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Peculiar properties of internal transport barrier formation near the q = 1 and q = 2 surfaces in tokamaks

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Abstract. A new type of internal transport barrier (ITB) was found in the T-10 tokamak plasma for the first time. It is created by sawtooth oscillations which are almost damped by off-axis electron cyclotron resonance heating and electron cyclotron current drive (ECRH and ECCD). During the ITB formation, the electron temperature, $T_e$, at a relative radius $r/a \leq 0.45$ rapidly rises to a new quasi-steady state, while the turbulence level, which is measured at the ITB, falls below its pre-crash value, and the turbulence spectrum shrinks in a wide range of frequencies. The ITB appears near the q = 1 magnetic surface and exists for approximately 50–70% of the plasma energy confinement time. During this process, accumulation of impurities was not observed. An abrupt and non-local reduction of the electron heat flux (ITB-event) around the q=1 surface (within 1 ms in the spatial zone with a relative radius $0.2 < r/a < 0.5$) was observed for the first time for the case with a gas puffing cut-off in OH T-10 discharges with an increasing high density. In contrast to the ITB that forms during the ECR heating, in this case, impurities begin to accumulate simultaneously with the ITB event. Analysis of the D-III-D experiments with a weak reverse magnetic shear shows that the appearance of a $q_{min} = 2$ surface leads to this ITB event in a very wide spatial region (the relative radius of the plasma column is $0 < r/a < 0.7$).

1. Introduction

The important role of low-order rational magnetic surfaces with a safety factor of q = 1, 1.5, 2, 2.5, 3... in the formation of internal transport barriers (ITBs) has been demonstrated earlier both in the plasmas of T-10 tokamak (major radius R = 150 cm, minor radius a = 30 cm) [1–6] and in the plasmas of many other tokamaks (e.g., see review [7]). In T-10, ITB has been recognized by analyzing the slow heat pulse propagation (HPP), which is induced by the onset of central electron cyclotron heating (ECRH) in a sawtooth-free plasma created via off-axis ECRH at the first and second harmonics [1–2]. The ITB forms near the q = 1 surface. The abrupt non-local reduction of transport (ITB-event) in the central part of plasma column often occurs together with the appearance [3] (or slightly before [4]) of the q = 1 surface in T-10 sawtooth-free plasmas. The role of magnetic shear has been demonstrated in T-10 experiments with co/contra ECCD (electron cyclotron current drive) at the center of plasma column [5–6].

The paper shows new peculiarities of the local and non-local processes of ITB formation in the plasmas of T-10 and D-III-D tokamaks. The results of chapter 2 have been reported at the 25-th FEC conference [8], and the full paper has been presented at the International Zvenigorod Conference on Plasma Physics and Controlled Fusion in 2017.
2. ITB created by sawtooth oscillations is almost damped by off-axis ECRH/ECCD in the T-10 tokamak

A new phenomenon is observed in the ECR heated plasma in the stage after sawtooth oscillations with a period exceeding 30 ms (their usual period is 4–7 ms) become almost damped by off-axis ECRH/ECCD [8]. Figure 1 shows the unusual evolution of $T_e$ in the T-10 tokamak shot with a 100-ms period of sawtooth oscillations. Sawtooth oscillations create the rise of $T_e$ at the radius $r = 16$ cm during the fast MHD phase of the current crash in the tokamak, and then the initial rise of temperature disappears within 1–1.5 ms (the limiter is placed at 30 cm). After the current crash, the phase inversion radius $r$, and the $q = 1$ surface are located near the radius $r = 12$ cm. Later, the value of $T_e$ (at the radius $r = 12$ cm) increases by 12% during 1-2 ms at the radius $r = 12$ cm, and the value of grad ($T_e$) increases by 40% between $r = 12.5$ and 16 cm. The heat pulse does not propagate outside the plasma column during the ITB existence (~20 ms). The value of electron thermal conductivity coefficient $\chi_e$ becomes 2.5 times lower compared with its value determined using the L-mode scaling on the T-10 tokamak. Figure 2 shows the evolution of turbulence during similar crashes in the T-10 tokamak shot 66049 ($I_p = 250$ kA, $B_t = 2.15$ T, $P = 1$ MW, $n_{line\ av} = 3 \times 10^{19}$ m$^{-3}$, $I_{ECCD} = 6$ kA), which is measured using a three-wave heterodyne correlation reflectometer (see details in [9]). The reflectometer data shows an enhanced turbulence level during 1–2 ms after the crash at frequencies 40-120 kHz. Later, during the ITB formation slightly outside the $q = 1$ surface (the outer edge of ITB lies at $r \approx 16$ cm), the turbulence level falls slightly below its pre-crash stationary value, and the spectrum of the turbulence shrinks.

The simulations of sawtooth behavior preformed using the transport code ASTRA [10] for the T-10 tokamak shot no. 63446 are shown in Fig. 1. The quantities and profiles of the absorbed EC power and driven current were calculated by solving the Fokker-Plank equation using the OGRAY code [11]. The calculations using the Kadomtsev reconnection model [12] supplied with the critical shear criterion [13] reasonably describe the sawtooth period. This is the case of the most effective sawtooth damping, which occurs at ECCD slightly outside of $q = 1$ [14]. Figure 3 shows the evolution of the $q$ profile, which is calculated between the current crashes, which are shown in Fig. 1. The EC current is generated in the narrow ~1.5-cm-wide zone (the poloidal angle of the mirror is 8°). The region with a reversed magnetic shear appears soon after the crash in the same region and survives for a long time.

Figure 1. Timetraces of $T_e$ in the T-10 tokamak shot no. 63446 ($I_p = 220$ kA, $B_t = 2.15$ T, $P = 0.8$ MW, $n_e$ line\ av = $1.8 \times 10^{19}$ m$^{-3}$, $I_{ECCD} = 10$ kA). $T_e$ increases at radius $r = 12$ cm, and the heat pulse does hot propagate outside the plasma column.
3. Abrupt and non-local reduction of the electron heat flux (ITB-event) around the \( q = 1 \) surface after gas puffing is cut-off in the OH regime in T-10 plasmas

The abrupt cut-off of gas puffing in discharges with high-density plasmas (in this case, the electron density \( n_e \) at the center of plasma column is equal to \( 7 \times 10^{19} \text{ m}^{-3} \)) initially creates a reduction of electron density \( n_e \) at the plasma edge starting at \( t = 823 \text{ ms} \). Figure 4 shows the evolution of electron temperature \( T_e \). The temperature increase starts simultaneously with an 8-ms delay in the plasma column zone with a radius \( 5 \text{ cm} < r < 15 \text{ cm} \) (the inversion radius or \( q = 1 \) surface is at the relative radius \( r/a = 0.25 \)), while the variation of electron density \( n_e \) is small at the central part of the plasma column. Since the variation of electron temperature gradient \( \text{grad} \ T_e \) is negligible, the following simple expression allows us to calculate the jump of the electron heat flux \( \delta \Gamma_e \), where \( A \) is the enclosed surface [15]:

\[
\langle \delta \Gamma_e A \rangle = -\langle \delta \Gamma_e \rangle \{ n_e \nabla T_e A(r) \} = -1.5 \{ \int n_e \langle \delta T_e \rangle \} \text{dV} \]  

(1)

The values of \( \delta \Gamma_e \) and \( \chi_e \) decrease in a wide radial zone (30–40\% of the minor radius) and decrease nearly twofold at a relative radius \( r/a = 0.4–0.5 \). In contrast to the case reported in chapter 2, impurities begin to accumulate simultaneously with the ITB event. The rise of soft X-ray (SXR) radiation strongly exceeds the rise of \( T_e \) since \( \left( \frac{\delta I_{\text{SXR}}}{dt} / I_{\text{SXR}} \right) \approx 6 \left( \frac{\delta \Gamma_e}{dt} / \Gamma_e \right) \).
4. Abrupt and non-local reduction of the electron heat flux (ITB-event) at the appearance of the $q_{\text{min}} = 2$ surface in the D-III-D tokamak

The evolution of $T_e$ in weak reverse shear plasmas during the gradual decay of the minimum q value, $q_{\text{min}}$, was presented in [16]. The appearance of $q_{\text{min}} = 2$ surface results in the increase of electron temperature $T_e$ inside the magnetic surface $q_{\text{min}}$ and electron temperature decay outside this surface. The $T_e$ perturbation profiles after the ITB event, which is presented in [16], were obtained 20 ms after the ITB event. Heat pulse propagation broadens the profile of $\delta\Gamma_e$, which is obtained using equation (1), by averaging over a significant time interval. We use a 5-ms time interval and a constant electron density $n_e(r) = \text{const}$ [this reduces spatial width of the heat flux $\delta\Gamma_e$, see Eq. (1)]. The application of expression (1) to the data presented in Fig. 5 [16] brings the appearance of a very wide profile of the electron heat flux perturbation $\delta\Gamma_e$ at a relative plasma column radius $0 < r/a < 0.7$ around the location of $q_{\text{min}}$. The width of $\delta\Gamma_e$ is wider compared with the one calculated in similar JT-60U tokamak experiments with a stronger reverse shear (there, the relative radius is $0.3 < r/a < 0.7$) [17]. Nevertheless, the maximum of the absolute value of the heat flux reduction $\delta\Gamma_e$ lies near the position of $q_{\text{min}}$ in both cases.

5. Conclusions

A new type of ITB, which is created by almost damped sawtooth oscillations (the ones with a strongly increased period) and off-axis ECRH/ECCD, is found in the T-10 tokamak for the first time. The electron temperature $T_e$ increases outside the phase inversion radius $r_s$ of the oscillations just after a sawtooth crash. The reflectometer data shows the significantly enhanced turbulence level and spectrum amplitude of the density fluctuations during ~1 ms after the crash in the outside wide spatial zone (in a wide range of frequencies, mainly at 40–120 kHz). The electron temperature $T_e$ decays fast during ~1 ms after the crash. Later, during the ITB formation, the electron temperature $T_e$ increases inside the relative radius $r/a = 0.45$ ($q = 1$ surface) to a new steady-state, and the heat pulse does not propagate outside the plasma column during 15–20 ms (50–70% of the plasma energy confinement time). The plasma heat conductivity $\chi_e$ value decreases by 2.5 times compared with the L-mode scaling, and the accumulation of impurities is absent. The turbulence level, which is measured at ITB, falls below its pre-crash value, and the turbulence spectrum shrinks in a wide range of frequencies. The calculations, which are performed using the ASTRA/OGRAY codes, show the appearance of the
reversed magnetic shear zone near the $q = 1$ surface soon after the crash. The appearance of the reverse shear appear is a necessary condition for the formation of the ITB. The abrupt and non-local reduction of the electron heat diffusivity (ITB event) around the $q = 1$ surface (in the zone $0.2 < r/a < 0.5$) in the new case is also reported for the first time. The ITB event occurs after the cut-off of the gas puffing in OH T-10 discharges with a high increasing density. In contrast with the ECRH case described above, impurities begin to accumulate simultaneously with the ITB event.

The analysis of the experiments with a weak reverse shear on the D-III-D tokamak shows that the appearance of the minimum q value surface with $q_{\text{min}} = 2$ leads to the ITB event in a very wide spatial region ($0 < r/a < 0.7$). A similar event also occurs in JT-60U tokamak plasmas with a stronger reverse shear around the position of $q_{\text{min}}$ in a more narrow region ($0.3 < r/a < 0.7$) [17]. The maximum of the absolute value of the heat flux reduction lies near the position of $q_{\text{min}}$ in both cases.

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