Transport Barrier Dynamics with Lower Hybrid Heating in the FT-2 Tokamak Experiments

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The possibility to control of transport processes in the tokamak plasma in the Lower Hybrid Heating (LHH) experiment has been demonstrated. The paper describes experimentally observed transport barrier formation initialized by the LH heating for various plasma experiment scenario [1]. The key factor in all cases is the additional radial electric field generated by plasma processes during additional heating.

First one was found during effective central LHH. In the experiment the high value of the initial Ohmic electron temperature is needed to prevent the parametric decay of the pump wave. The central ion temperature rises from 100 eV up to 300 eV when P_{rf} = 100 kW is applied at 28.5 ms (Δt_{rf} = 5ms). One can see, that if ion temperature rise is triggered by the RF pulse start, the central electron heating is realized 1.5 ms later. Furthermore, the increase of the T_e(r = 2cm) from 360 eV up to 650 eV during LHH is followed by heating up to 700 eV in post heating stage. The T_i(r), n_e(r) and T_e(r) profiles measured by CX-analyzer and Thomson scattering diagnostics and plotted versus the magnetic surface radius of the discharge are shown in Fig.1. The conservation of the high T_e(r) after the RF pulse indicates that electron heating is caused not only RF power absorption, but improved plasma confinement also. ASTRA code simulation shows 8-fold decrease of the electron thermal diffusivity χ_e from the ohmic heating (OH) level [1]. An increase of plasma poloidal E_rxB rotation shear is supposed to be responsible for the transport barrier formation. The simulation showed that these radial electric field variations are caused by strong central ion heating during LH pulse. The shear achieves about $8{*}10^4 s^{-1}$ at the core (r ≈ 4cm) at 1.5 ms after 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.1, the ion temperature and density transport barriers are located at radii r = 5cm÷7cm. This fact was manifested more sharply during the post heating stage. The simulation of the improved core confinement shows that increase of the shear $\omega_{E\times B}$ higher than $5{*}10^4$ s^{-1} can result in the drop of particle transport

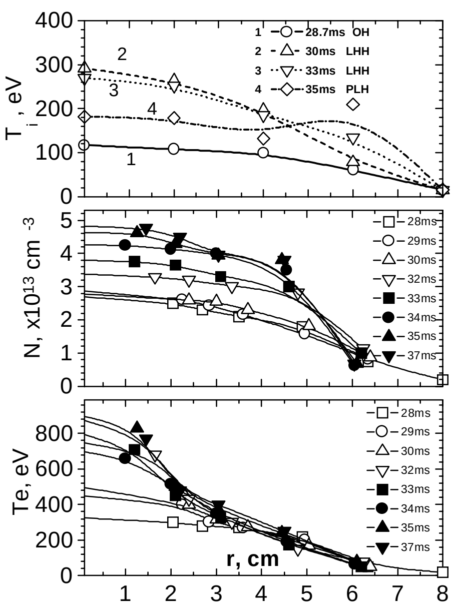

Fig. 1

coefficients and transport barrier formation [2]. The measurements by the multyelectrode Langmuir probes during L - H transition show the sharp decrease of the radial particle fluxes in limiter shadow. The poloidaly averaged radial particle fluxes in limiter shadow caused by density fluctuation is declined during improve confinement [3].

The next method to trigger improved confinement is combination of a fast Current Ramp-Up (CRU) with Lower Hybrid Heating (LHH) [4]. At combination of fast current ramp up and LHH the plasma current was ramped from 20 up to 30 kA during 0.5 ms (20MA/sec). The data are compared with either different scenario or LHH, or only CRU experiment. The fast increase of the central electron temperature and the decrease in the thermal diffusivity coefficient $\chi_e(r)$ has been observed when CRU is applied only [5]. As well as the ohmic heating case with CRU, the combination CRU + LHH reveals the fast rise of the T_e in the plasma center but additionally demonstrates a fast density and ion temperature profiles evolution simultaneously with (CRU+LHH) start [1]. The prompt density rises at radii 2cm, 5cm and 6cm are shown in Fig.2 in comparison with the mentioned above LHH data. The mechanisms of internal barrier formation has been put forward to explain the observed regimes of improved core confinement [4, 6]. New features of Ware pinch in inhomogeneous toroidal electric field $E_\Phi(r,t)$ in combined CRU and LHH are emphasised. First, it is necessary to take into account the fact, that the Ware drifts of ions and electrons are not automatically equal to each other because $\nu^*_i > \nu^*_e$ [6]. This fact results in radial current generated by Ware pinch $j^{(2)}$ depended on the toroidal electric field $E_\Phi = U_{loop}/2\pi R$ and collisionality parameters of electrons and ions. Second, in the presence of a non-uniform toroidal electric field, the radial drift of the banana particles resolutions to additional radial current $j^{(3)}$ generated by Ware pinch of the high energy trapped ions arisen from direct plasma LH wave interaction. This current is a linear function of both second spatial and temporal derivatives of the toroidal electric field $E_\Phi(r,t)$. The compensation of this radial current by the main ion current results in the additional electric radial electric field [6]. Thus, E_r can be found from the conditions $j^{(1)} + j^{(2)} + j^{(3)} = 0$ **(1),** where $j^{(1)}=\sigma(E_r - E_r^{neo})$. The appropriate increase of the plasma poloidal E_rxB rotation shear could be responsible for the transport barrier formation, which arises at once when LH pulse and CRU are applied. The additional current $j^{(3)}$ makes clear the difference between CRU and CRU+LHH experiment. On the other hand, the additional electric field when CRU+LHH is applied results in faster formation of transport barrier in density and ion temperature profiles at the r =(5 – 7) cm, than in the case of LHH without CRU (Fig. 2). This situation is similar to the experiments with the biasing

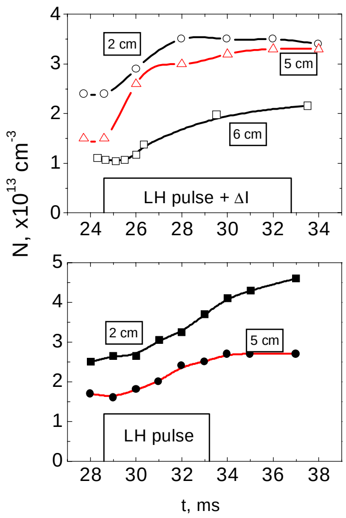

Fig. 2

electrode. Additional benchmarking of the theoretical model as well as the new experimental data of plasma parameters particularly in the scrap-off-layer are required.

Recently, new visible spectroscopy data have been obtained. The experiment shows, that transport barrier resulted by $E_\Phi(r,t)$ is generated both at CRU and CRU+LHH in the FT-2 experiments but with different timing scenario. The spectroscopy diagnostic consists of two monochromators M1 and M2. One high resolution Czerny-Turner spectrometer M1 (f/7, grating 1200 g/mm, 0.5nm/mm resolution in the second order, $\Delta\lambda_{inst}$ = 0.036nm) collects the light from vertical viewing lines and second one M2(f/2.5, 1200g/mm, 2nm/mm) collects the light from horizontal viewing lines. The Helium is puffed from bottom port via a piezo valve. The spectral line profile detected shot by shot by photomultiplier tube with measurements. The monochromator M2 is used as monitor of line emission. Spectral emission is imaged at the entrance slit of M1 using 90mm, f/9 quartz lens, resulting in spatial resolution of 5 mm at the middle plane of the vacuum chamber. The measurements of spectral line profile of ionized helium provides local values of T_i and poloidal rotation v_θ. The ion temperature is calculated from the Doppler broadening and the poloidal velocity from the Doppler shift of the HeII(468.54nm) spectral line, assuming a Gaussian shape of the spectral line. The Doppler broadening $\Delta\lambda_D$ of the observed line is proportional to the ion temperature T_i(eV) according to $\Delta\lambda_D = 7.7 \times 10^{-5}(T_i / \mu)^{1/2}\lambda_0$, with μ (in amu) and λ_0 (in A) being the atomic mass and the wavelength, respectively. The Doppler shift $\Delta\lambda = \lambda_0(v_\theta / c) \cos\theta$ of the spectral lines is a direct measure of the He^+ ion poloidal velocity v_θ . Here c and θ being the light velocity and the angle between the velocity and the viewing chord, respectively.

The line-integrated emissivities were measured by M1 and M2 in order to evaluate the regions of maximal emission of HeII. The $T_i(r)$ and $v_\theta(r)$ data were calculated assuming that chord observations give the lower values than local ones [7]. The measured change in $v_\theta = \nabla_r P_{iz} / Zen_{iz}B - E_r / B$ is directly related to a change of E_r. Sheared poloidal rotation of impurity ions is equivalent to a strong radial variation of the E_r. Another possibility to drive the poloidal rotation is the ion pressure gradient ∇P_{iZ} itself. The ion temperature profiles measured by CX analyzer and spectroscopy diagnostic for different moments of the CRU and CRU + LHH experiments are shown in Fig. 3 and Fig. 4, respectively. The $T_{i\ opt}$(r = 7cm and 8cm) are compared with He^+ ion temperature data. One can see the prompt pedestal formation at T_i(r = 5cm - 7cm) in CRU+LHH experiment. In the case when only CRU is applied, ion temperature pedestal rises at 1,5ms later (Fig. 4).

Typically, that the ion temperature T_{iCX}(r=6cm) in Fig. 3 measured by CX analyzer (at first ms from RF pulse and CRU start) decreases as well as $T_{i\ opt}$ (r=7cm, r=8cm). The pedestal formation is observed at r = 5cm – 7cm. The ion temperature rise at r<5cm corresponds to density fast increase (Fig. 2). In the case CRU without of LHH pulse the pedestal formation at $T_i(r)$ is observed about 2 ms later. Simultaneously the average density $N_e(=2.6x10^{13}cm^{-3})$ rise starts. In Fig. 5 the N_e, H_β line emission, plasma current $I_{pl,}$ as well as He^+ ion poloidal velocity v_θ *(r = 7cm, r = 8 cm)* are shown for both experiments. The positive direction for velocity is ion diamagnetic drift direction. A neutral Helium line emission will be used for local measurements of T_e and n_e for further detailed analysis of $\nabla P_{iz}(r)$ at SOL

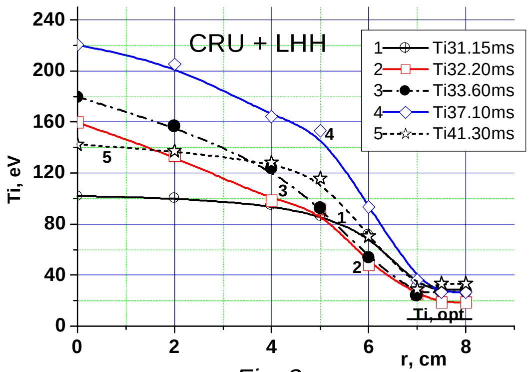

Fig. 3

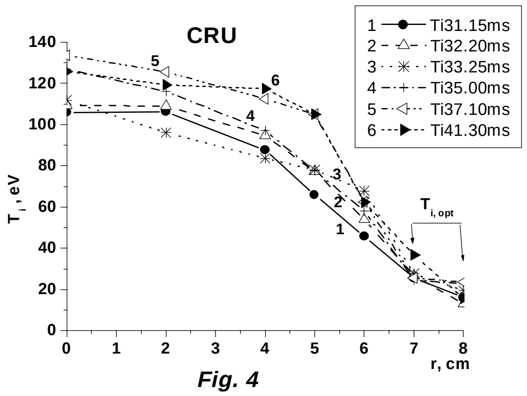

Fig. 4

similar to [8]. Previously one can say, that the region of maximal ion He$^+$ density is *r ~ 7 cm*. HeII chord profile emission indicates a rise of ∇P_{iz}(r=8cm) during additional heating. So, the fast decrease of the v_θ due to a strong negative E_r generation resulted by $E_\Phi(r,t)$ rise (1). According to Fig.5 in the CRU scenario there is fast decrease of v_θ at r = 8cm and 7cm at the first moment. In CRU+LHH case the fast decrease of v_θ observed r < 7cm. One can suppose, that E_r induced by CRU+LHH is realized in a deeper plasma layers. This preliminary analysis of the line profiles measurements show that the poloidal velocity change in FT-2 can be understood in terms of a radial electric field at the edge resulted by $E_\Phi(r,t)$. These CRU data are under further analysis.

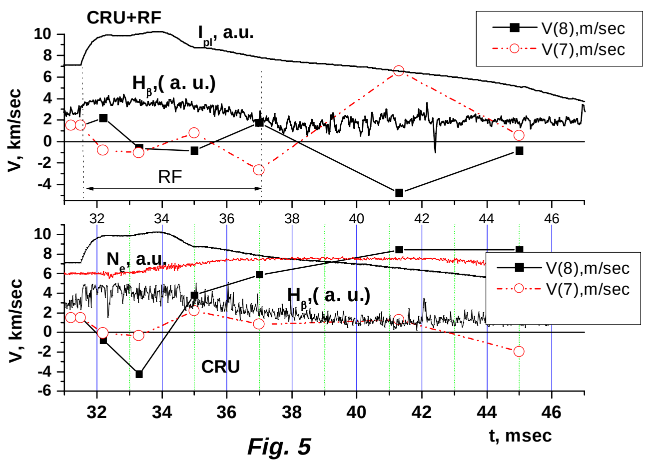

Fig. 5

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