Role of runaway electrons in LHCD regimes with improved confinement on CASTOR tokamak.

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Introduction

Recent lower hybrid current drive (LHCD) experiments in low density plasmas on ASDEX [1], CASTOR [2], WT-3 [3], VERSATOR [4] and HT-6B [5] tokamaks demonstrated an improvement of the particle confinement at moderate lower hybrid powers (P_{LH}). Moreover, the experiments [1] and [2] have shown that a reduction of edge electrostatic fluctuations is resposible for this improvement. However, the mechanism behind the reduction of fluctuations has remained unclear.

Here we try to explain the reduction of fluctuations by an enhanced population and non-ambipolar losses of runaway electrons with LHCD adopting the model presented in [6].

Experiment

Experiments were carried out on the CASTOR tokamak (R = 0.4 m, a = 0.085 m) at B_t = 1T, I_p = 12 kA and density n = 6E18 m-3. For the non-inductive current drive, the lower hybrid wave (f = 1.25 GHz and P_{LH} < 40 kW, launched into the plasma via the three-waveguide multijunction grill [2]), was used.

Evolution of a typical LHCD shot is shown in Fig. 1a. The drop of loop voltage U, proportional to the LH driven current I_{LH}, is accompanied by an increase of line average density, H-alpha emission from different sections of the torus decreases. This is interpreted as an improvement of particle confinement. Simultaneously, we observe a reduction of the edge fluctuations for all LH powers available, as shown in Fig.1b. The best confinement and the minimum level of fluctuations is achieved when the total power $P_{TOT} = P_{OH} + P_{LH}$ is minimum ($P_{OH} = U*I_p$ is the residual ohmic power).

Model

Here, we will discuss a possibility that the fluctuations are reduced due to an enhanced population of electrons, with energies higher than a threshold (runaway electrons):

$$W_{run} = E_{Dr} m v_{Te}^2 / E \sim n/U \qquad (1)$$

($E_{Dr} = m* \nu * v_{Te}/e$ - Dreiser el. field, $E = U/2\pi R$ - toroidal electric field). Let us assume that, in OH case, the threshhold energy W_{run} is within an interval of energies (W_1, W_2) representing the boundaries of the LH-wave spectrum. In LHCD case, even at low LH power, the number of runaway growths in spite of the fact that the loop voltage decreases, as schematically shown in Fig.2. The population of runaways will increase with LH power until the loop voltage is low enough so that $W_{run} > W_2$. Then it drops sharply. It is clear that the population of runaways should have a maximum for $P_{OH} > 0$.

Further, we calculate the radial losses of the runaway electrons due to the interaction with fluctuations. The non-ambipolar fluxes of particles of different kind lead to the generation of sheared radial electric field stabilizing the fluctuations via a sheared poloidal plasma rotation. Therefore, the model is selfconsistent.

We start with the quasilinear kinetic equation for suprathermal electrons

$$\frac{\partial f}{\partial t} = St(f) + \frac{\partial}{\partial v_{||}} D_{ql} \frac{\partial f}{\partial v_{||}} + \frac{\partial}{\partial r} D \frac{\partial f}{\partial r} - \nu \frac{E}{E_{Dr}} \frac{\partial f}{\partial v_{||}} \quad , \tag{2}$$

taking into account collisions with bulk electrons (St(f)), the quasilinear diffusion of fast electrons with a diffusion coefficient $D_{ql} \sim W_{k,LH}$ (where $W_{k,LH}$ is the spectral energy density of LH waves), the radial diffusion of the fast electrons with a coefficient $D \sim \tilde{W}$ (where $\tilde{W}$ is the density of energy of fluctuations) and. finally the acceleration of particles by the external electric field E. We are interested in the total number of particles n with energy $W > W_{run}$. The balance equation for n(r) has a form

$$\frac{\partial n}{\partial r} = -\nu n + CP_k(W_{run}) - \mathrm{div}\ \Gamma_{run} \tag{3}$$

where the first term describes maxwellization of the fast electrons. The second term is the source of particles determined by their LH-wave-induced flux into a region of acceleration in the velocity space (here P_k is spectral energy density of LH wave, C = const). To obtain this term the stationary quasilinear equation for the energy density of LHW is used: $P_k \sim D_{ql} \partial f / \partial r$. The third term describes the anomalous radial diffusion of the fast electrons (according [6]):

$$\Gamma_\alpha = -\tilde{W} n_\alpha (C_{n,\alpha} \nabla n_\alpha / n_\alpha + C_{T,\alpha} \nabla T_\alpha / T_\alpha + C_{\phi,\alpha} e_\alpha \phi / T_\alpha) \tag{4}$$

where C = const, α= e,i,run. The energy density of fluctuations $\tilde{W}$ is modelled as

$$\frac{\partial \tilde{W}}{\partial t} = \gamma_0 \tilde{W} - \gamma_1 \mid \phi \mid \frac{\tilde{W} - W_k}{\tilde{W} - W_0} - \gamma_2 \tilde{W}^2 \tag{5}$$

The plasma potential in the edge plasma Φ , responsible for reduction of fluctuations, is derived from ambipolarity condition for total electron and ion fluxes

$$\sum_{\alpha = i,e,run} \Gamma_\alpha = 0 \quad . \tag{6}$$

The detail description of this set of equations is given in [6]. To close this system we use the dependence of $W_{run}(P_{LH})$ derived from (1) and from the folllowing equations

$$I_p = I_{OH} + I_{LH} \tag{7}$$
$$U = I_{OH} * R_b \tag{8}$$
$$P_{LH} = I_{LH} * (1/\eta - U) \tag{9}$$

Here I_{LH} and I_{OH} are LH and inductive currents, R_b - bulk plasma resistivity, η – LHCD efficiency in absence of an electric field. Equation (9) describes the stationary energy balance of suprathermal electrons.

Results and comparison with experiment

Model equations were solved by the 1D ASTRA code. Results of computation are shown in Fig.3, where radial profiles of the threshhold energy W_{run}, density of runaway electrons n, the source term in eq.3 ($S = CP_k(W_{run})$) and resulting edge plasma potential and level of fluctuations are plotted for two values of LH power and compared with the OH case.

For LH power at which the best confinement is achieved ($P_{LH} = 11$ kW), the population of runaway electrons increases accordingly with the growth of W_{run} and $P_k(W_{run})$ (in this calculation we use the gaussian spectrum peaked at W^0=8keV, and $W^0 > W_{run}$, when U=0). The increase of runaway electrons lead to the growth of edge potential, which is significantly higher than in the OH case. Edge fluctuations are reduced similarly as in the experiment.

For a higher power ($P_{LH} = 30$ kW), the population of runaway electrons decreases in central parts of the plasma column. The source term of runaway electrons S is shifted towards the plasma edge. However, the edge potential is still high and consequently the edge fluctuations are reduced nearly as effectively as in the previous case.

Comparison of the computed level of fluctuations in the whole range of LH powers (full line) with experimental data (points) (shown in Fig. 1.b) suggests that free parameters of the simulation can be choosen such a way that the results of simulation follow the experiment quite reasonably. It should be emphasize, however, that the best fit is obtained only assuming the LHW spectrum significantly narrower and peaked at lower energies than expected from calculations of the grill used in the experiment. We believe, however, that a more realistic form of the LH wave spectrum can be used, if ray tracing will be taken into account in our model.

Finally, it should be noted that our model is consistent with behaviour of hard X-ray emission observed in LHCD eperiments on ASDEX [7].

Conclusions

Modelling of LHCD regimes with improved confinement on the CASTOR tokamak demonstrates, that the possible reason of creating such regimes is an enhanced population of runaway electrons. The nonambipolar losses of such electrons lead to a growth of edge potential with subsequent reduction of fluctuation. Such sequence of events is similar to that describing a standard H-mode regimes except of:

i) regime is triggered by runaway electrons instead of hot ions;
ii) there is no threshold power to initiate this regime.

To confirm the proposed model in more detail, additional experimental data about runaway electrons and radial electric field deeper inside the plasma are necessary.

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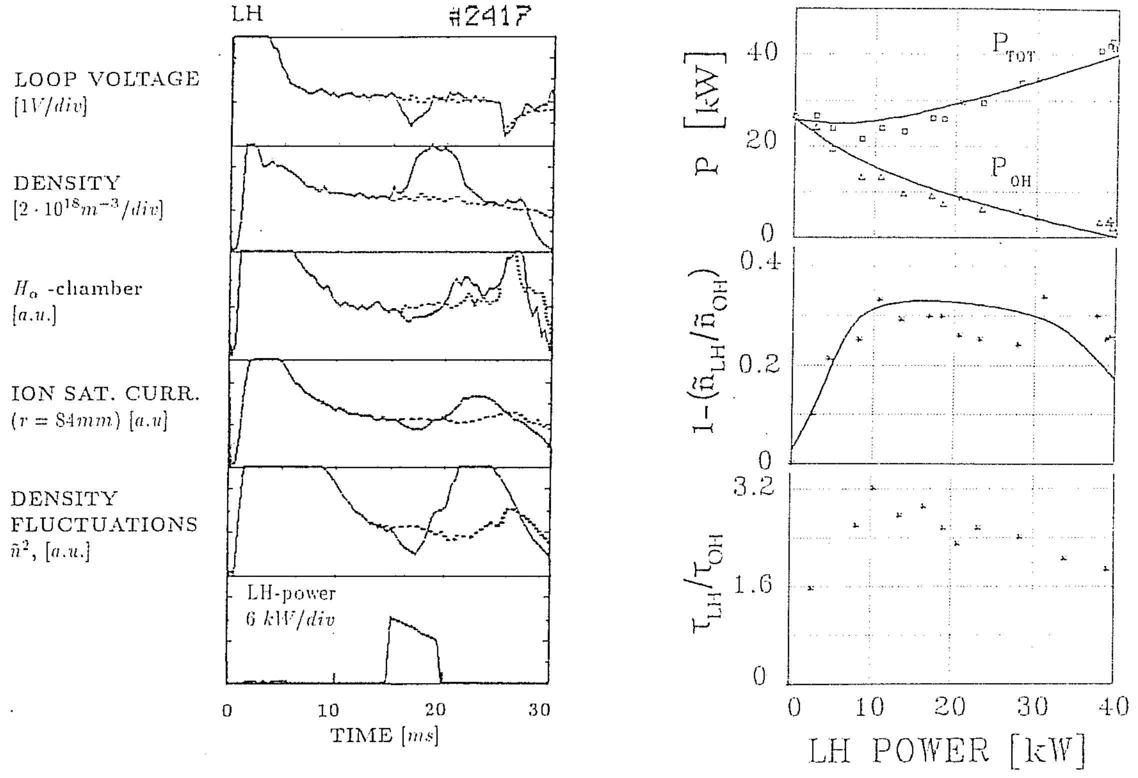

Fig.1.

a) Evolution of a LHCD shot on CASTOR

b) LH power scan of residual ohmic and total powers P_{OH}, P_{TOT}, global particle confinement time normalized to the OH value, relative drop of density fluctuations
$P_{OH0} = I_p{**}2\ R_b = 26$ kW, $P_{LH0} = I_p/\eta = 45$ kW.

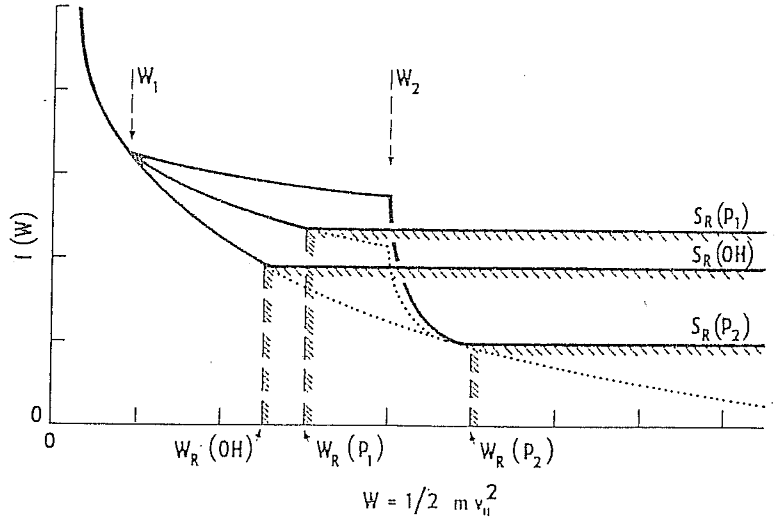

Fig.2.
The electron distribution function for inductive (OH) and combined (OH + LH) current drive (schematically).

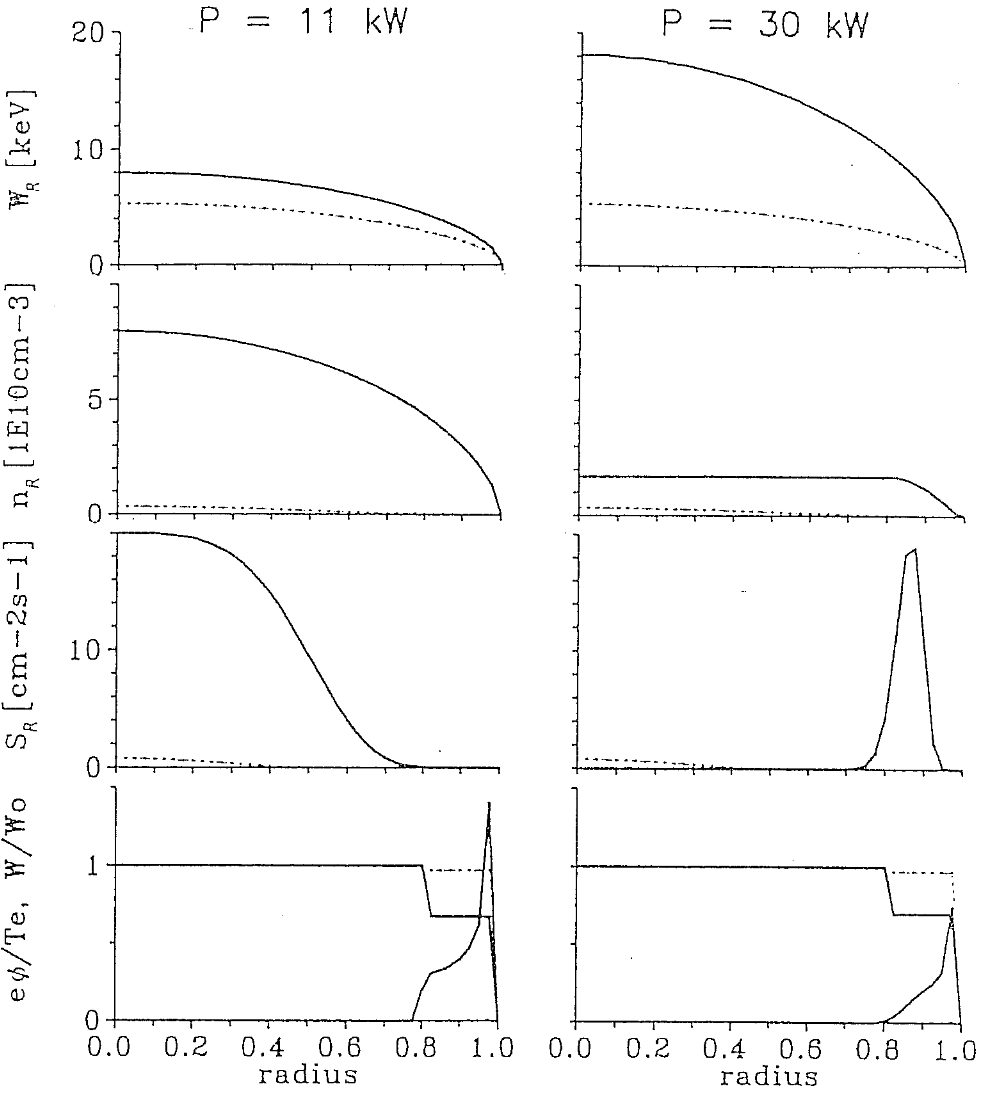

Fig.3.
Results of the numerical simulation for two values of LH power compared with OH regime (dotted lines). Radial distributions of:

a) Threshold energy of runaway electrons W_{run};
b) Density of runaway electrons $n_R(r)$;
c) Source term of runaway electrons S_R =C P_k(Wrun);
d) edge plasma potential and level of fluctuations;

for: I_p = 12 kA, W_o = 8 keV, dW = 1.5 keV, T_e = 100 eV,
n_e = n_o(1-(r/a)**2), n_o = 1E13 cm-3