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A STUDY OF THE LHCD TERMINATION MECHANISM IN THE FT-2 TOKAMAK

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The efficiency of Lower Hybrid Current Drive (LHCD) in a tokamak is well known to be dropped with a plasma density increase. The LHCD is terminated at the plasma densities well less than LH resonance density. In the hypothesis [1], the termination mechanism is associated with a parametric decay of the launched RF wave to slowed down waves which contribute to ion heating instead of electron current drive. The experimental test of the hypothesis in the FT-2 tokamak is presented in the report.

The main parameters of the FT-2 tokamak are as follows: R=55 cm, a=8 cm, B_T=2.2 T, I_P = 20 kA, T_{eOH} = 400 eV, T_{iOH} = 90 eV, Z_{eff} = 3. RF power (P_{RF} = 100 kW, f_0 = 920 MHz, τ_{RF} =5.5 ms) was launched in the plasma by a two-waveguide grill at $N_{||}$ = 2.5. The LH resonance density for this wave is about $5{*}10^{13}$ cm^{-3}, whereas the plasma density in the center of the discharge was $2{*}10^{13}$ cm^{-3}. The density was chosen such that LHCD regime was terminated during RF pulse. This made it possible to study the termination mechanism in dynamics and to make clear a number of its important features.

The evolution of the main plasma parameters in the experiment is shown in Fig. 1. There are two different regimes during the RF pulse. First, a typical LHCD regime is started from the beginning of the RF pulse and is clearly indicated by the loop voltage drop. During the LHCD stage the plasma density and ion temperature remain about constant, but the electron temperature decreases significantly. The evolution of the electron temperature and density profiles measured by high repetition rate Thomson scattering diagnostics [2] are shown in Fig. 1 and 2. At the second stage, the LHCD

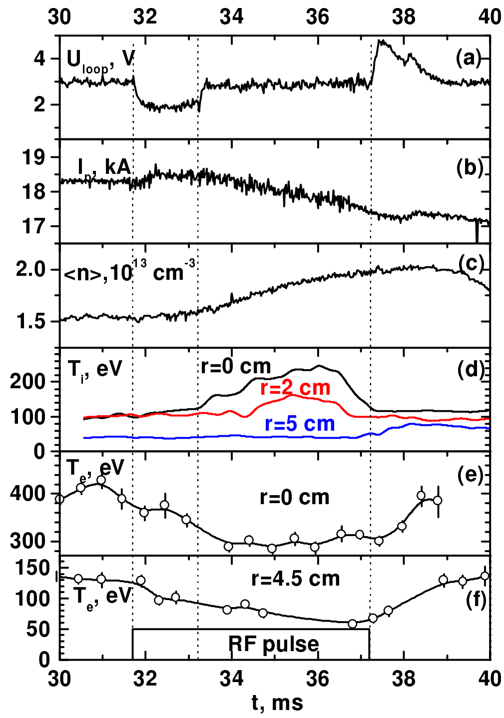

Fig. 1
Evolution of loop voltage(a),plasma current (b), average density (c), ion temperature (d) and electron temperature (e, f).

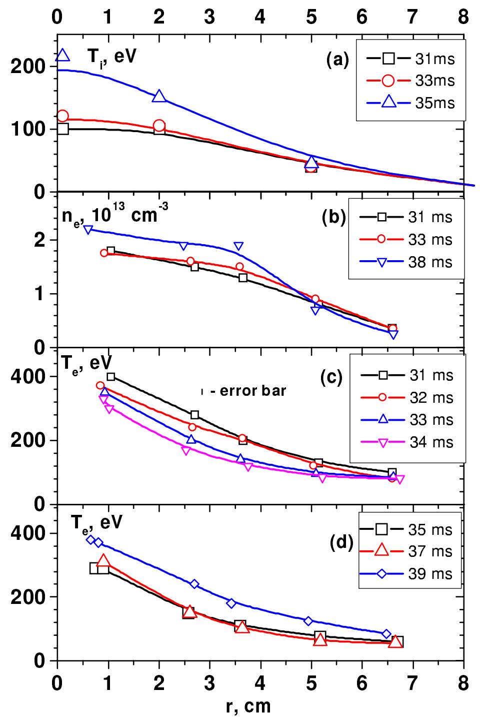

Fig. 2
Spatial profiles of ion temperature (a), electron density (b) and temperature (c, d).

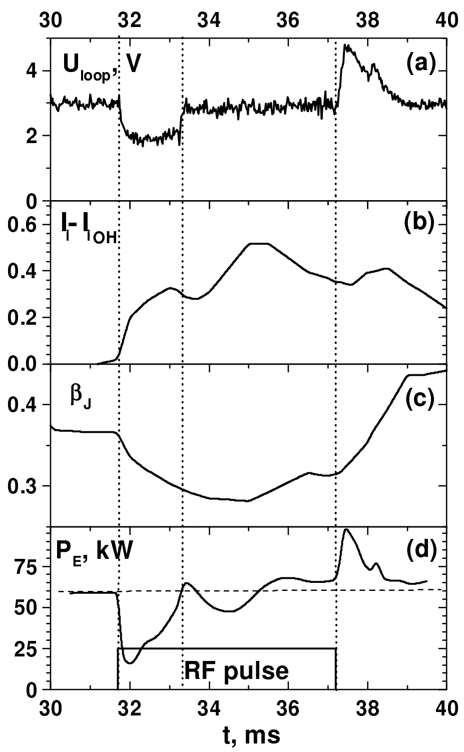

Fig. 3
Evolution of loop voltage(a), l_i (b), β_J (c) and P_E (d).

transforms to an ion heating regime. A significant central ion temperature rise (Fig. 1d and 2) is accompanied by an increase in the plasma density, which is typical for LH heating regimes.

We suggest the electron temperature decrease to be the principal cause for the transition from LHCD to LH heating regime.

The electron temperature falls because of the Ohmic power drop during LHCD. The power P_E contributed to both thermal and suprathermal electrons from the inductive electric field is derived from the power balance:

$$P_E = I_P U_{loop} - \frac{d(LI_P^2/2)}{dt}$$

Here, L is plasma column inductance and $LI_P^2/2$ is the poloidal magnetic field energy. The internal plasma inductance l_i (Fig. 3b) was found from the $\beta_J+l_i/2$ value measured by poloidal magnetic probes. The β_J value (Fig. 3c) was calculated from the electron and ion temperature and plasma density spatial profiles shown in Fig. 2. The derived P_E value is shown in Fig. 3d. The abrupt changes of P_E at the start and finish of the RF pulse are related to a fast redistribution of plasma current density during the pulse switch on and off. The fractions of the LH current estimated from the P_E jumps are 70% and 45% of the total plasma current correspondingly at the LHCD start and at the LHH stage. At the LHH, the total plasma current is shared between the inductive (10 kA) and LH driven current (8 kA) resulting in the low electron temperature during this stage.

The launched LH waves with $N_{||}$~2-3 have no LH resonance in the plasma and interact only with 25-50 keV suprathermal electrons, run away by the inductive electric field. The termination of LHCD indicates a considerable part of RF power absorbed in a different way.

New channels of RF power absorption are fast ions and suprathermal electrons more close to the bulk electrons. The LHCD-LHH transition is immediately followed by 1 keV ion rise in the very center of the plasma column, resulting in a significant ion heating (Fig. 1 and 2). The ion energy balance shows about 6 kW of an auxiliary power absorbed by ions after the transition.

This strong effect can be explained only by a RF power absorption in the plasma center. An effective ion absorption requires a high enough refraction index $N_\perp$ to provide the phase resonance interaction, $v_i \sim c/N_\perp$, of the wave with a considerable part of ions. The entire absorption of LH waves by ions takes place at $N_\perp > c/3v_{Ti}$ [3]. The increase of 1 keV ions in the plasma center (Fig 4b) observed by CX diagnostics during the LHH stage confirms this suggestion and gives the estimation of $N_\perp \sim 600$.

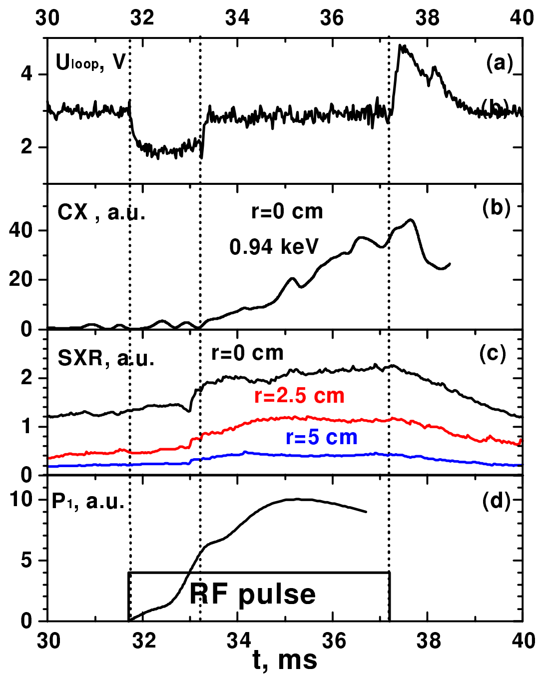

Fig. 4
Evolution of loop voltage(a), CX neutral fluxes (b), SXR emission (c) and first satellite power in the RF fluctuation spectra(d).

The dispersion of the 920 MHz wave at $2*10^{13}$ cm^{-3} plasma density results in about linear dependence between parallel and perpendicular refraction indexes: $N_\perp \sim \omega_{pe} N_{||}/\omega_0$. This relation gives the estimation of $N_{||} \sim 11$.

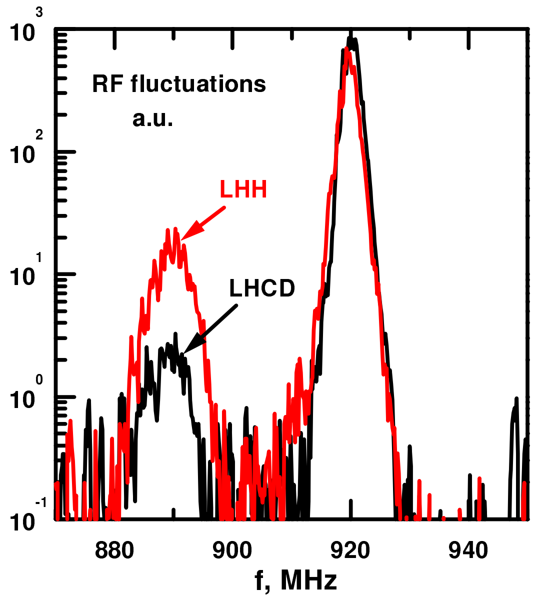

Fig. 5
RF fluctuation spectra

The existence of the slowed down waves in the plasma is supported by soft X-ray measurements. SXR emission is conserved during LHCD stage because the launched LH wave with $N_{||} \sim 2\text{-}3$ is Landau dumped by 25-50 keV electrons which do not contribute to SXR signals. The increase of SXR emission in Fig. 4c indicates an abrupt rise of electrons with energies higher 2 keV over all the plasma column just ahead of the transition. These electrons are in the phase resonance with the slowed down waves of $N_{||} < 11$.

The slowed down waves, in the hypotheses [1], arise due to a parametric decay of the launched LH wave. Such a decay was observed on the plasma periphery. Fig. 5 presents RF fluctuation spectra measured by a 5-electrode Langmuir probe [4] operated as RF antenna and placed by π/2 angle from the LH grill. There are two spectra in the figure, measured during LHCD and LHH stages. The absence of blue satellites in the spectra indicates a parametric decay of LH waves. The interval between the main peak and first red satellite in Fig. 5 corresponds to the ion cyclotron resonance frequency f_{ci} in the region r~7 cm at the low field side of the tokamak. In this region, the launched LH wave of f_0 frequency is suggested to be decayed to daughter waves of f_0 - nf_{ci} frequencies and higher $N_{||}$. The penetration of the slowed down waves into the plasma core results in the termination of LHCD and the transition to LH heating regime.

As is seen from Fig. 4d, this parametric instability is developed just ahead of the LHCD-LHH transition and precedes all the discussed phenomena. Its development is caused by the reduction of a parametric decay threshold with an electron temperature decrease, P_{thr}~T_e/n_e [5]. Note, that in the accordance with this scaling the parametric instability level remains constant during LHH stage.

CONCLUSION

A study of the transition from lower hybrid current drive to ion heating in the FT-2 tokamak has shown a good agreement between the experimental results obtained and the concept of parametric mechanism of the current drive termination. A significant electron temperature decrease during the LHCD has been found to be the main factor responsible for the current drive termination at plasma densities lower the LH resonance density.

With decreasing electron temperature the thresholds of parametric decays fall resulting in the development of a parametric instability in plasma. The launched LH waves is decayed to slowed down waves which terminate a part of RF power from the current drive. This terminated power can contribute to ion heating and results in the transition from LH current drive to LH heating.

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