# Processes in SOL Plasma at the Transition into Improved Confinement Mode in FT-2 Tokamak

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## Abstract

Study of the processes in Scrape of Layer (SOL) of the tokamak shows the direct influence of the periphery effects on confinement parameters of the plasma core. The paper illustrates experimentally observed transport barrier formation initialized by the LH heating. The experimental data near LCFS and in SOL were obtained by means of an enhanced movable multielectrode Langmuir probe and spatial spectroscopic technique fit up by helium puffing. The preliminary analyses of the spectral line profile measurements show that the poloidal velocity change can be understood in terms of a radial electric field change at the plasma edge generated by high LH ion heating. It was found, that L – H transition is accompanied by the marked reconstruction of the poloidal and radial plasma parameter distribution in the SOL and limiter shadow region.

## 1. Introduction

Experimental investigations of peripheral processes in a tokamak plasma are necessary to create a reliable theoretical model of the anomalous transverse particle and energy transport. These investigations take on particular interest in the light of the discovery and intensive studies of regimes with improved plasma confinement (H-regimes), that have emphasized a close relationship between peripheral processes (specifically the nature of the peripheral microturbulence and particle fluxes attributed to it) and plasma parameters in the main part of a tokamak. Studies of processes in the Scrape off Layer (SOL) of the tokamak show a direct influence of periphery effects on confinement parameters of the plasma core.

The purpose of this work is obtaining the periphery data near the last close magnetic flux surface (LCFS), which associate with the transition to improved confinement (IC) mode in a small tokamak FT-2 (R = 0.55m, a = 0.08m, $B_{tor}$ = 2.2T, $I_{pl}$ = 22kA). The L – H transition has been observed in the experiments with additional plasma heating by Lower Hybrid (LH) waves [1, 2]. The LH wave (920 MHz, 100 kW) was launched by a two-waveguide grill from the low field side, with refractive index $N_{//}$ =2 ~ 3. The central density n(r=0) before the additional heating is resonance density for absorption of LH wave by ions. This paper describes the experimental results when a transition into improved core confinement (ICC) initiated by LHH is followed by the formation of an external transport barrier (ETB). New experimental data and a model for ETB formation are discussed.

## 2. Experiment

A comparative study of plasma confinement for two typical RF heating scenarios was performed in the experiment [2, 3]. The $T_i$(r), $n_e$(r) and $T_e$(r) profiles were measured by a CX-analyzer and a high-resolution multipulse Thomson scattering diagnostic. In the first scenario the central ion absorption of RF power was achieved, which lead to a pronounced ion heating from 100 eV to 300 eV localised at the discharge axis. In this case while the ion temperature rise is triggered by the RF pulse start, the central electron heating is realized only 1.5 ms later. Furthermore, the increase of $T_e$(r = 2cm) from 400 eV up to 650 eV during LHH is followed by a further heating up to 700 eV in the post heating stage. The persisting high values of $T_e$(r) after the RF pulse indicate that electron heating is not only due to RF power absorption, but also due to improved core plasma confinement (ICC) (See Fig. 1 in [2]). In the second scenario characterized by a slightly higher central plasma density, exceeding the LH resonance value, the power deposition region was shifted from the axis, which resulted in a broader ion temperature profile and smaller ion heating effect from 100 eV to 200 eV (Fig. 1). In this alternative case, the central electron temperature rises only slightly during the RF pulse and quickly decreases after its end. (The well pronounced steepening of the electron temperature profile observed in the post heating stage for the first case could be accounted for an internal core confinement). It should be underlined, that the common feature for both scenarios is that the ion temperature and density transport barriers formed during LHH probably exist at radii r = 5cm÷7cm for both cases with the central and non-central ion absorption of RF power. An increase of the plasma poloidal ($E_r$xB) rotation shear $\omega_{E\times B}$ is supposed to be responsible for the ICC and internal transport barrier (ITB) formation [3, 4]. The improved confinement effect during LHH experiment is approved by diamagnetic, spectroscopic, reflectometry and Mirnov probes measurements [5]. This fact is strongly manifested during the post heating stage, when the $H_\beta$ line emission after ELM's spikes is sharply reduced. This indicates an L – H transition after the RF pulse with additional external transport barrier (ETB) formation. Plasma parameters near the last close flux surface (LCFS) will be discussed in this paper. We have the additional experimental evidence that heat and particle transport is decreased near the LCFS during of LHH the same as in the region of a scrape-of layer (SOL) after the LHH pulse ends.

**3. Spectral and Langmuir probe data**

As it is seen in Fig.1 the ion temperature and density transport barriers formed during LHH probably exist at radii r = 5cm÷7cm.. These suppositions were confirmed recently by a new visible spectroscopy diagnostic [6]. The diagnostic consists of a high resolution Czerny-Turner spectrometer and a piezo valve puffing additional helium via the bottom port. The time and the spatial resolution used here was $\Delta t$ = 1 ms and $\Delta r$ = 5 mm, respectively. The spectral line HeII (468.54nm) profile was detected shot by shot by a photo-multiplier tube. The measurements of spectral line profile of ionised helium provide local values of $T_i$ and poloidal rotation $v_\theta$. Line-integrated emissivities were measured in order to evaluate the regions of maximal emission of HeII (The maximal emission $I_{max}$ of the spectral line HeII is located in the region of r = 5.5 – 7cm). The $T_{i,\ opt}$(r) and $v_\theta(r)$ data were simulated assuming that chord observations give the lower values than local ones [7]. Doppler broadening $\Delta\lambda_D$ of the observed line is proportional to the ion temperature $T_i$(eV) where as 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 $v_\theta$. The impurity velocity measured by the spectral diagnostic in general differs from the velocity of the main ions. The evolution of ion temperature for different radii simulated from chord measurements is shown in Fig. 2. As it is seen, the ion temperature $T_{iCX}$(r=6cm) measured by the CX analyser at r=6cm, and by the spectrometer at r = 7cm and 8cm decreases during first 1.5 ms after the RF is on, which is typical for the formation of outer region of transport barrier.

We present here the first result from a detail analysis of the profile evolution of the impurity velocity, the ion temperature evolution, the perpendicular electric field and the neutral density. The ion temperature $T_{i,opt}$(r=5,5cm, 6cm and 6.5cm) measured by the spectrometer, the $He^+$ ion poloidal velocity $v_\theta\ (r = 6cm,\ r = 6.5\ cm)$ as well as the average $N_e$ along the central line of sight, the $H_\beta$ line emission, are shown for LHH experiment in Fig. 3. The positive direction for velocity is ion diamagnetic drift direction. One can see the prompt $\Delta T_i$ rise from ~ -15eV/cm up to ~ -90eV/cm at r = 6cm in 1,5ms later of the RF pulse start. There is the same rise of $|\Delta T_i|$ after LHH pulse end.

The measured change in $v_\theta = \nabla_r P_{iz} / Zen_{iz}B - E_r / B$ can be related to a change of $E_r$ or variation of the diamagnetic drift of the helium ions. 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 $\nabla P_{iZ}$ itself. The preliminary analysis of the line profile measurements show that the poloidal velocity change in FT-2 can be understood in terms of a radial electric field variation in the edge plasma region [6]. These estimations give the variation of the $E_r$ for region at r =(5 – 6) cm from - (2-5)kV/m at t = 30ms up to -20kV/m at 32 –34ms. Smooth decrease of the $H_\beta$ line emission correlates with transport barrier formation in the same way as the small instability and ELM's spikes at the $H_\beta$ line correlate with decrease of the $|\Delta T_i|$. The end of RF pulse followed by L – H transition, when abrupt decrease of the $H_\beta$ line emission and gradual rise of $|\Delta T_i|$ and shift the well of the negative radial electric field to the periphery (from r = 5 –6 cm to r = 6 – 7cm) are observed. The fast decrease of the transport near periphery is due to a strong negative $E_r$ generation caused by LH additional heating. These plasma periphery region data inside of LCFS are under further analysis.

For the outside region of the LCFS (r≥78mm), scrape-off layer (SOL), we have the additional experimental evidence that particle transport is decreased there after the LHH pulse ends. The SOL width is estimated as $\lambda_{SOL}= (D_{\perp}L/c_s)^{1/2} \approx 3$ mm, where $D_{\perp}$ is a cross-field particl diffusion coefficient, $c_s$ is a sound speed and L = πRq/n, where n is the number of poloidal limiters [8]. Three movable multielectrode Langmuir probes allowed us to measure the time dependence of local electron temperature, plasma density, spatial potential, electric field, as well as quasistationary and fluctuation-induced ExB drift flux densities practically at any poloidal angle. Fluctuations of local plasma parameters in the wide range of frequencies (10-600 kHz) and local values of fluctuation-induced particle flux were measured [9]. This flux is considered as one of the most significant particle transport mechanisms in the plasma periphery. The integral radial flux $\Gamma_{rad}$ at r=8 cm shows that, after the additional heating is switched off, the transition to H-mode is accompanied by a reduction of this flux by nearly a half of its ohmic value [9]. An approximately double increase in the energy confinement time in the improved confinement mode compared to the ohmic regime is realised [4]. Spectrum and cross-correlation characteristics of fluctuations in plasma density and electric field have been studied by means of the digital equipment. A statistical coefficient of correlation $C_{n^{(\sim)}E^{(\sim)}}$ between $n^{(\sim)}$ and $E^{(\sim)}$ fluctuations determined by (1) describing the time evolution of the fluctuation-induced particle flux and also the cross-coherence function $\gamma^2$(f) determined by (2) describing the contribution of different harmonics were calculated.

$$C_{n^{(\sim)},E^{(\sim)}} = \frac{\langle n^{(\sim)}E^{(\sim)}\rangle - \langle n^{(\sim)}\rangle\langle E^{(\sim)}\rangle}{\sqrt{\langle n^{(\sim)2}\rangle - \langle n^{(\sim)}\rangle^2}\sqrt{\langle E^{(\sim)2}\rangle - \langle E^{(\sim)}\rangle^2}} \tag{1}$$

$$\gamma^2(\mathrm{f}) = \frac{\left|n^{(\sim)}(\mathrm{f})E^{(\sim)}(\mathrm{f})\right|^2}{\left|n^{(\sim)}(\mathrm{f})\right|^2\left|E^{(\sim)}(\mathrm{f})\right|^2} \tag{2}$$

Here $n^{(\sim)}$(f) and $E^{(\sim)}$(f) stand for Fourier-components of plasma density and electric field fluctuations. For $C_{n^{(\sim)}E^{(\sim)}}$ and $\gamma^2$(f) calculation $n^{(\sim)}$ and $E^{(\sim)}$ fluctuations were measured in the 10…600 kHz range of frequencies. These measurements were made on the outer side of the toroidal plasma cord within the symmetric poloidal angle range $\pm 60°$ in respect of the equatorial plane with a step of 30° (See Fig. 2 and Fig.3 in [8]).

In the ohmic regime the correlation coefficient between the electric field and the density fluctuations is typically about 0.3, and it decreases to practically zero after the LHH pulse. This tendency is exhibited at all poloidal angular positions where the measurements have been made.

The cross-coherence function describing the contribution of different harmonics of the fluctuation-induced particle flux also decreases for all observed frequencies (10 – 600kHz). In the steady state of the discharge in the ohmic regime the cross-coherence function typically equals about 0.5 within the 10…200 kHz range of frequencies and it is about 0.1…0.2 for the harmonics above 200 kHz. The transition to improved confinement after the LHH pulse corresponds to the decrease of the cross-coherence function to about 0.1 for all observed frequencies. The effect of the reduction in the intensity of plasma parameter fluctuations in the H-regime has also been observed in the experiments but this did not take place at all values of the poloidal angle. On the inner poloidal bypass a substantial reduction in the fluctuation levels was registered whereas on the outer side of the torus the intensity of the fluctuations did not undergo any significant changes or even indicated an increase at some spatial positions. It should be noted that a similar behaviour of the peripheral plasma turbulence after the LH heating pulse switch off was observed by reflectometry [10]. In such a way, the effect of the suppression of fluctuations is of local nature, while the decrease in the cross-coherence and correlation coefficient has been registered at all points were the measurements were made.

Figure 4 presents the quasistationary radial electric field ($E_r$) profiles at several poloidal angles at the outer perimeter of the torus. The x-coordinate is measured from the limiter rim (r = 78mm). These profiles were obtained using smoothed radial profiles of the electron temperature and floating potential measured by Langmuir probes. The transition to the external transport barrier (ETB) is seen to be accompanied by the appearance of a significant nonuniformity in $E_r$ (in both poloidal angle and radius). Thus a feasible reason for the transport reduction is a nonuniform $E_r$ that leads to the chaotic structure of drift particle fluxes. Fig. 5 demonstrates a sharp increase in the density gradient near the LCFS for the probe located at the poloidal angle of 30 degrees (at the outer perimeter of the torus). The local density of poloidal fluctuation-induced flux also changes at this probe position, which is manifest in Fig. 5. Because there is a small outward shift of the plasma column during LHH [4], more detailed investigations of the poloidal structure of the SOL are needed, which is the subject of future studies.

## 4. Discussions and Conclusions.

A possibility of controlling the transport processes in the tokamak plasma with Lower Hybrid Heating (LHH) has been demonstrated. It was shown that the key factor for the improved central confinement and L-H transition is an additional radial electric field generated by high central ion heating. An increase of the plasma poloidal $E_r$ x B rotation shear apparently leads to an internal transport barrier formation for particles and ion thermal energy at r = 5 ~ 7 cm. Study of the processes in the Scrape off Layer (SOL) of the tokamak shows a direct influence of the periphery effects on confinement parameters of the plasma core and vice versa.

The experimental data at the plasma periphery and in the SOL were obtained by spatial spectroscopic technique fit up by helium puffing and by means of an enhanced movable multielectrode Langmuir probe-based diagnostic technique. The spectroscopy diagnostic with high wavelength resolution of the helium ion line provides measurement of local values of $T_i$ and poloidal velocity $v_\theta$ $He^+$ ion in the plasma column periphery. The measured changes in $v_\theta$ are directly related to the change of $E_r$ and ion a pressure gradient itself. The preliminary analyses of the spectral line profile measurement show that the poloidal velocity change can be understood in terms of a radial electric field at the plasma edge.

The ETB formation seems to be due to the observed shift of ITB outward to the LCFS. The strongly non-uniform $E_r$ after the LHH pulse switching off apparently leads to the chaotic structure of drift particle fluxes and to the transport reduction near LCFS and in the SOL. The electric field shear evolve around LCFS only after the L – H transition on a time scale ~ 1 ms. This fact corresponds to the conclusions obtained on COMPASS-D, where the poloidal velocity and electric field shear clearly evolve around the 95% flux surface after L – H transition [11]. This fact can be understood if mean that recycling of neutrals in the main plasma depends on parallel heat conduction along the SOL [8], but an evolution of main plasma parameters is determined by cross-field transport coefficients. More detailed investigations of plasma periphery will be the subject of the future study.

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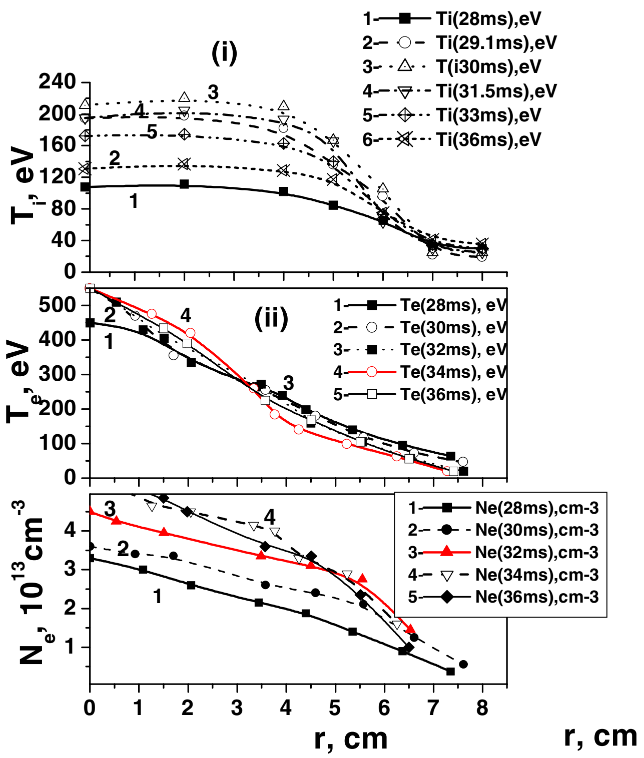


*Fig. 1*

***The behavior of main plasma parameters for the second's scenario, when ion absorption of RF power was shifted from the axis. (i) -$T_i(r)$ is measured by a CX-analyzer, (ii) - $T_e(r)$ and $N_e(r)$ profiles were measured by a high-resolution multipulse Thomson scattering diagnostic.***

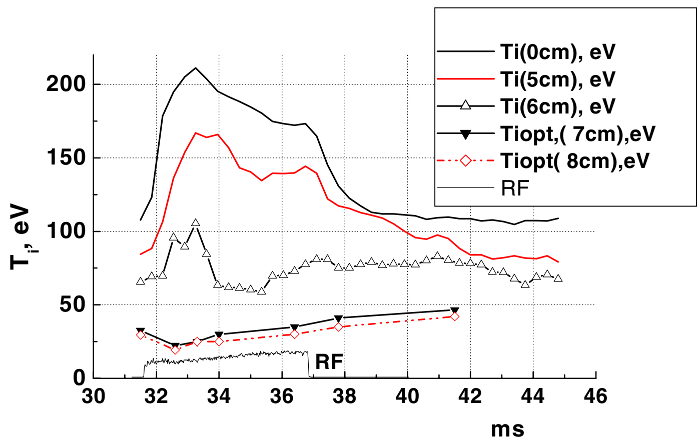


*Fig.2*

***The evolution of ion temperature for different radii***

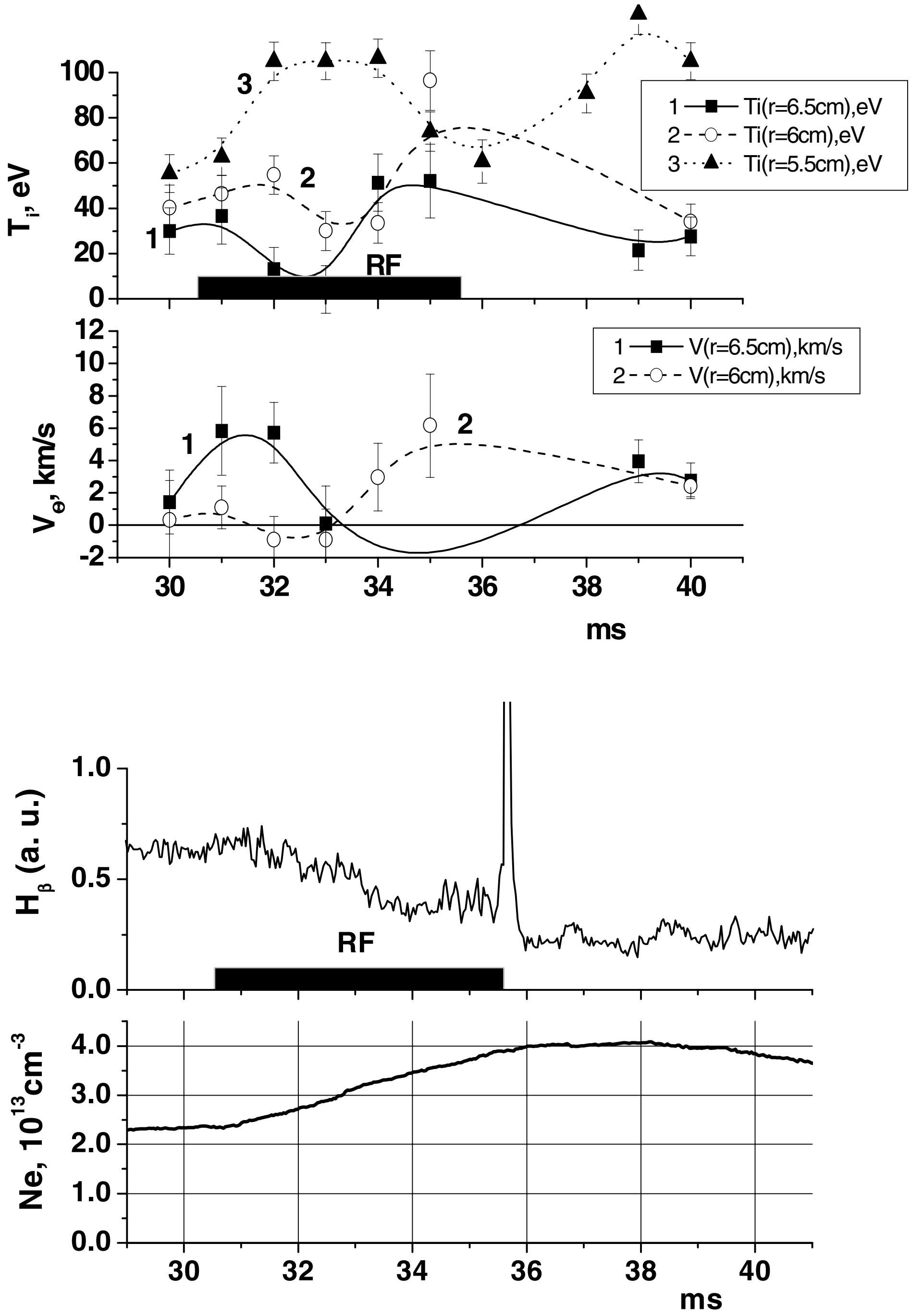


***Fig.3***

***. The ion temperature $T_{i,opt}$(r=5,5cm, 6cm and 6.5cm) measured by spectrometer, the $He^+$ ion poloidal velocity $v_\theta$ (r = 6cm, r = 6.5 cm) as well as average $N_e$ alone central veaw, $H_\beta$ line emission, are shown for LHH experiment***

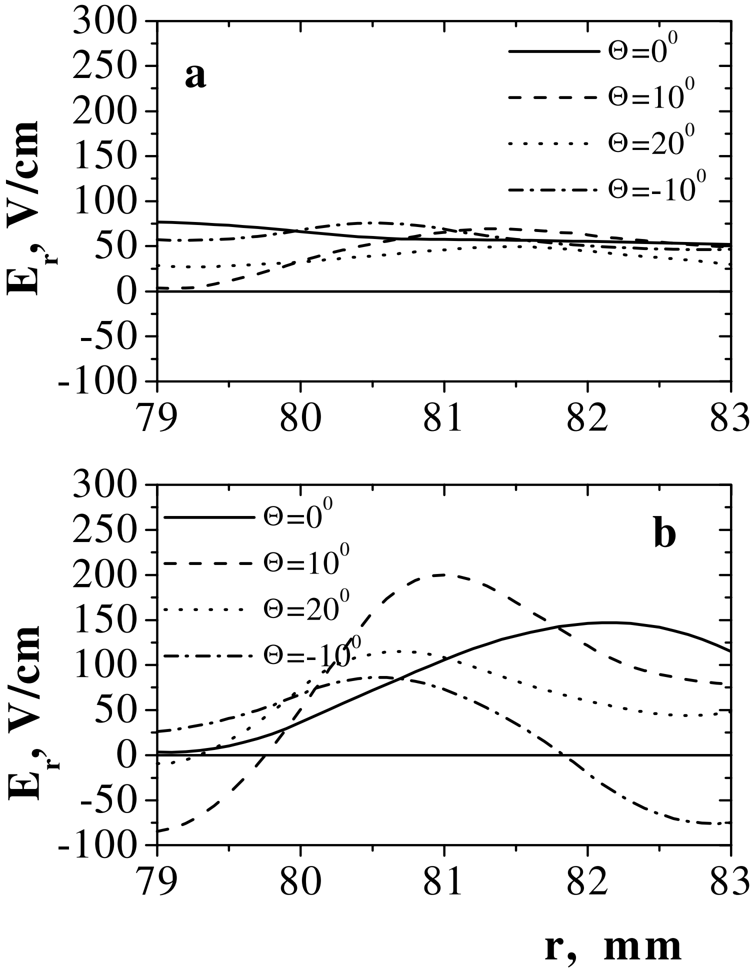


***Fig. 4***

***The radial dependence of $E_r$. The upper picture (a) refers to time before RF pulse (ohmic regime), lower picture (b) – the end of RF pulse (improved confinement regime). Dependence brings for several angular position.***

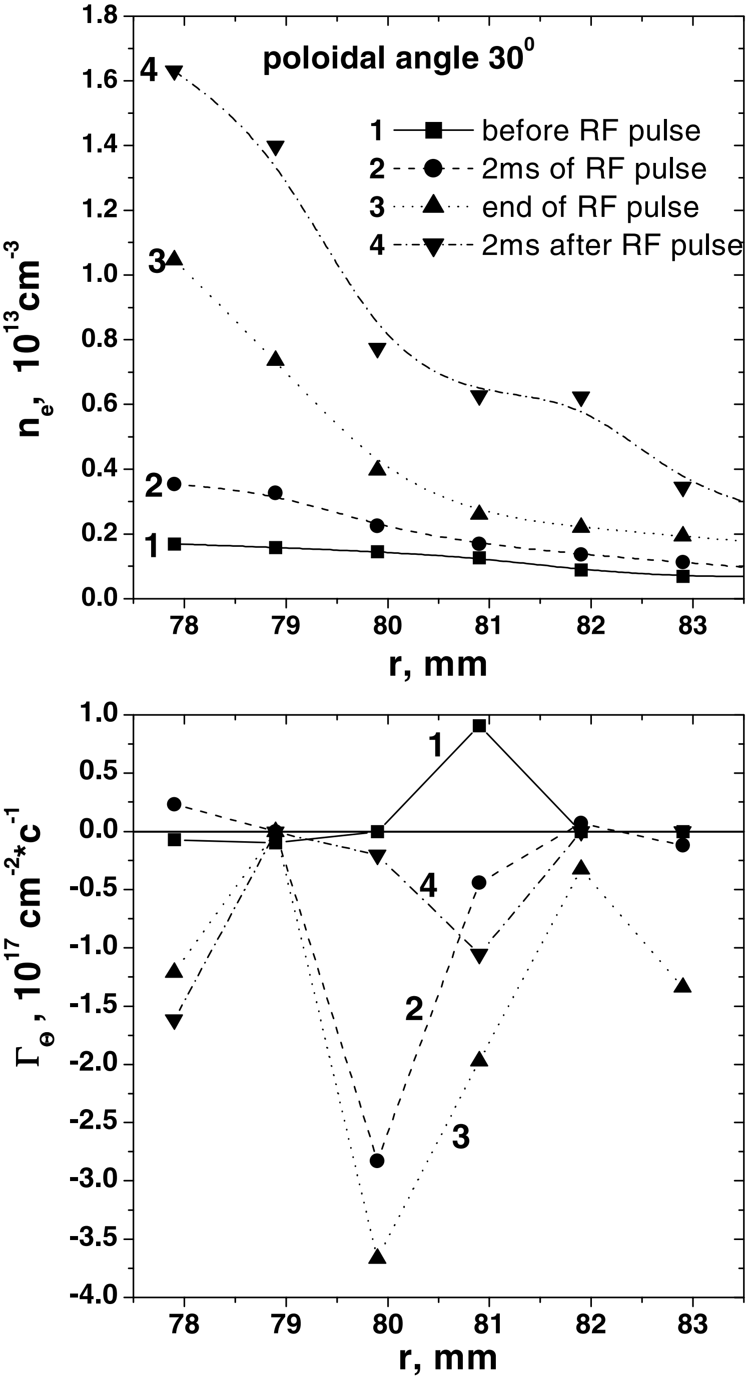


***Fig. 5***

***The density gradient increase and poloidal fluctuation-induced flux $\Gamma_\Theta$ changes near the LCMS for 30 degree of poloidal angle probe position at the outer perimeter of the torus.***