

Dynamics of the Transport Barrier Formation on the FT-2 Tokamak Caused by Low Hybrid Heating

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The recent experiments on the FT-2 tokamak [1] have demonstrated an effective LH plasma heating, which was accounted for by both direct absorption of RF power and plasma transport suppression. The Improved Core Confinement (ICC) accompanied by Internal Transport Barrier (ITB) formation was observed. It was confirmed by measurements of the peculiarities of the density and the electron and ion temperature profiles and by diamagnetic, spectroscopic, reflectometry and Mirnov probes diagnostics. It was also shown that the RF pulse switch off is followed by triggering of L–H transition and the External Transport Barrier (ETB) formation near the Last Closed Flux Surface (LCFS) ($r = 7.8$ cm), when the abrupt decrease of the H_{β} line emission was observed. It was found that the L–H transition is accompanied by a significant alteration of the poloidal and radial plasma parameter distribution in the SOL and limiter shadow region and by formation of strongly nonuniform radial electric field, which is probably responsible for the onset of ETB [2].

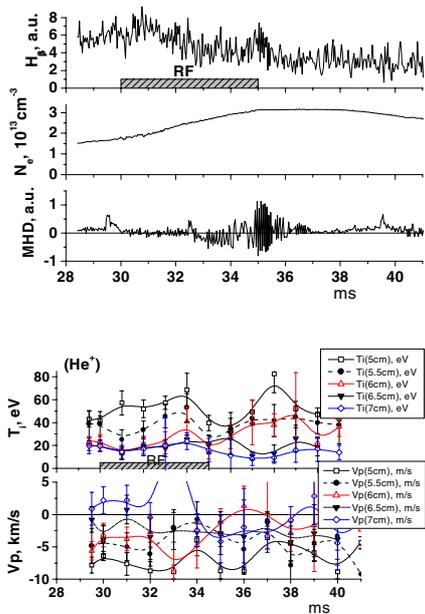


Fig. 1

Experiments carried out on many tokamaks showed that the improved confinement and the formation of transport barriers are associated with the suppression of microscale turbulence by the shear of the poloidal $E_r \times B$ drift velocity $\omega_{E \times B}$. [3]. The present paper is devoted to a much more detailed study of the radial electric field E_r behaviour in the region of ITB and ETB and its influence on the tokamak

microturbulence in these regions. The new experimental data were obtained by spatial spectroscopic technique retooled with additional pulse helium puffing in hydrogen plasma at the plasma region ($r = 5-7$ cm), where ITB is formed [2]. The high-resolution spectroscopy of a helium ion line He II provides local measurement of local $T_{i,opt}$ and poloidal velocity v_{θ} of He^+ ion at the plasma column periphery. The time and the spatial resolution used here were $\Delta t =$

1 ms and $\Delta r = 5$ mm, respectively. The spectral line He II (468.54 nm) profile was detected shot by shot by a photo-multiplier tube. The intensities of the spectral line He II were used for determination of the density scale length $L_n = n_{\text{He}^+} / \Delta n_{\text{He}^+}$ of the n_{He^+} radial profile.

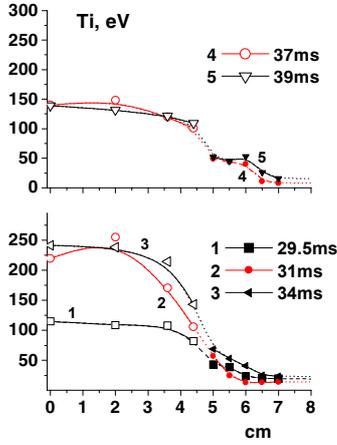


Fig. 2

different moments of the discharge. According to the radial force balance equation [4], the measured change of the ion poloidal velocity is $v_\theta = \nabla_r P_{iz} / Z e n_{iz} B_\phi - E_r / B_\phi + v_\phi B_\theta / B_\phi$, where $B_\phi \gg B_\theta$. We assumed that the toroidal velocity v_ϕ of the He⁺ without external momentum is smaller than v_θ and being weighted with $B_\theta / B_\phi \approx 0.04$ it is negligible.

Change of the poloidal rotation of helium ions is resulted from a strong radial variation of the plasma radial electric field E_r and $\nabla_r P_{iz}$ of the helium ions. These estimations give the variation of the E_r for the region $r = 5-6$ cm from -10 kV/m at $t = 30$ ms up to -20 kV/m at 31–32 ms when ITB is formed (Fig. 3). This alteration of the E_r is in good correlation with E_r value calculated from neoclassical theory and ASCOD code simulation [2, 5]. Smooth decrease of the H β line emission correlates with the internal transport barrier formation in the same way as the small instability, and the burst of the spikes at the H β line correlate with decrease of the $|\Delta T_i|$. The maximum of the $|E_r|$ at the level of 15 kV/m is shifted outward to the region $r = 6.5$ cm

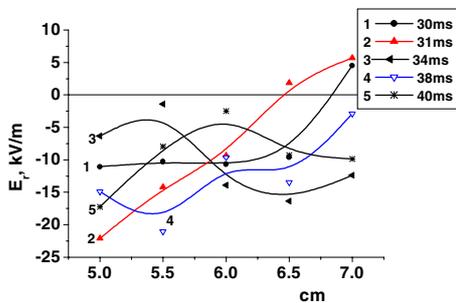


Fig. 3

The ion temperature $T_{i,\text{opt}}$ ($r = 5$ cm, 5.5 cm, 6 cm, 6.5 cm and 7 cm) measured by the spectrometer, the He⁺ ion poloidal velocity v_θ (at the same radii) as well as the average n_e along the central line of sight and the H β line emission from the periphery of the discharge are shown for LHH experiment in Fig. 1. The positive direction for velocity is ion diamagnetic drift direction. One can see the prompt ΔT_i rise from ≈ -16 eV/cm up to ≈ -40 eV/cm at $r = 5-5.5$ cm in 1.5 ms after the start of RF pulse. There is the same rise of $|\Delta T_i|$ after the end of LHH pulse at $r = 5-5.5$ cm and at $r = 6-7$ cm. The ion temperature profiles composed from CX analyser data ($r = 0-4.5$ cm) and mentioned above optical measurements at radii from 5 to 7 cm are shown in Fig. 2 for

when the small instability appears (curve 3). The end of RF pulse was followed by L–H transition with abrupt decrease of the H β line emission and additional gradual rise of $|\Delta T_i|$ at $r = 7$ cm. It could be explained by appearance of the additional shear maximum near LCFS ($r = 7$ cm, curve 4 in Fig. 3) which was observed previously by Langmuir probes [2]. So, the L–H transition as well as the fast decrease of the transport near $r = 5-6$ cm at 32–34 ms is due to a strong negative E_r generation caused by LH additional heating. It is

confirmed by spectral measurements. The plasma periphery data near LCFS are under further analysis.

Simultaneously microscale plasma density oscillations in the frequency band 10 kHz–2 MHz are observed by the local enhanced microwave scattering (ES) diagnostics sensitive to the turbulence behaviour in the upper hybrid resonance (UHR) of the probing wave [6, 7]. In this technique the probing extraordinary microwave is launched from the high magnetic field side of the torus and comes to the UHR located at the low field side. The back scattered wave possessing information on density small scale fluctuations with $q > 2\omega_{ce}/c$ ($q \sim 200\text{cm}^{-1}$) are measured. The measurements are carried out in the region of the plasma column where the shear of the poloidal drift velocity $\omega_{E \times B}$ increases and a transport is formed. Here we present the first result from an

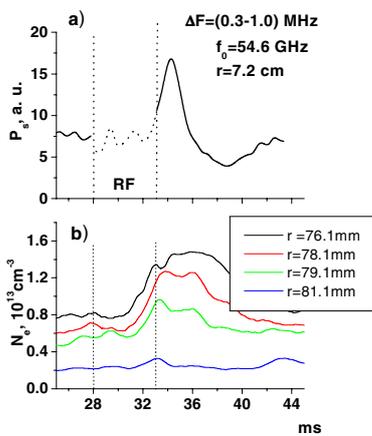


Fig. 4

analysis of the enhanced microwave scattering diagnostics data. The plasma region $r = 4.3\text{--}7.2$ cm is scanned shot by shot by shifting the UHR location, when probing frequency $f_0 = 69.6\text{--}53.6$ GHz is changed. Unfortunately, we were restricted to the analysis of the micro-turbulence variation only for the post-heating period, when ETB near r_{LCFS} is formed, because there is a large influence of the LH pumping wave on the short-wave receiver. It was discovered that only the back-scattered (BS) signal from $r_{UHR} = 7.2$ cm reveals the suppression of the microturbulence at 38 ms, after its sudden rise at 33–35 ms. The time history of the BS signal P_s in the band of frequencies ΔF from 0.3 to 1.0 MHz is shown in Fig. 4a.

(We would like to draw the attention to the fact that in these measurements the start of the RF pulse is shifted to 28 ms). There is a good correlation of the BS signal suppression with the increase of the negative value of the E_r and its shear near $r = 7$ cm at the 3rd ms after the end of RF pulse (Fig. 3). We do not have an adequate explanation of the sudden rise of BS signal at 33–35 ms. Apparently, it is associated with the rise of the MHD activity before the end of RF pulse (Fig. 1). The increase in the density gradient near the LCFS ($r_{LCFS} = 7.8$ cm) measured by the Langmuir probe located at the poloidal angle of 310° (at the outer perimeter of the torus) after the end of RF pulse (Fig. 4b) correlates with the suppression of the fluctuations. So, experiments demonstrate that the L–H transition is associated with the modification of microscale turbulence by the poloidal $E_r \times B$ rotation shear $\omega_{E \times B}$. The microwave scattering (ES) diagnostics data at the plasma region inside LCFS are under further analysis [7].

This conclusion is also confirmed by X-mode fluctuation reflectometry observations. The extraordinary wave launched from the high magnetic field side of the torus is scattered back from the upper cut-off (UC), located at high field side, possesses the information on the density fluctuations with wave numbers ($q \sim 1\text{--}10\text{cm}^{-1}$) lower than data from ES diagnostics. Fig. 5 demonstrates a sharp decrease of the reflectometry signal P_s in the frequency band ΔF from 0.2

to 0.5 and from 0.5 to 1.0 MHz during and after RF pulse. Fig. 6 shows that the decrease of the P_s signal is resulted mainly from the suppression of the higher frequency part of the spectrum.

The microwave reflectometry measurements correlate with the data obtained by Langmuir probes in the plasma edge near LCFS [8]. The recent Langmuir probe measurements

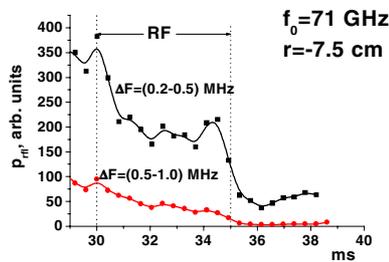


Fig. 5

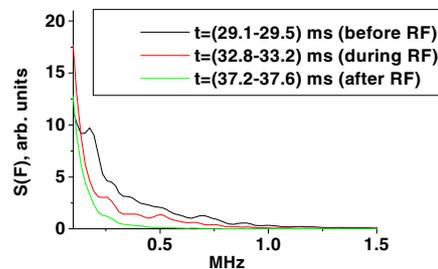


Fig. 6

show the decrease of the fluctuation particle flux by approximately one order of magnitude during and after RF pulse at $r = 7.4$ cm with probe located at the poloidal angle of 230° (at the inner perimeter of the torus). The Langmuir probe measures the long-wave turbulence, approximately with the same fluctuation wave numbers $|q|$ as the X-reflectometer. The radial

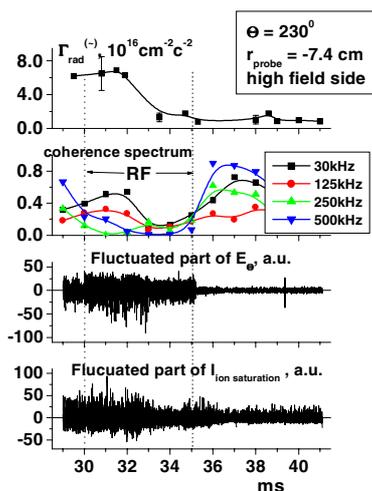


Fig. 7

particle flux suppression during LHH is provided by decrease of the coherence of fluctuations in plasma density and electric field. The cross-coherence function γ^2 [8] describing the contribution of different harmonics within the 10-500 kHz range of the frequencies is shown in Fig. 7. In H-mode, after the RF pulse, the reduction of the radial flux after the end of RF pulse is provided by substantial reduction of the level of poloidal electric field fluctuations $E_\theta^{(-)}$, though the coherence function γ^2 increases.

So, the dynamics of the transport barrier formation on the FT-2 tokamak caused by Low Hybrid Heating has been elaborated by new spectral microwave scattering diagnostics and Langmuir probe data.

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