Non-local turbulent effect on internal transport barrier collapse in reversed shear configuration

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Abstract. The mechanism of transport barrier collapse in reversed shear configuration is investigated using a global ion temperature gradient driven drift wave (ITG) turbulence simulation code. The transport barrier collapse event is explained in the context of non-local meso-scale interaction. It is found that the turbulence evolution and the sustainment of the transport barrier is sensitive to the safety factor profile. However, some common meso-scale modes are excited via various non-linear interaction channels whether or not a meso-scale mode in the vicinity of the \( q \) profile minimum has resonant surfaces. The non-linear interaction among these non-local modes makes long range correlation possible and carries energy from the core region to the \( q \) minimum region. It was shown that such linkage can lead to the collapse of the transport barrier and the change of the global temperature profile.

1. Introduction

Recently, the internal transport barrier (ITB) has been observed in many tokamaks with a reversed-magnetic-shear (RS) configuration. The ITB is beneficial for the steady-state operation of International Thermonuclear Experimental Reactor (ITER) and advanced tokamak reactors. The improved performance with ITB was surveyed in multi-machine comparisons [1]. The analysis of experimental ITB database has made remarkable progress in understanding the ITB formation [2]. It is reported that there exist different kinds of ITB, such as the box-type or parabolic-type, depending on the magnetic field configuration [3]. The key physics of ITB and its characteristics have been studied by the database analysis and 1.5D transport simulation [4, 5, 6]. Thus far, many works on ITB formations have been done theoretically [7] and numerically [8, 9, 10, 11]. The velocity shear and the negative magnetic shear as well as the zonal flow play an important role in the ITB formation [12]. In addition, the suppression of turbulence is affected by the coupling with the zonal flow and the geodesic acoustic modes (GAMs) [13]. Recently, turbulence spreading is also investigated in terms of the barrier propagation [14, 15, 16]. The turbulent spreading can allow turbulence to penetrate the regions where local analysis predicts a low level of turbulent transport [17]. Moreover, turbulence spreading can dynamically couple different regimes of plasma such as the edge and core, so that it gives rise to non-local effects. The important issue remaining to be clarified is the mechanism of ITB collapse. Possible causes
reviewed in [23] include the barrier localized mode [18, 19], momentum transfer events [20, 21], and X-event [22].

In this paper, we report results from global simulations on ITB formation and collapse in reversed shear plasmas. Numerical calculations using a simple gyro-fluid model of the ITG turbulence are performed. We observed the formation of ITB similar to parabolic-type ITB and its expansion to the outside of q_{min}. The edge of the ITB outside of q_{min} is referred to as the ITB foot in this paper. It is found that the ITB collapse occurs due to the global mode which spreads out near the q_{min} surface. This mode is excited for both resonant and off-resonant cases by various energy channels, however, once it is excited the sequence of the ITB collapse is similar. Non-local interaction takes place between the core region and the ITB region, which excites the global mode near q_{min} region. During the collapse of the region inside the ITB, the ITB foot still remains for a short time due to the velocity shear stabilization, however, when ITG turbulence overcomes it, then the ITB foot collapse is triggered.

2. Model

2.1. Model equations

We employ the simplified version of the “3+1” gyro-fluid model [24] proposed by Ottaviani et al. [25] and modified by Yagi [16] to investigate the ITG turbulence transport by global simulation. The set of equations is described by the ion density, the ion parallel momentum and the ion temperature evolution equations as follows:

\[
\frac{dW}{dt} + \kappa_n \frac{1}{r} \frac{\partial \Phi}{\partial \theta} + A \nabla || V = \epsilon \omega_d F + \rho_s q \frac{\mu_{NC} \partial U_p}{\partial r} - \rho_s^2 \mu \nabla^2 F
\]  

(1)

\[
\frac{dV}{dt} = -A \nabla || F + 4 \mu \nabla^2 V - \mu_{NC} U_p - A \sqrt{\frac{T}{\tau}} \frac{\nabla ||}{\tau} \frac{\sqrt{\pi}}{\nabla \nabla || T}
\]  

(2)

\[
\frac{3}{2} \frac{dT}{dt} + \kappa_n \frac{1}{r} \frac{\partial \Phi}{\partial \theta} = \frac{\epsilon n}{dt} + \kappa_n \frac{1}{r} \frac{\partial \Phi}{\partial \theta} - \frac{9}{5 \sqrt{\pi}} \frac{\sqrt{T}}{\tau} \frac{\nabla \nabla || T}{\nabla \nabla || T}
\]  

(3)

where, \( W = n - \nabla^2 F \) is the generalized vorticity, \( n = \Phi - \langle \Phi \rangle \) the fluctuating density, \( F = \Phi + p/\tau \) the generalized potential, \( \tau = T_{ei}/T_0 \), \( p = n + T \) the fluctuating ion pressure and \( \langle \Phi \rangle \) the flux surface averaged potential, which is equivalent to \( \Phi_{m=0,n=0} \) in Fourier space. The approximation \( p_1 = T_{i0}(r_s) n_1 + n_0(r_s) T_{i1} \) is made where \( r_s = 0.6 \) indicates the location of the q_{min} surface. Here \( U_p = V + \rho_s \frac{\partial \Phi}{\partial \theta} \) represents the poloidal velocity, \( \kappa_T = -d \ln T_0/dr \) and \( \kappa_n = -d \ln n_0/dr \) indicate the inverse of the gradient scale length of the ion temperature and density, respectively, \( \omega_d = 2 \cos \frac{1}{r} \frac{\partial}{\partial \theta} + 2 \sin \frac{\partial}{\partial r} \) is the curvature operator, \( A = \epsilon / \rho_s \) is the ratio of the normalized ion gyro-radius \( \rho_s = \rho_s / a \) and the inverse aspect ratio \( \epsilon_s = a / R_0 \). We also introduced \( \epsilon = r / R_0 \) the local inverse aspect ratio. The transport coefficients are given by the ion thermal diffusivity \( \chi \), the neoclassical ion viscosity \( \mu_{NC} \) and the ion viscosity \( \mu \). Ion Landau damping is also taken into account as a collisionless dissipation \[26].

**Normalization:** \( t/t_B \rightarrow t, \ r/a \rightarrow r, \ z/R_0 \rightarrow z, \ e \Phi/T_{i0} \rightarrow \Phi, \ V/c_s \rightarrow V, \ T/T_{i0} \rightarrow T, \ \chi/(\rho_s c_s) \rightarrow \chi, \ \mu/(m_i n_0 \rho_s c_s) \rightarrow \mu, \ \mu_{NC} a^2/(\rho_s c_s) \rightarrow \mu_{NC} \) is used, where \( t_B = a^2 / \chi_B \) represents the Bohm time determined by the Bohm diffusion \( \chi_B = c T_{i0}/(e B) \).

2.2. Initial conditions

We introduce a heat source term into the model. It is given by \( S(r) = -8.0 \times 10^{-3} (2r^2 - 1)/(1 - r^2)^2 \) with \( r_s = 0.6 \) and is added to the ion temperature evolution equation (3). The equilibrium density profile is given by \( n_0(r) = (1 - r^2)/(1 - r_s^2) \) which is not changed during the simulation due to the relation \( n = \Phi - \langle \Phi \rangle \). The ion temperature is not separated into equilibrium and perturbative components \( T = T_0 + \tilde{T} \), but rather solved as a whole.
Figure 1. Safety factor profile for cases with $q_{\text{min}} = 1.35$ and $q_{\text{min}} = 1.30$. Magnetic shear has a null point at $r = 0.6$ in both cases. In the case with $q_{\text{min}} = 1.30$, the (4,3) mode has resonant surfaces at $r = 0.528$ and 0.666.

For the safety factor $q$ profile, we employ a reversed magnetic shear profile, proposed by Garbet et al. [10], which is given by $q(r) = q_{\text{min}} + C_2(r^2 - r_s)^2 + C_3(r^2 - r_s)^3$, with $r_s = 0.6$, $C_2 = 4.66$, and $C_3 = -0.987$. Here, we investigate two cases with $q_{\text{min}} = 1.35$, and $q_{\text{min}} = 1.30$. Note that in the case with $q_{\text{min}} = 1.35$, the $(m,n) = (4,3)$ mode is off-resonant. On the other hand, in the case with $q_{\text{min}} = 1.30$, the (4,3) mode has resonant surfaces around $r = 0.6$ as shown in figure 1.

3. Simulation results

3.1. Off-resonant case

At first, we investigate the case with $q_{\text{min}} = 1.35$. The system starts from $T(r) = 0$, and gradually evolves according to the transport equation. In this simulation, the heat source directly supplies the energy to the $T_{m=0,n=0}$ component where $m$ indicates the poloidal mode number and $n$ the toroidal mode number. In the early stages of evolution, the temperature gradient is small enough that the system is stable for the ITG modes and fluctuations are suppressed to a negligible level. When the temperature gradient exceeds the threshold value of the ITG instability ($t \sim 60$), the energy of the most unstable modes including (29,20), (30,20) and so on starts to grow at $r \sim 0.4$. Then, the energies of the zonal flow (0,0) and GAM (1,0) begin to increase. These modes saturate at finite amplitude by the non-linear interaction.

3.1.1. Time evolution of fluctuating energy

The top of figure 2 shows the temporal evolution of the fluctuating internal energies of some important modes during the saturation phase of the ITG modes. It should be noted that $\langle T \rangle$ cannot be separated into its equilibrium and fluctuating parts, so that we do not plot $T_{0,0}$ at the top of figure 2.

The (4,3), (7,4) and (11,7) modes are found to be non-linearly excited by the three wave
coupling. These modes are linearly stable, which is confirmed by solving the linearized equations and keeping the toroidal coupling. The non-linear eigenfunctions of the (7,4) and (11,7) modes are localized at each rational surface. Therefore, these are not low-n ballooning modes. Firstly, the (7,4) mode starts to grow at \( t \sim 70 \), then (11,7) and (4,3) modes start to grow at \( t \sim 75 \). These modes reach the same amplitude at \( t \sim 88 \) and the (4,3) mode still increases over the level of other modes. It saturates at \( t \sim 96.1 \). The behavior of the (4,3), (7,4) and (11,7) modes are related to the ITB collapse events as shown in the next section.

The bottom of figure 2 shows the temporal evolution of the fluctuating parallel ion kinetic energy. The zonal component \((0,0)\) has a large amplitude as does GAM \((1,0)\) in the saturation phase \((60 < t < 88)\). At \( t \sim 96 \), the (4,3) mode exceeds the level of the \((0,0)\) mode and dominates the system.

After the quench of the (4,3) mode at \( t \sim 96 \), the global structure of the ion temperature is changed, and all modes show quasi-periodic behavior. In this phase, intermittent bursting heat transport occurs, accompanied with a temperature profile relaxation concurrent with the avalanches [16].

3.1.2. ITB collapse

The time slices of the radial profile of the turbulent transport coefficient are shown in figure 3. At \( t \sim 75 \), the transport barrier is formed around \( r \approx 0.6 \). The barrier starts to collapse from inside at \( t \approx 88 \). However, the ITB foot \((r \approx 0.66)\) still remains till \( t \approx 95 \). Then it collapses abruptly and energy flows away at \( t \sim 96 \). As is shown in figure 2, the ITB collapse is due to the growth of the off-resonance (4,3) mode whose energy is fed by the non-linear coupling of the (7,4) and (11,7) modes. The trigger of the ITB foot collapse is related to the destabilization of the ITG modes near \( r \sim 0.66 \) at \( t \sim 96 \).

![Figure 3. Turbulent transport coefficient radial profiles with \( q_{\text{min}} = 1.35 \) from \( t = 75 \) to \( t = 96.1 \). Transport barrier is formed around \( r = 0.6 \) until \( t \sim 89 \).](image1)

![Figure 4. Time evolution of fluctuating internal energy with \( q_{\text{min}} = 1.30 \). The ITB starts to collapse at \( t \sim 71 \). The ITB foot collapses at \( t \sim 81 \).](image2)
3.2. Resonant case
Next, we investigate the case with (4,3) resonant surfaces near $q_{\text{min}}$. Figure 4 and 5 show temporal evolution of the fluctuating internal energy and time slices of the radial profiles of the turbulent transport coefficient in the case with $q_{\text{min}} = 1.30$.

In this case, the (4,3) mode starts to grow earlier than the (7,4) and (11,7) modes do in the off-resonant case. Until $t \sim 64$, it is driven by the non-linear coupling of the ITG modes such as the (30,20) and (34,23) modes; then its growth becomes slower at $t \sim 64$. Similar behavior is observed in the Neoclassical Tearing Mode (NTM) simulation [27] and is identified due to the beat interaction of drift waves [28]. Since the energy transfer channels are different from the previous case, they indicate different behavior in the growing phase ($70 < t < 76$). For example, the (7,4) and (11,7) modes are fed by (4,3) mode instead. Although the collapse of the ITB occurs at an earlier time, the sequence after $t \sim 76$ is similar to the previous case.

4. Discussion
4.1. Non-local turbulent transport effect on ITB collapse
Figure 6 shows time slices of the absolute value electrostatic potential profiles $|\Phi_{m,n}(r)| = \sqrt{\Phi_m^* \Phi_m}$ for the (4,3), (7,4) and (11,7) modes in the case with $q_{\text{min}} = 1.35$. At $t \sim 74.5$, (figure 6a), the (7,4) mode is excited at its resonant surface. It develops and spreads out (figure 6b). Once it reaches the resonant surface of the (11,7) mode, the (11,7) mode starts to grow (figure 6c). At the same time, the (4,3) mode is excited by non-linear coupling of these modes which is shown in figure 2. After that, the (4,3) mode develops around $r = 0.6$ (figure 6d). Then, the ITB starts to collapse from inside (figure 6e), however, the ITB foot still remains until $t = 95.9$. At $t \sim 96.0$, the stored energy inside the ITB abruptly bursts out (figure 6f). The (4,3) mode loses energy, however the (7,4) and (11,7) modes survive at rational surfaces (figure 6g). The connection between the (4,3) and (7,4) modes remains and interaction between them is sustained after collapse ($115 < t$ in figure 2).

Figure 7 shows the time slices of the absolute value radial profiles of these modes and the (15,10) mode in the case with $q_{\text{min}} = 1.30$. In the earlier phase ($t \sim 62$), the (4,3) mode is non-linearly driven by the (30,20) and (34,23) modes (figure 4). Then, the (15,10) mode grows at its resonant surface at $t \sim 68$ (figure 7a) and (11,7) mode is non-linearly excited by non-linear coupling between the (15,10) and (4,3) modes (figure 7b). Subsequently, the (7,4) mode is excited by the (11,7) and (4,3) modes (figure 7c). After that, similar sequence as the previous case is observed (figure 7d-g).

Although the (4,3) mode is off-resonant in one case and is resonant in the other case, the global eigenfunction of the (4,3) mode plays an essential role for the ITB collapse. In both cases, three modes with relatively small $k_r$, (7,4) located in the core region, (4,3) near the $q_{\text{min}}$ and (11,7) in between them, interact with each other. Once the connection between these modes has
been established, the internal energy stored in the core region is transferred to the ITB region.

We perform the simulation in which all non-linear interactions are suppressed in the (4,3) mode evolution equations except for the toroidal coupling. Figure 8 shows the time evolution of the fluctuating internal energy in the case when all non-linear interactions are suppressed in the (4,3) mode evolution equations. Figure 9 shows the transport coefficient radial profiles. In this case, the (4,3) mode does not grow so much, and the ITB collapse does not occur. It indicates that the (4,3) mode which is excited by three wave coupling plays an essential role in the global collapse of the ITB.

We also perform another simulation in which the all non-linear interactions are suppressed in the (7,4) and (11,7) modes evolution equations except for toroidal coupling. In this case, other mediator modes such as the (10,6) and (14,9) modes are excited instead of (7,4) and (11,7). Then, the (4,3) mode is non-linearly excited by three wave coupling with mediator modes, and causes the collapse of the ITB.

The long range interaction among the meso-scale turbulent rolls can destroy the internal

**Figure 6.** Time slices of absolute value radial profiles of (4,3), (7,4) and (11,7) modes with $q_{\text{min}} = 1.35$.

**Figure 7.** Time slices of absolute value radial profiles of (4,3), (7,4), (11,7) and (15,10) modes with $q_{\text{min}} = 1.30$. 
transport barrier non-linearly. The (4,3) mode is excited as the driver which leads to the energy minimum state, i.e., ITB collapse state. Our simulation shows that the channel of mediator mode generation is flexible. However, the non-local mode excited near $q_{\text{min}}$ is intrinsically chosen by the system.

4.2. Trigger of ITB foot collapse

Figure 10(a) indicates the radial profiles of the zonal component of the parallel velocity at $t = 92.0$ and $t = 95.7$. The velocity shear exists at $r \sim 0.68$ till $t \sim 93$. The ITB foot can be sustained by the shear flow stabilization of the ITG modes before the collapse.

Recent theoretical studies showed that only $E \times B$ flow shear is the dominant contributor to the shearing rate for the flute-like fluctuations. However, both $E \times B$ flow shear and toroidal flow shear contribute to the shearing rate for the ballooning-like fluctuations in toroidal plasmas [29]. Coupling of the (0,0) component of the $v_\parallel$ and ITG modes occurs via parallel dynamics. Actually, we observe the toroidal ITG mode near the ITB foot where the finite magnetic shear (finite $k_\parallel$) exists. In the vicinity of the $q_{\text{min}}$ region, the magnetic shear is weak and slab-like ITG might be excited, in this case, the zonal flow may play an important role for ITG suppression. We also perform a non-linear simulation suppressing the generation of the (0,0) component of $v_\parallel$ and confirm that the collapse of the ITB foot occurs at an earlier time ($t \sim 86$) due to the weak stabilization effect.

Figure 10. Radial profiles of (a) zonal component of parallel velocity, (b) transport coefficient, (c) $\hat{\kappa} = 2/3\kappa_T - \kappa_N$ the driving term of ITG mode, (d) fluctuating internal energy.
Figure 10(b) shows the profile of the transport coefficient at $t = 95.7$. The contribution from the (4,3) mode to the transport is not large outside the ITB foot ($0.7 < r < 0.8$), although the (4,3) mode spreads out in this region shown in figure 10(d).

Figure 10(c) indicates the radial profile of driving term of the ITG mode $\hat{\kappa} \equiv \frac{2}{3} \kappa_T - \kappa_n$. $\hat{\kappa}$ has a peak value at $r \sim 0.7$, i.e., the position of steep temperature gradient, which indicates the destabilization of the ITG modes near the ITB foot.

Figure 10(d) shows the absolute value of the fluctuating internal energy of the ITG modes destabilized near the ITB foot before collapse and the (4,3) mode in the $q_{\text{min}} = 1.35$ case at $t = 95.7$. For $t \leq 93$, the ITG modes such as (29,20) are excited at $r \sim 0.45$, i.e., the resonant surface inside the $q_{\text{min}}$ surface, but the ITG modes such as (43,31) and (29,20) have small amplitude outside of $q_{\text{min}}$. In the simulation in which all non-linear interactions are suppressed in the (4,3) mode evolution equations, we observe the weak excitation of the ITG modes in the vicinity of the ITB foot. It indicates that the global collapse of the ITB driven by the (4,3) mode gives rise to the quasi-linear profile modification which destabilizes ITG modes at the ITB foot. From $t \sim 93.0$, the zonal flow profile starts to change according to the growth of the (43,31) and (29,20) modes. At $t \sim 96.0$, these modes cannot be suppressed any more by the velocity flow shear, and the collapse of the ITB foot occurs.

Accompanied with the burst, the peak of $\hat{\kappa}$ propagates outward and decays as shown in figure 11, which indicates avalanches. The temperature profile is modified by this large-scale relaxation. After the collapse of the ITB foot, the zonal flow is regenerated by excited micro turbulence. However, transport suppression inside the ITB is not as complete as before. As a result, the system indicates quasi-periodic oscillation with intermittent energy transport accompanied with avalanche as is shown in figure 12.

Figure 11. Time slices of radial profile of $\hat{\kappa}$. The peak at $r \sim 0.7$ indicated by (x) spreads out in a short period. Other small peaks indicated by (o,+) also spread in and out.

Figure 12. Intermittent heat transport measured at $r = 0.7$ in the $q_{\text{min}} = 1.35$ case. The bursts are synchronized with the decay of the (4,3) mode in figure 2.
5. Conclusion

We investigate the multi-scale interaction between transport and turbulence in the reversed shear configuration, using the global ITG simulation code. It is found that the (4,3) mode plays an important role in the ITB collapse for cases with or without the (4,3) rational surface. However, the development of the (4,3) mode is controlled by the different energy channels causing the timing of the collapse to vary. For the off-resonant case, the (4,3) is excited by the non-linear coupling between the (7,4) and (11,7) modes and the ITB collapse occurs later than in the resonant case. For the resonant case, the (4,3) mode is excited by the (30,20) and (34,23) modes in the early non-linear phase, but in the later non-linear phase, similar behavior to the off-resonant case is observed. The ITB foot remains for a while during the ITB collapse due to velocity shear stabilization of the ITG modes after which it abruptly bursts out. It is concluded that the ITG modes excited near the ITB foot trigger the collapse of ITB foot. Afterwards, the avalanche occurs and the temperature profile is modified by the large-scale relaxation. Then, the system takes on a quasi-periodic oscillation with intermittent energy burst. Thus, the analysis in this article provides the basis to understand the quasi-periodic onsets of barrier collapse in plasmas with internal transport barrier [23].

The phenomena is attributed to non-local interactions with different spatial and temporal scale. We have shown one example of multi-scale interaction between transport and turbulence.

We have also shown that the timing of collapse is sensitive to the safety factor profile since the meso-scale mode is excited by the different energy channels. Therefore, it is necessary to solve Ohm’s law to investigate the effect of the safety factor profile on the ITB collapse more accurately by taking into account the q profile evolution, which requires electromagnetic dynamics be included in the simulation. This is left for a future work.

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