J. Plasma Fusion Res. SERIES, Vol. 4 (2001) 229–233

Formation of Transport Barrier in Lower Hybrid Experiment on FT-2 Tokamak

LASHKUL Sergei*, BUDNIKOV Vladimir, DYACHENKO Valerii, ESIPOV Lev, ITS Evgenii, KANTOR Mihail, KOUPRIENKO Denis, POPOV Alexei, GONCHAROV Pavel[1], GOUREVICH Evgenii[1], SHATALIN Sergei[1], YERMOLAEV Vladimir[1], VEKSHINA Elena[1]**, KURKI-SUONIO Taina[2]*** and HEIKKINEN Jukka[3]

A.F Ioffe Physico-Technical Institute, 194021, St. Petersburg, Russia

[1]St. Petersburg State Technical University, 195251, St. Petersburg, Russia

[2]Assn Euratom-Tekes, Helsinki Univ. of Tech., P.O. Box 2200, FIN-02015 HUT, Finland

[3]Assn Euratom-Tekes, VTT Chemical Technology, P.O. Box 1404, FIN-02044 VTT, Finland

(Received: 5 December 2000 / Accepted: 18 August 2001)

Abstract

The possibility to control the transport processes in an LH-heated tokamak plasma has been demonstrated. The paper presents experimentally observed transport barrier formation, initialised by the LH heating. The effects of the improved confinement are observed by the Thomson scattering diagnostics, the CX analyser, diamagnetic, spectroscopic, bolometer, reflectometer movable multi-electrode Langmuir and MHD probes measurements. Mechanisms for internal (ITB) and external transport barrier (ETB) formation have been put forward to explain the observed regime of improved core confinement. The increased shear of the radial electric field stimulates the improved core confinement (ICC) regime and a transition to the H-mode.

Keywords:

lower hybrid heating, transport barriers, radial electric field, shear, ICC

1. Introduction

Improvement in plasma confinement during the Lower Hybrid Heating (LHH) experiment is observed at the FT-2 tokamak (I_{pl} = 22 kA, B_t = 2.2 T, R = 0.55 m, r = 0.08 m). The LH wave (920 MHz, 100 kW) was launched by a two-waveguide grill from the low field side, with refractive index $N_{\|} = 2 \sim 3$ [1]. The central density $n(r = 0)$ before additional heating is resonance density for absorption of LH wave by ions. When the initial Ohmic electron temperature is above the threshold for parametric instabilities, $P^{th} \propto T_e^{\alpha}/n_e^{\beta}$, the central ion heating $T_i(0)$ from 90 up to 300–350 eV by LHH is observed. This paper describes the experimental results when a transition into improved core confinement (ICC) is initiated by LHH. A model for the formation of an internal (ITB) and an external (ETB) transport barrier is discussed. In the second part, peculiarities of the LHH experiment, together with computer simulations that explain the physical processes, are presented.

2. Experiment

The time history of the plasma parameters $T_i(0)$, $T_e(r = 2\text{ cm})$, U_{pl} and H_β line emission are shown in Fig.1. In this experiment the central ion temperature rises from 100 eV up to 300 eV. One can see that while

*Corresponding author's e-mail: *Serguey.Lashkul@pop.ioffe.rssi.rui, **Lena Vekshina@pop.ioffe.rssi.ru, ***taina.kurki-suonio@hut.fi*

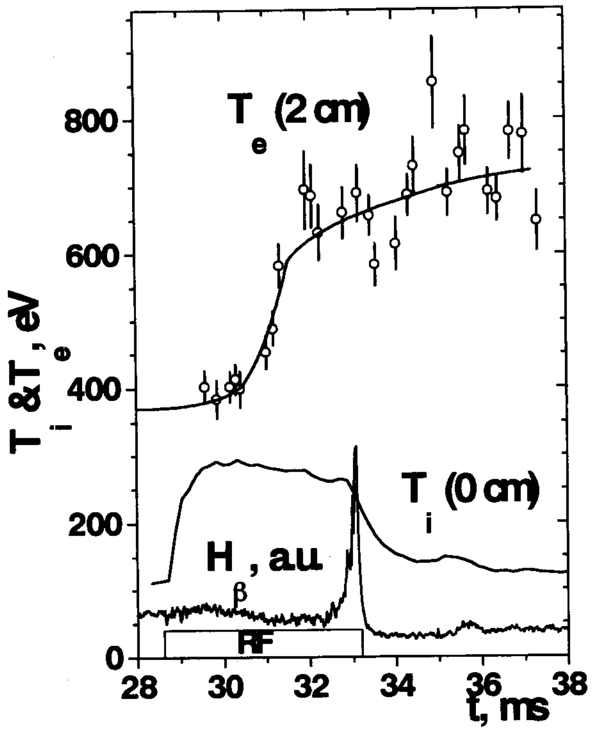

Fig. 1 The time history of the central plasma parameters $T_i(0)$, $T_e(r = 2\text{ cm})$; U_{pl} and H_β line emission.

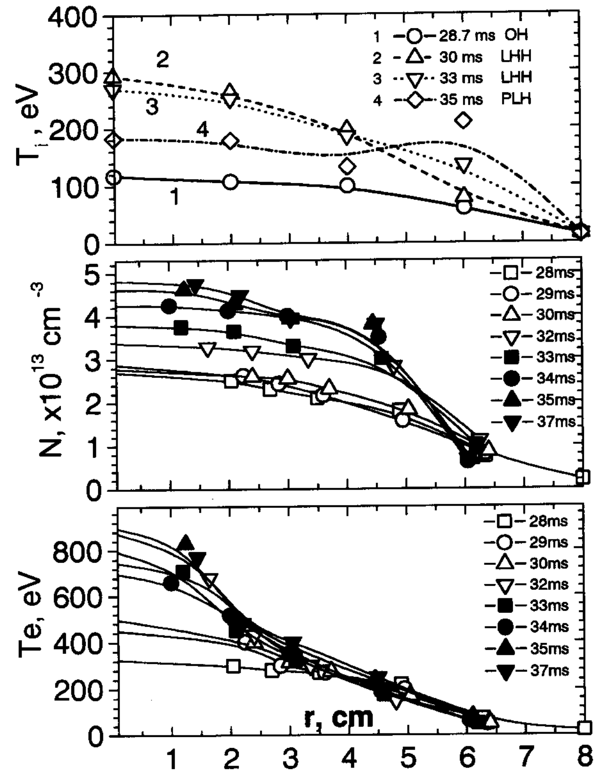

Fig. 2 $T_i(r)$, $n_e(r)$ and $T_e(r)$ profiles measured by CX-analyzer and Thomson scattering diagnostics and plotted versus the magnetic surface radius of the discharge.

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 $T_e(r = 2\text{ cm})$ 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). The $T_i(r)$, $n_e(r)$ and $T_e(r)$ profiles were measured by the CX-analyzer and high-resolution multipulse Thomson scattering diagnostics, Fig. 2. The ion temperature and density transport barriers exist at radii $r = 5$ cm ~ 7 cm [2]. This fact is strongly manifested during the post heating stage, when the H_β 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 closed magnetic surface (LCMS) will be discussed latter.

The ASTRA simulations were done assuming changes in electron thermal diffusivity χ_e and accounting radiation losses. The simulations show an 8-fold decrease in χ_e from the ohmic heating (OH) level [3]. An increase of the plasma poloidal ($\boldsymbol{E}_r \times \boldsymbol{B}$) rotation shear $\omega_{E\times B}$ is supposed to be responsible for the ICC and internal transport barrier (ITB) formation. The rotation shear reaches about 8×10^4 s^{-1} in the core ($r \approx 4$ cm) in 1.5 ms after the pulse start, then it is shifted outward and rises up to 5×10^5 s^{-1} ($r = 5 - 8$ cm) before the RF pulse is switched off [2]. The improved confinement effect during LHH experiment is approved by diamagnetic, spectroscopic, reflectometry and Mirnov probes measurements [4]. Near the LCMS we have the additional experimental evidence that particle transport is decreased there after the LHH pulse ends.

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 $\boldsymbol{E}\times\boldsymbol{B}$ drift flux densities practically at any poloidal angle. Fluctuations of local plasma parameters in the wide range of frequencies (10–500 kHz) and local values of fluctuation-induced particle flux were measured [5]. This flux is considered as one of the most significant particle transport mechanisms in the plasma

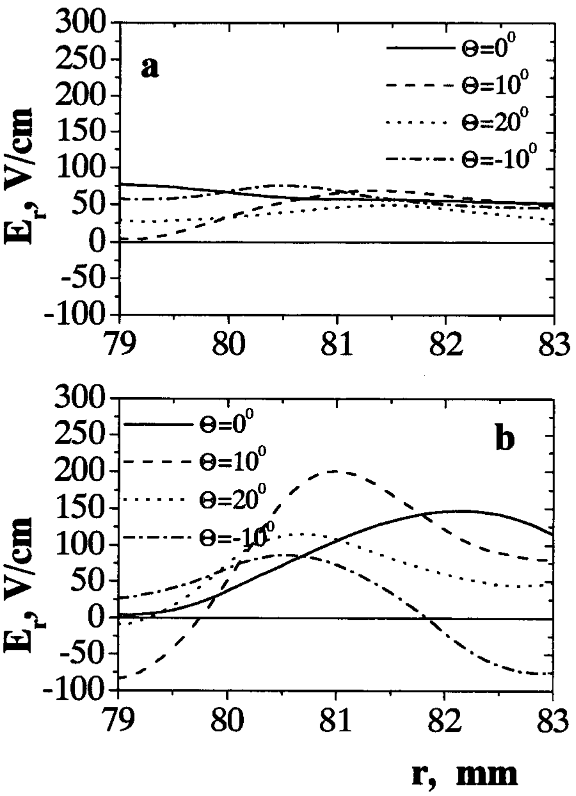

Fig. 3 The radial dependence of E_r. The upper picture (a) refers to time before RF pulse (ohmic regime), lower picture (b) – the end of RF pulse (improved confinement regime). Dependence brings for several angular position.

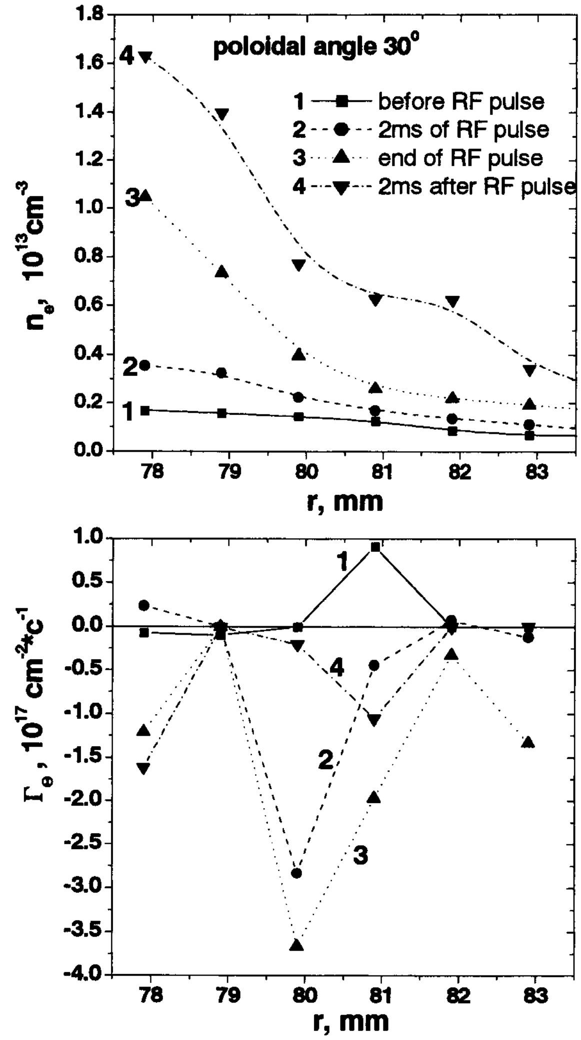

Fig. 4 The density gradient increase and poloidal fluctuation-induced flux Γ_θ changes near the LCMS for 30 degree of poloidal angle probe position at the outer perimeter of the torus.

periphery. The integral radial flux Γ_{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 [3,5]. An approximately double increase in the energy confinement time in the improved confinement mode compared to the ohmic regime is realised [4]. 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. The cross-coherence function describing the contribution of different harmonics of the fluctuation-induced particle flux also decreases for all observed frequencies (10 – 600 kHz).

Figure 3 presents the quasistationary radial electric field (E_r) profiles at several poloidal angles at the outer perimeter of the torus. The r-coordinate is measured from the limiter rim (r = 78 mm). 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. 4 demonstrates a sharp increase of the density gradient near the LCMS for poloidal angle of 30 degree of probe position (at the outer perimeter of the torus). The local density of poloidal fluctuation-induced flux changes is shown in Fig. 4 also. Of course, the poloidal structure of this parameter needs a more detailed investigation, which is subject of future study.

3. Simulations

The FT-2 tokamak has some exceptional features: due to the small plasma current (I_p = 22 kA) the poloidal magnetic field is small compared to the toroidal field (B_T = 2.2 T, q = 5–6). This leads to trapped orbits with very large banana widths, of the order 1/2 of the minor radius (a = 8 cm, R = 55 cm). Also the toroidal ripple is quite large, and the ripple-loss region extends deep into the bulk plasma. By simulating FT-2 plasmas we investigate the significance of neoclassical effects in the formation of a radial electric field. The ASCOT code follows the guiding center trajectories of test particles in a tokamak magnetic geometry with a toroidal ripple [6]. Collisions with stationary background plasma are simulated using binomially distributed Monte Carlo operators derived from the Fokker-Planck equation. In ASCOT, the effect of LH-waves are included using Monte Carlo operators [7] that give the change in the particle perpendicular energy $W_\perp$, the magnetic surface coordinate ρ, and the toroidal momentum p_φ due to the LH-wave during a time step Δt. We first evaluate the shape and magnitude of the E_r-field that is created due to finite orbit effects. Also, even a modest E_r creates an $\boldsymbol{E}\times\boldsymbol{B}$-drift that compensates the poloidal drift velocity $V_{\nabla B}$ and, thus, extinguishes the orbit losses altogether except for periphery. The simulations show that orbit losses alone steepen the E_r profile mostly at the edge [6]. For very steep gradients in the central region, a deep (30 – 40 kV/m) electric field well is formed inside the plasma. Large enough radial electric field well confines the banana and ripple blocked ions at closed orbits and provides their thermalisation during LHH.

As shown previously, particles blocked in a magnetic ripple can be utilized to observe changes in the radial electric field. A large enough radial electric field can confine the ripple-blocked ions. After obtaining the E_r-field from the simulations, we calculate the CX-(charge exchange) neutral fluxes observed by neutral particle analyzers in the presence of this field. The CX-signal to a neutral particle analyzer that views ripple-blocked ions above the thermal energy should respond to changes in the radial electric field. For large tokamaks this diagnostic is considered useful for E_r-detection only in the edge region, because normally the ripple-loss region is limited to the plasma periphery. However, in FT-2 the ripple-loss region extends all the way to the magnetic axis. This fact is supported by the CX neutral flux profiles. In Fig. 5 the experimental pick chord profile and the ASCOT-code simulation of the CX neutral flux are compared. It appears that the central CX-signal might provide not only ion temperature measurements but also a means to detect changes in the central radial electric field (to be published). Finally, the ripple-losses do not seem to play an important role in forming E_r for a quasistationary phase, hence the effect of altered plasma profiles is more significant than the generation of energetic tail ions.

To explain ICC we assume that effective central heating of ions (from 100 eV to 300 eV) changes radial electric field E_r profile and, as a consequence, the shear of the poloidal rotation $\omega_{E\times B}$. This process may be a key factor causing suppression of anomalous transport. Improved core confinement regime (ICC) of FT-2 tokamak was simulated by BATRAC transport code [8]. Transport coefficients were assumed to be the functions of shear of $\boldsymbol{E}_r\times\boldsymbol{B}$ poloidal drift, while the evolution of the electric field profile was addressed consistently with the transport equations. The radial electric field was obtained from the equation, where both ion and electron parallel neoclassical viscosity were taken into account. The triple increase of ion temperature during the first millisecond of LHH governs to substantial change of the radial electric field and shear $\omega_{E\times B}$ profiles. The internal transport barrier formation is initiated by reducing the transport coefficients, which depend on electric field shear. Modelling yields dynamics of the transition to ICC regime including the formation of internal particle and heat transport barrier in FT-2. Particle source and RF heating source are determined by the experimental data. The rise of the density, electron and ion temperatures obtained from the numerical simulations agree with the experimental measurements [2,8]. In general, the model appears to be consistent with many

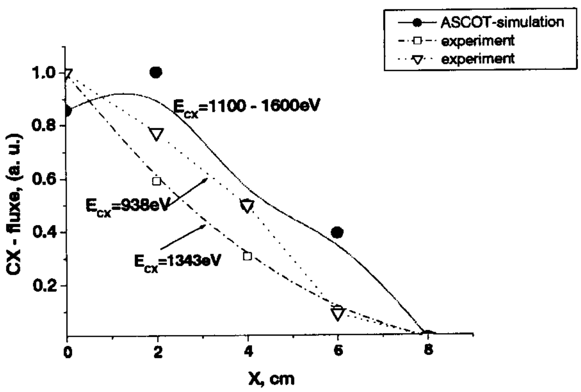

Fig. 5 Chord profiles of high energy CX-flux particles for end of LHH pulse. Experiment and ASCOT-code simulation.

features of an ICC transition during LH heating observed on FT-2 tokamak.

4. Summary

The possibility of controlling the transport processes in the tokamak plasma with Lower Hybrid Heating (LHH) has been demonstrated. The key factor for the improved central confinement and an L-H transition is the additional radial electric field generated by high central ion heating which stimulates the central electron heating (1.5 ms later RF pulse start). The increase of the plasma poloidal $\boldsymbol{E_r}\times\boldsymbol{B}$ rotation shear apparently leads to the internal improved confinement ($r < 5$ cm) for electrons, and to an internal transport barrier formation for particles and heat at $r = 5 \sim 7$ cm. The ETB formation is due to a strongly nonuniform E_r after the LHH pulse switching off which leads to a chaotic structure of drift particle fluxes. Simulations show that a large enough radial electric field well can confine the banana and ripple blocked ions at closed orbits and provide their thermalisation during LHH pulse. The effect of altered plasma profiles is more significant in forming E_r for a quasistationary phase, than the generation of energetic tail ions.

The study was performed with the support of the Ministry of General and Professional Education of Russian Federation (1997 grant contest) and the Russian Fund for Fundamental Research Grant 97-02-18119 and 98-02-18346.

References

[1] Budnikov V.N. and Irzak M.A., Plasma Phys. Control. Fusion **38**, 12A, A135 (1996).

[2] Lashkul S.I *et al.*, Plasma Phys. Control. Fusion. **42**, A169 (2000).

[3] Lashkul S.I *et al.*, 1999, *26th EPS Conf. on Control. Fusion and Plasma Phys.*, Maastricht, p.1729.

[4] V.N. Budnikov *et al.*, JETP Lett., **59**, 687 (1994).

[5] E.O. Vekshina *et al.*, Pis'ma v Zh. Tekh. Fiz, **26**, **19**, 52 (2000).

[6] T. Kurki-Suonio *et al.*, *27th EPS Conf.* Budapest, **24**B, 1641 (2000).

[7] J.A. Heikkinen and S.K. Sipilä, Phys. Plasmas **2**, 3724 (1995).

[8] S.P. Voskoboinikov *et al.*, *27th EPS Conf.* Budapesht, **24B**, 288 (2000).