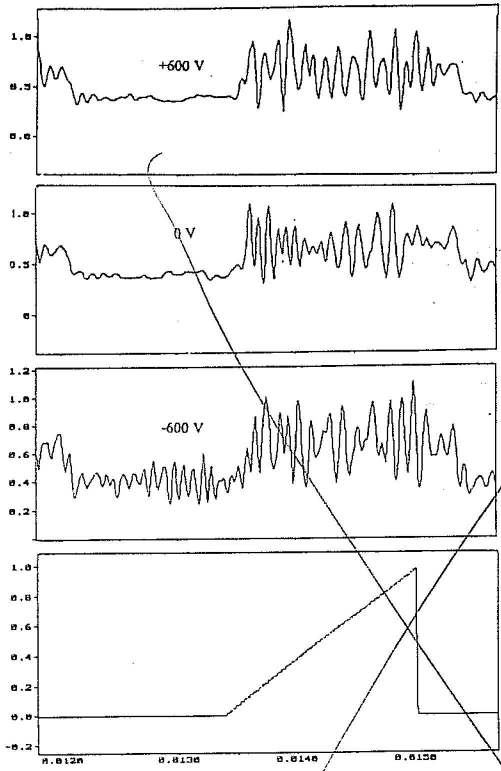

Fig.6

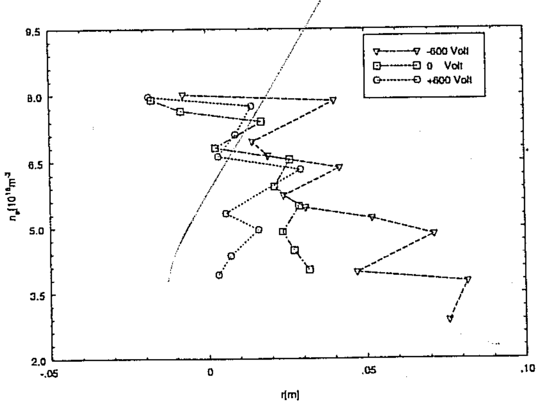

Fig.7

4-CONCLUSIONS: The most important conclusions of these preliminary measurements on our small tokamak are: (i)- the machine produces regularly discharges, that are quite reproducible from shot to shot; (ii)- we identified several discharge regimes among which one with a controlled sawtooth activity, and another one extremely reproducible, with a constant current and long duration and therefore suitable for external perturbation experiments. (iii) - The latter regime is characterized by a central plasma density of 0.8-1.2 x 10^{19} m^{-3}, an electron temperature in excess of 200 eV (ion beam diagnostic indication), an "ion temperature" between 200 and 400 eV (C^{III} line broadenning), $q_{(r=a)}$~5, $q_{r(r=0)}$~1.2, β~0.6% and τ_E~1.5 ms. (iv) - a positive biasing of one of the limiters has enhanced confinement and reduced density fluctuations level at the edge, leading to an hypothetical H-mode. Negative biasing of the limiter has lead to confinement degradation. This last observation is in disagreement with the results presented in [2] where negative biasing is also claimed to lead to an ohmic H-mode.

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

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Introduction

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 probably responsible for this effect. However, the mechanism behind the reduction of fluctuations has remained unclear.

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

Experiment

Experiments were carried out on the CASTOR tokamak ($R = 0.4$ m, $a = 0.085$ m) at $B_t = 1$ T, $I_p = 12$ kA and density $\bar{n}_e = 6 \cdot 10^{18}$ m^{-3}. For LHCD, the lower hybrid wave ($f = 1.25$ GHz, $P_{LH} \leq 40$ kW) was launched into the plasma via the three-waveguide multijunction grill [2].

Evolution of a typical LHDC shot is shown in Fig. 1a. The drop of loop voltage U, proportional to the LH driven current, is accompanied by an increase of the line average density, while the H_α 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 reached when the total power $P_{TOT} = P_{OH} + P_{LH}$ is minimum ($P_{OH} = UI_p$ is the residual ohmic power).

Model

We discusse a possibility that the fluctuations are reduced due to an enhanced population of suprathermal electrons having energies higher than a threshold (runaway electrons):

$$W_R = E_{Dr} m v_{Te}^2 / E \quad \sim n/U \tag{1}$$

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

Further, we calculate the non-ambipolar losses of runaway electrons due to their interaction with plasma fluctuations. The non-ambipolar fluxes of particles (bulk/runaway electrons and ions) lead to a creation of a sheared radial electric field at the plasma edge, stabilizing the fluctuations via a sheared poloidal plasma rotation. Therefore, the model is selfconsistent.

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We start with the quasilinear kinetic equation for suprathermal electrons

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

taking into account collisions with bulk electrons , 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 the LH wave), 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_R with energy $W > W_R$. The balance equation for $n_R(r)$ has a form

$$\frac{\partial n_R}{\partial r} = -\nu n_R + C P_k(W_R) - div\, \Gamma_{run} \quad , \qquad (3)$$

where the first term on the right side 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 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]):

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

where $C_{i,j} = const, \alpha = e, i, run$. The energy density of fluctuations $\tilde{W}$ is modelled as:

$$\frac{\partial \tilde{W}}{\partial t} = \gamma_0 \tilde{W} - \gamma_1 \mid \phi \mid \frac{\tilde{W} - W_k}{\tilde{W} - W_0} - \gamma_2 \tilde{W}^2 \quad . \qquad (5)$$

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

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

The detailed description of this set of equations is given in [6]). To close this set, we use the dependence of $W_R(P_{LH})$ derived from (1) and from the following relations:

$$I_p = I_{OH} + I_{LH}, \quad U = I_{OH} R_b, \quad P_{LH} = I_{LH}(1/\eta - U) \quad . \qquad (7)$$

I_{LH}, I_{OH} are LH- and inductively driven currents, R_b - bulk plasma resistivity and η is the LH current drive efficiency (in units [A/W]) in absence of the electric field. The last relation in (7) describes the stationary energy balance of suprathermal electrons.

Results and comparison with experiment

The model equations are solved by the 1D- ASTRA code. Results are shown in Fig. 3, where the radial profiles of threshold energy W_R, density of runaways n_R, the source term in eq. 3 ($S_R = CP_k$) and resulting edge plasma potential and level of fluctuations are plotted for two values of LH power and compared with the OH case. We use here a Gaussian spectrum peaked at $W^0 = 8\ keV$, with a halfwidth $\Delta W = 1.5\ keV$). The density profile is assumed as parabolic with $n(0) = 10^{19}\ m^{-3}$. The eletron temperature is taken uniform, $T_e = 100\ eV$.

For LH power at which the best confinement is achieved ($P_{LH} = 11\ kW$), the population of runaways increases accordingly with the growth of W_R and $P_k(W_R)$. This leads to a growth of the edge potential, which appears to be significantly higher than in the OH regime. The edge fluctuations are reduced similarly as in the experiment.

For a higher power ($P_{LH} = 30\ kW$), the population of runaways decreases in the core plasma. The source term S_R is maximum at the plasma edge. Nevertheless, the edge potential is still high enough to reduce the edge fluctuations nearly so 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) (see Fig. 1b) suggests that free parameters of simulation can be choosen in such a way that the computed results follow the experiment quite reasonably. It should be emphasized, however, that the best fit is obtained only assuming the LHW power spectrum significantly narrower and peaked at lower energies than expected from grill calculations [7] . We expect, however, that a more realistic form of the 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 qualitatively consistent with behaviour of hard x-ray emission observed in LHCD experiments on ASDEX [8].

Conclusions

Modelling of LHCD regimes on CASTOR demonstrated that the possible reason for the observed improved confinement is the enhanced population of runaway electrons. The non-ambipolar losses of such electrons lead to a growth of edge potential with a subsequent reduction of fluctuations. This sequence of events is similar to that describing the standard H-mode regimes, except of:

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

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

Acknowledgement: Authors are indepted to V.V. Parail and R. Klíma for valuable discussions. The work was performed under the Grant of Czech Acad. Sci. No. 14310 and supported by the IAEA Contract No. 6702/R1/RB

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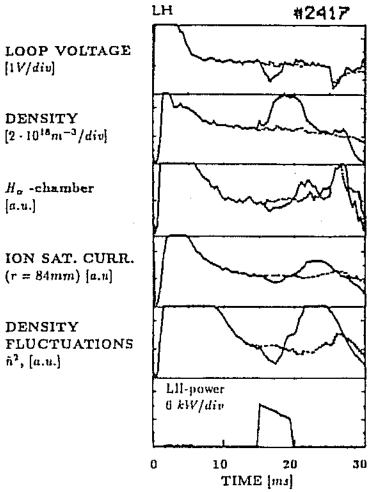


Fig 1a. Evolution of a LHCD shot

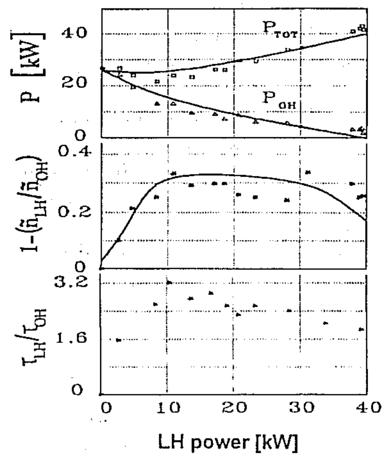
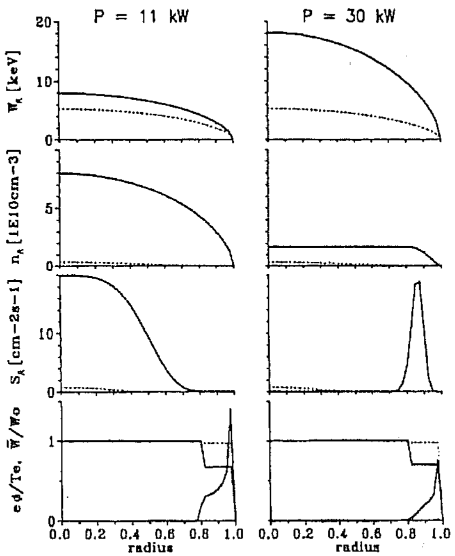


Fig. 1b. LH power scan

P_{OH}, P_{TOT}- residual ohmic and total power (lines are evaluated according eqs.7), $1-(\tilde{n}_{LH}/\tilde{n}_{OH})$ - relative drop of density fluctuations (line is result of computation), τ_{LH}/τ_{OH} - normalized global particle confinement time.



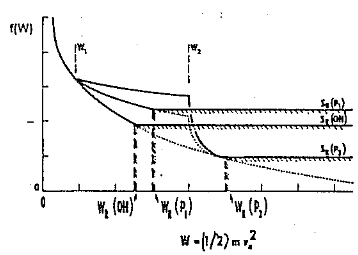


Fig. 2. Electron distribution for inductive and combined OH + LH current drive (schematically)

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

The VH-mode at JET

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Introduction

Some of the high performance JET discharges, in particular those obtained during the campaign of experiments leading up to the preliminary tritium experiment (PTE), make a transition to a mode of enhanced confinement, after the transition from L- to H-mode. This transition usually coincides with the disappearance of the ELMs observed in the H-mode phase. The energy confinement time in this enhanced mode reaches values a factor of 2 above that of the ITER H92-P scaling and a factor of 3 above that of the Goldston L-mode scaling. The high confinement is associated with reduced energy transport near the edge, and is often terminated by a so-called 'X-event', possibly associated with high beta, which is marked by a collapse of the neutron production rate; the enhanced confinement is not recovered after this collapse.
During the high confinement phase, a large bootstrap current appears near the edge, associated with the large pressure gradient, and the total current profile broadens. The high edge current results in the coalescence of the first and second regions of stability against ballooning modes and gives access to the second region. At the onset of confinement degradation, the pressure gradients decrease, as MHD activity increases. However, second stable access is maintained.
These results point to the existence of a qualitatively different mode of very high confinement, the VH-mode.

General behaviour of VH-mode discharges

The evolution of four typical PTE discharges is shown in Fig 1i, with additional parameters shown for the VH-phase of one discharge in Fig 1ii; the plasma parameters and neutral beam power are similar, but pulse 25432, which does not exhibit VH-mode confinement, has a different magnetic configuration. The ELMs that are present in the early phase of the discharges, as manifested by the D_α signal, disappear as the energy confinement time increases above the ITER H92-P value. The local ion diffusivity is reduced at the onset of the ELMs, decreasing further in the VH-phase; at the same time, the bootstrap current increases markedly and the total current profile is consequently broadened. It has also been observed that, at the transition to the VH-mode, the toroidal rotation increases within a certain flux surface and decreases outside. The eventual termination of the VH-mode may be due to an internal kink mode, whose computed amplitude is found to increase with pressure; this mode is exacerbated by the large density gradient. The ion temperature and the closely connected neutron production rate, which increase during the VH-phase, collapse some 0.15s after the confinement time starts to decrease; at the same time, the ion heat flux to the edge increases rapidly; this culminates in dramatically increased impurity content and radiation (carbon bloom).

Ballooning stability

We have investigated the stability of high-performance discharges against the ballooning mode and possible access to the second stability region, using a