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Improved Confinement Transition in Lower Hybrid Heating Experiment on FT-2 Tokamak

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Introduction. The Lower Hybrid Heating (LHH) scheme has been routinely used at FT-2 tokamak to provide ion and electron heating [1] and a transition to improved confinement regimes with Internal Transport Barrier (ITB) at RF power level 100 - 120 kW [2]. Recently the possibility of LHH at enhanced power level ($P_{\rm LHH} \approx 2P_{\rm OH} = 180$ kW) resulting in a transition to improved energy confinement regime in the post heating stage has been demonstrated (#061505) [3]. The LH heating efficiency of the ion component at the high level of $P_{\rm LHH} \approx 2P_{\rm OH} = 180$ kW remains as high as at the lower RF powers, $P_{\rm LHH} \approx 100$ - 120 kW. Also the central electron temperature increases. After LHH end the L – H transition with hydrogen recycling decrease and density turbulence suppression are observed in the plasma periphery and SOL [3, 4]. In the present paper this effect was reproduced (#053106 run), and the evolution of the plasma poloidal rotation and turbulence levels have been studied using spectroscopic, Lengmuir probes [2], Doppler reflectometry [5] and the Upper Hybrid Resonance (UHR) Doppler backscattering (BS) techniques [6]. The data measured with these diagnostics were analyzed and compared to each other.

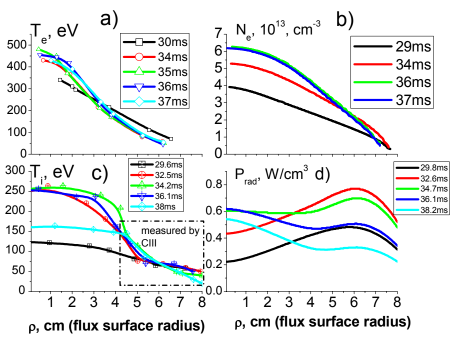

Fig. 1. Plasma parameters

Experiment. The characteristic features of the FT-2 plasma parameters are the following: the safety factor is $q = 6$ ($R = 0.55$m, $a = 0.079$m, $I_{pl} = 22$kA and $B_t = 2.2$T) and the line–of-sight averaged density $\langle n_e\rangle \approx 3{,}2\cdot 10^{20}$m^{-3}. The RF pulse ($P_{\rm LHH} \approx 160$kW, $\Delta t_{LH} = 5$ms, $f = 920$MHz) is applied in the middle of a $\Delta t_{pl} = 60$ms plasma shot. Fast drop down of the H_β (481.8nm) spectral line intensity together with the decrease in the periphery radiation losses indicates L - H transition [3]. The reproduced (#053106) experiment demonstrates the rise of T_i, T_e and n_e during additional RF heating. Figure 1 shows plasma parameters measured by Neutral Particle Analyzer (NPA) and spectroscopy, by the laser Thomson scattering (TS) diagnostics, and a 2mm interferometer. It should be noted that during additional heating a small shift (without any plasma current disruptions) of the plasma column outward along of the major radius R is observed [4]. The shifts of the circular flux surfaces (FS) (due to plasma core and Shafranov's FS shifts), resulting from the process of inverting the density chord profiles (Fig. 1b), have been taken into account in Fig. 1, where ρ is FS radii. The TS electron temperature data versus ρ is presented in Fig. 1a. The $T_i(\rho)$ profiles and the radiation losses $P_{rad}(\rho)$ measured by scan bolometric technique are presented in Fig 1(c) and (d), respectively. The experimental data for the ion component demonstrate that during on-axis LHH $T_i(\rho)$ rises with ITB formation at $\rho = (4\div5)$ cm (32ms and 34ms). This is consistent with the previous observations [2, 3]. Also the central electron temperature increases and remains at the high level for about 5 ms after the RF pulse switch off. This fact at relatively high density level permits proposed that electrons are not heated directly by LH waves [1, 7]. The ASTRA code modeling, shown in Fig. 2b, indicates that the thermal conductivity plasma core decreases, which leads to doubling of the energy confined time τ_E towards the end of LHH, see Fig. 2d. Figures 2a and 2c depict sharpening of the plasma current density $j(\rho)$ and steepening of the safety factor gradient $q(\rho = 4\div7.5\text{cm})$. It seems that the central electron temperature rise could be explained by the $j(\rho)$ sharpening.

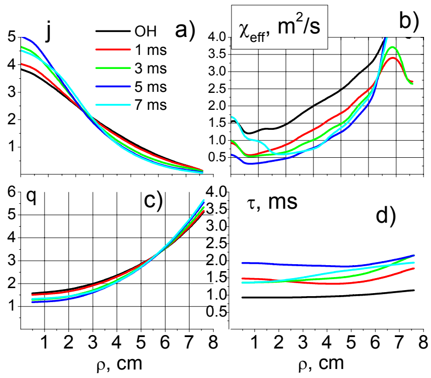

Fig. 2. ASTRA code modeling data

Evolution of E_r. I) It is well known that a change in the radial electric field E_r can suppress turbulence level (and anomalous transport) by strong $E_r\times B$ poloidal plasma rotation shear ω_s [8]. The $E_r(\rho)$ field and the corresponding poloidal plasma $E_r\times B$ rotation can be measured spectroscopically using the CIII (464.7nm) line emissivity. Spectral measurements in the visible region are made by two monochromators that record fast parameter changes at the periphery of the plasma column [4]. E_r is calculated using the MHD force balance equation (see, e.g., Ref [9]) for the C^{2+}impurity ion. Resulting poloidal ion velocity v_θ is defined as $v_\theta = \nabla_r P_{iz} / Zen_{iz}B_\Phi - E_r / B_\Phi + v_\Phi B_\theta/B_\Phi$, where the first term is due to the diamagnetic drift and the second due to electrostatic drift. The third term with the toroidal velocity v_Φ was neglected because $B_\theta/B_\Phi \approx 0.04$. The results of the $v_\theta^{C2+}(\rho)$ measurements for C^{2+} ion emissivity region (where CIII spectral line is detected) of the plasma column during LHH experiment (#053106) are presented and discussed in detail in the paper (P2.148) at this Conference [4]. The $E_r(\rho)$ values obtained from the force balance equation are presented in Fig. 3 at three times: during OH before LH heating (29ms), at the end of RF pulse (34.7ms), and during the post heating phase (36ms). Measurements demonstrate that E_r data are differed from the standard neoclassical values [8] (dash-dot lines). They are larger at the middle radii and smaller at the LCFS vicinity. One could propose that a sudden rise of the E_r and its shear ω_s in the region 4÷5cm could result in the ITB formation observed at $T_i(\rho)$ profiles during LHH (Fig. 1c). Monte Carlo simulations of the E_r evolution in a low current tokamak FT-2 have shown that E_r can make a spontaneous transition to higher negative value during LHH, if the local Mach number is about one [10]. In the post heating phase (36ms), a sharp decrease in the magnitude of E_r in vicinity of 4 – 5cm is observed.

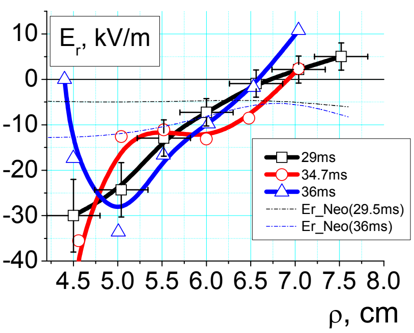

Fig. 3. Spectroscopically measured $E_r(\rho)$

Such a reduction in $E_r(\rho)$ exceeds diagnostic uncertainties and needs additional experimental verification and theoretical analysis.

II). As mentioned above, in the vicinity of the LCFS there are characteristic differences between the spectroscopically measured E_r and E_r^{NEO}. In particular, $E_r(\rho)$ is smaller than E_r^{NEO} and even changes sign near $\rho \sim 6.5\text{cm} < a = 7.9$ cm. The corresponding radial profiles of $V_{Er\times B}(\rho)$ velocity are compared with the profiles of the poloidal velocity derived from the Doppler Reflectometry (DR) measurements. In the Doppler reflectometry the rotation velocity is obtained from the Doppler frequency shift of the backscattered radiation under oblique incidence onto the cutoff surface [5]. The DR operated in the K-band (26-37 GHz for O-mode propagation) with the microwave beam tilted at a fixed angle 16.2^0 with respect to the normal of the LCFS. The actual velocity extracted from the Doppler shift consists of two terms: $V_\theta = V_{\text{ph}} + V_{\boldsymbol{E}\times\boldsymbol{B}}$, where V_{ph} is the phase velocity of the scattering fluctuation and $V_{\boldsymbol{E}\times\boldsymbol{B}}$ is the plasma drift velocity caused by a radial electric field. If the phase velocity of the density fluctuation is negligible, then the measured V_θ may be interpreted as the $E_r \times B$ drift velocity. The same sum of velocities was estimated in the SOL region by Langmuir probe correlation technique. Figure 4 depicts the poloidal velocity, measured by the three diagnostics, for the plasma periphery, 5.5÷8cm. It is seen that the spectroscopic and RD profiles are close to each other, in particular, for the end of the heating pulse and in the post-heating stage. It is remarkable that two diagnostics show approximately the same radial location for the point where $V_{\boldsymbol{E}\times\boldsymbol{B}}$ changes its direction. This point is close to the resonance magnetic surface q = 4 (recall Fig. 2c), where the radial electric field may be significantly modified by the magnetic island itself. Indeed, different MHD behavior is identified by Mirnov probes for slightly different (mentioned above) displacement of the plasma column along the major radius. In this case DR measurements register two slightly different V_θ profiles (black and red points in Fig. 4). Black points correspond to discharges with strong MHD activities and red points correspond to weak one, which have been observed in the post heating stage (36ms and 38ms). The plausible reason of occurrence of rotation in the ion diamagnetic drift direction (recall Fig. 4 at 36ms and 38ms) is a change in the electron–ion balance due to the magnetic flux surface distortion caused by MHD activity or/and plasma column displacement along the major radius [11]. Observed differences between the spectroscopic and DR $V_{\boldsymbol{E}\times\boldsymbol{B}}$ profiles are more than diagnostic uncertainties and need further analysis. Langmuir probe-measured poloidal velocities of the fluctuation floating potential data [12] are marked by stars in Fig. 4 for the plasma LCFS vicinity and SOL (r = 7.2÷8cm). Those data show a good agreement in the region where the diagnostics overlap and can be useful for diagnostics comparison in the future.

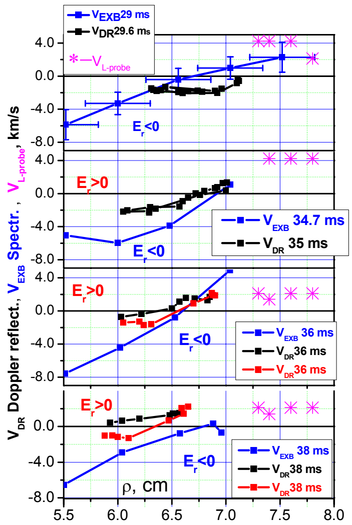

Fig. 4

Turbulence suppression. It is remarkable, that the drastic fluctuation suppression, measured by DR approximately across all frequencies (fluctuation frequency band f<1MHz and k~(1÷6)cm^{-1}), is detected slightly before the velocity inversion (Fig. 5). The red curve Δf gives the temporal behavior of the Doppler frequency shifts. In Fig. 5 f and Δf are presented in the same frequency scales (see left axis). The black curve shows the cut-off radius displacement (right axis). The observed suppression of the density fluctuations is in good agreement with the Langmuir probe measurements. One can assume that the fluctuation suppression is just near of strong shear of rotation, it is the vicinity of the point where there is velocity inversion (recall Fig. 4 at 35ms). That agrees with theoretical prediction of plasma turbulence suppression via increasing plasma rotation shear [8].

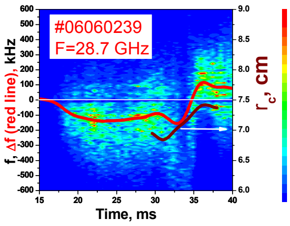

Fig. 5 Spectrogram of the Doppler reflectometer signal

The UHR Doppler BS diagnostics with X-mode 20 mW power probing in V-band from high magnetic field side with +1.5 cm vertical displacement above the equatorial plane was implemented for investigating the density turbulence dynamics with shorter scales ($\lambda < c / 2f_i$) compared to DR. Scanning the plasma region from $r = 5$ cm to 7.5 cm has shown that two small-scale drift modes are observable on the plasma periphery [6]. The first mode with frequency less than 1.5 MHz is probably associated with the small-scale component of TEM. The second mode with frequency higher than 2 MHz is associated with the ETG mode [13]. In the present experiment, as in the previous (#061505) one [3], both types of turbulence were suppressed during LH-heating. After the RF-pulse the first mode usually grows, in accordance with the peripheral rise of the electron thermal conductivity (recall Fig.2b), whereas staying suppressed the ETG mode is rather consistent with the gradient scale length of electron temperature and density profiles [13]. Therefore the recent efforts in the regime with Improved Confinement Transition strongly suggest investigating the direct role of the ETG mode on transport through the barrier under conditions when other drift modes are suppressed.

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