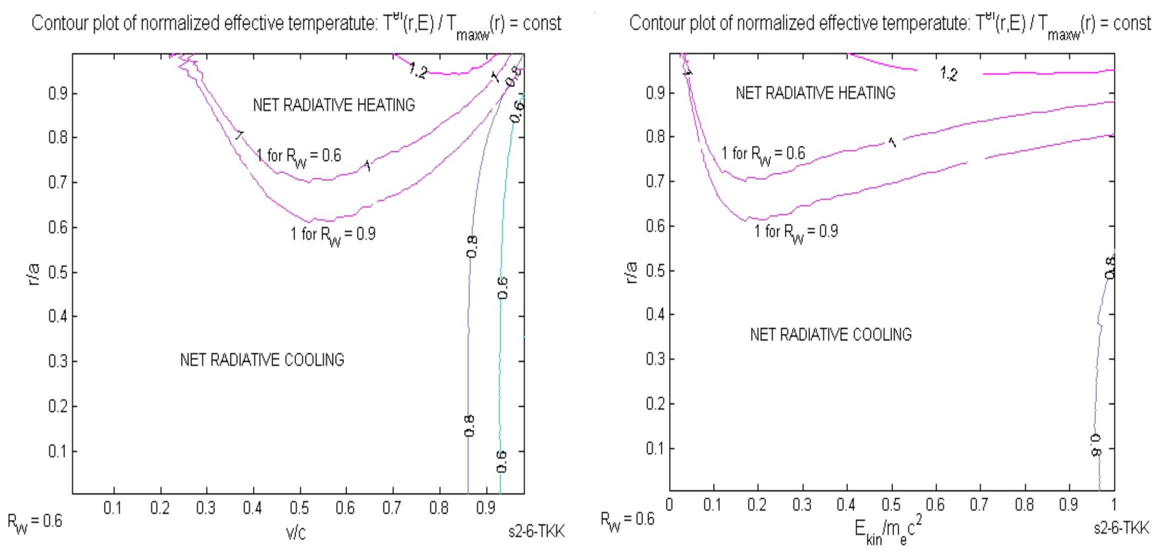

Fig. 4. Contour diagrams of the function in Fig. 3 for v/c<0.98 (left) and v/c<0.87 (right). Here, wall reflection coefficient is $R_W = 0.6$. For comparison, the line $T^{eff}(r,E)/T_{maxw}(r) = 1$ is shown also for $R_W = 0.9$.