# Mechanism of the Transport Barriers Formation at Lower Hybrid Heating in the FT-2 Tokamak Experiments

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Experiments in the FT-2 tokamak ($I_{pl}$ = 22 kA, $B_t$ = 2.2T, R=0.55m, r=0.08m) demonstrate effective plasma heating by LH wave explained both by direct absorption RF power and plasma transport change. In respect to plasma-wave interaction, the experiments show that one can provide the condition for either parametric or linear absorption of LH wave in plasma at the same launched auxiliary RF power [1]. The LH wave (920 MHz, 100 kW) was launched by two-waveguides grill from the low field side, $N_{\parallel}$ =2÷3. When the initial Ohmic electron temperature is above the threshold of parametric instabilities, $P^{th} \propto T_e^{\alpha}/n_e^{\beta}$, the central ion heating $T_i(0)$ from 90 up to 350 eV by LHH is observed, the electron temperature preserves the ohmic heated value. Strong parametric instabilities are excited at lower electron temperature plasma ($T_e(0)$< 350eV). The control outward shift of the plasma column results in the increase of the central electron temperature higher the threshold and the linear absorption of LH wave in plasma is observed [2]. For inward shifted plasma, when the initial lower Ohmic electron temperature ($Te^{OH}$ (0) ~ 250 eV) is realized, the parametric decay is observed. The distribution of $T_i(r)$ for inward shift is typical for the non-central heating. The increase of ion temperature $\Delta T_i(0)$ is 100 eV. The electron temperature and density increase for the opposite outward shifted plasma. An analysis using ion energy balance equation shows that in the outward and inward shifted plasma RF power absorbed by ions equals to about $P_{RF}$ = 20 kW÷25 kW. The estimation of the maximal RF power absorbed by electrons have been obtained for inward case assuming that electron thermal diffusivity $\chi_e$ is kept at the ohmic level. This value $\Delta P_{RF}$ with takeing into account radiation losses is about 40 kW. But, of course,
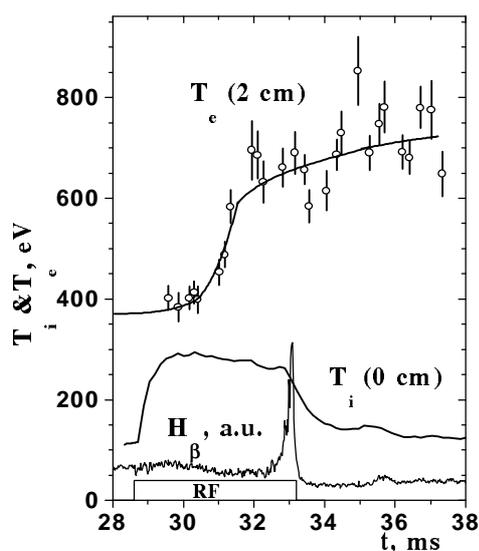


*Fig. 1*

this conclusion should be changed if we take into account improved confinement processes observed in some LHH experiments. This paper deals with improved confinement initiated by LH heating and discussion of the transport barrier formation mechanism.



Fig. 2

In the experiment with central plasma position and higher electron temperature a central ion heating is the same as for the outward case [2]. Plasma parameters $T_i(0)$, $T_e(r = 2$ cm$)$, $U_{pl}$ 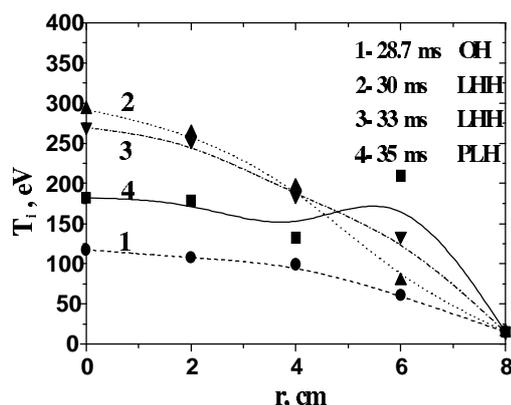and $H_\beta$ are shown in Fig.1. The ion temperature profiles for various moments of the LH experiment are shown in Fig.2. The central ion temperature rises from 100 eV up to 300 eV. But in contrast to the outward shifted plasma an electron heating occurs in this case. But one can see, that if ion temperature rise is triggered by the RF pulse start, the central electron heating is realized $1 \div 1.5$ ms later. Furthermore, the increase of the $T_e(r = 2$cm$)$ up to 700 eV in post heating stage followed by heating from 400 eV up to 650 eV during LHH [2]. Fig.3 demonstrates the $n_e$ (r) and $T_e(r)$ data measured by Thomson scattering diagnostics. These data are shown plotted versus the magnetic surface radius of the discharge because there is small plasma column shift outward along major **R** radius during LH heating (see Fig.6). Accordingly Fig.1 and Fig.3 one can say, that electrons are heated not only by RF power but also by improve energy confinement, because when RF pulse is turned off, the rise of $T_e(0)$ is observed. For simulation one can assume that electron heating is described by RF power absorption at least at the first moment and electron thermal diffusivity $\chi_e$ is of the ohmic level. This result in $P_{e,RF} = 10$ kW absorbed in the electrons at the first
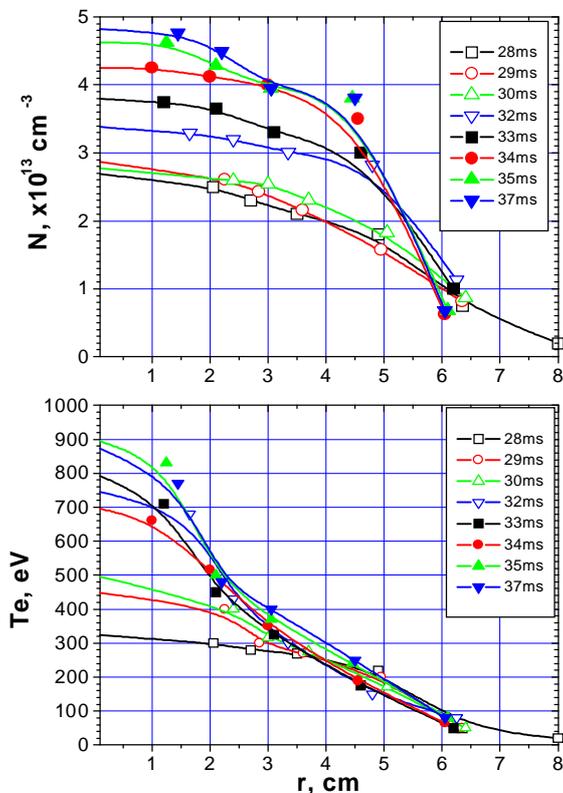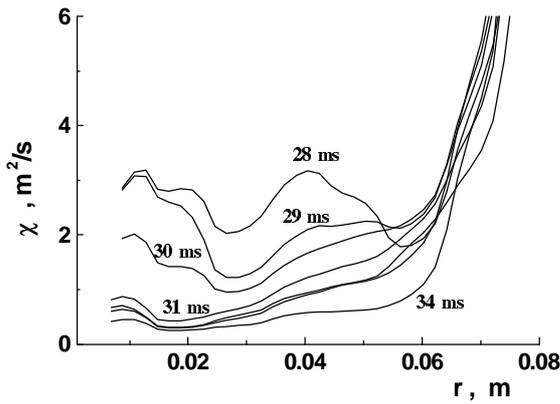


Fig. 3

Fig. 4

moment [3] (without taking into accounting the radiation losses). This power has to decrease well up to 0 before pulse termination. In the frame of such suggestion, ASTRA code simulations show 8-fold decrease of electron thermal diffusivity $\chi_e$ during RF heating from OH level ($t_{OH}$ = 28 ms). These calculations taking into account electron-ion power and pinch contributions are shown in Fig. 4. $\chi_e$ during first a few msec is decreased distinctly at the middle radii and than remains at low level in a core for a long time at post heating stage. This gystiresis effect associated with L–H transition has been manifested early in our experiments. The improve confinement effect during LHH experiment is approved by diamagnetic, spectroscopic, reflectometry and Mirnov probes measurements [4, 5].

In this paper an increase of plasma poloidal $E_r$xB rotation shear is supposed as a mechanism for the transport barrier formation. Remind, that the neoclassical ambipolar radial electric field is given by $E_r^{neo} = T_i/e \left( d(ln\,n)/dr + (1-k)\,d(ln\,T_i)/dr \right)$, where coefficient k (= 1.5 for plateau ) depends on plasma collisionality. For our calculations we elaborate the equation for $E_r$ using the model which takes into account the fact, that the Ware drifts of ions and electrons are not automatically equal to each other [6]. This effect results in some radial electric field $E_r^*(E_{II}, v^*_i, v^*_e)$ related with. $E_{II} = U_{loop}/ 2\pi R$ and collisionality parameters of electrons and ions additional to $E_r^{neo}$. One can rewrite $E_r$ as $E_r = E_r^{neo} + E_r^*$. The simulation showed, these radial electric field variations are caused by strong central ion heating during LH pulse. The poloidal rotation velocity shear $\omega_{E\times B}$ is shown in Fig. 5. The high shear at the core (r ≈ 4cm) achieves about $8*10^4 s^{-1}$ in 1.0 ms from the pulse start. The maximal $\omega_{E\times B}$ value subsequently is shifted outward and rises up to $5*10^5$ s$^{-1}$. According to Fig.2 and 3, the ion temperature and density transport barriers are located at radii r = 5cm÷7cm. This fact was manifested during post heating stage more sharply. The increase of the shear $\omega_{E\times B}$ higher than $5*10^4$ s$^{-1}$ can result in sharp decrease of
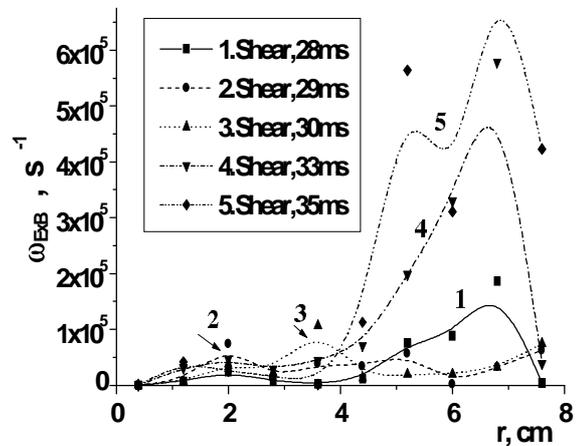


Fig. 5

particle transport coefficients and transport barrier formation [7]. We have the additional experimental evidence that particle transport is decreased in the limiter shadow. Three movable multielectrode Langmuir probes enable measure the time dependence of local values of the electron temperature, plasma density, spatial potential, electric field, quasistationary and fluctuation-induced **ExB** drift flux densities practically at any poloidal angle. It is typically that the fluctuation-induced **ExB** drift flux density is increased during LH pulse only at low field side. In the other poloidal probes positions when L-H transition is happened this fluctuation-induced **ExB** drift flux is decreased. On the whole the poloidaly averaged radial particle fluxes in limiter shadow resulted by density fluctuation is declined as it is shown in Fig 6. The small plasma column shift **$\Delta r$** measured by magnetic probes located at r=10cm is marked in Fig.6 also.

So, this paper illustrates experimentally observed transport barrier formation initialized by the LH heating. The key factor in these effects is the additional radial electric field caused by high central ion heating. The increase of the plasma poloidal $E_r$ x B rotation



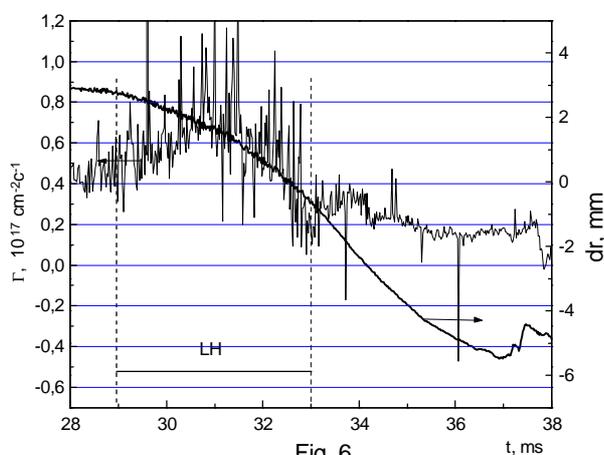Fig. 6

shear apparently lead to the internal improve confinement (r < 6cm) for electrons and periphery transport barrier formation located  for density and ion temperature profiles at r = 5÷7 cm. During modeling the plasma heating by LH wave and absorbed RF-power one should take in to account the effect of transport change.

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