Spontaneous drop of the Li-containing flake as a trigger of ITB-event in plasmas of the T-10 tokamak during simultaneous co+counter injection of EC waves

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Abstract. Various triggers of ITB-events (ITB-event is an abrupt and non-local reduction of the heat flux within a radius of ~50% of the minor radius) have been previously found at the JT-60U, the T-10 tokamaks and the LHD stellarator. This short paper describes a new trigger of ITB-events discovered in the T-10 plasmas in experiments on simultaneous co+counter axial EC current drive performed using the X-wave with a frequency equal to the second ECR harmonic. In these experiments, the tungsten limiter and lithium wall coating were used. The ionization of atoms in the Li-containing flake, which occurs at the plasma edge, generally causes the rise of the electron temperature and density in the core of the plasma column. The electron heat flux reduces abruptly within the radial range of 0.2 < r/a < 0.8, just as it was at the LHD in experiments on the injection of small C⁸H₈ pellets. The energy confinement time abruptly increases by ~10%. After the transient phase, the ITB appears, which is located between the radii corresponding to the safety factors of q = 1 and q ≈ 1.4. Typically, the ITB lifetime is equal to the plasma energy lifetime. As far as we know, the triggering of ITB-events by the drop of Li-containing flake has been never reported in tokamaks and stellarators.

1. Introduction
The various triggers of ITB (Internal Transport Barrier) events (ITB-event is an abrupt decay of the heat and particles fluxes within the radial range of 40–60% of the minor radius; it was first observed at the JT-60U in the shots with the reverse magnetic shear (RS) configurations [1]) have been previously found at the JT-60U [1–4], the T-10 [5–7] tokamaks and the LHD [8] stellarator. In RS shots with NBI (Neutral Beam Injection) heating at the JT-60U, ITB-events were triggered either when the minimum safety factor q_min approached the low rational values, or when the internal and external MHD-activities were observed [1–3, 6]. The external MHD activity was considered to be the trigger in the JT-60U NBI-heated plasmas with the normal shear [4, 6]. In the T-10, at the flat q profile, ITB-events were triggered when the safety factor q tended to q = 1 in the central region of the plasma column after full [5] or partial [6] switching-off of the off-axis ECRH (Electron Cyclotron Resonance Heating). In the OH (ohmic heating) T-10 regimes, in the shots without obvious evolution of q-profile, the ITB-events are triggered by switching-off the strong gas puffing [7]. In ECRH regimes at the LHD, the abrupt reduction of the heat flux in the axial plasma region has been observed after the injection of the small C₆H₆ pellets [8]. The variation of plasma parameters has a considerable effect on the appearance of ITB-events in the LHD.
In the central region of the ECRH-heated T-10 plasmas, an increase in the electron temperature $T_e$ was previously observed after the injection of a medium-sized deuterium pellet, which was ionized in the outer half of plasma column [9]. The similar phenomenon was observed after the spontaneous drop of a carbon flake into the NBI-heated TFTR plasmas [10]. Nevertheless, in [9–10], it was not analyzed whether the heat flux jump was local or not local.

In experiments with different ECRH powers and various ECCD directions (EC current drive), the Li-containing flakes fall in a random way from the tungsten limiter into the plasmas. In the present paper, we describe a new trigger of ITB events at the T-10 tokamak ($R = 150$ cm, $\delta_{limiter} = 30$ cm) discovered in a series of shots with co+counter ECCD and 1.5 MW heating power. The shots were selected from the database collected over several years. After the atoms in the Li-containing flake were ionized at the plasma edge, the electron heat flux decreases abruptly within the radial range of $0.2 < r/a < 0.8$. The regime with co-counter ECCD was carefully considered (the work was reported at the 20-th EC International Workshop 2018, see ref. [11]), since the preliminary comparison of the X-ray spectra (PHA measurements) and the electron cyclotron emission (ECE) data shows that the electron energy distribution function of plasma in the axial heating region becomes considerably non-Maxwellian. The quantities and profiles of the absorbed EC power and driven current were calculated by the solution of Fokker-Plank equation with code OGRAY [12]. In the regime with co+counter injection, the plasma energy content in the EC-resonance region is higher than that in the regime with co+co injection. Moreover, in this regime, the spontaneous non-local L-H transition was observed at the T-10 tokamak [11].

The main results of the present work were presented at the 46th International Zvenigorod Conference on Plasma Physics and Controlled Fusion in 2019.

2. The spontaneous drop of Li-containing flake as a trigger of ITB-event
In this chapter we analyze the typical ITB-event occurring in plasmas in experiments on simultaneous co+counter ECCD (see the experimental scheme in [11]). Figure 1 presents time dependences of the central-line-averaged electron density $N_{e \text{ line av}}(0)$ (measured using microwave interferometer) and the $T_{e \text{ ECE}}$ electron temperature(ECE measurements, 11.5 cm) recorded in shot #71834 with the Li-flake drop (the electron density was $N_{e \text{ line av}}(0) = 2.6 \times 10^{13}$ cm$^{-3}$, the plasma current was $I_p = 250$ kA, the toroidal magnetic field was $B_t = 2.42$ T, $q_L = 3.5$) and in the similar reference shot #71836 without Li-flake drop. Both gyrotron pulses start at $t = 700$ ms.

![Figure 1](image1.jpg)

**Figure 1.** Time evolution of $N_{e \text{ line av}}(0)$ and $T_{e \text{ ECE}}(11.5 \text{ cm})$ for pulses #71834 and #71836 (reference shot).

![Figure 2](image2.jpg)

**Figure 2.** Time evolution of intensities of the optical spectral lines of deuterium $D_\beta$, singly ionized lithium and atomic tungsten for shot #71834.
In the reference shot, in the OH phase of the discharge, the $N_e \text{ line av} (0)$ density is 4% lower. In both discharges, the quasi-steady state is reached at $t = 740$ ms. In shot #71834, the $N_e \text{ line av} (0)$ density starts to increase at $t = 746$ ms after the fast ionization of atoms in the Li-containing flake.

Intensity of the spectral line of singly ionized lithium sharply increases during 2 ms (see Fig. 2). Figure 3 shows the time dependences of the $T_e$ temperature measured at different radii.

The $T_e$ temperature starts to increase simultaneously at all radii within a wide radial range. At the same time, the intensities of the optical spectral lines of deuterium $D_\beta$ (providing information on the plasma-wall interaction) and atomic tungsten (sprayed from the limiter) begin to decrease. Three radial $T_e$ profiles (measured in the OH phase just before ECRH, in the ECRH stage before the ITB-event and at $t = 762$ ms) are shown in Figure 4. The weak ITB forms between $r = 11.5$ cm (sawtooth inversion radius $r_s$, or $q = 1$ surface) and $r = 17$ cm. According to the Kadomzev reconnection model, the mixing region is equal to 15 cm and $q(17 \text{ cm}) \approx 1.3$. Since the $T_e$ gradient remains almost unchanged during the ITB-event, the jump in the electron heat flux $\delta \Gamma_e$ can be calculated from the simple equation ($S$ is the enclosed surface, and brackets mean the averaging over few ms) [1–4]:

$$<\delta \Gamma_e(S) > = -n_e <\delta \chi > \nabla (T_e) S(r) = -3/2 \int_0^\infty \delta <\partial (n_e T_e) / \partial t > dV$$

(1)

After the transition, the radial profile of $\delta (\partial T_e/\partial t)$ is slightly asymmetric both at the low and high field sides, since the Shafranov shift gradually increases after the ITB-event. The data from both sides of the plasma column was averaged. The average inversion radius (outside which the $T_e$ temperature starts to decrease) is equal to $r = 17$ cm. In this particular case, the rise of the $n_e$ density is important, since in the outer half of the plasma column, $\delta (\partial T_e/\partial t)/T_e < \delta (\partial n_e/\partial t)/n_e$.

Figure 3. Temporal evolution of the electron temperature $T_e$ at different radii for shot #71834.

Figure 4. $T_e$ profiles measured in OH phase, before the ITB event, at $t = 740$ and 762 ms, $a_{\text{limiter}} = 30$ cm.

Let us briefly discuss time evolution of the $n_e(r)$ profile measured using 10 channels of the microwave and laser interferometers. Time evolution of the $N_e \text{ line av} (0)$ density was measured with very high accuracy. The inversion and mixing radii of the sawtooth oscillations are equal to 11 cm and 15 cm, respectively. No perturbations of the $N_e \text{ line av} (0)$ density arose during the sawtooth oscillations crash, which occurred few milliseconds before the ITB-event. It means that the $n_e$ profile is flat within $r < 15$ cm. And vice versa, the positive jumps in the $N_e \text{ line av} (0)$ density appear after the ITB-event. It means that the $n_e$ profile becomes non-monotonic, and the $n_e$ density is higher in the radial range of $11 \text{ cm} < r < 15 \text{ cm}$ as compared to that in the radial range $r < 11 \text{ cm}$. This is the direct evidence of the fact that, during the ITB-event, the electron density flux really reduces at the core of the plasma column.
Figure 5. Profile of the electron heat flux jump $-\delta \Gamma_e$ during the ITB-event

The $-\delta \Gamma_e(r)$ profile obtained using Eq. (1) is shown in Figure 5. We do not expect the considerable decrease in the $-\delta \Gamma_e(r)$ at the plasma periphery, since the temperature $T_e$ is low and the density increases. The phase of the reduced transport lasts for 19 ms (the electron temperature and density start to decrease after $t = 765$ ms, see Figs. 1, 3) and this time is equal the energy confinement time. The data on the energy content $W_{\text{dia}}$ are averaged over time. The energy content $W_{\text{dia}}$ starts to increase after the ITB-event, the $dW_{\text{dia}}/dt$ rise rate being equal to $\approx 0.17$ MW, and the energy lifetime $t_{\text{E}}$ increases by $\approx 10\%$. And vice versa, at $t = 765$ ms after the failure of the improved confinement regime, the energy content $W_{\text{dia}}$ starts to decay, the $dW_{\text{dia}}/dt$ decay rate being equal to $\approx -0.2$ MW. The accumulation of impurities is absent.

3. Conclusions

This short paper describes the new trigger of ITB-events discovered in the T-10 plasmas in the core region of the plasma column in experiments on simultaneous co-counter axial EC current drive, which were performed using the tungsten limiter and the lithium wall coating. The ionization of atoms in the Li-containing flake, which occurs at the plasma edge, generally causes the rise of the electron temperature and density in the core of the plasma column. Such an increase in the electron temperature and density is typically observed in various series of shots with the ECRH power of 1.5 MW. The electron heat flux reduces abruptly within the radial range of $0.2 < r/a < 0.8$, as it was at the LHD during the injection of small $C_8H_8$ pellets [8]. The energy confinement time abruptly increases by $\approx 10\%$. The important direct evidence of the abrupt reduction of the electron density flux inside the plasma column ($0.35 < r/a < 0.5$) is the appearance of the sawtooth density oscillations with the inverse phase after the ITB-event. After the transient phase, the ITB appears, which is located between the radii corresponding to the safety factors $q = 1$ and $q \approx 1.4$. Typically, the ITB lifetime is of the order of the energy confinement time. As far as we know, the triggering of ITB-event by the drop of Li-containing flake has been never reported in tokamaks and stellarators.

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